A Risk Based Approach for Proactive Asset Management of Sewer Structural Conditions in England and Wales

Oluwagbenga Samuel Tade

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Division of Civil and Building Services Engineering

School of the Built Environment and Architecture

London South Bank University

October, 2018

Abstract

The aim of this research is to create a risk based framework to prioritise proactive investment for sewers in England and Wales. This research proposes a sewer deterioration model that will enhance and not replace the industry's business as usual process and it also recommends how standard sewer assessment reports can be better utilised to inform business decisions.

The methodology used to complete this research project is a mixture of qualitative and quantitative approaches to analyse a total length of 24,252 km which represents 703,156 records of historic sewer structural condition inspection data. This was used to build an improved deterioration model. Proactive investment (future condition prediction) assessments have been made within Thames Water and other wastewater utilities in the UK. The approaches are reviewed, compared, limitation identified and a robust approach was defined, devising means to mitigate the limitations identified. Existing approaches within and outside the industry to assess sewer condition and model sewer deterioration for risk management was reviewed. Data analytical software such as MATLAB and Tibco Spotfire were used to create an intuitive risk framework that will aid sewer investment decision making.

An improved deterioration model and inspection frequencies for sewers were developed as a premise for proactive investment. This deterioration model and the inspection frequencies were then used to create a risk based framework to help set proactive priorities for sewer management. This would enable sewerage asset owners with large kilometres of sewers to manage the sewerage system more proactively before they reach a critical point and reduce the reliance on industry expert judgement and further surveys. The improved deterioration model and inspection frequencies provided in this research would enable sewer asset managers to determine the most cost-effective time to invest in repairs or replacement. Also, a plausible and reliable validation that was provided would give a high level of confidence in the risk based framework.

Keywords: Sewer condition, Deterioration modelling, Condition scores, Asset management, Risk, Proactive investment

Disclaimer

This thesis is submitted to London South Bank University and must not be published as it is commercially confidential. The views expressed in this thesis do not necessarily reflect the views of any participating utilities. Neither the Water companies and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

Confidentiality sign off form

I have checked this research title **"A Risk-Based Approach for Proactive Asset Management of Sewer Structural Condition in England and Wales"** and I am satisfied that it satisfies confidentiality agreement.

Comments:

………………………………………………………………………………………………….........................

....

....

....

....

....

....

....

....

....

....

Signature: … Siobhan O'Neill…..

Dr Siobhan O'Neill

Date: …………13/09/2018………

Thames Water Utilities Ltd

Reading, Berkshire, United Kingdom

Declaration

I hereby declare that to the best of my knowledge this research title **"A Risk-Based Approach for Proactive Asset Management of Sewer Structural Condition in England and Wales"** is the original work of Oluwagbenga Samuel Tade and has not been submitted to any university or learning institute for the award of higher degree.

The data collected and used in this thesis is authentic and property of Thames Water Utilities Ltd.

Signature: ……*Olugbenga*…………………

Oluwagbenga Samuel Tade

Date: ………01/10/2018………………………………………...

Acknowledgement

The success of this thesis required a lot of support and guidance from supervisors and colleagues.

I will like to thank my supervisor, Dr Amer Ali for his guidance, support and immense contribution towards the successful completion of this thesis. I will also like to thank Dr Ali Bayyati my second supervisor as well for his guidance and contribution.

I will like to thank Dr Siobhan O'Neill, Tracey Williams, Chris Hinton, Dr Sivaraj Valappil, Michael McSweeney and Paul Woodburn of Thames Water for their support and contribution in making all necessary data, reports and training available.

Kenneth Smith my former supervisor for his support and immense contribution even after his retirement.

God bless you all!

I will like to say a big thank you to Thames Water Utilities limited most especially Martin Baggs the former CEO for giving me the opportunity to work on this project and Stephen Pattenden for giving me the privilege to apply the model.

Finally, I will like to say a big thank you to London South Bank University and TUNS Consult Limited for the matched funded scholarship.

Dedicated to…

Ethan Tade

My Ming, thanks for bringing sunshine to my life. Thanks for making me smile and laugh in times of frustration.

Siobhan O'Neill

Thanks for your encouragement and moral support. Your faith in me gave me the confidence to persevere even when I struggled. Thanks for making me believe I can do this even when I thought I couldn't. Your patience and immense contribution to this PhD is really appreciated.

Elizabeth Tade

My champion and my support

Thanks for your encouragement, love and understanding during the PhD research.

Mr & Mrs Nwabuche

Thanks for your support throughout this research.

My parents, Engr & Mrs Oluyole Tade and my siblings; Lola, Busola and Opeyemi

Thanks for your support and prayers

You guys are my heroes

Table of Contents

List of Figure

List of Tables

List of Equations

General List of Abbreviations

AHP	Analytical Hierarchy Process
AIDM	Artificial Intelligence Deterioration Models
AM	Asset Management
ASCE	American Society of Civil Engineers
BAU	Business as Usual
CCTV	Closed Circuit Television
CNRC	Canadian National Research Council
COF	Consequence of Failure
CSM	Cohorts' Survival Model
DDM	Deterministic Deterioration Model
DM	Deterioration Model
DSR	Data Source Reliability
FSM	Fuzzy Set Model
GIS	Geographic Information Systems
ICG	Internal Condition Grade
LOF	Likelihood of Failure
LRM	Logistic Regression Model
MDM	Multiple Discriminant Model
MM	Markov Model
MSCC	Manual for Sewer Condition Classification
MSSN	Maintenance Strategies for Sewer Network
NAPPI	The North American Association of Pipeline Inspectors

NASSCO	National Association of Sewer Service Companies
NNM	Neural Networks Model
NRC	National Research Council of Canada
OFWAT	Water Services Regulation Authority
OSCPF	Optimized Sewer Condition Priority Formula
PACP	Pipeline Assessment and Certification Program
PDM	Probabilistic Deterioration Model
SMM	Semi-Markov Model
RBF	Risk-Based Framework
ROF	Risk of Failure
SCG	Structural Condition Grade
SRM	Sewer Rehabilitation Manual
WRc	Water Research Centre

List of Abbreviations for Sewer Material Types

AC	Asbestos Cement
BL	Bitumen Lining
BRK	Brick
CC	Concrete Chute
CI	Cast Iron
CL	Cement mortar Lining
CP	Concrete Pipe
CS	Concrete Segment
CSB	Concrete Segment Bolted
CSU	Concrete Segment Unbolted
DI	Ductile Iron
EP	Epoxy
FC	Fibre Cement
FRP	Fibre Reinforced Plastics
GI	Grey cast Iron
GRC	Glass fibre Reinforced Concrete
GRP	Glass fibre Reinforced Plastics
HDPE	High Density Polyethylene
I	Unidentified Iron
MAC	Masonry – in regular courses
MAR	Masonry –Randomly coursed
MDPE	Medium Density Polyethylene

PE	Polyethylene
PF	Pitch Fibre
PL	Plastic
PP	Polypropylene
PS	Polyester
PSC	Pre-stressed Concrete
PVC	Polyvinyl Chloride
RC	Reinforced Concrete
RPM	Reinforced Plastic Mortar
SI	Spun Iron
SPC	Sprayed Concrete
ST	Steel
UPVC	Un-plasticized Polyvinyl Chloride
UPVCC	Un-plasticized Chlorinated Polyvinyl Chloride
UPVCE	Un-plasticized light weight Polyvinyl Chloride
UR	Unidentified
VC	Vitrified Clay
X	Unidentified material
XI	Unidentified type of iron or steel
XP	Unidentified type of plastics
Z	Other (details should be recorded in the remarks section)

Chapter 1
Introduction

"**Gentility of speech is at an end- it stinks, and whoso once inhales the stink can never forget it and count himself lucky if he lives to remember it" (Press, 1858).** The River Thames became a dumping site for wastes from paper mills, abattoir, breweries, and various household wastes. The Thames became polluted and of public concern. At the peak of the outbreak of cholera in 1849, it was reported that 2000 Londoners were dying from the disease per week (Stephen, 1999). In the 19th century, Joseph Bazalgette constructed the Victorian sewers which alleviated the cholera outbreak (Cook, 2001). This event is a reminder of the importance of a Sewer Network (SN).

The SN system consists basically of the following: a series of pipes of different properties (gravity networks and rising mains), manholes and pumping stations (WRc, 2014). This research focuses on gravity sewers and a sewer is defined in this context as a manhole to manhole length. These sewers are of different material types, sizes, ages, shapes, depths, lengths, surrounding soil types, effluent characteristics and in different locations around England and Wales.

The SN in the United Kingdom contains some of the oldest network of sewers in the world with a net reported length of 624 000 km. In England and Wales, the water industry is currently responsible for some 350 000 km of sewers, operates some 9000-sewage treatment works and is responsible for over 25000 intermittent discharges to the environment from wastewater systems annually (UKWIR, 2015). For example, Thames Water manages one of the largest areas of 13,000 square kilometers including the City of London with a total length of 106,000 km of sewers. Increase in population and ageing of the SN in England and Wales has necessitated an improved Asset Management (AM) model to be developed. AM of SN involves condition assessment of sewers. This requires routine inspections and analysis of inspection data from which overall rehabilitation and maintenance plan can be obtained. Future investment requirements can also be determined as well. As a result of the expense and duration of sewer condition inspection and condition grading, processes that would allow greater initial prioritization and enhanced value from the inspection should be sought (Mashford, et al., 2011).

Condition grading or scoring protocols are used to assign sewer conditions scores. There are many sewer condition scoring protocols available, but this research focuses on the WRc (Water Research Centre) condition scoring. The WRc condition scoring protocol is what is used in the UK and the majority of wastewater utilities around the world (Rahman & Vanier, 2004). The WRc condition classification protocol is regarded as the embryo code as it was based on this scoring protocol that other protocols were developed (Thornhill & Wildbore, 2005).

Understanding the rate of deterioration in SN and evaluating the condition of sewers is very crucial to wastewater utilities as it is the premise of proactive AM and investment decision. Investment in the SN involves assessment expenditure (CCTV inspection) and rehabilitation expenditure. Deterioration Models (DMs) are essential to determine the future condition of an infrastructural asset and to estimate future investment requirements; hence DMs is an intrinsic part of AM (Ens, 2012).

1.1 Degradation process and properties of materials in sewers

There are numerous sewer material and composite material types that have been used for sewers in the UK. These materials are shown in Table 1.1.

Table 1.1. Sewer material types in the UK (BPSHCA, 2013)

Asbestos cement, Bitumen lining, Brick, Concrete chute, Cast iron, Cement mortar lining, Concrete, Concrete segment, Concrete segment bolted, Concrete segment unbolted, Ductile iron, Epoxy,	Fibre cement, Fibre reinforced plastics, Grey cast iron, Glass fibre reinforced concrete, Glass fibre reinforced plastics, Pre-stressed concrete, Polyvinyl chloride, Reinforced concrete,	Reinforced plastic mortar, Spun iron, Sprayed concrete, steel, High density polyethylene, Masonry – in regular courses, Masonry randomly coursed, Medium density polyethylene, Polyethylene, Pitch fibre,	Plastic, Polypropylene, Polyester, Un-plasticized polyvinyl chloride, Un-plasticized chlorinated polyvinyl chloride, Un-plasticized light weight polyvinyl chloride, Vitrified clay

Four major sewer material types are focused on in this research as they represent the majority of sewers in England and Wales. These four major sewer material types are; vitrified clay, concrete, cast iron and brick. Their mechanical properties are shown in Table 1.2. More details on the physical and mechanical properties of some other different materials used for sewers can be found in Appendix I. Apart from the properties listed in Table 1.2, Appendix I also includes; environmental resistance, maximum service temperature and material price per kilogram of the different materials.

Table 1.2. Mechanical properties of the major material types used in sewers (Adapted from Cambridge, 2003 and Liddell, 1922)

Material	Melting Temperature	Density	Young's Modulus	Yield Stress	Tensile Strength	Fracture Toughness	Poisson Ratio
	T_m	ϱ	E	σ_y	σ_{ts}	K_{IC}	K_{IC}
	(^{O}C)	(Mg/m3)	(GPa)	(MPa)	(MPa)	(MPa√m)	(MPa√m)
Vitrified Clay	1000.00 - 1600.00	2.00 - 2.88	20.00 - 50.00	11.00 - 29	15.00 - 40.00	1.70 - 2.00	0.30 - 0.45
Concrete	927.00 - 1227.00	2.20 - 2.60	25.00 – 38.00	32.00 - 60.00	2.00 - 6.00	0.35 - 0.45	0.10 - 0.20
Cast Iron	1130.00 - 1250.00	7.05 - 7.25	165.00 - 180.00	215.00 - 790.00	350.00 - 1000.00	22.00 - 54.00	0.20 - 0.30
Brick	927.00 - 1227.00	1.90 - 2.10	10.00 - 50.00	50.00 - 140.00	7.00 - 14.00	1.00 - 2.00	0.12 - 0.29

To understand the deterioration of sewers, it was necessary to understand the failure mechanism of defects in the different sewer material types. Failure pathway for a crack is as shown in Figure 1.1. The failures that occur in sewers include; ring failure, bending failure and brick sewer failure (UKWIR, 2015).

The Sewer Rehabilitation Manual (SRM) developed by WRc subdivides the mechanism of sewer structural failure into three stages; formation of an initial defect, deterioration of the pipe arising from defects and collapse of the weakened sewer (WRc, 2001). This failure could be caused by a mechanical or chemical attack in sewers.

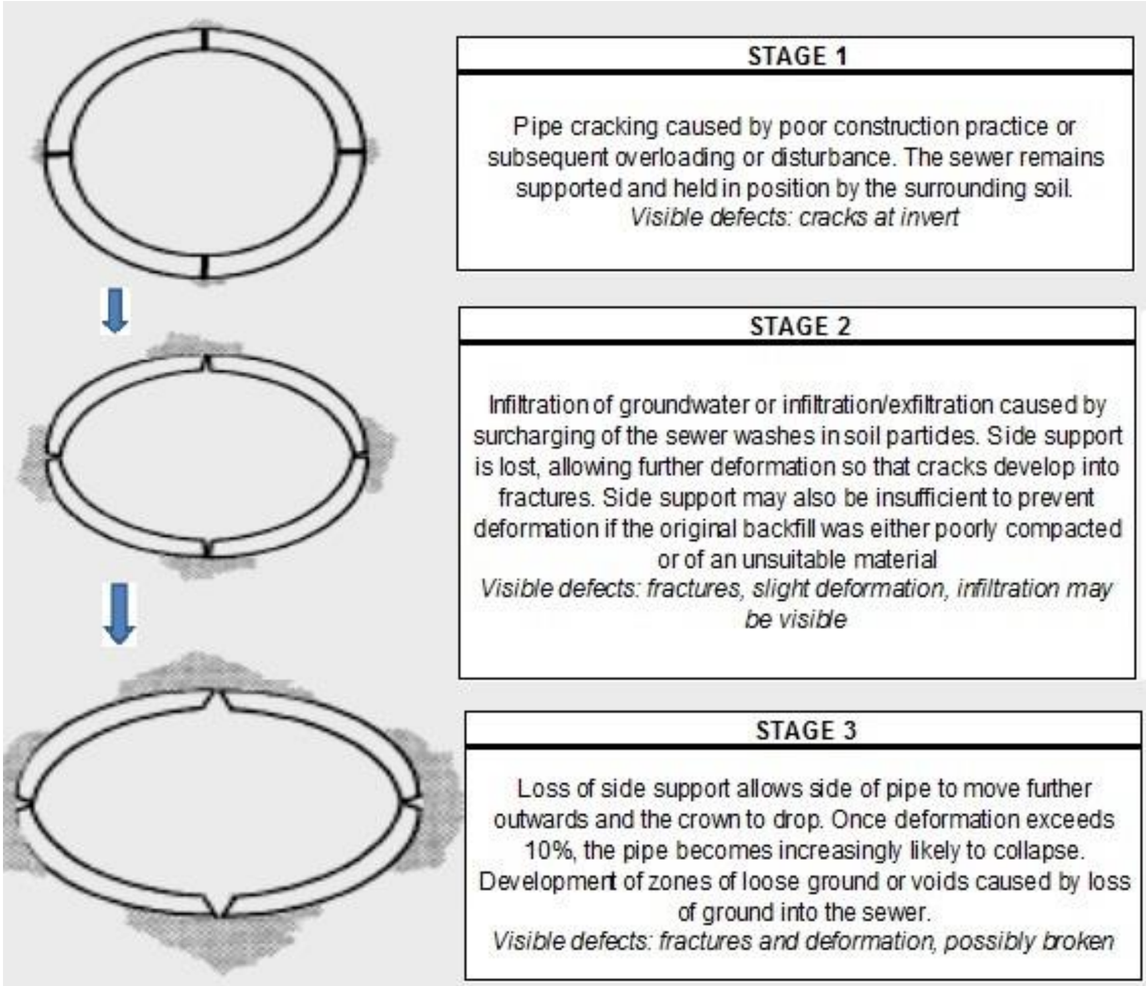


Figure 1.1. One of the most common sewer failure mechanisms (Adapted from Davies et al, 2001)

Vitrified clay: Vitrified clay pipe is one of the oldest types of pipe used in sewage system. It is fabricated from the vitrification of shale and clay (Ing et al., 2004). The use of vitrified clay pipe has improved over the years. Manufactured to British and European standard BS EN 295-1, it is strong, sustainable, inert, reliable and has flexible watertight joints (NCPI, 2015). Figure 1.2 shows the installation of a vitrified clay sewer with an arrow pointing to the watertight joint. The yellow material is a flexible rubber coupling which provides root resistance, flexibility, corrosion resistance and provides tightness to the joint (Evans & Spence, 1985).

Figure 1.2. Modern Vitrified Clay (NCPI, 2015)

Clay pipes are generally designed to withstand a crushing test of 28kN/m to 72kN/m and with a bending moment resistance of between 2kNm to 9 kNm depending on the size (BS EN 295-1: 2013). The main chemical constituents of clay are Silicon dioxide (SiO_2) and Aluminium oxide (Al_2O_3) (Chin et al., 2017). Unlike some other material types, clay is inert (resistant to chemical attacks such as acids, alkalis and solution attacks) and rust with the exception of hydrofluoric acid which is hardly found in sewers (UoM, 1946). It was a suitable alternative to the costly replacement caused by corrosion and rusting of other material types such as concrete and iron. It is exceptionally resistant to abrasion and durable (NCPI, 2015). In most cases, failure in vitrified clay sewers occurs as a result of mechanical failure when they are loaded beyond their design carrying capacity. This excessive loading induces cracking as shown in Figure 1.3.

Figure 1.3. Cracked Vitrified Clay sewer (Balkan, 2017)

Concrete pipes: Concrete pipes are mostly made by mixing cement and aggregates with suitable water to cement ratio. They are known for their high strength, rigidity and hydraulic efficiency. Unlike iron pipes, they are resistant to rusting and can be made to suit a loading condition.

Concrete pipes are also suited for situations where resistance to flammability is of importance, especially for temperatures that are not extreme, because they do not burn easily (Ezekiel, 2015). The durability of concrete pipes is dependent on some factors such as climatic condition of the surrounding environment where the pipe is located, the construction materials (reinforcement cover and admixtures) and the processes of manufacturing used. The chemical degradation of concrete pipes can be caused by acid, salt or alkalis. One of the major factors affecting the durability of concrete is sulphate attack such as sodium sulphate (Na_2SO_4), Magnesium sulphate

($MgSO_4$) which causes concrete to lose its strength by affecting $Ca(OH)2$ (Kamau and Ahmed, 2017). Figure 1.4 shows an example of concrete sewer sections.

Figure 1.4. Concrete pipe sections (Marshalls-CPM, 2018)

Effect of acid on concrete pipes: The effect of acid on concrete pipes is a microbial corrosion process caused by the presence of bacteria (*Thiobacillus ferrooxidans*) in untreated wastewater (Wei *et al.,* 2014). The bacteria oxidise hydrogen sulphide present in the untreated water to sulphuric acid. The produced acid reacts with the calcium hydroxide present in cement to produce water-soluble calcium sulphate that causes aggressive deterioration of the cement (Hongguang & Zhigang, 2018). The microbial induced corrosion process is shown in Figure 1.5 and the reaction is shown in Equation 1.1.

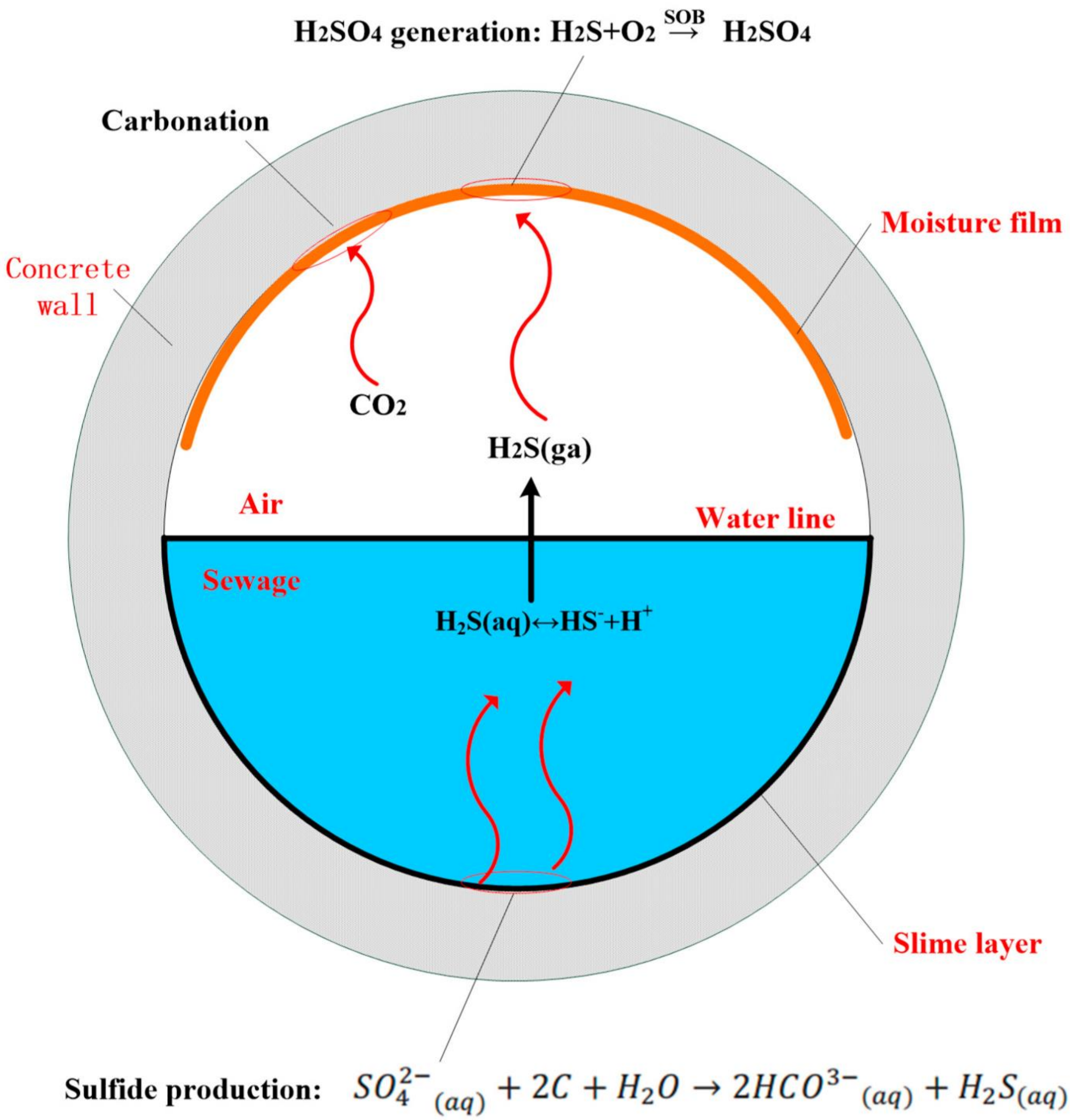


Figure 1.5. Microbial induced corrosion hydrogen sulphide attack (Linping et al., 2018)

Equation 1.1.Acid attack on portlandite

$$Ca(OH)_2(portlandite) + \ H_2SO_4 \rightarrow CaSO_4 + 2H_2O$$

$$3CaSO_4 + 2H_2O(gypsum) + 3CaO.Al_2O_3 + 26H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4\ .32H_2O\ (ettingite)$$

As shown in Figure 1.6, acid can corrode the internal lining of concrete sewer and thereby exposing the rebar for a chemical attack such as rusting which will be discussed under cast iron material. This process reduces the structural integrity of concrete sewer which could eventually lead to a collapse.

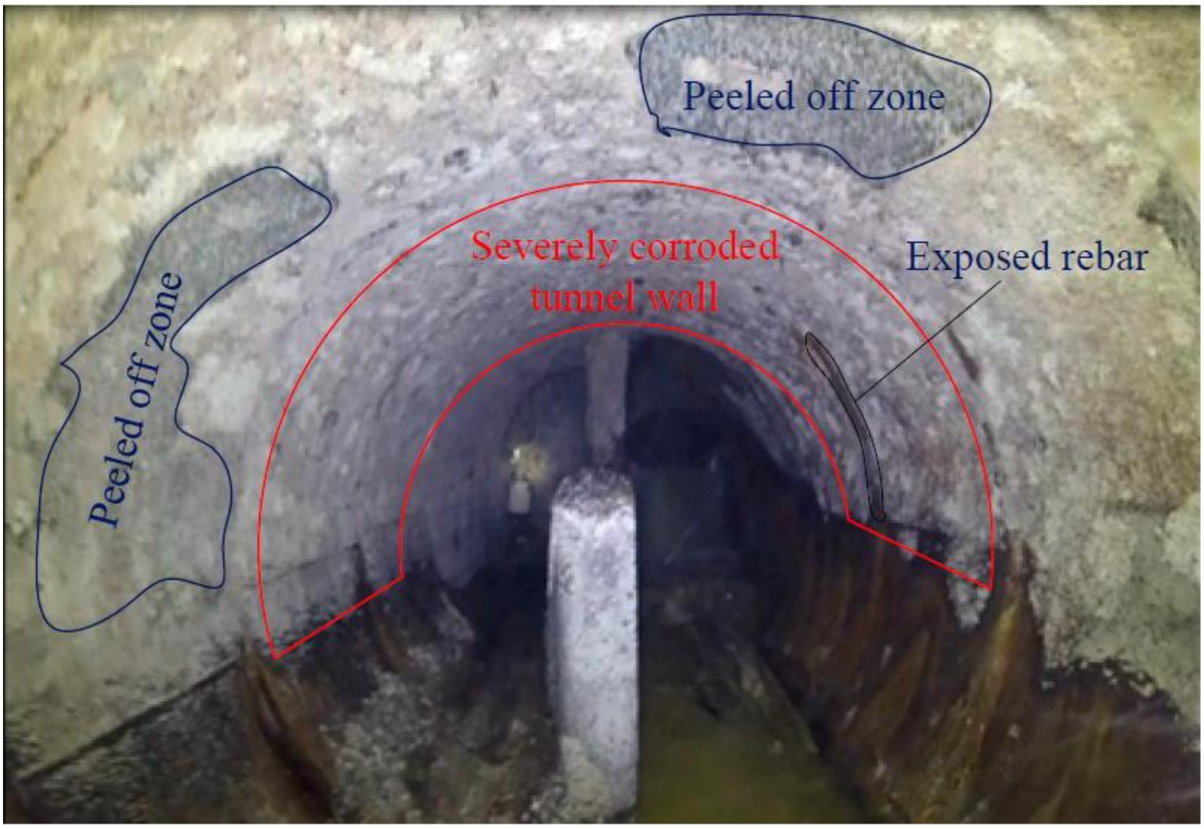


Figure 1.6. Corrosion conditions in a concrete sewer (Linping et al., 2018)

Effect of alkali on concrete: Alkali deterioration of concrete results in the development of cracks in concrete and consequently leads to a collapse. Two types of alkali can cause deterioration in concrete sewers; the alkali silica process and the alkali carbonate process. The most common type of deterioration is the alkali silica process; because the concrete aggregates containing silica materials are mostly used (Fernandes & Broekmans, 2013). Figure 1.7 shows the process of alkali attack on concrete sewer.

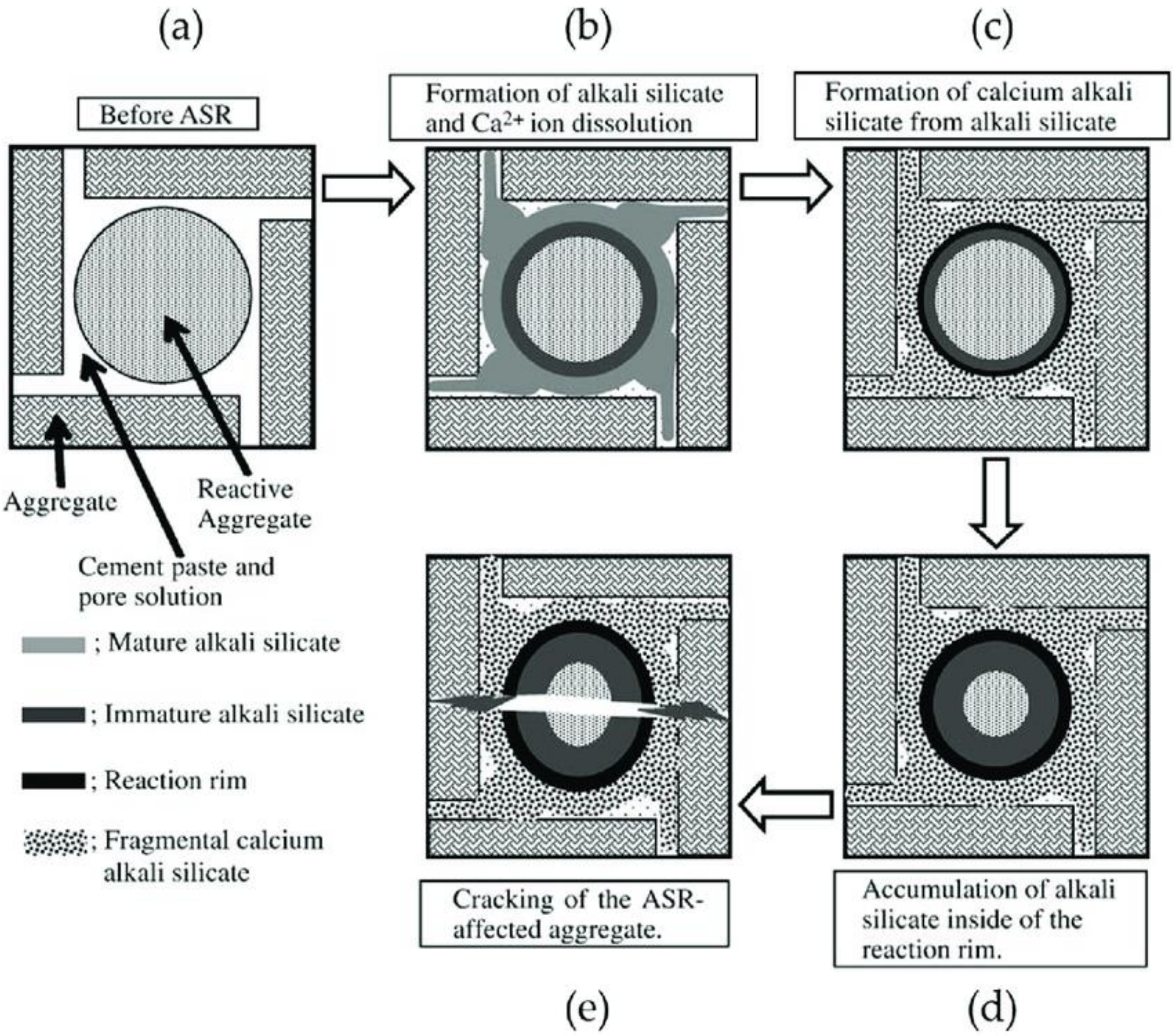


Figure 1.7. Alkali silicates attack on concrete (Kunpeng et al*, 2016)*

Cast iron pipes: Corrosion is a gradual deterioration process caused by the interaction of metals with oxygen and moisture present in the surrounding air which results in the formation of oxides (U. R. Evans, 1967). There are different types of iron pipes used for sewers in England and Wales. They include; cast iron, ductile iron, spun iron and grey cast iron. The major difference between these irons is their carbon content.

The corrosion of iron (Fe) is called rusting and it is of higher significance because iron is the most commonly found metal in the environment (Frey & Reed, 2012).

When iron is exposed to air in the presence of moisture, electrochemical cells are formed at the surface of contact (Osei, 1985). Figure 1.8 shows the formation of rust at the surface of contact.

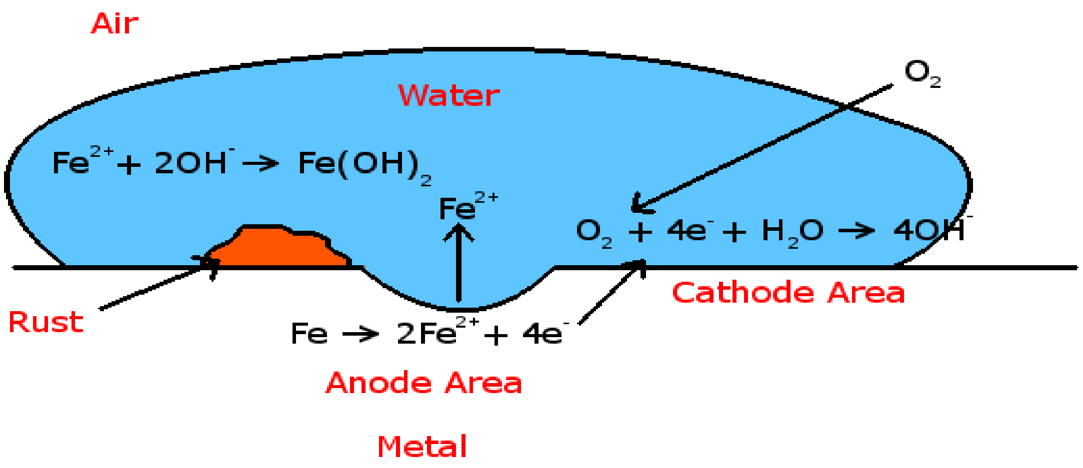


Figure 1.8. Rusting in Iron. (Deleanu et al., 2009)

Rusting is an electrochemical process and the steps involved are as explained below;

Step 1: At the anode, iron is oxidized to give iron (II) ions Fe^{2+} as shown in the chemical equation below.

Equation 1.2. Oxidation half-reaction:

$$Fe(s) \rightarrow Fe^{2+}(aq) + 2e -$$

Step 2: At the cathode, oxygen from the air dissolves in the water layer present on the surface of the metal consequently increasing the level of oxygen in the water. The oxygen is then reduced by the electrons produced from the anode to give hydroxide ions, OH^-.

Equation 1.3.Reduction half-reaction:

$$O_2(g)\ + 2H_2O(l) \rightarrow 4e-\rightarrow 4OH-(aq)$$

Equation 1.4. Overall reaction

$$2Fe(s) +\ O_2(g) + 2H_2O \rightarrow 2Fe^{2+}(aq) + 4OH-(aq)$$

Figure 1.9 shows the exchange of ions during rusting.

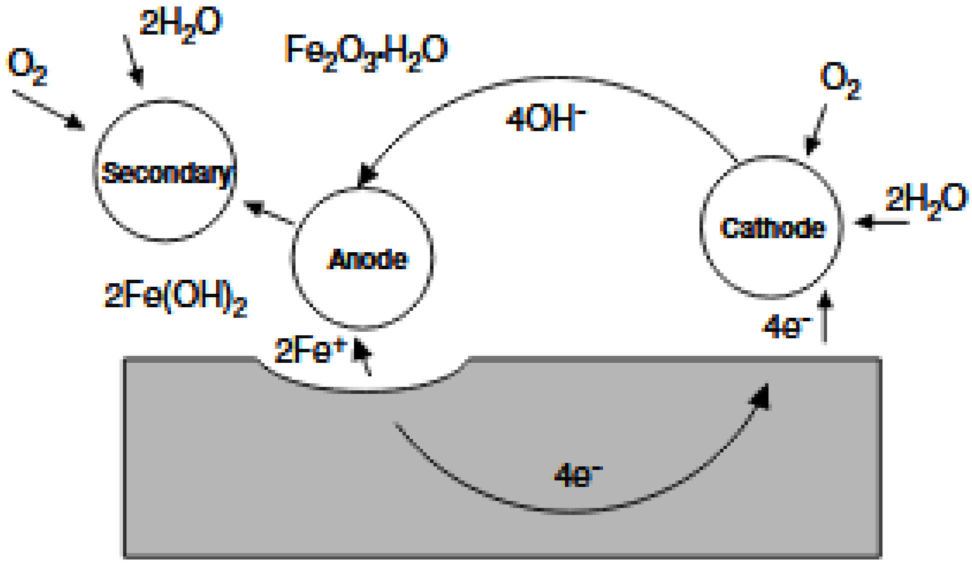


Figure 1.9. Exchange of Ions during Rusting (PCA, 2002)

Step 3: Iron (II) and hydroxide ions formed from the anode and cathode regions then combine to form iron (II) hydroxide, Fe $(OH)_2$

Equation 1.5. Formation of iron (II) hydroxide

$$Fe^{2+}(aq) + 2OH-(aq) \rightarrow Fe(OH)_2(s)$$

Step 4: Iron (II) oxide formed undergoes further oxidation by the dissolved oxygen to form hydrated iron (III) oxide, $Fe_2OH_3.xH_2O$ which is brownish in colour and is referred to as rust.

Equation 1.6. Formation of rust

$$4Fe(OH)_2(s) + O_2(g) + xH_2O(l) \rightarrow 2Fe_2O_3.(x+4)H_2O(s)Rust$$

Figure 1.10 shows 50 mm cast iron stormwater sewers damaged by rust. Rust disintegrates iron and affects the structural integrity of the pipe making it susceptible to mechanical failure such as a fracture.

Figure 1.10. Rust in iron pipes (Morgan & Morgan, 2019)

An experiment on the corrosion of cast iron under three simulated environmental conditions using various techniques to analyse and measure corrosion behaviour of cast iron was carried out by Mohebbi and Li (2011). The experiment found that the microstructure of cast iron is a key determinant of its corrosion behaviour. Also, in aerated tap water, the dissolution of the iron and - OH on the ferrous surface determines the corrosion behaviour.

It can be concluded that, in the absence of historical data, long-term tests can provide practically useful information on corrosion behaviour of cast iron pipes in a range of service environments (Mohebbi & Li, 2011).

Brick Pipes: Most bricks are made from clay materials and hence are resistant to chemical attack due to the inert nature of clay. However, the mortar between bricks is cement which is susceptible to chemical attack as explained under the chemical attack of concrete material. This mortar acts as a binder between bricks and once the binder is attacked, some of the bricks are displaced and the whole brick structure loses its structural integrity. This is because the strength of a brick sewer is a function of the quality of mortar used (Narayanan & Sirajuddin, 2013).

Another problem with brick pipes is tree roots. Tree roots can easily penetrate the mortar joining the bricks to one another. This can result in the bricks been displaced and therefore affecting the structural integrity of the whole pipe.

Figure 1.11 shows an example of a brick sewer weakened by corrosion of the mortar binding the bricks together.

Figure 1.11. A brick sewer weakened by corrosion (Channeline, 2007)

From this discussion, it can be inferred that vitrified clay and brick sewers are resistant to corrosion. The only problem with brick sewer is the mortar joining the bricks together which can be easily corroded in a similar way to concrete sewer. Concrete and cast iron sewer are highly susceptible to corrosion which could impact their service life significantly.

Table 1.3 shows the durability of the 4 major sewer material types typically used in the UK. Information on some other sewer material can be found in Appendix II.

Table 1.3. Durability of the most common sewer material types in the UK (CPDA, 2001)

Sewer Material	Strength of Pipe Material at 50 years	Initial Internal Corrosion resistance	Initial External Corrosion resistance	Design Basis	Typical Seal Pressure Rating	Longevity, Greater than 100 years
Vitrified Clay	100%	Excellent at any pH (pH 0 to pH 14)	Excellent at any pH (pH 0 to pH 14)	Rigid	>2bar depending upon manufacturer and joint type	Excellent, demonstrated long life
Concrete	100% where there are no corrosion effects	Poor in corrosive conditions	Poor in corrosive conditions	Rigid	> 1bar	Poor in an internal or external corrosion environment
Cast Iron	100% where there are no corrosion effects	Very poor	Very poor	Rigid	Welded	Poor in the presence of corrosion and good in the absence of corrosion
Brick	100% where there are no corrosion effects	Poor as mortar is susceptible to corrosion	Poor as mortar is susceptible to corrosion	Rigid	Mortar Joints	Excellent if no corrosion present

1.2 Problem statement

Sewers will deteriorate with time like all other assets and it will get to a point where replacement or repair becomes inevitable as the required level of service can no longer be guaranteed or there is a risk of collapse. For some less critical assets, a failure can lead to a minimal service impact and therefore it may be least cost to let such an asset fail before repair or replacement. In some other instances such as critical assets, failure could lead to significant service impact. Significant impact such as flooding, pollution or public health risks such as contamination or a train derailment could arise from the failure of critical assets. In these instances, investment in repair needs to take place before failure. To avoid this significant impact, industries are investing intensively in critical assets to avoid failure. Therefore, failure instances, for very critical assets are very few within the industry. Hence, failure or collapse rates cannot be used for deterioration assessments. Nevertheless, the condition change in sewers can still be observed. Also, penalties are imposed on utilities by OFWAT (Water Services Regulation Authority) and the government when there is a significant service impact.

For example, Figure 1.122 shows a failed small size cast iron sewer. The sewer is in a very busy high street in London and hence there was significant disruption to traffic.

Figure 1.12. A sewer failure at Oxford street in London taken on the 28th of July 2017 (Source: The Author- O.S. Tade)

A key component of investment decision supports systems is the ability to assess and predict the remaining life of the assets (Marlow, et al., 2009). Recent analysis of the deterioration of infrastructures underpins the increasing risk to public health and the environment posed by deteriorating sewers (ASCE, 2009). As a result of the risk posed to business by these sewers, there is a need to assess sewer condition and rehabilitate sewers within a timely manner to manage risk and avoid an unacceptable level of serviceability. However, due to the large number of sewers in England and Wales as well as the high cost and practicalities of inspection, there is decision making around how to utilize the available limited resources to target critical assets. The SN in the UK is the oldest in the world (Clegg, et al., 1989). In England and Wales alone, it was estimated that it would cost £104 billion to replace 302 000 km of public sewers (OFWAT, 2000). By 2014, this cost had risen to an estimate of £254.8 billion and only £12.9 billion was available to the utilities to maintain this asset from 2010 to 2015 (OFWAT, 2009b). Thames Water have 109,000 km of sewers themselves. For any maintenance activity to be carried out; there must be an assessment to determine the sewer condition and to decide an appropriate maintenance strategy; hence prioritization of condition assessment is very important.

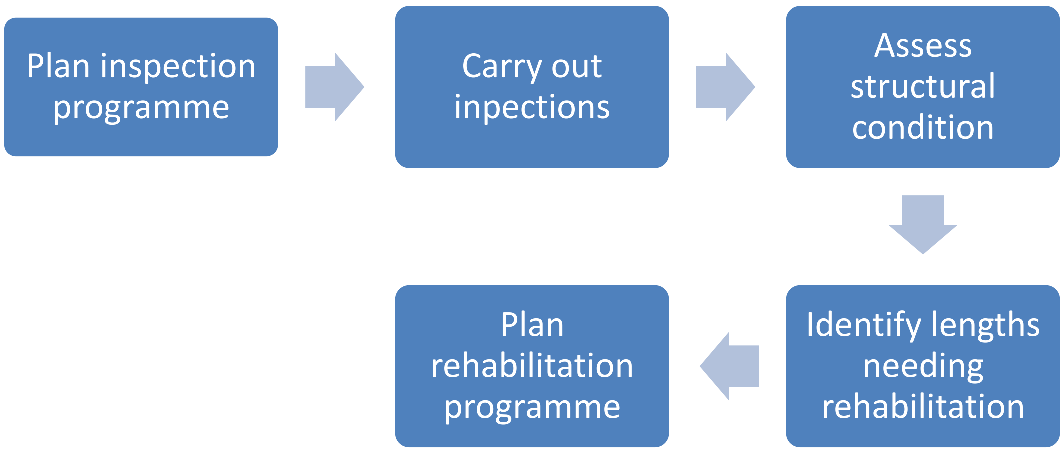


Figure 1.13. Phase 2a Assessing Structural Condition (SRM, 1994)

As set out in the 1994 SRM, planning of inspection programs are the premise of all other processes in the whole AM cycle (Figure 1.13). It would cost an estimate of £921 million to inspect the entire sewer in the Thames Valley at the rate of £9.21 per meter (BPSHCA, 2013). This does not account for the cost of man-entry survey for large sewers (>1200mm in size) and sewer access cost which could add significantly to the total cost of the inspection. This problem is not peculiar to the UK. A 1998 report card on infrastructures in American produced by America Society of Civil Engineers gave the country's SN a grade D+ (ASCE, 2017). This is a very poor grade on the grading system used in America. It was estimated that $137 billion was needed for rehabilitation to meet the America Clean Water Act requirement in 4 years (EPA, 1998). As a result of this huge cost, inspection and rehabilitation cannot be completed for all sewers at the same time, hence; there is a need to prioritize investment proactively in the SN and concurrently justifying the investment.

To understand the deterioration rate of any asset, there must be condition monitoring to check the change in the condition of the asset with time. This is done by analyzing historical sewer assessment data to identify the rate of sewer condition change. For sewers, the most relied upon condition monitoring technique in the UK is the WRc scoring protocol which is derived from CCTV sewer inspection. This is carried out to ascertain a simplified value for the Internal Condition Grade (ICG) of the sewer, but unfortunately, the cost and other physical constraints prevent this from being completed for all sewers as will be discussed in Chapter 2. Hence; during inspection planning, there is a need to prioritize inspection. The practice around the utilities in the UK is for prioritization to be done in the form of criticality and risk assessment. Criticality is a measure of repair cost, environmental impact and the cost of service failure such as fines and compensation to customers. Risk is a function of the Likelihood of Failure multiply by the Consequence of Failure (LOF*COF).

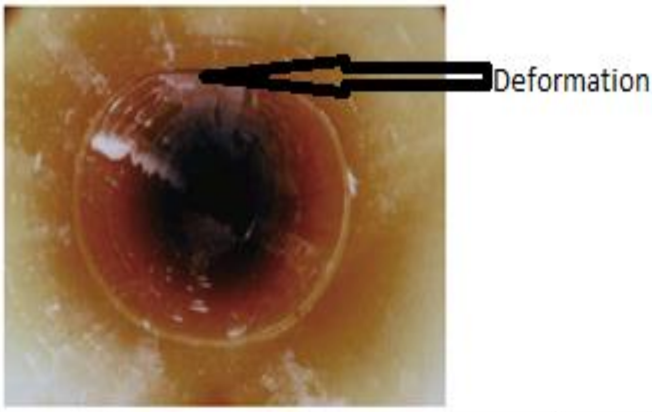
Wastewater utilities in the U.K are interested in identifying the risk from their sewers; unfortunately, they understand the consequences of their sewer failure but not the LOF with the level of granularity desired. Hence; this research focuses on the LOF. The LOF is an estimate of when a sewer condition will reach an unacceptable level of serviceability which can be deduced from Deterioration Models (DMs). The Manual for Sewer Condition Classification (MSCC) developed by WRc assigns scores from 1 - 5 (*Table 1.5*) to sewers during CCTV inspection with 1 being good as new and condition 5 meaning sewer collapse or failure is likely in the short term.

This scoring protocol measures sewer condition as a function of the most severe defect found in a sewer. In basic terms, condition grade 5 means a severe defect was found in a section of the entire sewer length. MSCC also provides the total, mean and peak defect score according to sewer condition scoring standard (BSEN13508-2, 2011) for identifying sewer defects and assigning corresponding defect code and score. This and other forms of sewer assessment techniques will be further discussed in Chapter 2.

1.3 Process of sewer condition assessment

For the wastewater utilities in England and Wales, 75% of the high-consequence sewers are in the City of London. The access points to most of these sewers are on roads and will require traffic disruption when manhole access is required. One of the consequence factors that are considered during risk analysis are shut down of busy roads and railway lines. Hence, there is the need to evaluate the inspection process and investigate the sewer assessment option with minimal disruption.

During sewer assessment, a camera typically attached to a sewer CCTV inspection monitor is lowered into the sewer via the upstream manhole and the technician controls the camera as it moves through the entire length of the sewer. Whilst watching the footage, the technician applies a code according to BS EN 13508-2 to all the defects found in the entire sewer length.



Code	Characterisation		Quantification		Circumferential Location		Joint	Remarks
BAA	A		10%		11	1		

Figure 1.14. Sewer condition scoring. (Adapted from www.scanprobe.com)

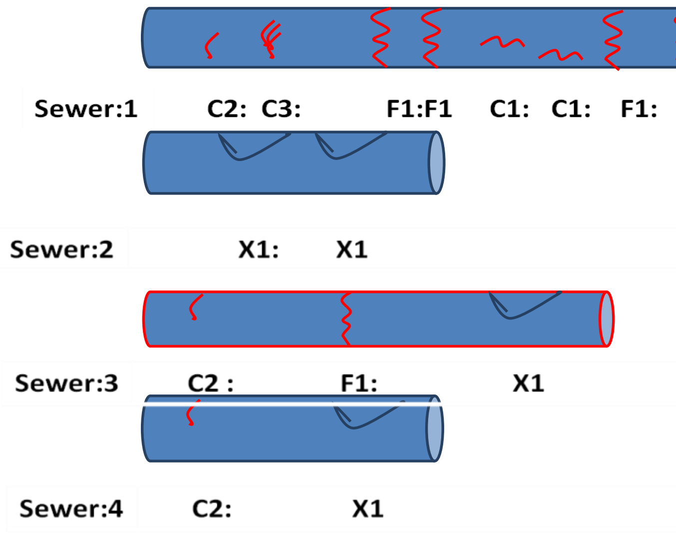
In Figure 1.14, the code BAA A is applied for a vertical deformation with the meterage recorded as well. For example, going through sewer 3 in Figure 1.15, the code BAB was recorded for a crack, further down the sewer length, a circumferential crack was found and recorded as BAB C, and further down, a collapse found was recorded as BAD D as shown in Table 1.4. Table 1.4 shows how the condition score of sewer 3 in Figure 1.15 is calculated.

Table 1.4. Scoring of sewer defects in Figure 1.15 using existing scoring system (Source: The Author- O. S. Tade)

Defects	BS EN 13508-2	WRc Score	Peak score	Mean score	Total score	Condition grade
Circumferential Crack	BAB C	20	165	15.25	305	5
Dropped Invert	BAB B	120				
Collapse	BAD D	165				

These defects are recorded against the corresponding meterage where the defects were found. The codes are then converted to the corresponding WRc defects scores shown in Table 1.5.

The peak score is the highest individual score found anywhere in the sewer, the total score is the addition of all the individual scores found along the sewer length, the mean score is the total score divided by the length from manhole to manhole of the sewer and the structural condition score is a function of the peak score shown in *Table 1.5*.



Code/BS	WRC score	Defects
C1 (BAB B A)	20	Longitudinal crack
C2 (BAB B C)	20	Circumferential crack
C3 (BAB B C)	20	Complex crack
F1 (BAB C B)	120	Circumferential fracture
X1 (BAD D)	165	Collapsed

Figure 1.15. Schematic diagram of sewer defect scoring (Source: The Author- O. S. Tade)

The defect score assigned to a structural defect is dependent upon the defect's severity and pipe material, and the condition grades are calculated based on the peak defect score (Chughtai & Zayed, 2008) as illustrated in *Table 1.5*.

Table 1.5. WRC condition grades (WRC, 2004)

Structural Condition Grade	**Peak Score**
1	Less than 10
2	10 - 39
3	40 - 79
4	80 - 164
5	165+

Figure 1.16 shows a CCTV survey report for a 55.3 m long, egg-shaped, brick sewer. According to (BSEN13508-2, 2011) for identifying defects and assigning corresponding defect code and score (Appendix III-VIII), the sewer has got 4 defects of Missing Brick (MB) and 2 defects of Displaced Bricks (DB). The existing WRc scoring scheme bases the overall condition of this entire length of sewer on one DB

which is the most severe defect found in the entire sewer length as it has the highest defect weighting score.

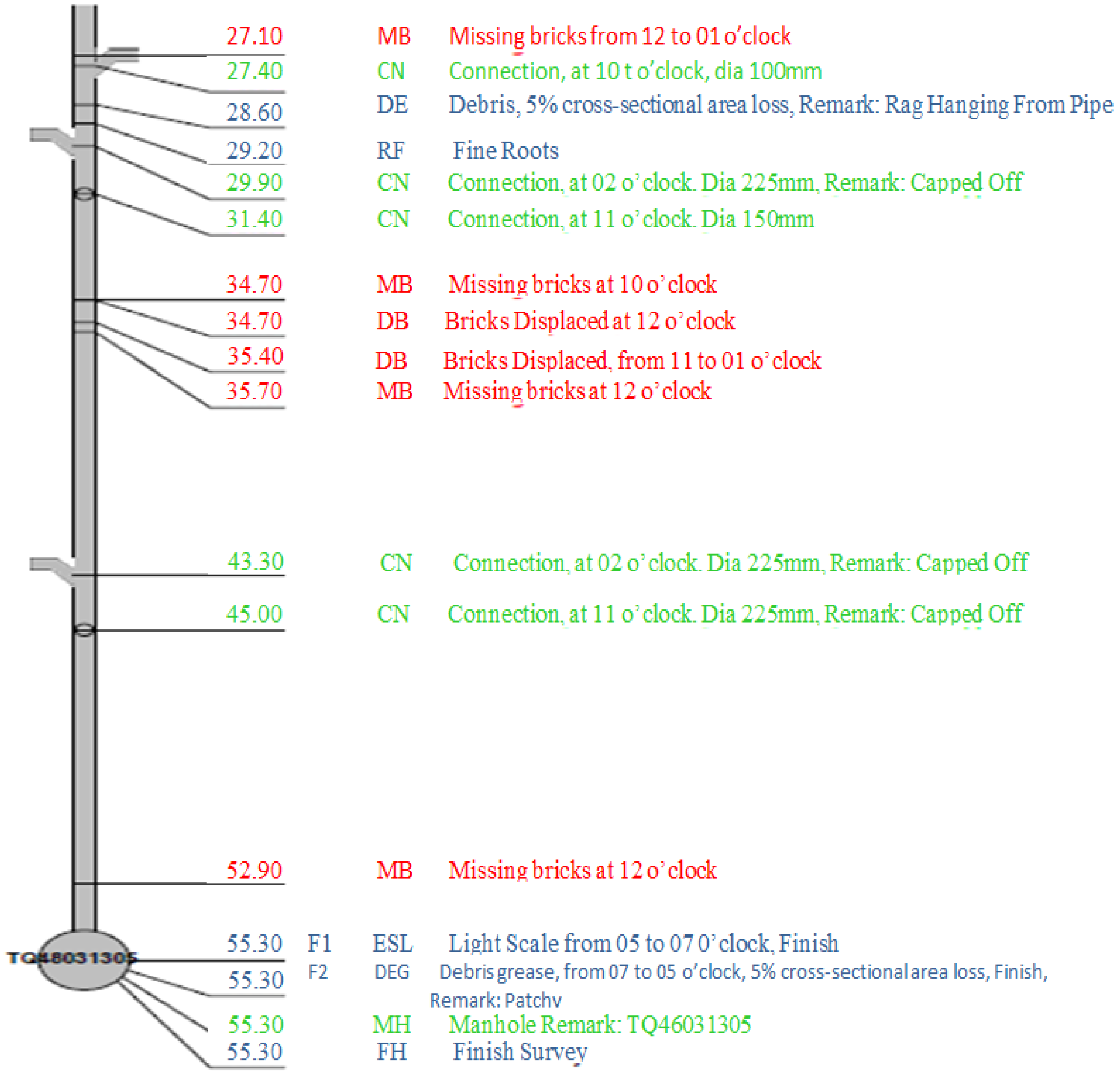


Figure 1.16. CCTV survey report for a brick sewer (TW Sewer survey report, 2016)

Ideally, it is expected that a sewer with at least a severe defect should be repaired or replaced.

Research Question 1: The question is; what is the level of priority of this sewer compared to other sewers in terms of collapse risk to the utilities?

Research Question 2: How will utilities justify inspection frequencies of when re-inspect sewers found in good or satisfactory conditions?

The existing scoring protocol available now may be effective for small sewer asset owners with the capacity to periodically inspect, review, and repair or replace all sewers with at least one severe defect. Also, a critical look at the scoring protocol, it appears that to understand the rate of sewer deterioration, there are little inferences that could be made from a single defect representing the condition grade of a sewer. Hence it is difficult to model deterioration with some degree of confidence and granularity with these scores. The MSCC condition grades appear to be numbers that don't translate to a time-dependent LOF which enables cost-effective and timely intervention without the need for additional inspections or expert engineer assessment. It also limits the potential for accurate investment planning in the medium to long term. This means that unforeseen risks can materialize and impact short term plans.

If CCTV inspection and proactive sewer rehabilitation are to be directed most effectively in the coming years, then it is essential that the factors associated with sewer structural deterioration and failure are identified and the complex relationship understood (Ana E, et al., 2008). For deterioration model to be effective, the factors associated with the condition of the infrastructure must be quantified (Ens, 2012).

To understand how these factors correlate with structural deterioration and failure, there is a need to identify and review each factor in Chapter 2 and quantify effects of each factor on deterioration in Chapter 5 of this thesis. This is because lack of detailed knowledge of the properties and the condition of sewer networks escalates the wastewater utilities' vulnerability to catastrophic failures (Zayed & Chunhtay, 2007a; 2007b; 2008).

Another problem that could arise is the issue of data availability in quantity and quality. A review carried out on DMs in available sewer investment models indicates that most approaches assume that all input data are available in the utilities to apply the approach developed. This is not the case, as a review of industry data systems in the UK and recent research suggest otherwise. This is one of the reasons why wastewater utilities have not been able to apply available approaches. Most of the existing investment approaches are data intensive and therefore becomes difficult to apply in the absence of data. The existing DMs are deterministic, probabilistic or artificial intelligence which will be discussed in subsequent Chapters. The issue of insufficient data was escalated in 2011 by section 103A of the 2003 Water act (WaterAct, 2003). This act transferred private sewer ownership to ten water and wastewater utilities in the UK. Asset Information such as physical properties, location, condition and repair history of these acquired sewers, in most cases were largely unknown (WaterUK, 2013).

1.4 Aim and objectives

The aim of this research is to develop a Risk-Based Framework (RBF) to prioritize proactive identification of sewers for inspection in England and Wales and at the same time able to justify these investments. To also enhance the MSCC scoring protocol in a way that would allow for deterioration monitoring and modelling of sewers to allow greater value to be derived from the expensive sewer condition assessment process. This will be done by developing an additional score other than the MSCC peak score, mean score, total score and condition grade. The developed score will prioritize the condition grades by giving greater granularity in the final risk score. This would allow wastewater utilities to know which of their sewers already classified to a given condition grade are in a more critical state than others. For example, according to WRc ICG 5 means collapse or imminent collapse. Considering two sewers in condition grade 5, this more granular system will be able to set priorities between these two sewers in the same grade 5 conditions, tell which is more likely to collapse before the other and provide a measure of sewer health. This will essentially translate the condition score to an enhanced assessment of the entire sewer length instead of grading being dominated by one severe defect found in a section of the sewer. Cohorts and areas of the sewer network could therefore be classified as having a “healthy status” based upon the likelihood of service reliability during the planning period.

This would put sewer asset owners in a better position to understand how the conditions of their sewer change with time and allow for proactive investment in the SN. The primary aim of this research is to develop a working and easy to apply RBF for sewers AM. This will look at a risk-based approach for prioritizing and justifying proactive investment in the SN by:

- Critically reviewing; literature on AM processes, sewer condition scoring and existing deterioration models of SN.

- Identify and review the constraints preventing existing models from being applied by wastewater utilities.
- Collect and critically review the quality and quantity of sewer condition assessment data.
- Interview/discuss data collected and existing deterioration models with experts in the wastewater utilities.
- Analyze sewer condition assessment data.
- Develop deterioration rates for sewers and corresponding intervention frequencies i.e. when to re-inspect a sewer found in a satisfactory condition.
- Develop an appropriate formula to reflect the actual condition of the sewer to make the scores fit for proactive investment purpose.
- Develop an RBF to make sure the model fits into the industry's BAU process.
- Validate the model.

1.5 Contribution to knowledge

The outcome of this research project will be an improved sustainable sewer assets management framework. It will also provide clarity and a measure of asset health by developing a leading sewer condition indicator to support operational decisions. This will provide wastewater utilities with the ability to manage critical assets proactively to ensure business plan targets are met and mitigate the risk of penalties. Targeting critical asset would allow utilities to direct investment in the right direction.

The end users (Utilities) have found existing deterioration models difficult to apply and only effective as an overview of their asset condition. Utilities have also found these models difficult to convert to strategic investment decisions at the asset level especially in justifying the statistical output. Moreover, most of the available deterioration models are top to bottom models which somehow miss out the details at the sewer pipe level and could direct investment in the wrong direction. Apart from applying a top to bottom approach, this research also applies a bottom to top approach by considering the sewer behavioural variation and uniqueness that makes sewers deteriorates at different rates.

Review of existing approaches shows that there are no plausible validations for most of the existing approaches and this have also made it difficult for utilities to apply them as they have a low level of confidence in these approaches. In practice, this means operations have correlations and predictions with low certainty, so they revert to increased sewer inspections, engineering assessment and more reactive approach than necessary.

This is a timely intervention as the participating industry affirms this research to be a possible solution to the challenge in managing SN. This would enable them to move from a reactive investment approach to a more proactive one, whilst assuring timely cost-effective investment.

1.6 Research focus and summary

This research proposes an improved prioritisation solution that is informed by historical performance data to prioritise the process of CCTV survey and re-survey or repair after risk analysis. It also reduces the reliance on engineering review (Expert's judgement).

As earlier stated, DMs are enshrined in the fabric of an AM plan. The accuracy of any DM is a function of its premise. The premise of a DM is the condition assessment process (inspection method and condition scoring) and the data gathered from the condition assessment of the asset. For SN, the condition assessment process is by CCTV inspection (survey) and the condition scoring is by the WRc's MSSC as earlier stated. There is a need to investigate each individual component of this fabric (sewer inspection, condition scoring and deterioration modelling). Hence, Chapter 2 will review the premises of DMs to investigate and identify the problem preventing existing models from being applied in the utilities. Chapter 3 presents the methodology adopted for this research. Also, the existing DM will be applied in Chapter 4 and the problems preventing them from being used by utilities will be identified from a practical perspective. Chapter 5 will present the analysis and results of how the identified problems are mitigated using the developed framework. Chapter 6 will further analyse and discuss the framework and Chapter 7 is the conclusion Chapter and recommendation for future work.

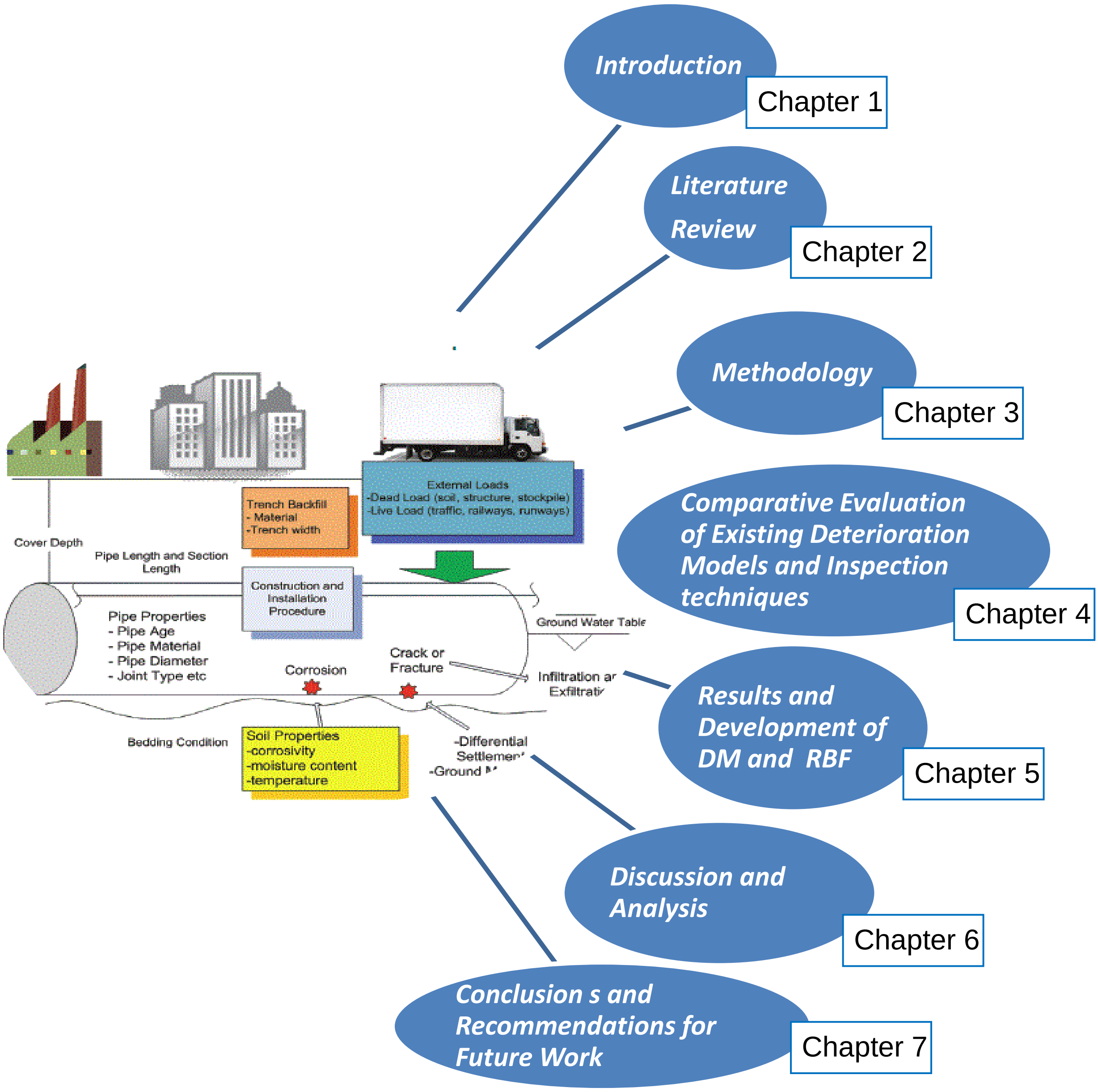


Figure 1.17. Research structure (Adapted from: WEF, 2017)

Chapter 2

Literature Review

This Chapter reviews and presents a background on AM and management of sewers. It covers aspects of best practice AM and its application to wastewater assets. It reviews existing deterioration models and condition assessment processes. The Chapter also identifies and discusses sewer properties and how they affect sewer deterioration. Existing DMs, industry's approach in managing sewerage system and the challenges of applying existing DMs in the risk-based approach of wastewater utilities are discussed.

2.1 Asset management of sewerage network

In the area of infrastructure, the term asset management (AM) was used in a publication by American Highway Administration in 1978 (Berger, 1978). Around 1900 in the financial industry, the Pelican example highlighted that; while increasingly important, investment and AM remained a subsidiary activity and not a primary one at most life insurance companies (Nigel, 2017). Contemporaneously, engineers were making records of the effectiveness of physical asset declining in condition with time in areas of water supply for AM purpose (Colebrook & White, 1938).

AM is a very vital tool for virtually all the institutions concerned with service delivery in the world of today as it combines both the financial, management, technical, as well as the engineering practices. These help in ensuring that the service delivery level is up to the expectations of the customers, while at the same time ensuring minimal cost and assured longevity of such facilities. AM consists of a series of frameworks for designing the best processes and instigating decisions for creation, operation, conservation, inspection, regeneration, enhancement as well as discarding of such physical assets with an aim of delivering safe service and economic infrastructure.

This subject has a great influence on the profitability and operational performance of such companies involved in the asset operation (IAM, 2012). Therefore, in order for any company to embrace AM, it must be in a position to successfully handle and operate the asset throughout its life cycle with profitable output assured with very definite safety and service standards put in place. Infrastructural AM is involved with the analysis of such assets that are vital to the whole society which includes; sewers, power grids, water network, telecommunication systems and any other asset that may be used communally, though a service charge may apply. In this research, DM for proactive AM of sewer conditions is going to remain as the point of focus, under which a literature review and systematic analysis of sewer condition change will be carried out.

The AM discipline incorporates both the analysis of conservation and replacement, as well as analysis of the system failure and economics. This field has gained very magnanimous recognition within the past two decades. Three reasons as to the increase in the interest have been put forward (Brint *et al*., 2009). These are:

- Very comprehensive digital asset modelling systems have replaced the asset registers based on paper which has enhanced a much better prediction and analysis of the performance of the asset. This has also improved asset's availability which has resulted from the technological advancement in such fields.
- Such assets are quickly ageing yet their quality of service expectancy is constantly on the rise. Due to the rising population, the assets that are already in place are expected to serve a larger population than initially planned and at the same time for a longer time. There thus, comes the need for a proper maintenance of the already existent network assets.
- Even the private utilities, unlike in the past, are of late expected to periodically make submission of their plans of AM for intermittent review in which each company's investment and performance plans should be identified. This, therefore, calls upon the utilities to substantiate their funding for the future investment.

There are numerous benefits that can be derived from the application of the techniques of AM in any given utility. This is because, the solutions of AM are vital for the safety of the system, increase in the availability of the asset, increased lifetime of the asset, increased productivity of the asset, reduced cost of the asset's life cycle as well as being compliant with the laid down legislative measures. The AM can help reduce the risks of catastrophic failures of the system as well as surprises in the budget (Vinnari & Hukka, 2009). For instance, the failure of sewerage asset utilities to ensure proper maintenance of the infrastructure's good condition could result in very hazardous effects on the health of humans and the environment. This could even influence the stability of the society (NRC, 2006). Proper infrastructural maintenance of the sewers must thus be done in time to curb the consequences of the disastrous failures and ensure maximum lifetime of the vital sewerage assets. This is especially because the failure of a single critical asset or a section of an asset can lead to a very tremendous economic loss (Motorola, 2009).

AM must take into consideration all the varied kinds of factors peculiar to the asset with their respective needs, and finally applying an all-inclusive approach that gives focus to the network's total value. Most prognostic techniques applied in the management of assets help in the making of decisions with regards to a specified threshold on the information forecasted on the individual assets by taking into consideration the time of failure. However, in a case whereby the individual asset is interdependent with other assets thus forming a network, such approaches may not be in a position of giving the most reliable result (Camci, 2009). For the SN, that seems somehow a bit more complex, its complex network structure, as well as the interconnections that exist amongst the components, renders that a very contentious system feature. There is also a variation in material, size and age of sewers. The unique nature, as well as the properties variation that exist amongst sewers, also renders a very contentious system. The characteristic of the network, usually, becomes very impossible to describe just by the analysis of the very separate cohort, which is very distinct when sewers are considered independently (Dewan, 2004). There, thus, is a need to analyze the individual characteristics of the different sewer cohort in the network in order to establish the vulnerability of such a network system, which will eventuate the decision pertaining to the maintenance, operation as well as the optimal design (Zio, 2009).

2.1.1 Asset management framework

There are a number of conservation strategies which may be applied in an AM of SN in order to ensure that the network is retained and restored in its original state long enough for it to be in a position of delivering the expected service delivery level. Each sewer repair will need to satisfy a cost-benefit target. Therefore, to sustainably manage the condition of an asset, the maintenance options of such an asset should be calculated and the cost calculations should be done to ensure maximum service level while incurring the lowest expense. In this research, the focus has been on inspection planning to support an effective decision on future investments. Another key factor to take note of is the need to consider the varied types of sewers to deal with the additional system complexity of the network system.

Another complication of sewer management in the UK is coordinating the existing reactive investment within a 5 years externally audited asset management plan (AMP), with the as yet defined ambition for growth over 25 years. This issue was raised in a recent ICE (Institution of Civil Engineers) lecture on the challenging requirement of AMP 7 (ICE, 2018). This is currently underdeveloped. Who will pay today for SN assets that provide resilience decades later? This intergenerational investment needs to be supported by today's customers and bill payers.

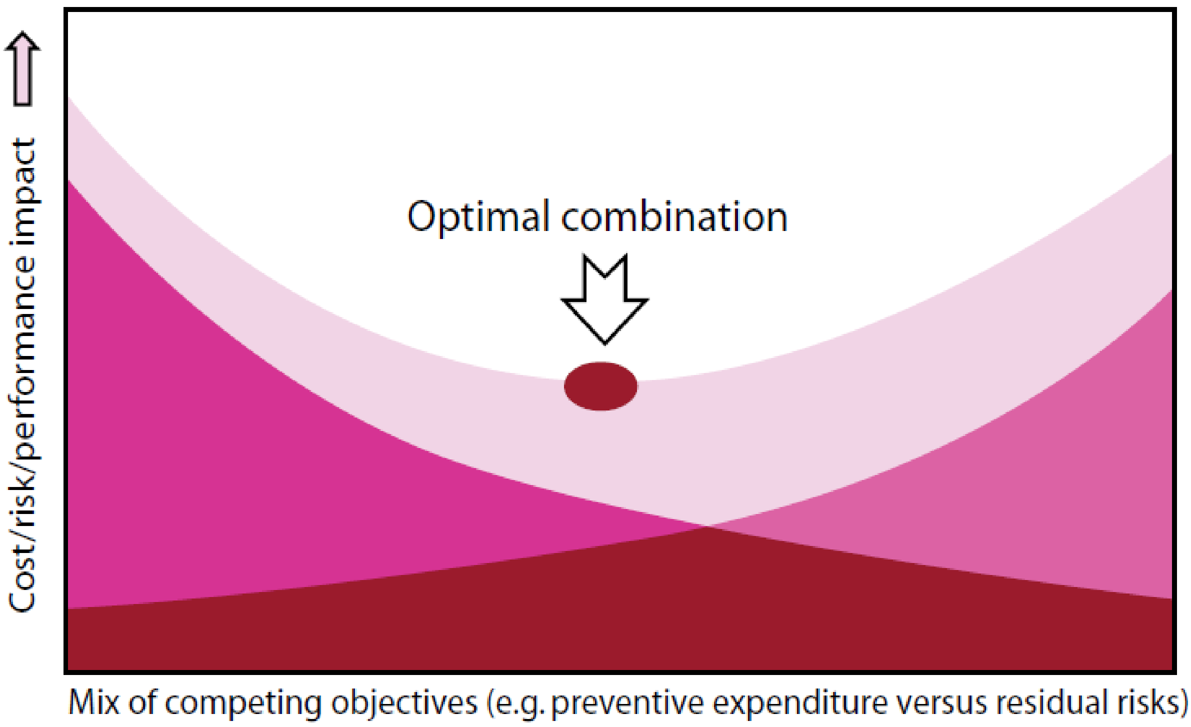


Figure 2.1. Best value achieved by optimizing the total cost, risk and performance impact Adapted from (ISO55000, 2014)

2.1.2 Asset management approach

With regards to the framework put forward by the Institute of Asset Management, the management process of the asset begins from the optimization of the life cycle of the very small components of the system and goes on until the point of considering the projects expected value. This is obtained from the entire system of portfolio; information, knowledge, people, network, and all the other components as presented in Figure 2.2. Increase in the complexity of the system is represented by each layer with the key challenges of substantiating the costs, sustainability, performance and the risks shown in every layer in Figure 2.1 (ISO55000, 2014). Companies are also looking at today's decisions impact on natural capital and social value.

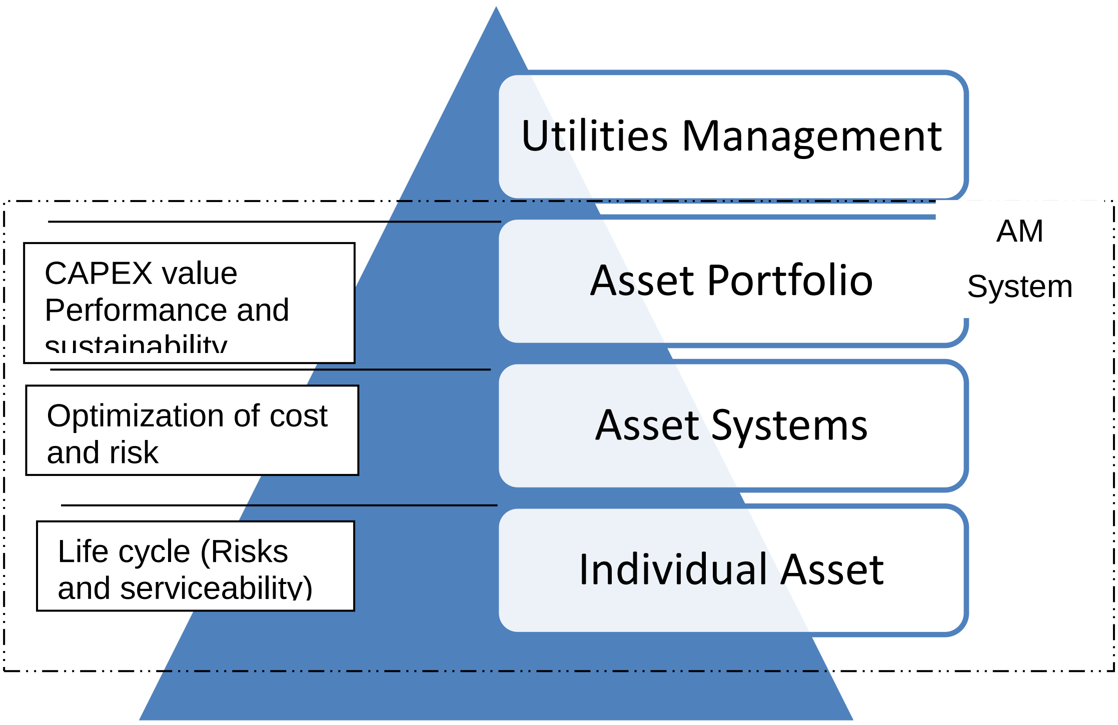


Figure 2.2. Levels of the AM system Adapted from (IAM, 2012)

2.1.3 Asset Maintenance Strategies for Sewer Network (MSSN): Critical analysis

The SN is a very vital part of the physical infrastructure within any given city. It, however, has a varied range of challenges both from the system's operation and the public health's viewpoints respectively. In particular, the buried nature of this asset makes identifying faults and problems difficult. The management of the SN is constantly evolving and becoming more and more sophisticated with time. This is because the systems are wearing out over time and being rendered more vulnerable to failures thus increasing the cost of operation and maintenance.

There are a varied number of strategies that have been put in place for the maintenance of the asset. Such approaches can either be reactive or even proactive depending on the asset type. A preventive or proactive approach to intervention or mitigation is aimed at the reduction of the chances of the occurrence of the system failures that lead to disruption. A corrective or reactive measure, on the other hand, is performed to rehabilitate an already failed system to make it assume its initial and original working condition. Such maintenance strategies are, however, in line with the importance and the condition of such an asset in the system. In this approach, the MSSN are put under four categories variant in the reliability and the cost of maintenance.

Maintenance based on the condition of the sewer: This comes in two stages namely, occasional or continuous monitoring and the maintenance carried out only when required. This considers the condition of the sewer, but not its importance. In this case, continuous monitoring is introduced when the sewer is at a critical condition and occasionally at mid condition. According to WRc, category "A" sewer has a significant cost consequence, category "B" is of medium consequence and category "C" has very low-cost consequence.

Maintenance based on the reliability of the sewer: This entails the priority list, the risk management and the outlines of the relationship between the asset condition and failure effect. That is; prioritizing asset register in terms of service risk and wider consequences, against sewer condition. This takes into consideration both the condition of the sewer as well as the importance of the sewer. An example is a category "A" sewer in the SRM (SRM, 2013).

Maintenance based on time: This entails a fixed interval of time for carrying out the inspections and the maintenance. It takes into consideration the importance of the sewer but not its condition. This could be seen as bureaucratic but not heuristic.

Maintenance for correction: This is never done until in the event of a serious breakdown. It does not take into consideration both the condition of the asset as well as its importance. An example is a category "C" sewer in the SRM (SRM, 2013).

2.1.4 Risk management

In the management of risks, the key potential hazards must first and foremost be defined, their potential impacts and likelihoods analyzed, and eventually outlining the most appropriate procedures that can be applied in response to their occurrence. Analysis of risks forms a very basic component of management of such risks as it defines as well as dissolves them, whereas the risk management seeks to establish the solution to such shortcomings. In an approach to analyzing the SN, there is need to carry out an intensive theoretical and conceptual study. This is analogous to RAG (Red, Amber, and Green) in Construction Design and Management regulations (CDM, 2015) as shown in *Figure 2.3*.

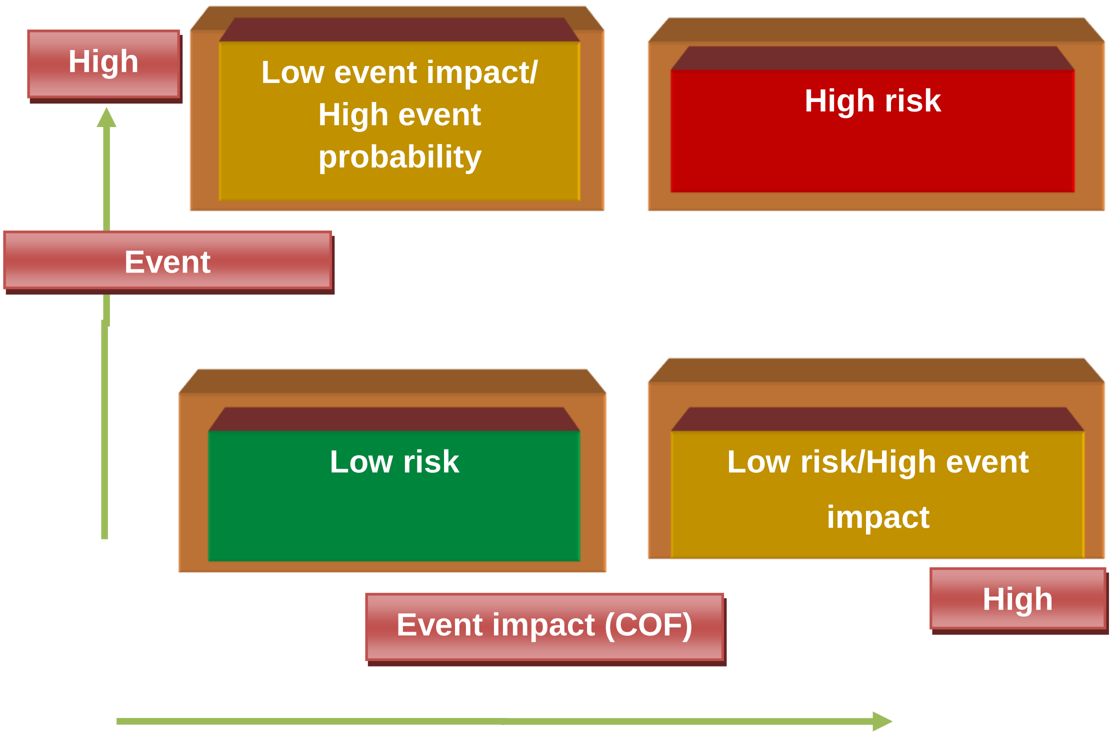


Figure 2.3. Risk chart (Source: The Author- O. S. Tade)

Another very vital factor that plays a very significant role in the selecting of the most appropriate MSSN to be put in place is the condition of the assets. This is based on the grounds that the condition of the asset is the key determinant of the rate of failure of the asset and its reliability (Rajani & Kleiner, 2001). An example of a bathtub curve used in AM is shown in *Figure 2.4*

The bathtub curve

The hypothetical failure rates against the time span of the network

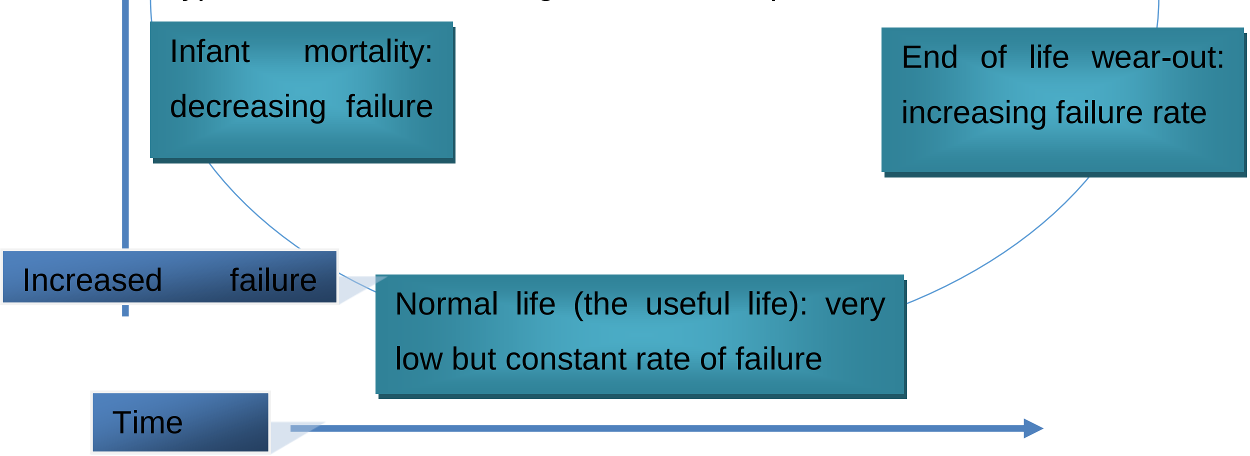


Figure 2.4. Bathtub curve, Chart reference: Acertus™ Risk Assessment: adapted (http//www.weibull.com/hotwire/issue21/hottopics21.html)

The successful management of risks arising as a result of failure is the capacity to identify the critical cohorts within the SN. There is the need to see to it that the assets which are set in high ranking are given more priority than those set to the lower ranking (NRC, 2006). In the SN, the assets are noted in the three categories of high, medium and low risk.

AM is quite a novel concept in wastewater utilities, with some of the utilities having a positive attitude and can thus adopt it easily, whereas others are still not very ready to give it an attempt. Companies have a predominantly fix on failure approach whilst understanding that they don't know whether the failure rate in the future will be the same as the past.

With the aid of information technology, AM has a very significant assistance to the utilities by helping SN in conveying effluent in an efficient and cost-effective way, thus improving the performance and reliability of such network. Such positive outcomes include; reduction in time and expense of sewer maintenance, availability of more information, funding towards all critical elements of the assets in a prioritized manner, fast decision making as well as the prediction of the varied lines of actions to be taken. In implementing of the MSSN, it is very crucial that an effective deterioration model of the system is already put in place and that at all points, there is sufficient pressure for the analysis to be successful. Thus, there is the need for the wastewater utilities to make AM their single source of truth and to embrace the move in order for them to be in a position of getting the best outcome which would also assure the customers of the best as well.

It is clear from this discussion of AM of SN that identification of both present and future sewer condition is an essential core component of AM. This can only be provided by sewer deterioration models.

2.2 Sewer deterioration model approaches

This section of Chapter 2 reviews and discusses the approaches that have been explored for sewer deterioration modelling and the limitation preventing utilities from converting them to targeted and timely proactive investment.

DMs can be either applied at the sewer level or at the cohort level (Ana & Bauwens, 2010). Sewer level DMs are used to predict the deterioration rates of an individual sewer. This is useful to set priorities and justify investment in AM of SN most especially in the short or mid-term AM planning (Kley, et al., 2013). Sewer cohort DMs are used to predict the deterioration rate of a group of sewers. This is useful to support strategic decision making for long term AM plan (Kley & Caradot, 2013).

As shown in Table 2.1, DM of SN can be deterministic, probabilistic or artificial intelligence.

Table 2.1. Available sewer deterioration approaches Adapted from (Vitor, et al., 2013)

Deterioration model	Artificial intelligence	Case-Based Reasoning (CBR)	Fenner *et al.* (2007)
		Fuzzy Set	Yan and Vairavamoorthy(2003); Kleiner *et al.* (2004a, 2004b, 2006)
		Neural Networks (NNs)	Najafi and Kulandaivel (2005); Tran *et al.* (2006); Tran (2007); Ana (2009); Khan et al. (2010)
		Support Vector Machines (SVMs)	Mashford *et al.* (2011)
	Deterministic	Linear regression	Gedam, A *et al.* (2016); Chughtay and Zayed (2007a, 2007b, 2008)
		Non-linear regression	Newton and Vanier (2006); Wirahadikusumah *et al.* (2001)
	Genetic programing	Evolutionary Polynomial Regression (EPR)	Savic *et al.* (2006); Ugarelli *et al*. (2008); Savic *et al*. (2009)
	Stochastic	Discriminant analysis	Tran (2007); Ana (2009)
		Markov chains	Wirahadikusumah *et al.* (2001); Micevski *et al.* (2002); Coombes *et al.* (2002); Baik *et al.* (2006); Koo and Ariaratnam (2006); Newton and Vanier (2006); Tran (2007); Le Gat (2008)
		Ordinal regression	Yang (1999); Davies et al. (2001b); Ariaratnam *et al*. (2001); Pohls (2001); Ana (2009)
		Semi-Markov chains	Kleiner (2001); Dirksen and Clemens (2008); Ana (2009)
		Survival function	Hörold and Baur (1999); Baur and Herz (2002); Baur *et al.* (2004); Ana (2009)

2.2.1 Deterministic Deterioration Models (DDMs)

DDMs are either empirical or mechanistic which could be in the form of a linear or non-linear equation. The DDM “ExtCorr” that was developed by Konig (König, 2005) was used to study the rate of external corrosion in Concrete (CO) pipes by evaluating; the quality of cement used in making the pipe, the surrounding soil moisture content and the soil aggressivity. Another DDM was “WATS” developed by Vollersten and Konig (Vollersten & König, 2005). WATS uses a differential equation to evaluate the non-linear relationship between internal degradation rates and microbial and chemical transformation. Corrosion is just an aspect of sewer deterioration which can be described empirically and modelled accordingly. Nevertheless, deterioration of sewer cannot be completely understood as it is a complex process (Schmidt, 2009).

2.2.1.1 Types of deterministic model

Mechanistic: This is based on the physics of an asset. For example, in the deterioration of sewers, deterioration can be calculated with the relationship stress $\sigma = \frac{F}{A}$and strain $\varepsilon = \frac{\delta}{L}$.where F is the Force or load on the sewer, A is the cross sectional Area of the sewer, L is the Length of the sewer and δ is the change in length or deflection. This is not effective because there are so many explanatory factors affecting sewer deterioration such as highlighted in item 2.3 of this Chapter which are not considered.

Empirical models: 91% of agencies in America and Canada who responded to a study by Schram on the deterioration of footway use Empirical deterioration models (Schram, 2008). This model adopts a regression method to relate explanatory factors such as outlined in item 2.3 of this Chapter to ICG. This model is preferred as sewer deterioration is a complex process and cannot be determined by mechanistic models alone. It is preferred because it considers the possible explanatory factor affecting sewer deterioration. This method was used by Konig, (2005) to model corrosion degradation of sewers (König, 2005). DDM is the simplest model which relies on basic assumptions that don’t account for the vast uncertainty in sewer deterioration. This is because sewers in the same cohort can have variable deterioration rates. Hence; deterioration cannot be precisely determined by DDM without data stratification to evaluate the variation of the different sewer physical properties.

2.2.2 Probabilistic Deterioration Models (PDMs)

PDMs are based on the premise that sewer deterioration is a complex process and in fact random in nature. So, it considers the stochastic nature of sewers deterioration by using historical sewer assessment data to describe correlations between factors affecting deterioration (explanatory factors) and sewer condition.

2.2.2.1 Cohorts' Survival Model (CSM)

CSM is a type of PDM that determines sewer deterioration by analysing deterioration by homogenous sewer groups. A group (cohort) consists of sewer sharing similar explanatory factors. An example of CSM was developed in Germany by Baur and Herz (Baur & Herz, 2002). This model was developed to compare different investment scenarios in SN. Also, this can be used to investigate the relationship between investment and the resulting improvement in the condition of the SN. This is in use by several consulting firms in Germany. This is based on the assumption that sewer in the same group tends to have similar behaviour and hence; deteriorates at the same rate. It is an average estimate of the deterioration rates of all the sewers in that cohort. Hence; the deterioration rate for individual sewer cannot be predicted accurately. This is useful as an overview of the sewer asset condition to support long term strategic AM.

2.2.2.2 Cohort survival model description

For every sewer cohort, there is a distinct condition change over the sewer's service life. There is an assumption that there is a probability that a sewer will survive and remain in a discrete condition in any year during its service life. Therefore, the probability that the sewer will remain in a condition reduces whilst the probability of the sewer being in the next condition increases over the sewer's service year. This is called transition probability or survival function which can be calibrated according to the sewer cohort (Kley & Caradot, 2013). Transition probability can be estimated using Herz distribution to follow the pattern of a bathtub curve similar to that in Figure 2.4.

Equation 2.1. Survival function calculation for CSM

$$\boldsymbol{S(t)_{i\rightarrow i+1}} = \frac{\boldsymbol{(a)_{i\rightarrow i+1}+1}}{\boldsymbol{a_{i\rightarrow i+1}+e^{(b)_{i\rightarrow i+1}(t-c_{i\rightarrow i+1})}}} \text{ (Herz, 1995, 1996)}$$

Where;

- $S(t)_{i \rightarrow i+1}$ is the portion of the entire sewer that have survived until ICG i
- a is the ageing factor
- b is the transition parameter
- C is the resistance time and determines the age when deterioration stops.

The transition curve in Figure 2.5 is for Norwegian SN. It can be used to estimate the remaining life for the sewer cohort analysed. As shown in Figure 2.5, the minimum year required for this sewer cohort to get to ICG 5 is 48 years, the average year is 80 years and the maximum years required is 105 years. Therefore, the first sewer to get to ICG 5 in this group will take 48 years and the last sewer will take 105 years.

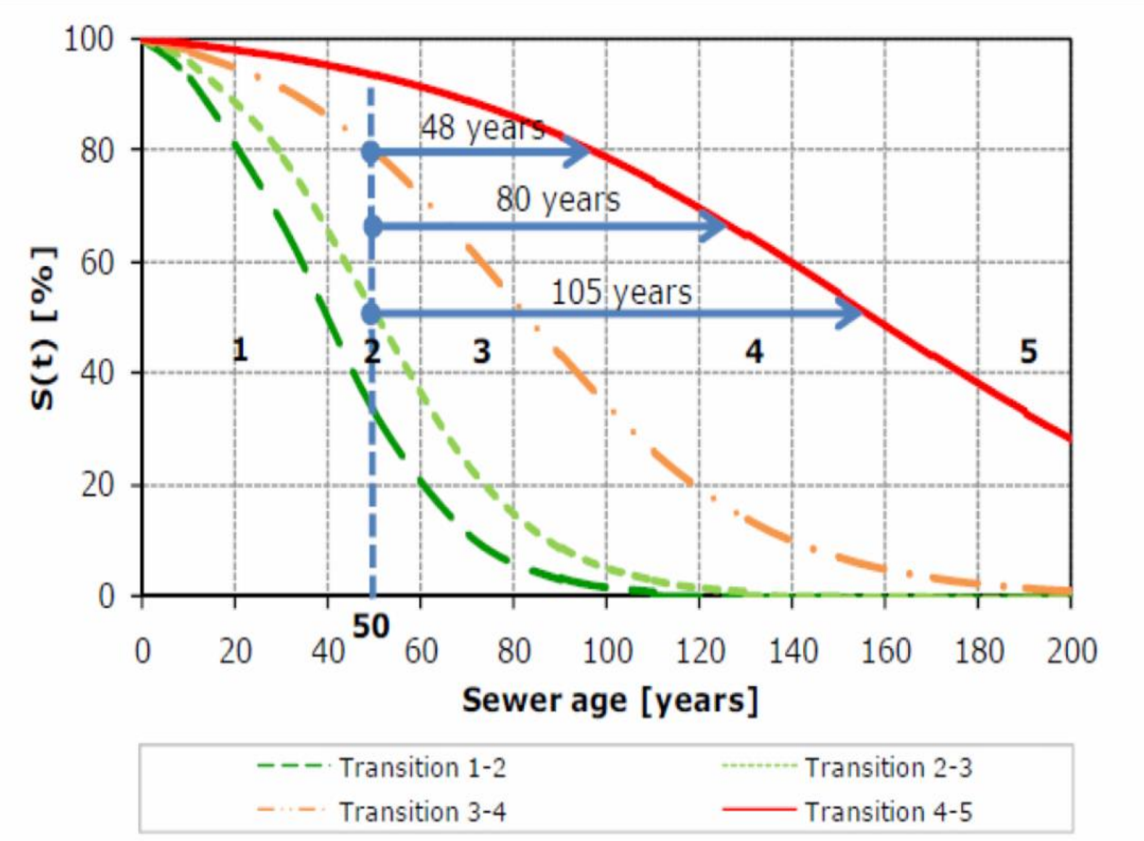


Figure 2.5. Norwegian network transition function (Hörold, 1998)

Table 2.2 summarises the advantages and disadvantages of CSM.

Table 2.2. Advantages and disadvantages of cohort survival model (Adapted from (Kley & Caradot, 2013)

Pros of CSM	**Cons of CSM**
Easy to model and apply.	Requires extensive inspection data set that is sufficient enough to represent the variation within this cohort.
	Sufficient data in each condition grade is also required. In most cases, there are not enough inspection data for a certain sewer type in a given ICG (Ana & Bauwens, 2010).
	The cohort must be small enough to be considered homogenous and large enough to produce a statistically significant result (Kleiner, et al., 2007).
	The inspection data sample used is rarely random since inspections are triggered by reactive investment programme. In most cases, the focus could be on sewers in a poor level of serviceability, specific area or old sewers.
	The remaining life is subjected to significant error due to the large variation of deterioration that exists from sewer to sewer.

2.2.2.3 Markov Model (MM)

MM is a type of PDM which is a stochastic model that describes the deterioration pattern of an asset passing through a measurable or finite condition state. It is a memoryless random process as the future condition is independent of past events but solely on the present condition. At any given step, the condition of the sewer may change from a present condition 1 to 2 or remain in condition 1 according to a given probability. It is very difficult to link deterioration to physical properties at the sewer element level. This is similar to CSM as it also makes use of transition probability. *Examples of MM are "STATUS" and "Gompitz" which was developed by LeGat,* *(2008). Other researchers have also applied MM to predict the future condition of assets such as road pavements, bridges and water network as shown in Table 2.1.*

The major problem with MM is that it requires a large amount of sewer inspection data that represent each cohort in different ICGs and ages.

2.2.2.4 MM description

Transition probabilities from one ICG to the next is observed and expressed as an n by n matrix W. "n" is the number of possible ICGs and ICG 5 which is the worst condition state is defined as i = n. The addition of the entire elements in a row is always 1. This is for the model to take the view that the ICG can only get worse. The only exceptions are when there is a repair or replace intervention. Hence; the majority of all the elements in the matrix are set to be zero (LeGat, 2008).

$$W(t, t+1) = \begin{matrix} w_1^{(t,t+1)} & 1 - w_1^{(t,t+1)} & 0 & 0 \\ 0 & w_1^{(t,t+1)} & 1 - w_1^{(t,t+1)} & 0 \\ 0 & 0 & w_{m-1}^{(t,t+1)} & 1 - w_1^{(t,t+1)} \\ 0 & 0 & 0 & w_m^{(t,t+1)=1} \end{matrix}$$

Where;

$w_1^{(t,t+1)} is\ the\ probability\ that\ the\ sewer\ remain\ in\ condition\ i\ between\ the\ time\ t$

$and\ t + 1$.

$1 - w_1^{(t,t+1)}$ is the probability that the pipe will transit to the next advanced condition between the time t and t+1.

MM can be homogeneous (not time dependent) or non-homogenous which is time-dependent. Time-dependent MMs are used for sewer DM as the probabilities of transition from one ICG to the next is a function of sewer age and older pipes in most cases, deteriorate the fastest (Kleiner, 2001).

2.2.2.5 Semi-Markov models

In this type of model, apart from the condition of the sewer being independent of past events but solely on the present condition, it also depends on time already spent in the current ICG (Dirksen & Clemens, 2008). The time spent in each ICG is random as it is not evenly distributed (Kleiner, 2001). Similar to CSM, transition probability can be estimated using Weibull distribution to follow the pattern of a bathtub curve similar to that in *Figure 2.4*. Semi-Markov model is calibrated for predefined sewer cohorts and the factors affecting sewer deterioration are considered as independent variables (covariables) (LeGat, 2008). As a result of this, it will be misleading to apply a deterioration model calibrated with Canada sewers to U.K sewers. The expected future condition of the sewer is simulated by transition probabilities.

Equation 2.2. The vector probability calculation for semi-Markov model

$$c^T(t+s) = c^T(t)\prod_{i=1}^{s} W(t, t+i).$$

The ICG state vector C (t) specifies the distribution probability of the ICGs at any time t. The vector probability C (t+1) at time t+1 is calculated by the current ICG vector w^2(t) multiply by transition matrix W(t, t+1). For the distribution probability at time “t+s”, Equation 2.2 is used.

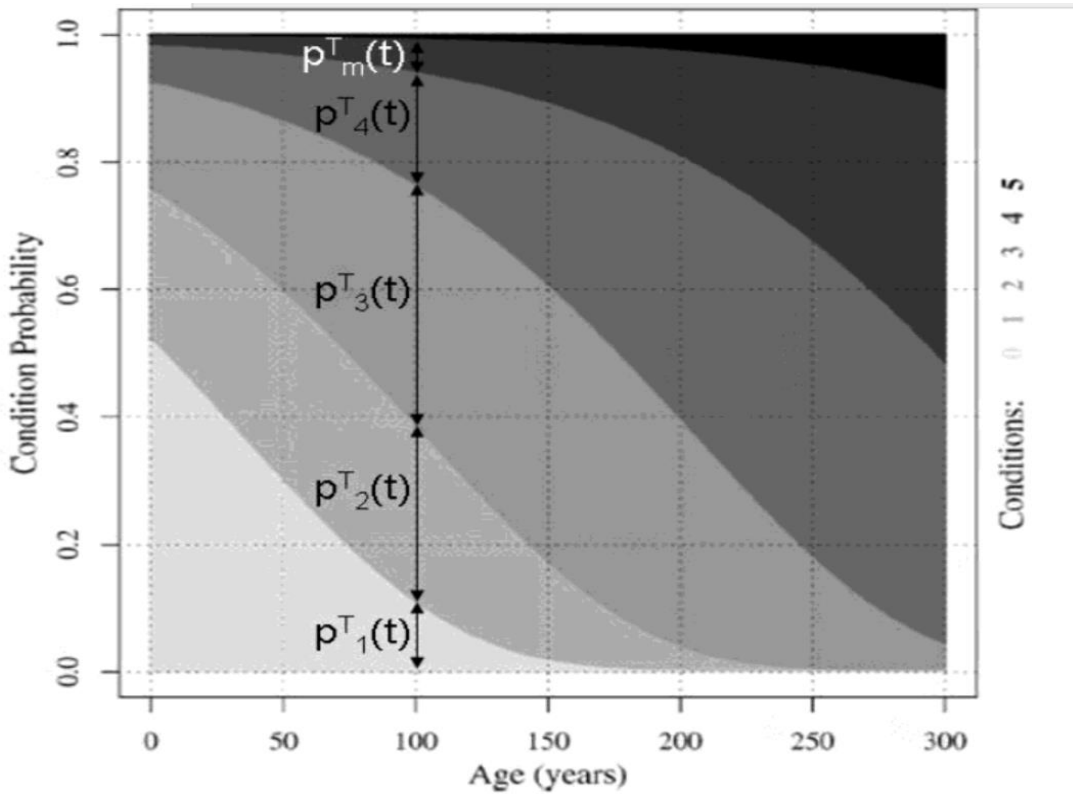


Figure 2.6. Gompertz condition survival function for SN in Germany (LeGat, 2008)

Figure 2.6 shows an example of the condition survival function for Dresden SN in Germany. This is an example of an ICG state at age 100. Table 2.3 describes the advantages and disadvantages of MM.

Table 2.3. Advantages and disadvantages of MM (Source: The Author- O.S. Tade)

Pros of MM	Cons of MM
In the calibration of the transition function, it considers pipe specific independent variable.	The model requires a large amount of sewer inspection data that represent each cohort in different ICGs and ages.
The amount of homogenous cohort can be reduced because more deterioration factors can be included in the survival function.	Data of repeat survey on an individual pipe over time are often missing (LeGat, 2008).
They are not condition states like cohort survival but condition probabilities such as used in (LeGat, 2008) and (Ana & Bauwens, 2010).	

2.2.2.6 Logistic Regression Model (LRM)

A regression model is a type of PDM used to determine the failure probability at the individual sewer level. LRM uses regression method to predict the result of categorical variables. Variables such as factors affecting deterioration outlined in Item 2.3 of this Chapter and results such as discrete ICGs.

An example of LRM is a binary logistic regression developed to estimate the LOF of SN in Edmonton, Canada (Ariaratnam, et al., 2001). Also, multiple regression techniques were applied by (Chughtai & Zayed, 2008) to predictor variables (deterioration factors) to predict sewer ICG. Another example was an LRM developed to analyse sewer inspection data of Cincinnati, a city in America (Salman, 2010). However, LRM is less accurate to represent complex deterioration processes such as in SN.

2.2.2.7 LRM description

LRM is a special linear regression method in which the dependent variable is converted into the logit form of failure probability (Salman, 2010). Equation 2.3 is a probability calculation formula for LRM.

Equation 2.3. Probability calculation for LRM

$$Log(\frac{P}{1-p}) = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots \beta_n X_n$$ *(Kley & Caradot, 2013)*

Where;

- $P\ is\ the\ probability\ for\ a\ pipe\ in\ a\ good\ condition$
- $1 - P\ is\ the\ probability\ for\ a\ pipe\ to\ be\ in\ a\ bad\ condition$
- $X_1 are\ the\ deterioration\ factors\ (independent\ variables)$
- $\alpha\ and \beta_1\ are\ the\ offset\ and\ slope\ of\ the\ regression$

This model only considers independent variables that are relevant and if two variables are strongly correlated, one will be excluded. This correlation can be checked using a Wald test. For the model calibration, the discrete ICGs are converted to binary results. ICGs 4 and 5 are combined into one and ICGs 1, 2 and 3 are combined to form the second result. To optimise the result with the collected data, $\alpha\ and\ \beta_1$ are calculated using the highest estimation of LOF (Salman, 2010). Table 2.4 describes the advantages and disadvantages of LRM.

Table 2.4. Advantages and disadvantages of LRM (Source: The Author- O.S. Tade)

Pros of LRM	**Cons of LRM**
LRM is a very simple model as the probability result provided can be directly used for analyzing risk.	A large amount of data is required.
Correlating the deterioration factor with the sewer condition provides clarity and a better understanding of the deterioration process (Ana & Bauwens, 2010).	Linear regression between ICGs and deterioration factors is less accurate to depict a complex deterioration process (Salman, 2010).
	The better the quantity and quality of variable data the better the regression coefficient obtained.

2.2.2.8 Multiple Discriminant Model (MDM)

MDM is a type of PDM use to calculate the linear relationship between independent variables and single ICG (dependent variable). MDM is similar to LRM but has a different calculation of coefficients. MDM is developed to distribute independent variables by making assumptions, unlike LRM where no assumptions on the distribution of independent variables are made. Hence; LRM is more appropriate for DM of SN but MDM should give better results only if the assumptions are fulfilled (Pohar, et al., 2004). An example of MDM was used for stormwater sewer deterioration modelling (Tran, et al., 2006). Also, (Ana, 2009) used MDM to predict the condition change of sewers in Leuven and Antwerp in Belgium. The major problem with MDM which could be a constraint in its application is that it makes assumptions on the distribution of its predictor variables.

2.2.2.9 MDM model description

MDM uses independent variables (linear function) to estimate ICGs. The ICGs are called classification functions. Equation 2.4 shows the formula to calculate the classification function for MDM.

Equation 2.4. Classification function calculation for MDM

$$W_1 = \alpha + \beta_{i1} X_1 + \beta_{i2} X_2 + \ldots \beta_{in} X_n$$ *(Kley & Caradot, 2013)*

$$i = 1, k = -1$$

Where;

- W_1 *is the classification function*
- k *is the number of ICGs*
- X_i *are the independent variables*
- β_i *are the classification coefficients*
- n *is the number of independent variables*
- α *is the offset*

Every inspection data sample can be visualised in a dot spatial arrangement. "W_1" is a new calculated axis in spatial k-1 dimension. This enables individual dots to be aggregated into clusters of ICGs with each ICG having a centroid as shown in Figure 2.7. The new cluster formed can be calculated by taking the average values of the individual factor. To predict the condition of a sewer, the sewer is classified into the cluster with the closest centroid.

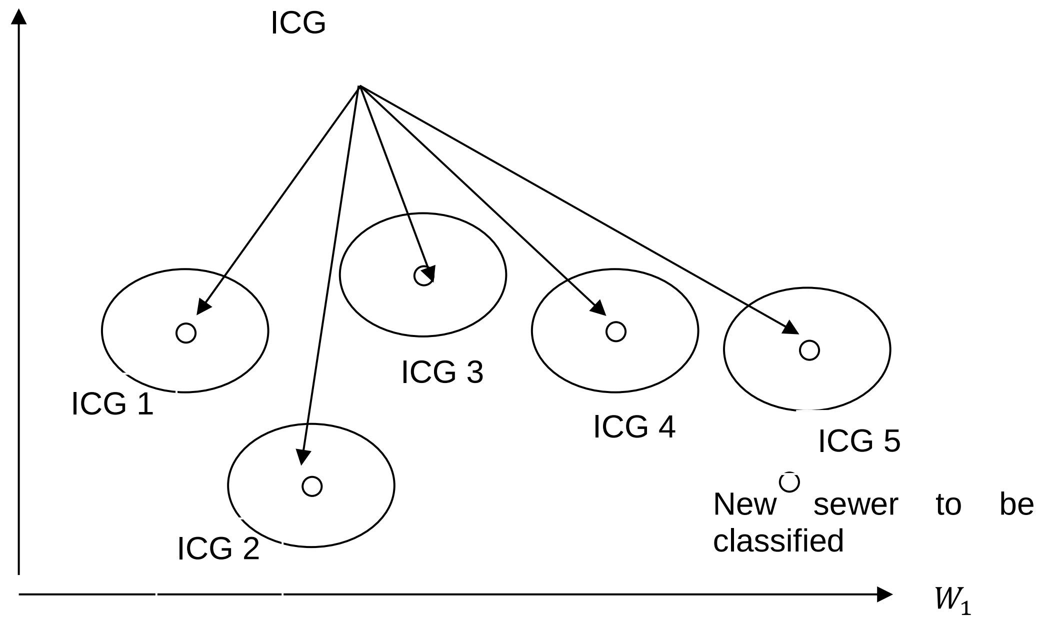


Figure 2.7. Illustration of DDM with 5 ICGs (Adapted from Tran 2007)

The illustration of MDM shown in Figure 2.7 is a condition classification example with 5 classes (ICG 1-5, k=4). Table 2.5 describes the advantages and disadvantages of MDM.

Table 2.5. Advantages and disadvantages of MDM (Source: The Author- O.S. Tade)

Pros of MDM	**Cons of MDM**
MDM has a robust methodology that considers the stochastic nature of sewer deterioration (Tran, 2007).	Assumptions on the predictor variables distribution are made. This could present a constraint in its application.
It can handle the output of ordinal data (Kley & Caradot, 2013).	
Similar to LRA, the method put clarity and provides a better understanding of the deterioration process by relating important deterioration factors to ICGs.	

2.2.3 Artificial Intelligence Deterioration Models (AIDM)

AIDM is the process of using a computer algorithm to understand the complex relationship in sewer deterioration and produce results to help predict the rate of deterioration.

2.2.3.1 Neural Networks Model (NNM)

NNM is a type of AIDM. There are 2 types of NNM, probabilistic neural network (PNN) and backpropagation neural networks (BPNN). This was described in (Marlow, et al., 2009) and an example was illustrated in Chapter 1. NNM help investigates and establishes the mathematical relationship between input (Independent variable/predictors) and output (dependent variable/response or discrete ICGs). The NNM learn patterns from a set of training data (historical CCTV sewer survey data) and use the lesson learned to predict the ICG of a new sewer (Tran, et al., 2007). An example of NNM was created by Tran et al, (2007) to demonstrate the application of NN using sewer survey data collected from Dandenong in Australia. Another example was designed by Khan et al. (2010) to evaluate NNM for deterioration modelling. The major problem with NNM is the amount of data required for DM.

2.2.3.2 NNM model description

NNMs are made up of artificial neurons connected to one another in layers similar to the human cerebral cortex. The connections between these neurons are called interneurons. Each interneuron has a weight associated with it and the weights are determined by reducing the error between observed output and the predicted results (Salman, 2010). The historical sewer survey data is divided into two, a larger sample for training and a smaller sample for testing. This data includes; the independent variables as the inputs and the dependent variable as the output. Table 2.6 describes the advantages and disadvantages of NNM,

Table 2.6. Advantages and disadvantages of NNM (Source: The Author- O.S. Tade)

Pros of NNM	**Cons of NNM**
It can replicate hidden, complex and non-linear relationships between predictors and responses.	It is a data-driven model that requires a large sample of data.
It can handle ordinal data and it is very useful where there is no alternative theoretical model (Tran, 2007).	It is a black box model as the understanding of the training process is limited (Tran, 2007).

2.2.4 Fuzzy Set Model (FSM)

FSM is a type of AIDM. It uses engineering experts' judgment to predict the deterioration rate of sewer (Marlow *et al.,* 2009). This model is very useful when there are no, insufficient or poor data.

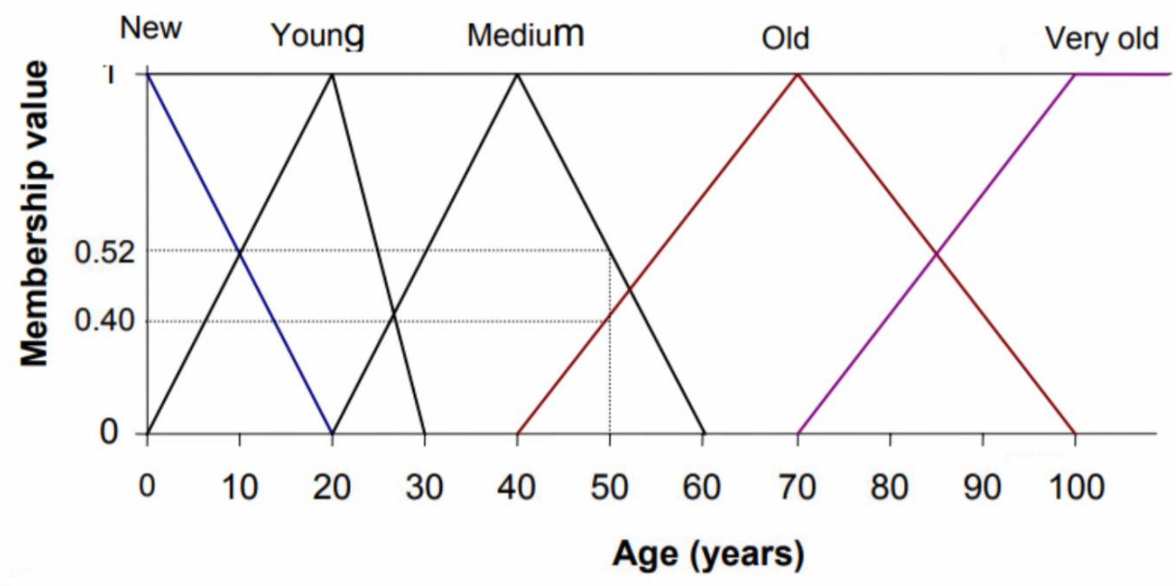


Figure 2.8. Example of FSM (Kleiner et al., 2004)

FSM converts a quantitative description of independent variables into fuzzy numerals. Fuzzy numerals are numbers representing independent variables such as sewer age which can be categorised on a quantitative scale (old age, middle age or new sewer). These quantitative scales can be converted to fuzzy numerals. An example is as shown in Figure 2.8 for a 50 years old sewer. The fuzzy set, in this case, is (0, 0.52, 0, 0.40) and the sewer is classified as between medium and old age.

An example of the application of FSM was presented by (Rajani, et al., 2006) to illustrate how the ICG of a surveyed sewer can be converted to a fuzzy result. This process is called fuzzification (Kley & Caradot, 2013). The processes in fuzzy condition conversion as presented by (Rajani, et al., 2006) are;

- CCTV coded defects are converted to fuzzy quantitative scales to reflect the severity of the individual defect from new, good, to collapse.
- Grouping of defects into different classes. Each group reflects the component of specific sewers such as the joints and sewer lining. Defects indicators are

combined to reflect the severity of each group. This combination is a function of the level of importance of the defect as judged by experts.

- The expert's judgement is used to assign a weighting to the categories which are used to calculate the fuzzy condition result.

As earlier stated, it was found from discussion with acknowledged experts that expert judgements are sometimes bias or lack current behaviour in the network; hence, utility tends not to use this approach.

2.2.5 Summary of sewer deterioration model approaches

From this review, it appears that the majority of the approaches available now are statistical and may simplify the approach. They do not include the breadth of understanding of the BAU processes used within the utilities and the understanding of the quantity of data held by utilities, the variation and vast uncertainties that exist around sewer failure. These have sometimes prevented the outputs of academic research from being converted to business strategic plans. Hence an often in period, reactive investment approach is being adopted across the industry with a wider industry view that there is underinvestment and poorer understanding about the requirements for proactive investment in sewer AM to manage risk for the long term.

Also, the quality of this identified approach has been questioned on numerous occasions by experts in the industry as a result of contradictory or no validation results. From discussion with acknowledged industry experts, some of the approaches are too complex to understand, become difficult to apply and are mistrusted as they represent a "black box approach".

Most importantly Kley and Caradot review of deterioration models in 2013 indicate the numerous problems with these approaches.

The numerous statistical approaches that have been developed could be used as a likelihood factor where there are no other alternatives. In such a case, the models could be used in developing a risk model to decide which of the yet to be assessed sewers should be assessed but it is not feasible to use the same approach to predict which of the sewers should be re-assessed after assessment as they are based on probability which could be directing sewer investment in the wrong direction.

Deterministic DM uses mathematical equations to estimates a quantitative relationship between sewer ICG and factors affecting deterioration. A clear relationship between these factors and ICG is assumed without accounting for the uncertainty associated with sewer deterioration. Deterministic DM can also be used to measure the condition change in a network using linear or non-linear regression. Ignoring the drawback, this approach seems to be the most reliable as it represents the actual deterioration observed in a sewerage network. Utilities want to know what is actually happening in their network to enable them to plan appropriately.

Statistical or stochastic DM, in addition to estimating a quantitative relationship between sewer ICG and factors affecting deterioration, it considers the uncertainties associated with sewer deterioration. These uncertainties are considered in the form of a probability-based equation. However, it requires sufficient data in each condition grade to determine transition probability. It also requires extensive inspection data set that is sufficient enough to represent the variation within different cohorts. To determine transition probability, repeat inspection data is required for a group of sewers. This quantity of inspection data is unavailable in any utility.

Artificial intelligence DM estimates the relationship between independent variables and dependent variables. The independent variables are the factors affecting deterioration whilst the dependent variables are the ICG (ICG 1 to 5). These variables are referred to as predictors and responses. A model is built based on a sample of historical sewer assessment data. The model learns the relationship between predictors and responses. The more the data sample, the more the lessons learned by the model. Hence; it is a data-driven model that represents a black box as the computation is hard to understand.

Hence; the deterioration model developed in this research must;

- Check the data quality and quantity.
- Be able to create deterioration with available data in each sewer condition grade.
- Account for the vast uncertainties that exist in the sewer deterioration process.
- Be useful both at the cohort and sewer level.
- Know the influence of assumptions on outcomes.

- Be able to model deterioration in the absence of repeat inspection data by the superimposition of inspection histories of stratified data.

Sewer deterioration is a complex process as it is affected by various sewer properties (Yan & Vairavamoorthy, 2003). Although sewers are designed for a lifespan, under standard operating condition their deterioration appears to never follow a set pattern (Najafi & Kulandaivel, 2005). This has made modelling sewer deterioration difficult. Each sewer is unique as no sewer is 100% the same in terms of internal properties, use and external influences. For example, two sewers could have similar properties, but one different property is enough for the sewer to have different deterioration pattern. For effective modelling, detailed knowledge of the following is required:

- Factors affecting sewer deterioration such as size, material type, depth etc.
- CCTV inspection process.
- The WRc condition scoring system.
- The utilities' existing BAU framework for investment in sewerage network.

2.3 Factors affecting sewer deterioration

As earlier stated in Chapter 1, If CCTV survey work and proactive sewer rehabilitation are to be directed most effectively in the coming years, and then it is essential that the factors associated with structural deterioration and failure are identified and understood. Having reviewed some of UK utilities' DMs and academic research articles, the following factors were identified by experts and researchers in the wastewater field to affect sewers deterioration either significantly on moderately;

1. Collapse history (burst history)
2. Bus flow (Loading)
3. Construction period (method)
4. Debris
5. Goods vehicle flow
6. Groundwater regime
7. Infiltration
8. Road classification
9. Root intrusion
10. Sewer age

11. Depth
12. Length
13. Location
14. Material
15. Shape
16. Size
17. Sewer slope
18. Use (Purpose)
19. Soil corrosivity (soil type)
20. Soil fracture potential
21. Vehicle flow
22. Proximity to bomb site
23. Presence of H_2S
24. Seismic zone
25. Type of waste
26. Proximity to other ground installation

Nevertheless, some factors have greater influence than others. *Figure 2.9* shows the frequency in the use of these factors for sewer deterioration modelling in the utilities and in academia. These are experts and researchers' perception of what attributes are important in terms of sewer deterioration.

The percentage of research articles with the opinion that each factor was important out of the total research articles reviewed was estimated. Also, the percentage of external and internal reports from utilities in the UK that believe each factor was important out of the total reports reviewed was estimated as well. *Figure 2.9* illustrated research articles as 'Research' and industry reports as TWUL. It can be seen from *Figure 2.9* that both the industry and research article agree that sewer material type is very important. However, this is different for most others such as sewer age and size as the percentage in research articles is higher than the industry.

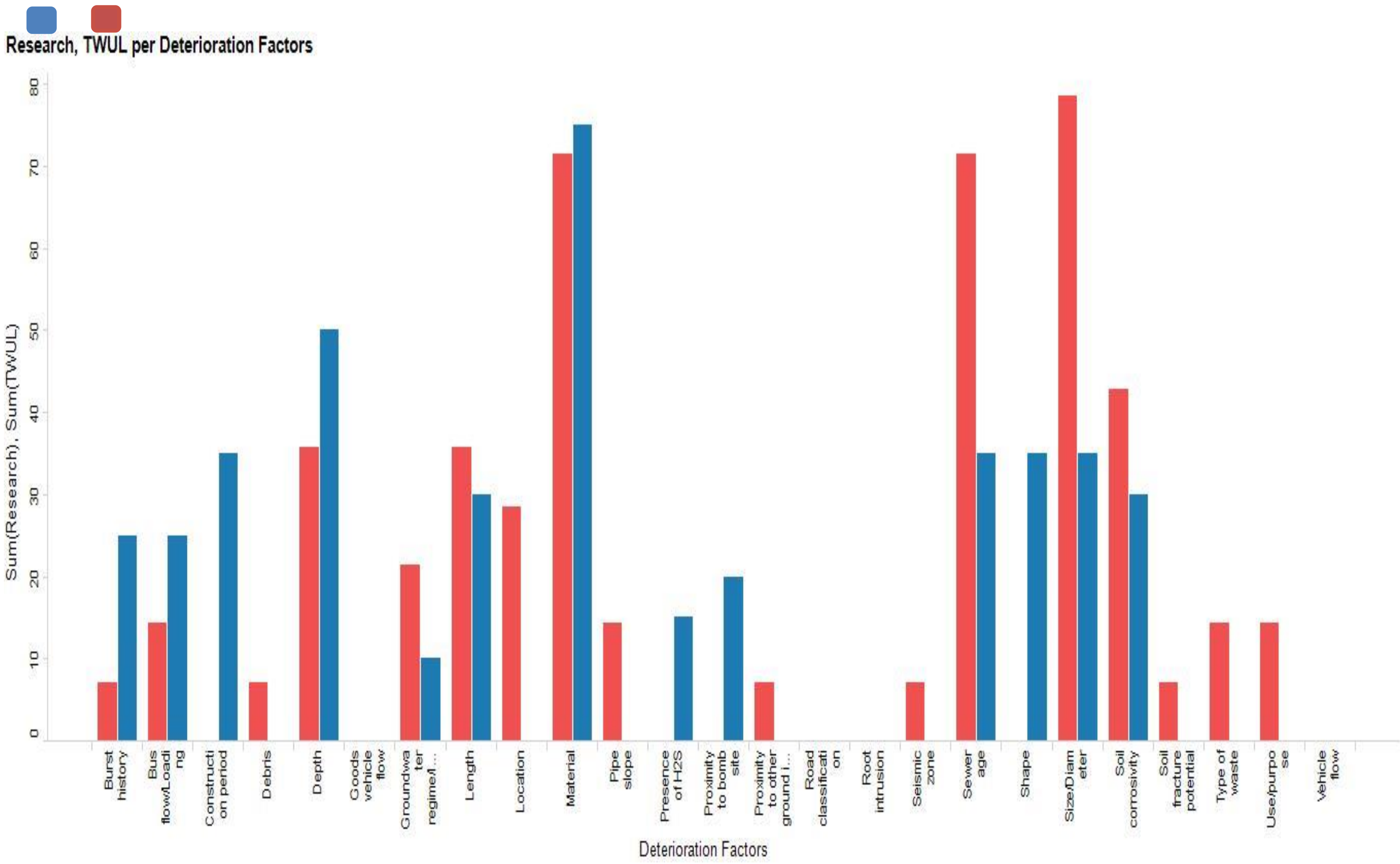


Figure 2.9. Bar chart of factors affecting sewer deterioration (Source: The Author- O. S. Tade)

To understand how these factors associate with structural deterioration and failure, there is a need to review each factor as lack of detailed knowledge of how these factors affect the condition of sewer networks escalates vulnerability to catastrophic failures (Chughtai & Zayed, 2008).

Loading: Sewer loading is of two types, imposed loading and overburden loading. In most cases, the overburden load is been factored into the design. Nevertheless, this could be increased by unexpected pore water pressure that wasn't factored into the original design. Pore water pressure is the pressure created by groundwater and held within soil particles when the water level rises to fill the void within these particles. This additional loading could be difficult to estimate during design and hence may not be factored into the design. Loading a material beyond its carrying capacity will eventually result in collapse. Imposed loads are usually from vehicular movement. The factors identified from the literature review as important are Bus flow, Goods vehicle flow, Road classification and Vehicle flow. The road classification determines the loading imposed on the sewer i.e. the loading imposed on a sewer underneath an open field will be less than that underneath an LGV (Large Goods Vehicle) road and less than an HGV (Heavy Goods Vehicles) road respectively.

Collapse history or Burst history: It was reported that a history of frequent collapse in sewer cohort could be an indication of a possible future collapse. However, it is important to note that this factor could be invalid if the problem causing a series of collapse in the past is rectified.

Construction period: Sewers commissioned between the 1940s and 1950s were found to deteriorate faster than others (Balmer & Meers, 1982). However, some studies found sewer commissioned after 1940 to be deteriorating faster than sewers constructed before the 1940s (Baur & Herz, 2002); (Ana E, et al., 2008).

Debris or Sediment level: The accumulation of sediment in a sewer could be the beginning of sewer deterioration most especially in a low gradient sewer.

Groundwater regime or Infiltration: The variable flow velocity in a sewer and groundwater level can result in seasonal infiltration and exfiltration. Constant exfiltration and infiltration erode the sewer soil support and consequentially affect stability, most especially when the water table rises above the sewer (Rogers, 1986). Loss of sewer stability induces deterioration.

Root intrusion or Presence of trees: Proximity of trees to a sewer could allow roots to penetrate and damage sewer lining (WRC, 1994). The growing root expands these cracks until the sewer reaches a breaking point and eventually collapse (Reed, 1982). This is impacted also by sewer material type. For example, root can easily penetrate sewer with joints such as brick sewer whilst root cannot penetrate rigid sewers such as iron in good condition.

Sewer age: The consensus is that as a result of wear and tear, older pipes are more likely to fail than newer ones. But a discussion with experts in the UK utilities suggested that old pipes are not necessarily in poor condition but an indication to start condition assessment. Majority of Victorian clay sewers have outlived some newer ones (McSweeney, 2017).

Depth: The findings by (Lester & Farrar, 1979); (Anderson & Cullen, 1982); (O'Reilly, et al., 1989); (Fenner & Sweeting, 1999) and (Fenner, 2000) showed that the number of defects decreases with depth. The frequency of defects in sewers decreases with depth as a result of a diminishing impact of surface elements like vehicular movement and loading from structures. However, it was also found that increment in depth increases pressure from soil overburden and consequently increasing the frequency of defects (Eliseo & Ana, 2009).

(Ana E, et al., 2008); (Ariaratnam, et al., 2001) and (Davies, et al., 2001) found no correlations between depth and deterioration.

Length: The longer a sewer, the more likely it is that one can find defective parts and sections (Park & Lee, 1998). Also, long sewers are susceptible to differential settlement. This allows debris to accumulate in the sewer till blockage occurs which consequentially result in deterioration.

Location: (O'Reilly, et al., 1989); (Davies, et al., 2001) and (Ana E, et al., 2008) found no difference between sewers underneath HGV, LGV and other locations, hence, their conclusion was that location has no influence on sewer deterioration. Contrary to this, (Parande, et al., 2006) found that CP sewers located close to industries are deteriorating more as a result of toxic industrial waste discharged directly into the SN.

Material: (Micevski, et al., 2002), (Ana E, et al., 2008) found CP pipe to last longer than other material types. Contrary to this (Ariaratnam, et al., 2001); (Davies, et al., 2001) found material type to have no influence on sewer deterioration.

Shape: Circular sewers are generally the most durable of all the sewer material types (Modica, 2007); (Ana E, et al., 2008). But on the contrary, (Baur & Herz, 2002) found Egg-shaped sewers to be the most durable.

Size: This is one of the most contentious properties affecting sewer deterioration. Some studies such as (Lester & Farrar, 1979) found no correlation between sewer deterioration and sewer diameter. Some others found that large size sewers deteriorate slower than smaller ones (Balmer & Herz, 1982); (O'Reilly, et al., 1989), (Davies, et al., 2001); (Baur & Herz, 2002); (Micevski, et al., 2002); (Ana E, et al., 2008) and (Tade, *et al.,* 2018). As a result of weight and bulk density, larger diameter sewers are difficult to install precisely and therefore more susceptible to damage (Whetman, 1979). Also, small diameter sewers are generally laid shallow as they are mostly stormwater sewer which discharges into surface water causes (Tade, 2018). Hence, are directly impacted by surface loading. Contrary to this, the study by (Baik, et al., 2006) indicates that small size sewers deteriorate slower than larger ones. This was attributed to the large surface area of a large diameter sewer in contact with its surroundings.

Sewer slope: In sewers affected by hydrogen sulphide attacks such as cementitious sewer, a flat gradient supports the formation of this toxic gas as the flow velocity is low which gives room for hydrogen sulphide formation (EPA, 1992); (Ayoub, et al., 2004); (Baur & Herz, 2002). This causes corrosion and consequently increases deterioration rates. Also, a flat gradient is more susceptible to debris deposition which can result in deterioration.

Contrary, steeper gradient are less stable and have a high flow velocity which erodes the internal lining of sewer facilitating deterioration (Baik, et al., 2006).

Use/Purpose or Type of waste: Foul sewers deteriorate faster than combined sewers (Baur & Herz, 2002). The concentration of sewage in foul sewers can result in a chemical attack on the sewer lining and hence a higher deterioration rate than combined sewers with diluted sewerage (Eliseo & Ana, 2009).

Soil corrosivity, Soil type or Soil fracture potential: The rate of ground loss around sewers is a function of the type of soil surrounding it. Increased ground loss can exacerbate sewer defects such as cracks and fractures. Cohesive soils are less susceptible to ground loss than cohesionless soil (WRC, 1994).

Contrary, (Balmer & Meers, 1982) and (O'Reilly, et al., 1989) indicates that the rate of deterioration of sewers in cohesive soil is higher than in cohesionless soil.

Proximity to bomb site or Seismic zone: Ground movement can result in differential soil settlement which could eventually result in a collapse. The greater the intensity of the movement, the more likely it will result in a collapse of the buried asset.

Presence of H_2S: The presence of H_2S most especially in cement and CP sewer often erode the lining of the sewer. Some materials such as CP are affected by H_2S whilst some such as Iron are not.

Proximity to other ground installation: Maintenance or repair of other nearby services could damage sewers. Activities such as excavation can disturb the stability of underground sewers. In an investigation of the effect of ground movement on buried services, (Chard & Carder, 1982); (Rumsey, et al., 1982) found ground excavation to affect the stability of buried services. However, the larger the buried asset the less likely it is affected by excavation.

A critical look at these factors shows they fall into these categories; fixed inherent or physical factors, variable or environmental factors and operational or imposed factors. From a detailed review of utilities' knowledge and literature, it is obvious that there is no consensus on how these factors affect deterioration and how important the factors are, as authors and experts have different perspectives. It is also very interesting to know that during a joint discussion of this factors, the author, industry experts and supervisors also find the level of importance of these factors very contentious as there were different opinions on which is more important than the other. This is not productive for the utilities. The focus is, under standard condition, which factors would cause variable deterioration rates and by how much. This is yet to be understood and sufficient research has not been carried out to quantify how these different factors influence deterioration. Also, some factors can only influence a certain type of other factors. For example, the presence of H_2S has no effect on certain material types, and the effect of roots and sewer length is highly variable on different materials. The material type appears to have more dependency than any other property as a variation of other factors can have from no deterioration effects to significant deterioration effect. Analytical Hierarchy Process (AHP) will be discussed and used to estimate and quantify the importance of these factors in Chapter 5.

There are guidelines for sewerage condition evaluation and intervention, and this recommends prioritization of sewer inspection as the primary premise of the decision-making process, for the best intervention to be sought (WRc, 2004); (Bennis, et al., 2003).

2.4 Sewer condition scoring protocols

Sewer condition scoring has become significant for the wastewater utilities around the world to ascertain the performance and condition of infrastructural assets (Thornhill & Wildbore, 2005). The first sewer condition scoring scheme was developed in 1977 by WRc in the UK. It was on this basis that different sewer condition scoring protocols showed in Figure 2.10 were developed around the world. The CERIU (Centre for Expertise and Research on Infrastructures in Urban areas) condition scoring protocol is being used in Canada and the NASSCO's (National Association of Sewer Services Companies) PACP (Pipeline Assessment Certification Program) is used in North America (Alain, et al., 2011)

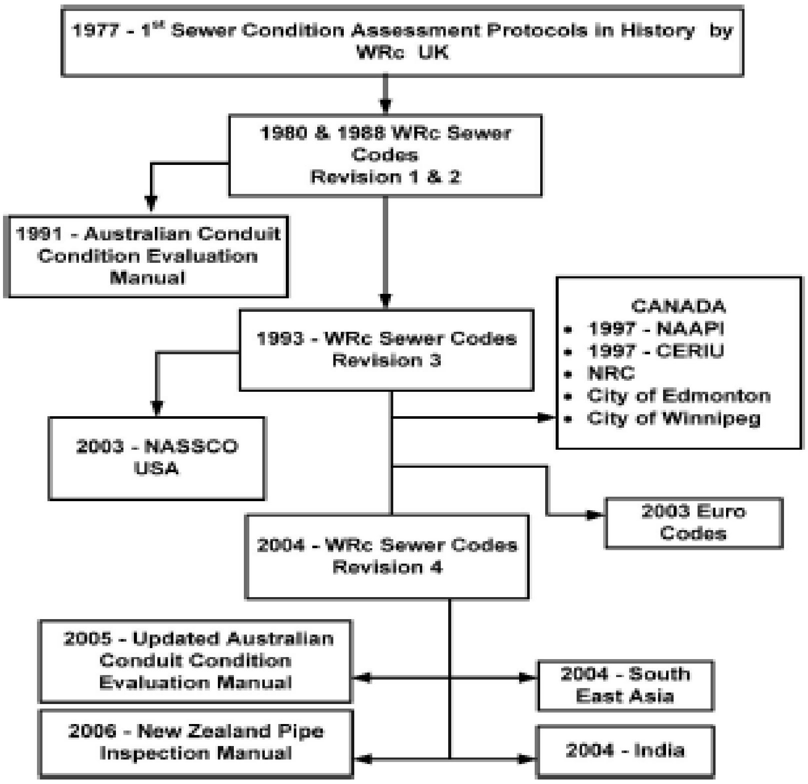


Figure 2.10. The existing scoring system (Chughtai & Zayed, 2011)

Sewer condition scoring protocols are used to assess the current ICG of a sewer to formulate a benchmark for investment (rehabilitation and replacement) prioritization. Sewer condition assessment is a premise for a successful AM strategy (Rahman & Vanier, 2004).

2.4.1 Water Research Centre (WRc)

The WRc commenced a 5-year investigation in 1978 to research the collapse of over 250 sewers. The investigation found the need for WRc to develop an SRM (Sewerage Rehabilitation Manual). Hence; the SRM was developed (WRc, 2001). The SRM sets out planning guidelines to be considered for sewer rehabilitation. Over the years, the manual was reviewed and updated to include new findings. For example, SRM 3 was updated to SRM 4 to include current maintenance, operation and environmental practices. This also included sewer defect coding that was compiled according to European standards for defect coding and latest renovation strategies (Rahman & Vanier, 2004). The Manual of Sewer Condition Classification (MSCC) in the SRM sets out the procedure for coding and classification of defects. The latest SRM was introduced in 2013 as shown in Table 2.7 (SRM, 2013). The MSCC introduced in 2013 (MSCC5) was updated to include new codes for latest identified defects. Also, consequence factors were introduced to support users of this manual in risk management. The limitation of the WRc scoring protocol and the others will be discussed in the summary section.

Table 2.7. Timeline for WRc manual (Source: The Author- O S. Tade)

WRc	Description	WRc Release date
SRM 1	Sewerage Rehabilitation Manual	1983 / corrected in 1985
SRM2	Sewerage Rehabilitation Manual	1986
SRM3	Sewerage Rehabilitation Manual	1994
SRM4	Sewerage Risk Management	2001
SRM 5	Sewerage Risk Management	2013

2.4.1.1 Locating defect in a sewer

As part of the update that was included in SRM 3, a method was included to identify the location of observed defects in a sewer. This method was called the "clock reference" as shown in Figure 2.14.

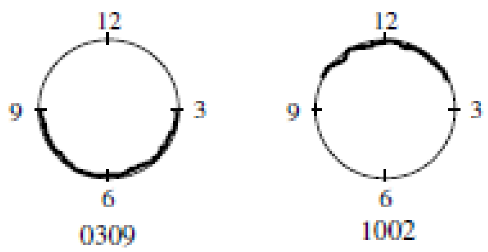


Figure 2.11. Clock reference method (Rahman & Vanier, 2004)

The dark area represents the defect location in the sewer whilst the light area represents the rest of the sewer without defects. Similar to a clock, the top part of the sewer is 12 o'clock, the right side is 3 o'clock, the bottom side is 6 o'clock and the left side is 9 o'clock. The first example in Figure 2.14 is 0309 defect location (the bottom part of the sewer is defective), the second example is 1002 (the defect is in this region of a clock).

2.4.1.2 Defects values and condition grades

The MSCC determines the structural and operational conditions of sewers from the defects obtained from sewer CCTV or man entry survey. The MSCC assigns weighted values to these defects to obtain operational and structural condition scores and grades. These defects are referred to as deduct values (SRM, 2013). The deduct values are between the range of 1 to 165 for both operational and structural condition as shown in Table 2.8. The scores obtained are mean deduct value, peak deduct value and the total deduct value. The peak deduct value which is the worst defect found in the sewer is used to determine the sewer condition grade and the ICG is between 1 to 5 with 1 meaning good condition and 5 meaning sewer collapsed or collapse is imminent.

Table 2.8. WRc structural and operational deduct score: Adapted from (Rahman & Vanier, 2004)

Condition Grade (ICG)	1	2	3	4	5
Structural	<10	10 to 39	40 to 79	80 to 164	165 and >
Operational	<1	1 to 1.9	2 to 4.9	5 to 9.9	10 and >

2.4.2 National Research Council of Canada (NRC)

IRC (Institute for Research in Construction) is a subsidiary of NRC. IRC published guidelines for rehabilitation and condition assessment of large size sewers (Zhao, et al., 2001). Several council authorities in Canada partnered with IRC to develop these guidelines for utilities in charge of SN management. The guidelines include; defects and their definitions and inspection and rehabilitation strategies. These guidelines defined weighted operational and structural defects scores according to their severity for sewer above size 900 mm. Hence, the NRC guidelines are only for large size sewers. The deduct values are between the range of 1 to 10 for both operational and 1 to 20 for structural condition as shown in Table 2.9.

Table 2.9. NRC structural and operational deduct score: Adapted from (Rahman & Vanier, 2004)

Condition Grade (ICG)	0	1	2	3	4	5
Structural	0	1 to 4	5 to 9	10 to 14	15 to 19	20
Operational	0	1 to 2	3 to 4	5 to 6	7 to 8	9 to 10

The ICG is between 0 to 5 with 0 meaning excellent condition and 5 meaning sewer collapsed or collapse is imminent.

2.4.3 City of Winnipeg – sewer management study

In 2001, the existing methods of managing SN were reviewed by Winnipeg's sewer management (Winnipeg, 2001). The study was in 3 volumes.

Volume 1 includes; The overview of sewer management, integrated approach for sewer inspection and recommendation of sewer assessment protocol.

Volume 2 includes; Detailed description of current rehabilitation techniques and the procedures for designs in dealing with social cost (direct and indirect cost).

Volume 3 includes: Recommendation and description of strategies for sewer maintenance.

This method was based on WRc's SRM and a grading system was developed for the city of Winnipeg by NAPPI (The North American Association of Pipeline Inspectors). This study was carried out to recommend best practice for SN management.

2.4.3.1 Defects values and condition grades for sewer management study

The study suggested that it was necessary to calculate the ICG of sewer from CCTV survey and from the actual defect value (not the deducted value) (Rahman & Vanier, 2004). It was recommended that the ICG should be a function of surcharge frequency and soil type. The final score was called SPG (Structural Performance Grade) based on the risk posed by surcharge frequency and soil type. The defect value for each defect ranges from as small as 0.1 to 165 and the ICG is between 1 and 5 similar to SRM 3 (WRc, 1986). This process of conversion is as shown in Table 2.10.

Table 2.10. ICG with corresponding risk factor (SPG) (Rahman & Vanier, 2004)

Condition Grade (ICG)	Soil Type	Structural Performance Grade Frequency of Surcharge		
		Rarely	Frequently	Daily
4	High Risk	4	5	5
3	Silts and fine sands; medium to	3	4	5
2	coarse sands	2	3	3
4	Medium Risk	4	4	5
3	Low plasticity clays, fine, medium	3	4	4
2	and well graded sandy gravels	2	2	3
4	Low Risk	4	4	5
3	Medium to high plastic clays and	3	3	3
2	low plastic clays if sewer constructed by tunneling	2	2	2

2.4.4 City of Edmonton

A report on the standardization of sewer condition rating system was developed by the city of Edmonton in Canada (Edmonton, 1996a). This was developed with a manual for sewer physical condition classification (SPCCM). SPCCM has been in use to evaluate the conditions of sewers in Edmonton. This condition rating system is used to prioritise investment in Edmonton's SN. The manual describes each defect and their severity with a photo of the defect obtained from CCTV. This manual was based on WRc's SRM 2 (WRc, 1986).

2.4.4.1 Defects values and condition grades for city of Edmonton

This report presents a very comprehensive condition scoring system for both operational and structural condition scores. The severity of each defect is described, and the corresponding defect deduct value is provided to calculate the final ICG. Defects deduct values ranges from 1 to 3 for operational defects and 1 to 115 for structural defects. From these, the total, mean and peak score is then obtained. Similar to WRc's MSCC, the ICG is a function of the peak score and it ranges from 1 to 5 with 1 being excellent and 5 meaning sewer collapse or collapse is imminent.

2.4.5 NAAPI and NASSCO

National Association of Sewer Services Companies (NASSCO) uses Pipeline Assessment Certification Program (PACP) which was implemented in 2004

(NASSCO, 2004). This was implemented to evaluate and standardize the condition scoring of sewers using CCTV survey report. Unlike all other scoring protocol with just operational and structural condition score, NASSCO has maintenance score in addition to this. Similar to WRc's MSCC, NASSCO assigns ICG 1 to 5 for sewer condition with 1 meaning excellent and 5 meaning failed. But instead of using WRc's MSCC, it uses the PACP condition matrix code. The addition of the peak scores for the contributing sewer section is the overall pipe condition score.

NAAPI condition scoring protocols assign condition defects scores to defects and final ICG to the sewer according to WRc's MSCC. The only difference is in the CCTV survey process where NAAPI provide training for CCTV operator on how to effectively capture necessary data during the CCTV survey.

2.4.6 Comparison and discussion of protocols

The condition scoring protocols discussed in this Chapter differ in defect naming (coding), deduct values, internal condition grading and the prioritization of sewers conditions.

2.4.6.1 Comparison of defect coding systems

The defect code for joint defects (severe > ½ pipe wall thickness) is JDS, JS and JDL for NRC, Edmonton and WRc respectively. More details for this can be found in the manuals for sewer condition scoring protocols in Appendix III-VIII. The major difference is the choice of letters and the number of letters. WRc and NRC use three letters and Edmonton used two. The last character in the defect code represents the severity and first or first 2 characters represent the defect type.

2.4.6.2 Comparison of deduct Values

Deduct or defect value for the discussed sewer condition scoring protocols is as shown in Table 2.11.

Table 2.11. Deduct value for sewer condition scoring protocols (SRM, 2013)

Protocols	WRc	NRC	Edmonton	Winnipeg
Structural Defects	1 - 165	1 - 20	1 - 115	0.1 - 165
Operational defects	1 - 20	1 - 10	1 - 3	-

2.4.6.3 Comparison of condition grades

The sewer condition score is a function of the value of the defect. The condition grade is assigned if the peak score falls between the bands shown in Table 2.12.

Table 2.12. Defect score bands and corresponding condition score (Source: The Author- O. S. Tade)

	Peak Score					
Condition Grade	WRc	NRC	Edmonton	Winnipeg	NAAPI	NASSCO
0	-	0	-	-	-	-
1	<10	1 – 4	<1.0	<10	<10	<10
2	10 – 39	5 – 9	1.0 – 2.0	10 – 59	10 – 39	10 – 39
3	40 – 79	10 – 14	2.1 – 3.0	60 – 99	40 – 79	40 – 79
4	80 – 164	15 – 19	3.1 – 5.0	100 – 149	80 – 164	80 – 164
5	165 and >	20 and >	5.0 and >	150 and >	165 and >	165 and >

2.4.7 Summary of condition scoring protocols

All these scoring techniques suffer from at least one problem as they are all based on WRc scoring regime which is the embryo code as earlier stated. The New Zealand inspection manual describes the mean score as the overall condition of the sewer (NZWWA, 2006) but this doesn't reflect the overall condition of the sewer as it assumes that defects concentrated in an area are evenly distributed along the sewer length. The available condition scoring protocols are useful for CCTV surveyors to translate sewer defects into numbers. These are only useful to utilities with the capacity to rehabilitate or resurvey all their condition grade 4s and 5s sewers according to their reassessment schedule without worrying about the above problems. It becomes difficult for sewer risk modeller and asset managers of larger kilometres of sewer such as wastewater utilities in the UK to translate the scoring to a strategic investment plan. The existing scoring protocols only show the condition of the most severe defect in a section of a sewer at the time of inspection which does not reflect the overall condition of the entire sewer length. It is difficult to tell the change in the sewer condition with this score; hence, it is difficult to model deterioration rate with any degree of confidence. Moreover, there are so many unpredictable parameters that could affect, or cause sewer deterioration as earlier identified in this Chapter. After a critical look at the scoring protocols, it was found that there is little correlation between these numbers and the deterioration rate of sewers. What researchers using this score are predicting is the probability or likelihood of a sewer developing one severe defect. The WRc condition scoring scheme does not translate to likelihood with the level of granularity required by proactive AM planners. Hence the need to granulize these scores.

There are three major problems:

- Three different surveys done 5 years apart on a sewer could have condition grade 4 on the first inspection, still on the same condition grade 4 on the second inspection and moved to condition grade 5 on the third inspection. It is difficult to know if it is a circumferential crack with condition score 10 that deteriorated to circumferential or complex fractures to make condition 5 in the last survey.
- Condition grade 5 sewers according to WRc means collapse is imminent or the sewer has collapsed. These scores do not tell wastewater utilities with a large number of sewers which of the condition grade 5s sewers are already collapsed.
- The WRc condition score is a function of the peak score. It only considers one severe defect and the other defects are ignored regardless of severity or proximity to each other.

This shows that the WRc condition scoring used in the UK is quite coarse and apart from measuring the entire sewer condition based on a peak score, it puts numerous sewers in the same condition, leaving sewerage owners with the problem of prioritising in terms of likelihood.

ıs_cctv_survey - Copy_0

ole	material	shape	size_1	hard_wired_s...	hard_wired_s...	mean_score	peak_score	total_score
	VC	C	150.	1	1	0.	0.	0.
	VC	C	150.	1	1	0.	0.	0.
	VC	C	150.	1	1	0.	0.	0.
	VC	C	150.	1	1	0.	0.	0.
	VC	C	150.	1	1	0.	0.	0.
	VC	C	150.	1	1	0.	0.	0.
	VC	C	375.	1	1	0.	0.	0.
	VC	C	150.	3	1	0.	0.	0.
	VC	C	150.	1	1	0.	0.	0.
	VC	C	150.	1	1	0.	0.	0.
	VC	C	150.	1	1	0.	0.	0.
	VC	C	300.	2	2	1.0410000000...	10.	10.
	VC	C	375.	3	3	1.7054263565...	40.	110.
	VC	C	375.	2	4	3.57[illegible]...	80.	230.
	VC	C	150.	1	5	3.4033701509...	165.	165.
	VC	C	300.	1	1	0.	0.	0.
	VC	C	300.	3	4	2.6058631921...	80.	80.
R	VC	C	375.	4	4	2.6760563380...	120.	190.
	CO	C	1200.	3	2	2.8449502133...	20.	200.
	VC	C	375.	1	1	0.	0.	0.
	VC	C	150.	1	1	0.	0.	0.
	PF	C	150.	3	2	0.6756756756...	20.	20.
	CO	C	375.	3	2	0.5128205128...	10.	10.

Figure 2.12. Spotfire's extract for sewer survey works (Source: The Author- O. S. Tade)

Figure 2.15 shows an extract from Spotfire analysis done using collected inspection data which confirms how WRc scoring protocol measure sewer defects as a function of the peak score. This is further explained in Table 2.13.

Table 2.13. Condition grading scores (Source: The Author- O. S. Tade)

Sewer condition grade	Peak score	Comment
1	0	Peak score < 10
2	10	Peak score 10 to 39
3	40	Peak score 40 to 79
4	80	Peak score 80 to 164
5	165	Peak score is >= 165

2.5 Investment prioritization of sewer

To prioritise investment, the criticality of the SN is analysed. A sewer could be critical or non-critical. Generally, criticality is a measure of COF and COF is a function of;

- The level of sewer importance.
- Likely collateral damage from a failure or collapse of a sewer.
- Sewer replacement cost.
- Sewer location.

The SRM grouped sewer criticality into 3 categories. These categories depend on the cost implication as a consequence of the surface features above the sewer, (type of building above such as highway, railway or hospital area), sewer depth, sewer material type and soil condition (WRc, 2001). The existing proactive investment approach (sewer inspection frequencies) is as in Table 2.14. Table 2.14 shows the inspection frequencies for the different sewer criticalities provided by WRc and ASCE as summarised by Zhao *et al* (2001). These are the leading organisations in areas of sewerage rehabilitation in the U.K and U.S respectively.

Table 2.14. Investment priorities (Adapted from WRc, 2001 and Zhao et al, 2001)

Condition Grades	Criticality	Survey Frequencies			Investment Priority	
		Category A	Category B	Category C		
5	High	0 years	0 years	Not provided	Immediate	
4	High	0 years	5 years	Not provided	High	
3	Medium	3 years	15 years	Not provided	Medium	
2	Low	5 years	20 years	Not provided	Low	
0 - 1	Low	10 years	20 years	Not provided	Not required	

The survey frequencies provided appears to be too ambiguous as it has a very low level of granularity. This is a problem for utilities managing a large amount of sewer where a large portion of sewers could be in ICGs 4 and 5 and in category A criticality. This highlights research question 1 in Chapter 1 of how the business will prioritize and justify investment in the face of scarce resources (monetary). Hence; the RBF developed in this research must;

- Provide a score that reflects the condition of the entire sewer length.
- Provide justifiable priorities on investment in SN.

2.6 Literature review summary

As earlier stated, sewer deterioration can be modelled as a group (cohort) or pipe level (Ana E, et al., 2008). In 2006, a survey carried out by UKWIR (UK Water Industry Research) concluded that the data available in the UK water utilities' repository on sewer performance, failures and attributes cannot be used at that time for deterioration modelling at an individual sewer level (UKWIR, 2006). This calls for a review of the data available. For sewer investment, two main methods have been identified from reviews of literature;

Evidence or substance-based method: This method assigns scores to prioritise sewers in order of the total length of sewer sections that requires repair or replacement.

Priority-based method: This method assigns scores to sewer in order of the most severe defects found in the sewer length, the length and severity/density of the defect (Kley, et al., 2013).

This research explores a hybrid method looking at all the defects in the entire sewer length. It gives priority to the sewer with the most severe single defect and the most count of defects.

Around the world, different approaches have been explored but because of different methodologies in aggregating sewer defects, it is difficult to benchmark or apply another municipality's approach (Kley, et al., 2013). So also, it is difficult to make or apply methods and standards as there are no consistent way of capturing data because different utilities have different methods and approaches (UKWIR, 2015). Understanding the terminologies and differentiating their different meaning from engineering to business terms is important. The concept of risk in the business world is the consequence multiplied by the likelihood but in the engineering world, it is severity by the likelihood. So also, the concept of sewer deterioration portrayed by some research literature could be misleading because they have failed to clearly define the concept. Some of the available literature looks at deterioration by identifying the likelihood or probability of a sewer or cohort being in a critical condition whilst this research looks at the deterioration in a real sense by evaluating the actual change in the condition of an individual sewer or cohort over time.

The major problems in deriving investment programmes in sewerage systems are therefore being able to priorities and identify individual sewers with this unacceptable level of service or condition within the numerous sewers identified to a condition grade. This also raises research question 2 of after identification and condition assessment, when is reassessment for rehabilitation required as shown in Figure 2.16.

So many approaches have been explored to predict what proportion of sewers will have an unacceptable condition and risk of service failure, but little has been done around accurately predicting or identifying when reassessment or rehabilitation will be required.

Table 2.15. Industrial approach for the schedule of sewers reassessment (BPSHCA, 2013)

Condition grade 5 – Annual survey
Condition grade 4 – survey every 2 years
Condition grade 3 – survey every 5 years
Condition grade 1 / 2 – random sample to supporting modelling

Table 2.15 shows the inspection frequencies for sewers in different condition grades as advised by experts in the industry.

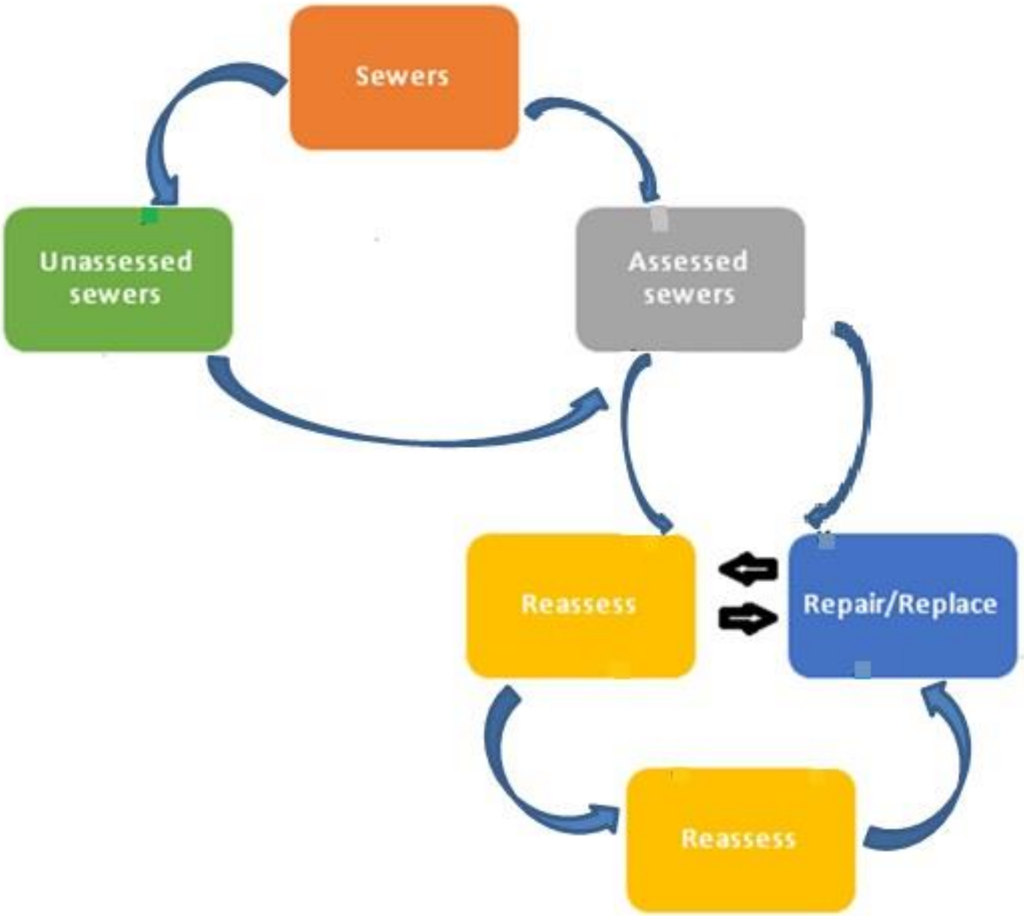


Figure 2.13. Sewer investment process (Source: The Author- O. S. Tade)

To buttress the research question raised, Figure 2.17 is an example of how a large number of sewers could be in the same condition classification and hence would require prioritisation.

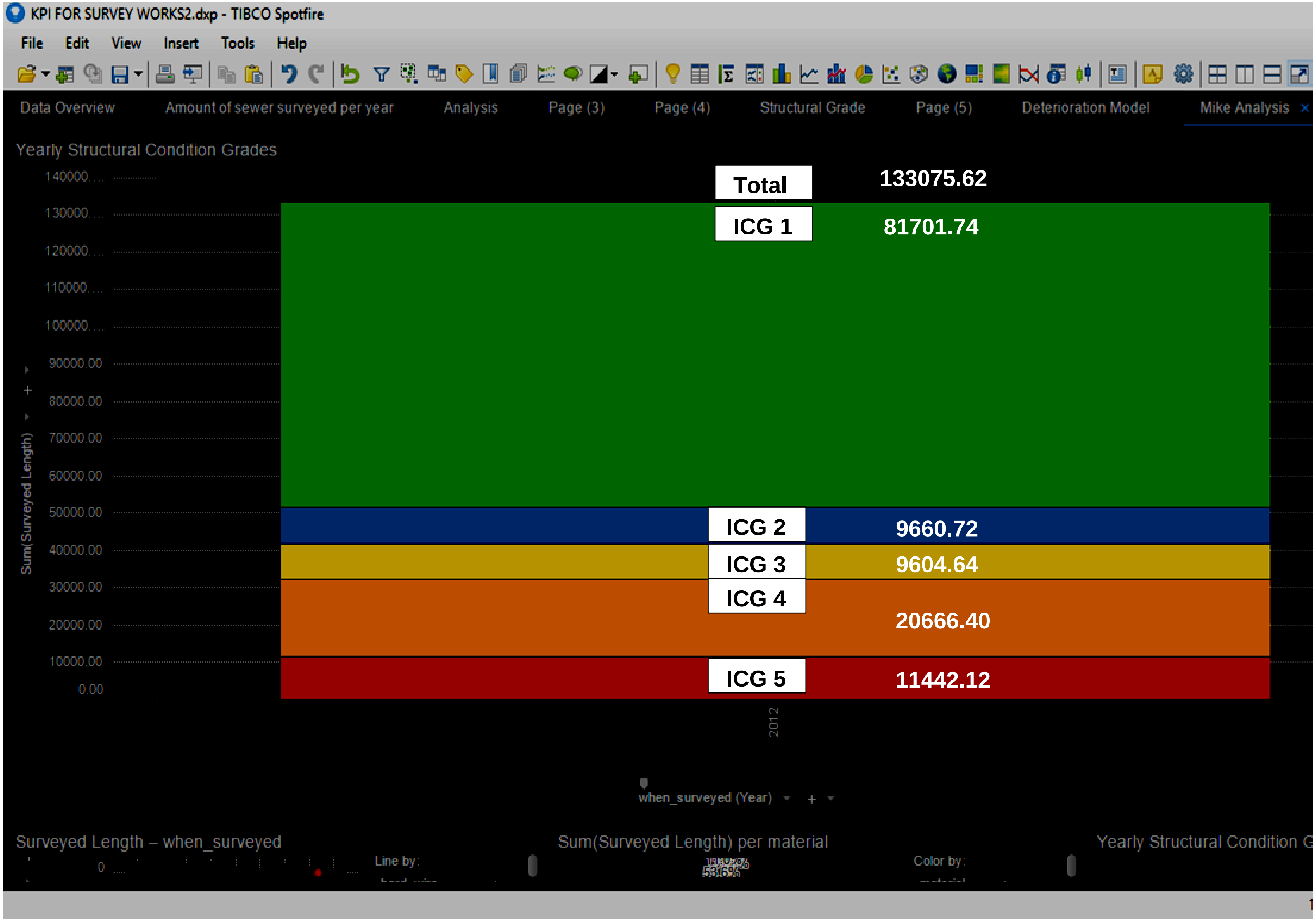


Figure 2.14. Analysis of surveyed sewers in 2012 using Spotfire (Source: The Author- O. S. Tade)

Spotfire is a data analytical tool designed by Spotfire (2018). As showed in *Figure 2.14*, out of 133,075 m of sewers inspected in 2012, 32,108.52 m was found to be in condition grades 4 and 5. This reflects the prioritization of surveys for assets where there is an existing condition concern. There are 310 manhole to manhole sewer lengths in this cohort with an average length of 103.24 m. The question is how are these 310 manholes to manholes sewers going to be ranked for proactive investment. Hence, the condition scoring protocol available does not provide the level of granularity expected as these scores are too coarse for proactive investment. This means that the sewers invariably require a critical engineering review as the argument is that the 310 sewers would be subjected to engineering review for prioritization. However, it would take some considerable man-hours to painstakingly review 13.075 km of sewers. The sewerage system is failing rapidly as the rate of sewer inspection and rehabilitation is lower than the rate of sewer deterioration (Tuccillo, et al., 2010). The higher the number of sewers required to be reviewed, the more obvious the problem with the scoring system. Nevertheless, wastewater utilities with the capacity to routinely rehabilitate or repeat inspection of their sewers would use these scores conveniently without worrying about the problems mentioned. Unfortunately, the majority of wastewater utilities don't have the capacity to invest in all of their public sewers. The problem becomes obvious with large sewerage assets owners as it is difficult for sewer risk modellers and asset managers to translate the scores to strategic investment plans without critical engineering review. Additionally, all water utilities in the UK have inherited transferred private assets, for some utilities, this is a 100% increase with no information on inherited asset age, material or condition of the sewer.

It is not cost (time and money) effective to subject all the sewers to engineering review but a trigger for engineering review should be designed into the sewerage asset management plan. This would allow only for a portion of the sewers that requires an engineering review to be reviewed

Many researchers have used this scoring scheme to model sewer condition prediction but failed to provide a validation process for their result as identified by Kley and Caradot, 2013. Most of the approaches available estimate the likelihood or probability of yet to be assessed sewers being in a critical state but not the rate of deterioration.

Chapter 3
Methodology

This Chapter presents the method adopted for this research, describes the data used and presents an Analytical Hierarchy Process (AHP) for data quality check. The methodology set out to review literature, hold discussions with experts in the utilities, analyse data, develop an enhanced Deterioration Model (DM) and develop a Risk-based Framework (RBF). The method adopted in this research is a mixture of quantitative and qualitative approach.

A qualitative approach was carried out to understand the industrial processes involved in sewerage investment. Several discussions, meetings and presentation were done at the participating utilities' office to understand the limitation preventing utilities from applying existing DMs and how this framework will fit into their BAU process. Training was done on the use of one of the leading data analytics and business intelligence tool used in the industry (Spotfire, 2018). Training was also done on the process involved in sewer condition assessment using existing scoring techniques. This was to allow for an understanding of the premise of the condition grades. The quality of the available data was reviewed to identify suitable means to improve quality. Factors that were identified as affecting deterioration was critically reviewed in Chapter 2 and the factors that were found to have the most influence on sewer deterioration in Chapter 5 was used as the basis for cohort formation. This cohort was further stratified for an attempt to observe deterioration at the sewer level.

A quantitative approach was used to analyse the available sewer data collected. The individual sewer defect scores extracted from the sewer inspection data was converted to a score that will reflect the condition of the entire sewer length (Manhole to Manhole length). These developed scores were used as the condition of the sewer at the time of survey to replace the existing MSCC condition grade. The historical CCTV survey result was stratified into cohorts in terms of the property that influences deterioration the most. The rate of deterioration of each sewer cohort was determined from historical CCTV inspection data made available by the participating industry using an enhanced Deterministic Deterioration Model (DDM). Having reviewed existing DMs, DDM was found to be the most appropriate as it depicts the ideal performance of the network.

This was enhanced by superimposing condition grades over the years as repeat inspection data were missing.

This deterioration is the transition time of a cohort's condition from date built to its worst condition. This would allow for proactive investment as utilities in charge of managing sewers would know how long the different sewer cohort would take to get to the worst condition state. Also, a means to determine deterioration at the sewer level was attempted since defects deteriorate at different rates under different sewer conditions. Although DDM does not consider the uncertainty around sewer deterioration, another enhancement was to introduce a means to consider the uncertainty which will be extensively discussed in Chapter 5. The framework is then developed showing the AM planning prioritization processes of determining inspections and re-inspection frequencies.

It was necessary for the analysis to be done based on sewers with similar properties (cohort) as the rate of deterioration of defects differs in different sewers most especially different material type as each pipe material fails differently (Angkasuwansiri, 2013).

The enhanced DDM will maximise the use of all available data to ensure the model provides the best possible prediction for rehabilitation and reassessment by providing the actual condition of sewers at the time of inspection and estimates with a high degree of confidence the future condition grade for sewers. This would allow Utilities to understand the condition of their gravity SN in a more detailed manner and be able to assess different investment options. Most importantly, instead of subjecting all the sewers in ICGs 4 and 5 to engineering review which is not cost effective as earlier stated in Chapter 1, a similar approach to system analysis used by (Tade, et al., 2015) would be used to decide which of these assets requires engineering review.

3.1 Data description and statistical insights

In the UK wastewater utilities, sewer data are held in a GIS database and CCTV inspection records held in a separate database which links into GIS. The sewer inspections were carried out to ascertain the ICGs. Recorded parameters during the CCTV inspection includes; the survey date, location, manhole identification number, sewer material type, surveyed length, size, shape, effluent characteristics, WRc structural and service ICGs. This information collected by the sewer CCTV surveyor can also be used to validate the existing information held on this asset by the utility in the GIS database and hence there is a high level of reliability in this data and is very useful for the intended purpose. Data used includes 2,385,342 records of sewer held in GIS with a total length of 66,578 km.

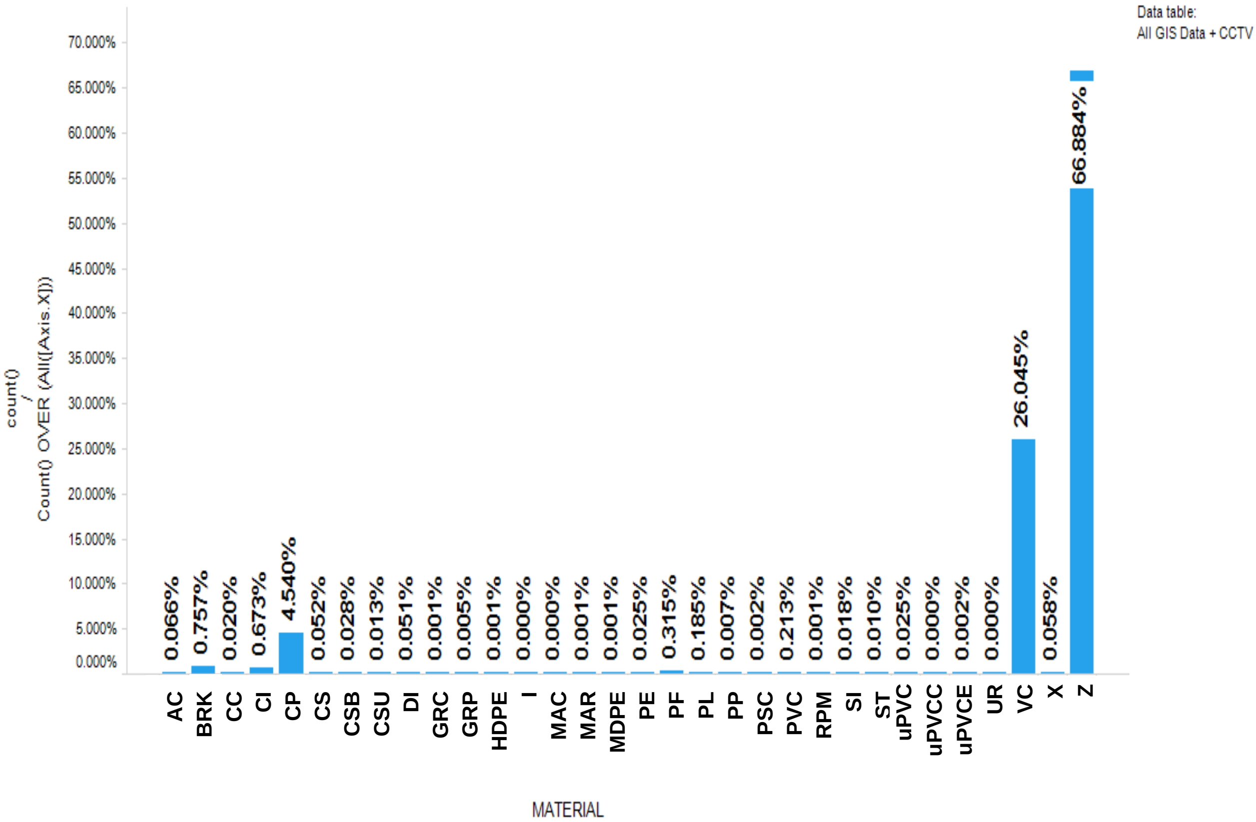
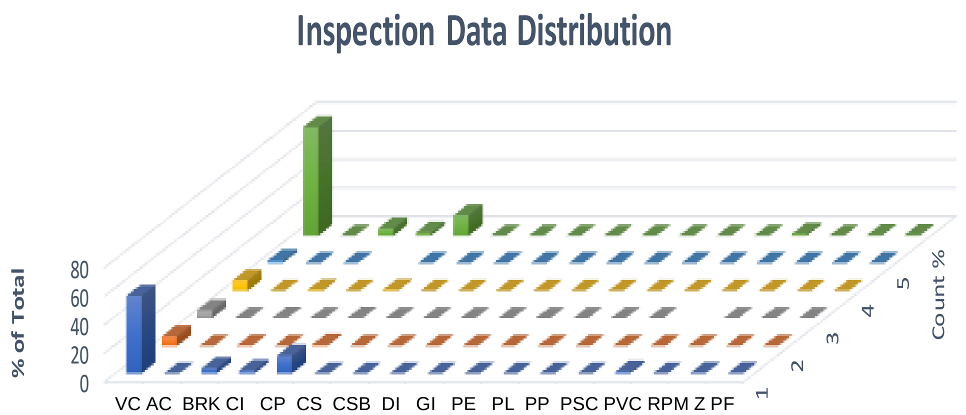


Figure 3.1. Percentage distribution of data in GIS (Source: The Author- O.S. Tade)

Data used also includes 703,156 records of sewers inspected between 1989 and 2014 with a total length of 24,252 km. This inspection was done by sewer survey CCTV cameras for sewers less than a diameter of 1200 mm and man entry survey for sewers larger than 1200 mm as described in Chapter 1.



	VC	AC	BRK	CI	CP	CS	CSB	DI	GI	PE	PL	PP	PSC	PVC	RPM	Z	PF
1	54.4	0.04	3.8	2.2	12.5	0	0	0	0	0.08	0	0	0	1.3	0	0.4	0.3
2	6.7	0	0.3	0.02	0.8	0	0	0	0	0	0	0	0	0.01	0	0	0.03
3	5.6	0	0.3	0.02	0.3	0	0	0	0	0	0	0	0		0	0	0
4	7.3	0	0.6	0.03	0.6	0	0	0	0	0	0	0	0	0.01	0	0	0.05
5	2	0	0.1		0.1	0	0	0	0	0	0	0	0	0.01	0	0	0.09
Count %	76	0.04	5.1	2.27	14.3	0	0	0	0	0.08	0	0	0	1.33	0	0.4	0.47

Figure 3.2. Percentage distribution of data held for sewer inspection data (Source: The Author- O.S. Tade)

Figure 3.2 shows that 76% of the total inspection data are clay. The implication of this quantity of data is that more variations can be visualised with clay sewers than the other material types with fewer data. This data was discussed with acknowledged experts in the industry to understand the process of data gathering and how to spot errors that could possibly affect the result. Errors such as outlier characters different from what is expected in each field column.

Data visualisation: Tibco Spotfire (Spotfire, 2018) was used to stratify and visualise correlations and relationships within the data. Stratification such as slicing deterioration of a material type into different sewer sizes.

Data cleaning and sorting: This process was done by using Microsoft Excel VBA and power query to extract the parameters needed and remove all the likely errors. AHP was used to quantify the quality of the data using the percentage of data completeness as one of the criteria.

Data infilling: The data infilling method adopted was the combination of different legacy databases. A method of database reliability was used to infill some missing data most especially the sewer material type. This will be discussed in detail in Chapter 5.3. When this was done the data provided in Table 3.1 was used for the analysis.

Table 3.1. Statistics of data used (Source: The Author- O.S. Tade)

Material	Size(mm)	Data count	Length(km)	Average length (m)	Mode of year built
VC	0 to 4,590	253,515	8,958.89	35.34	1937
AC	150 to 600	134	4.41	32.92	1974
BRK	9 to 3,600	10,269	421.55	41.05	1869
CI	80 to 2,000	9,063	331.7	36.6	1937
CP	0 to 4,300	53,935	2,346.83	43.51	1900
CS	225 to 2,450	115	8.7	75.83	1968
CSB	350 to 2,820	23	2.88	125.08	1870
DI	150 to 1,425	109	4.81	44.09	1914
GI	300	1	0.1	96.9	1981
PE	150	37	1.43	38.58	1996
PP	100 to 305	11	0.35	31.94	1916
PSC	100 to 1,200	19	0.55	28.8	1979
PVC	100 to 914	1,539	37.77	24.54	1996
RPM	150 to 900	42	0.94	22.3	1999
Z	0 to 750	156	1.81	11.63	1919
PF	100 to 450	1,353	29.02	21.45	1961

3.2 Data quality analysis using AHP

Data quality has 4 major dimensions. These dimensions are completeness, accuracy, relevancy and timeliness (Reza, et al., 2017).

Completeness: The proportion of measured samples available against the expected or reference sample size. In this case, it is a measure of the percentage of non-empty cells.

Accuracy: The degree to which the measured sample represents or depicts reality. It is a measure of the validity of the inputs. From discussion with acknowledged experts in the industry, format and nature of what to expect from each data column was described and any input contrary to these were assumed invalid. An example is a numeric character where alpha characters are expected.

Timeliness: The degree to when the measured sample is still regarded valid. The factors under consideration in this analysis are not time-bound as they are fixed inputs. Hence, timeliness will not be considered

Relevancy: The degree to which the input under consideration addresses the need of data user.

AHP is a popular Multi-Criteria Decision-making Tool (MCDT). This approach was proposed by Thomas Satty in the 1960s (Golden, et al., 1989). Since it has been adopted by various researchers and industries as an MCDT. The methodology continues to evolve and grow as a way of decision making for multi-criteria type problems. It has been used in the fabrication of metalworks in the engineering industry (Kuo, et al., 2010). Multi-dimensional problems are subjective as a different result can emanate from different dimensions. AHP allows for discrete numerical quantification of prioritised dimensions. This technique presents reality by prioritising the important criteria in analysis and their contribution to the overall outcome of the factors under consideration. It allows pairwise comparisons between options or criteria. For the collected data, the factors under consideration are; sewer ID, location of the sewer, the date of survey, its size, material and length, shape, use and condition. The important criteria for data quality check are completeness, accuracy and relevancy and the sub-criteria are the factors under consideration as shown in Figure 3.3. AHP is a noggin vector calculation for paired comparisons that are formed into a matrix and raised to infinite powers and the eigenvector is calculated to give relatives pairwise comparison of the sub-criteria. This process includes;

- Creating AHP structure (Figure 3.3)
- Creating a comparison table and decimal matrix for the criteria.
- Creating comparison table for sub criteria per criteria and creating corresponding decimal matrix.
- Calculation of results

A step by step calculation of the Analytical Hierarchy Process is explained in Appendix IX.

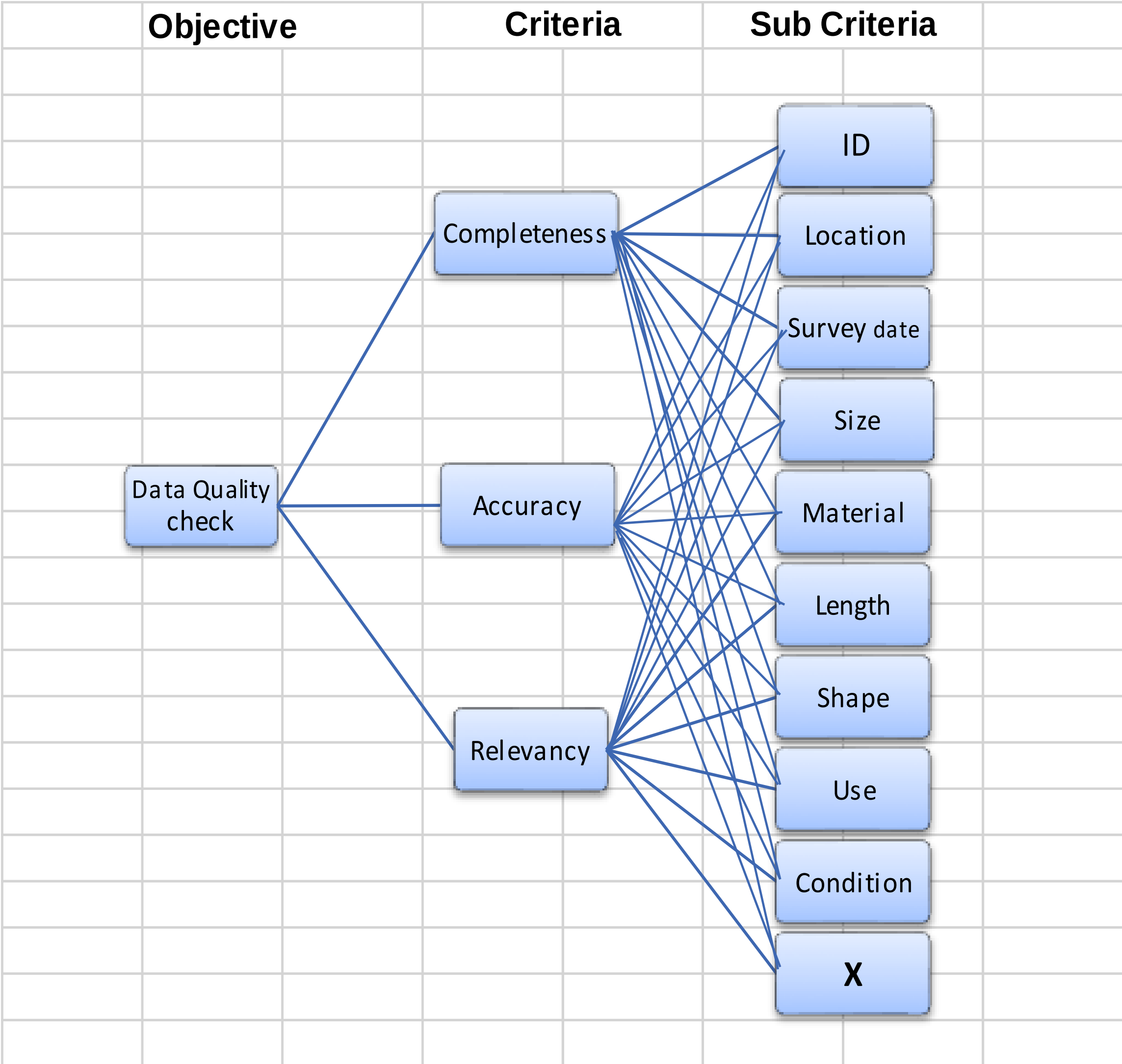


Figure 3.3. AHP Hierarchy structure (Source: The Author- O. S. Tade)

The data quality criteria for the sub-criteria were measured from the data in percentages and converted to a scale of 1 – 9 for AHP analysis as in Table 3.2.

Table 3.2. AHP percentage conversion table (Source: The Author- O.S. Tade)

Sub Criteria Percentage	**AHP Equivalent**
< 1%	1
1% to 4%	2
5% to 9%	4
10% to 14%	6
15% to 19%	8
>20%	9

For the data quality analysis, an ideal sub-criterion X was introduced with 100% completeness, accuracy and relevancy. This will serve as a benchmark to measure the quality of the other sub-criteria. For example, if the completeness of a sub-criterion compared to the introduced sub-criterion X is less than 1%, they are set to have equal completeness. But if 1% to 4%, criterion X is set to have 2 times more completeness than the sub-criterion under consideration as shown in Table 3.2.

Table 3.3. Creation of decimal matrix for criteria (Source: The Author- O. S. Tade)

Criteria	Accuracy	Completeness	Relevancy
Accuracy	**1.000**	3.000	9.000
completeness	0.333	**1.000**	9.000
Relevancy	0.111	0.111	**1.000**

The data quality criteria for this analysis were discussed with experts to measure how these criteria compare to each other. The conclusion from the discussion was accuracy is 3 and 9 times important than completeness and relevancy respectively, and completeness is also 9 times better than relevancy for this analysis as shown in Table 3.3. The AHP result is as shown in Table 3.4.

Table 3.4. AHP result for criteria (Source: The Author- O. S. Tade)

Criteria				Row tota	EIGEN VECTOR	Hierachy
Accuracy	**3.000**	7.000	45.000	55	**0.651**	Most important
completeness	1.667	**3.000**	21.000	25.6667	0.304	**Important**
Relevancy	0.259	0.556	**3.000**	3.81481	0.045	Least important
			Total	84.4815	1	

The first criterion considered was accuracy. For example, in the matrix formation in Table 3.5, sub-criterion size is 6 times more accurate than the sub-criterion length and the sub-criterion condition is 2 times more accurate than sub-criterion location. The eigenvector calculation is as shown in *Table 3.6*.

Table 3.5. Accuracy sub-criteria (Source: The Author- O. S. Tade)

Sub Criteria	ID	Location	Survey date	Size	Material	Length	Shape	Use	Condition	X
ID	**1**	2	1	1	1	6	1	1	1	1
Location	1/2	**1**	1/2	1/2	1/2	4	1/2	1/2	1/2	1/2
Survey date	1	2	**1**	1	1	6	1	1	1	1
Size	1	2	1	**1**	1	6	1	1	1	1
Material	1	2	1	1	**1**	6	1	1	1	1
Length	1/6	1/4	1/6	1/6	1/6	**1**	1/6	1/6	1/6	1/6
Shape	1	2	1	1	1	6	**1**	1	1	1
Use	1	2	1	1	1	6	1	**1**	1	1
Condition	1	2	1	1	1	6	1	1	1	1
X	1	2	1	1	1	6	1	1	1	1

Table 3.6. Accuracy sub criteria matrix (Source: The Author- O. S. Tade)

Sub Criteria	ID	Location	Survey d	Size	Material	Length	Shape	Use	Conditio	X	Total	EIGEN
ID	**10.000**	19.500	10.000	10.000	10.000	62.000	10.000	10.000	10.000	10.000	161.5	**0.115**
Location	5.167	**10.000**	5.167	5.167	5.167	32.000	5.167	5.167	5.167	5.167	83.3333	0.059
Survey date	10.000	19.500	**10.000**	10.000	10.000	62.000	10.000	10.000	10.000	10.000	161.5	0.115
Size	10.000	19.500	10.000	**10.000**	10.000	62.000	10.000	10.000	10.000	10.000	161.5	0.115
Material	10.000	19.500	10.000	10.000	**10.000**	62.000	10.000	10.000	10.000	10.000	161.5	0.115
Length	1.625	3.167	1.625	1.625	1.625	**10.000**	1.625	1.625	1.625	1.625	26.1667	0.019
Shape	10.000	19.500	10.000	10.000	10.000	62.000	**10.000**	10.000	10.000	10.000	161.5	0.115
Use	10.000	19.500	10.000	10.000	10.000	62.000	10.000	**10.000**	10.000	10.000	161.5	0.115
Condition	10.000	19.500	10.000	10.000	10.000	62.000	10.000	10.000	10.000	10.000	161.5	0.115
X	10.000	19.500	10.000	10.000	10.000	62.000	10.000	10.000	10.000	10.000	161.5	0.115
Total											**1401.5**	**1**

The second criterion considered was completeness. For example, in the matrix formation in *Table 3.7*, sub-criterion material is 2 times more complete than sub-criterion location and sub-criterion shape has the same completeness as sub-criterion survey date. The eigenvector calculation is as shown in *Table 3.8*.

Table 3.7. Completeness sub-criteria (Source: The Author- O. S. Tade)

Sub Criteria	ID	Location	Survey date	Size	Material	Length	Shape	Use	Condition	X
ID	**1**	2	1	1	1	1	1	1	1	1
Location	1/2	**1**	1	1/2	1/2	1/2	1/2	1/2	1	1/2
Survey date	1	1	**1**	1	1	1	1	1	1	1
Size	1	2	1	**1**	1	1	1	1	1	1
Material	1	2	1	1	**1**	1	1	1	1	1
Length	1	2	1	1	1	**1**	1	1	1	1
Shape	1	2	1	1	1	1	**1**	1	1	1
Use	1	2	1	1	1	1	1	**1**	1	1
Condition	1	1	1	1	1	1	1	1	1	1
X	1	2	1	1	1	1	1	1	1	1

Table 3.8. Completeness sub criteria matrix (Source: The Author- O. S. Tade)

Sub Criteria	ID	Location	Survey d	Size	Material	Length	Shape	Use	Conditio	X	Total	EIGEN
ID	**10.000**	18.000	11.000	10.000	10.000	10.000	10.000	10.000	11.000	10.000	110	**0.106**
Location	6.000	**10.000**	6.500	6.000	6.000	6.000	6.000	6.000	6.500	6.000	65	0.062
Survey date	9.500	17.000	**10.000**	9.500	9.500	9.500	9.500	9.500	10.000	9.500	103.5	0.099
Size	10.000	18.000	11.000	**10.000**	10.000	10.000	10.000	10.000	11.000	10.000	110	0.106
Material	10.000	18.000	11.000	10.000	**10.000**	10.000	10.000	10.000	11.000	10.000	110	0.106
Length	10.000	18.000	11.000	10.000	10.000	**10.000**	10.000	10.000	11.000	10.000	110	0.106
Shape	10.000	18.000	11.000	10.000	10.000	10.000	**10.000**	10.000	11.000	10.000	110	0.106
Use	10.000	18.000	11.000	10.000	10.000	10.000	10.000	**10.000**	11.000	10.000	110	0.106
Condition	9.500	17.000	10.000	9.500	9.500	9.500	9.500	9.500	10.000	9.500	103.5	0.099
X	10.000	18.000	11.000	10.000	10.000	10.000	10.000	10.000	11.000	10.000	110	0.106
Total											**1042**	**1**

The last criterion considered was relevancy. For example, in the matrix formation in *Table 3.9*, sub-criterion survey date is 9 times more relevant to this analysis than sub-criterion shape and sub-criterion material is as relevant as the sub-criterion survey date. The eigenvector calculation is as shown in Table 3.10.

Table 3.9. Relevancy sub-criteria (Source: The Author- O. S. Tade)

Sub Criteria	ID	Location	Survey date	Size	Material	Length	Shape	Use	Condition	X
ID	**1**	1	1/9	1/9	1/9	1	1	1/9	1/9	1/9
Location	1	**1**	1/9	1/9	1/9	1	1	1/9	1/9	1/9
Survey date	9	9	**1**	1	1	9	9	1	1	1
Size	9	9	1	**1**	1	9	9	1	1	1
Material	9	9	1	1	**1**	9	9	1	1	1
Length	1	1	1/9	1/9	1/9	**1**	1	1/9	1/9	1/9
Shape	1	1	1/9	1/9	1/9	1	**1**	1/9	1/9	1/9
Use	9	9	1	1	1	9	9	**1**	1	1
Condition	9	9	1	1	1	9	9	1	1	1
X	9	9	1	1	1	9	9	1	1	1

Table 3.10. Relevancy sub criteria matrix (Source: The Author- O. S. Tade)

Sub Criteria	ID	Location	Survey d	Size	Material	Length	Shape	Use	Conditio	X	Total	EIGEN
ID	**10.000**	10.000	1.111	1.111	1.111	10.000	10.000	1.111	1.111	1.111	46.6667	**0.017**
Location	10.000	**10.000**	1.111	1.111	1.111	10.000	10.000	1.111	1.111	1.111	46.6667	0.017
Survey date	90.000	90.000	**10.000**	10.000	10.000	90.000	90.000	10.000	10.000	10.000	420	0.155
Size	90.000	90.000	10.000	**10.000**	10.000	90.000	90.000	10.000	10.000	10.000	420	0.155
Material	90.000	90.000	10.000	10.000	**10.000**	90.000	90.000	10.000	10.000	10.000	420	0.155
Length	10.000	10.000	1.111	1.111	1.111	**10.000**	10.000	1.111	1.111	1.111	46.6667	0.017
Shape	10.000	10.000	1.111	1.111	1.111	10.000	**10.000**	1.111	1.111	1.111	46.6667	0.017
Use	90.000	90.000	10.000	10.000	10.000	90.000	90.000	**10.000**	10.000	10.000	420	0.155
Condition	90.000	90.000	10.000	10.000	10.000	90.000	90.000	10.000	10.000	10.000	420	0.155
X	90.000	90.000	10.000	10.000	10.000	90.000	90.000	10.000	10.000	10.000	420	0.155
Total											**2706.67**	**1**

Having calculated the eigenvectors for the sub-criteria per criteria, it was possible to calculate a pairwise comparison of the sub-criteria using Equation 3.1

Equation 3.1. Data quality calculation using AHP

$$T_x = \sum_{i=3}^{n} A_i \, . D_i(x)$$

Where:

$\mathrm{T_x}$ is the data quality result for each x sub-criteria

n is the number of criteria

$\mathrm{A_i}$is the weight of sub-criteria

$\mathrm{D_i}$is the weight of criteria

Calculations:

$T_x = A_x . D_{accuracy} + A_x . D_{completeness} + A_x . D_{relevancy}.$

$\mathrm{T_{ID}} = (0.1152 * 0.6510) + (0.1056 * 0.3038) + (0.0172 * 0.0452) = 0.1079.$

$\mathrm{T_{Location}} = (0.0595 * 0.6510) + (0.0624 * 0.3038) + (0.0172 * 0.0452) = 0.0584.$

$\mathrm{T_{Survey\ date}} = (0.1152 * 0.6510) + (0.0993 * 0.3038) + (0.1552 * 0.0452) = 0.1122.$

$\mathrm{T_{Size}} = (0.1152 * 0.6510) + (0.1056 * 0.3038) + (0.1552 * 0.0452) = 0.1141.$

$\mathrm{T_{Material}} = (0.1152 * 0.6510) + (0.1056 * 0.3038) + (0.1552 * 0.0452) = 0.1141.$

$\mathrm{T_{Length}} = (0.0187 * 0.6510) + (0.1056 * 0.3038) + (0.0172 * 0.0452) = 0.0450.$

$\mathrm{T_{Shape}} = (0.1152 * 0.6510) + (0.1056 * 0.3038) + (0.0172 * 0.0452) = 0.1079.$

$\mathrm{T_{use}} = (0.115 * 0.651) + (0.1056 * 0.3038) + (0.155 * 0.045) = 0.1141.$

$\mathrm{T_{Condition}} = (0.1152 * 0.6510) + (0.0993 * 0.3038) + (0.1552 * 0.0452) = 0.1122.$

$\mathrm{T_X} = (0.115 * 0.651) + (0.1056 * 0.3038) + (0.155 * 0.045) = 0.1141.$

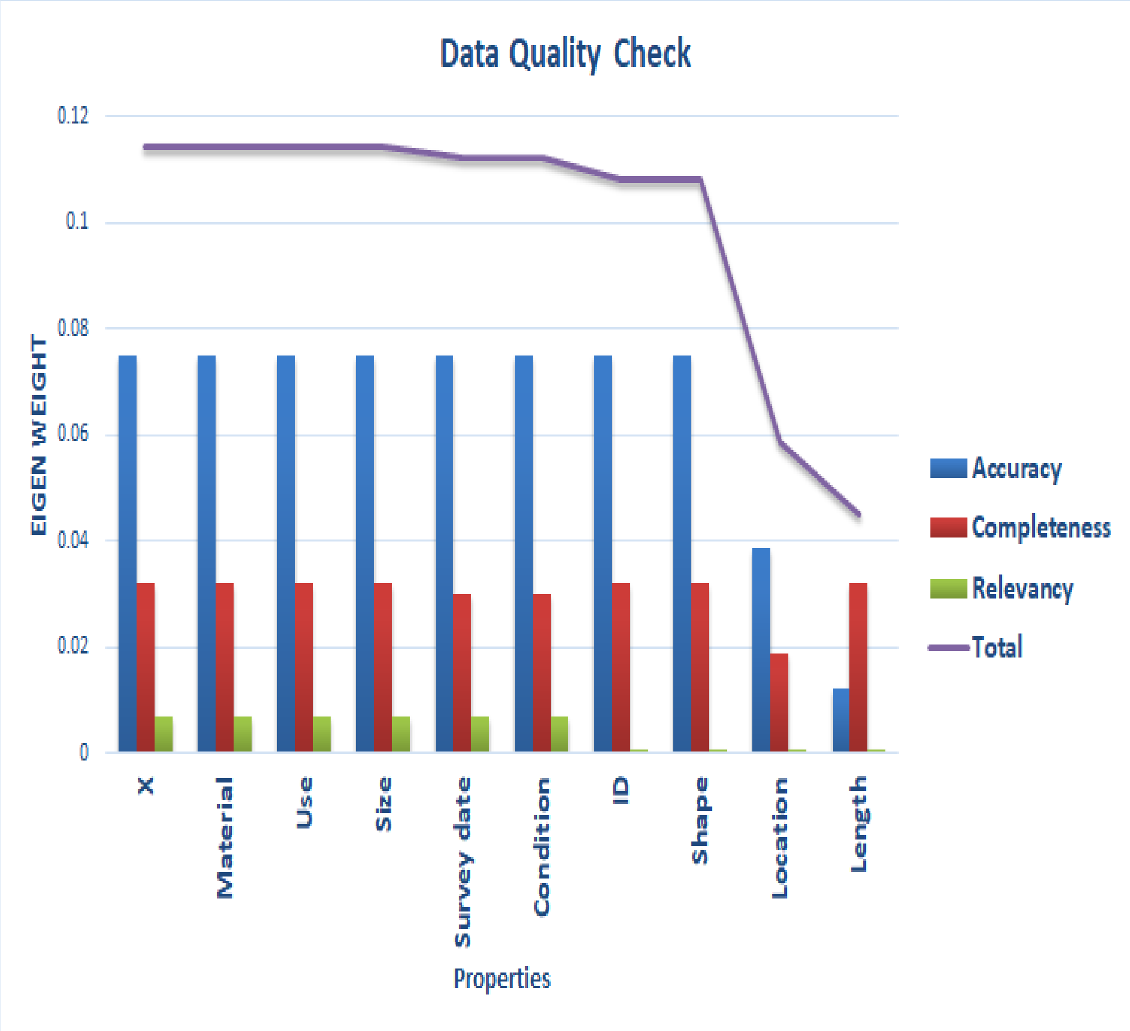


Figure 3.4. Data quality result (Source: The Author- O. S. Tade)

The sewer properties used for this analysis are material, use (effluent characteristics), size, survey date and condition. Comparing the data quality results of these properties to the benchmark X as in Figure 3.4, it can be concluded that they are of good quality because their results are very close to X.

3.3 Approach to system analysis

In an approach to decide which of the identified sewers with a high likelihood of failure should be subjected to engineering review, Figure 3.5 is used as similarly presented at a conference in the first year of this research.

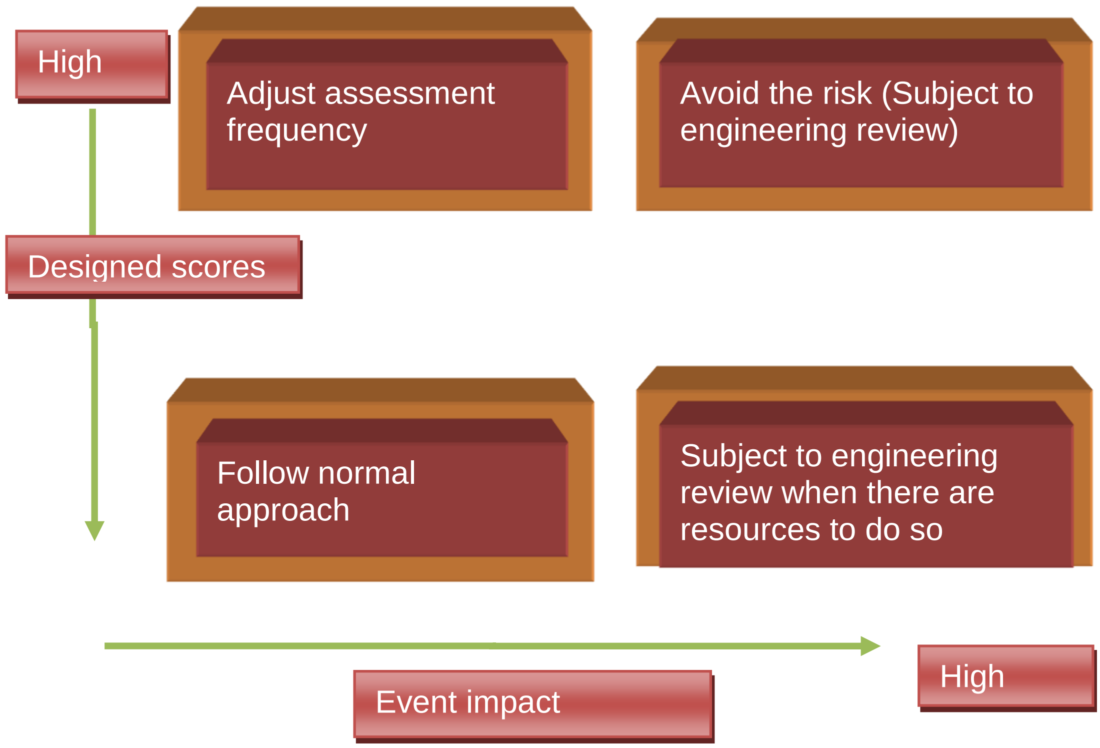


Figure 3.5. Risk assessment approach (Adapted from Tade et al, 2015)

Event impact, in this case, include; service loss to customers, road disruption or accident, rail disruption or accident, leakage of sewage or pollution.

This will allow the industry to:

- Understand their wastewater assets health and factors attributed to deterioration.
- Understand the journey of previous work done in the utilities to avoid reinventing the wheel and to apply lessons learned where necessary in future analysis.
- Sort the best approach possible with the existing dataset.
- Prioritise and justify proactive investment in the sewerage network.
- Prioritise future work requirements to enhance BAU data systems and models.

3.4 Proposed data flow for the framework

In UK water and wastewater utilities, every 5 years from privatisation is an AMP (Asset Management Planning) period.

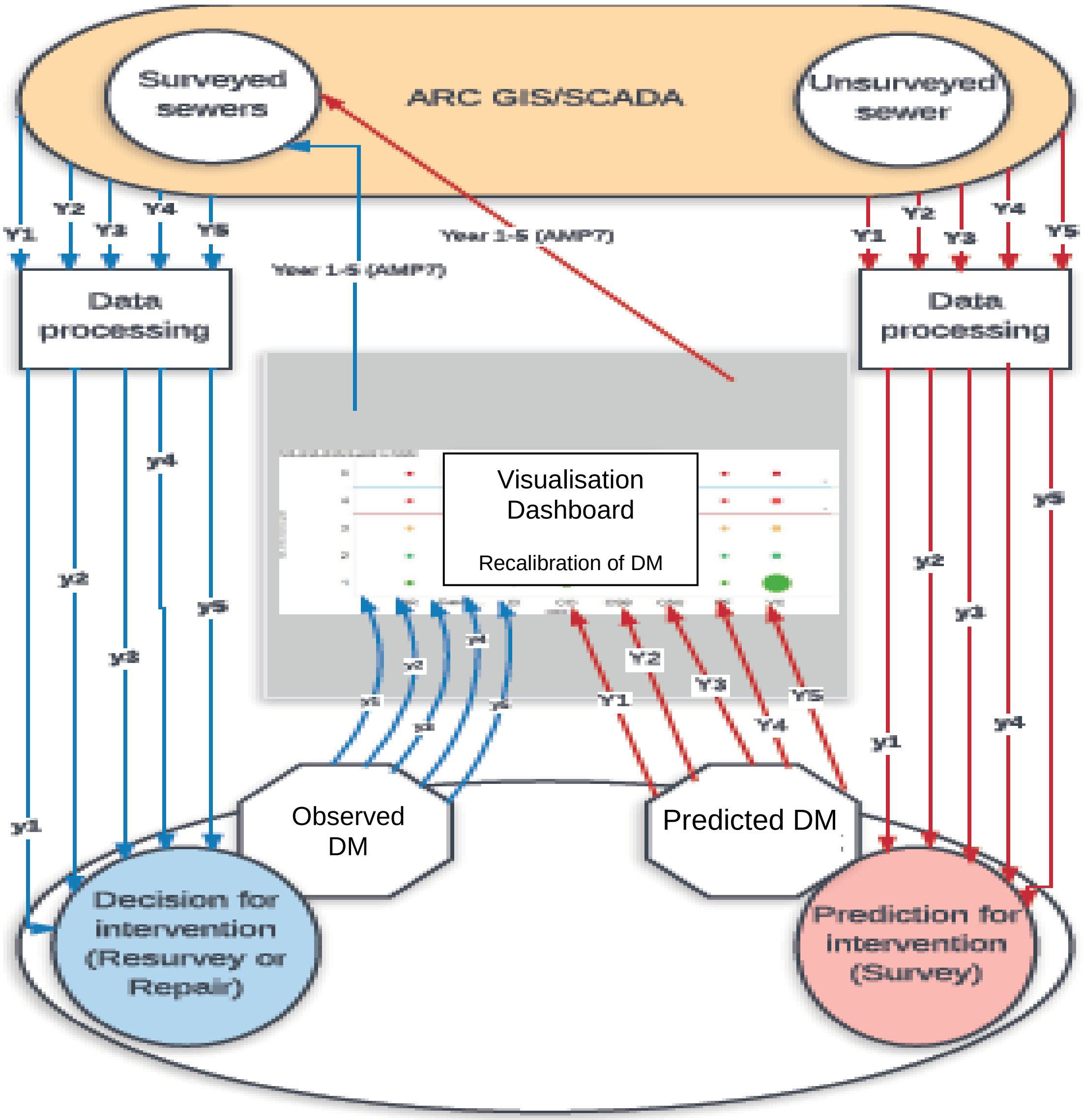


Figure 3.6. Data flow and for the proposed framework (Source: The Author- O.S. Tade)

The sewer CCTV survey collected every year in a PR (Periodic Review) of an AMP will be analysed for prioritisation for rehabilitation or resurvey as shown in Figure 3.6. ARC GIS and SCADA are the repositories of sewer data from which data are drawn for analysis. The data processing includes data cleansing and sorting for analysis. The DMs and the COF are the triage system in the RBF which could be displayed on a dashboard from which rehabilitation or reassessment decisions would be made. This will be further elaborated in Chapter 5 and 6. For the prediction for re-survey intervention, observed DM is used. For the un-surveyed sewers, the enhanced DDM developed in this research will be used to predict which sewer should be inspected. The observed and predicted DM goes into a recalibration system which can be visualised on a dashboard. An example of a similar dashboard developed as part of this research is in Appendix X.

3.5 Validation process

The validation of the process is very important in modelling deterioration as it allows the utilities to have a high level of confidence in the output (Kley, et al., 2013). The validation process would be done by benchmarking the collapse data collected with the predicted result. So also, it is expected that the number of reactive responses to sewer collapses would reduce if the model is applied and proactive interventions are carried out. For the purpose of this research, the validation focus was only on benchmarking the deterioration model on collapse data. This was done by checking the collapse date to confirm if the deterioration model would have been able to identify the collapsed sewer for inspection before the collapse date.

Wastewater utilities can also revalidate this model by monitoring the number of reactive sewer collapse responses over one year to five years period and compared with the previous years to identify if there is a reduction in the number of collapse reactive responses. If the investment has not been made, the reactive response could be confirmed with the priority list. This would provide more confidence in the application of this deterioration model to critical sewers where failure must be avoided.

Although some of the documents reviewed were confidential and could not be referenced in detail in this report, their different limitations identified are being considered in the output.

Chapter 4

Comparative Evaluation of Existing Deterioration Models and Inspection techniques

This Chapter evaluates and compares the existing Deterioration Models (DMs) and sewer inspection techniques. This is done from a practical perspective. The DMs discussed in Chapter 2 is applied to a sewer material cohort to identify limitation by evaluating their applicability. The available sewer inspection techniques are compared with the conventional CCTV inspection technique to identify limitations preventing a paradigm shift from the conventional CCTV method to newly developed techniques. This Chapter also presents a summary of the identified limitations of the existing sewer condition scoring protocols.

4.1 Applicability and comparison of sewer deterioration models

As earlier stated in Chapter 2, DMs can either be deterministic, probabilistic or stochastic, genetic programming or artificial intelligence model as shown in Table 2.1. These approaches have been developed by different researchers over the years and the wastewater utilities in the UK have attempted to apply them. Unfortunately, the utilities have been unable to apply these models in their AM plan due to different constraint which has been discussed in Chapter 2 and will be further discussed in this Chapter from their practicality's perspective. This Chapter applies the DMs discussed in Chapter 2 to the data available, analyses the outputs and identifies practicable limitations preventing DMs from being applied in the industry. Data on Cast Iron (CI) sewers were used for this analysis. The data consist of 9063 records of manhole to manhole CI sewers. The total length observed from the data was 331.7 km of sizes between 80 mm to 2000 mm.

4.1.1 Deterministic approach

This approach involves generating linear or non-linear equation from historical asset condition data but does not consider the vast uncertainties associated with the failure (Marlow, et al., 2009). The simplest form of this approach is a linear regression model. Linear regression is the form of the equation;

Equation 4.1. Deterministic formula

$$Y = a + bx$$

For mechanistic model, Y is deterioration rates and X is a variable explanatory factor such as sewer size, depth, age and effluent characteristics. For empirical model, Y is the year, a is the resistance age, b is the ageing factor and x is the condition of the sewer.

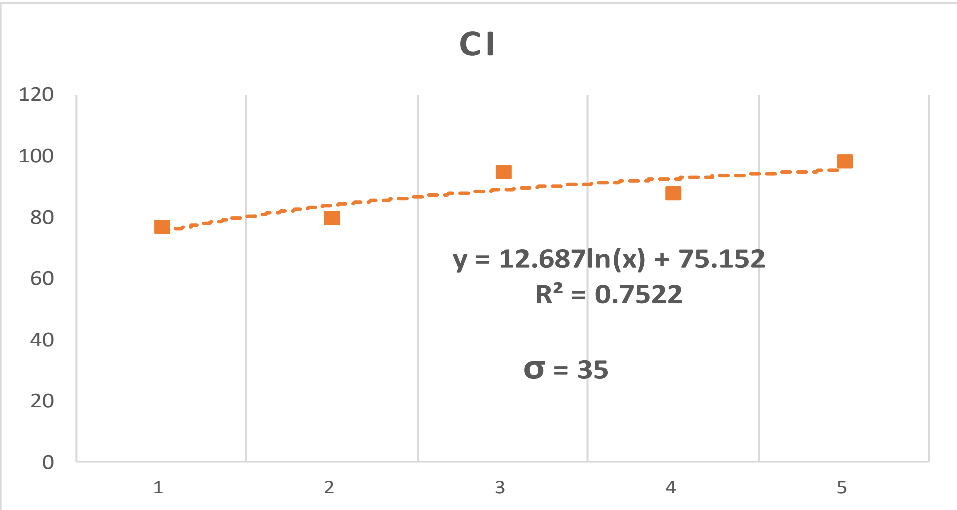


Figure 4.1. Deterministic deterioration model for cast iron sewer (Source: The Author- O.S. Tade)

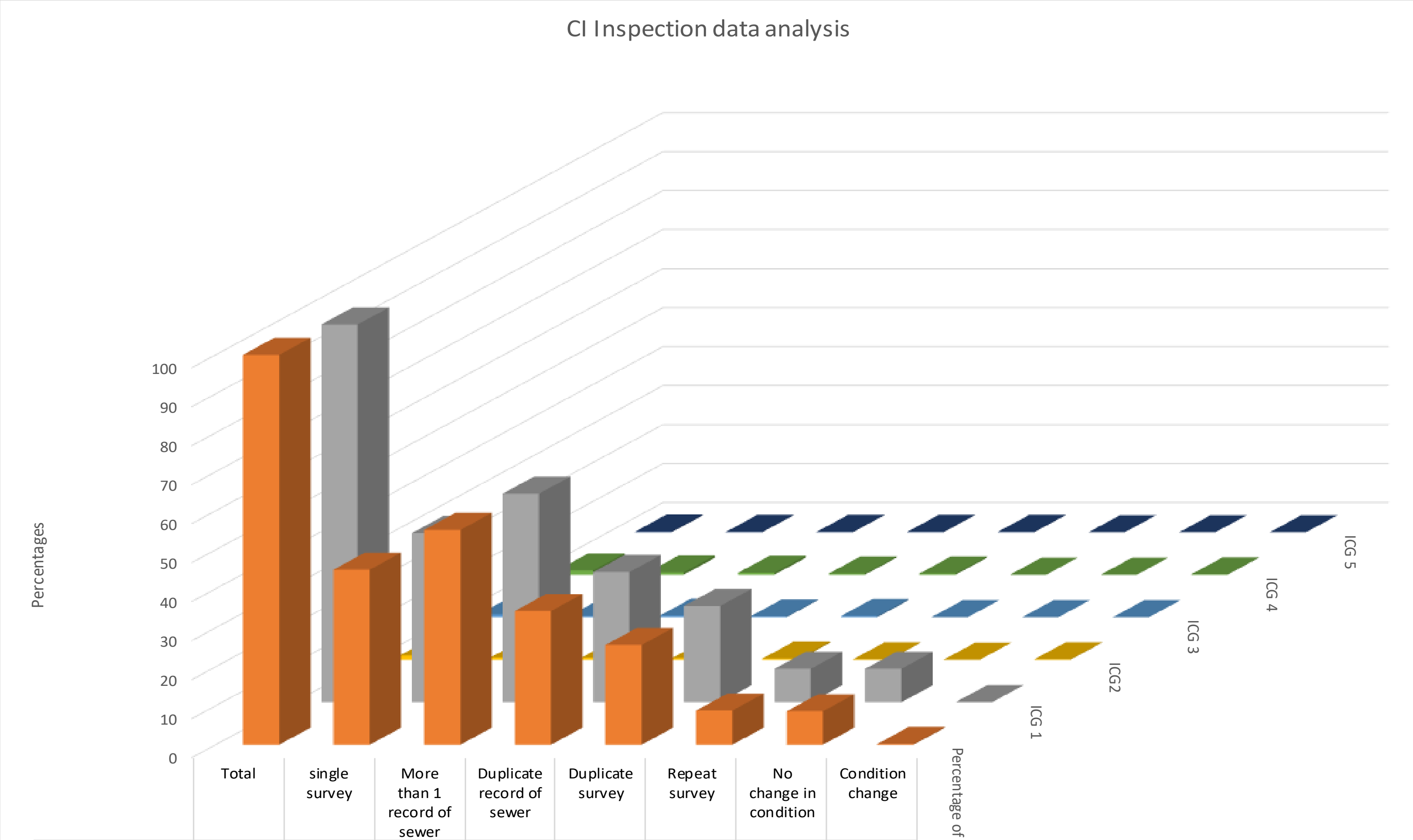
The only reason why DDM is not effective for sewer deterioration modelling is because of the uncertainty that exists around sewer deterioration. This was made evident by the standard deviation (σ = 35) in Figure 4.1. This is not effective for critical asset because of the result obtained is a summary of all observed deterioration rates. The uncertainty could result in sewer failure before or after the value obtained. It was reported that a more accurate result can be obtained if logarithmic, exponential and other more complex function can be used (Ens, 2012). However, applying logarithmic or exponential function will not remove the uncertainty around the deterioration curve. Logarithmic function was applied to Figure 4.1 represented by the dotted line which didn't have any significant effect on the value of the standard deviation which represents the magnitude of the uncertainty.

4.1.2 Stochastic approach

This is a statistical approach based on probability. This approach as shown in Table 2.1 could be Markov chain, survival function, regression or discriminant. Literature shows that the first two statistical approaches are useful for modelling deterioration at the sewer cohort level. However, the prediction quality is highly a function of data availability (quantity and quality) (Ens, 2012). This is the reason why the quality of the data used was checked in Chapter 3. MM and CSM both make use of transition function to follow a pattern similar to the bathtub curve. It estimates the probability that a sewer in condition x in time t will either remain in its present condition or in a worse condition in a future time t+n. From the review of literature, MM seems quite popular for deterioration modelling. It is a probabilistic approach that can be used to describe a deterioration process or an event but cannot be used to predict the event precisely.

Both CSM and MM relies on the logic that if a group of sewers were inspected in a time t and are all found to be in different ICGs from 1 to 5, it is expected that in a future time t+n, the percentage of sewers in ICG 1, 2, and 3 should reduce respectively whilst in 4 and 5 increases respectively. Has n increases, the sewers will keep graduating to a worse ICG till all the sewers are in the worst condition. The major problem in applying these models is the quantity of repeat inspection data sufficient enough to represent each condition grade for a given cohort. An analysis of the quantity of data available for CI cohort in each condition grades is as shown in Figure 4.2.

As shown in Figure 4.2, 44.9% of the sewers in the data have just a single record of inspection data and 55.1% of the data has more than one inspection records. The data only contains 8.8% of the repeat survey. Out of this, there was no condition change in 8.6% of the data and condition change can only be observed in 0.2% of the data. The distribution of condition grades within these percentages is very low hence stochastic models cannot be applied effectively. Apart from the problem mentioned, regression and discriminant were found to perform very low in predicting sewer condition (Kley & Caradot, 2013). This shows that it is necessary to stratify data and combine records to get a population of results so that a record of ICG 1 through 5 can be created.



	Total	single survey	More than 1 record of sewer	Duplicate record of sewer	Duplicate survey	Repeat survey	No change in condition	Condition change
Percentage of Total	100	44.9	55.1	34.3	25.6	8.77	8.6	0.2
ICG 1	96.9	43.4	53.5	33.4	24.7	8.6	8.6	0.04
ICG2	1.1	0.6	0.5	0.4	0.3	0.1	0.01	0.1
ICG 3	0.7	0.3	0.4	0.2	0.3	0.02	0.01	0.01
ICG 4	1.1	0.6	0.5	0.3	0.3	0.01	0.01	0.1
ICG 5	0.2	0.1	0.1	0.1	0.1	0	0	0

Figure 4.2. Cast iron inspection data analysis (Source: The Author- O.S. Tade)

4.1.3 Artificial intelligence

This approach involves the use of neural network, fussy set, case-based reasoning and support vector machines as shown in Table 2.1. As described in Chapter 2, this involves the use of computer-based algorithms to identify sewers in critical condition using the lesson learned from training historical data sets. This approach is highly data-driven; hence it is as good as the quality and quantity of data. The quality of the data has been confirmed to be good in Chapter 3, but the quantity of the data has been found not sufficient for an artificial intelligence model. Also, most industries tend not to use this approach because of the black box nature of the approach (Tran, 2007).

4.1.3.1 Initial analysis using artificial neural network for sewer deterioration modelling

The fundamental principle of DMs is that there is a relationship between conditions and asset physical properties. DMs tend to use known variables such as age, material type, size, depth and effluent characteristics to determine sewer condition. As part of this research, an initial analysis was done to investigate this relationship using Artificial Neural Network (ANN). ANN is a written algorithm loosely modelled to behave or mimic the human cerebral cortex on a very minute scale (Caudill, 1989). Neural network depends on training using data to initialise the process; the identified training data set educates the process with the knowledge to make inferences from future input data (Medsker & Liebowith, 1994).

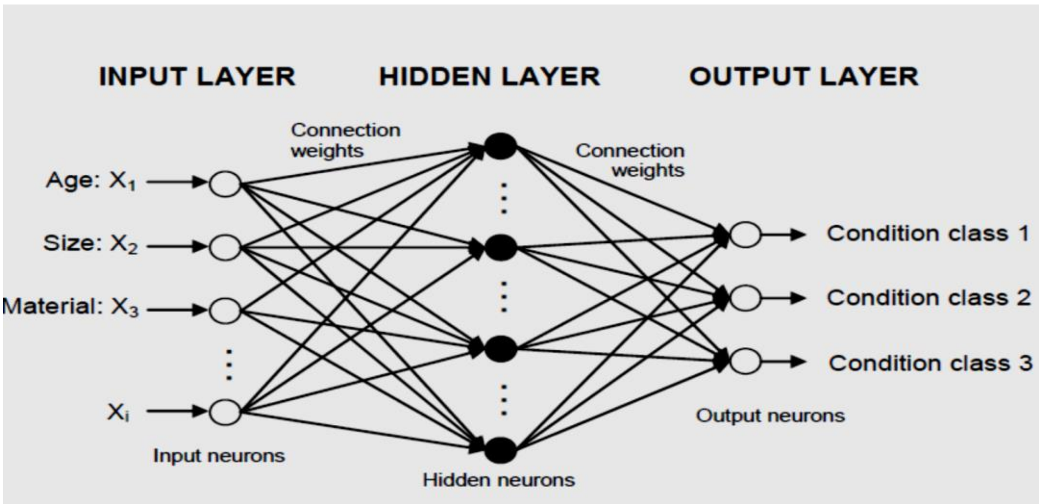


Figure 4.3. Schematic diagram for BPNN (Tran et al. (2007)

Figure *4.3* illustrates a typical process of ANN. For this analysis, MATLAB (a programming application) was used to create ANN. Diameter, length, shape, material and effluent characteristics were used in the input layer and the condition grade was used in the output layer. The result in Figure 4.4 was obtained.

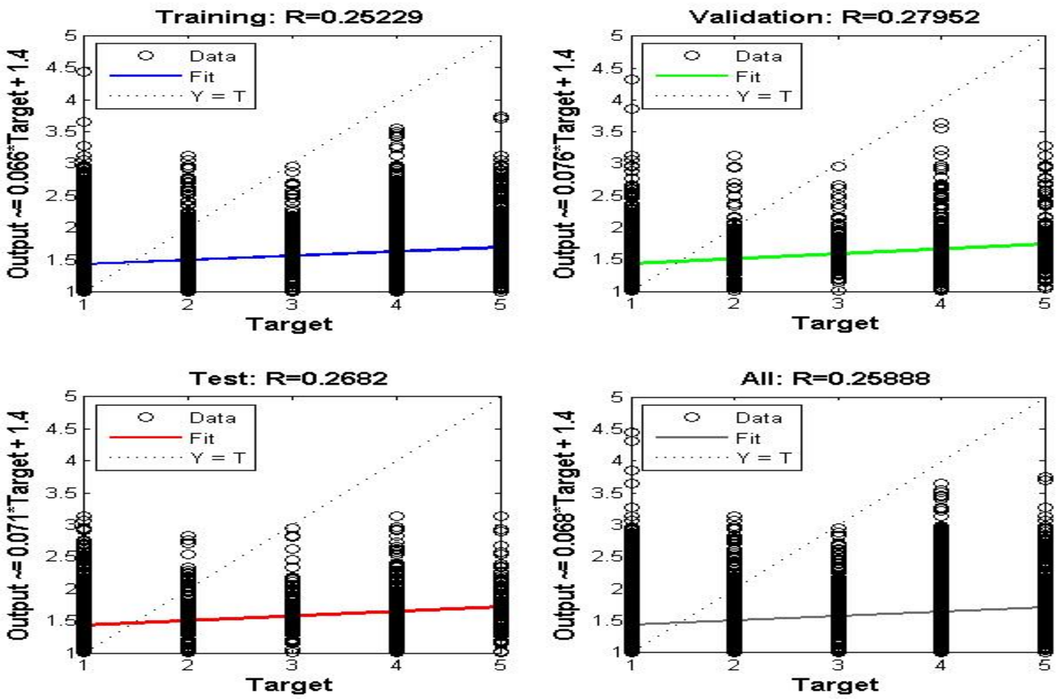


Figure 4.4. MATLAB's neural network results (Source: The Author- O. S. Tade)

Figure 4.4 shows the plots of the training, validation and testing results. The dotted diagonal line in the plot represents a perfect result, and best fit or linear regression line is the solid line. The R value indicates the relationship between output and its target which is input, and output respectively as illustrated in Figure *4.3*. The closer R gets to 0 (zero), the lower the linear relationship and the closer R get to 1 the higher the linear relationship is. In this analysis, the training data indicates a bad fit because the R values are close to 0. This suggests that it is not possible to predict sewer conditions with a reasonable degree of confidence using the existing scoring protocol or there is a problem with the inputs data. The input data are very low explanatory factors. For example, the input "material" could only explain 12% of the output.

4.1.4 Relationship between sewer properties and condition Score

Neural network was also used to investigate the relationship between sewer physical properties and conditions. A neural network is ideally suited to describe the spatial and temporal dependence of tracer-tracer correlations (Lary, et al., 2004). Tracer correlation is used to examine the relationship between variables. To confirm which of the identified sewer properties influences the deterioration rates, a feed forward back-propagation was developed to identify the tracer correlation between some of the identified sewer properties and condition grade.

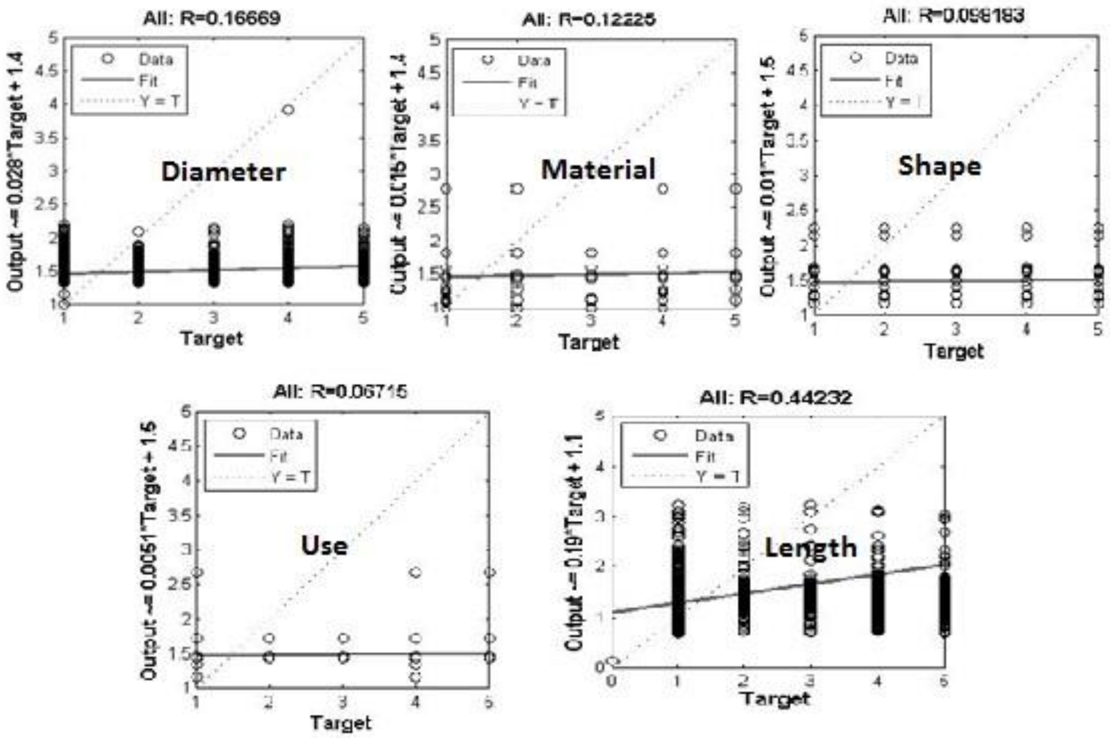


Figure 4.5. MATLAB's neural network analysis of sewer property influence of condition scores (Source: The Author- O. S. Tade)

Figure 4.5 shows the relationship between sewer property and condition grades. The dotted diagonal line in the plot represents a perfect result and best fit or linear regression line is the solid line. *Figure 4.6* shows the comparison between the R values of the sewer properties.

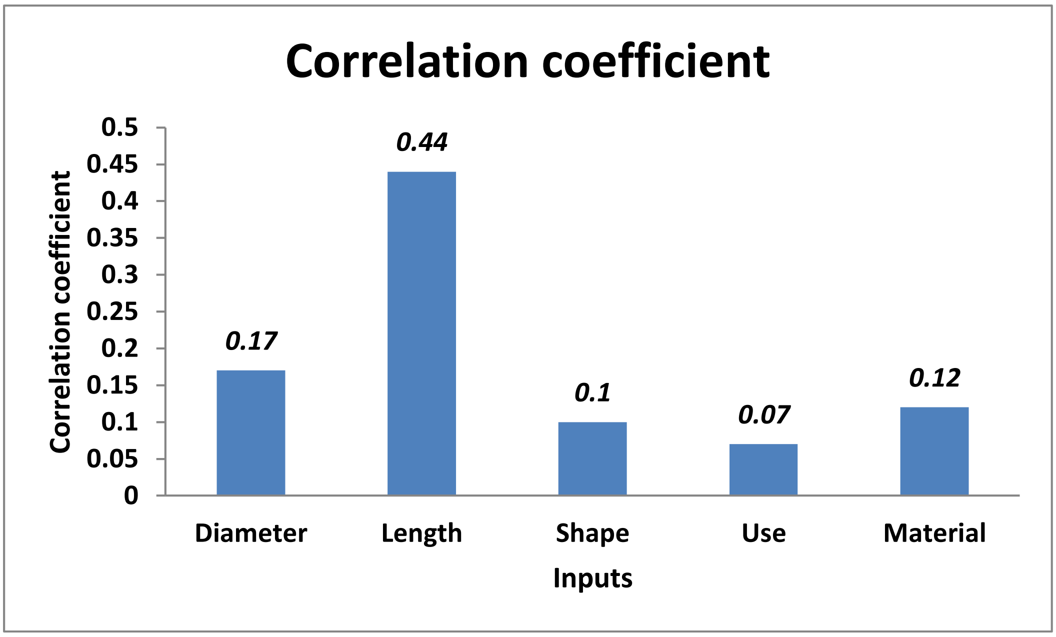


Figure 4.6. Bar chart of sewer properties and r value (Source: The Author- O. S. Tade)

As shown in *Figure 4.6*, although the R values from this analysis are quite low, but it was able to rank the properties in order of influence. As a result of the low R values, two hypotheses were raised.

Hypothesis 1: The existing condition scoring protocol does not reflect the actual condition of sewers.

Hypothesis 2: There are large uncertainties around sewer deterioration.

These hypotheses will be investigated in Chapter 5 and Chapter 6.

Table 4.1. Comparison between deterministic and probability models (Source: The Author- O.S. Tade)

Deterministic	Probabilistic	Artificial Intelligence
A mathematical model in which results are determined through know relationships among events or states without allowance for random variation.	A mathematical and statistical representation of a random phenomenon defined by events within a space sample.	A mathematical representation of a complex deterioration process.
Outcomes are precisely determined.	Outcomes are determined by the probability of an event occurring again based on observed historical data or events.	Outcomes are determined by a computer algorithm.
Results from given input will always be the same.	Even with the same initial conditions, results are likely to be different as there are elements of chance or uncertainty.	Results from given input will always be the same.
Deals with systematic and definitive outcomes as opposed to random results.	There are elements of randomness in the model which implies possible alternative solutions.	The process is difficult to understand as it is a black box approach.
Does not make allowances for error.	Makes allowances for error.	Garbage in garbage out process.
Hypothesized an exact relationship between variables (McClave, et al., 2014).	The probabilistic model includes both a deterministic component and a random error component (McClave, et al., 2014).	
Allows to make predictions and to see how one variable affects the other.	Allows to make predictions but difficult to determine how one variable affects the other.	
Example; If the stress on a sewer is σ, stress will always be known F and A are known. $\sigma = F/A$	$\sigma = F/A$ + random error.	
It assumes certainty in its solution.	It assumes uncertainty in its solution.	It assumes certainty in its solution.

4.2 Comparison of sewer inspection devices

Utilities in the UK periodically perform CCTV inspections to ascertain the structural and operational integrity on SN that are at risk of structural and service failure. The primary purpose of the CCTV survey is to carry out the following:

- Planned cleaning surveys.
- Blockage hotspot surveys.
- High-risk asset surveys, and
- Operational reactive surveys.

4.2.1 Solo RedZone robotics

The solo was designed to achieve more with fewer resources. Assessment resources are; the number of crew and allowance for several inspections to be conducted simultaneously. A trial was conducted by the participating industry to confirm the effectiveness of the solo device. The trial was successful as it was able to conduct three times more surveys than the conventional CCTV system with the same resources. The benefit of Solo includes;

- Shorter period spent at each location.
- Minimal street disruption.
- Increased safety to survey crew.
- Less inconvenience to customers.

The autonomous nature of this device is the major advantage over the conventional CCTV survey. Although the solo robot was found to be more effective from the trial, a number of improvements were identified that would allow the system to be used as a BAU (Business as Usual) tool. The survey team can deploy up to four robots simultaneously.

For the trial, a target of 1000 m per day over 10 days period was set but a variation of between 582 m to 1568.62 m was done. This was as a result of different constraint:

- Parked cars.
- Surcharged sewer.
- Heavy traffic delaying survey crew from moving within the survey area.
- Seized or buried manhole covers.

- Heavy manhole covers.
- Robot maintenance.

It was found from this trial that the survey time increased significantly due to the presence of a large amount of debris in the pipe, inability for the robot to locate finish or downstream manhole. Surveys were not completed for some sites due to debris, grease, encrustation roots, pipework defects, and holes or displaced joint. Also, the survey was abandoned if elevated hydrogen sulphide level was detected. It is also worth knowing that there was eight hours maintenance time required to clean, recharge batteries and replace service components.

For Solo robots to become a BAU tool in the U.K, it must be certified as intrinsically safe or a safe work system (Valappil, et al., 2017). The solo robot is yet to be certified intrinsically safe for use in the UK. Hence, it cannot be used as a BAU tool.

Table 4.2. Comparison between Solo and Conventional CCTV (Valappil, et al., 2017)

SOLO	Conventional CCTV survey
Unmanned autonomous survey robot	Controlled by operator, subject to variability
Portable hand-held equipment – deployment in awkward access possible	Large units
Deployment time typically less than 20 minutes	Longer set-up and deployment time
Increased safety due to being in the highway for a shorter duration	More safety precautions required
Data coding in office	Data coding in the field
Minimal traffic disruption	Possible significant traffic disruption
Traffic notices may not be required if the units can be deployed within 15 mins	Traffic notices needed
Survey distance of up to 983m/day possible	Survey distance generally 300m/day
Not currently intrinsically safe certified	Intrinsically safe models available
200-300mm pipe diameter	Larger range of pipe diameters can be surveyed

4.2.2 Multi-sensory inspection (MSI) and conventional CCTV

The MSI was designed to gather more extensive sewer condition information than the conventional CCTV by combining HDcam, laser and sonar. A trial of this device was also conducted by the participating industry. The trial was to survey 400 m of sewer which were two locations of 200 m per location. This was a pilot trial to understand the technique and unforeseeable practical issues. The benefits found were:

- Condition data was gathered quickly with minimal disruption to traffic.
- More concise condition reports of large diameter sewers.
- Debris can be quantified and hence maintenance cost can be quantified more accurately.
- Detailing potential collapse and failure points caused by corrosion which cannot be picked up by conventional CCTV.
- Improved planning and delivery of sewer inspection with the opportunity to avoid lengthy road occupation and hence minimal traffic disruption.
- Quick result in one visit (Reduction in the need for repeat visit). Faster identification of problems and avoidance of road occupation as a result of the ability to complete survey remotely.

Table 4.3. Comparison between MSI and conventional CCTV (Valappil, et al., 2017)

MSI Survey	Conventional CCTV Survey
Limited to cable length, weight and chamber location access.	Useable in various sewers (375mm – 3000mm) that have never been previously surveyed due to size and access
Limited to access in and out and requires in-depth planning regarding safety	Large diameter profiling using a modular, self-contained system with, no trailing power or data cables.
Subject to flow diversions and time constraints, would normally be off-peak out of hours (increased costs).	High-resolution picture/video output is allowing user full pan, tilt and 2 x Zoom control on all surveys.
One dimensional view, report i.e.what you can see.	Over 6hours continuous recording (battery power).
Time-consuming for limited data recorded due to onsite recording	Max of 4000m sewer length with all distances overlaid within the report and only limited by tether (rope) availability.
Potential access issues, in most cases, require additional costs for road notices, permits, site time restrictions and costly Traffic Management requirements.	Detailed reporting including corrosion, debris levels, pipe integrity, and accurate pipe measurements
Safety factors increased more personnel, safety rescue teams, and engineers.	Accurate siltation reports recorded throughout the system to determine if cleaning is required or not and this, in turn, Identifying the correct tools, equipment, and resources resulting in huge potential cost saving
Real-time view of the footagesections can be reassessed if necessary.	Footage can only be reviewed once the survey has finished – resulting in potential resurveying being required.
	Start and finish points can be tailored to eliminate access issues where required, reducing potential costs for permits and Traffic Management, etc.

Although Solo is the cheapest inspection technique, however until it is certified intrinsically safe for use in the UK, it cannot be used as a BAU tool. The MSI is the most expensive but apart from being able to record footage of the internal condition of a sewer; it can also be used to access the structural integrity of the sewer using a laser scan. For MSI to be adopted as a BAU tool, a justification of its cost would be necessary. Until this is done, it would be difficult for a paradigm shift into a new inspection technique other than the conventional CCTV.

4.3 Comparison of sewer condition scoring protocol

As earlier stated in Chapter 2, the WRc is referred to as the embryo code as all other protocol was developed from the WRc condition scoring protocol. Hence; most of these protocols adopt the use of the worst defect (peak score) for condition classification or grading. From a comparative analysis of existing sewer scoring protocol, it was found that the ICG does not reflect the entire condition of the entire sewer length. The ICG is a function of the worst defect found in any segment of the entire sewer length. This could result in the assignment of the wrong criticality category or consequence to a sewer. An example is a sewer length with a section underneath the highway and the other section underneath an opened field. The location of the point defect which characterises the ICG could make a lot of difference as the open field has a different consequence compared to the highway. The existing scoring techniques can be improved by providing an additional score that would reflect the condition of the entire sewer length.

Chapter 5

Results and Development of DM and RBF

This Chapter quantifies the importance of factors affecting sewer deterioration and presents an analysis of the historical sewer assessment data. The deterioration model (DM) was developed in Chapter 5.4 by sewer material cohort, which was found to have the highest influence on deterioration. The Risk-Based Framework (RBF) was then developed.

5.1 Quantifying the importance of sewer deterioration factors using AHP

As discussed in Chapter 3, AHP is a very useful tool for making a decision amongst options with a complex web of criteria to be considered. Criteria complexity in a multi-dimensional problem could result in a subjective priority like in the case of factors affecting deterioration. There is a complex relationship between these factors as the effect of a factor could be a function of the type of others. This is the major reason why deciding which factor is important and how important to sewer deterioration is highly contentious. In this research, the multi-dimensional problem is deciding which of the factors in 2.3 of Chapter 2 are important in terms of sewer deterioration and by how much.

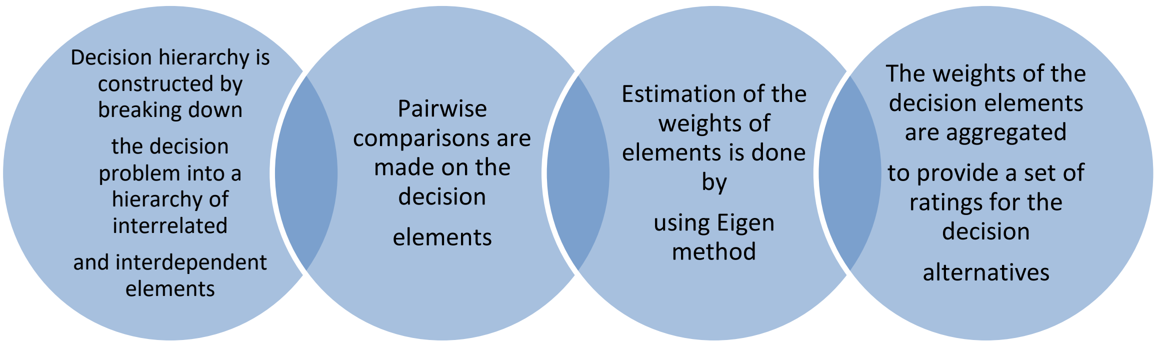


Figure 5.1. AHP process adapted from (Sehra, et al., 2012)

The process of AHP application is as shown in Figure 5.1. As described in Chapter 3, AHP allows for pairwise comparison of all the factors under different criteria.

To prioritise the factors affecting deterioration, four major dimensions were defined. These dimensions were variation, dependency, research perception and industrial perception.

Variation: This is a measure of the disparity or alternatives that exist within each sewer properties. For example, material has several variations such as brick, clay, iron, steel, concrete, plastic and pitch fibre. This is an important factor as this variation is a prerequisite for deterioration variation as different sewer material have different deterioration rates.

Dependency: This is a measure of the extent to which one property depends on the others. Some factors are irrelevant under certain circumstances. For example, the presence of H_2S is a function of the material type as earlier stated. H_2S affects concrete sewers significantly but have little or no effect on iron sewer. This is a strong measure of importance as a very important property would have more dependent factors.

Research perception: The degree to which the majority of academic research articles perceive the importance of these factors.

Industrial perception: The degree to which industrial experts perceive the importance of these factors.

AHP is a noggin vector calculation for paired comparisons that are formed into a matrix and raised to infinite powers and the eigenvector is calculated to give relatives pairwise comparison of the sub-criteria (Tade *et al.,* 2018).

The selected criteria for determining the level of importance of these factors to sewer deterioration are variation, dependency, research perception and industrial perception and the sub-criteria are the factors under consideration as shown in Figure 5.2. These factors under consideration are 17 factors affecting sewer deterioration which was identified in Chapter 2.

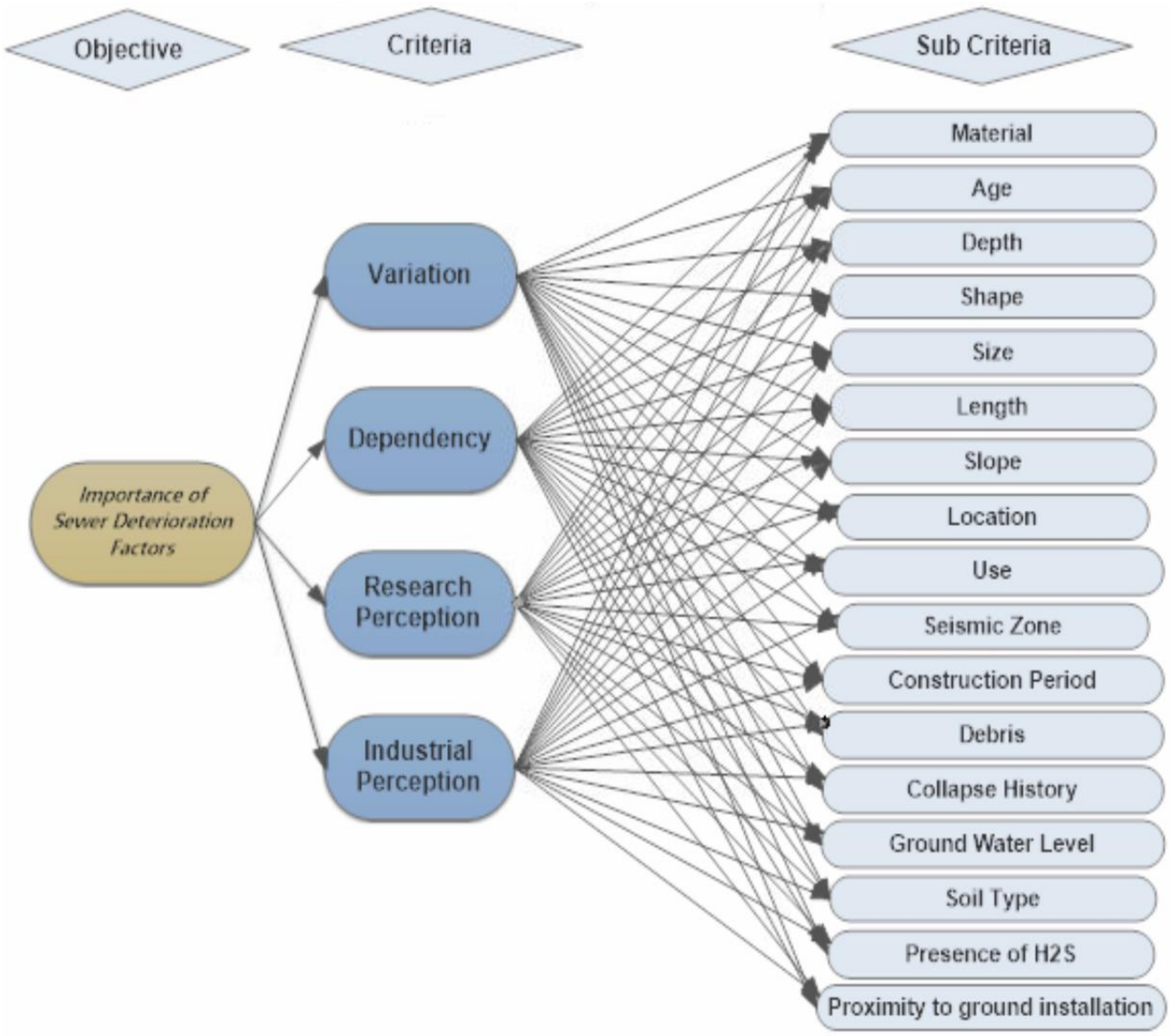


Figure 5.2. AHP Hierarchy structure (Source: The Author – O. S. Tade)

The sub-criteria were determined from literature review and discussed with acknowledged experts in the industry. For research and industrial perspective, the result of criteria and sub-criteria were converted to a scale of 1 – 9 for AHP analysis. For example, if the difference is less than 5%, the sub-criteria are equal and if the difference is from 5% to 14%, then the sub-criteria have 2 times more difference than the compared sub-criteria.

0% to 4% = 1

5% to 14% = 2

15% to 24% = 3

25% to 34% = 4

35% to 44% = 5

45% to 54% = 6

55% to 64% = 7

65% to 74% = 8

75% to 100% = 9

Table 5.1. Creation of decimal matrix for criteria (Source: The Author – O. S. Tade)

Criteria	Variation	Dependency	Research perception	Industrial perception
Variation	1.000	0.333	3.000	2.000
Dependency	2.000	1.000	4.000	3.000
Research perception	0.333	0.250	1.000	0.500
Industrial perception	0.500	0.333	2.000	1.000

The criteria for this analysis were discussed with experts to measure how these criteria compare to each other. The conclusion from the discussion was that for these studies, variation is 3 and 2 times more important than research perception and industrial perception respectively, and dependency is 2, 4 and 3 times more important than variation, research perception and industrial perception respectively as shown Table 5.1. The AHP result is as shown in Table 5.2. The eigenvector shows a measure of how important these criteria are. This also quantifies the criteria as well.

Table 5.2. AHP result for criteria (Source: The Author – O. S. Tade)

Criteria	Variation	Dependency	Research perception	Industrial perception	Row Total	Eigen Vector	Hierachy
Variation	3.667	2.083	11.333	6.500	23.583333	0.264	2
Dependency	6.833	3.667	20.000	12.000	42.5	0.476	1
Research perception	1.417	0.778	4.000	2.417	8.6111111	0.097	4
Industrial perception	2.333	1.333	6.833	4.000	14.5	0.163	3
			Total		89.194444	1.000	

Under each criterion, the sub-criteria were pairwise compared. The first criterion considered is variation has shown in *Table 5.3*. For example, in the matrix formation in *Table 5.3*, sub-criterion material varies 7 times more than sub-criterion age and sub-criterion shape varies 8 times more than the sub-criterion slope. The eigenvector calculation is as shown in *Table 5.4*.

Table 5.3. Variation sub-criteria (Source: The Author – O. S. Tade)

Sub Criteria	Material	Age	Depth	Shape	Size	Length	Slope	Location	Use	Seismic Zone	Construction period	Debris	Collapse history	Groundwater level	Soil type	Presence of H2S	Proximity to ground installation
Material	1	7	6	4	5	8	8	1/2	7	8	7	8	8	8	2	8	8
Age	1/7	1	1/3	1/6	1/2	1	1	1/8	1/6	1	1/2	1	1	1	1/7	1	1
Depth	1/6	3	1	1/4	1/2	1	1	1/8	1/4	1	1	1	1	1	1/7	1	1
Shape	1/4	6	4	1	4	8	8	1/3	1	6	7	7	8	8	1	7	1
Size	1/5	2	2	1/4	1	2	1	1/7	1/4	2	1	2	1	1	1/7	2	2
Length	1/8	1	1	1/8	1/2	1	1	1/8	1/5	1	1	1	1/2	1	1/7	1	1
Slope	1/8	1	1	1/8	1	1	1	1/8	1/5	1	1	1	1/2	1	1/7	1	1
Location	4	8	8	3	7	8	8	1	8	8	8	8	8	8	6	8	8
Use	1/3	6	4	1	4	5	5	1/8	1	5	4	6	1	3	1	4	4
Seismic Zone	1/8	1	1	1/6	1/2	1	1	1/8	1/5	1	1	1	1/2	1	1/7	1	1
Construction period	1/7	2	1	1/7	1	1	1	1/8	1/4	1	1	2	1	1	1/6	1	2
Debris	1/8	1	1	1/7	1/2	1	1	1/8	1/6	1	1/2	1	1/3	1	1/8	1	1
Collapse history	1/8	1	1	1/8	1	2	2	1/8	1	2	1	3	1	1	1/7	2	2
Groundwater level	1/8	1	1	1/8	1	1	1	1/8	1/3	1	1	1	1	1	1/7	2	1
Soil type	1/2	7	7	1	7	7	7	1/6	1	7	6	8	7	7	1	8	8
Presence of H2S	1/8	1	1	1/7	1/2	1	1	1/8	1/4	1	1	1	1/2	1/2	1/8	1	1
Proximity to ground installation	1/8	1	1	1	1/2	1	1	1/8	1/4	1	1/2	1	1/2	1	1/8	1	1

Table 5.4. Variation sub-criteria matrix (Source: The Author – O. S. Tade)

Sub Criteria																		Row Total	Eigen Vector
Material	19.333	204.000	157.333	39.036	129.000	195.000	190.000	14.756	50.467	187.000	156.500	215.000	128.667	164.000	30.452	194.000	169.000	2243.544	0.188
Age	2.181	17.000	14.357	3.821	11.089	17.143	16.643	1.597	5.576	16.810	13.524	18.786	11.810	14.810	2.946	17.952	16.452	202.498	0.017
Depth	2.722	23.167	17.000	4.655	13.708	21.583	21.083	2.043	6.535	21.083	16.774	23.726	15.917	19.083	3.625	22.226	20.726	255.657	0.021
Shape	12.615	116.417	93.167	17.000	73.083	110.667	106.667	10.405	30.400	108.667	88.417	126.667	75.000	93.167	15.970	117.667	110.667	1306.640	0.109
Size	3.576	31.543	24.010	6.627	17.000	27.993	26.993	2.774	8.186	27.493	22.150	30.136	19.160	24.493	4.531	28.636	27.136	332.434	0.028
Length	2.284	19.325	14.883	3.917	11.300	17.000	16.500	1.662	5.235	16.750	13.907	18.718	12.033	15.100	3.010	17.818	17.068	206.510	0.017
Slope	2.384	20.325	15.883	4.042	11.800	18.000	17.000	1.733	5.360	17.750	14.407	19.718	12.533	15.600	3.081	18.818	18.068	216.503	0.018
Location	27.436	270.000	214.667	57.845	180.000	256.000	249.000	18.000	80.883	250.000	208.000	283.000	183.667	221.000	44.333	259.000	241.000	3043.831	0.255
Use	8.937	89.333	69.000	16.292	51.542	79.667	75.667	7.363	18.333	77.667	63.333	85.667	55.167	70.667	11.548	81.667	76.667	938.514	0.078
Seismic Zone	2.295	19.575	15.050	3.959	11.467	17.333	16.833	1.676	5.276	17.000	14.199	19.010	12.367	15.433	3.051	18.110	17.110	209.742	0.018
Construction period	2.890	24.524	19.262	5.577	14.327	22.702	21.702	2.196	6.660	22.417	17.000	24.976	15.369	19.702	3.673	23.476	22.619	269.073	0.023
Debris	2.176	17.940	14.030	3.792	10.446	16.018	15.518	1.577	4.910	15.732	13.125	17.000	11.351	14.351	2.869	16.833	15.476	193.145	0.016
Collapse history	3.588	32.625	26.583	6.750	19.500	30.000	29.000	2.771	8.093	29.750	23.607	33.018	17.000	25.000	4.881	30.018	29.268	351.452	0.029
Groundwater level	2.616	22.625	17.917	4.381	13.333	20.667	19.667	1.938	6.243	20.417	16.440	23.018	13.667	17.000	3.411	21.351	20.601	245.291	0.021
Soil type	14.049	136.833	107.667	25.976	78.667	125.333	118.333	11.917	32.867	123.333	96.333	139.333	83.500	105.333	17.000	131.333	124.333	1472.142	0.123
Presence of H2S	2.234	19.107	14.530	3.905	10.946	16.768	16.268	1.609	5.118	16.482	13.625	18.500	11.601	14.768	2.988	17.000	16.643	202.091	0.017
Proximity to ground installation	2.439	23.750	17.958	4.753	14.375	23.625	23.125	1.894	6.017	21.625	19.625	24.000	18.458	21.625	3.833	23.500	17.000	267.603	0.022
Total																		11956.671	1

The second criterion to be considered is dependency. For example, in the matrix formation in Table 5.5, sub-criterion length has 2 times more dependency than sub-criterion debris and sub-criterion collapse history have 3 times more dependency than sub-criterion soil type. The eigenvector calculation is as shown in Table 5.6.

Table 5.5. Dependency sub-criteria (Source: The Author – O. S. Tade)

Sub criteria	Material	Age	Depth	Shape	Size	Length	Slope	Location	Use	Seismic Zone	Construction period	Debris	Collapse history	Grundwater level	Soil type	Presence of H2s	Proximity to ground installation
Material	1	8	5	7	6	6	6	6	7	7	8	9	3	5	6	6	8
Age	1/8	1	1/3	1	1/2	1/2	1/2	1/2	1	1	1	1	1/5	1/3	1/2	1/2	1
Depth	1/5	3	1	2	1	1	1	1	2	2	3	3	1/2	1	1	1	3
Shape	1/7	1	1/2	1	1	1	1	1	1	1	1	1	1/4	1/2	1/2	1	1
Size	1/6	2	1	1	1	1	1	1	1	1	2	2	1/3	1	1	1	2
Length	1/6	2	1	1	1	1	1	1	1	1	2	2	1/3	1	1	1	2
Slope	1/6	2	1	1	1	1	1	1	1	1	2	2	1/3	1	1	1	2
Location	1/6	2	1	1	1	1	1	1	1	1	2	2	1/3	1	1	1	2
Use	1/7	1	1/2	1	1	1	1	1	1	1	1	1	1/4	1/2	1/2	1	1
Seismic Zone	1/7	1	1/2	1	1	1	1	1	1	1	1	2	1/4	1/2	1	1	1
Construction period	1/8	1	1/3	1	1/2	1/2	1/2	1/2	1	1	1	1	1/5	1/3	1/2	1/2	1
Debris	1/9	1	1/3	1	1/2	1/2	1/2	1/2	1	1/2	1	1	1/5	1/3	1/3	1/2	1
Collapse history	1/3	5	2	4	3	3	3	3	4	4	5	5	1	2	3	3	5
Groundwater level	1/5	3	1	2	1	1	1	1	2	2	3	3	1/2	1	1	1	3
Soil type	1/6	2	1	2	1	1	1	1	2	1	2	3	1/3	1	1	1	2
Presence of H2s	1/6	2	1	1	1	1	1	1	1	1	2	2	1/3	1	1	1	2
Proximity to ground installation	1/8	1	1/3	1	1/2	1/2	1/2	1/2	1	1	1	1	1/5	1/3	1/2	1/2	1

Table 5.6. Dependency sub-criteria matrix (Source: The Author – O. S. Tade)

Sub Criteria																		Row Total	Eigen Vector
Material	17.000	179.000	78.500	135.000	98.500	98.500	98.500	98.500	135.000	124.500	179.000	193.000	34.850	78.500	90.000	98.500	179.000	1915.850	0.262
Age	1.740	17.000	7.525	13.508	10.017	10.017	10.017	10.017	13.508	12.508	17.000	18.625	3.458	7.525	8.850	10.017	17.000	188.331	0.026
Depth	4.082	40.100	17.000	32.400	22.700	22.700	22.700	22.700	32.400	29.900	40.100	43.300	8.000	17.000	20.200	22.700	40.100	438.082	0.060
Shape	2.258	23.393	10.548	17.000	13.107	13.107	13.107	13.107	17.000	16.000	23.393	25.036	4.562	10.548	11.940	13.107	23.393	250.605	0.034
Size	3.079	32.000	13.667	24.500	17.000	17.000	17.000	17.000	24.500	22.500	32.000	34.167	6.183	13.667	15.667	17.000	32.000	338.929	0.046
Length	3.079	32.000	13.667	24.500	17.000	17.000	17.000	17.000	24.500	22.500	32.000	34.167	6.183	13.667	15.667	17.000	32.000	338.929	0.046
Slope	3.079	32.000	13.667	24.500	17.000	17.000	17.000	17.000	24.500	22.500	32.000	34.167	6.183	13.667	15.667	17.000	32.000	338.929	0.046
Location	3.079	32.000	13.667	24.500	17.000	17.000	17.000	17.000	24.500	22.500	32.000	34.167	6.183	13.667	15.667	17.000	32.000	338.929	0.046
Use	2.258	23.393	10.548	17.000	13.107	13.107	13.107	13.107	17.000	16.000	23.393	25.036	4.562	10.548	11.940	13.107	23.393	250.605	0.034
Seismic Zone	2.452	25.393	11.381	19.000	14.107	14.107	14.107	14.107	19.000	17.000	25.393	27.536	4.929	11.381	12.774	14.107	25.393	272.166	0.037
Construction period	1.740	17.000	7.525	13.508	10.017	10.017	10.017	10.017	13.508	12.508	17.000	18.625	3.458	7.525	8.850	10.017	17.000	188.331	0.026
Debris	1.627	16.056	7.039	12.578	9.267	9.267	9.267	9.267	12.578	11.744	16.056	17.000	3.236	7.039	8.100	9.267	16.056	175.440	0.024
Collapse history	8.612	87.667	38.333	67.333	49.000	49.000	49.000	49.000	67.333	61.833	87.667	95.000	17.000	38.333	44.167	49.000	87.667	945.945	0.129
Groundwater level	4.082	40.100	17.000	32.400	22.700	22.700	22.700	22.700	32.400	29.900	40.100	43.300	8.000	17.000	20.200	22.700	40.100	438.082	0.060
Soil type	3.475	35.000	15.000	27.500	19.500	19.500	19.500	19.500	27.500	25.000	35.000	37.167	6.883	15.000	17.000	19.500	35.000	377.025	0.051
Presence of H2S	3.079	32.000	13.667	24.500	17.000	17.000	17.000	17.000	24.500	22.500	32.000	34.167	6.183	13.667	15.667	17.000	32.000	338.929	0.046
Proximity to ground installation	1.740	17.000	7.525	13.508	10.017	10.017	10.017	10.017	13.508	12.508	17.000	18.625	3.458	7.525	8.850	10.017	17.000	188.331	0.026
Total																		7323.4385	1

The third criterion considered was research's perspective. For example, in the matrix formation in Table 5.7, the research world considered sub-criterion seismic zone to be equal to sub-criterion location and sub-criterion soil type to be 4 times more significant than sub-criterion depth. The eigenvector calculation is as shown in Table 5.8.

Table 5.7. Research Perspective sub-criteria (Source: The Author – O. S. Tade)

Sub Criteria	Material	Age	Depth	Shape	Size	Length	Slope	Location	Use	Seismic Zone	Construction period	Debris	Collapse history	Grundwater level	Soil type	Presence of H2s	Proximity to ground installation
Material	1	5	8	4	5	5	8	8	8	8	4	8	5	7	5	6	8
Age	1/5	1	4	1/2	1	1	4	4	4	4	1/2	4	1	3	1	2	4
Depth	1/8	1/4	1	1/5	1/4	1/4	1	1	1	1	1/5	1	1/4	1/2	1/4	1/3	1
Shape	1/4	2	5	1	2	2	5	5	5	5	1	5	2	4	2	3	5
Size	1/5	1	4	1/2	1	1	4	4	4	4	1/2	4	1	3	1	2	4
Length	1/5	1	4	1/2	1	1	4	4	4	4	1/2	4	1	3	1	2	4
Slope	1/8	1/4	1	1/5	1/4	1/4	1	1	1	1	1/5	1	1/4	1/2	1/4	1/3	1
Location	1/8	1/4	1	1/5	1/4	1/4	1	1	1	1	1/5	1	1/4	1	1/4	1/3	1
Use	1/8	1/4	1	1/5	1/4	1/4	1	1	1	1	1/5	1	1/4	1	1/4	1/3	1
Seismic Zone	1/8	1/4	1	1/5	1/4	1/4	1	1	1	1	1/5	1	1/4	1	1/4	1/3	1
Construction period	1/4	2	5	1	2	2	5	5	5	5	1	5	2	4	2	3	5
Debris	1/8	1/4	1	1/5	1/4	1/4	1	1	1	1	1/5	1	1/4	1/2	1/4	1/3	1
Collapse history	1/5	1	4	1/2	1	1	4	4	4	4	1/2	4	1	3	1	2	4
Grundwater level	1/7	1/3	2	1/4	1/3	1/3	2	2	2	2	1/4	2	1/3	1	1/3	1/2	2
Soil type	1/5	1	4	1/2	1	1	4	4	4	4	1/2	4	1	3	1	2	4
Presence of H2s	1/6	1/2	3	1/3	1/2	1/2	3	3	3	3	1/3	3	1/2	2	1/2	1	3
Proximity to ground installation	1/8	1/4	1	1/5	1/4	1/4	1	1	1	1	1/5	1	1/4	1/2	1/4	1/3	1

Table 5.8. Research Perspective sub-criteria matrix (Source: The Author – O. S. Tade)

Sub Criteria																		Row Total	Eigen Vector
Material	17.000	65.333	236.000	39.450	65.333	65.333	236.000	236.000	236.000	236.000	39.450	236.000	65.333	173.000	65.333	108.167	236.000	2355.733	0.246
Age	5.712	17.000	66.600	11.317	17.000	17.000	66.600	66.600	66.600	66.600	11.317	66.600	17.000	47.400	17.000	27.033	66.600	653.979	0.068
Depth	1.477	4.758	17.000	3.161	4.758	4.758	17.000	17.000	17.000	17.000	3.161	17.000	4.758	12.392	4.758	7.367	17.000	170.349	0.018
Shape	8.196	26.833	104.000	17.000	26.833	26.833	104.000	104.000	104.000	104.000	17.000	104.000	26.833	74.750	26.833	44.167	104.000	1023.280	0.107
Size	5.712	17.000	66.600	11.317	17.000	17.000	66.600	66.600	66.600	66.600	11.317	66.600	17.000	47.400	17.000	27.033	66.600	653.979	0.068
Length	5.712	17.000	66.600	11.317	17.000	17.000	66.600	66.600	66.600	66.600	11.317	66.600	17.000	47.400	17.000	27.033	66.600	653.979	0.068
Slope	1.477	4.758	17.000	3.161	4.758	4.758	17.000	17.000	17.000	17.000	3.161	17.000	4.758	12.392	4.758	7.367	17.000	170.349	0.018
Location	1.548	4.925	18.000	3.286	4.925	4.925	18.000	18.000	18.000	18.000	3.286	18.000	4.925	12.892	4.925	7.617	18.000	179.254	0.019
Use	1.548	4.925	18.000	3.286	4.925	4.925	18.000	18.000	18.000	18.000	3.286	18.000	4.925	12.892	4.925	7.617	18.000	179.254	0.019
Seismic Zone	1.548	4.925	18.000	3.286	4.925	4.925	18.000	18.000	18.000	18.000	3.286	18.000	4.925	12.892	4.925	7.617	18.000	179.254	0.019
Construction period	8.196	26.833	104.000	17.000	26.833	26.833	104.000	104.000	104.000	104.000	17.000	104.000	26.833	74.750	26.833	44.167	104.000	1023.280	0.107
Debris	1.477	4.758	17.000	3.161	4.758	4.758	17.000	17.000	17.000	17.000	3.161	17.000	4.758	12.392	4.758	7.367	17.000	170.349	0.018
Collapse history	5.712	17.000	66.600	11.317	17.000	17.000	66.600	66.600	66.600	66.600	11.317	66.600	17.000	47.400	17.000	27.033	66.600	653.979	0.068
Groundwater level	2.577	7.464	27.810	5.121	7.464	7.464	27.810	27.810	27.810	27.810	5.121	27.810	7.464	20.000	7.464	11.357	27.810	276.165	0.029
Soil type	5.712	17.000	66.600	11.317	17.000	17.000	66.600	66.600	66.600	66.600	11.317	66.600	17.000	47.400	17.000	27.033	66.600	653.979	0.068
Presence of H2S	3.911	11.083	42.667	7.617	11.083	11.083	42.667	42.667	42.667	42.667	7.617	42.667	11.083	30.333	11.083	17.000	42.667	420.561	0.044
Proximity to ground installation	1.477	4.758	17.000	3.161	4.758	4.758	17.000	17.000	17.000	17.000	3.161	17.000	4.758	12.392	4.758	7.367	17.000	170.349	0.018
Total																		9588.071	1.000

The last criterion considered was industrial perspective. For example, in the matrix formation in Table 5.9, the industry considered sub-criterion age to influence deterioration 4 times more than sub-criterion shape and sub-criterion use to be 2 times more significant than sub-criterion shape. The eigenvector calculation is as shown in Table 5.10.

Table 5.9. Industrial Perspective sub-criteria (Source: The Author – O. S. Tade)

Sub Criteria	Material	Age	Depth	Shape	Size	Length	Slope	Location	Use	Seismic Zone	Construction period	Debris	Collapse history	Grundwater level	Soil type	Presence of H2s	Proximity to ground installation
Material	1	2	5	8	1	5	6	5	7	7	8	7	7	6	4	8	7
Age	1/2	1	4	7	1/2	4	5	4	6	6	7	6	6	5	3	7	6
Depth	1/5	1/4	1	4	1/5	1	2	1	3	3	4	3	3	2	1/2	4	3
Shape	1/8	1/7	1/4	1	1/8	1/4	1/3	1/4	1/2	1/2	1	1/2	1/2	1/3	1/5	1	1/2
Size	1	2	5	8	1	5	6	5	7	7	8	7	7	6	4	8	7
Length	1/5	1/4	1	4	1/5	1	2	1	3	3	4	3	3	2	1/2	4	3
Slope	1/6	1/5	1/2	3	1/6	1/2	1	1/2	2	2	3	2	2	1	1/3	3	2
Location	1/5	1/4	1	4	1/5	1	2	1	3	3	4	3	3	2	1/2	4	3
Use	1/7	1/6	1/3	2	1/7	1/3	1/2	1/3	1	1	2	1	1	1/2	1/4	2	1
Seismic Zone	1/7	1/6	1/3	2	1/7	1/3	1/2	1/3	1	1	2	1	1	1/2	1/4	2	1
Construction period	1/8	1/7	1/4	1	1/8	1/4	1/3	1/4	1/2	1/2	1	1/2	1/2	1/3	1/5	1	1/2
Debris	1/7	1/6	1/3	2	1/7	1/3	1/2	1/3	1	1	2	1	1	1/2	1/4	2	1
Collapse history	1/7	1/6	1/3	2	1/7	1/3	1/2	1/3	1	1	2	1	1	1/2	1/4	2	1
Groundwater level	1/6	1/5	1/2	3	1/6	1/2	1	1/2	2	2	3	2	2	1	1/3	3	2
Soil type	1/4	1/3	2	5	1/4	2	3	2	4	4	5	4	4	3	1	5	4
Presence of H2S	1/8	1/7	1/4	1	1/8	1/4	1/3	1/4	1/2	1/2	1	1/2	1/2	1/3	1/5	1	1/2
Proximity to ground installation	1/7	1/6	1/3	2	1/7	1/3	1/2	1/3	1	1	2	1	1	1/2	1/4	2	1

Table 5.10. Industrial Perspective sub-criteria matrix (Source: The Author – O. S. Tade)

Sub Criteria																		Row Total	Eigen Vector
Material	17.000	22.745	64.667	240.000	17.000	64.667	101.500	64.667	158.000	158.000	240.000	158.000	158.000	101.500	43.050	240.000	158.000	2006.795	0.192
Age	13.227	17.000	47.250	189.000	13.227	47.250	76.000	47.250	121.500	121.500	189.000	121.500	121.500	76.000	31.033	189.000	121.500	1542.738	0.148
Depth	5.560	6.981	17.000	73.450	5.560	17.000	26.650	17.000	44.300	44.300	73.450	44.300	44.300	26.650	11.833	73.450	44.300	576.083	0.055
Shape	1.365	1.876	4.888	17.000	1.365	4.888	7.231	4.888	10.990	10.990	17.000	10.990	10.990	7.231	3.451	17.000	10.990	143.134	0.014
Size	17.000	22.745	64.667	240.000	17.000	64.667	101.500	64.667	158.000	158.000	240.000	158.000	158.000	101.500	43.050	240.000	158.000	2006.795	0.192
Length	5.560	6.981	17.000	73.450	5.560	17.000	26.650	17.000	44.300	44.300	73.450	44.300	44.300	26.650	11.833	73.450	44.300	576.083	0.055
Slope	3.704	4.705	11.217	46.733	3.704	11.217	17.000	11.217	27.867	27.867	46.733	27.867	27.867	17.000	7.983	46.733	27.867	367.279	0.035
Location	5.560	6.981	17.000	73.450	5.560	17.000	26.650	17.000	44.300	44.300	73.450	44.300	44.300	26.650	11.833	73.450	44.300	576.083	0.055
Use	2.263	2.962	7.262	27.702	2.263	7.262	10.798	7.262	17.000	17.000	27.702	17.000	17.000	10.798	5.176	27.702	17.000	224.151	0.021
Seismic Zone	2.263	2.962	7.262	27.702	2.263	7.262	10.798	7.262	17.000	17.000	27.702	17.000	17.000	10.798	5.176	27.702	17.000	224.151	0.021
Construction period	1.365	1.876	4.888	17.000	1.365	4.888	7.231	4.888	10.990	10.990	17.000	10.990	10.990	7.231	3.451	17.000	10.990	143.134	0.014
Debris	2.263	2.962	7.262	27.702	2.263	7.262	10.798	7.262	17.000	17.000	27.702	17.000	17.000	10.798	5.176	27.702	17.000	224.151	0.021
Collapse history	2.263	2.962	7.262	27.702	2.263	7.262	10.798	7.262	17.000	17.000	27.702	17.000	17.000	10.798	5.176	27.702	17.000	224.151	0.021
Groundwater level	3.704	4.705	11.217	46.733	3.704	11.217	17.000	11.217	27.867	27.867	46.733	27.867	27.867	17.000	7.983	46.733	27.867	367.279	0.035
Soil type	7.849	9.843	25.250	108.333	7.849	25.250	40.667	25.250	67.000	67.000	108.333	67.000	67.000	40.667	17.000	108.333	67.000	859.624	0.082
Presence of H2S	1.365	1.876	4.888	17.000	1.365	4.888	7.231	4.888	10.990	10.990	17.000	10.990	10.990	7.231	3.451	17.000	10.990	143.134	0.014
Proximity to ground installation	2.263	2.962	7.262	27.702	2.263	7.262	10.798	7.262	17.000	17.000	27.702	17.000	17.000	10.798	5.176	27.702	17.000	224.151	0.021
Total																		10428.92	1

Having calculated the eigenvectors for the sub-criteria per criteria, it was possible to calculate a pairwise comparison of the sub-criteria using Equation 5.1.

Equation 5.1. AHP formula for prioritizing factor affecting sewer deterioration

$$T_x = \sum_{i=3}^{n} A_i \,.\, D_i(x)$$

Where: $\mathrm{T_x}$Is the data quality result for each x sub-criteria

n is the number of criteria

$\mathrm{A_i}$is the weight of sub-criteria

$\mathrm{D_i}$is the weight of criteria

Calculations:

$$\mathrm{T_x = A_x.D_{variation} + A_x.D_{dependency} + A_x.D_{research\ perspective} + A_x.D_{industrial\ perspective}}$$

$$\mathrm{T_{Material}} = (0.1876 * 0.2644) + (0.2616 * 0.4765) + (0.2457 * 0.0965) + (0.1924 * 0.1626) = 0.2293$$

$$\mathrm{T_{Age}} = (0.0169 * 0.2644) + (0.0257 * 0.4765) + (0.0682 * 0.0965) + (0.1479 * 0.1626) = 0.0474$$

$$\mathrm{T_{Depth}} = (0.0214 * 0.2644) + (0.0598 * 0.4765) + (0.0178 * 0.0965) + (0.0552 * 0.1626) = 0.0449$$

$$\mathrm{T_{Shape}} = (0.1093 * 0.2644) + (0.0342 * 0.4765) + (0.1067 * 0.0965) + (0.0137 * 0.1626) = 0.0577$$

$$\mathrm{T_{Size}} = (0.0278 * 0.2644) + (0.0463 * 0.4765) + (0.0682 * 0.0965) + (0.1924 * 0.1626) = 0.0673$$

$$\mathrm{T_{Length}} = (0.0173 * 0.2644) + (0.0463 * 0.4765) + (0.0682 * 0.0965) + (0.0552 * 0.1626) = 0.0422$$

$$\mathrm{T_{Slope}} = (0.0181 * 0.2644) + (0.0463 * 0.4765) + (0.0178 * 0.0965) + (0.0352 * 0.1626) = 0.0343$$

$$T_{\text{Location}} = (0.2546 * 0.2644) + (0.0463 * 0.4765) + (0.0187 * 0.0965) + (0.0552 * 0.1626) = 0.1001$$

$$T_{\text{Use}} = (0.0785 * 0.2644) + (0.0342 * 0.4765) + (0.0187 * 0.0965) + (0.0215 * 0.1626) = 0.0424$$

$$T_{\text{Seismic zone}} = (0.0175 * 0.2644) + (0.0372 * 0.4765) + (0.0187 * 0.0965) + (0.0215 * 0.1626) = 0.0276$$

$$T_{\text{Construction period}} = (0.0225 * 0.2644) + (0.0257 * 0.4765) + (0.1067 * 0.0965) + (0.0137 * 0.1626) = 0.0307$$

$$T_{\text{Debris}} = (0.0162 * 0.2644) + (0.0240 * 0.4765) + (0.0178 * 0.0965) + (0.0215 * 0.1626) = 0.0209$$

$$T_{\text{Collapse history}} = (0.0294 * 0.2644) + (0.1292 * 0.4765) + (0.0682 * 0.0965) + (0.0215 * 0.1626) = 0.0794$$

$$T_{\text{Groundwater level}} = (0.0205 * 0.2644) + (0.0598 * 0.4765) + (0.0288 * 0.0965) + (0.0352 * 0.1626) = 0.0424$$

$$T_{\text{Soil type}} = (0.1231 * 0.2644) + (0.0515 * 0.4765) + (0.0682 * 0.0965) + (0.0824 * 0.1626) = 0.0771$$

$$T_{\text{Presence of H2S}} = (0.0169 * 0.2644) + (0.0463 * 0.4765) + (0.0439 * 0.0965) + (0.0137 * 0.1626) = 0.0330$$

$$T_{\text{Proximity to other ground installation}} = (0.0224 * 0.2644) + (0.0257 * 0.4765) + (0.0178 * 0.0965) + (0.0215 * 0.1626) = 0.0234$$

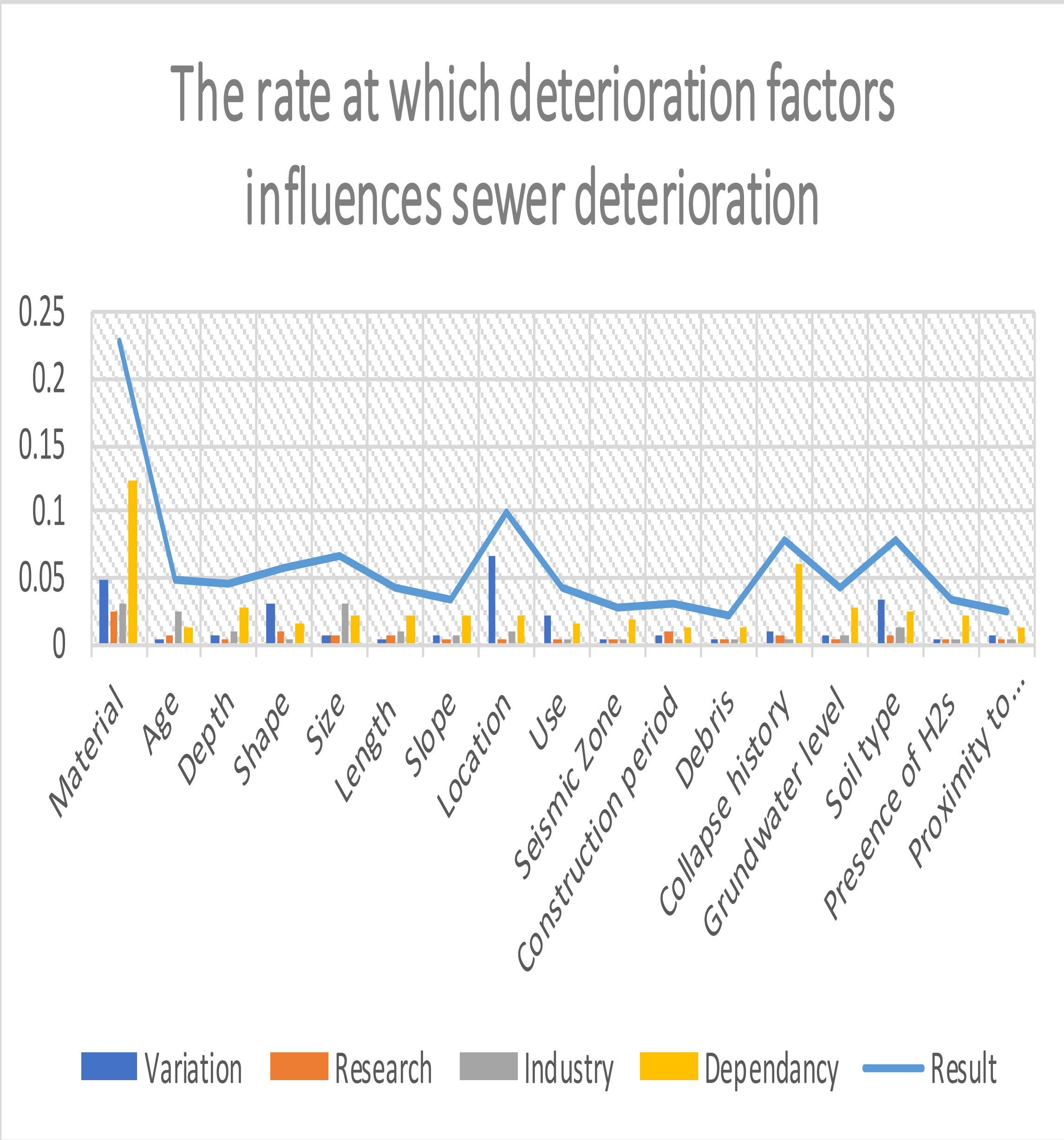


Figure 5.3. Factors affecting sewer deterioration (Source: The Author – O. S. Tade)

The result shown in Figure 5.3 indicates that sewer material type influence deterioration the most. This is because of the different sewer material types that exist and their behaviour under a vast variation of other identified factors. For the unknown sewer properties, a method that could help identify the material type will effectively support an investment plan. This will be the basis for sewer cohort formation in this Chapter.

5.2 Data analysis

Since sewer material type was found to be the most important sewer property affecting deterioration, it was necessary for the data on the material type to be properly analysed and investigated. As stated in Chapter 3 and shown in Figure 3.1, the total count of sewers in GIS was found to be 2,385,342. Z and X are the unknown material types which are 66.88% and 0.581% respectively and represent a total number of 1,596,798 sewers. Figure 5.4 shows the length of the sewers covered by each material type. Although the accuracy of these sewer lengths tagged by Shape length in GIS is yet to be investigated, the total length was found to be 66,578km. There was a discussion with industry experts that the amount of unknown is unacceptable and a method of sewer infilling should be developed. Although some tools such as the Asset Investment Model (AIM) used by the utilities adopted a method of data infilling, however, the accuracy of this inferred data has been questioned by acknowledged experts in the utilities.

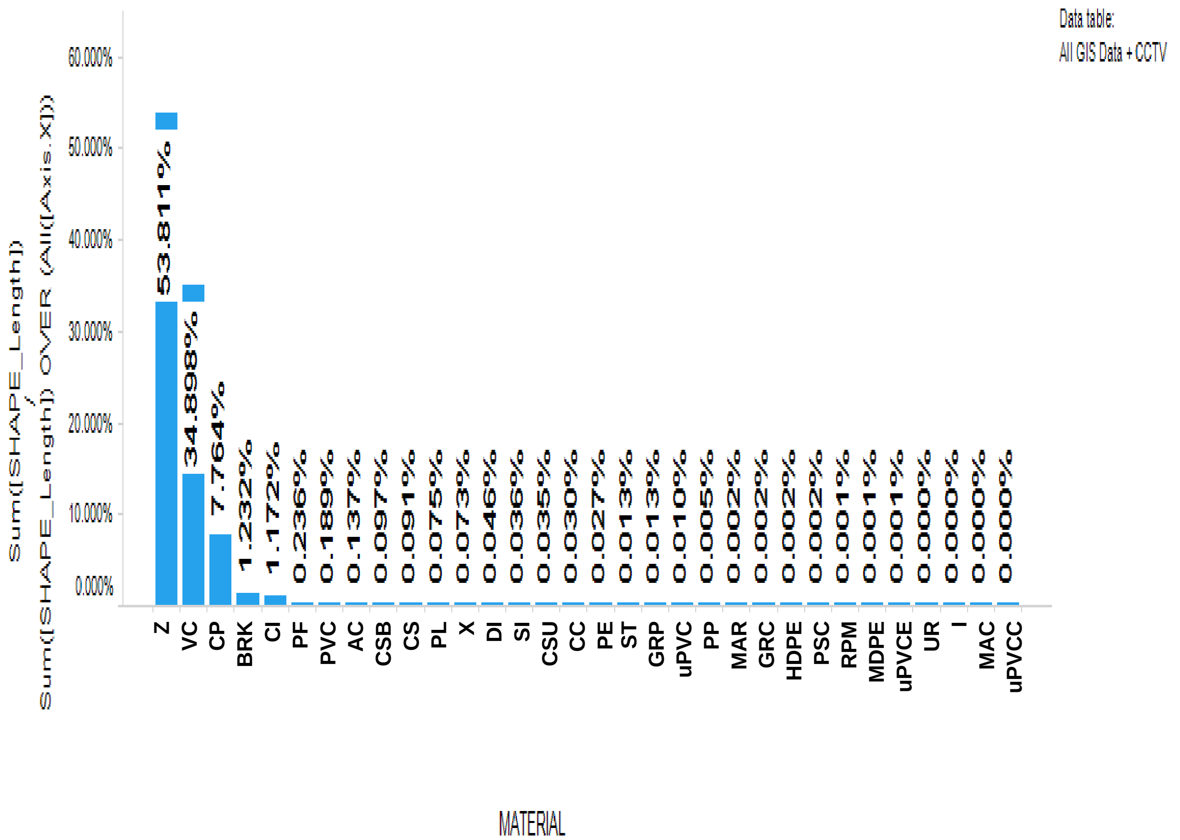


Figure 5.4. Length distribution of different sewer material type held in GIS (Source: The Author- O.S. Tade)

The sewer properties needed for modelling deterioration at the material cohort level were; sewer age, material type and CCTV survey date.

The age of the sewer can only be found in the GIS database whilst the CCTV inspection date can only be found in the CCTV inspection database. There was a need to link these two sources of data together to identify the ages of the inspected sewers and also validate the material types in these 2 databases.

Out of the 703,156 numbers of sewers surveyed between 1990 till 2014, only 47% of these were being able to match back to GIS data. This was because sewer upstream and downstream manhole IDs was not recorded to the same standard in both databases. For example, upstream manhole ID in GIS could be downstream manhole ID in CCTV data and in some cases where survey for a sewer started from the upstream manhole and was not completed (abandoned) the upstream manhole ID was not recorded hence 53% of the inspection data couldn't be matched back to GIS. Also, in some cases 2 or 3 sewers were surveyed together, hence the upstream manhole ID for the first sewer was recorded and the downstream manhole ID for the last sewer was recorded. It was concluded that only 47% of CCTV survey data that could be matched back to GIS data will be used for deterioration modelling. It was assumed that sewers before 1860 have been repaired or replaced so sewers build earlier than 1860 were excluded from the analysis.

5.3 Material type analysis

As stated in Chapter 3, a method of Data Source Reliability (DSR) was adopted to create a new column for material type "Material GB". Also, as earlier stated in this thesis and as identified by an internal report (MWH), CCTV material data is the most reliable source, followed by GIS. A criterion was set to assign material type found in CCTV inspection data to all sewers that have been inspected. For sewers that have never been inspected, the material type in GIS was assigned if available and if missing (unknown, -, x or z), inferred material type in GIS was assigned.

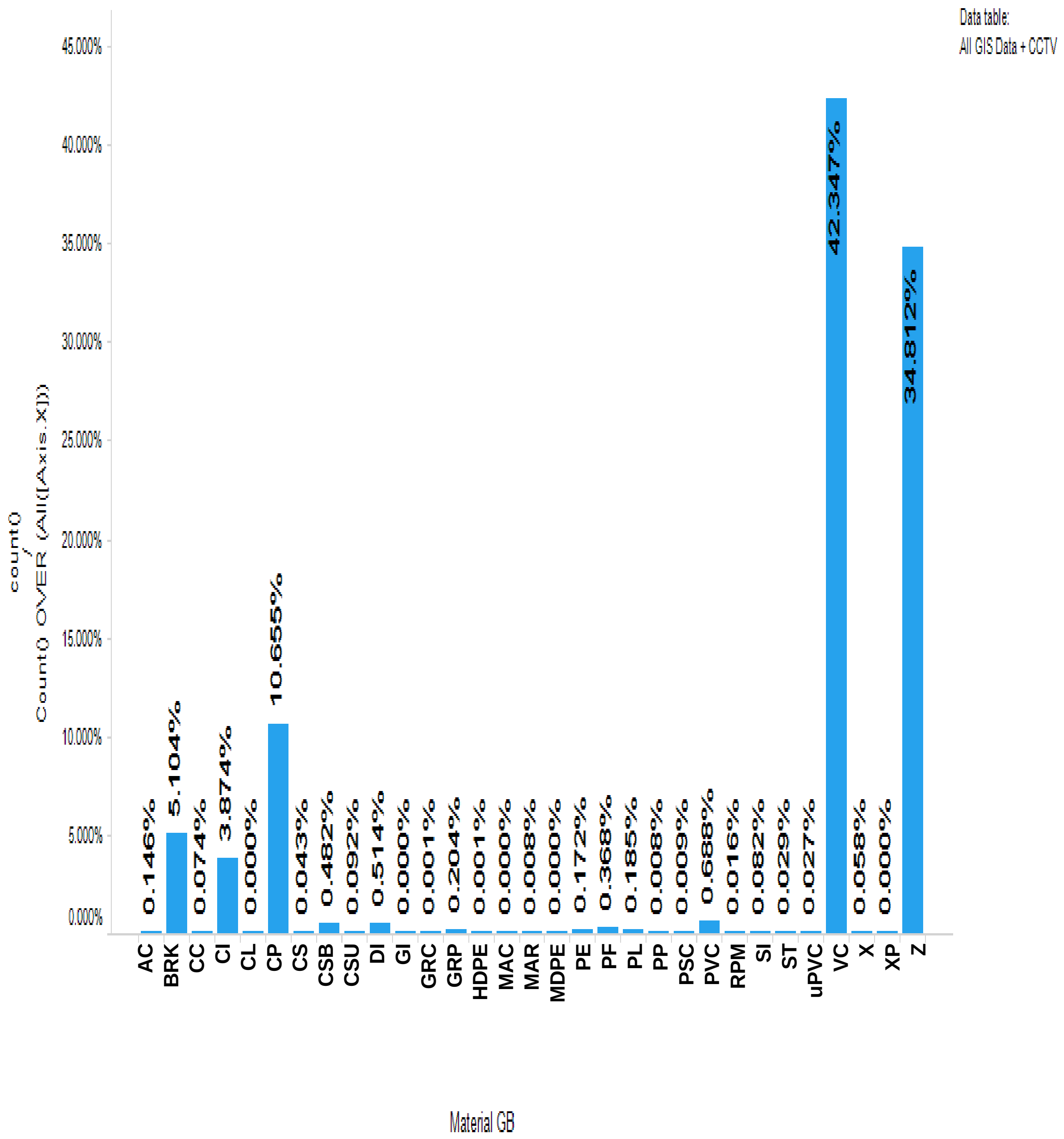


Figure 5.5. Material type distribution after DSR was applied (Source: The Author-O.S. Tade)

This method was able to reduce the amount of unknown material type in GIS (Z and X) from 66.88% and 0.581% in Figure 3.1 in Chapter 3 to 34.81 and 0.058% respectively as shown in Figure 5.5 and the corresponding lengths for these materials are as shown in Figure 5.6.

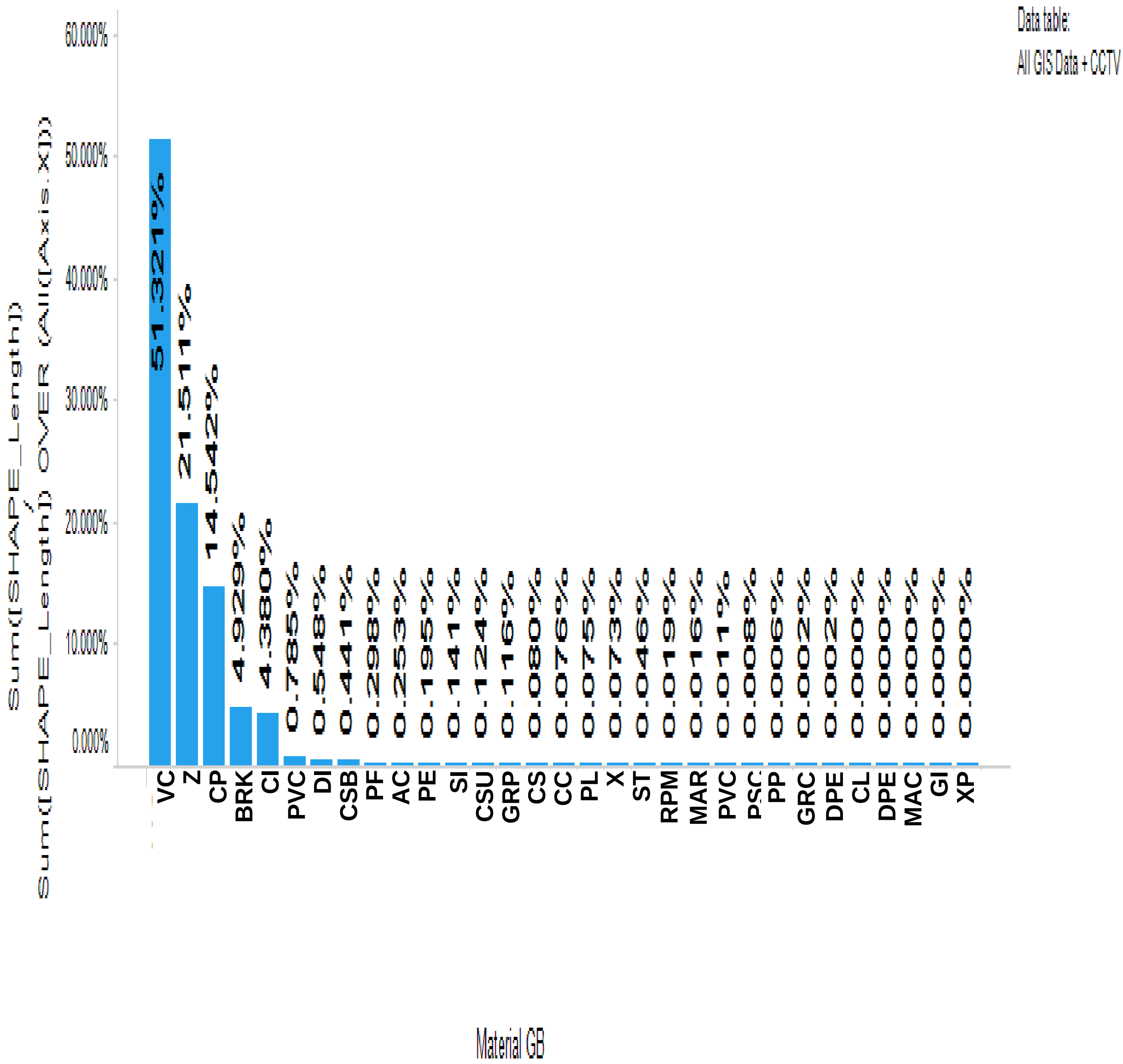


Figure 5.6. Lengths of material for DSR (Source: The Author- O.S. Tade)

5.4 Enhanced Deterministic Deterioration models

Using the sewer inferred age, the condition change time for each sewer was calculated. This is the time from date built for a sewer to get to the condition grade at the inspection time. In the absence of repeat inspection data, the DM was created by the superimposition of inspection histories of stratified data.

Using Tibco Spotfire, the data was stratified into material cohorts and corresponding degradation graphs were created. As shown in Figure 5.5 and Figure 5.6, most of the material types available do not have enough data samples for deterioration modelling.

Hence; only VC, CP, CI and BRK was analysed. The logarithmic deterioration formulas, standard deviations and correlation coefficients were then obtained for stratified sewer cohorts.

Table 5.11. Statistics obtained for clay sewers (Source: The Author- O.S. Tade)

ICG	**Data count**	**Min condition change time (Years)**	**Max condition change time (Years)**	**Most common condition change time (Years)**
1	46,984	19	153	61
2	3,089	12	148	61
3	1,375	6	148	73
4	2,097	16	150	73
5	416	1	141	70

Table 5.11 shows the statistics behind the deterioration graph for VC presented in Figure 5.7. The data count informing each condition grade, the minimum value obtained, the max value obtained and the most common condition change value.

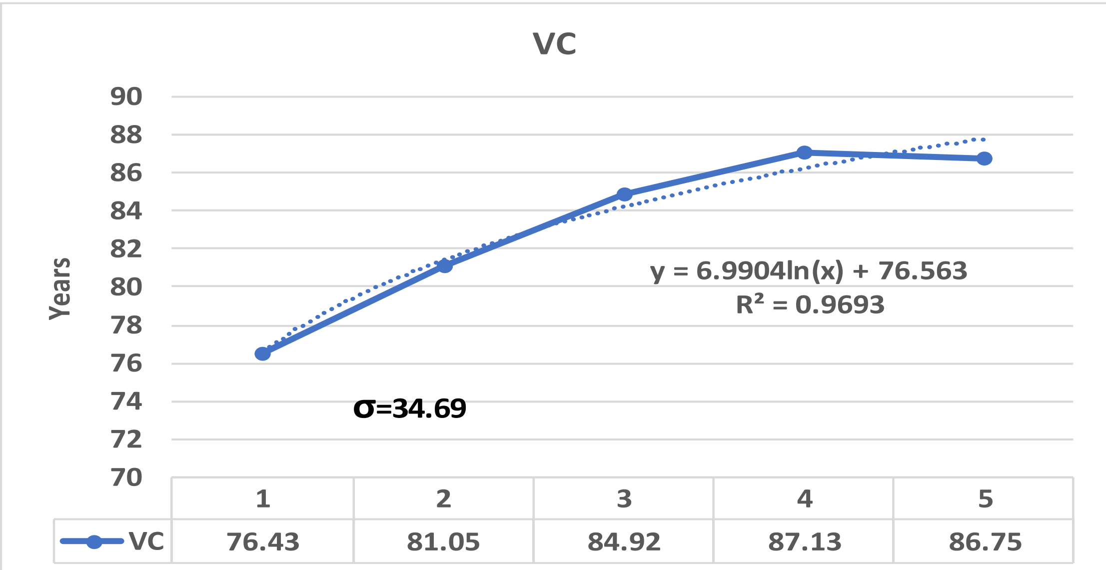


Figure 5.7. Deterioration graph for Vitrified Clay (Source: The Author- O.S. Tade)

Figure 5.7 shows the deterioration curve for VC sewers and the standard deviation around the curve. This is a very reliable degradation as it has a very high correlation coefficient of 97% and the most important as it represents 42% of the utility's gravity sewer network.

Table 5.12. Statistics obtained for concrete sewers (Source: The Author- O.S. Tade)

ICG	**Data count**	**Min condition change time (Years)**	**Max condition change time (Years)**	**Most common condition change time (Years)**
1	46,984	19	153	61
2	3,089	12	148	61
3	1,375	6	148	73
4	2,097	16	150	73
5	416	1	141	70

Table 5.12 shows the statistics behind the deterioration graph presented in Figure 5.8. The data count informing each condition grade, the minimum value obtained, the max value obtained and the most common condition change value.

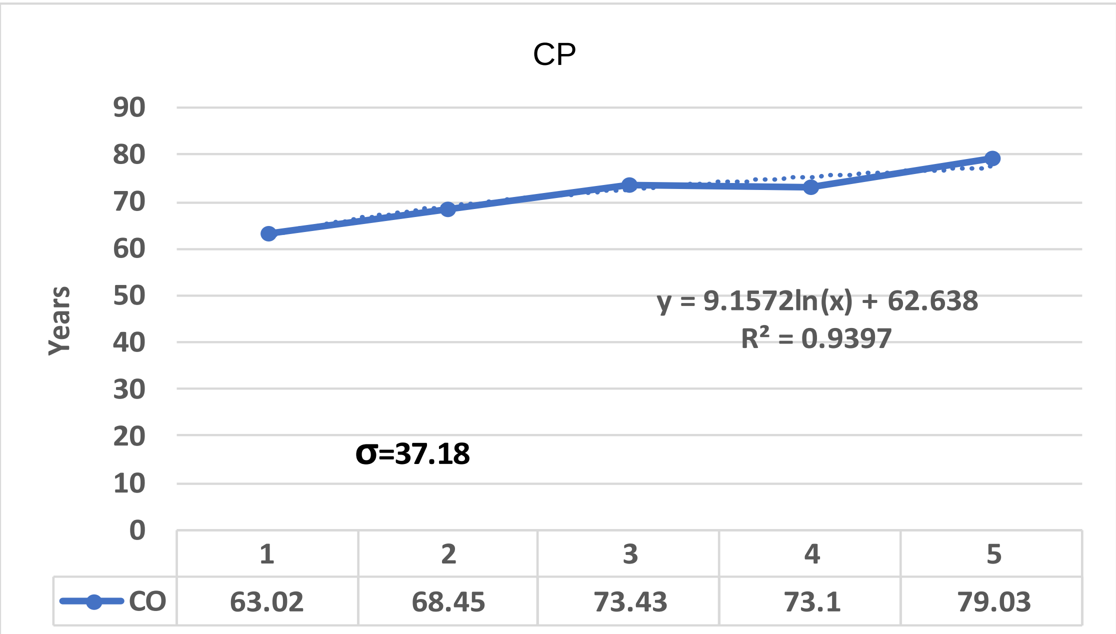


Figure 5.8. Deterioration graph for concrete sewer (Source: The Author- O.S Tade)

This is also a reliable degradation curve as it has a very high correlation coefficient of 94% and the second most important as it represents 10.66% of the sewer network in the Thames Valley.

Table 5.13. Statistics obtained for cast iron sewers (Source: The Author- O.S. Tade)

ICG	Data count	Min condition change time (Years)	Max condition change time (Years)	Most common condition change time (Years)
1	8,783	19	153	61
2	97	5	146	78
3	63	20	148	111
4	104	17	153	71
5	16	62	133	125

Table 5.13 shows the statistics behind the deterioration graph in Figure 5.9. The data count informing each condition grade, the minimum value obtained, the max value obtained and the most common condition change value.

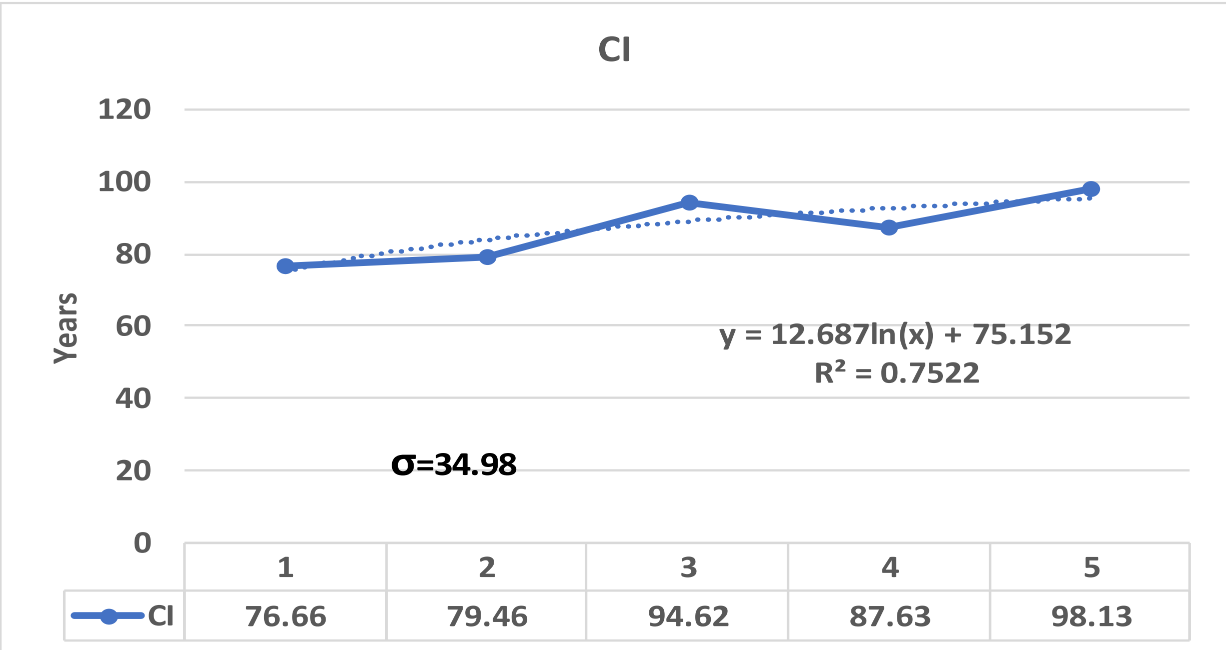


Figure 5.9. Deterioration graph for cast iron sewers (Source: The Author- O.S Tade)

This is also a reliable degradation curve as it has a high correlation coefficient of 75% and it represents 3.87% of the sewer network in the Thames Valley.

This is a significant improvement on any previous research as it represents transparency, a measure of confidence and uncertainty around sewer deterioration. This improvement was found by one of the UK water utilities to have the potential of changing practice in the area of sewer asset management.

5.5 Setting investment priorities for RBF

The individual component of the RBF will be discussed. Using Concrete (CP) sewer as a case study, the deterioration curve for CP and the standard deviation is as shown in Figure 5.8. CP has a life of 79 years as can be seen on the deterioration curve and the standard deviation around this life is 37 without considering third party impact. The practice for prioritising investment in SN in the UK is to analyse the criticality of the SN as highlighted in SRM. A sewer could be critical or non-critical. Generally, criticality is a measure of cost which a knock-on effect created by COF. COF is a function of;

- The level of sewer importance.
- Likely collateral damage from a failure or collapse of a sewer.
- Sewer replacement cost.
- Sewer location.

Clearly, there is a cost overlap between criticality and COF.

WRc's SRM provides guidance on the process of managing SN. This SRM grouped sewer's criticality into 3 categories A, B and C. As stated in Chapter 2, these categories depend on the surface theme (the type of building above such as highway, railway or hospital area), sewer depth, sewer material type and soil condition (WRc, 2004). These factors can potentially result in a very high cost of repair (Reactive cost).

Category A (CAT A): Sewer failure will directly or indirectly have an extreme cost consequence to the utility. The reactive cost is 6 times greater than the proactive cost (WRc, 2001).

Category B (CAT B): Sewer failure will result in a moderate cost consequence to the utility. The reactive cost is between 3 to 6 times the proactive costs (WRc, 2001).

Category C (CAT C): Sewer failure will result in a low consequence to the utility. The reactive cost is less than 3 times the proactive cost (WRc, 2001).

To avoid this consequential cost, the existing proactive investment timing for sewers provided by WRc and ASCE (American Society of Civil Engineers) is as summarised in Table 2.14 in Chapter 2 and brought forward to Table 5.14. These reactive and proactive cost factors of 3 and 6 might be regarded as almost traditional.

Table 5.14. Investment frequencies and priorities provided by ASCE and WRc (Adapted from WRc, 2001 and Zhao et al, 2001)

Condition Grades	Criticality	Survey Frequencies			Investment Priority
		Category A	Category B	Category C	
5	High	0 years	0 years	Not provided	Immediate
4	High	0 years	5 years	Not provided	High
3	Medium	3 years	15 years	Not provided	Medium
2	Low	5 years	20 years	Not provided	Low
0 - 1	Low	10 years	20 years	Not provided	Not required

As earlier stated in Chapter 2, from discussion with experts in the wastewater utility in the UK, it was found that the survey frequencies provided in the SRM are too ambiguous as it has a very low level of granularity for proactive investment. An example of deterioration rates for CP sewers in the Thames valley catchment has been presented in Figure 5.8. As earlier stated, sewer material ranges from brick, iron, vitrified clay, pitch fibre, plastic, composite materials and concrete. Ideally, it is expected that these materials will deteriorate at different rates. Hence; it will be nothing short of reactive to manage all these different sewer material types with these same investment priorities or inspection frequencies provided by SRM and ASCE in Table 5.14.

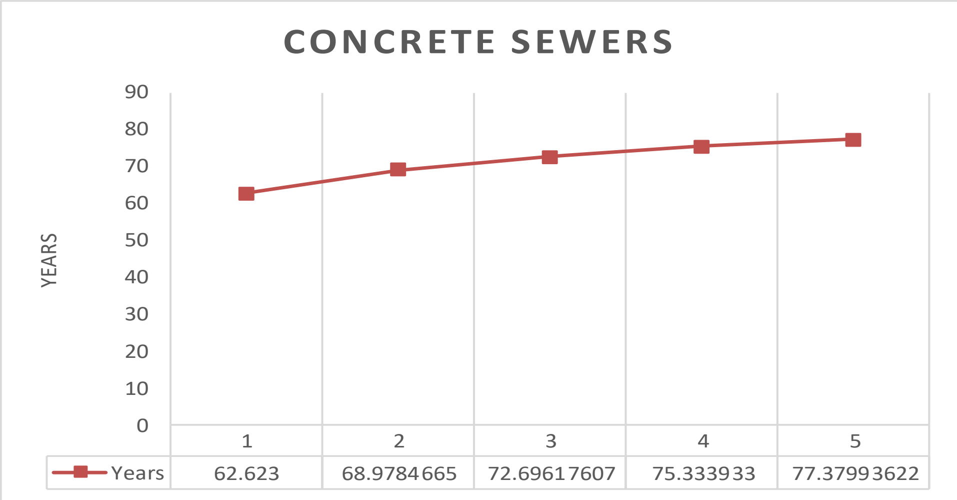


Figure 5.10. Deterioration curve for concrete sewer (Source: The Author- O.S. Tade)

The deterioration can be derived from Equation 5.2;

Equation 5.2. Deterministic equation for concrete sewer

$$Y = 9.169 * ln(x) + 62.23$$

It can be seen from the deterioration curve that it will take an average of 2 years for CP sewer type to get to ICG 5 from ICG 4. This is very higher than the 0 years provided by WRc in Table 5.14. For a comprehensive comparison, the investment priorities provided by WRc is compared with the observed in Table 5.15.

Table 5.15. Inspection frequencies comparison (Source: The Author- O.S Tade)

ICG	Observed Deterioration	WRc CAT A	WRc CAT B	WRc CAT C
1 to 5	15	5	20	Reactive
2 to 5	8	3	15	Reactive
3 to 5	5	0	5	Reactive
4 to 5	2	0	0	Reactive

A critical look at Table 5.15, it appears that there are significant discrepancies between the observed rates of condition change and the ones provided by the existing WRc and ASCE framework. For CAT A with the costliest reactive investment, the observed frequency of inspection is very much higher than already provided. This implies that the utility would have to spend more on sewer inspection than necessary for CP sewers. For CAT B, the frequency of inspection already provided appears to be more than observed. This implies that if the provided frequency was used, some CP sewers will be failing before assessment which will result in a reactive form of maintenance. The justification for the lower figures for CAT A provided by WRc and ASCE is that there are uncertainties around sewer deterioration. Hence; it is necessary to inspect sewer condition more frequently. Nevertheless, for CAT B sewer, the frequency of inspection provided doesn't appear to be proactive as the observed is lower than the ones provided. Another major problem is for utilities managing a large SN such as the participating utility where a large portion of sewers could be in ICGs 3, 4 and 5, in CAT A criticality. This raises research question 1 in Chapter 2; how the business will prioritize and justify inspection frequencies within 3 years specified by WRc and ASCE in the face of scarce resources (monetary). Hence; there is the need to modify current inspection frequencies for better AM. After further analysis of the deterioration curve in Figure 5.10, it was found that a standard deviation of 30 years exist around the average year obtained for ICG 5 after third-party action has been considered.

In this research, it was observed that sewer degradation follows a Gaussian distribution as shown in Appendix XI. This means that risk management techniques used for other engineering systems such as new concrete superstructures are valid. This method was adopted to enhance the DDM. In concrete buildings in Europe, a standard deviation of 1.64 gives design strength such that 95% of the material will exceed that value.

As shown is Figure 5.11, the uncertainty was analyzed as a Factor of Safety (FOS) to manage risk. The average value obtained in the deterioration curve is at 50%. 50% means, 50% of the sewers analyzed survived at this point and 50% has failed. At 65%, 65% of the sewers analyzed survived and 35% has failed at that point and at point 80%, 80% of the sewer analyzed survived and 20% has failed at that point.

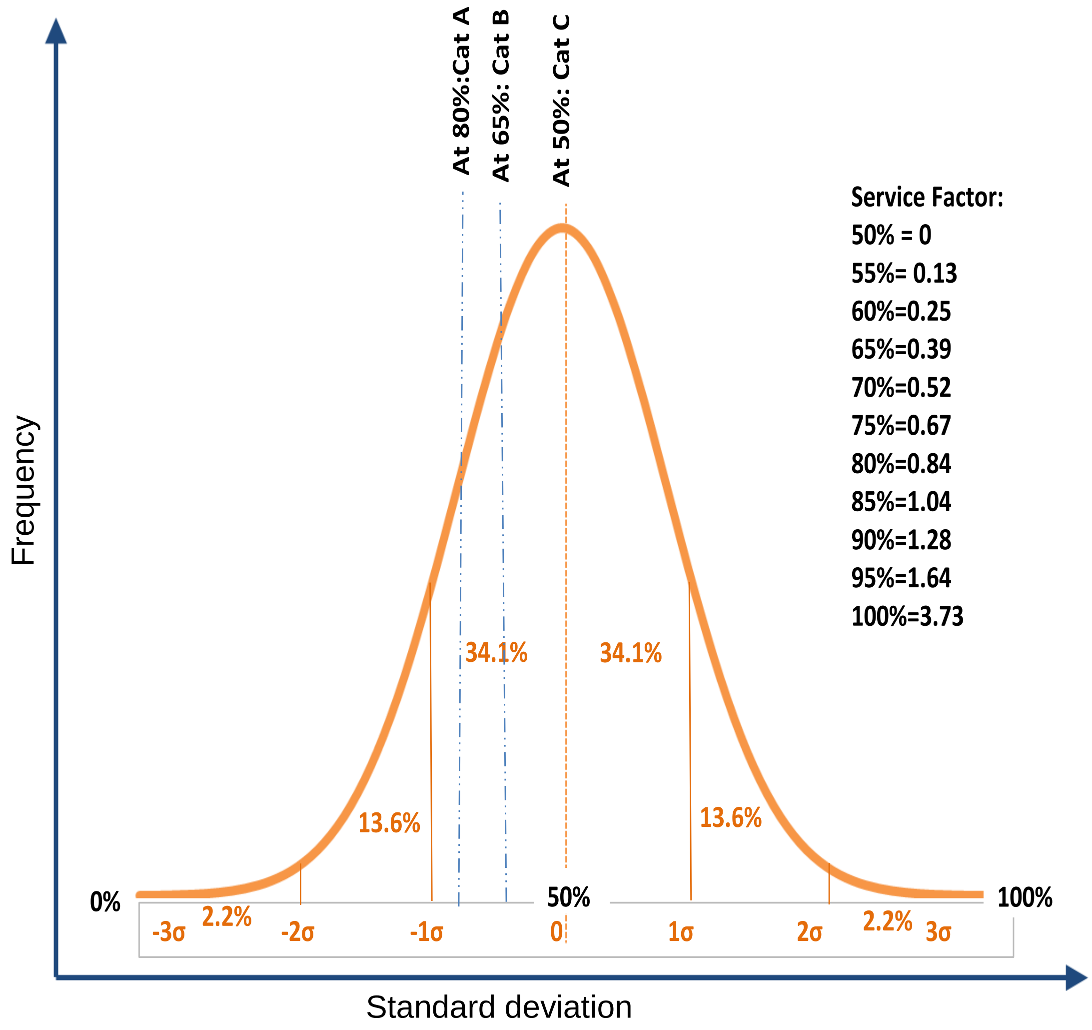


Figure 5.11. Standard deviation analysis of uncertainty around deterioration (Source: The Author- O.S. Tade)

Equation 5.3. Design strength calculation

$$F_{Design} = F_{Mean} - 1.64 * \sigma$$

Where;

F_{Design} is the design strength

F_{Mean} is the mean strength

σ is the standard deviation

If the asset manager therefore had the risk appetite such that no more than 20% of the asset would have failed for a CAT A sewer, the intervention time in Equation 5.4

would be used, if no more than 35% for a category B sewer, Equation 5.5 is used and for category C where only half would have failed Equation 5.6 is used.

Equation 5.4. Design strength formula for CAT A sewers

$$T_{iA} = Y_{Mean} - 0.84 * \sigma$$

Equation 5.5. Design strength formula for CAT B sewers

$$T_{iB} = Y_{Mean} - 0.39 * \sigma$$

Equation 5.6. Design strength formula for CAT C sewers

$$T_{iC} = Y_{Mean}$$

Where;

T_{iA} is the intervention time for category A sewers

T_{iB} is the intervention time for category B sewers

T_{iC} is the intervention time for category C sewers.

Y_{Mean} is the average life of the sewers.

As a statistically proven process, this gives a picture of the overall behaviour and it is not predictive at any sewer element level. Although this gives an improved planning tool, the allocation of a CAT A status to a link of sewer will always prioritize it over a CAT B. For example, in the management of sewers in a catchment of 40 CAT A sewers, this would allow effective management.

There could still be a localized failure but if a link is that critical, a wireless sensor monitor might be an option in a beyond CAT A sewer.

To put this analysis into perspective; for a set of 416 CP sewers in ICG 5, several explanatory factors such as depth, location, length, size, slope, effluent type, and soil type have resulted in different deterioration rates within the CP material cohort. The average of this variable deterioration rates is taken and the deviation around this rate is derived to capture the uncertainty. This uncertainty is used to dissolve the risk. For example, it takes an average of 77 years for CP sewers to get to ICG 5 as shown in Figure 5.12 and the standard deviation (SD) is 30. For a criticality “A” sewer, the SD is used to estimate the time it takes 80% of the sewers to get to ICG 5.

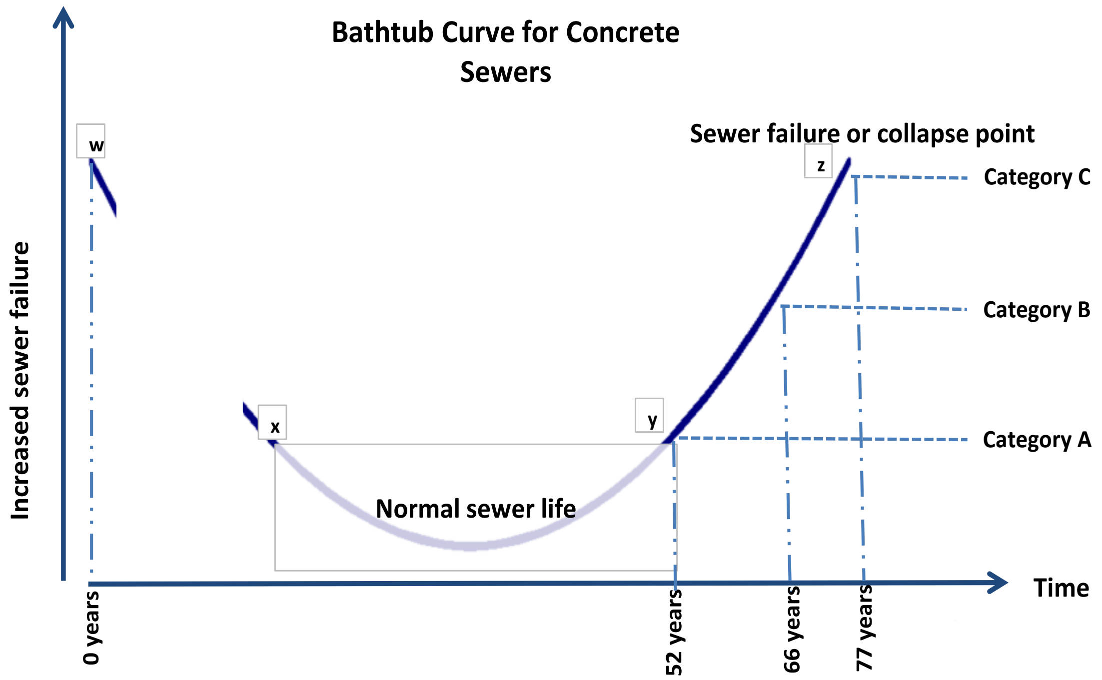


Figure 5.12. Failure rates against the time span of the network (Source: The Author-O.S Tade)

Point w: sewer commissioning

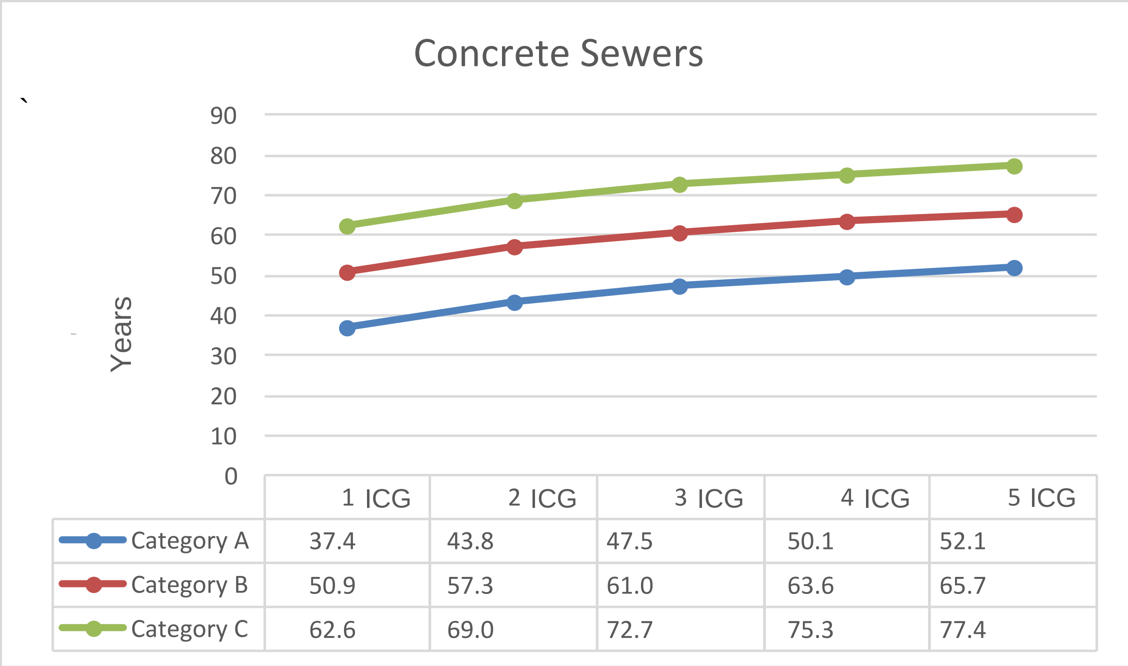
Point w to x: Infant mortality, decreasing failure rate

Point x to y: Normal life (the useful life): Very low but constant rate of failure

Y to z: Deterioration begins and increasing failure rate

Z: sewer end of life.

For yet to be surveyed sewers, the point of intervention for the different criticality categories shown on the bathtub curve in Figure 5.12 can be used. For example, for a CAT A sewer, CP sewers older than 52 years would be inspected and for CAT B CP sewers older than 66 years would be inspected.



	1 ICG	2 ICG	3 ICG	4 ICG	5 ICG
Category A	37.4	43.8	47.5	50.1	52.1
Category B	50.9	57.3	61.0	63.6	65.7
Category C	62.6	69.0	72.7	75.3	77.4

Figure 5.13. Deterioration curves for 3 criticalities (Source: The Author- O.S. Tade)

To estimate the difference in inspection frequencies between category C which represents the observed deterioration curve and category A, the percentage change formula as in Equation 5.7 is used.

Equation 5.7. Percentage change formula from CAT C to CAT A

$$\%\Delta = \frac{Category\ C - Category\ A}{Category\ A} * 100$$

To estimate the difference between category C which represents the observed deterioration curve and category B, the percentage change formula in Equation 5.8 is used.

Equation 5.8. Percentage change formula from CAT C to CAT B

$$\%\Delta = \frac{Category\ C - Category\ B}{Category\ B} * 100$$

Percentage shift or change between curve category C and curve category A at mid-point is 53%. Also, the percentage shift or change between curve Category C and curve category B is 4%. When this percentage shift was applied to the observed inspection frequencies, Table 5.16 was obtained.

Table 5.16. Observed for CP vs WRc specification inspection frequencies (Source: The Author- O.S. Tade)

ICG	Observed	WRc Category A	Designed Category A	WRc Category B	Designed Category B	WRc Category C
1 to 5	15 years	5 years	7 years	20 years	14 years	Reactive
2 to 5	8 years	3 years	4 years	15 years	8 years	Reactive
3 to 5	5 years	0 years	3 years	5 years	5 years	Reactive
4 to 5	2 years	0 years	1 years	0 years	2 years	Reactive

The analysis presented in Table 5.16 has shown that there are differences between the experimentally observed values from data analysis and WRc's SRM guides. This means that the SRM can be revised.

5.6 Development of RBF

To create the RBF using CP sewers as a case study, the deterioration curve for CP and the standard deviation application is as shown in the RGF presented in Figure 5.14. Data from the utility's database are analyzed to identify levels of criticalities. The individual criticality goes into different programmes;

- Criticality A: Into proactive inspection programme because the cost of reactive repair is very high.
- Criticality B: Into proactive inspection programme because the cost of reactive repair is high.
- Criticality C: Into reactive maintenance programme because the cost of proactive could be significantly more than reactive

For sewers that have never been surveyed before, the program makes use of material cohort deterioration models. This is done such that in criticality A inspection program, 80% survival rate is used and the predicted ICGs is used to set inspection priorities. In the criticality B inspection program, 65% survival rate is used and the predicted ICGs are used to set inspection priorities. For example, for sewers in CAT A, CP sewers older than 52 years will be inspected first as they are expected to be in ICG 5 based on 80% risk appetite. All the CP sewers that are to be inspected before 52 years will be prioritized by risk analysis. The risk analysis process will be presented in Chapter 6

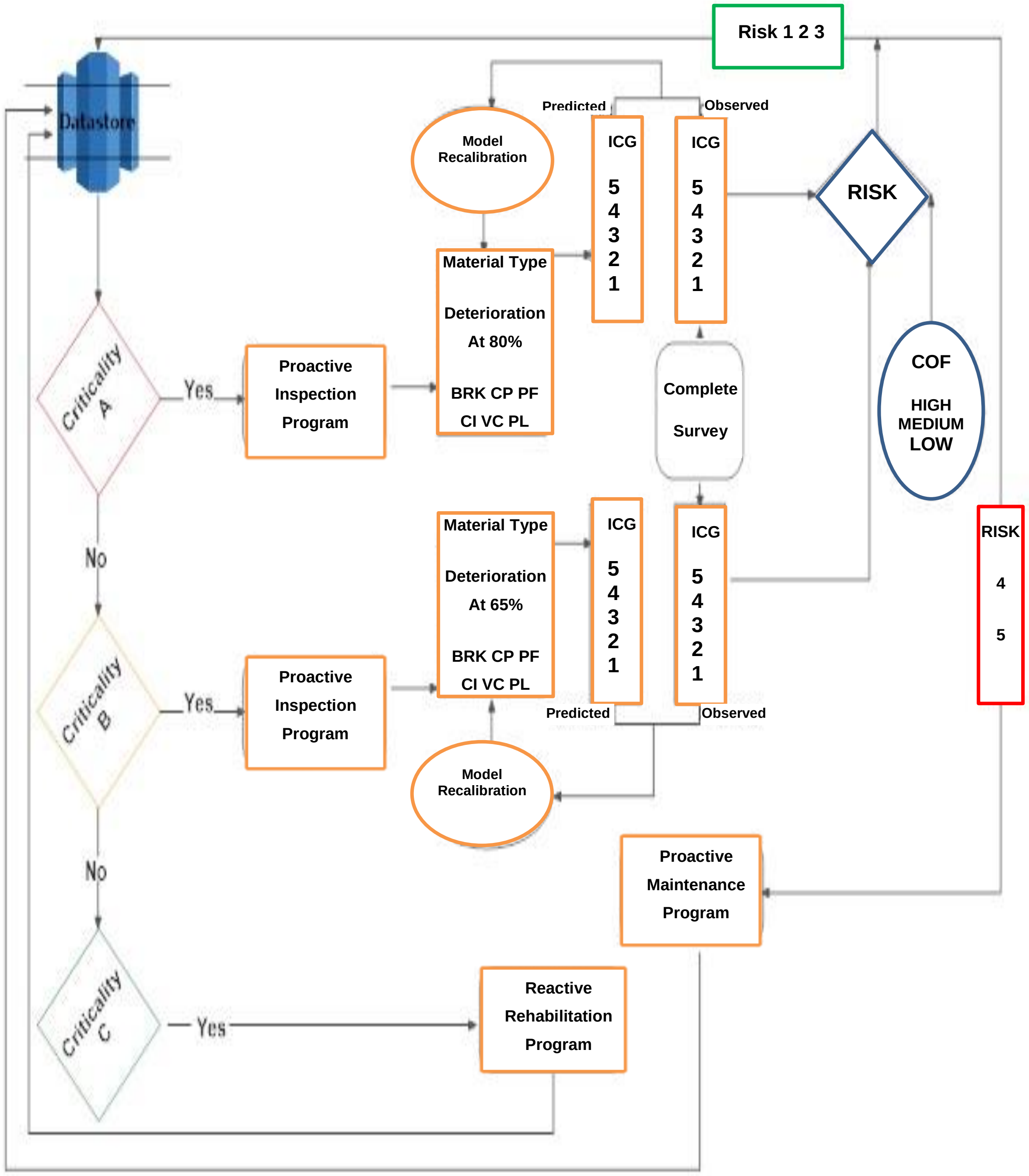


Figure 5.14. Framework for proactive AM of SN (Source: Author- O.S. Tade)

As earlier stated, these percentages can be adjusted to suit the risk appetite of the utilities.

After sewer CCTV survey, the observed and the predicted ICGs go into a recalibration model for the deterioration model to be recalibrated. This would allow the model to adjust to any shift in the deterioration rates & pattern. The recalibrated model is used to set priorities for future CCTV inspections. When the actual condition is observed, the inspection frequencies for different criticalities in different ICGs are used as in Table 5.16 for CP sewers. Also, from the risk analysis using the COF and observed ICGs, sewers with risk levels 1, 2, and 3 go back into the database for another cycle of risk analysis to be carried out in due re-inspection frequencies. Sewers with risk level 4 and 5 go into proactive maintenance program for rehabilitation. This maintenance programme can now be done in such a way that sewers with risk 5 are attended to first.

Chapter 6

Discussion and Analysis

This Chapter presents further analysis of the enhanced Deterioration Model (DM) and RGF (Risk-Based Framework) presented in Chapter 5. This was done by increasing the granularity of the model and evaluating the process of risk analysis for inspected sewers. In Chapter 4, the applicability of existing DMs using the available data was evaluated and discussed. It was found that the data available cannot be used to evaluate deterioration at the sewer element level. However, it was necessary to give the model some form of granularity by stratifying the data as much as the data permits.

6.1 A better understanding of increased granularity

Existing degradation approaches summarised in Chapter 2.2 have low granularity as results presented by most of these approaches represents a summary of the conditions of the asset; in most cases, at the material level. The level of granularity that will be presented in this Chapter to visualise variations from material stratified down to size and further to effluent characteristics does not exist in any of the research available at the moment. There is a significant long-term cost benefit for utilities to incorporate asset degradation with a low level of granularity. For a sustainable proactive AM approach to succeed there must be an improved understanding of different sewer lifetimes that considers the granularity of the data based on measured attributes. Combinations of different eras of construction, different diameters, overburden thicknesses, internal chemical or hydraulic attrition as much as the data permits. It could be significant for one zone of the network, but not for another – or at least not in the same weighted combinations. There is in practice no useful generalised equation such as assumed in regression models; each zone must be described separately as necessary and as much as the data permits. The approach is not that dissimilar to that taken in repairing heritage structures; first, the structure must be monitored and understood, and then it can be repaired. To paraphrase the conservation engineer, one must listen to what the network is saying (Dirksen & Clemens, 2008). This is one of the reasons why a deterministic approach was considered as the best option as it is an approach that can be used to listen to the network. Figure 6.1 illustrates the major difference in the deterioration of 3 different sewer material types. This difference is in parta result of the high durability and compressive strength of cast iron. Concrete is susceptible to hydrogen sulphide attack in low flow situations and inevitably increasing its degradation as made evident in the degradation curves shown in Figure 6.1. These may vary in different zones of the network.

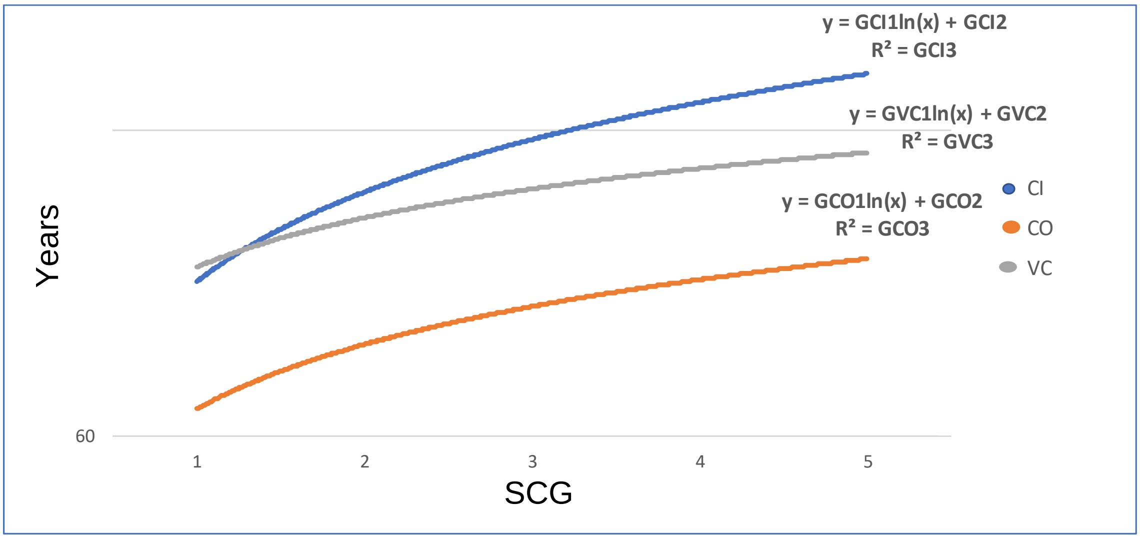


Figure 6.1. Comparison of the deterioration curves for 3 sewer material type (Source: The Author- O.S. Tade)

The result of the analysis shown in Figure 6.2, shows a variation of between 2 to 7 years between 3 different VC sewer sizes.

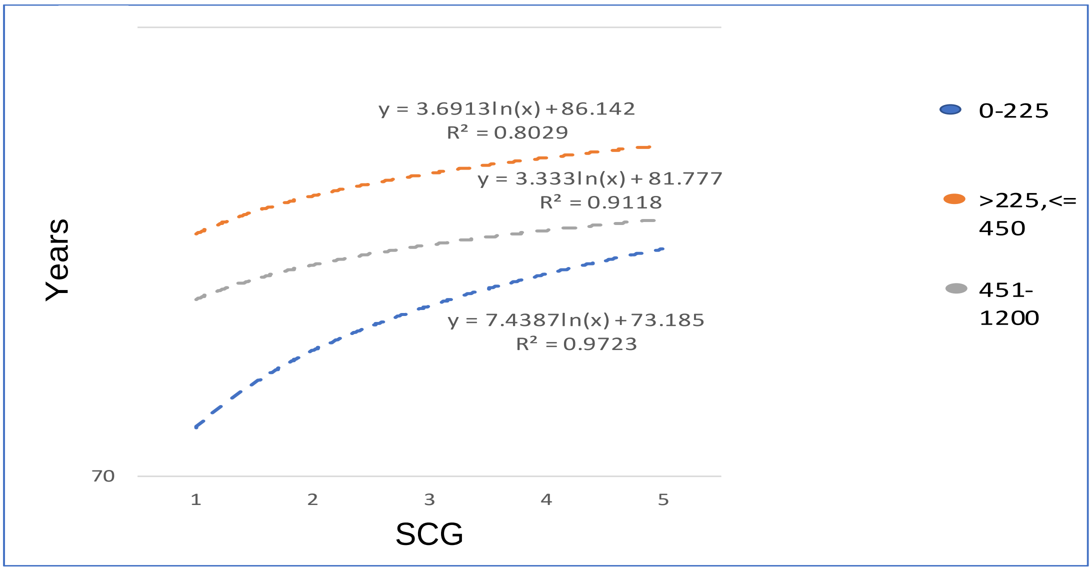


Figure 6.2. Comparison of the deterioration curves for 3 sizes strata of VC (Source: The Author- O.S. Tade)

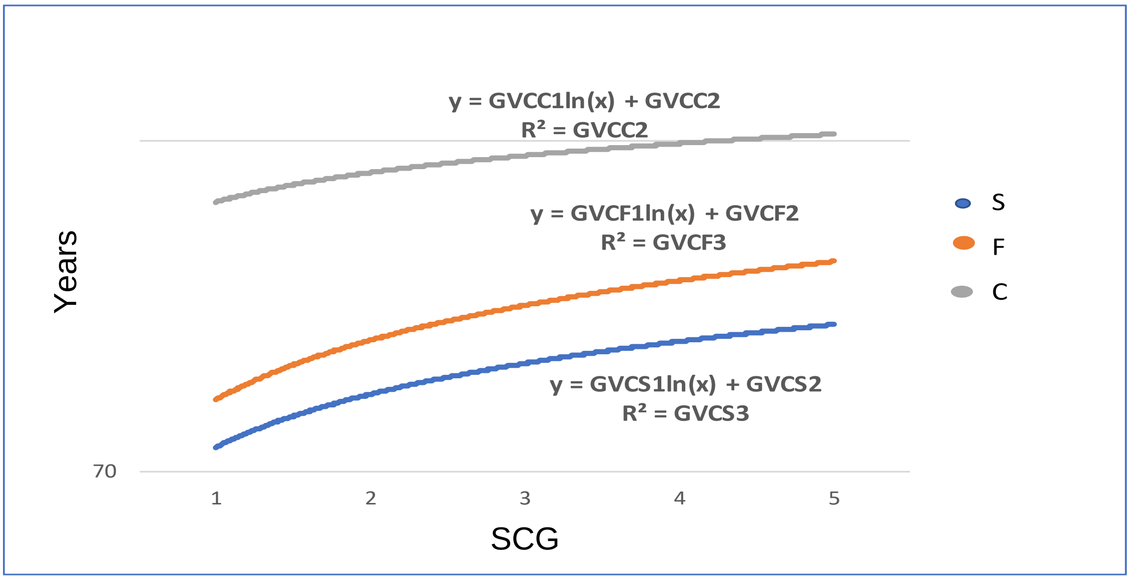


Figure 6.3. Degradation curve for all vitrified clay stratified by effluent characteristics (Source: The Author- O.S. Tade)

When the different size cohorts within VC cohort were further stratified by effluent characteristics as shown in Figure 6.3 for all sizes, Figure 6.4 for 0-225mm and Figure 6.5 for >450mm, the variation became more obvious. A difference of 17 years was found between stormwater sewers and combined in Figure 6.3. It was found that stormwater sewer deteriorates faster than the 2 others. Stormwater sewers are generally shallow and of small sizes, as they discharge into surface water bodies which makes them susceptible to deterioration due to surface loads.

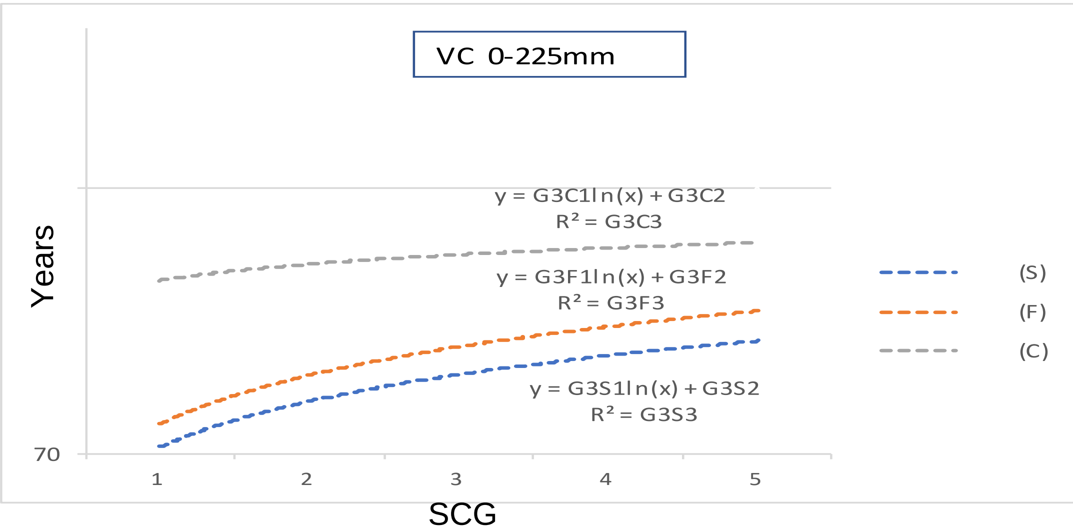


Figure 6.4. Degradation curve for vitrified clay of sizes >=225, stratified by effluent characteristics (Source: The Author- O.S. Tade)

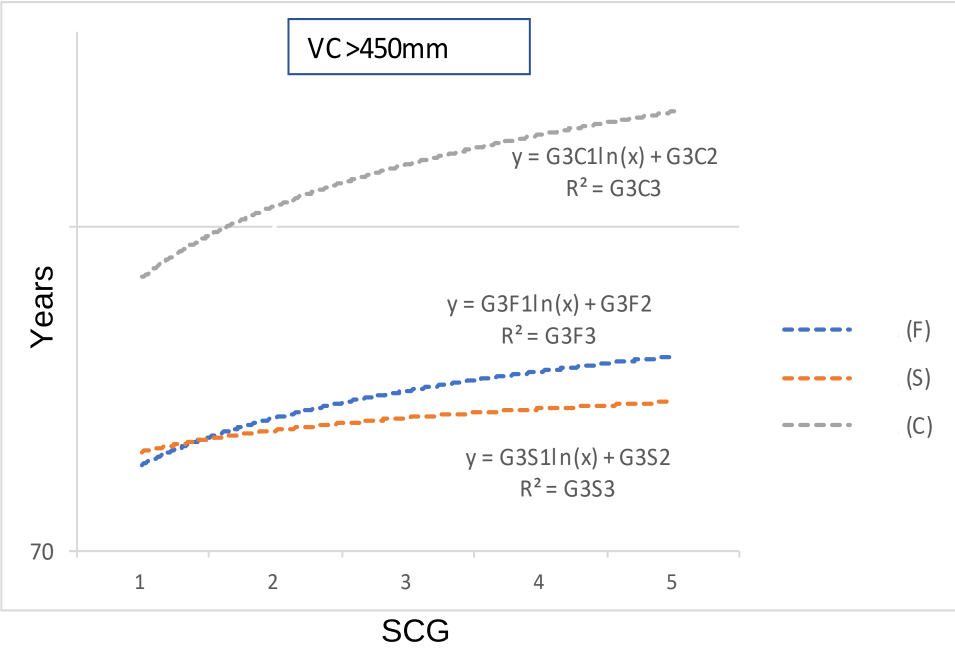


Figure 6.5. Degradation curve for vitrified clay of sizes >450mm stratified by effluent characteristics (Source: The Author- O.S. Tade)

Using more refined estimates of the likelihood of collapse, leakage or other condition 5 events means that repair prioritisation, within current industry practice, could progress without the confusion of introducing an additional process of engineering review except it is necessary. With more sewers exceeding 150 years age, and many experienced engineers retiring, the Capex vs Opex discussion will need to be rigorously well informed by reliable, audited and accessible data. As better estimates of sewer lifetimes are obtained, the incorporation of repair and new construction data must be stored, incorporating the aims of PAS 256-2017, in an agreed format. There is a proliferation of software platforms available to manage, work, assets and data and a key criterion is the ability of these to communicate with each other and with the industries legacy systems. It is likely more use of robots for sewer inspection and repair will become popular and the databases in the future will need to be able to communicate with these.

6.1 Proposed Optimized Sewer Condition Prioritization Formula (OSCPF)

As earlier stated in Chapter 2, the existing MSCC grading put all sewers in 5 ICGs as shown in Figure 6.6. Hence, it was paramount that an optimized sewer condition priority score was developed.

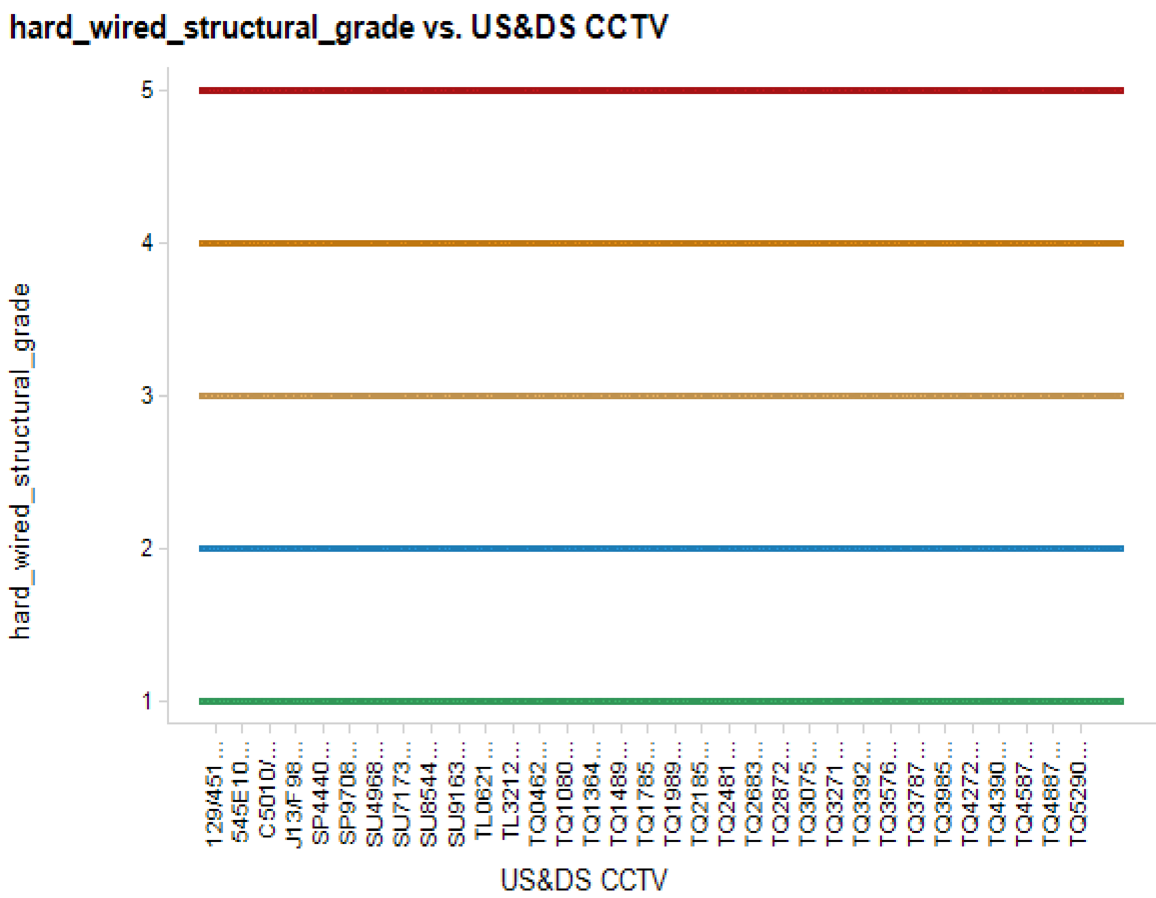


Figure 6.6. Existing condition grading system (Source: The Author- O.S. Tade)

The developed OSCPF in this research captures the utilities' expertise knowledge and the requirement for prioritizing sewer condition. Six experts around the UK utilities were given four identified sewers to prioritise in order of sewer condition. Table 6.1 captures the feedbacks from all six of the experts. It was interesting to find out that they all have the same view on prioritising sewers condition.

Table 6.1. Expert sewer defect scoring (Source: The Author- O.S. Tade)

Sewer ID	Expert1	Expert2	Expert3	Expert4	Expert5	Expert6	Overall
SU71***203 to SU71***202	4	4	4	4	4	4	4
SU71***2P0 to SU71***554	2	2	2	2	2	2	2
SU71***551 to SU71***551	1	1	1	1	1	1	1
SU71***402 to SU71***401	3	3	3	3	3	3	3

The proposed OSCPF starts from the highest single defect score found in any section of the entire sewer length and addition of the cumulative effect of all other defects present in the sewer. This gives a more granular scoring for each WRc CG.

Equation 6.1. Optimized sewer condition priority formula

$$SCPR = CG + \left(\frac{0.1 - Peak\ Score}{Total\ Score + Defect\ Count}\right) + 1$$

When the designed formula in Equation 6.1 was applied to the same set of sewers, the result in Table 6.2 was obtained.

Table 6.2. OSCPF sewer defect scoring (Source: The Author- O.S. Tade)

Sewer ID	Length	Total score	Peak score	CG	Defect count	SCPF
SU71***203 to SU71***202	20m	210	120	4	8	4.45
SU71***2P0 to SU71***554	20m	285	165	5	3	5.4274
SU71***551 to SU71***551	20m	540	165	5	9	5.6996
SU71***402 to SU71***401	20m	260	120	4	5	4.5475

OSCPF was able to prioritize sewer condition similar to the way an industrial expert would. When OSCPF was applied to the same set of sewers in Figure 6.6, Figure 6.7 was obtained.

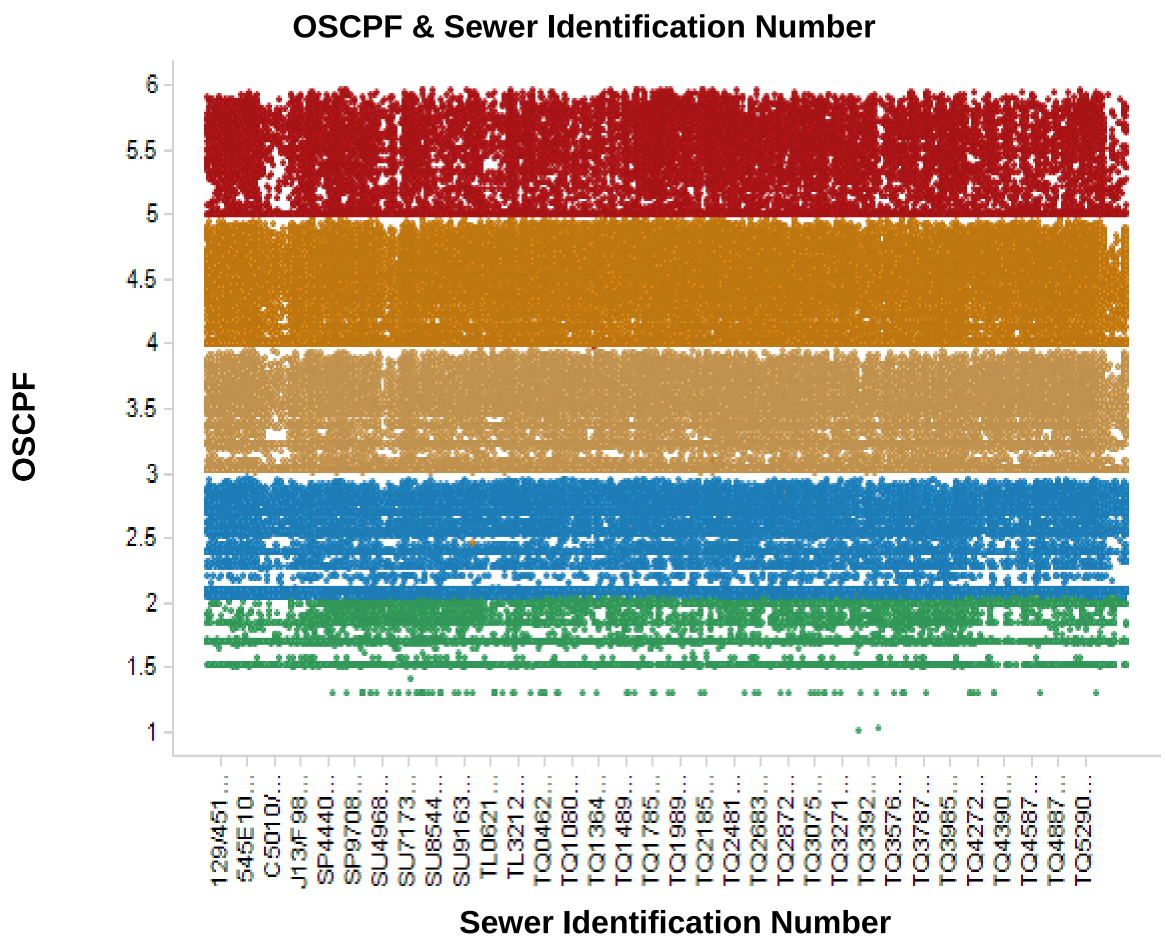


Figure 6.7. Prioritised sewers using developed OSCPF (Source: The Author- O.S. Tade)

A hierarchy of conditions was observed in Figure 6.7 when the OSCPF was plotted against the sewer identification numbers. This hierarchy was based on the cumulative of all the defects in the entire sewer length. The OSCPF multiplied by the COF was then used to obtain the risk in the RBF in Table 5.14. This is as analysed in Table 6.3. Consequences 1 and 2 were grouped into low COF, consequence 3 to medium COF and consequences 4 and 5 were grouped into high COF. The risk classification is as shown in Table 6.3. For example, a sewer has risk level 3 if the following criteria are fulfilled;

- Has a 2 low COF and in ICG 5
- Has a 3 medium COF and in ICG 4
- Has a 4 high COF and in ICG 3
- Has a 5 high COF and in ICG 2

Table 6.3. Risk analysis (Source: The Author- O.S. Tade)

COF	ICG	Risk Calculation	Risk Level
1 Low COF	1	1 * Equation 6.1	1
	2		1
	3		1
	4		1
	5		2
2 Low COF	1	2 * Equation 6.1	1
	2		1
	3		2
	4		2
	5		3
3 Medium COF	1	3 * Equation 6.1	1
	2		2
	3		2
	4		3
	5		4
4 High COF	1	4 * Equation 6.1	1
	2		2
	3		3
	4		4
	5		5
5 High COF	1	5 * Equation 6.1	2
	2		3
	3		4
	4		5
	5		5

Risk calculation in Table 6.3 will be used to set priorities for different risk levels. For example, if hypothetically, 1000 sewers were found in ICG 2 in the same criticality and it is required that they are to be re-inspected in 10 years, the prioritization would be according to the risk calculation in Table 6.3.

6.2 Validation of the deterioration model

The validation of the enhanced Deterministic Deterioration Model (DDM) developed in this research as stated in Chapter 3.5 looks at sewer collapse data and checks if the DDM would have been able to identify the sewer for rehabilitation before the collapse date. 2,120 records of collapsed data were collected for this validation and grouped into the decade in which the sewers were installed as shown in Figure 6.9. To validate the DDM for concrete sewers presented in Figure 5.11, the count of collapsed concrete sewers were isolated from the analysis. The result of this isolation is as shown in Figure 6.9. This represents a small subset of ICG 5

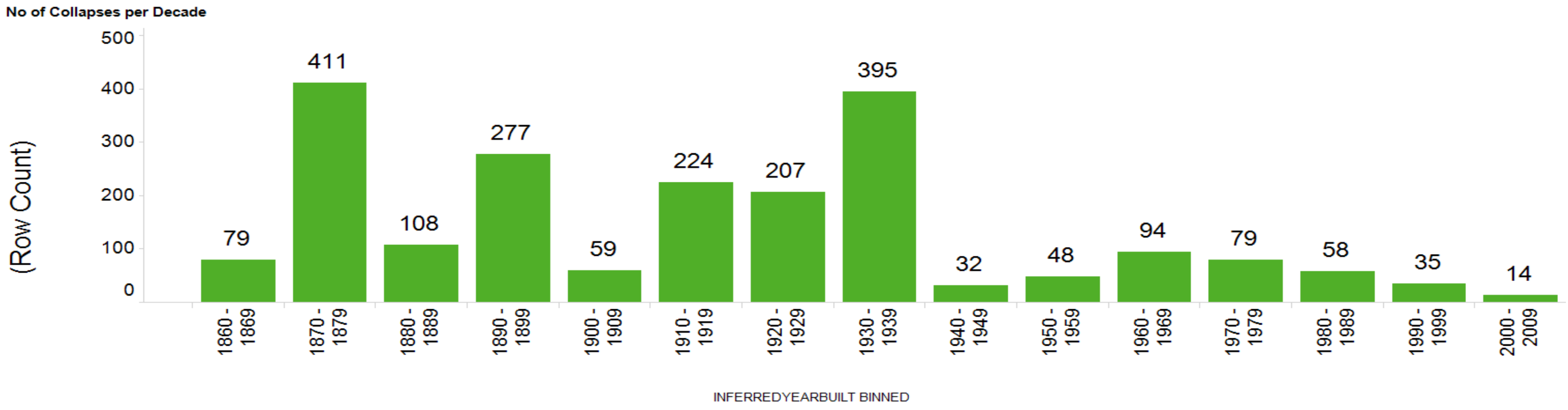


Figure 6.8. Collapses by decade distribution for all sewer material types (Source: The Author- O.S. Tade)

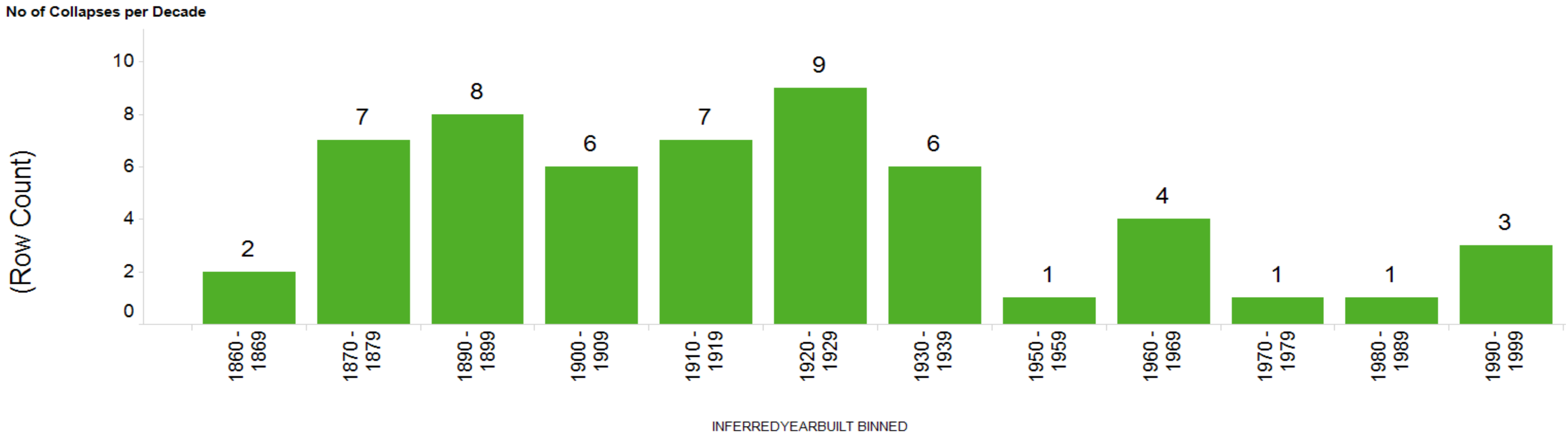


Figure 6.9. Collapses by decade distribution for concrete sewer material type (Source: The Author- O.S. Tade)

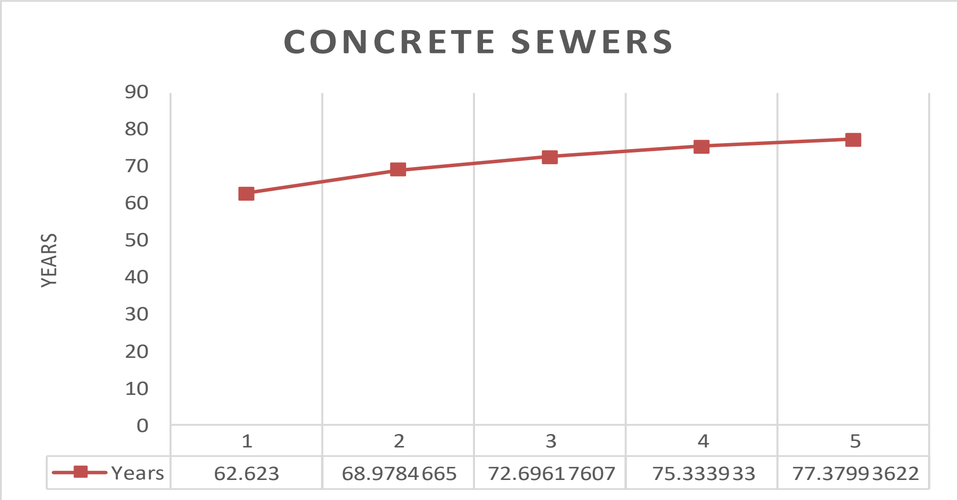


Figure 5.11. Deterioration curve for concrete sewer (Source: The Author- O.S. Tade)

From the bathtub curve provided in Figure 5.13, the time for inspection and rehabilitation of sewers in different criticality categories is as follows:

Category A: 52 years at the point where typically, not more than 20% of the sewers would have failed

Category B: 66 years at the point where not more than 35% of the sewers would have failed.

Category C: 77 years at the point where not more than 50% of the sewers would have failed.

It was stated in Chapter 5 that if the asset manager therefore had the risk appetite such that no more than 20% of the asset would have failed for a CAT A sewer, the intervention time in Equation 5.4 which gave 52 years for concrete sewers would be used, if no more than 35% for a category B sewer, Equation 5.5 which gave 66 years would be used and for category C where only half would have failed Equation 5.6 which gave 77 years would be used.

Using the collapse data, the percentage of concrete sewers that collapsed before 52 years for CAT A, 66 years for CAT B, and 77 years for CAT C was calculated using Figure 6.10.

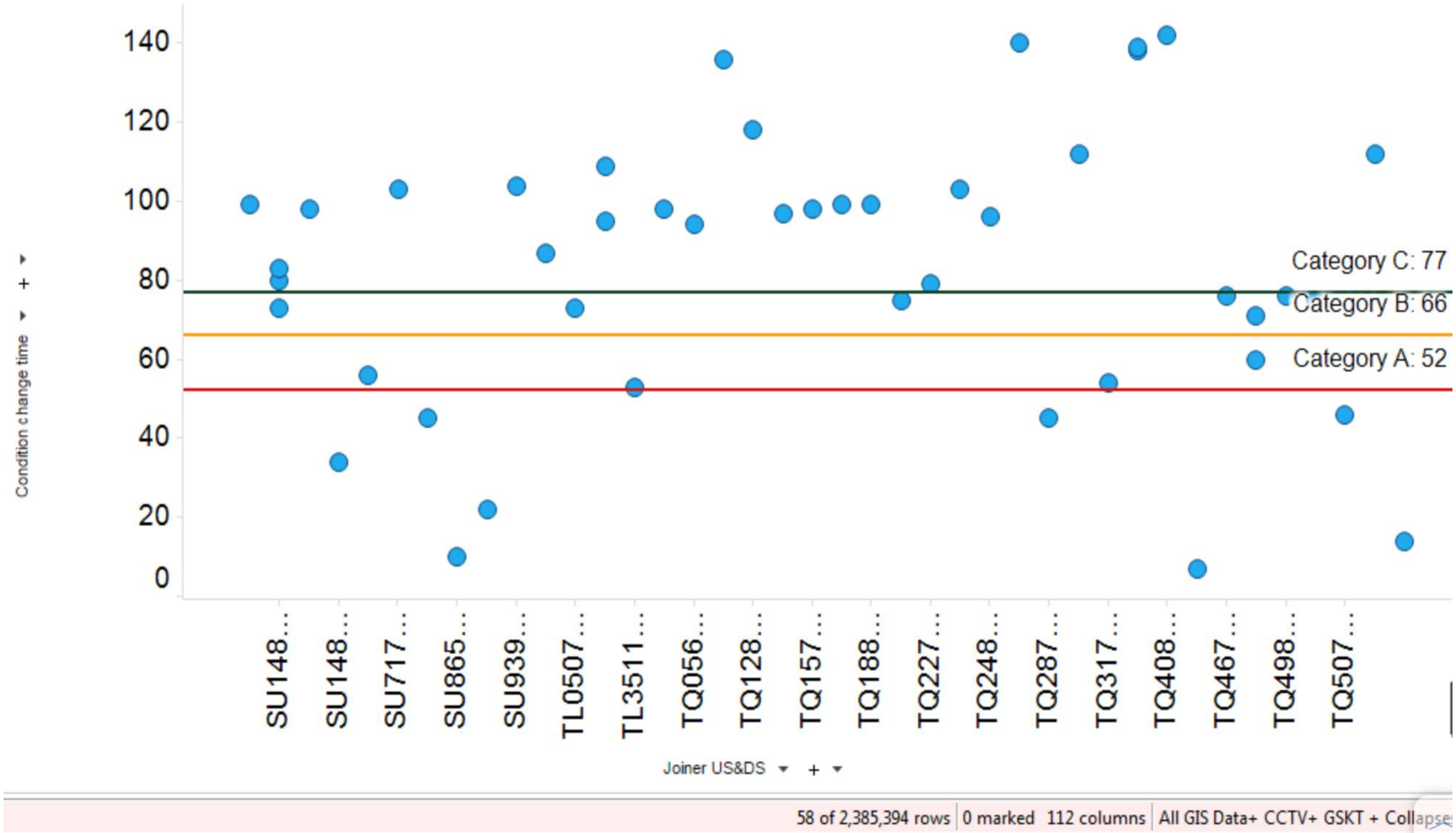


Figure 6.10. Validation result (Source: The Author- O.S. Tade)

The percentage collapse allowance given in the deterioration model for each criticality categories was compared with the observed in the validation result shown in Figure 6.10. Table 6.4 shows the comparison between the percentage allowance in the deterioration model and the observed in the validation result.

Table 6.4. Comparison between developed DDM and validation result (Source: The Author- O.S. Tade)

Categories	Inspection/Rehab year	Percentage from DDM	Percentage from validation
A	52	20%	18%
B	66	35%	29%
C	77	50%	45%

The validation results as shown in Table 6.4 indicates the predicted allowed percentage to be higher (safer than) than validation result. This confirms that the deterioration model in the RBF is valid.

6.3 Cost-benefit demonstration

Using 2 scenarios, the cost-benefit of the approach is demonstrated assuming that the rehabilitation date identified by the existing model for all sewers was 2017 and all survey resulted in patch works. The average cost for man entry survey and patch works is £15.00 per meter and the average cost for CCTV survey is £10.00 per meter as shown in Table 6.5

Table 6.5. Cost analysis of sewer assessment (Source: The Author- O.S. Tade)

Effluent type	Count	Man entry survey	Cost £15.00 per m	CCTV survey	Cost £10.00 per m	Total cost	Investment date
C	23,068	8,969	£134,535.00	14099	£140,990.00	£275,525.00	2029
F	175,497	39	£585.00	175,458	£1,754,580.00	£1,755,165.00	2019
S	63855	36	£540.00	63,819	£638,190.00	£638,730.00	2012
ALL	262,420	9,044	£135,660.00	253376	£2,533,760.00	£2,669,420.00	2017

Scenario 1: Using the RBF with stratified deterioration presented in Figure 6.3.

Scenario 2: Using available approaches developed by different researchers including deterioration curves or inspection frequencies provided by WRc and ASCE presented in Chapter 5;

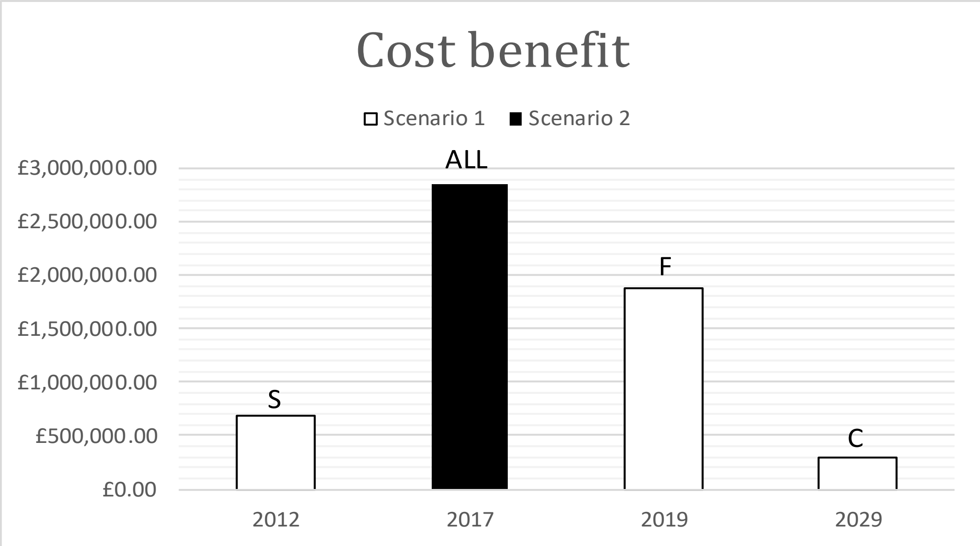


Figure 6.11. Comparison between existing curve and developed stratified curve (Source: O.S. Tade)

Figure 6.11 highlights the benefit of using the RBF with stratified degradation compared to using existing degradation methods presented by different researchers around the world and the inspection frequencies provided by WRc and ASCE. The utility would have to invest £2,854,291 in or around a year to keep these sewers at an acceptable level of serviceability. The RBF, on the other hand, would feasibly facilitate this cost to be spread over 17 years obtained in Figure 6.3. These frequencies would vary for a different stratified cohort. Also, the inspection frequencies for different material would further help to spread the cost over a long period of time. This is different from using the same inspection frequencies for all sewers as provided by ASCE and WRc which would result in a lot of sewers to be inspected in a year. This will enable a coordinated investment activity that will allow utilities to realise more value from their investment (IAM, 2012).

6.4 Research summary

Proactive management in the context of this research is the ability to identify and repair sewers before failure and risk is a function of consequence multiply by the likelihood of sewer failure. The consequence of sewer failure could be flooding of properties, pollution of land or water body or some form of risk to public health. This research is of the understanding that the wastewater utilities understand the consequence of their sewer failure but not the likelihood of failure with the level of granularity and understanding expected. Hence; the focus of this research was on the likelihood of sewer failure. The target failure is sewer collapse or service loss. Hence for proactive management, internal condition grade 5 (ICG 5) is the target as it is at this point that a sewer is most likely to collapse or experience a service loss.

This would allow utilities to set investment priorities for their sewerage network (SN). As stated in Chapter 1, this prioritization is needed because:

- For some less critical sewer, a failure can lead to a minimal service impact and therefore it may be least cost to let such asset fail before repair or replacement.
- In other instances, for more critical sewers, failure could lead to significant service impact – such as flooding or pollution or public health risk such as contamination or a train derailment. In these instances, investment in repair needs to take place before failure.

As a result of this, the American Society of Civil Engineers (ASCE) and Water Research Centre (WRc) divided sewers into 3 criticality categories as stated in Chapter 5.5. The categories are Category A, B and C, with A meaning the failure of a sewer will result in extreme cost consequence, B meaning the failure of a sewer will result in moderate cost consequence and C meaning sewer failure will result in a low-cost consequence. The issue of incomplete data was also raised.

From the literature review and discussion with some experts in the wastewater utilities, two research questions were raised in Chapter 1:

Research question 1: What is the level of priority of a sewer compared to the other ones in terms of collapse risk to the utilities? Which sewer should be inspected before the others in a situation where all sewers cannot be inspected?

Research question 2: How will utilities justify inspection frequencies i.e. when to re-inspect sewers found in good or satisfactory conditions?

To answer some of these research questions, ASCE and WRc provided inspection frequencies for all sewer in the different criticality categories as shown in Table 5.14. For example, ASCE and WRc specify a category A and B sewers found in ICG 2 to be re-inspected in 5 years and 20 years' time respectively. It could be inferred that all sewers regardless of the material type should use these inspection frequencies, but this research found that different sewer material types have different inspection variation. The ability to determine the deterioration and inspection frequencies for the different sewer material type would enable utilities to spread huge investment cost over a long period of time.

To achieve the aim, some objectives were set out. These objectives include literature review, data collection and development of a risk-based framework. It was mentioned that deterioration models (DMs) are essential to determine the future condition of an infrastructural asset and to estimate future investment requirements. This deterioration model can be derived from sewer condition assessment. It was further discussed in Chapter 2 that because of the expense and duration of sewer condition assessment, asset management processes that would allow greater prioritization and enhanced value should be sought. Hence the need for an effective deterioration model to be developed. There are several deterioration models, but they all suffer from one problem or the other. This has prevented utilities around the world to utilize these approaches to model deterioration effectively. The fundamental principle of DMs is that there is a correlation between conditions and asset physical properties. DMs tend to use known variables such as age, material type, size, depth and effluent characteristics to determine sewer condition. Initial analysis using neural network showed that there is no correlation between these variables and the condition of the sewer. This means it would be almost impossible to predict the condition of a sewer.

As a result of this, two hypotheses were discussed:

Hypothesis 1: Does the existing condition scoring protocol reflect the condition of sewers? Discussion with experts and literature review showed the industry benefit of reviewing this condition scoring protocol as the existing protocol is a function of the most severe defect found in a section of the sewer. This doesn’t reflect the entire condition of the whole sewer length. Hence the optimized condition priority formula in Equation 6.1 was developed in Chapter 6.

Hypothesis 2: Is there uncertainty around sewer deterioration? The uncertainty around sewer deterioration was investigated. It was interesting to find a large standard deviation (34 years) around the deterioration model of vitrified clay sewer as shown in Figure 5.7. These represent the uncertainty around the deterioration model.

As a result of these findings, it was necessary to review existing deterioration models. From this review, it was found that the existing deterioration models suffer from one problem or the other.

The problems with the existing deterioration models were discussed in Chapter 2. Chapter 2 reviewed the existing deterioration models and highlighted their limitations. The existing deterioration model includes; Deterministic Deterioration Model (DDM), Cohort Survival Model (CSM), Markov Model (MM), Semi-Markov Model (SMM), Logistic Regression Model (LRM), Multiple Discriminant Model (MDM), and Neural Network (NN). The limitation affecting existing deterioration models are:

- DDM uses mathematical equations to estimates a quantitative relationship between sewer ICG and factors affecting deterioration. A clear relationship between these factors and ICG is assumed without accounting for the uncertainty associated with sewer deterioration. It can be used to represent the observed deterioration in a network.
- Statistical or stochastic DM such as CSM, MM, SMM, LRM and MDM, in addition to estimating a quantitative relationship between sewer ICG and factors affecting deterioration, it considers the uncertainties associated with sewer deterioration. These uncertainties are considered in the form of a probability-based equation. However, it requires sufficient data in each condition grade to determine transition probability. It also requires extensive inspection data set that is sufficient enough to represent the variation within different cohorts. To determine transition probability, repeat inspection data is required for a group of sewers.
- Artificial intelligence DM such as NN estimates the relationship between independent variables and dependent variables. The independent variables are the factors affecting deterioration whilst the dependent variables are the ICGs (ICG 1 to 5). These variables are referred to as predictors and the ICGs as responses. A model is built based on a sample of historical sewer assessment data. The model learns the relationship between predictors and responses. The more the data sample, the more the lessons learned by the model. Hence; it is a data-driven model that represents a black box as the computation is hard to understand.

DDM was found the most suitable as it depicts what is happening in the network. The only drawback in that the model does not consider the uncertainty around sewer deterioration. Hence, it was necessary to enhance the DDM as described in Chapter 5.

Sewer asset management process and factors affecting sewer deterioration were reviewed in Chapter 2. Also, for effective AM of sewers, the premises of sewer assessment (inspection techniques and condition scoring protocols) were discussed.

The quantitative and qualitative methodology discussed in Chapter 3 for this research was based on an enhanced bottom-up data analysis of sewer degradation by looking at the variations in degradation that exist at the stratified sewer cohort level. A validation method was also proposed in Chapter 3. The validation method adopted is the use of sewer collapse data to validate the deterioration model.

In Chapter 4, a comparative analysis of the existing deterioration model was carried out using the available data. The problem with these existing models was further alighted from a practical perspective.

In Chapter 5, an enhanced deterioration model that mitigates the limitation of the existing models was created. This deterioration model developed was an enhanced DDM. The DDM was enhanced by applying the risk management techniques used for other engineering systems such as new concrete superstructures to dissolve the uncertainty around DDM. This is similar to the factor of safety method used in concrete buildings in Europe; a standard deviation of 1.64 gives design strength such that 95% of the material will exceed that value. Also, the analysis of factors influencing deterioration in Chapter 5 would help utilities to understand their asset better. Sewer material type that was found in Chapter 5 to be the factor that influences deterioration the most was used as the bases for cohort formation. However, during the data analysis, the sewer material type was largely unknown. 67% of the data have sewer material type missing. Hence, it was necessary for data infilling to be carried out. A method of database reliability was employed to infill this missing sewer material data. Three data sources were found to contain different quantities of material data. CCTV inspection data source, GIS data source and inferred data source. It was found that when sewer inspection is done the material type was recorded. A method of database reliability (DBR) was employed. From discussion with experts in the industry, CCTV inspection data is the most reliable data source, then GIS data source and inferred was the least reliable data source. So, for every sewer, the material type was assigned in that order. By the time this was done, the quantity of missing data was reduced to 35%.

After this, the deterioration model was applied. The deterioration model provided in this research has made use of the largest quantity of data available in the UK at the moment with the count of data behind the model provided. This represents a more transparent approach compared to the existing deterioration models. It is the first time that this large quantity of data has been used to produce degradation graph with the level of detail that gives insight into the large variation that exists between different sewer cohorts. These summarise hundreds of thousands of sewers inspection records and will be of value to utilities in the UK to prioritise and justify proactive investment in SN and as a benchmark for smaller operators. Application of the RBF with stratified degradation will enable utilities to be able to spread huge investment cost over a long period in a timely manner. The RBF allows for improved reliability for predicting the remaining lives of sewers. It also improves practice by allowing the risk appetite of the asset manager to be reflected in the assignment of modified service factor or standard deviation to the sewer deterioration. This RBF with more precise information permits the asset manager to prioritize inspection plans and control the risk to satisfy a cost-benefit target. There is anecdotal evidence that in a modified way, SN follows a bathtub and this thesis clarifies the medium and long-term characteristics once the system has been commissioned.

Chapter 7

Conclusions and Recommendations for Future Work

This Chapter discusses the conclusion from this research and recommends how this research can be improved in future work.

7.1 Conclusions

The developed Deterioration Model (DM) in this research provides an improved reliability for predicting the remaining lives of sewer cohorts. It also improves practice by allowing the risk appetite of the asset manager to be reflected in the assignment of modified service factors to the standard deviation of the degradation curve. This more precise information permits the asset manager to prioritise inspection plans and control the risk by using the developed frequencies of inspections. There is anecdotal evidence from the experts consulted that a Sewer Network (SN) follows a bathtub curve and this research clarifies the medium and long-term characteristics once the system has been commissioned. As shown in Table 5.15, there are some invaluable insights. Often, CAT A, B and C are defined as repair cost consequences whereby CAT A and CAT B are sewers with reactive cost 9 times and 6 times the cost of proactive investments. This is somewhat arbitrary as is the selection of traditional WRc and ASCE inspection frequencies shown in Table 5.14. This thesis shows that once condition 1 is observed in a sewer, for example, CP sewers, it typically takes 15 years till a condition 5 failure occurs. This means that the WRc CAT A inspection frequencies of 5, 3, 0, 0 are over anxious. It also means that the 20 and 15 for CAT B are too relaxed and need to be modified. These inspection frequencies are different for other material types and it is a significant and rational improvement on traditionally accepted values. Clearly, some urgency is introduced for a sewer link by triggering an earlier inspection time for CAT A compared to CAT B. There will be outlier failures, but the proposed practice will generate efficiencies for the whole sewer population. Hence; WRc and ASCE inspection frequencies can be safely adjusted for this population as a result of this analysis.

As infrastructure asset holding companies are traded internationally by financial asset specialists, the value of networks should incorporate the repair liabilities and these sub-models offer more precision in that respect.

7.2 Recommendation for further work

Due to data limitation, the historical CCTV survey result cannot be stratified into more cohorts with the level of granularity desired. Although the individual defects that could be found in a sewer were identified, the deterioration model can be significantly improved using sewer failure mechanism in Chapter two. This will be analysed to determine the rate of deterioration of each defect in a cohort. If there were enough historical repeats CCTV survey data and footages, the transition time for a defect to reach its worst condition could be observed. This would allow for better proactive investment at the defect level as sewer asset owners would know that a sewer with defects C1:C1:F1 would become C3:F1: X1 in let's say 10years time as shown in *Figure 7.1*. This will be very appropriate for modelling deterioration at the sewer level and means of applying to relevant cohorts can then be sought since defects deteriorate at different rates under different conditions. Research evidence has shown that the rate of deterioration of defects differs in different sewers most especially different material type as each pipe material fails differently (Angkasuwansiri et al, 2013).

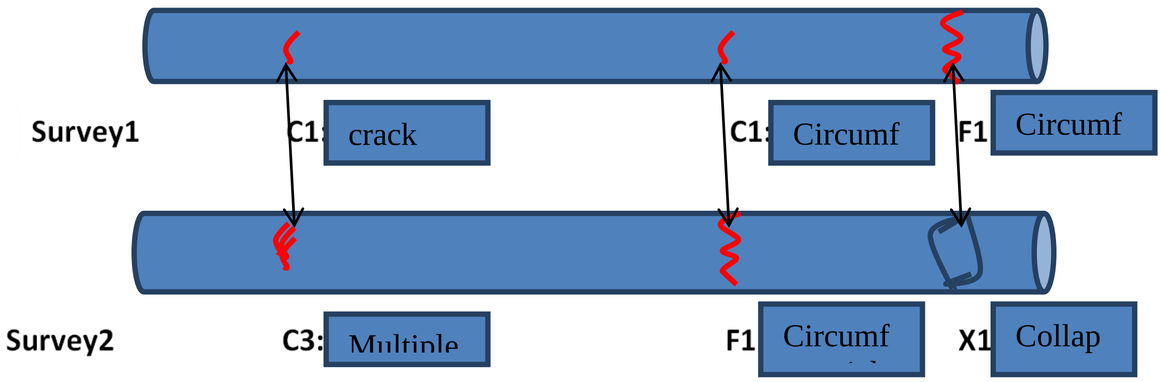


Figure 7.1. Schematic diagram for sewer change in condition (Source: The Author- O. S. Tade)

7.3 Research reflection

It is important that either engineers remain involved in the process of AM, or the software specialists trace the data down to the physical asset behaviour and that all understand the implications for their decisions at the fatberg face. For large networks we may see the development of a new dual profession of macro network asset managers, although bearing in mind the requirements of the CDM Regulations, that one should at the design stage consider the construction, use maintenance, and demolition of a system (and from other sources the recycling of materials) then many traditionalists would see 'AM' as 'just engineering'. That said, the skills of the macro network asset manager will be increasingly valuable to employers. It is essential however that the form of analysis of the large network must have enough degrees of freedom, what we have called granularity, for it to be relied upon.

7.4 The key original contribution of the research

a) The WRc and ASCE sewer rehabilitation inspection frequencies have been challenged with a comprehensive large data analysis reflecting material and environmental variables. As a result of this research, the industry is now modifying its internal approach to asset management.
b) Those researches that have treated sewer network as homogenous data sets should realise that their work is of limited applicability.
c) The engineering deterioration model has been integrated into a commercial risk model that improves asset management expenses and allows a proactive approach to replacing a reactive one. This is an improved deterioration model.
d) Linked to a modern BIM or AIM practice and automated inspection, the model can be refined for further efficiency. It acts as a benchmark piece of in-depth research for other sewer networks, most of which will be much smaller.

This thesis started with a quotation of the great stink that led to Bazalgette's sewer construction. To end; in 2007, over 11,000 readers of the British Medical Journal voted the provision of clean water and sewerage as the greatest medical advance since 1840; greater than antibiotics and greater than anaesthetics.

In times of continuing austerity, the original contribution to knowledge in this thesis will help asset managers keep the sewer network functioning until the nation can afford to replace the whole network.

References

Alain, T., Lubini & Musandji, F., 2011. *Modelling of the Deterioration Timeline of Sewer Systems. ,* Montréal, Canada: Canadian Journal of Civil Engineering, Ecole Polytechnique de Montréal, 2500.

Ana E, W. et al., 2008. *Investigating the effects of specific sewer attributes on sewer ageing – a Belgian case study. International Conference on Urban Drainage, Edinburgh, Scotland, UK, 2008. ,* s.l.: s.n.

Ana, E. V., 2009. *Sewer Asset Management: Structural Deterioration Modeling and Multicriteria Decision Making in Sewer Rehabilitation Projects Prioritization, PhD thesis,* Brussel: Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Brussel.

Ana, E. V. & Bauwens, W., 2010. *Modelling the Structural Deterioration of Urban Drainage Pipes: The State-of-the-art in Statistical Methods,* s.l.: Urban Water Journal 7 47-59..

Anderson, D. & Cullen, N., 1982. *Sewer Failures 1981, The Full Year.WRc External Report No 73E.,* s.l.: Water Research Council.

Angkasuwansiri, T., 2013. *Development of Wastewater Pipe Performance Index and Performance Prediction Model: Thesis submitted in partial fulfilment of the requirements for the degree of PhD in Civil Engineering,* Blacksburg, Virginia: Faculty of the Virginia Polytechnic Institute and State University.

Ariaratnam, S. T., El-Assaly, A. & Yang, Y., 2001. *Assessment of infrastructure inspection needs using logistic models,* s.l.: Journal of Infrastructure Systems 7 160-165.

ASCE, 2009. *Report card for America’s infrastructure,* s.l.: American Society of Civil Engineers.

ASCE, 2017. *Infrastructure Report Card, A Comprehensive Assessment of America's Infrastructure,* Washington D.C: America Society of Civil Engineers.

Ayoub, G. M., Azar, N., El Fadel, M. & Hamad, B., 2004. *Assessment of Hydrogen Sulphide Corrosion of Cementitious Sewer Pipes: A Case Study,* s.l.: Urban Water Journal, 1(1), 39-53.

Baik, H. S., Jeong, H. S. & Abraham, D. M., 2006. *Estimating Transition Probabilities in Markov Chain-Based Deterioration Models for Management of Wastewater Systems,* s.l.: Journal of Water Resources Planning and Management, 132(1), 15-24.

Balkan, D., 2017. *Always Do A Sewer Line Inspection Before Buying A Home,* New York: Joseph L. Balkan INC.

Balmer, R. & Meers, K., 1982. *Surveying Severn Trent's Sewers, Restoration of Sewage Systems, Proceeding of an International Conference.* London: London: Thomas Telford.

Baur, R. & Herz, R., 2002. *Selective inspection planning with ageing forecast for sewer types,* s.l.: Water Science and Technology 46 (6-7) 389-96. A Journal of the Association of Water Pollution Research

Bennis, S., Bengassem, J. & Lamarre, P., 2003. *Hydraulic Performance Index of a Sewer Network,* s.l.: Journal of Hydraulic Engineering, 129(7), 504-510.

Berger, R. H., 1978. *Extending the service life of existing bridges by increasing their load carrying capacity,* Washington DC: A report by The Federal Highway Administration.

BPSHCA, 2013. *Business Plan for Survey of High Consequence Asset,* Reading: Thames Water Internal Report.

BS EN 295-1., 2013. Vitrified clay pipes and fittings and pipe joints for drains and sewers. Requirements, S.l.: British Standard.

BSEN13508-2, 2011. *Investigation and Assessment of Drain and Sewer System outside Buildings. Visual Inspection Coding System: 2003+A1,* UK: BSI.

Camci, F., 2009. *System Maintenance Scheduling with Prognostics Information Using Genetic Algorithm., Journal Paper.* IEEE Transaction on Reliability, 58 3s.l.: s.n.

Caudill, M., 1989. *Neural Networks Primer VI, VII and VIII' A book on AI Expert,* s.l.: s.n.

CDM, 2015. *Managing Health and Safety in Construction, Construction (Design and Management) Regulations,* s.l.: Health and Safety Executive.

Channeline, 2007. GRP Structural Lining Systems for Large Diameter Circular and Non-circular Pipeline Rehabilitation, Dubai, United Arab Emirates: www.channelineinternational.com.

Chard & Carder, D. R., 1982. *Ground Movements Caused by Deep Trench Construction. I. F. Symons, B, Department of the Environment Department of Transport TRRL Report LR 1047: Transport and Road Research Laboratory, Crowthorne.*

Chin, C. L., Ahmad, Z. A. and Sow, S. S. 2017 'Journal paper: Relationship between the thermal behaviour of the clays and their mineralogical and chemical composition: Example of Ipoh, Kuala Rompin and Mersing (Malaysia)', Applied Clay Science, 143, pp. 327–335. doi: 10.1016/j.clay.2017.03.037.

Chughtai, F. & Zayed, T., 2008. *Infrastructure condition prediction models for sustainable sewer,* s.l.: Journal of Performance of Constructed Facilities 22 333-341.

Chughtai, F. & Zayed, T., 2011. *Integrating WRC and CERIU Condition Assessment Models and Classification Protocols for Sewer Pipelines M. ASCE2,* s.l.: Journal of Infrastructure Systems. American Society of Civil Engineers.

Chughtai, F. Z. T., 2007a. *Structural Condition Models for Sewer Pipeline,* International Conference on Pipeline Engineering, Boston, USA: Advances and Experiences with Trenchless Pipeline Projects, 8–11 July.

Chughtai, F. Z. T., 2007b. *Sewer Pipeline Operational Condition Prediction Using Multiple Regression,* International Conference on Pipeline Engineering, Boston, USA: Advances and Experiences with Trenchless Pipeline Projects, 8–11 July, .

Clegg, D., Eadon, A. T. & Fiddes, D., 1989. *State of the art sewerage rehabilitation,* UK: Water Science and Technology. A Journal of the Association of Water Pollution Research.

Colebrook, C. F. & White, C. M., 1938. Carrying Capacity of Pipes with Age. *Journal of the Institute of Civil Engineers,* p. 381.

Cook, G. C., 2001. *Construction of London's Victorian sewers: the vital role of Joseph Bazalgette,* London: Postgraduate Medical Journal; Dec2001, Vol. 77 Issue 914, p802-804, 3p, 1 Black and White Photograph, 1 Illustration.

CPDA, 2001. *Durability of Clay Pipe,* s.l.: Clay Pipe Development Association.

Davies, J. P., Clarke, B. A., Whiter, J. T. & Cunningham, R. J., 2001. *Factors Influencing the Structural Deterioration and Collapse of Rigid Sewer Pipes.,* s.l.: Elsevier Urban Water, *Journal of the International Water Association*.

Deleanu, F., Lorenz, K. & Engelhardt, C., 2009. *Corrosion of Metals,* Moscow: Moscow Bavarian - Joint Advanced Student School (MB-JASS) Course Material.

Dewan, S. A., 2004. *Pavement Management and Asset Management Side-by-Side,* Arizona: 6th International Conference on Managing Pavements.

Dirksen, J. & Clemens, F. H. L. R., 2008. *Probabilistic Modeling of Sewer Deterioration Using Inspection Data,* s.l.: Water Science and Technology 57 (10) 1635-41. A Journal of the Association of Water Pollution Research.

Edmonton, 1996a. *Standard Sewer Condition Rating System Report,* City of Edmonton: Transportation Department, Drainage Engineering Section.

Eliseo, V. & Ana, J., 2009. *Sewer Asset Management – Sewer Structural Deterioration Modelling and Multicriteria Decision Making in Sewer Rehabilitation Projects Prioritization. Thesis submitted in fulfilment of the requirements for the award of (Doctor in Engineering),* s.l.: Promotor: Prof. W. Bauwens.

Ens, A., 2012. *A Framework for Deterioration Modelling Development in Infrastructure Asset Management,* Toronto: Department of Civil Engineering University of Toronto. A thesis submitted in conformity with the requirements for the degree of Master of Applied Science.

EPA, 1992. *Detection, Control, and Correction of Hydrogen Sulfide Corrosion in Existing Wastewater Systems,* Washington DC: Office of the Wastewater Enforcement and Compliance, US Environmental Protection Agency (EPA).

EPA, 1998. *Drinking Water Infrastructure Needs Survey. First Report to Congress,* s.l.: U.S. Environmental Protection Agency 1997a.

Evans, J. & Spence, M. N., 1985. The Evolution of Jointing Vitrified Clay Pipe. Advances in Underground Pipeline Engineering. Pipeline Division, ASCE / Madison, WI / August 27-29, 1985. Conference paper

Ezekiel, S. 2015 'Fire Resistance Simulation for High Strength Reinforced Concrete (PhD thesis)'. doi: 10.18744/PUB.002084.

Fenner, R. A., 2000. *Approaches to Sewer Maintenance: A Review.,* s.l.: Urban Water Journal, 2(2000), 343-356.

Fenner, R. A. & Sweeting, L., 1999. *A Decision Support Model for the Rehabilitation of Non-Critical Sewers.,* s.l.: Water Science and Technology Journal, 39(9), 193-200.

Fernandes, I. & Broekmans, M., 2013. Alkali-Silica Reactions: An Overview. Part I. *Metallography, Microstructure, and Analysis,* 2(4), pp. 257-267.

Frey, P. A. & Reed, G. H., 2012. The Ubiquity of Iron. *ACS Chemical Biology,* 7(9), pp. 1477 - 1481.

Golden, B. L., Wasil, E. A. & Harker, P., 1989. *The Analytic Hierarchy Process Applications and Studies,* s.l.: eBooks & Journals in Mathematics & Statistics.

Herz, R., 1995. *Alterung und Erneuerung von Infrastruturbeständen - ein Kohoertenüberlebensmodell,* s.l.: Jahrbuch für Regionalwissenschaft Jg. 14/15, p. 5-29.

Herz, R., 1996. *Ageing Processes and Rehabilitation needs of Drinking Water distribution networks,* s.l.: Journal of Water Resources Planning and Management 45 221-231.

Hongguang Min and Zhigang Song. 2018 "Investigation on the Sulfuric Acid Corrosion Mechanism for Concrete in Soaking Environment," Advances in Materials Science and Engineering, Journal paper. vol. 2018, Article ID 3258123, 10 pages, 2018. https://doi.org/10.1155/2018/3258123.

Hörold, S., 1998. *Forecasting Rehabilitation Needs: Evaluation of the Aqua WertMin software for service life and total cost estimation, SINTEF Report,* Trondheim, Norway: SINTEF Technology and Society, Trondheim, Norway.

IAM, 2012. *Asset Management,* s.l.: The Institute of Asset Management.

ICE, 2018. *Meeting the Challenging Requirements of AMP7 Workshop,* London: Institutes of Civil Engineers.

Ing. D. Stein, Dipl.-Ing. R. Stein, R., 2004. *Rehabilitation and Maintenance of Drains and Sewers,* Germany: Trenches Technology Center.

ISO55000, 2014. *Asset Management,* s.l.: BSI Standards Publication.

Kamau, J. and Ahmed, A. 2017. Performance of Ternary Corncob Ash and Anthill Soil Concrete in Sulfate Solutions. European Journal of Engineering Research and Science. 2, 9 (Sep. 2017), 12-16. DOI:https://doi.org/10.24018/ejers.2017.2.9.456.

Khan, Z. Z. T. M. O., 2010. *Structural Condition Assessment of Sewer Pipeline,* s.l.: Journal of Performance of Constructed Facilities, 24(2):170-179.

Kleiner, Y., 2001. *Scheduling inspection and renewal of large infrastructure assets,* s.l.: Journal of Infrastructure Systems 7(4) 136-143.

Kleiner, Y., Rajani, B. & Sadiq, R., 2004a. *Modelling Failure Risk in Buried Pipes using Fuzzy Markov Deterioration Process,* Porto, Portugal: 4th International Conference on Decision Making in Urban and Civil Engineering, 28-30 October, l, pp. 1-11.

Kleiner, Y., Rajani, B. & Wang, S., 2007. *Consideration of static and dynamic effects to plan water main renewal,* Manama, Bahrain.: Proceedings Middle East Water 2007, 4th International Exhibition and Conference for Water Technology, Manama, Bahrain.

Kleiner, Y. S. R. R. B., 2004b. *Modelling Failure Risk in Buried Pipes using Fuzzy Markov Deterioration Process,* San Diego, California, USA: Conference Proceedings, ASCE, pp. 7-16.

Kleiner, Y. S. R. R. B. B., 2006. *Modeling Failure Risk in Buried Pipes using Fuzzy Markov Deterioration Process,* s.l.: Journal of Water Supply Research and Technology: Aqua, 55(2):67-80.

Kley, G. & Caradot, N., 2013. *Review of Sewer Deterioration Models,* Berlin: Kompetenzzentrum Wasser Berlin gGmbH report.

Kley, G., Kropp, I., Schmidt, T. & Caradot, N., 2013. *Review of Available Technologies and Methodologies for Sewer Condition Evaluation,* Berlin, Germany: KWB report, project SEMA, 2013, p 41,

König, A., 2005. *WP2 External Corrosion Model Description, Computer Aided Rehabilitation of Sewer networks (Care-S),* Trondheim, Norway: SINTEF Technology and Society.

Koo, D. H. & Ariaratnam, S. T., 2006. *Innovative Method for Assessment of Underground Sewer Pipe Condition,* s.l.: Journal Paper: Automation in Construction.

Kunpeng, Z. et al., 2016. Elastic Modulus of the Alkali-Silica Reaction Rim in a Simplified Calcium-Alkali-Silicate System Determined by Nano-Indentation. *National Institute of Health. Journal of Materials (Basel),* v.9(9)(PMC5457071) Doi: 10.3390/ma9090787

Kuo, C. F. J., Tu, H. M., Liang, S. W. & Tsai, W., 2010. *Optimization of Microcrystalline Silicon Thin Film Solar Cell Isolation Processing Parameters Using Ultraviolet Laser,* s.l.: Journal paper: Optics & Laser Technology, 42: 945–955.

Lary, D. J., Müller, M. D., and Mussa, H. Y.: Using neural networks to describe tracer correlations, Journal Paper: Atmospheric Chemistry and Physics., 4, 143-146.

LeGat, 2008. *Modelling the deterioration process of drainage pipelines,* s.l.: Urban Water Journal 5 97-106..

Lester, J. & Farrar, D. M., 1979. *An Examination of the Defects Observed in 6km of Sewers. TRRL Supplementary Report 531,* s.l.: TRRL.

Liddell, D. M., 1922. *Handbook of Chemical Engineering.* 1st ed. New York: Mc Graw-Hill Book Company, Incorporated.

Linping Wu, Chaoshi Hu and Wei Victor Liu (2018). The Sustainability of Concrete in Sewer Tunnel — A Narrative Review of Acid Corrosion in the City of Edmonton, Canada. Journal of Scientific Research 10(2), 517; https://doi.org/10.3390/su10020517.

Madhu Goyal1, J. L. (2007). Decisión Making in Multi-Issue e-Market Auction Using Fuzzy Techniques and Negotiable Attitudes. Australia: Journal of Theoretical and Applied Electronic Commerce Research.

Marlow, D. et al., 2009. *Remaining Asset Life: A State of the Art Review,* Alexandria, VA, US: Journal of Water Environment Research Foundation (WERF)

Marshalls-CPM, 2018. *Applegate.* [Online] Available at: https://www.applegate.co.uk/suppliers/marshalls-cpm-1564132/news?page=1 [Accessed 1 January 2019]

Mashford, J., Marlow, D., Tran, T. & May, R., 2011. *Prediction of Sewer Condition Grade Using Support Vector Machines,* s.l.: Journal of Computing in Civil Engineering, 25(4):283-290..

McClave, J. T., Benson, G. P. & Sincich, T. T., 2014. *Statistics for Business and Economics.* 12th Edition ed. Florida: Pearson.

Medsker, L. & Liebowith, J., 1994. *Design and development of expert systems and neural networks. Macmillan, U.S.A.,* s.l.: s.n.

Micevski, T., Kuczera, G. & Coombes, P., 2002. *Markov Model for Storm Water Pipe Deterioration,* s.l.: Journal of Infrastructure System, 8(2), 49-56.

Modica, G. R., 2007. *The History of the Newark Sewer System,* http://www.usgennet.org/usa/nj/state/EssexNewarkSewer.htm (accessed 7 December 2017): The New Jersey Homepage of the American Local History Network.

Mohebbi, H. & Li, C. Q., 2011. Experimental Investigation on Corrosion of Cast Iron Pipes. *Hindawi Publishing Corporation International Journal of Corrosion,* p. doi:10.1155/2011/506501.

Morgan & Morgan, 2019. Cast Iron Pipes Lawsuit. [online] Available at: https://www.forthepeople.com/class-action-lawyers/cast-iron-pipes-lawsuit/ [Accessed 17 Jan. 2019].

Motorola, 2009. *RFID Solutions in the Oil and Gas Industry,* s.l.: Industry Brief.

Najafi, M. & Kulandaivel, G., 2005. *Pipeline Condition Prediction using Neural Network Models,* s.l.: Proceedings of the ASCE Pipeline Division Specialty Conference. Pipelines 2005, ASCE, Reston, VA, USA, pp. 767–775..

Narayanan, S. P. & Sirajuddin, M., 2013. Properties of Brick Masonry for FE Modeling. *American Journal of Engineering Research (AJER),* Volume 1, pp. 06 - 11.

NASSCO, 2004. *National Association for Sewer Service Companies,* s.l.: 1st June 2004: http://www.nassco.org.

NCPI (National Clay Pipe Institute Vitrified Clay), 2015. Pipe Engineering Manual. United State of America.

NRC, 2006. *Drinking Water Distribution Systems. Assessing and Reducing Risks,* Washington DC: National Research Council: The National Academies Press. Sciences Engineering Medicine

OFWAT, 2000. *Serviceability of the water mains and sewer networks in England and Wales up to March 1999,* London: OFWAT information Note No 35A, March 2000.

OFWAT, "Future water and sewerage charges 2010-15: Final," [online] www.ofwat.gov.uk/pricereview/pr09phase3/det_pr09_finalfull.pdf, London, 2009b.

O'Reilly, M. P., Rosbrook, R. B., Cox, G. C. & McC, 1989. *Analysis of Defects in 180 km of Sewer Pipes in Southern Water Authority, TRRL Research Report 172,* s.l.: TRRL.

Osei, Y. A, 1985. New school chemistry for senior secondary schools. Third edition.

Parande, A. K. et al., 2006. *Deterioration of Reinforced Concrete in Sewer Environments.,* s.l.: Proceedings of the Institute of Civil Engineers. Journal paper: Municipal Engineer 159

Park, H. & Lee, I. K., 1998. *Existing Sewer Evaluation Results and Rehabilitation Strategies,* The City of Seoul, Korea: Journal: Environmental Technology, 19(7), 733-739.

Pohar, M., Blas, M. & Turk, S., 2004. *Comparison of Logistic Regression and Linear Discriminant Analysis: A Simulation Study,* s.l.: Journal Paper: Metodološki zvezki 1(1) 143-161.

Press, T. C., 1858. *London's Great Stink,* London: London City Press.

Rahman, S. & Vanier, D. J., 2004. *An Evaluation of Condition Assessment Protocols for Sewer Management,* Canada: National Research Council.

Rajani, B. & Kleiner, Y., 2001. *Comprehensive review of structural deterioration of water mains: physically based models,* s.l.: Urban Water Journal.

Rajani, B., Kleiner, Y. & Sadiq, R., 2006. *Translation of Pipe Inspection Results Into Condition Ratings Using The Fuzzy Synthetic Evaluation Technique,* s.l.: Journal of Water Supply Research and Technology-Aqua, 55, 11-24.

Reed, E. C., 1982. *The Assessment of the Problem in the UK.Restoration of sewerage systems,* s.l.: London: Thomas Telford.

Reza Vaziri, Mehran Mohsenzadeh & Jafar Habibi (2017) Measuring data quality with weighted metrics, Journal paper: Total Quality Management & Business Excellence

Rogers, C. J., 1986. *Sewer Deterioration Studies the Background to the Structural Assessment Procedure in the Sewerage Rehabilitation Manual (2nd edition). WRc Report ER199E.,* s.l.: WaterResearch Council.

Rumsey, P. B., Cooper, I. & Kyrou, K., 1982. *Ground Movement and Pipe Strain Associated with Trench Excavation,* s.l.: Restoration of Sewerage Systems; Conference Paper: 1 Jan 1982 (105–115).

Salman, B., 2010. *Infrastructure Management and Deterioration Risk Assessment of Wastewater Collection Systems, PhD thesis,* s.l.: University of Cincinnati.

Schmidt, T., 2009. *Modellierung von Kanalalterungsprozessen auf der Basis von Zustandsdaten, PhD thesis,* Dresden, Germany: Institut für Stadtbauwesen und Straßenbau, Technical University Dresden.

Schram, S. A., 2008. *Mechanistic-empirical modeling and reliability in network-level pavement management: Dissertations,* North Dakota: North Dakota State University, ProQuest Dissertations Publishing, 2008. 333756.

Sehra, S. K., Brar, Y. S. & Navdeep, K., 2012. *Multi-Criteria Decision Making Approach for Selecting Effort Estimation Model,* s.l.: International Journal of Computer Applications (0975 – 8887) Volume 39– No.1, January 2012.

Spotfire, 2018. *Data Analytical Tool,* s.l.: TIBCO.

SRM, 1994. *Sewerage Rehabilitation Manual,* London: WRC, UK.

SRM, 2013. *Sewerage Risk Management,* s.l.: Water Research Council.

Stephen, H., 1999. *The great stink of London: Sir Joseph Bazalgette and the cleansing of the Victorian capital / Stephen Halliday; foreword by Adam Hart-Davis.* London: Stroud: Sutton, 1999.

Tade, O. S., Smith, K., Ali, A. & Opoku, A., 2015. *Lessons for Specifying the System Boundaries of an Asset Management Plan from 4 Case Studies of Failure,* London: LSBU CIOB Conference.

Thornhill, R. & Wildbore, P., 2005. *Sewer Defect Codes: Origin and Destination,* s.l.: NASSCO.

Tran, D., 2007. *Investigation of deterioration models for stormwater pipe systems, PhD thesis,* s.l.: School of Architectural, Civil and Mechanical Engineering, Victoria University.

Tran, D. H., Perera, B. J. & Ng, A. W. M., 2007. *Neural Network Based Prediction Models for Structural Deterioration of Urban Drainage Pipes, Land, Water and Environmental Management: Integrated Systems for Sustainability,* s.l.: Proceedings, Christchurch pp 2264-2270.

Tran, D., Perera, A. W. M. & Davis, P., 2006. *Application of Probabilistic Neural Networks in Modeling Structural Deterioration of Stormwater Pipes,* s.l.: Urban Water Journal 3 (3) 175-184.

Tuccillo, M. E., Jolley, J., Martel, K. & Boyd, G., 2010. *Report on condition Assessment of Wastewater Collection Systems,* Cincinnati, Ohio.: EPA, United States Environmental Protection Agency.

UKWIR, 2015. *A Guide to modelling Intermittent Discharges,* London: UK Water Industry Research Ltd.

UoM (University of Michigan)., 1946. *Clay Pipe Engineering Manual. National Clay Pipe Institute.* Michigan: Clay Sewer Pipe Association, Inc.

U. R. Evans, F., 1967. The Mechanism of Rusting. *Quarterly Reviews, Chemical Society,* Issue 1, pp. 29-42.

Valappil, S., Vernon, D. & Cunningham, R., 2017. *Multi-Sensor Robotic Inspection (Survey Trial),* Reading: Thames Water Utility Ltd, Internal Report.

Vinnari, J. & Hukka, J., 2009. *An International Comparison of the Institutional Governance of Water Utility Asset Management and Its Implications for Finland,* s.l.: s.n.

Vitor, S., Jose, M. P. & Nuno, A. M., 2013. *Risk Assessment of Sewer Condition Using Artificial Intelligence Tools Application to the SANEST,* s.l.: IST, UTL.

Vollersten, J. & König, A., 2005. *WP2 Report D6: Model testing and evaluation, Computer Aided Rehabilitation of Sewer networks (Care-S),* Trondheim, Norway: SINTEF Technology and Society,

WaterAct, 2003. *Elizabeth II. Chapter 37.,* London, UK: Her Majesty's Stationery Office.

WaterUK, 2013. *Water UK 2013 Private sewers transfer. See (accessed 19/10/2013)..* [Online] Available at: http://www.water. org.uk/home/policy/private-sewers-transfer/customer-info [Accessed 19 October 2013].

WEF, 2017. Sanitary Sewer Rehabilitation. Water Environmental Federation. The Water quality People. Fact Sheet

Wei, S., Jiang, Z., Liu, H., Zhou, D., & Sanchez-Silva, M. (2014). Microbiologically induced deterioration of concrete--a review. Brazilian journal of microbiology :

[publication of the Brazilian Society for Microbiology], 44(4), 1001-7. doi:10.1590/S1517-83822014005000006

Whetman, G., 1979. *A Contractor's Experience.Public Health, 7(4),* s.l.: s.n.

Winnipeg, 2001. *Sewer Management Study: Technical Memoranda for Sewer Condition Assessment,* Winnipeg: Sewer Rehabilitation Design, and Sewer Maintenance Management for the City of Winnipeg, July 2001.

WRc, 1986. *Sewer Rehabilitation Manual, Second Edition,* s.l.: Water Research Centre, UK.

WRC, 1994. *Sewerage Rehabilitation Manual.* London: Water Research Council.

WRc, 2001. *Sewerage Rehabilitation Manual, Fourth Edition,* s.l.: Water Research Centre, UK.

WRc, 2004. *Sewerage Rehabilitation Manual, Fourth Edition,* UK: Water Research Centre.

Yan, J. & Vairavamoorthy, K., 2003. *Fuzzy Approach for Pipe Condition Assessment,* s.l.: Proc., Conference Paper: New Pipeline Technologies, Security, and Safety, ASCE, Reston, Va., pp. 466–476.

Zayed & Chunhtay, 2007a; 2007b; 2008. *developed a function-based deterministic degradation model,* s.l.: s.n.

Zhao, J. Q., McDonald, S. E. & Kleiner, Y., 2001. *Guidelines for Condition Assessment and Rehabilitation of Large Sewers,* Ottawa: Institute for Research in Construction, National Research Council of Canada.

Zio, E., 2009. Reliability Engineering: Old Problems and New Challenges. Journal Paper: *Reliability Engineering and System Safety,* pp. 94, 125-141.

Appendices

Appendix I. Properties of different materials used in sewer system (Cambridge, 2003)

Appendix II. Durability of some sewer material type (CPDA, 2001)

Appendix III. Condition grades for Brick sewers (not exceeding 3 ring)

Appendix IV. Condition Grades for Clay ware, Concrete and Plastic Pipe Sewers

Appendix V. Scoring Sheets - Scores for Brick and Masonry Sewers (MSCC Codes)

Appendix VI. Scoring Sheets - Scores for Brick and Masonry Sewers (EN13508)

Appendix VII. Scores for Rigid Pipe Sewers (MSCC Codes)

Appendix VIII. Scores for Rigid Pipe Sewers (EN13508-2 Codes)

Appendix IX. A step by step Analytical Hierarchy Process (AHP) Calculation (Madhu Goyal1, 2007)

Appendix X. A sample of the dashboard used for visualising deterioration and data correlations

Appendix XI. Evidence of sewer deterioration following a Gaussian distribution

Appendix XII. Sewer condition assessment devices

Appendix I

Properties of different materials used in sewer system

II. PHYSICAL AND MECHANICAL PROPERTIES OF MATERIALS

II.1 MELTING (or SOFTENING) TEMPERATURE, T_m

All data are for melting points at atmospheric pressure. For polymers (and glasses) the data indicate the glass transition (softening) temperature, above which the mechanical properties rapidly fall. Melting temperatures of selected elements are given in section VIII.

		T_m (°C)
Metals		
Ferrous	Cast Irons	1130 - 1250
	High Carbon Steels	1289 - 1478
	Medium Carbon Steels	1380 - 1514
	Low Carbon Steels	1480 - 1526
	Low Alloy Steels	1382 - 1529
	Stainless Steels	1375 - 1450
Non-ferrous	Aluminium Alloys	475 - 677
	Copper Alloys	982 - 1082
	Lead Alloys	322 - 328
	Magnesium Alloys	447 - 649
	Nickel Alloys	1435 - 1466
	Titanium Alloys	1477 - 1682
	Zinc Alloys	375 - 492
Ceramics		
Glasses	Borosilicate Glass (*)	450 - 602
	Glass Ceramic (*)	563 - 1647
	Silica Glass (*)	957 - 1557
	Soda-Lime Glass (*)	442 - 592
Porous	Brick	927 - 1227
	Concrete, typical	927 - 1227
	Stone	1227 - 1427
Technical	Alumina	2004 2096
	Aluminium Nitride	2397 - 2507
	Boron Carbide	2372 - 2507
	Silicon	1407 - 1412
	Silicon Carbide	2152 - 2500
	Silicon Nitride	2388 - 2496
	Tungsten Carbide	2827 - 2920
Composites		
Metal	Aluminium/Silicon Carbide	525 - 627
Polymer	CFRP	n/a
	GFRP	n/a
Natural		
	Bamboo (*)	77 - 102
	Cork (*)	77 - 102
	Leather (*)	107 - 127
	Wood, typical (Longitudinal) (*)	77 - 102
	Wood, typical (Transverse) (*)	77 - 102

		T_m (°C)
Polymers [1]		
Elastomer	Butyl Rubber (*)	– 73 - – 63
	EVA (*)	– 73 - – 23
	Isoprene (IR) (*)	– 83 - – 78
	Natural Rubber (NR) (*)	– 78 - – 63
	Neoprene (CR) (*)	– 48 - – 43
	Polyurethane Elastomers (elPU) (*)	– 73 - – 23
	Silicone Elastomers (*)	– 123 - – 73
Thermoplastic	ABS (*)	88 - 128
	Cellulose Polymers (CA) (*)	– 9 - 107
	Ionomer (I) (*)	27 - 77
	Nylons (PA) (*)	44 - 56
	Polycarbonate (PC) (*)	142 - 205
	PEEK (*)	143 - 199
	Polyethylene (PE) (*)	– 25 - – 15
	PET (*)	68 - 80
	Acrylic (PMMA) (*)	85 - 165
	Acetal (POM) (*)	– 18 - – 8
	Polypropylene (PP) (*)	– 25 - – 15
	Polystyrene (PS) (*)	74 - 110
	Polyurethane Thermoplastics (tpPU) (*)	120 - 160
	PVC	75 - 105
	Teflon (PTFE)	107 - 123
Thermoset	Epoxies	n/a
	Phenolics	n/a
	Polyester	n/a
Polymer Foams		
	Flexible Polymer Foam (VLD) (*)	112 - 177
	Flexible Polymer Foam (LD) (*)	112 - 177
	Flexible Polymer Foam (MD) (*)	112 - 177
	Rigid Polymer Foam (LD) (*)	67 - 171
	Rigid Polymer Foam (MD) (*)	67 - 157
	Rigid Polymer Foam (HD) (*)	67 - 171

[1] For full names and acronyms of polymers – see Section V.
(*) glass transition (softening) temperature
n/a: not applicable (materials decompose, rather than melt)
(Data courtesy of Granta Design Ltd)

II.2 DENSITY, ρ

		ρ (Mg/m^3)
Metals		
Ferrous	Cast Irons	7.05 - 7.25
	High Carbon Steels	7.8 - 7.9
	Medium Carbon Steels	7.8 - 7.9
	Low Carbon Steels	7.8 - 7.9
	Low Alloy Steels	7.8 - 7.9
	Stainless Steels	7.6 - 8.1
Non-ferrous	Aluminium Alloys	2.5 - 2.9
	Copper Alloys	8.93 - 8.94
	Lead Alloys	10 - 11.4
	Magnesium Alloys	1.74 - 1.95
	Nickel Alloys	8.83 - 8.95
	Titanium Alloys	4.4 - 4.8
	Zinc Alloys	4.95 - 7
Ceramics		
Glasses	Borosilicate Glass	2.2 - 2.3
	Glass Ceramic	2.2 - 2.8
	Silica Glass	2.17 - 2.22
	Soda-Lime Glass	2.44 - 2.49
Porous	Brick	1.9 - 2.1
	Concrete, typical	2.2 - 2.6
	Stone	2.5 - 3
Technical	Alumina	3.5 3.98
	Aluminium Nitride	3.26 - 3.33
	Boron Carbide	2.35 - 2.55
	Silicon	2.3 - 2.35
	Silicon Carbide	3 - 3.21
	Silicon Nitride	3 - 3.29
	Tungsten Carbide	15.3 - 15.9
Composites		
Metal	Aluminium/Silicon Carbide	2.66 - 2.9
Polymer	CFRP	1.5 - 1.6
	GFRP	1.75 - 1.97
Natural		
	Bamboo	0.6 - 0.8
	Cork	0.12 - 0.24
	Leather	0.81 - 1.05
	Wood, typical (Longitudinal)	0.6 - 0.8
	Wood, typical (Transverse)	0.6 - 0.8

		ρ (Mg/m^3)
Polymers [1]		
Elastomer	Butyl Rubber	0.9 - 0.92
	EVA	0.945 - 0.955
	Isoprene (IR)	0.93 - 0.94
	Natural Rubber (NR)	0.92 - 0.93
	Neoprene (CR)	1.23 - 1.25
	Polyurethane Elastomers (elPU)	1.02 - 1.25
	Silicone Elastomers	1.3 - 1.8
Thermoplastic	ABS	1.01 - 1.21
	Cellulose Polymers (CA)	0.98 - 1.3
	Ionomer (I)	0.93 - 0.96
	Nylons (PA)	1.12 - 1.14
	Polycarbonate (PC)	1.14 - 1.21
	PEEK	1.3 - 1.32
	Polyethylene (PE)	0.939 - 0.96
	PET	1.29 - 1.4
	Acrylic (PMMA)	1.16 - 1.22
	Acetal (POM)	1.39 - 1.43
	Polypropylene (PP)	0.89 - 0.91
	Polystyrene (PS)	1.04 - 1.05
	Polyurethane Thermoplastics (tpPU)	1.12 - 1.24
	PVC	1.3 - 1.58
	Teflon (PTFE)	2.14 - 2.2
Thermoset	Epoxies	1.11 - 1.4
	Phenolics	1.24 - 1.32
	Polyester	1.04 - 1.4
Polymer Foams		
	Flexible Polymer Foam (VLD)	0.016 - 0.035
	Flexible Polymer Foam (LD)	0.038 - 0.07
	Flexible Polymer Foam (MD)	0.07 - 0.115
	Rigid Polymer Foam (LD)	0.036 - 0.07
	Rigid Polymer Foam (MD)	0.078 - 0.165
	Rigid Polymer Foam (HD)	0.17 - 0.47

1 For full names and acronyms of polymers – see Section V (Data courtesy of Granta Design Ltd).

II.3 YOUNG'S MODULUS, *E*

		E (GPa)
Metals		
Ferrous	Cast Irons	165 - 180
	High Carbon Steels	200 - 215
	Medium Carbon Steels	200 - 216
	Low Carbon Steels	200 - 215
	Low Alloy Steels	201 - 217
	Stainless Steels	189 - 210
Non-ferrous	Aluminium Alloys	68 - 82
	Copper Alloys	112 - 148
	Lead Alloys	12.5 - 15
	Magnesium Alloys	42 - 47
	Nickel Alloys	190 - 220
	Titanium Alloys	90 - 120
	Zinc Alloys	68 - 95
Ceramics		
Glasses	Borosilicate Glass	61 - 64
	Glass Ceramic	64 - 110
	Silica Glass	68 - 74
	Soda-Lime Glass	68 - 72
Porous	Brick	10 - 50
	Concrete, typical	25 - 38
	Stone	6.9 - 21
Technical	Alumina	215 413
	Aluminium Nitride	302 - 348
	Boron Carbide	400 - 472
	Silicon	140 - 155
	Silicon Carbide	300 - 460
	Silicon Nitride	280 - 310
	Tungsten Carbide	600 - 720
Composites		
Metal	Aluminium/Silicon Carbide	81 - 100
Polymer	CFRP	69 - 150
	GFRP	15 - 28
Natural		
	Bamboo	15 - 20
	Cork	0.013 - 0.05
	Leather	0.1 - 0.5
	Wood, typical (Longitudinal)	6 - 20
	Wood, typical (Transverse)	0.5 - 3

		E (GPa)
Polymers [1]		
Elastomer	Butyl Rubber	0.001 - 0.002
	EVA	0.01 - 0.04
	Isoprene (IR)	0.0014 - 0.004
	Natural Rubber (NR)	0.0015 - 0.0025
	Neoprene (CR)	0.0007 - 0.002
	Polyurethane Elastomers (elPU)	0.002 - 0.003
	Silicone Elastomers	0.005 - 0.02
Thermoplastic	ABS	1.1 - 2.9
	Cellulose Polymers (CA)	1.6 - 2
	Ionomer (I)	0.2 - 0.424
	Nylons (PA)	2.62 - 3.2
	Polycarbonate (PC)	2 - 2.44
	PEEK	3.5 - 4.2
	Polyethylene (PE)	0.621 - 0.896
	PET	2.76 - 4.14
	Acrylic (PMMA)	2.24 - 3.8
	Acetal (POM)	2.5 - 5
	Polypropylene (PP)	0.896 - 1.55
	Polystyrene (PS)	2.28 - 3.34
	Polyurethane Thermoplastics (tpPU)	1.31 - 2.07
	PVC	2.14 - 4.14
	Teflon (PTFE)	0.4 - 0.552
Thermoset	Epoxies	2.35 - 3.075
	Phenolics	2.76 - 4.83
	Polyester	2.07 - 4.41
Polymer Foams		
	Flexible Polymer Foam (VLD)	0.0003 - 0.001
	Flexible Polymer Foam (LD)	0.001 - 0.003
	Flexible Polymer Foam (MD)	0.004 - 0.012
	Rigid Polymer Foam (LD)	0.023 - 0.08
	Rigid Polymer Foam (MD)	0.08 - 0.2
	Rigid Polymer Foam (HD)	0.2 - 0.48

1 For full names and acronyms of polymers – see Section V
(Data courtesy of Granta Design Ltd) .

II.4 YIELD STRESS, σ_y, AND TENSILE STRENGTH, σ_{ts}

			σ_y (MPa)	σ_{ts} (MPa)
Metals				
	Ferrous	Cast Irons	215 - 790	350 - 1000
		High Carbon Steels	400 - 1155	550 - 1640
		Medium Carbon Steels	305 - 900	410 - 1200
		Low Carbon Steels	250 - 395	345 - 580
		Low Alloy Steels	400 - 1100	460 - 1200
		Stainless Steels	170 - 1000	480 - 2240
	Non-ferrous	Aluminium Alloys	30 - 500	58 - 550
		Copper Alloys	30 - 500	100 - 550
		Lead Alloys	8 - 14	12 - 20
		Magnesium Alloys	70 - 400	185 - 475
		Nickel Alloys	70 - 1100	345 - 1200
		Titanium Alloys	250 - 1245	300 - 1625
		Zinc Alloys	80 - 450	135 - 520
Ceramics				
	Glasses	Borosilicate Glass (*)	*264 - 384*	22 - 32
		Glass Ceramic (*)	*750 - 2129*	62 - 177
		Silica Glass (*)	*1100 - 1600*	45 - 155
		Soda-Lime Glass (*)	*360 - 420*	31 - 35
	Porous	Brick (*)	*50 - 140*	7 - 14
		Concrete, typical (*)	*32 - 60*	2 - 6
		Stone (*)	*34 - 248*	5 - 17
	Technical	Alumina (*)	*690 5500*	350 665
		Aluminium Nitride (*)	*1970 - 2700*	197 - 270
		Boron Carbide (*)	*2583 - 5687*	350 - 560
		Silicon (*)	*3200 - 3460*	160 - 180
		Silicon Carbide (*)	*1000 - 5250*	370 - 680
		Silicon Nitride (*)	*524 - 5500*	690 - 800
		Tungsten Carbide (*)	*3347 - 6833*	370 - 550
Composites				
	Metal	Aluminium/Silicon Carbide	280 - 324	290 - 365
	Polymer	CFRP	550 - 1050	550 - 1050
		GFRP	110 - 192	138 - 241
Natural				
		Bamboo	35 - 44	36 - 45
		Cork	0.3 - 1.5	0.5 - 2.5
		Leather	5 - 10	20 - 26
		Wood, typical (Longitudinal)	30 - 70	60 - 100
		Wood, typical (Transverse)	2 - 6	4 - 9

(Data courtesy of Granta Design Ltd)

			σ_y (MPa)	σ_{ts} (MPa)
Polymers [1]				
	Elastomer	Butyl Rubber	2 - 3	5 - 10
		EVA	12 - 18	16 - 20
		Isoprene (IR)	20 - 25	20 - 25
		Natural Rubber (NR)	20 - 30	22 - 32
		Neoprene (CR)	3.4 - 24	3.4 - 24
		Polyurethane Elastomers (elPU)	25 - 51	25 - 51
		Silicone Elastomers	2.4 - 5.5	2.4 - 5.5
	Thermoplastic	ABS	18.5 - 51	27.6 - 55.2
		Cellulose Polymers (CA)	25 - 45	25 - 50
		Ionomer (I)	8.3 - 15.9	17.2 - 37.2
		Nylons (PA)	50 - 94.8	90 - 165
		Polycarbonate (PC)	59 - 70	60 - 72.4
		PEEK	65 - 95	70 - 103
		Polyethylene (PE)	17.9 - 29	20.7 - 44.8
		PET	56.5 - 62.3	48.3 - 72.4
		Acrylic (PMMA)	53.8 - 72.4	48.3 - 79.6
		Acetal (POM)	48.6 - 72.4	60 - 89.6
		Polypropylene (PP)	20.7 - 37.2	27.6 - 41.4
		Polystyrene (PS)	28.7 - 56.2	35.9 - 56.5
		Polyurethane Thermoplastics (tpPU)	40 - 53.8	31 - 62
		PVC	35.4 - 52.1	40.7 - 65.1
		Teflon (PTFE)	15 - 25	20 - 30
	Thermoset	Epoxies	36 - 71.7	45 - 89.6
		Phenolics	27.6 - 49.7	34.5 - 62.1
		Polyester	33 - 40	41.4 - 89.6
Polymer Foams				
		Flexible Polymer Foam (VLD)	0.01 - 0.12	0.24 - 0.85
		Flexible Polymer Foam (LD)	0.02 - 0.3	0.24 - 2.35
		Flexible Polymer Foam (MD)	0.05 - 0.7	0.43 - 2.95
		Rigid Polymer Foam (LD)	0.3 - 1.7	0.45 - 2.25
		Rigid Polymer Foam (MD)	0.4 - 3.5	0.65 - 5.1
		Rigid Polymer Foam (HD)	0.8 - 12	1.2 - 12.4

[1] For full names and acronyms of polymers – see Section V.

(*) NB: For ceramics, yield stress is replaced by *compressive strength*, which is more relevant in ceramic design. Note that ceramics are of the order of 10 times stronger in compression than in tension.

II.5 FRACTURE TOUGHNESS (PLANE STRAIN), K_{IC}

		K_{IC} (MPa√m)
Metals		
Ferrous	Cast Irons	22 - 54
	High Carbon Steels	27 - 92
	Medium Carbon Steels	12 - 92
	Low Carbon Steels	41 - 82
	Low Alloy Steels	14 - 200
	Stainless Steels	62 - 280
Non-ferrous	Aluminium Alloys	22 - 35
	Copper Alloys	30 - 90
	Lead Alloys	5 - 15
	Magnesium Alloys	12 - 18
	Nickel Alloys	80 - 110
	Titanium Alloys	14 - 120
	Zinc Alloys	10 - 100
Ceramics		
Glasses	Borosilicate Glass	0.5 - 0.7
	Glass Ceramic	1.4 - 1.7
	Silica Glass	0.6 - 0.8
	Soda-Lime Glass	0.55 - 0.7
Porous	Brick	1 - 2
	Concrete, typical	0.35 - 0.45
	Stone	0.7 - 1.5
Technical	Alumina	3.3 4.8
	Aluminium Nitride	2.5 - 3.4
	Boron Carbide	2.5 - 3.5
	Silicon	0.83 - 0.94
	Silicon Carbide	2.5 - 5
	Silicon Nitride	4 - 6
	Tungsten Carbide	2 - 3.8
Composites		
Metal	Aluminium/Silicon Carbide	15 - 24
Polymer	CFRP	6.1 - 88
	GFRP	7 - 23
Natural		
	Bamboo	5 - 7
	Cork	0.05 - 0.1
	Leather	3 - 5
	Wood, typical (Longitudinal)	5 - 9
	Wood, typical (Transverse)	0.5 - 0.8

(Data courtesy of Granta Design Ltd)

		K_{IC} (MPa√m)
Polymers [1]		
Elastomer	Butyl Rubber	0.07 - 0.1
	EVA	0.5 - 0.7
	Isoprene (IR)	0.07 - 0.1
	Natural Rubber (NR)	0.15 - 0.25
	Neoprene (CR)	0.1 - 0.3
	Polyurethane Elastomers (elPU)	0.2 - 0.4
	Silicone Elastomers	0.03 - 0.5
Thermoplastic	ABS	1.19 - 4.30
	Cellulose Polymers (CA)	1 - 2.5
	Ionomer (I)	1.14 - 3.43
	Nylons (PA)	2.22 - 5.62
	Polycarbonate (PC)	2.1 - 4.60
	PEEK	2.73 - 4.30
	Polyethylene (PE)	1.44 - 1.72
	PET	4.5 - 5.5
	Acrylic (PMMA)	0.7 - 1.6
	Acetal (POM)	1.71 - 4.2
	Polypropylene (PP)	3 - 4.5
	Polystyrene (PS)	0.7 - 1.1
	Polyurethane Thermoplastics (tpPU)	1.84 - 4.97
	PVC	1.46 - 5.12
	Teflon (PTFE)	1.32 - 1.8
Thermoset	Epoxies	0.4 - 2.22
	Phenolics	0.79 - 1.21
	Polyester	1.09 - 1.70
Polymer Foams		
	Flexible Polymer Foam (VLD)	0.005 - 0.02
	Flexible Polymer Foam (LD)	0.015 - 0.05
	Flexible Polymer Foam (MD)	0.03 - 0.09
	Rigid Polymer Foam (LD)	0.002 - 0.02
	Rigid Polymer Foam (MD)	0.007 - 0.049
	Rigid Polymer Foam (HD)	0.024 - 0.091

[1] For full names and acronyms of polymers – see Section V.

Note: K_{IC} only valid for conditions of linear elastic fracture mechanics (see I. Formulae & Definitions). Plane Strain Toughness, G_{IC}, may be estimated from $K_{IC}^2 = E\,G_{IC}/(1-\nu^2) \approx E\,G_{IC}$ (as $\nu^2 \approx 0.1$).

II.6 ENVIRONMENTAL RESISTANCE

			Flammability	Fresh water	Salt water	Sunlight (UV)	Wear resistance
Metals							
	Ferrous	Cast Irons	A	B	C	A	A
		High Carbon Steels	A	B	C	A	A
		Medium Carbon Steels	A	B	C	A	A
		Low Carbon Steels	A	B	C	A	A
		Low Alloy Steels	A	B	C	A	A
		Stainless Steels	A	A	A	A	B
	Non-ferrous	Aluminium Alloys	B	A	B	A	C
		Copper Alloys	A	A	A	A	A
		Lead Alloys	A	A	A	A	C
		Magnesium Alloys	A	A	D	A	C
		Nickel Alloys	A	A	A	A	B
		Titanium Alloys	A	A	A	A	C
		Zinc Alloys	A	A	C	A	E
Ceramics							
	Glasses	Borosilicate Glass	A	B	B	A	A
		Glass Ceramic	A	A	A	A	A
		Silica Glass	A	A	A	A	B
		Soda-Lime Glass	A	A	A	A	A
	Porous	Brick, Concrete, Stone	A	A	A	A	C
	Technical	Alumina	A	A	A	A	A
		Aluminium Nitride	A	A	A	A	A
		Boron Carbide	A	A	A	A	A
		Silicon	A	A	B	A	B
		Silicon Carbide	A	A	A	A	A
		Silicon Nitride	A	A	A	A	A
		Tungsten Carbide	A	A	A	A	A
Composites							
	Metal	Aluminium/Silicon Carbide	A	A	B	A	B
	Polymer	CFRP	B	A	A	B	C
		GFRP	B	A	A	B	C
Natural							
		Bamboo	D	C	C	B	D
		Cork	D	B	B	A	B
		Leather	D	B	B	B	B
		Wood	D	C	C	B	D

			Flammability	Fresh water	Salt water	Sunlight (UV)	Wear resistance
Polymers [1]							
	Elastomer	Butyl Rubber	E	A	A	B	B
		EVA	E	A	A	B	B
		Isoprene (IR)	E	A	A	B	B
		Natural Rubber (NR)	E	A	A	B	B
		Neoprene (CR)	E	A	A	B	B
		Polyurethane Elastomers (elPU)	E	A	A	B	B
		Silicone Elastomers	B	A	A	B	B
	Thermoplastic	ABS	D	A	A	C	D
		Cellulose Polymers (CA)	D	A	A	B	C
		Ionomer (I)	D	A	A	B	C
		Nylons (PA)	C	A	A	C	C
		Polycarbonate (PC)	B	A	A	B	C
		PEEK	B	A	A	A	C
		Polyethylene (PE)	D	A	A	D	C
		PET	D	A	A	B	C
		Acrylic (PMMA)	D	A	A	A	C
		Acetal (POM)	D	A	A	C	B
		Polypropylene (PP)	D	A	A	D	C
		Polystyrene (PS)	D	A	A	C	D
		Polyurethane Thermoplastics (tpPU)	C	A	A	B	C
		PVC	A	A	A	A	C
		Teflon (PTFE)	A	A	A	B	B
	Thermoset	Epoxies	B	A	A	B	C
		Phenolics	B	A	A	A	C
		Polyester	D	A	A	A	C
Polymer Foams							
		Flexible Polymer Foams	E	A	A	C	D
		Rigid Polymer Foams	C	A	A	B	E

[1] For full names and acronyms of polymers – see Section V.

Ranking:

A = very good; B = good; C = average; D = poor; E = very poor.

(Data courtesy of Granta Design Ltd)

III.5 MAXIMUM SERVICE TEMPERATURE

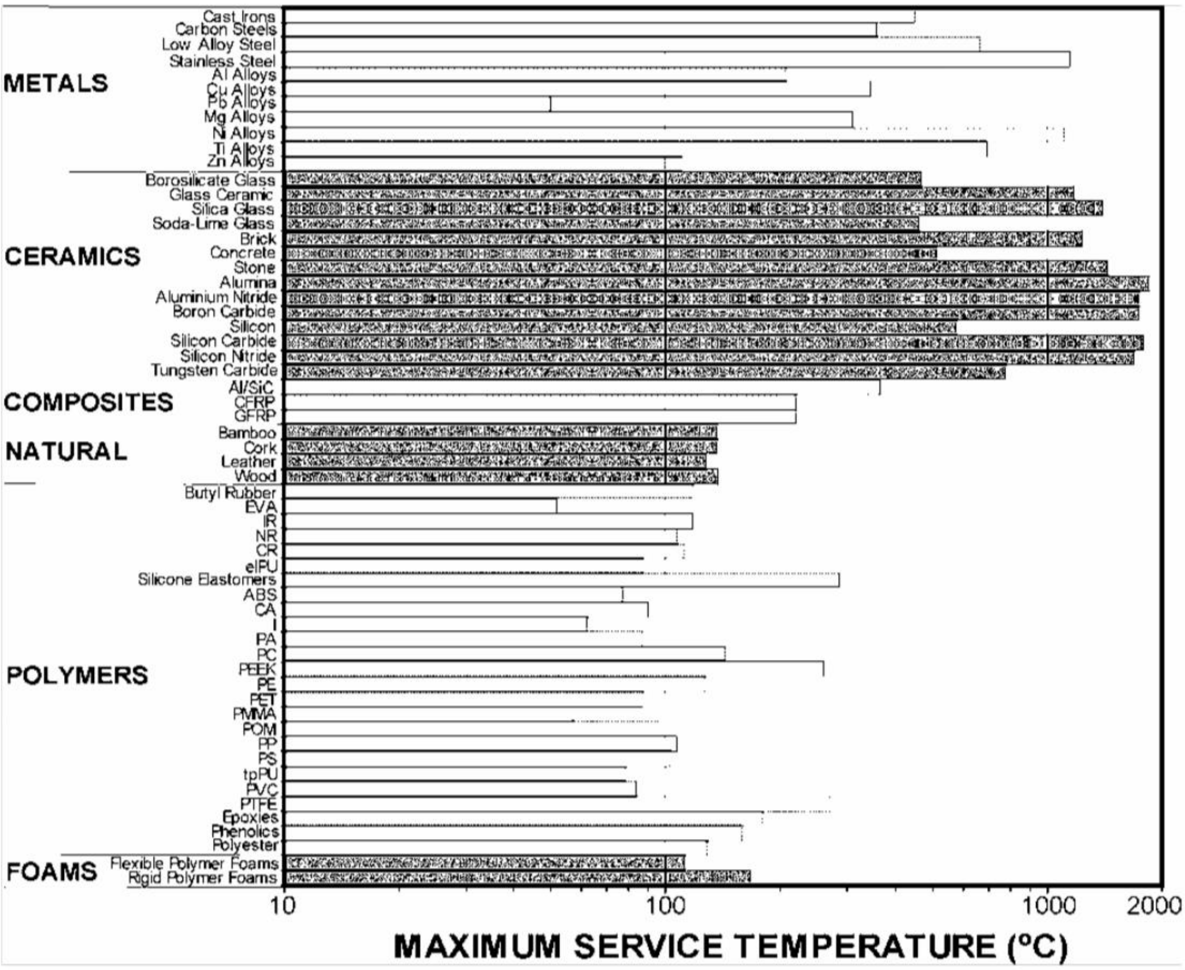


Figure 3.5: Maximum service temperature. The shaded bars extend to the maximum service temperature – materials may be used safely for all temperatures up to this value, without significant property degradation. (Note: there is a modest range of maximum service temperature in a given material class – not all variants within a class may be used up to the temperature shown, so caution should be exercised if a material appears close to its limit).

NB: For full names and acronyms of polymers – see Section V. (Data courtesy of Granta Design Ltd)

III.6 MATERIAL PRICE (PER KG)

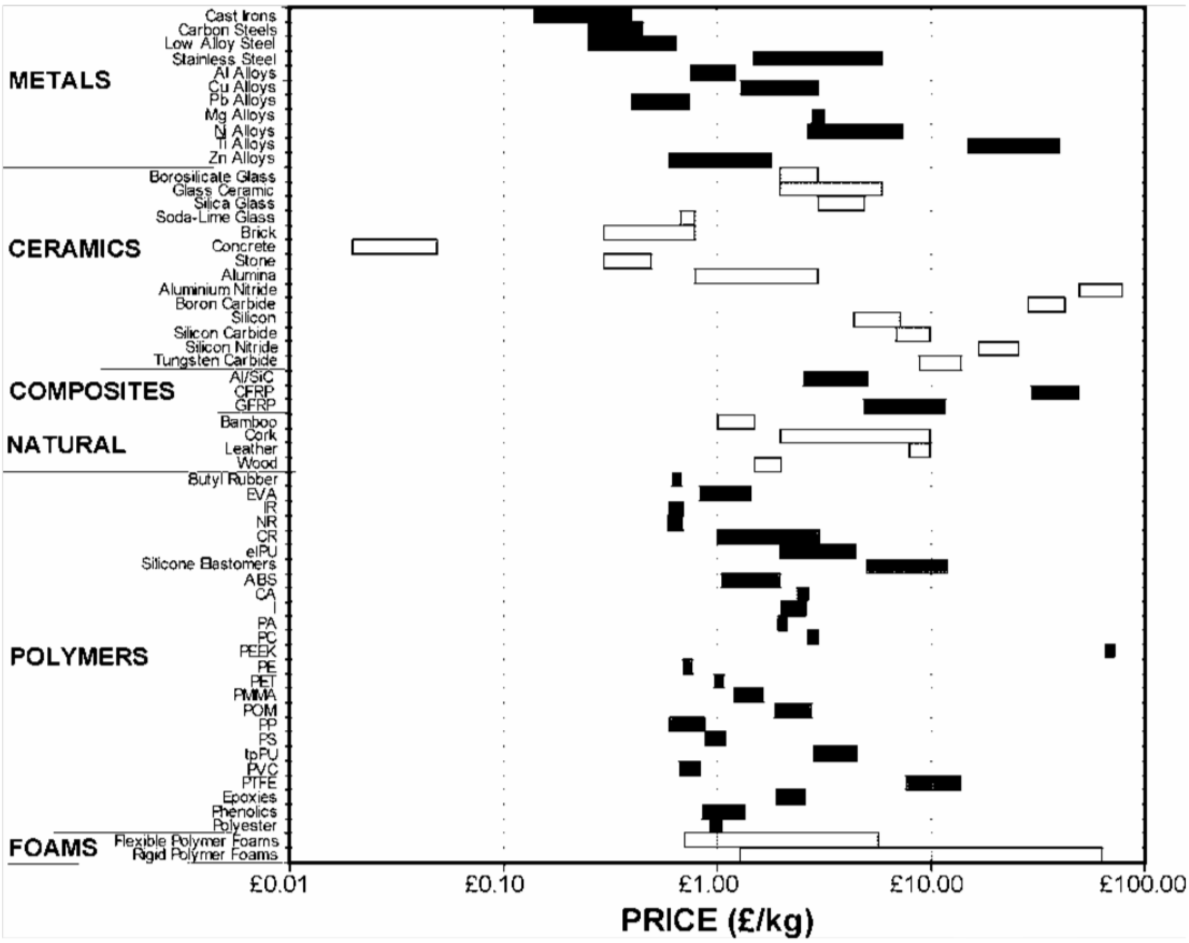


Figure 3.6: Material price (per kg), C_m (2003 data). C_m represents raw material price/kg, and does not include manufacturing or end-of-life costs.
NB: For full names and acronyms of polymers – see Section V. (Data courtesy of Granta Design Ltd)

Appendix II

The durability of some sewer material types

Sewer Pipe Material	Strength of Pipe Material at 50 years	Initial Internal Corrosion resistance	Initial External Corrosion resistance	Design Basis	Typical Seal Pressure Rating	Longevity, Greater than 100 years
GRP, glass fibers, sand, polyester	50% of initial, loss of cross-linking naturally occurs – accelerated by stress and corrosion elements. Water damage	Good, 1 pH – 10 pH (based upon 1.15 yr. extrapolation at 22º C.); deteriorates with temperature increase	Good, 1 pH – 10 pH (based upon 1.15 yr. extrapolation at 22º C.); deteriorates with temperature increase	Flexible	>2bar	Poor, extrapolated from 50% strength deterioration at 50 years, corrosion acceleration with stress and molecule linking failures with age
GRP, glass fibers, sand, polyester, vinyl ester interior coating	0% of initial, loss of cross-linking naturally occurs – accelerated by stress and corrosion elements	Very good, 1 pH – 10 pH (based upon 1.15 yr. extrapolation at 22º C.); deteriorates with temperature increase	Very Good, 1 pH – 10 pH (based upon 1.15 yr. extrapolation at 22º C.); deteriorates with temperature increase	Flexible	>2bar	Poor, extrapolated from 50% strength deterioration at 50 years, corrosion acceleration with stress and molecule linking failures with age
HDPE, high density polyethylene	70% to 80% loss of strength	Very good, but subject to deterioration in chemicals or high temperature	Very good, but subject to deterioration in contaminated soils including benzene or high temperature	Flexible	Fused or push joints varying pressure ratings	Poor, extrapolated from 70% to 80% strength deterioration at 50 years; corrosion acceleration from stress and molecule linking failure with age
PVC, polyvinyl chloride	65% to 80% loss of strength	Very good, but subject to deterioration in chemicals or high temperature	Very good, but subject to deterioration in contaminated soils including benzene or high temperature	Flexible	>1bar	Poor, extrapolated from 65% to 80% strength deterioration at 50 years; corrosion acceleration from stress and molecule linking failure with age

Polymer Concrete, graded sand and gravel, polyester	50% of initial, loss of cross-linking naturally occurs – accelerated by stress and corrosion elements	Good, 1 pH – 10 pH (based upon 1.15 yr. extrapolation at 22°C); deteriorates with temperature increase	Good, 1 pH – 10 pH (based upon 1.15 yr. extrapolation at 22 °C.); deteriorates with temperature increase	Rigid	>2bar	Poor, extrapolated from 50% strength deterioration at 50 years; corrosion acceleration with stress and molecule linking failures with age
Reinforced Concrete, sand, aggregates and cement	100%, less corrosion of concrete & rebar	Poor, in corrosive conditions	Poor, in corrosive conditions	Rigid	>1bar	Poor, in applications with internal or external corrosion environment
Reinforced Concrete with Plastic Liner, concrete, sand, aggregates and cement with a cast plastic liner	100%, less corrosion of concrete & rebar	Moderate, liners have shown short and moderate life <50 years	Poor, in corrosive conditions	Rigid	>1bar	Poor, in applications with internal or external corrosion environment
Steel, when used as carrier pipe	100% where there are no corrosion effects	Very poor	Very poor	Flexible	Welded	Poor, if corrosion possible. Good, if no corrosion present
Vitrified Clay, high temperature fired structural ceramic	100%	Excellent, pH 0 to pH 14	Excellent, pH 0 to pH 14	Rigid	> 2bar 10 psi, >17 psi depending upon manufacturer and joint type	Excellent, demonstrated long life

Appendix III

Condition grades for Brick sewers (not exceeding 3 ring)

Internal condition grade	Typical defect description
5	Already collapsed Missing invert Deformation >10% and fractured Displaced/handing brickwork and deformation <10% Extensive areas of missing brickwork
4	Total mortar loss (depth missing >50 mm) with deformation >10% Deformation up to 10% and fractured Displaced/handing brickwork Small number of missing bricks Dropped invert (drop >20 mm) Moderate loss of level Surface damage - spalling large (entire surface of brick is missing) Surface damage - wear large (entire surface of brick missing)
3	Total mortar loss (depth missing >50 mm) without other defects More than one longitudinal crack (at a single location) Multiple cracking Single bricks displaced Deformation <5%, no fracture and only moderate mortar loss Surface damage - spalling medium (large areas of chipped brick) Surface damage - wear medium (entire surface of brick is missing)
2	Circumferential cracking Single longitudinal crack Surface mortar loss (depth missing <15 mm) Surface damage - spalling slight (breaking away of small fragments from the surface) Surface damage - wear slight (increased roughness)
1	No structural defects

Note: Deformed sewers that have subsequently been relined with a structural lining can normally be considered to have no deformation.

Where there is visual evidence that displaced bricks are a feature of the construction method and no subsequent movement, the internal condition grade should be reduced accordingly.

Appendix IV

Condition Grades for Clay ware, Concrete and Plastic Pipe Sewers

Internal condition grade	Typical defect description
5	Already collapsed Deformation >10% and broken Extensive areas of missing brickwork Fracture with deformation >10%
4	Broken Deformation up to 10% and broken Fracture with deformation 6 - 10% Multiple fracture Serious loss of level Serious joint defects with voids or soil visible (open joint with >50mm soil or void visible or joint displacement >25% of diameter) Surface damage - spalling large (entire surface of brick is missing) Surface damage - wear large (entire surface of brick is missing)
3	Fracture with no deformation or deformation <5% Longitudinal cracking or multiple cracking Minor loss of level Severe joint defects i.e. open join (large) or joint displaced (large) Surface damage - spalling medium (large areas of chipped brick) Surface damage - wear medium (entire surface of the brick is missing)
2	Circumferential cracking Moderate joint defects, i.e. open joint (medium) or joint displaced (medium) Surface damage - spalling slight (breaking away of small fragments from the surface) Surface damage - wear slight (increased roughness)
1	No structural defects
Note: Deformed sewers that have subsequently been relined with a structural lining can normally be considered to have no deformation.	

Appendix V
Scoring Sheets - Scores for Brick and Masonry Sewers (MSCC Codes)

MSCC5 Defect	MSCC5 Code	Description	Score
Displaced bricks	DB	Single brick Extends up to 1/12th of circumference Extends up to 2/12th of circumference Extends up to 3/12th of circumference Extends up to 4/12th of circumference Extends up to 5/12th of circumference Extends up to 6/12th of circumference or more	40 80 80 80 80 80 165
Missing bricks	MB	Single brick Extends up to 1/12th of circumference Extends up to 2/12th of circumference Extends up to 3/12th of circumference Extends up to 4/12th of circumference Extends up to 5/12th of circumference Extends up to 6/12th of circumference or more	80 120 120 165 165 165 165
Mortar missing	MM	Slight (5-15 mm) Medium (15-50 mm) Total (50-100 mm)	10 20 40
Defective Repair, part of wall missing	RXM	Part of wall missing Extent up to 3/12th of circumference Extent more than 3/12th of circumference	 80 165
Increased roughness	SW		10
Surface damage Spalling	SS		40
Crack	CL CC CM CS	Longitudinal* Circumferential Multiple Spiral	20 20 20 20
Fracture	FL FC FM FS	Longitudinal* Circumferential Multiple Spiral	120 120 120 120
Dropped invert	DI		80
Collapse	XB		165
Cracked roof slab		Transverse Longitudinal*	20 80
Fractured roof slab		Transverse Longitudinal*	40 120
Deformed Vertically Horizontally	 DV DH	0-5% 6-10 % 10+ %	20 40 60

For peak score calculation:

1. Assume longitudinal defects extended for 1m, unless the"Continuous Defect" facility is in use.
2. Longitudinal defects are indicated thus*. Deformation should also be regarded as longitudinal where it extends over 1m or where it is associated with another longitudinal defect.

Mortar loss - only include the worse case of mortar loss at each location, regardless of the radial extent.

Appendix VI

Scoring Sheets - Scores for Brick and Masonry Sewers (EN13508)

EN13508-2 Defect	EN13508-2 Code	Description	Score
Displaced bricks	BAD A	Single brick Extends up to 1/12th of circumference Extends up to 2/12th of circumference Extends up to 3/12th of circumference Extends up to 4/12th of circumference Extends up to 5/12th of circumference Extends up to 6/12th of circumference or more	40 80 80 80 80 80 165
Missing bricks	BAD B	Single brick Extends up to 1/12th of circumference Extends up to 2/12th of circumference Extends up to 3/12th of circumference Extends up to 4/12th of circumference Extends up to 5/12th of circumference Extends up to 6/12th of circumference or more	80 120 120 165 165 165 165
Missing mortar	BAE	5-15 mm 15-50 mm >50 mm	10 20 40
Defective Repair, part of wall missing	BAL A	Part of wall missing Extent up to 3/12th of circumference Extent more than 3/12th of circumference	 80 165
Increased roughness	BAF A		10
Surface damage Spalling	BAF		40
Crack	BAB B A BAB B B BAB B C BAB B D	Longitudinal* Circumferential Complex Helical	20 20 20 20
Fracture	BAB C A BAB C B BAB C C BAB C D	Longitudinal* Circumferential Complex Helical	120 120 120 120
Dropped invert	BAD C		80
Collapse	BAD D		165
Cracked roof slab		Transverse Longitudinal*	20 80
Fractured roof slab		Transverse Longitudinal*	40 120
Deformation Vertically Horizontally	 BAA A BAA B	0-5% 6-10 % 10+ %	20 40 60

For peak score calculation:

1. Assume longitudinal defects extended for 1m, unless the"Continuous Defect" facility is in use.
2. Longitudinal defects are indicated thus*. Deformation should also be regarded as longitudinal where it extends over 1m or where it is associated with another longitudinal defect.

Mortar loss - only include the worse case of mortar loss at each location, regardless of the radial extent.

Appendix VII

Scores for Rigid Pipe Sewers (MSCC Codes)

MSCC5 Defect	MSCC5 Code	Description	Score
Open joint	OJ M OJ L OJ	Medium (between 1 and 1.5 x pipe thickness) Large (greater than 1.5 times pipe thickness) 1 to 1.5 x thickness of pipe wall > 1.5 x thickness up to 5% of diameter 5% of diameter to 10% of diameter >10% diameter	1 2 1 2 80 165
Joint displaced	JD M JD L JD	Medium (between 1 and 1.5 x pipe thickness) Large (greater than 1.5 times pipe thickness) 1 to 1.5 x thickness of pipe wall > 1.5 x thickness up to 5% of diameter 5% of diameter to 10% of diameter 10% to 20% diameter > 20% of diameter	1 2 1 2 40 80 165
Crack	CC CL CM CS	Circumferential Longitudinal# Multiple Spiral	10 10 40 40
Fracture	FC FL FM FS	Circumferential Longitudinal# Multiple Spiral	40 40 80 80
Broken	B		80
Hole	H H	Extent up to 3/12th of circumference Extent more than 3/12th of circumference	80 165
Collapsed	XP		165
Increased roughness	SW		5
Spalling	SS		20
Visible aggregate	SAV		5
Aggregate projecting	SAP	Aggregate projecting from surface	20
Visible reinforcement	SRV		80
Reinforcement projecting	SRP	Reinforcement projecting from surface	120
Corroded reinforcement	SRC		120
Corrosion products	SCP	This includes the presence of evidence of septicity attack on cemetitious materials as well as corrosion of metalic pipes	5
Sealing ring • Intruding • Broken • Other sealant intruding	 SR SRB SO		5
Defective Repair	RX		*
Defective Repair, part of wall missing	RXM	Extent up to 3/12th of circumference Extent more than 3/12th of circumference	80 165
Weld Failure (for plastic) (for steel)	WXL WXC WXS WXL WXC WXS	Longitudinal# Circumferential Helical Longitudinal# Circumferential Helical	40 40 80 10 10 40
Deformed	D	0 - 5% 6 - 10% >10	20 80 165
Surface Damage	SZ	Other Damage	*
Lining Defect	LX		*

For peak score calculation:

* The scoring system does not currently assess the code. If needed, a separate assessment should be made to determine the internal condition grade.

Assume longitudinal defects extended for 1m, unless the "Continuous Defect" facility is in use.

Longitudinal defects are indicated thus #. Deformation should also be regarded as longitudinal where it extends over 1m or where it is associated with another longitudinal defect.

If a number of circumferential defects appear at the same chainage, only the most severe single defect is included, regardless of the radial extent.

Appendix VIII

Scores for Rigid Pipe Sewers (EN13508-2 Codes)

EN13508-2 Defect	EN13508-2 Code	Description	Score
Displaced joint - Longitudinal	BAJ A	Medium (between 1 and 1.5 x pipe thickness) Large (greater than 1.5 times pipe thickness) 1 to 1.5 x thickness of pipe wall > 1.5 x thickness up to 5% of diameter 5% of diameter to 10% of diameter >10% diameter	1 2 1 2 80 165
Displaced joint - Radial	BAJ B	Medium (between 1 and 1.5 x pipe thickness) Large (greater than 1.5 times pipe thickness) 1 to 1.5 x thickness of pipe wall > 1.5 x thickness up to 5% of diameter 5% of diameter to 10% of diameter 10% to 20% diameter > 20% of diameter	1 2 1 2 40 80 165
Crack	BAB B B BAB B A BAB B C BAB B D	Circumferential Longitudinal# Complex Helical	10 10 40 40
Fracture	BAB C B BAB C A BAB C C BAB C D	Circumferential Longitudinal# Complex Helical	40 40 80 80
Break	BAC A		80
Missing	BAC B	Extent up to $3/12^{th}$ of circumference Extent more than $3/12^{th}$ of circumference	80 165
Collapse	BAC C		165
Increased roughness	BAF A		5
Spalling	BAF B		20
Visible aggregate	BAF C		5
Aggregate projecting	BAF D	Aggregate projecting from surface	20
Visible reinforcement	BAF F		80
Reinforcement projecting	BAF G	Reinforcement projecting from surface	120
Corroded reinforcement	BAF H		120
Corrosion products	BAF J	This includes the presence of evidence of septicity attack on cemetitious materials as well as corrosion of metalic pipes	5
Sealing ring • Intruding • Broken • Other sealant intruding	BAI A BAI Z		5
Defective Repair	BAL		*
Defective Repair, part of wall missing	BAL A	Extent up to $3/12^{th}$ of circumference Extent more than $3/12^{th}$ of circumference	80 165
Weld Failure (for plastic) (for steel)	BAM A BAM B BAM C BAM A BAM B BAM C	Longitudinal# Circumferential Helical Longitudinal# Circumferential Helical	40 40 80 10 10 40
Deformation	BAA	0 - 5% 6 - 10% >10	20 80 165
Surface Damage	BAF Z	Other Damage	*
Lining Defect	BAK		*

* The scoring system does not currently assess this code. If needed, a separate assessment should be made to determine the internal condition grade.

Assume longitudinal defects extended for 1m, unless the "Continuous Defect" facility is in use.

Longitudinal defects are indicated thus #. Deformation should also be regarded as longitudinal where it extends over 1m or where it is associated with another longitudinal defect.

If a number of circumferential defects appear at the same chainage, only the most severe single defect is included, regardless of the radial extent.

Appendix IX

A step by step Analytical Hierarchy Process (AHP) Calculation (Madhu Goyal1, 2007)

Step1: By using the AHP method, first establish the comparison matrix for the selection criteria:

$$E^1 = \begin{pmatrix} 1 & 1 & 1/2 & 1/2 \\ 1 & 1/2 & 1 & 1/3 \\ 2 & 1 & 2 & 1 \\ 2 & 1 & 3 & 1 \end{pmatrix} \Rightarrow \begin{pmatrix} 0.1635 \\ 0.1477 \\ 0.3270 \\ 0.3618 \end{pmatrix} \Rightarrow \begin{pmatrix} w_1^1 \\ w_2^1 \\ w_3^1 \\ w_4^1 \end{pmatrix}$$

$$E^2 = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1/2 & 1 & 1/2 \\ 2 & 1 & 1/2 & 1/3 \\ 2 & 3 & 1/2 & 1 \end{pmatrix} \Rightarrow \begin{pmatrix} 0.2643 \\ 0.1869 \\ 0.2008 \\ 0.3479 \end{pmatrix} \Rightarrow \begin{pmatrix} w_1^2 \\ w_2^2 \\ w_3^2 \\ w_4^2 \end{pmatrix}$$

$$E^3 = \begin{pmatrix} 1 & 1/2 & 1/3 & 1 \\ 1/2 & 2 & 1/3 & 1 \\ 1/4 & 1 & 2 & 3 \\ 4 & 3 & 2 & 1 \end{pmatrix} \Rightarrow \begin{pmatrix} 0.1354 \\ 0.1610 \\ 0.2345 \\ 0.4691 \end{pmatrix} \Rightarrow \begin{pmatrix} w_1^3 \\ w_2^3 \\ w_3^3 \\ w_4^3 \end{pmatrix}$$

Step 2: Three attitude matrixes are created for 3 possible bids

$$\begin{pmatrix} a_{11}^1 & a_{12}^1 & a_{13}^1 & a_{14}^1 \\ a_{21}^1 & a_{22}^1 & a_{23}^1 & a_{24}^1 \\ a_{31}^1 & a_{32}^1 & a_{33}^1 & a_{34}^1 \end{pmatrix} = \begin{pmatrix} L & VL & H & M \\ H & VH & M & ML \\ VH & L & H & VL \end{pmatrix}$$

$$\begin{pmatrix} a_{11}^2 & a_{12}^2 & a_{13}^2 & a_{14}^2 \\ a_{21}^2 & a_{22}^2 & a_{23}^2 & a_{24}^2 \\ a_{31}^2 & a_{32}^2 & a_{33}^2 & a_{34}^2 \end{pmatrix} = \begin{pmatrix} M & L & H & M \\ L & VH & M & ML \\ VH & M & H & VL \end{pmatrix}$$

$$\begin{pmatrix} a_{11}^3 & a_{12}^3 & a_{13}^3 & a_{14}^3 \\ a_{21}^3 & a_{22}^3 & a_{23}^3 & a_{24}^3 \\ a_{31}^3 & a_{32}^3 & a_{33}^3 & a_{34}^3 \end{pmatrix} = \begin{pmatrix} M & L & VL & M \\ L & VH & MH & ML \\ VH & M & L & VL \end{pmatrix}$$

Step 3: Aggregating belief vectors

$A_1^1 = w_1^{1*}a_{11}^1 + w_2^{1*}a_{12}^1 + w_3^{1*}a_{13}^1 + w_4^{1*}a_{14}^1$
$= 0.1635^*(0,0.1,0.3) + 0.1477^*(0,0,0.1) + 0.3270^*(0.7,0.9,1) + 0.3618(0.3,0.5,0.7)$
$= (0.3374, 0.4916, 0.6441)$

$A_2^1 = w_1^{1*}a_{21}^1 + w_2^{1*}a_{22}^1 + w_3^{1*}a_{23}^1 + w_4^{1*}a_{24}^1$
$= 0.1635^*(07, 0.9, 1) + 0.1477^*(0.9, 1, 1) + 0.3270^*(0.3, 0.5, 0.7) + 0.3618(0.1, 0.3, 0.5)$
$= (0.3817, 0.5668, 0.7205)$

$A_3^1 = w_1^{1*}a_{31}^1 + w_2^{1*}a_{32}^1 + w_3^{1*}a_{33}^1 + w_4^{1*}a_{34}^1$
$= 0.1635^*(0.9, 1, 1) + 0.1477^*(0, 0.1, 0.3) + 0.3270^*(0.7, 0.9, 1) + 0.3618(0, 0, 0.1)$
$= (0.3760, 0.4726, 0.5710)$

$A_1^2 = w_1^{2*}a_{11}^2 + w_2^{2*}a_{12}^2 + w_3^{2*}a_{13}^2 + w_4^{2*}a_{14}^2$
$= (0.2449, 0.3811, 0.7104)$
$A_2^2 = w_1^{2*}a_{21}^2 + w_2^{2*}a_{22}^2 + w_3^{2*}a_{23}^2 + w_4^{2*}a_{24}^2$
$= (4482, 0.6296, 0.7658)$
$A_3^2 = w_1^{2*}a_{31}^2 + w_2^{2*}a_{32}^2 + w_3^{2*}a_{33}^2 + w_4^{2*}a_{34}^2$
$= (0.3785, 0.4637, 0.5560)$

$A_1^3 = w_1^{3*}a_{11}^3 + w_2^{3*}a_{12}^3 + w_3^{3*}a_{13}^3 + w_4^{3*}a_{14}^3$
$= (0.3048, 0.4591, 0.6196)$
$A_2^3 = w_1^{3*}a_{21}^3 + w_2^{3*}a_{22}^3 + w_3^{3*}a_{23}^3 + w_4^{3*}a_{24}^3$
$= (0.3620, 0.5406, 0.6952)$

$A_3^3 = w_1^{3*}a_{31}^3 + w_2^{3*}a_{32}^3 + w_3^{3*}a_{33}^3 + w_4^{3*}a_{34}^3$
$= (0.2866, 0.3626, 0.4651)$

Step 4: The three agents have equal weights: $v_1 = v_2 = v_3 = 0.333$. The fuzzy decision vectors are

$r_1 = 0.333(A_1^1 + A_1^2 + A_1^3)$
$= 0.333((0.3374, 0.4916, 0.6441) + (0.2449, 0.3811, 0.7104) + (0.3048, 0.4591, 0.6196))$
$= (2.7714, 3.5903, 5.9282)$

$r_2 = 0.333(A_2^1 + A_2^2 + A_2^3)$
$= 0.333((0.3817, 0.5668, 0.7205) + (4482, 0.6296, 0.7658) + (0.3620, 0.5406, 0.6952))$
$= (3.5792, 5.1965, 6.5510)$

$r_3 = 0.333(A_3^1 + A_3^2 + A_3^3)$
$= 0.333((0.3760, 0.4726, 0.5710) + 0.3785, 0.4637, 0.5560) + (0.2866, 0.3626, 0.4651))$
$= (3.1264, 3.9006, 4.7810)$

Step 5: We get fuzzy positive are negative solution distances:

$$d_1^* = d(r_1, r^*)$$

$$= \sqrt{\frac{1}{3}[(2.7714-1)^2 + (3.5903-1)^2 + (5.9282-1)^2]}$$

$$= 3.0640$$

$$d_2^* = d(r_2, r^*) = 4.2670$$

$$d_3^* = d(r_3, r^*) = 3.0123$$

$$d_1^- = d(r_1, r-)$$

$$= \sqrt{\frac{1}{3}[2.7714^2 + 3.5903^2 + 5.9282^2]}$$

$$= 4.2980$$

$$d_2^- = d(A_2, r-) = 5.2538$$

$$d_3^- = d(A_3, r-) = 3.9936.$$

Step 6: Finally, we have

$$CC_1 = \frac{1}{2}(d_1^- + (1 - d_1^*))$$

$$= \frac{1}{2}(4.2980 + (1 - 3.0640)) = 1.117$$

$$CC_2 = \frac{1}{2}(d_2^- + (1 - d_2^*))$$

$$= \frac{1}{2}(5.2538 + (1 - 4.2670)) = 0.9934$$

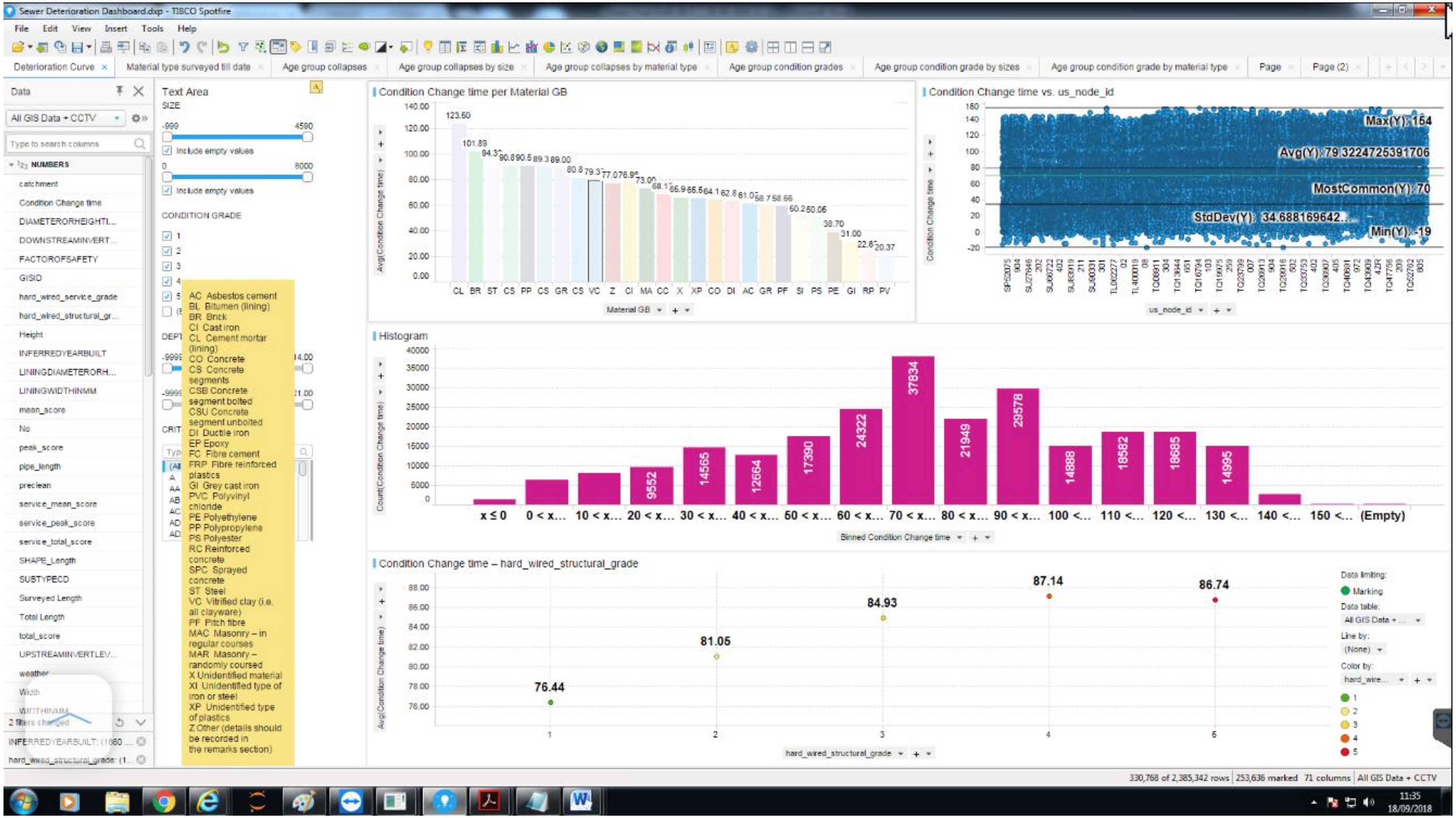
$$CC_3 = \frac{1}{2}(d_3^- + (1 - d_3^*))$$

$$= \frac{1}{2}(3.0036 + (1 - 3.0123)) = 0.9906$$

Since CC_1 is higher than CC_2 and CC_3, a most satisfactory bid for the item is the first bid.

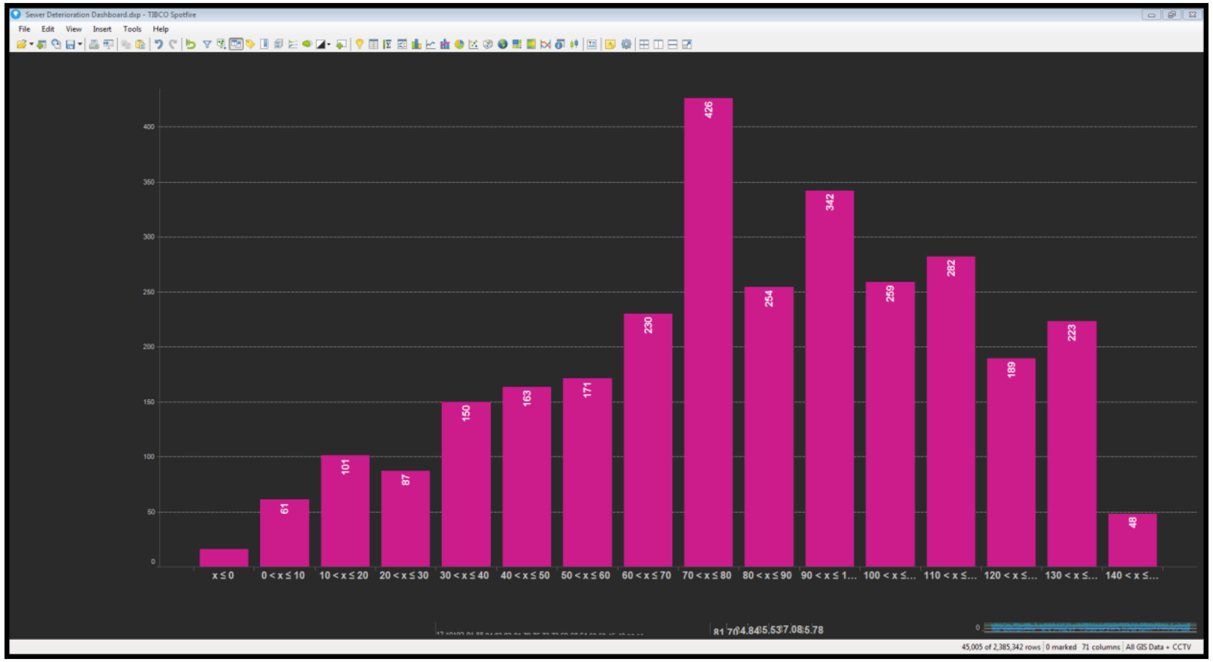
Appendix X

A sample of the dashboard used for visualising deterioration and data correlations



Appendix XI

Evidence of sewer deterioration following a Gaussian distribution



Appendix XII

Sewer condition assessment devices

There are three major sewer inspection devices; MSI (Multi-Sensor Sewer Inspection) sonar and laser profiler, SOLO Redzone robotics and the conventional sewer CCTV survey. But some constraint has prevented a paradigm shift from the existing conventional CCTV survey to recently developed ones which will be discussed.

MSI sonar and laser profiling

This is a CCTV inspection device capable of investigating large diameter sewers of 762 mm to 3000 mm. The MSI profiler combines sonar, laser and HDCam capabilities for in-depth reporting. This allows more condition data to be collected in suitable flow condition. For assessing sewer condition, a sonar profiler is mounted on HDSub or HDFloat as shown in Figure 2.14. It records video footage combined with a laser scan of the sewer. The laser records the structural condition above the water level and the sonar under the MSI device maps out the debris profile, including quantity and measured location. HDCam records the entire sewer length by allowing pan a tilt of the MSI camera known as the FlyEye. The recorded file is analysed and reported with a software called profiler.

A sample of a SONAR Profiler (Valappil, et al., 2017)

HDSub is used for sewers ranging from sizes 450 mm to 2200 mm and a flow height of 1/3 to surcharge whilst HDFloat is for sizes 1000 mm to 3000 mm and flow depth of between ¼ to ¾ of sewer heights.

Sample of MSI HDSub and HDFloat (Valappil, et al., 2017)

MSI has the following features:

- Capable of Multi-Sensor Inspection (MSI).
- High definition profiling (modular and no data cable).
- Capable of surveying sewers with sizes from 375 – 3000 mm.
- 6 hours of continuous video coverage.
- Over 4 km of tether pipeline length.
- Detailed reporting of precise pipe measurement, pipe integrity, corrosion, debris, water levels.

Solo Redzone robotics

The SOLO is an autonomous CCTV inspection device capable of inspecting a longer distance per day than the existing conventional CCTV system. It was manufactured by Red Zone Robotics in the US. A Solo robot is as shown in Figure 2.1.2

A sample of a SOLO Robot (Valappil, et al., 2017)

The SOLO robot takes 10 to 15 minutes to launch at the start manhole and the operator moves to a new start manhole to deploy another robot for a new survey. The operator can later return to the start manhole to retrieve the robot. The robot makes three attempts in a situation where it cannot reach the finish manhole. At the retrieving point, the operator checks to confirm the robot has completed the required survey distance. The process from launch to retrieve the robot was reported to be around 25 to 35 minutes. The robot records 360-degree coverage of the sewer internal condition and the footage is taken to the office to be analysed.

Solo was designed to mitigate the many inefficiencies of the conventional CCTV system, such as parked vehicles and on-site time to analyse data. Furthermore, there is no need for special storage, maintenance areas, multiple vehicles and generator (Valappil, et al., 2017). When the solo robot is deployed, it surveys the entire length of the sewer and returns to the deployment site.

The robot has the following features:

- Weight of 11 kg.
- Automatic data transfer.
- Capable of surveying sewers with sizes 200 – 300 mm.

- 360-degree video coverage.
- Rubber track wheels.
- Capable of capturing co-ordinate location of manhole using GPS (Global Positioning System).
- Intelligent autonomous operation.

The SOLO robot system has been in use extensively in the US and was reported to have completed over 7,620 km of sewer inspection (Valappil, et al., 2017). This has never been in use in the UK. The sewer terrain such as; manhole and sewer network design, road network and traffic condition are very different to that in the US. These will be further discussed and compared with the conventional CCTV in Chapter 4.