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Risk-based Rehabilitation of Wastewater Pipes

Master’s thesis in Master Programme Infrastructure and Environmental Engineering

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DIVISION OF GEOLOGY AND GEOTECHNICS

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MASTER'S THESIS ACEX30

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Cover:
The risk of failure (ROF) pipes in Kungsbacka municipalities wastewater pipe network. The colours are representing levels of risk. The figure is presented in detail on page 87 in the report.

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Abstract

Wastewater networks are part of society's underground infrastructure, intending to safely convey wastewater from consumers to Wastewater Treatment Plants (WWTP). This modern infrastructure has been recognised as an essential factor for sustaining public health, longevity and the environment. When, or if a failure occurs in this system, it can cause severe consequences to society, related to e.g. economy, public health and the environment. However, the reinvestments in wastewater pipe networks have been procrastinated, not just in Sweden but worldwide.

This thesis aims to present a risk-based model that provides decision support and facilitates the design of rehabilitation strategies for wastewater networks. The primary objectives for the thesis were set to; review state the of art risk-based strategies for wastewater rehabilitation; set up a risk-based model that can be used as decision-support and renewal planning for water utilities; and implement the model in a case study based on Kungsbacka Municipality wastewater pipe network.

The reviewed literature shows that that the most common methods to evaluate the probability of failure (POF) for individual wastewater pipes are Multi-Criteria Decision Analysis (MCDA) based on expert knowledge or statistical regression models, Bayesian Networks (BNs) and Artificial Neural Networks (ANNs). Further, the consequences of failure (COF) for individual pipes have been evaluated by classifying hazardous events into the economic, social and environmental consequences.

The result of this thesis is a risk-based rehabilitation model based on evaluating POF and COF for the individual pipes within the wastewater pipe network to identify pipes with a high risk of failure (ROF), which is used to set up a Closed-Circuit Television (CCTV) inspection plan. Further, the CCTV inspection is used, in combination with COF, to set up a rehabilitation and re-inspection plan. The model strive to give decision-support regarding which pipe to inspect, rehabilitate, and re-inspect to maintain a sound and good service wastewater pipe network.

The risk-based model was applied in a case study on Kungsbacka municipality's wastewater network, including 15,044 unique pipe IDs, with a total length of approximately 570 kilometres. First, POF was evaluated using multinomial logistic regression and MCDA. Next, COF was evaluated using economic, social and environmental consequences based on GIS data and MCDA. Further, the ROF was evaluated using the combination of POF and COF, where ROF was to a one-to-five scale, indicating; 1 (Low), 2 (Moderate), 3 (Moderate-to-high), 4 (High) and 5 (Very high) impact. As a result, the risk-based model could successfully evaluate 97.3% of the pipes within the wastewater pipe network regarding ROF and set up an inspection plan including 11,865 pipes and a rehabilitation priority, including 2,854 previously inspected wastewater pipes.

Keywords: Wastewater management, risk assessment, probability of failure, deterioration, consequence of failure, risk of failure, rehabilitation

Riskbaserad förnyelseplanering av spillvattennätverk

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Sammanfattning

Spillvattennätverk är en del av samhällens underjordiska infrastruktur, vars primära syfte är att på ett säkert och hållbart sätt transportera avloppsvatten från konsument till avloppsverk. Denna moderna infrastruktur har en av de viktigaste faktorerna för att upprätta folkhälsan och en minimera miljöpåverkan. Återinvesteringarna i spillvattennätverk har dock varit otillräckliga, både i Sverige och i resten av världen. När eller om fel i spillvattennätverket uppstår kan detta resultera i stora konsekvenser för samhället utifrån ekonomiska kostnader, folkhälsa och miljön.

Denna uppsats ämnar till att bidra med beslutsstöd genom att utveckla en riskbaserad modell som kan användas i VA-organisationers förnyelseplanering. De primära målen med uppsatsen har varit att; utvärdera tidigare riskbaserade strategier och metoder för rehabilitering av spillvattennätverk; utveckla en riskbaserad modell som kan användas av VA-organisationers för förnyelseplanering; implementera modellen i en fallstudie baserat på Kungsbacka kommuns spillvattennätverk.

Litteraturöversikten visade att metoder för att identifiera ledningar med hög sannolikhet för rör- eller driftfel (sannolikhetsledningar), har baserats på Multikriterieanalys (MKA), Statiska Regression Modeller, Bayesiska Nätverk (BN) och Artificiella Neuronnät (ANNs). Vidare har ledningar där konsekvenser är som störst (konsekvensledningar) identifierats genom att klassificera riskfyllda scenarion i ekonomiska-, sociala- och miljömässiga konsekvenser.

Resultatet i denna uppsats är en risk-baserad förnyelsemodell baserad på att analysera och utvärdera sannolikhets- och konsekvensledningar i spillvattennätverket och identifiera ledningar med hög risk (riskledningar) som används för att utforma en TV-inspektionsplan. TV-inspektionerna används, i kombination med konsekvensledningarna, för att konstruera en förnyelseplan. Modellen strävar att förse VA-organisationer med beslutsstöd för vilka ledningar som bör inspekteras, vilka ledningar som bör rehabiliteras och formulera en re-inspektionsplan, allt i syfte att upprätthålla ett hållbart och funktionellt spillvattennätverk.

Den riskbaserade modellen implementeras på Kungsbacka kommuns spillvattennätverk, en medelstor kommun med 85’000 invånare. Spillvattennätverket består av 15’044 unika lednings IDn, med en totallängd på cirka 570 kilometer. Sannolikhetsledningarna utvärderas genom Multinomial Logistisk Regression och MKA där indata bestod av TV-inspektioner och röregenskaper; ålder, material, längd och diameter. Konsekvensledningar utvärderades utifrån GIS data och ekonomiska-, sociala- och miljömässiga konsekvenser. Genom att kombinera sannolikhetsledningar och konsekvensledningar fastställdes riskledningar utifrån en ett-till-fem skala, med risknivåerna; (1) Låg, (2) Moderat, (3) Moderat-till-hög, (4) Hög och (5) Väldigt Hög. Riskledningarna användes för att sätta upp en TV-inspektionsplan, och utifrån Kungsbacka kommuns redan utförda TV-inspektioner fastställdes en rehabiliterings- och re-inspektionsplan.

Nyckelord: Avloppsvattenförvaltning, riskhantering, sannolikhetledningar, konsekvensledningar, konditionsutveckling, riskledningar, förnyelseplanering

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I would also like to give my acknowledgements to STVF (Sveriges TV-Inspektions Företag), allowing me to use their Closed-Circuit Television (CCTV) inspections as illustrations in my thesis.

Thank you all.

Rikard Lundberg
Göteborg, June 2021

List of Abbreviations

ANN	Artificial Neural Network
BN	Bayesian Network
CCTV	Closed-Circuit Television
COF	Consequence of failure
CSO	Combined Sewer Overflow
FOG	Fat, Oil & Grease
GIS	Geographic Information System
I & I	Infiltration & Inflow
IS	Importance Score
KB	Kortbetyg
MCDA	Multi-Criteria Decision Analysis
NRC	National Research Council Canada
POF	Probability of failure
ROF	Risk of failure
SCV	Sub-Criteria Value
SSO	Sanitary Sewer Overflow
SWWA	Swedish Water & Wastewater Association
W	Weight
WRC	Water Research Centre
WSM	Weighted Sum Method
WWTP	Wastewater Treatment Plant

1 Introduction

In Sweden and the rest of the world, an essential part of the infrastructure is underground, e.g., water distribution, district heating and wastewater transportation. When, or if a failure occurs in these systems, it can cause severe consequences to society related to e.g. economy, public health and the environment. This thesis is focused on the wastewater infrastructure and its future challenges.

Wastewater pipe networks are designed to collect and convey wastewater for further treatment. However, wastewater pipe networks do not last forever. Despite this, the reinvestments in wastewater infrastructure are lagging, not just in Sweden but worldwide. The American Society of Civil Engineers (ASCE, 2020) graded the U.S wastewater pipe network a "D+", indicating poor condition with a high risk of failure. To put it in context, an "A" represents an exceptional condition and fit for the future, a "B" good for now, a "C" represents a mediocre condition with a requirement for attention, and the worst grade "F" represents a failing infrastructure that does not meet for its purpose. Between 2012 and 2018, the water and wastewater pipe breaks increased by 27%, and the reinvestments needed to reach adequate water and wastewater infrastructure, a "B", is prognosticated to cost $109 billion per year. In Europe; Austria's reinvestments need to increase from 362 million €, to 490 - 830 million €; in Germany, approximately 20% of the wastewater pipe network needs rehabilitation. In Sweden, the wastewater infrastructure expanded rapidly between 1960 - 1970, and the wastewater pipe network at present consists of over 72,700 kilometres of pipe. The requirement of reinvestment is predicted to be doubled during the following decades, from 160 million € per year to 320 million € per year[1], where the most significant part of the investments are due to ageing and deterioration of the wastewater pipe network, but also on account of urbanisation (increased demand), stricter regulations and climate change (SWWA, 2020).

British and American medical associations have recognised the importance of wastewater convey and treatment as the most significant variable on public health and longevity (Lofrano and Brown, 2010). Wastewater transportation and treatment in industrialised societies are crucial to minimising contamination of soils and water bodies. Additionally, industries and other economic activities are dependent on water and wastewater distribution.

With high investments worldwide in the following decades in renovating, replacing, repairing and maintaining wastewater pipe networks, a crucial question arises. Which pipes should be prioritised to maximise the economic investment and level of service? Individual pipes in the wastewater network consist of differential material and dimensions; the age and installation era differs, and they are located in various settings related to land use and soil conditions. Further, to predict pipes condition, various inspection methods are available, and deterioration prediction models have been developed. Using a risk-based approach, individual pipes can be analysed, combining the probability of failure (POF) and consequence of failure (COF) to evaluate the risk of failure (ROF), where POF evaluates individual pipes likelihood to fail, and COF the severeness of the individual pipe's failure. Further, the ROF can be used to evaluate inspection precedence and rehabilitation priority.

[1] 1 SEK (Swedish crown) is 0.099 € (Euro) [2021-04-01]

1.1 Aim and objectives

This thesis aims to provide decision support that can be utilized to design a rehabilitation strategy for wastewater management. A risk-based approach will be used to develop a model for identifying high-priority pipes with respect to the probability of failure and the consequences of failure. The model will be applied to evaluate the wastewater pipe network in the municipality of Kungsbacka. The thesis has the following specific objectives:

- Review rehabilitation strategies and evaluation techniques for wastewater pipes from a risk perspective and identify important pipe parameters that can be applied in a risk-based model.
- Develop a model to identify high priority pipes considering the combination of the probability of failure and consequence of failure, providing decision support for rehabilitation measures.
- Apply the developed model on the Kungsbacka municipality wastewater pipe network and evaluate a rehabilitation priority.

1.2 Limitations

This thesis will only evaluate a risk-based rehabilitation for wastewater pipes. Hence, some essential parts of the wastewater pipe network will not be included in this thesis, e.g. pump stations and manholes. Further, the Closed-Circuit Television (CCTV) inspections used in the report has been analysed based on the final grade. Consequently, no analysis can be made of which specific defects are associated with each pipe. It should also be mentioned that Kungsbacka municipality carried out the data collection in GIS.

2 Theoretical Background

The knowledge of how vital sanitation is for public health is not new. This knowledge and the infrastructure of wastewater management have come and gone throughout time. The sanitation timeline is presented in Figure 2-1.

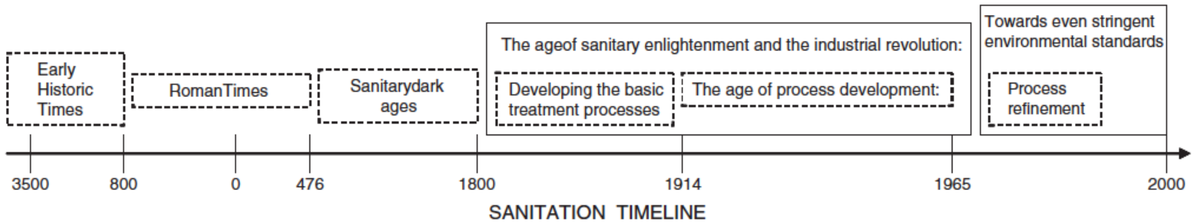


Figure 2-1: Sanitation Timeline. Retrieved from: (Lofrano and Brown, 2010)

The first more sophisticated attempts to handling wastewater were in the Mesopotamian Empire (3500- 2500 BC), where houses were connected to primitive drainage systems. The Egyptians (2100 BC) used bathrooms and toilets, the Ancient Greeks (300 BC) used drains from water closets to ponds outside the city walls, and the Romans developed infrastructure for water and wastewater (Lofrano and Brown, 2010). The Fall of The Roman Empire was the start of the sanitary-dark-age. Water was taken and disposed of in rivers and wells, which lead to the spreading of diseases. Even though some cities (mostly Italians) had the infrastructure, the most common way to deal with sanitary waste was to through it out in the street. For centuries, neglecting proper wastewater management led to diseases and epidemics and pollution, affecting seriously public health and the environment. (Lofrano and Brown, 2010). With the industrial revolution, Europe was urbanised, and technology such as wastewater pipes and pumps made it possible to transport wastewater from the city cores. However, there was no treatment in place, which led to, e.g., polluted water bodies. At the beginning of the 20th century, the technology of wastewater treatment and wastewater treatment plants (WWTPs) was established. The American and British Medical Associations have recognised the infrastructure and treatment technology for wastewater as the most significant variable on public health and longevity (Lofrano and Brown, 2010).

2.1 Wastewater management

Water is essential for all life and possesses unique properties. It is a suitable solvent, making it possible to transport salts and minerals to our bodies. We also use it in our day to day life in sanitary aspects such as washing dishes, clothes and personal hygiene. Water is also a scarce resource. Of all water, more than 97% are seawater (oceans), 3% is freshwater, where less than 1% is available for human consumption (e.g. groundwater, lakes, watercourses) (Lidström, 2013). The total amount of water is constant, and water bodies and groundwater recharge are possible through the water cycle; where precipitation, run-off, infiltration and recharge of groundwater storage and reservoirs are the input in the system; and evaporation and transpiration close the water cycle when water once again takes the form of precipitation. However, natural recharge is usually a slow process. Therefore, in order to satisfy communities and industrial activities with fresh water, an extra man-made loop in the water cycle is added, where freshwater is taken from reservoirs or groundwater reserves and treated in Water Treatment Plants (WTPs). The water is disturbed by water pipes to consumers. The consumed water turns into wastewater (industrial or domestic) and distributes through wastewater pipes (sewers) to WWTPs, where the water is treated and sent back to reservoirs.

In Figure 2-2, a simplified schematic view of the natural and human-made water cycle is presented, where the dashed lines represent the natural water cycle, the solid lines the human-made water cycle, and the solid red lines are wastewater pipes, the subject for this thesis.

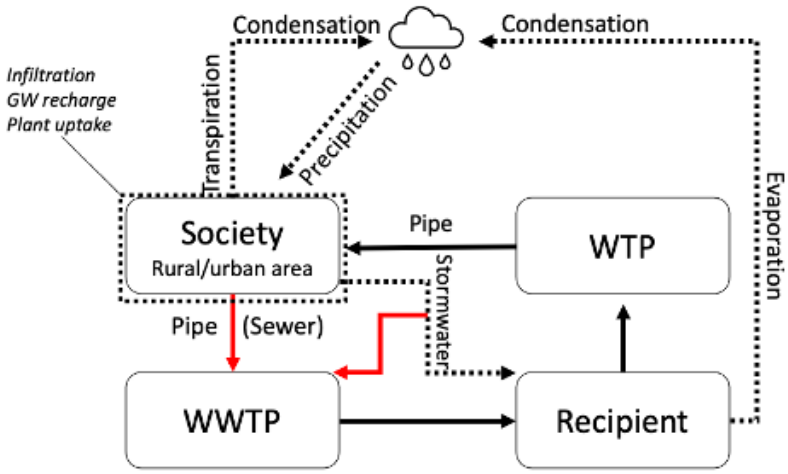


Figure 2-2:The natural and the human-made water cycle. Dashed lines – the natural water cycle. Solid lines – Man-made water cycle. The red lines, wastewater pipes (topic for this thesis).

2.1.1 Wastewater characteristics

Wastewater can be divided into three categories (UN-Water, 2015):

i. Stormwater runoff: water from, e.g. streets, channels.
ii. Industrial: from factories and production.
iii. Domestic (municipal wastewater): water from households, businesses (e.g., restaurants or hotels), and schools or offices.

Further, domestic water can be divided into grey and blackwater. Where greywater originates from laundry, kitchen and bathroom, and blackwater contains faeces and urine. Consequently, the composition of wastewater and pollutants are depended on the source. In Table 2-1 some of the most common contaminants in wastewater (domestic and industrial) are presented, with the associated recipient impact.

Table 2-1: Pollutants in wastewater, its origin and effect on the recipient. Pollutants in wastewater, its origin and effect on the recipient. 1: Fat, Oil and Grease, 2: Biochemical Oxygen Demand, and 3: Chemical Oxygen Demand. Adopted from: (Lidström, 2013)

Pollutant	***Origin***	***Impact on recipient***
FOG[1]	The food industry, kitchens, car washes etc.	Aesthetically, the possibility to block solar radiation for aquatic life
Solids (rags, plastics, etc.)	Households, industry	Aesthetically
BOD[2], COD[3]	Households, food industry, kitchens etc.	Oxygen demand
Solved organic matter (persistent, e.g., pesticides)	Households, food industry, kitchens	Toxic (accumulates in the food chain)
Phosphor & Nitrate	Households	Eutrophication
Metals (Cr, Ni, Pb, Cd)	Industry, stormwater	Toxic (accumulates in the food chain)
Pathogens (bacteria, viruses)	Households, hospitals	Diseases and infections
Smell & colour (e.g. hydrogen sulfide	Industry, households (chemic reaction in the pipe)	Toxic, corrosion, smell
Salts (chloride, calcium)	Industry, infiltration	Corrosion and precipitates

Stormwater runoff water can be a part of wastewater if combined systems are used. However, the pollutants differ from industrial and domestic water since runoff is water conveyed via roads, streets, buildings, and arable land. The pollutions often found in stormwater runoff is lead (Pb), copper (Cu), zink (Zn), phosphorus (P) and nitrogen (N) (SWWA, 2016).

2.1.2 Wastewater pipe network characteristics

The wastewater network's essential purpose is to convey wastewater and (or) drainage and stormwater from the origin to the WWTP. A schematic view of a conventional wastewater pipe network is shown in Figure 2-3.

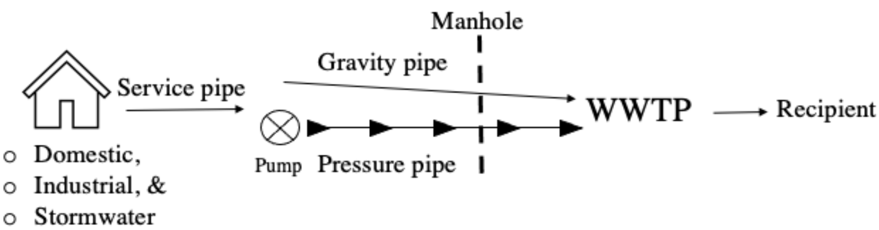


Figure 2-3: Schematic view of a conventional wastewater pipe network including origin, service pipe, type of pipe and pumps, manhole, WWTP and recipient.

Where the origin is domestic, industrial or stormwater, the service pipe is the dividing line between the property owner's pipe and the municipality's pipe. Further, wastewater pipes can be divided into combined or separate pipes. The combined system transports domestic, industrial and stormwater in one pipe to the WWTP. Contrary, in the separate system domestic and industrial water, and stormwater are transported in separate pipes. These systems are presented in Figure 2-4.

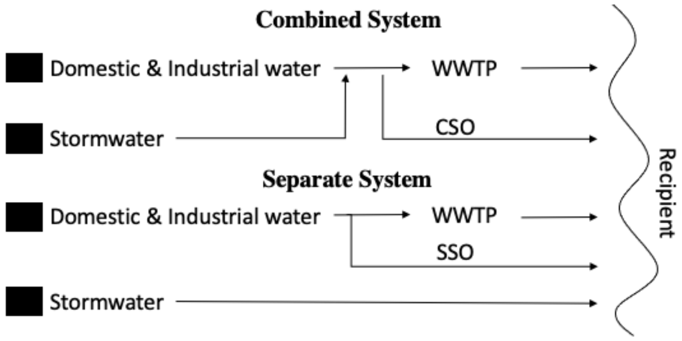


Figure 2-4: Combined and separate wastewater pipe systems. SSOs & CSOs are abbreviations for sanitary sewer overflows and combined sewer overflows. Adopted from: (Lidström, 2013)

There are gains and losses with separate and combined systems. In combined systems wastewater, regardless of origin, is transported the WWTP for treatment. However, the stormwater amount varies with seasons, which means that there are risks for Combined Sewer Overflows (CSOs) in rainy periods. Overflows with water from households and industries are often more polluted than solely stormwater, and since overflows often reach recipients, this implies an environmental risk, e.g. pollution and eutrophication (SWWA, 2013). Further, separate systems are often designed for Sanitary Sewer Overflows (SSOs) when capacity is insufficient.

The pipes themself can be designed as gravity or pressure pipes, depending mainly on the topography. Gravity pipes utilize the energy of position, using the difference in height between the starting and endpoints. Pressure pipes are used when the topography does not allow gravity pipes, and instead, pump stations are strategic placed to pump the wastewater. Problems with pressure pipes are that the retention time is extended, resulting in sedimentation and forming of hydrogen sulphide (Lidström, 2013).

Maintenance holes (manholes) are needed in the wastewater pipe network to access inspections, cleaning and sampling. Further, if the wastewater pipe network is seen as a network of straight lines and nodes, maintenance holes are the nodes that make the change of direction possible between manhole-to-manhole.

2.1.3 The Swedish Wastewater Pipe Network

The first buried water and wastewater pipes in Sweden were installed in 1860, in the early 20th century 80 Swedish cities had some wastewater drainage system (SWWA, 2016). With the water closet's inauguration (WC) in the early 20th century and further industrialisation, the demand for wastewater pipes accelerated. At that time (and before), the wastewater was conveyed directly to the recipient, consequently causing undesired environmental effects. The first WWTPs were formed in the 1930s to 1950s with mechanical treatment, conveyed by combined systems. With increased wastewater quantities, frequently back flooding, and capacity issues at the WWTPs, controlled CSOs were introduced. During the 60s and 70s, combined systems were rebuilt into separate systems, and the WWTPs developed biological treatment (SWWA, 2016). In the 19th century, the primary wastewater pipe material used was tree or bricks. Between 1860 and 1940, the quality increased when verified clay pipes were introduced. The quality increased even more with the concrete pipes in 1870 and was the material of choice until the 1990s. Further, plastic pipes were introduced in the 70s and have dominated the new installations since the 1990s. In Figure 2-5, the build-up of the Swedish wastewater pipe networks is presented. As seen, a big part of the network was established between the 1960s and 1970s.

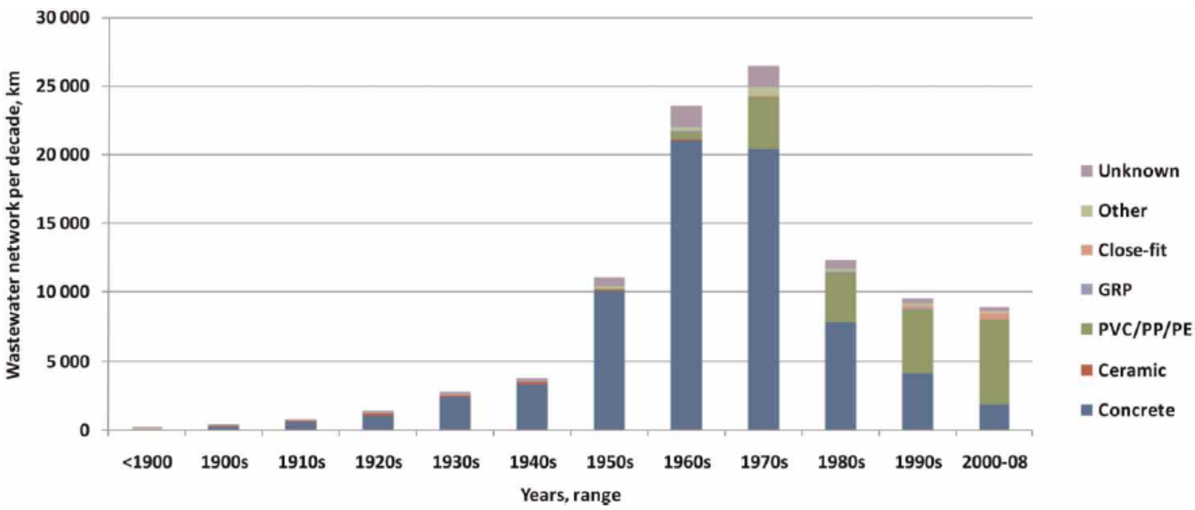


Figure 2-5: Material and amount of wastewater pipes installed in Sweden by decades. Retrieved from: (Malm et al., 2013)

From Figure 2-5, it can be observed that concrete has been the dominating material of choice until the 1990s. Consequently, an inventory by Malm et al. (2011b) showed that concrete pipes accounted for 66.6% of all pipes, followed by Plastic pipes 23.7%, where plastic pipes include Polyvinyl Chloride (PVC), Polypropylene (PP), Polyethene (PE), Glass Reinforced Plastics (GRP), and structure pipes (Figure 2-6).

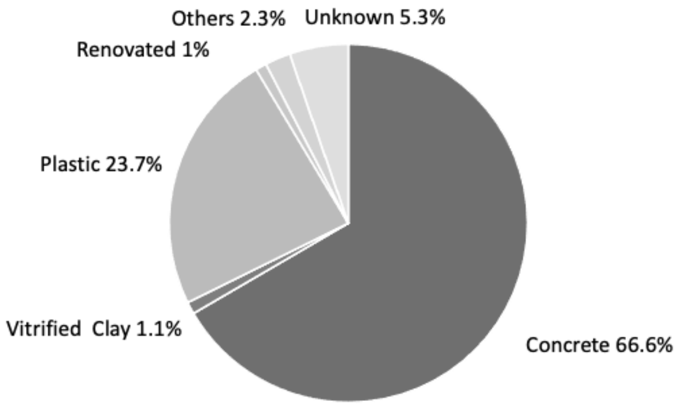


Figure 2-6: Composition of the wastewater pipe network in 2008. Adapted from: (Malm et al., 2011b)

Today over 8.5 million people in Sweden have access to wastewater treatment. The total length of the wastewater pipes was, in 2017, over 100,000 km. Further, 8% are combined pipes, 57% are separate pipes (wastewater), and 35% separate (runoff water) (SEPA, 2016). Figure 2-7 shows the composition of the 416 km newly installed pipe in Sweden 2016, where plastic pipes, especially PE and PP, dominating new installations.

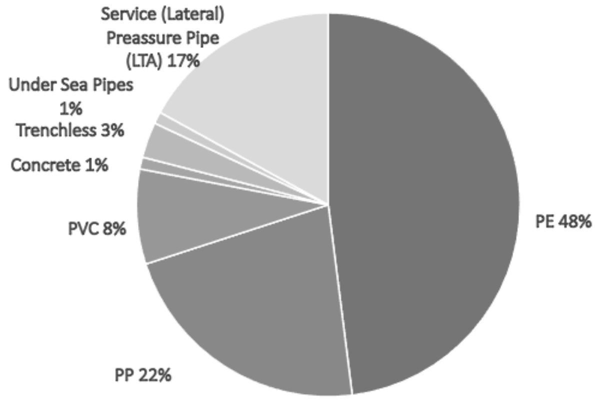


Figure 2-7: Composition of newly installed wastewater pipes in Sweden 2016. Adapted from: (SWWA, 2018).

2.2 Risk & decision theory

2.2.1 Risk assessment

The theory and concept of risk have a long history. However, risk assessment and risk management as a scientific field have been developed during the last 30 – 40 years. Risk assessment and management are used in several various disciplines such as economics, civil and mechanical engineering, ecology, social science, climate change, and energy. (Aven, 2018).

Society for Risk Analysis (SRA) describes risk assessment as a systematic process to identify hazardous events, understand why and how these occur, the expected consequences, incorporate uncertainties, and define risk using relevant criteria (Aven et al., 2018). Further, risk management is defined as covering all the risk activities.

There are several risk management frameworks. In this thesis, ISO 31000 (2018) will be used. However, frameworks presented by, e.g. Burgman (2005); IEC 31010 (2019) are very similar, and the main differences are schematic or linguistic. The different steps in ISO 31000 (2018) are presented in Figure 2-8.

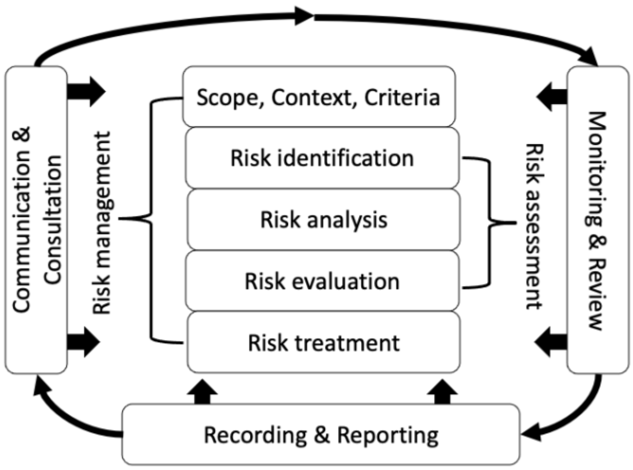


Figure 2-8: Risk management framework. Adapted from: (ISO 31000, 2018)

2.2.1.1 Scope, Context, Criteria

The scope, context, criteria strive to tailor the risk assessment to fit its purpose. In this setting, risk assessment within wastewater pipe networks, the following steps will be used:

i. Set up problem formulation regarding wastewater pipe rehabilitation.
ii. Define the wastewater pipe network system, characteristics, boundaries and risks.

The problem formulation sets up the thesis's scope and purpose, and the definition of the system determines the characteristics, boundaries and risk, consequence, and probability hotspots. Further conceptual models can visualise the structure and limits of the problem (Burgman, 2005). In this thesis, (i) and (ii) will be used to set up a conceptual model for wastewater pipe networks probability of failure (POF) and consequences of failure (COF).

2.2.1.2 Risk identification

The convey of wastewater from the origin to the WWTP includes risks, where failure in the system can lead to unwanted hazardous events. Wastewater pipe failure can be divided into

i. Operational failure.
ii. Structural failure.

In Table 2-2, wastewater pipe failure with corresponding hazardous event and impact are presented. These failure types and the hazardous events will be further discussed in section 2.3.

Table 2-2: Failure types with corresponding hazardous events and impact for wastewater pipe failure. 1: Infiltration & Inflow.

Failure Type	***Origin***	***Hazardous event***	***Impact***
Structural failure	Deformation, cracking, fracture & ultimately breakage	Collapse	Social, economic & environmental
Operational failure		Exflow	Environmental, social
	Blockage	Basement flooding’s	Economic, environmental
	Heavy rain	SSOs & CSOs	Economic, environmental.
	I & I[1]	Capacity issues at WWTP	Economic

2.2.1.3 Risk analysis

Risk analysis is the process that aims to evaluate the probability and consequences of undesired hazardous events. Generally, two types of risk analysis methods are used, qualitative or quantitative. A qualitative analysis is generally more subjective than quantitative risk analysis, taking advantage of expert opinions and quantifying POF and COF in non-numeric terms, such as low, medium, and high. Quantitative analysis evaluates risk using numeric values, where the probability of undesired events can be quantified, and uncertainties can be addressed in numerical terms (Ostrom and Wilhelmsen, 2012). Further, qualitative, and quantitative analysis can be combined in risk analysis taking advantages of both expert opinions and the numeric setting of probabilities and uncertainties.

The definition of risk varies, but can be seen as “effect of uncertainty on objectives” (ISO 31000, 2018) or “.. the change, within a time frame, of an adverse event with specific consequence." (Burgman, 2005). In this thesis, the aim of risk analysis will be based on the definition presented by Kaplan (1980), where three main questions will be answered:

i. What can happen?
ii. How likely is it?
iii. What are the consequences?

The three questions above can be used to defined risk as a triplet of scenario (*s*) probability (*p*) and consequence (*x*) Equation 2-1.

$$R = \langle\, s_i \mid p_i \mid x_i \,\rangle, \qquad for\ i = 1,2,\dots,N \qquad \textit{Equation 2-1}$$

Where s_i is the scenario, p_i is the probability, x_i the consequence and i, a natural number ranging from 1,2,3, ...N. Where N is the Nth value. Further, adding up the scenario (*s*), probability (*p*), consequence (*x*), and the additional cumulative probability (P_i) for i = 1, 2, 3, ..., N gives Table 2-3.

Table 2-3: Listed scenarios, probability, consequence, and cumulative probability. Adapted from: (Kaplan, 1980)

Scenario	***Probability***	***Consequence***	***Cumulative Probability***
s_1	p_1	x_1	$P_1 = P_2 + p_1$
s_2	p_2	x_2	$P_2 = P_3 + p_2$
s_i	p_i	x_i	$P_i = P_{i+1} + P_1$
s_{N-1}	p_{N-1}	x_{N-1}	$P_{N-1} = P_N + p_{N-1}$
s_N	p_N	x_N	$P_N = P_N$

Where $\langle x_i | P_i \rangle$ can be plotted as the staircase and smoothed risk function. In risk assessments regarding wastewater pipe failure, the probability, consequence and risk are usually referred to as probability of failure (POF), consequence of failure (COF) and risk of failure (ROF), respectively (Anbari et al., 2017; Salman and Salem, 2012; Vladeanu and Matthews, 2019). Where the linguistic description implies that ROF is defined as the combination of POF and COF. Further, if the risk is referred to as ROF, probability as POF and consequence as COF, ROF can be described as a triplet according to Equation 2-2.

$$ROF = \langle s_i | POF_i | COF_i \rangle \,;\ i = 1,2,3,\dots,N \qquad \textit{Equation 2-2}$$

Further, Kaplan (1980) defines the hazardous event (*H*) to a set of doubles (Equation 2-3) combining the scenario with corresponding COF, i.e. an event with a specific consequence.

$$H = \langle s_i | COF_i \rangle \qquad \textit{Equation 2-3}$$

The staircase function (dashed line) can be plotted as the COF_i and cumulative POF^C_i, presented in Figure 2-9, where the smoothed risk curve (solid line) representing levels of ROF with associated POF and COF.

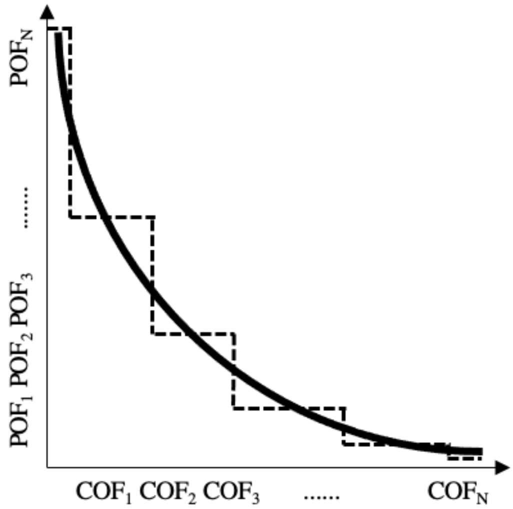


Figure 2-9: The linear relationship between COF and POF resulting in ROF.

The total ROF can be described as the area under the smoothed ROF curve.

2.2.1.4 Risk evaluation

Risk evaluation complements the risk analysis setting the qualitative or quantitative assessed risks in context, providing decision-support to evaluate and compare estimated risk levels. Further, the risk evaluation is the basis for the risk treatment process, where the evaluated risks can be addressed as tolerable or non-tolerable risks.

The As Low As Reasonably Practicable (ALARP) divide risk levels of tolerability; Broadly accepted, no risk reduction is needed; ALARP region, risk can be tolerable if risk reduction measure is implemented or if the profits exceed the consequences; Intolerable, are risk levels to high to be excused (IEC 31010, 2019).

Further, risk matrixes can be used to visualise the magnitude of risk, evaluated from, e.g. the ALARP, using a matrix with probability and consequences on the x and y-axis, highlighting the risk levels within the cells and often visualising them with colours and (or) numbers (IEC 31010, 2019).

2.2.1.5 Risk treatment & decision analyses

ISO 31000 (2018) described risk treatment as an iterative process of formulating, planning, implementing, and evaluating risk treatment alternatives effectiveness. Risk treatment can remove the source of ROF, decrease POF and (or) COF. In risk-based rehabilitation, the risk treatment is mainly based on the renovation or replacement of wastewater pipes.

Decision analysis is used to make good decisions, incorporating risk analysis. Good decisions are dependent on several factors such as: financial costs, environmental or social and political regulations (Aven, 2012). In Figure 2-10, the essentials from Aven (2012) process of decision-making is presented.

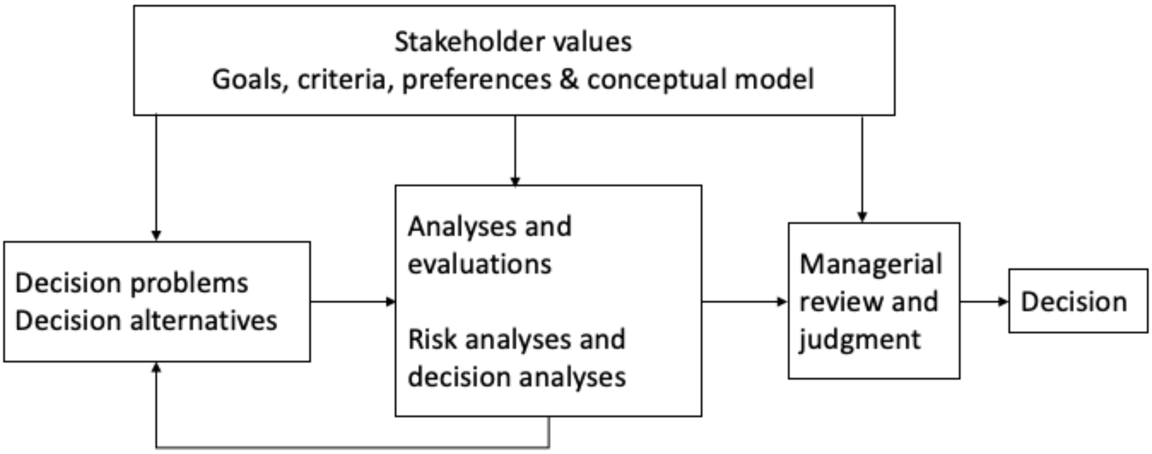


Figure 2-10: Decision-making process. Adopted from:(Aven, 2012)

Goals, criteria, preferences & conceptual model presents the problem formulation and provides the decision alternatives. *Risk and decision analyses* are conducted, evaluated, and treatments are suggested. Ultimately *stakeholders (managers) and expert's reviews* and *decide* between alternatives that are most suitable for the organisation.

2.2.2 Infrastructure asset management

Asset management is the umbrella definition of capital investment management, where *infrastructure asset management* is the management of public infrastructure from the cradle-to-grave, and equivalent to life-cycle management. Infrastructure asset management considers, e.g., roads, energy distribution, airports, and water- and wastewater pipes. The key activities in asset management can be described through the asset management triangle (Grigg, 2012), presented in Figure 2-11.

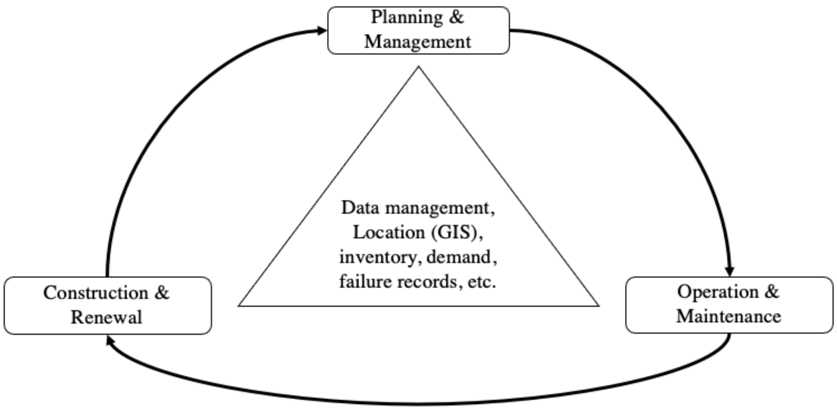


Figure 2-11: Key activities in infrastructure asset management. Adapted from: (Grigg, 2012)

Construction and renewal include new constructions, renovation and replacement, and quality control of new and older assets, where the main objective of the efforts is to maintain the infrastructure service and extend the assets life cycle. *Planning and management* should see to the level of service by operation and maintenance activities, the financing of construction and rehabilitation of assets and risk assessments should evaluate risks within the network. *Operation and maintenance* evaluate the assets condition and performance, supporting developing plans to improve the assets life-cycle (Grigg, 2012).

The schematic view of asset management must be seen as a circular process where all individual activities aim to optimise the life-cycle of the assets, maintain an adequate service level by monitoring the system, estimating the assets condition, and evaluating risks and uncertainties, and constantly improve the system (Grigg, 2012).

2.2.3 Uncertainties

The management of *uncertainties* is an essential part of risk assessment, where notable uncertainties should be addressed and significant impact on the risk assessment result should be highlighted. Generally, uncertainties are divided into three subcategories: epistemic, aleatory and linguistic. The epistemic uncertainty is those uncertainties within the model that can be described as the absence of knowledge. Consequently, these types of uncertainties can be treated or decreased with adequate data. The aleatory uncertainties can be described as the uncertainties within the data (or outcome) where the variability can be derived from that, e.g. the system or process is not fully understood (Burgman, 2005). The linguistic uncertainties are those produced by differences in the use of language (Herrmann, 2015).

The uncertainties can be addressed in quantitative models using Monte Carlo simulations, where simulations show how the model changes due to changes in variables (Burgman, 2005)

2.3 Wastewater pipe failure

Wastewater pipe failure is defined, in this context and thesis, as an event where the wastewater network does not function as intended. In most literature (Hawari et al., 2020; Mohammadi et al., 2019; Mohammadi et al., 2020), wastewater pipe failure is divided into two categories:

i. Operational failure.
ii. Structural failure.

2.3.1 Operational failure

Operational failure is defined as the state where the operational or hydraulic function of the pipe is inadequate due to factors that do not necessarily have to be a consequence of the structural condition, i.e. the pipes capacity to convey wastewater. In the following sections, failure types due to operational defects will be described.

2.3.1.1 Stoppage

Stoppage in wastewater pipes can origin from the pipes operational condition or structural defects, where operational defects often are root intrusion, sediment, FOG (fat, oil and grease), or blockages caused by, e.g., rags, forks or plastics (Malm et al., 2011a).

Basement flooding can be caused by stoppage and high flows, where high flows mainly occur under extreme weather and high precipitation. Consequences of basement flooding are; financial cost for public infrastructure and private residential; and risk for pollution and diseases (Irwin et al., 2018). Further, basement flooding's can occur due to flooding from surrounding water bodies or stormwater runoff in the presence of heavy rain. As the risk increases with high flows, combined wastewater systems are more vulnerable than separate systems. In Sweden, combined systems should be designed for precipitation in the magnitude of 10-year events (SWWA, 2004).

In Table 2-4, basement flooding's for 1,000 connected consumers per year are presented. Where the grade very good, good, moderate, and poor represent 0, 0 – 0.2, 0.2 – 0.5, > 0.5 basements flooding per thousand consumer per year (Malm et al., 2011a).

Table 2-4: Basement flooding's per 1000 consumers and year in Swedish municipalities. Adopted from (Malm et al., 2011a)

	20% of the best performance municipalities	***20 – 40 of the best performance municipalities***	***40 – 60 of the medium performance municipalities***	***20 – 40 of the worst performance municipalities***	***20% of the worst performance municipalities***
Basement flooding [1000 consumer/year]	0	0	0 – 0.4	0.4 – 0.8	0.8 – 7.5

2.3.1.2 Overflows

Sanitary sewer overflows (SSOs) and combined sewer overflow (CSOs) are mainly affected by the type of system (combined or separate), the pipes' dimensions and amount of precipitation. When heavy rain occurs, overflows is a method to decrease the probability of back floodings. The consequences of overflows are economical and mainly environmental when wastewater reaches the recipient. Hence, the environmental consequences are determined by; the magnitude of overflow, i.e. the volume of wastewater; the recipient's size determines the concentration of wastewater; and the wastewater characteristics determine the type of contamination (Irwin et al., 2018; Malm et al., 2011a). Further, SSOs or CSOs in dry weather consequently means a higher concentration of wastewater.

2.3.1.3 Infiltration & Inflow (I & I)

Under optimal condition, the wastewater conveyed to WWTP should be equal to the water produced at the WTP. However, this seldom occurs due to Infiltration & Inflow (I & I). Infiltration is the infiltration of groundwater and precipitation into wastewater pipes due to fractures, cracks, poor installation or inadequate joints. Inflow is the additional water in the system caused by an inappropriate connection from, e.g. roof or surface drainage (Clementson et al., 2020). The consequences of high amounts of I & I are basement flooding, CSOs or SSOs, and capacity issues at WWTP, i.e. the WWTP can not treat all incoming wastewater or skips treatment processes (Clementson et al., 2020). Further, the amount of I & I also depends on the groundwater table and soil type. If the pipe is located under the groundwater table, the risk of infiltration increase. Further, soils with high permeability, i.e. the ability for fluids to penetrate the soil, suffer higher risk for infiltration (SWWA, 2016).

In Table 2-5, I & I in litre per meter wastewater pipe per day from Swedish municipalities are presented. According to Malm et al. (2011a) the grade very good, good, moderate, and poor represent < 5, 5 – 15, 15 – 25, > 25-litre I & I per meter pipe and day.

Table 2-5: Infiltration & Inflow in litre per metre wastewater pipe per day, from Swedish municipalities. Adopted from:(Malm et al., 2011a)

	20% of the best performance municipalities	***20 – 40% of the best performance municipalities***	***40 – 60% of the medium performance municipalities***	***20 – 40% of the worst performance municipalities***	***20% of the worst performance municipalities***
I & I [litre per metre pipe and day)	0 – 15	15 – 22	22 – 29	29 – 42	42- 136

2.3.1.4 Climate change

The predicted climate change will mainly affect wastewater pipe networks in two ways. The first is the change in precipitation. More intensive or longer duration in precipitation will lead to more stormwater runoff to convey. In combined systems, the risk of CSOs will increase. For separate systems, the risk for SSOs will increase due to capacity issues in stormwater pipes. Increased precipitation will also accelerate infiltration, increasing the load on WWTPs, and the I & I will increase risks for SSOs and CSOs. Second, increased water levels in recipients block the convey of stormwater, and in consequence, the risk for floodings increase (Olsson et al., 2010; SWWA, 2016). To decrease the climate changes impact on wastewater management, Sustainable Stormwater Management aims to simulate the natural water cycle in an urban environment. Where the strategy is; Source control, e.g. green areas and green roofs, infiltration and local ponds; Onsite control including, e.g. permeable asphalt, ponds and green areas; Slow transport including, e.g. swales, ditches and channels; Downstream control, the recipient in the form of water bodies, lakes, larger ponds (SWWA, 2016).

2.3.2 Structural defects & failure

Wastewater pipes (and water supply pipes) failure and breakage have no clear definition, are complex, and more research are needed to understand the process entirely. However, the physical mechanism affecting pipe failure proposed by Rajani and Kleiner (2001) are:

i. The structural properties, material, interaction with soil type, and installation (e.g. transportation, jointing, bedding and backfill).
ii. Internal and external load, where external typically are soil overburden, live loads (e.g., traffic), and frost loads.
iii. The material deterioration which includes chemical processes such as corrosion and sulfuric acid.

The structural failure of wastewater pipe is a process where; the structural deterioration is the stepwise decrease in the condition due to, e.g. corrosion, loading, improper joint sealing and connections, settlements in soil or loads (discussed in section 2.4.1); and the structural failure (breakage) of the pipe as the final outcome. Three types of breakage have been described by (Rajani and Kleiner, 2001): circumferential breakage, longitudinal breaks and bell split or joint break.

Circumferential breaks (cracks or fractures), see Figure 2-12, often occur due to vertical loads combined with uneven bedding, which causes the pipe to be loaded like a beam, for which it is not dimensioned for. This failure type can occur due to small leaks that disturb the soil's bedding or by movements (settlements), usually in clays. The cracks can occur at the top, bottom and around the pipe (CPAA, 2008a), this type of failure is one of the most common break type and the rate decrease with a higher diameter (Misiunas, 2008).

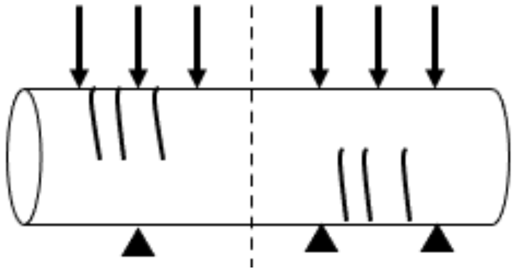


Figure 2-12. Circumferential crack or fractures. The uneven bedding results in bending moments that in combination with vertical loads can result in cracks or fractures.. Adapted from: (CPAA, 2008a)

Longitudinal breaks (cracks or fracture), see Figure 2-13, occur horizontally along the pipe walls. This type of cracks generally occurs due to overload but also cylinder (hoop) stress due to internal water pressure (CPAA, 2008b), and frost loads (Rajani and Kleiner, 2001). Often this kind of cracks starts with a slight deformation that can expand horizontally along the pipe.

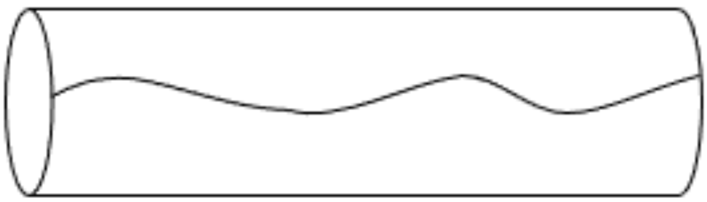


Figure 2-13. Longitudinal cracks or fractures. Adapted from: (CPAA, 2008b)

Bell splitting (or joint failure), see Figure 2-14, occurs because of inadequate or deterioration of joints or ground movements (Makar, 2000).

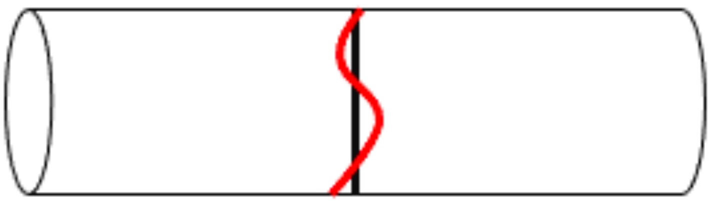


Figure 2-14: Bell splitting or joint failure. The red "line" presents the inadequate joint or bell splitting

Further, (Makar, 2000) suggested pipe blow-outs due to corrosion (corrosion holes) or internal pressure (WSAA, 2003) as a breakage category. This type of breakage starts with corrosion or a decrease in strength at a point (or several) on the pipe. Eventually, when wall thickness decreases, and the pipe's internal water pressure blows out a part of the pipe wall. In Figure 2-15, (a) is the initial hole and (b) the blow-out hole. This type of breakage is common in iron or plastic pipes.

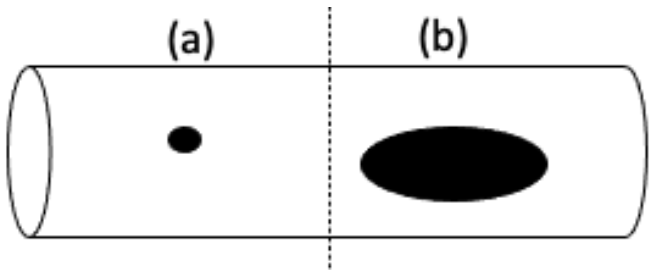


Figure 2-15. corrosion or internal water pressure hole. (a) initial small hole, (b) blow-out hole due to internal water pressure. Adapted from: (Makar, 2000)

However, pipe failure usually does not occur directly. Instead, it is a deterioration process where initial cracks form more extensive fractures and, combined with infiltration, disturbed bedding condition and ground movements, accelerate the deterioration process. The deterioration process from initial circumferential and longitudinal cracks to pipe failure is presented in Figure 2-16 and Figure 2-17. In Figure 2-16 the first stage (a), is the initial longitudinal cracks, present due to poor manufacturing, installation or overloading. The second stage (b), infiltration or exfiltration disturb the bedding condition and backfill, decreasing the side support and more severe fractures forms. In the final stage (c), the processes in (b) reach the limit, imposing failure (collapse) (Davies et al., 2001; WEF, 2009).

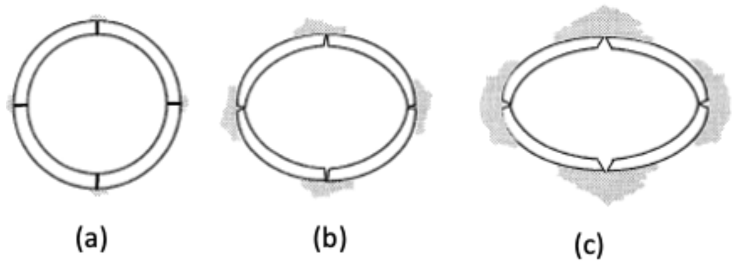


Figure 2-16. Stepwise deterioration for longitude fracture to collapse. Retrieved from: (Davies et al., 2001)

In Figure 2-17 the first stage (a), initial circumferential cracks are present. In the second stage (b), infiltration or exflow disturbs bedding condition and side support, more extensive fractures are presents, and the pipes start to move, i.e. displacements of the pipe. In the final stage (c), the pipe is displaced, and further loading and joint displacements accelerate the deterioration process, with the outcome pipe failure (WEF, 2009).

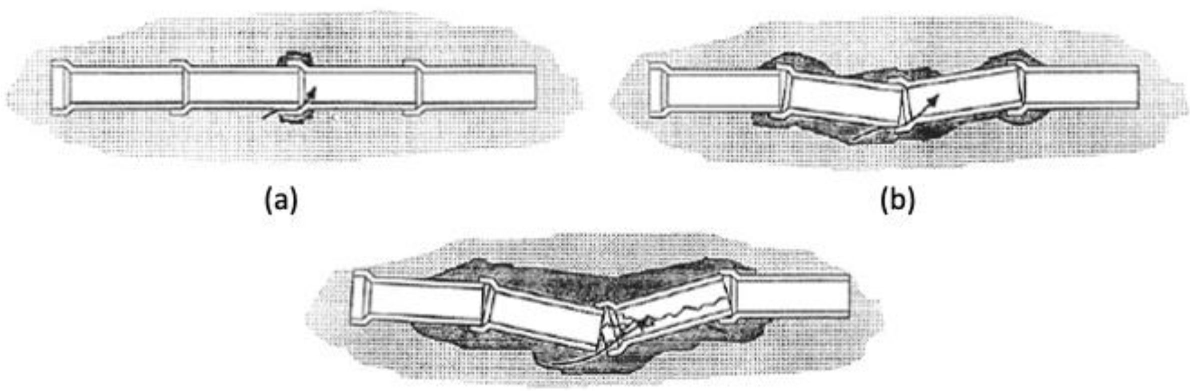


Figure 2-17. Stepwise deterioration for circumferential cracks. Retrieved from:(WEF, 2009)

2.4 Probability of Failure (POF)

The probability of failure (POF) is the estimated probability of a pipe failure in terms of collapse, breakage or non-functioning operational status. In the previous section, structural pipe failure was described as a result of initial defects, leading to more severe defects. Hence, POF can be seen as a function where the condition of the specific pipe is related to the deterioration process.

2.4.1 Deterioration of Wastewater pipes

Deterioration of wastewater pipe is a multifaceted process with several parameters and processes influencing its magnitude. (Hawari et al., 2020; Malek Mohammadi et al., 2020; Mohammadi et al., 2019). In Figure 2-18 four different approaches to visualise the process is presented.

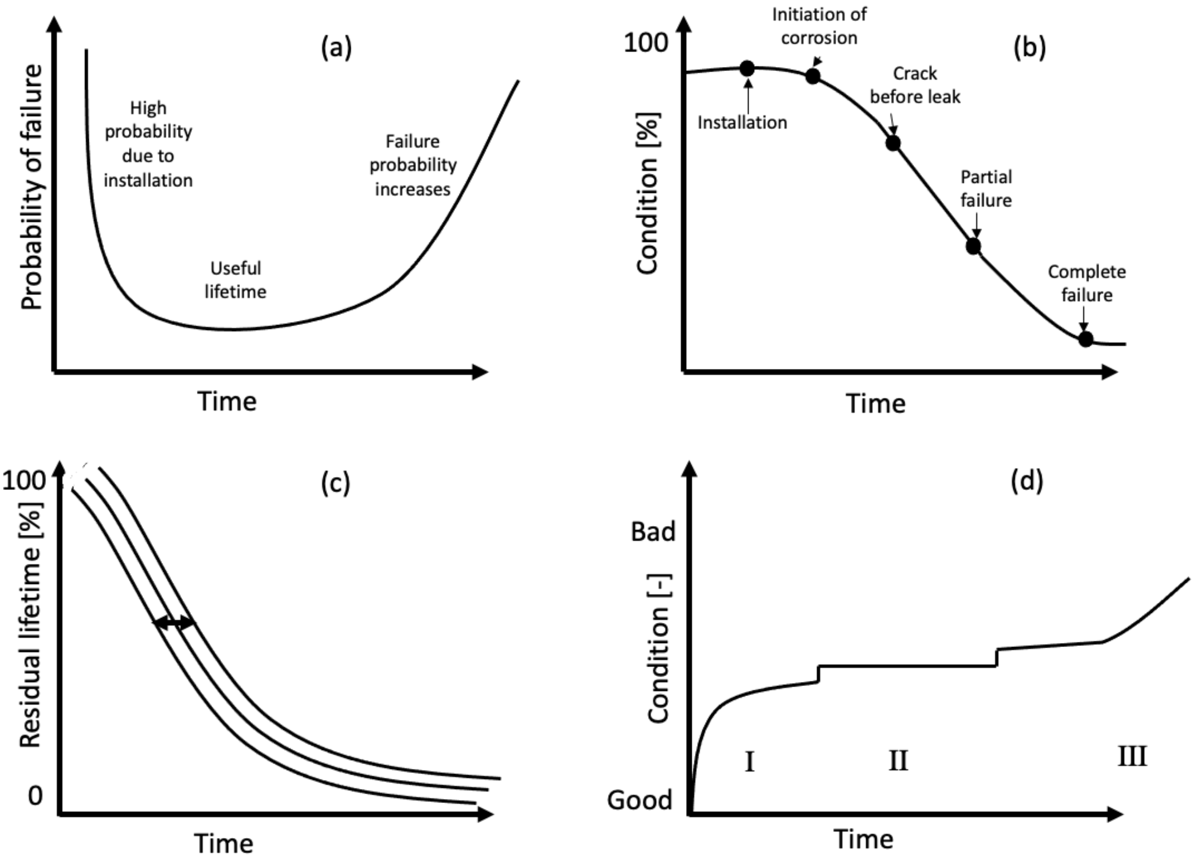


Figure 2-18: Deterioration process and probability of failure. (a) POF as a function of time (Davies et al., 2001). (b) Percentage of condition as a function of time (Misiunas, 2008). (c) Residual lifetime as a function of time (Malm et al., 2013). (d) Condition as a function of time (Lidström, 1996).

Davies et al. (2001) suggested the "bath-tub" curve, Figure 2-18 (a) to represent the probability of failure (POF). In the first phase, the pipe condition is determined by the pipe's initial condition and the installation's quality. The initial condition can be affected in transportation from the factory or caused by manufacturing faults. The second phase is the useful pipe lifetime, where the POF is low. In the third phase, deterioration is present, and the condition gets rapidly worse, and the POF increases.

Misiunas (2008) described the deterioration process (for water pipes) as a declining curve (Figure 2-18, b), where the condition is a hundred percent at the installation process. Initiation of corrosion starts the deterioration process. Fractures or corrosion holes lead to further stress on the pipe, leading to partial failure and complete failure.

The survival curve in Figure 2-18 (c) describes the deterioration process as; residual lifetime as a function of time. Different materials and soil conditions give different curves.

Lidström (1996), Figure 2-18 (d), described the deterioration process as a stepwise decline from good to bad condition. In the first phase, the condition is determined mainly by the installation quality and soil stability. Phase two represents the useful pipes lifetime. External loading, bedding condition, and material influence the condition, and initial fractures, cracks and deformation can occur. In phase three, accelerated deterioration occurs based on the initial defects in phase two. Further, Lidström (1996) research suggested that the declined condition in phase one were atypical. In two years, 95% had an unchanged condition, while 5% had some deformations.

2.4.2 Parameters influencing deterioration

In the following sections, the main parameters influencing wastewater pipe deterioration will be discussed.

2.4.2.1 Material, Age & Era

The two most common material for wastewater pipes in Sweden are concrete and plastic. Generally, different material has different failure patterns and reacts differently to adjacent soil and groundwater. Material has been a significant factor in predicting the deterioration process (deterioration models), where, e.g. reinforced concrete shown more resistance in terms of deterioration than clay or brick pipes (Malek Mohammadi et al., 2020). Pipe age, defined as the time between installation date until time of condition assessment (usually the time of CCTV inspection) or installation date until analysis date has shown a significant factor in most deterioration models. Further, the era of the pipe is defined as a period during which changes in material, production or quality have changed remarkably.

2.4.2.1.1 Plastic

Plastic wastewater pipes were introduced in Sweden in the 1950s and at the time used as pressure pipes. The most common plastic pipes used in Sweden (Malm et al., 2011b) are:

1. Polyethene (PE); and (PE**H**), (PE**L**), and (PE**M**). Where **H**, **L** and **M** stands for **H**igh-, **L**ow- and **M**edium density.
2. Polyvinyl Chloride (PVC).
3. Polypropylene (PP).
4. Glass Reinforced Plastics (GRP).

PE, PVC, and PP pipes are thermoplastic materials, while GRP is a thermosetting polymer. PE, PVC, and PP pipes are flexible, and the material can creep, while GRP pipes are more rigid and consequently can resist higher vertical loads. Generally, PE and PP pipes creeps the most, followed by PVC pipes.

The deterioration of thermoplastic pipes due to loads can be divided into three phases, see Figure 2-19. Phase I represents the useful lifetime; this phase varies among thermoplastic materials. Thermoplastic pipes from the early 50s or 60s can be in Phase 1 in a couple of decades, while newer PE and PVC pipes can be in Phase I for up to a hundred years (Malm et al., 2011b). High loads on the pipe in phase I give ductile deformations due to mechanical stress such as inward bend and change of shape. In Phase II, fractures are present, with ductile and brittle deformations. In phase III, brittle deformations are dominating, and the number of fractures accelerates. The accelerating factor in Phase III is chemical deterioration due to thermo-oxidative ageing (Makris et al., 2020; Malm et al., 2011b).

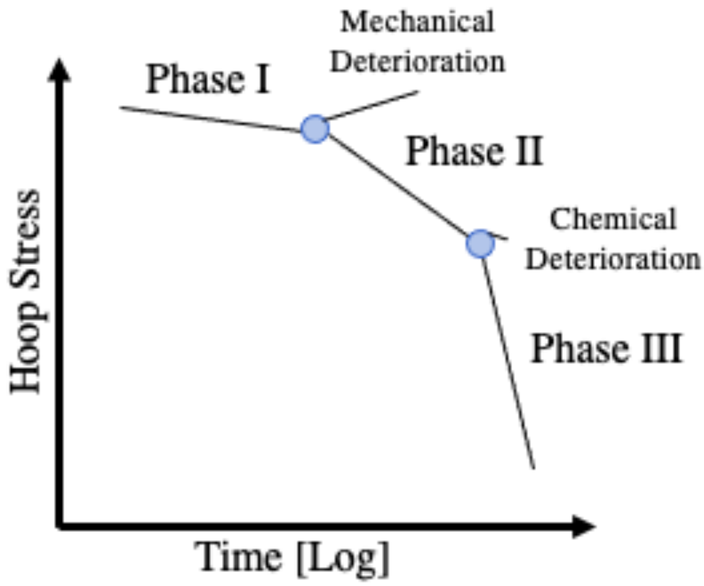


Figure 2-19: Deterioration process for thermoplastic pipes. Adopted from (Makris et al., 2020)

PE pipes have primarily been used as pressure pipes and as rehabilitation (discussed in section 2.6) for concrete pipes, where the new PE pipe is inserted into the old concrete pipe. PVC pipes have historically been used in higher frequency as gravity pipe. GPR pipes have been used on a limited scale.

Plastic pipes are not subject to internal corrosion or corrosion due to corrosive soils. They are also resistant against internal attacks of hydrogen sulfide (H_2S) and to abrasion (Moser and Steven, 2008). The thermo-oxidative degradation of thermoplastic materials is mainly influenced by temperature, light and the internal (hoop) pressure. However, neither the temperature of the wastewater nor surrounding soil in Sweden accelerates thermo-oxidative ageing significantly (TEPPFA, 2014).

Thermoplastic pipes are considered flexible (depending on material) and can resist horizontal movements due to, e.g. soil movements (clays) or small earthquakes better than rigid pipes. Closed-Circuit Television (CCTV) inspections of PVC pipes suggested that most common defects found in other material are present in plastic pipes; such as infiltration, deformation, joint displacement, bending and root intrusion (Makris et al., 2020).

In the mid-70s, the second generation of PE pipes was available to the Swedish market, and in the mid-80s, the third generation. The newer generations have a longer useful lifetime and are more resistant to loads. The third generation of PE pipes shows few defects. The first-generation PVC pipes manufactured before the mid-70s have shown to be brittle and have relatively high failure rates in terms of fractures. The joints in the first-generation PVC pipes were also of poor quality, which led to pipe failure. The second-generation PVC pipes were introduced after the mid-70s with improved material and joints. However, Malm et al. (2013) note that plastic pipe has not been used to a large extent before the mid-70s, see Figure 2-5.

Further, the expected lifetime for plastic pipe in poor conditions in terms of, e.g. corrosive, temperature or settlements is 20 – 40 years. Plastic pipe in optimal conditions can have a lifetime of 150 – 200 years, and the median lifetime is approximately 100 – 150 years (Malm et al., 2013).

2.4.2.1.2 Concrete

Concrete is by far the most common material in the Swedish wastewater pipe network The most common concrete types used in Sweden are:

i. Asbestos concrete.
ii. Sentab-, Arkel- and Premo concrete.

Where asbestos concrete pipes are reinforced with asbestos fibres and Sentab, Arkel and Premo with steel reinforcement.

For concrete wastewater pipes, microbiologically induced corrosion (MIC) is a deterioration process that can reduce the useful lifetime by 50% to 70% and, in extreme cases, 90%. The process of MIC can roughly be divided into four steps (EPA, 1991; Wu et al., 2019):

i. Sulfate-reducing bacteria's (SRB) consumes dissolved oxygen (DO); under these anaerobic conditions, sulfate (SO_4^{2-}) are converted to hydrogen sulfide ($H_2S_{(aq)}$).
ii. Hydrogen sulfide transforms into a gas ($H_2S_{(g)}$).
iii. The gas reaches the pipe's crown and sides, where sulfur-oxidising bacteria (SOB) converts $H_2S_{(g)}$ to sulfuric acid (H_2SO_4).
iv. The sulfuric acid reacts with the concrete, and MIC is present.

The deformations due to MIC are typically located at the crown and sides of the wastewater pipes. The process and location of the MIC are presented in Figure 2-20.

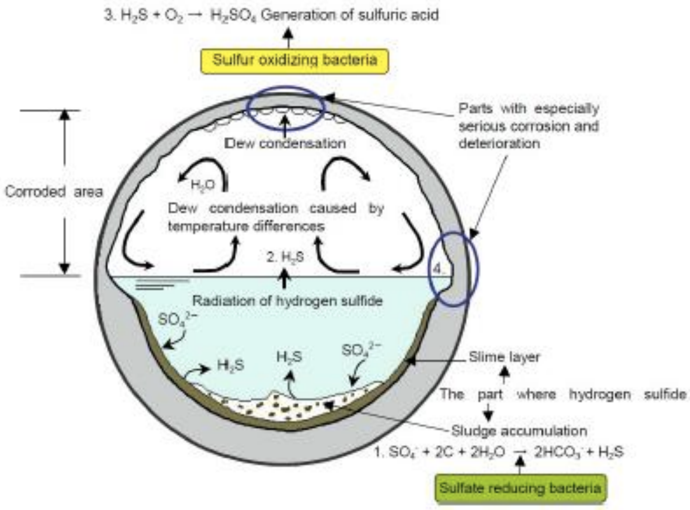


Figure 2-20: The process of MIC and location of corrosion. Retrieved from: (Wu et al., 2019)

The MIC rate in concrete pipes can be between 0,5 to over 10 millimetres per year. The main parameters influencing the presence and rate of MIC are mainly; Sulfate content, more sulfate stimulates SRB; BOD increases nutrients for bacteria; Higher temperature stimulates microbial activity; More SRB and SOB accelerates MIC (Wu et al., 2019).

Further, wastewater pipes with steel reinforcement, galvanic corrosion can attack the steel and form fractures in the concrete. Typically, this phenomenon occurs around small cracks or fractures in the pipes where water get in contact with the unprotected reinforcement.

Common structural failure types found in Swedish concrete pipes are fractures due to high vertical loads and poorly designed joints, resulting in infiltration and root intrusion in joints and connecting service pipes (Malm et al., 2011b).

The first concrete pipes, in Sweden, were introduced in the early 1920s, and regulations regarding concrete pipes strength were published in 1923 (Lidström, 1996). Concrete pipes were manufactured in local and small factories. At this time, over 80% was produced without considering any regulations that impacted the quality. In 1940 the quality of concrete pipes increased, and mass-produced pipes could be made with increased length, which also meant fewer joints. In the late 50s, the production got more advance, and the strength of concrete pipes got better, and the regulations stricter (Lidström, 1996). Further, in the 30s, the concrete pipes' quality suffered due to a lack of raw material in the post-war economy. During the 50s, The Control Council for Concrete (KRB), a control organ for concrete products, started to do cluster sampling, and in the 60s, regulations for concrete pipes strength was established (Lidström, 1996).

Lidström (1996) examined the condition and deterioration of concrete pipes. The deterioration was analysed for concrete pipes concerning dimension, bedding material, burial depth and sewer type (combined, separate or stormwater). The work concluded that pipes installed before 1950 had higher fracture rates than pipes installed after 1950. The author argued that the reason could be the difference in strength. Bedding with filling materials affected pipes installed before 1950 with higher fracture ratios, pipes installed after 1950 did not suffer these defects. Pipes with low burial depth had accelerating deterioration, especially pipes installed before 1950. Dimensions between 225 to 300 millimetres were analysed, but no connection between dimension and failure rates could be seen.

To complement the deterioration process presented in Figure 2-18 (d), Lidström (1996) suggested to separate the different eras of concrete pipes in relation to the change in condition for concrete pipes (Figure 2-21). Line I represent the concrete pipes with the highest lifetime, line II pipes with lower lifetime and line III pipes that suffered defects during installation. Further, the conclusions from Lidström (1996) research showed that line I represented 60% pipe installed before 1950 and 81% of pipe installed after 1950. Line II represented 35% pipes installed before 1950 and 15% pipes installed after 1950.

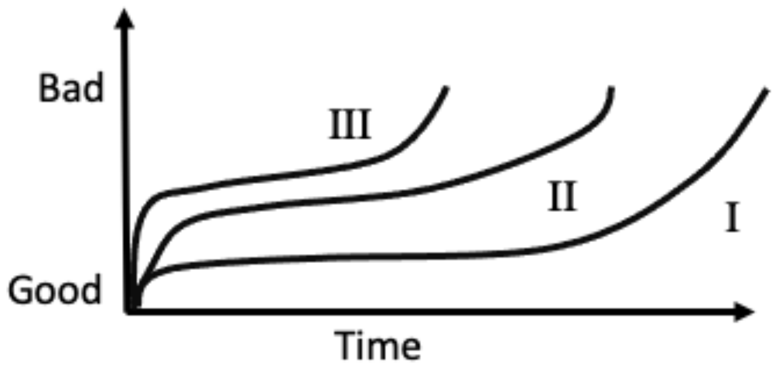


Figure 2-21: Change in condition for different pipe eras. Adopted from (Lidström, 1996)

The short-term, median-term and long-term expected lifetime for concrete pipes are presented in Table 2-6. Where the short-term represent concrete pipes installed in poor condition, the long-term concrete pipes installed in optimal condition and medium-term pipes installed in normal condition.

Table 2-6: Short-term, median-term and long-term expected lifetime. Adopted from (Malm et al., 2013)

Concrete pipes and installation era	***Short-term***	***Median-term***	***Long-term***
Concrete < 1950	20 – 40 years	60 – 100 years	90 – 150 years
Concrete 1950 - 1970	20 – 40 years	60 – 110 years	140 – 180 years
Concrete > 1970	20 – 40 years	110 – 140 years	150 – 200 years

2.4.2.2 Corrosion

Corrosion is mainly a problem in cast iron (CI) and ductile iron (DI) pipes. CI and DI are not used in Sweden as wastewater pipes but has historically been used in high frequency as water pipes. However, corrosion can occur on reinforced concrete pipes if cracks, fractures, erosion, or MIC deteriorate the aggregate, which exposes the reinforcement to corrosion (NAP, 2009).

2.4.2.3 Diameter

Pipe diameter is one of the most used parameters in pipe deterioration models, mainly due to the data availability. Generally, the theory is that pipes with small diameters more frequent breaks due to bending moments (Angkasuwansiri and Sinha, 2013).

A Comprehensive literature study by Wengström (1993) showed that pipe breakage increased with diameters less than 300 millimetres. Further, longitudinal fractures are more common for large diameters pipes, and circumferential breaks are more common for smaller diameters. One argument for the higher break rates was the thinner wall thickness. Other contradictory studies have shown that a larger diameter pipe suffered more defects due to increased weight, which means that defects can occur during transport and installation (Davies et al., 2001).

In deterioration models, diameter as a parameter has been both significant and non-significant. Some deterioration models found higher diameters was related to worse pipe condition (Mohammadi et al., 2020). One explanation is that larger diameter pipes have a greater surface exposed to surrounding soil and the wastewater. The main findings for decreasing diameter leading to worse condition are that small diameters pipes were related to worse condition, includes; larger diameter pipes are installed more carefully; and small diameter pipes suffer from more from beam stresses, blockages, and root intrusion. (Mohammadi et al., 2020).

2.4.2.4 Length

The length of wastewater pipes can be defined in two ways, where the first is the total length of a pipe section, i.e. manhole-to-manhole. The second is the length between joints. This section (and the rest of the thesis) will focus on the section length, which is the definition of length used in deterioration models. Ordinarily, a more extended length section is more vulnerable to ground movements (Angkasuwansiri and Sinha, 2013). Further, longer pipes sections in combination with small diameters are assumed to suffer higher bending stresses. Poorly quality or defective joints are the main reason for infiltration. Hence, a higher frequency of joints leads to a higher probability of infiltration (Davies et al., 2001). In deterioration models, longer pipe sections have been found to increase the probability of breaks (Malek Mohammadi et al., 2020).

2.4.2.5 Slope

For gravity pipes, the slope is significant because it determines the velocity. A flat slope means low velocity, which can lead to; higher risk of sedimentation and (or) blockages; and increases the risk for production of sulfuric acid. On the opposite, higher velocities results in higher operating pressure that increase the axial stresses, leading to fractures or cracks (Angkasuwansiri and Sinha, 2013). In deterioration, predicting models, both steeper and flatter slopes have found to increase the deterioration rate. For flat slopes, the explanation is increased risk for sedimentation, blockages, debris, and the pipe's self-clean ability (Mohammadi et al., 2020).

2.4.2.6 Installation & Environmental impact

The first step in the installation of wastewater pipes is the transportation of pipes from manufacturing to the construction site. Deformations in this phase can be small cracks from the transportation or the installation of the pipes. Typically, pipes are installed in trenches or more minor excavations. The trench width must be designed so that the pipe gets adequate side support (SS-EN 1295-1, 2019).

The bedding is the ground surface in the trench. The bedding and the material must be designed so that it is great enough to give adequate support for the whole pipe (SS-EN 1295-1, 2019). Inadequate bedding, i.e. uneven bedding, makes the pipes act as a loaded beam, which it is not designed for, with the ultimate consequences of circumferential fractures at the top or the bottom of the pipe (see Figure 2-12). Unevenness in the bedding can occur due to poor workmanship in the installation process or be caused by infiltration and exflow due to fractures or cracks in the pipe.

The soil's weight (backfill), often referred to as a dead load, can influence the pipe's condition. Marston's load theory can explain the reaction between the trench, pipe and surrounding soil. The theory is based on the assumption that load from the backfill soil over the pipe depends on the soil reaction (cohesion) between the backfill and trench walls (Rahman, 2010). Where the load, without considering the shearing effect, can be described by Terzaghi's equation (Knappett and Craig, 2012), presented in Equation 2-4.

$$\sigma_v' = \lambda * z - u \qquad \textit{Equation 2-4}$$

Where; σ_v' is the effective vertical stress; λ is the unit weight of the soil; z is the depth; and u the pore water pressure.

The load from the backfill acts differently on rigid pipes, e.g. concrete, and flexible pipes, e.g. PVC. In Figure 2-22, the load theory for (a) rigid pipes and (b) flexible pipes is presented. In the case of a rigid pipe (a), the black pipe represents the pipe before loading and the red after loading. The pipe will be pushed down, and the cohesion between the central prism and the soil at the trench walls will act as an additive load on the pipe. In the case of a flexible pipe, the pipe in Figure 2-22 (b) deforms, but no settlement occurs. The cohesion between the central prism and the trench walls acts upwards, meaning a relative decrease in load on the pipe (Rahman, 2010).

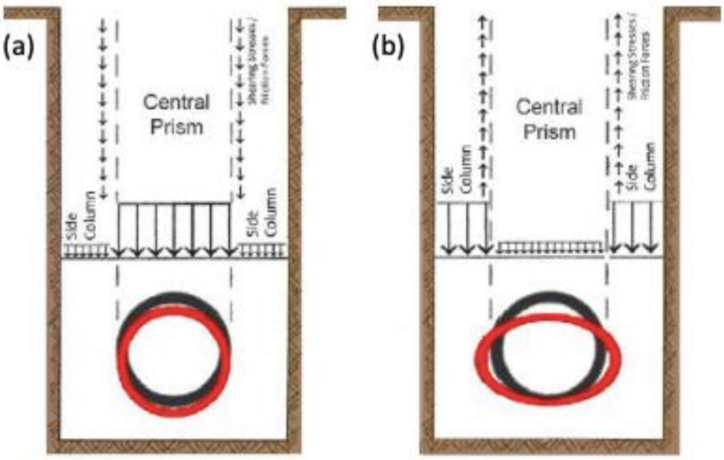


Figure 2-22. Marston's load theory. (a) for rigid pipes, and (b) for flexible pipes. (Rahman, 2010)

The conclusion gives that; Terghazis equation gives that deeper burial depth means higher dead load; and Marston theory says that rigid pipes suffer more relative load than flexible pipes.

The backfill of the trench in the final stage of installation affects the pipe's condition; the surrounding backfill material stabilizes the pipe and affects future settlements; and the degree of compaction affects the pipes structural strength (SS-EN 1295-1, 2019).

In general, a bedding angle of 90° is proof of sound installation. In combination with well-packed backfill, the pipe can manage a higher vertical imposed load. Without side support and (or) 90° bedding angle, the capacity of the pipe decreases. In Figure 2-23, three cases for (a) 90° bedding angle with side compressed backfill as side support, (b) 90° without side support and (c) 0° without side support (Lidström, 1996).

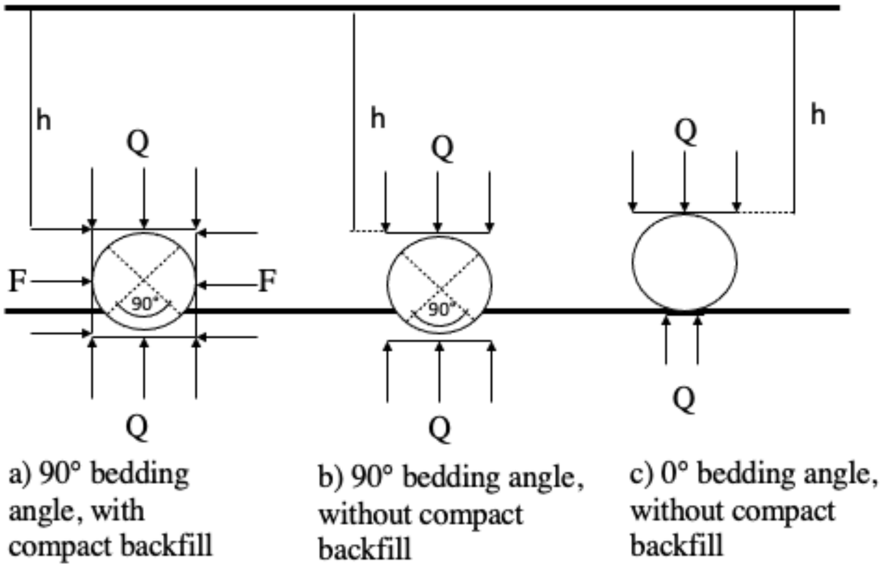


Figure 2-23: Bedding and backfill condition for; (a) 90° bedding angle, with backfill; (b) 90° bedding angle, without compact backfill; and (c) 0° bedding angle, without compact backfill. Where: h is the burial depth; Q the vertical load; and F the horizontal force from side support. Adopted from: (Lidström, 1996)

To exemplify the bearing capacity for a 300 mm concrete pipe in case a, b and c can be dimensioned for 7.8, 6.2, and 2.8 meters burial depth, respectively (Lidström, 1996).

2.4.2.7 External loads & surrounding soil

If the pipe is under or adjacent to roads or highways, live loads will affect the pipe. The load depends on traffic, often measured in average daily traffic (Angkasuwansiri and Sinha, 2013). The vibrations from the traffic can also disturb the bedding condition. However, the load decreases with depth and with burial depths over two-meter, the impact is limited (Lidström, 1996). Under cold temperatures, frost loads can increase the pressure on the pipe, which in turns can lead to cracks or fractures (Rajani and Kleiner, 2001).

Soils where settlements occur, typically clay, ground movements increase the risk for cracks and fracturs due to disturbance in the bedding and backfill soil support. If the wastewater pipe is located under the groundwater table, the risk for infiltration increases. The groundwater flow can also disturb the bedding and backfill (Davies et al., 2001).

For pipes installed before 1940, the installation was executed in narrow and hand-dug trenches. In the late 40s, the excavator was introduced on the Swedish market, and the trenches went from narrow hand-dug trenches with packed backfilling to wider trenches with poorer backfill, resulting in higher risk for settlements and higher vertical loads on buried pipes (Malm et al., 2011b). After 1966 more sufficient regulations have successively been implemented to assure sound pipe installation (Lidström, 1996).

2.5 Consequences of failure (COF)

Consequences of failure (COF) for wastewater pipes are generally be divided into three categories of impact (Baah et al., 2015; Salman and Salem, 2012; Vladeanu and Matthews, 2019).

i. Environmental.
ii. Social.
iii. Economic.

The economic consequences of wastewater failure are the direct cost of rehabilitating the broken or insufficient pipes. Further, the cost for reactive rehabilitation of pipes, i.e. repair, replacing or renovation when the pipe has already have failed, is three to four times more expensive than a proactive rehabilitation (WEF, 2009).

Social consequences are defined as the social costs because of pipe failure. One example is the breakage of a 400mm pipe that broke in Helsinki in 2009. The pipe was adjacent to a subway station where the economic consequence was about five million euros. However, the social costs was that the subway was out of use for three months (Laakso et al., 2017). Another extreme example is soil collapses, which have significant social consequences when they appear adjacent to, e.g. road, railways or other critical infrastructure.

The environmental consequences of wastewater failure are that the wastewater does not reach WWTP and instead pollutes the soil or adjacent water bodies.

2.6 Rehabilitation of wastewater pipes

Rehabilitation of wastewater pipes can be divided into; trenchless renovation, trenchless replacement, open trench replacement and reparation and maintenance. In Figure 2-24 a schematic view of different rehabilitation methods is presented.

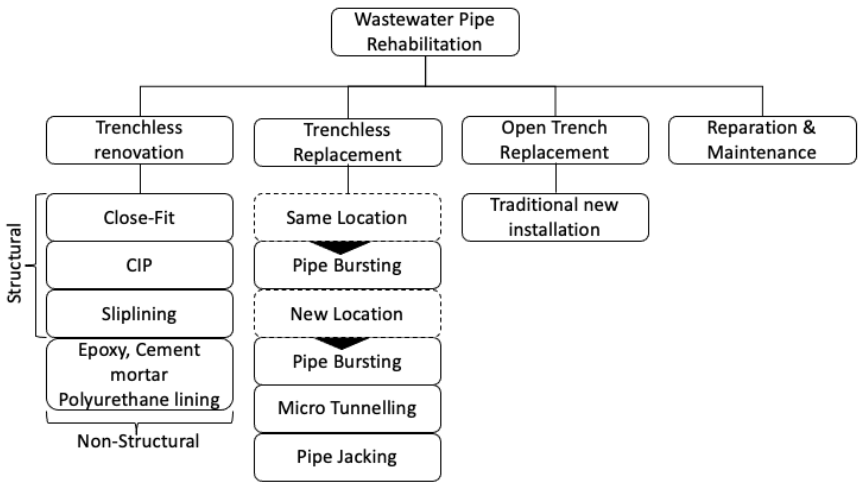


Figure 2-24. Schematic view of Wastewater Pipe Rehabilitation methods. Adapted from: (Borstad et al., 1993; ISTT, 2021)

2.6.1 Trenchless renovation

Trenchless renovations need little or no trench or excavation. Trenchless renovation can further be divided into structural and non-structural. Structural renovations often include a new pipe inserted via various techniques into the old pipe; Non-structural renovations do not significantly enhance the pipe's structural integrity.

2.6.1.1 Close-Fit

Close-Fit lining, which can also be referred to as *Swagelining*, is a trenchless method using PE pipes with the same diameter as the old pipe. The technique uses a continuous PE pipe folded into a U-shape inserted into the old pipe. When the pipe is in place, internal pressure with water steam presses the U-shaped pipe to its natural round shape. This rehabilitation method's benefits are that the new pipe segment is joint-less between manholes or access holes. The drawbacks are that it is complicated and need special equipment (SSTT, 2021a).

2.6.1.2 CIP

Cured-in-place (CIP) is a trenchless method that has been used to renovate wastewater pipes since the early 70s. CIP uses a flexible lining resin-saturated fibreglass or textile material that is installed in the existing pipe. The lining puts in place with internal water or air pressure. When the lining is in place, heat is added, and the curing process finalises the procedure (SSTT, 2021b; USEPA, 2009). Advantages with CIP is that it can be used on pipe with a diameter up to 800mm, it is a trenchless method and the pipes hydraulic capacity gets significantly improved. Disadvantages are that the slope remains the same after the procedure, and if deformations or collapses are present in the pipe segment, point repairs in the form of trenches must be done (SSTT, 2021b).

2.6.1.3 Sliplining

Sliplining is a method where a new pipe with a smaller diameter is inserted, pushed through the old pipe. Sliplining can be executed segmental or continuous within the pipe. The most common material is PE, but other materials can be used. The method is most effective when a decrease in capacity, i.e. smaller diameter, is acceptable (USEPA, 2009). However, the method often requires some excavation at the pipe's endpoints where the new pipe is installed. Further, there is a risk of difficulties with the gap between the old and new pipe (SSTT, 2021f).

2.6.1.4 Non-structural renovation methods

Epoxy, Cement mortar, and Polyurethane lining are non-structural renovations methods that increase pipes' useful lifetime. The installation procedure is based on the lining being sprayed upon the initial inner-pipe wall until an adequate layer is present; multiple layers can be used. The method is usually used to prevent further corrosion and is mainly used on water pipes made of CI or DI to enhance the water quality (SSTT, 2021c).

2.6.2 Pipe replacement

As the name implies, *Pipe replacement* is the procedure where the old pipe is replaced with a new pipe. From Figure 2-24 three types of replacements can be defined. The traditional open-trench method is described in section 2.4.2.6, where the new pipe is installed in an excavation or trench. Two trenchless methods will be described; Pipe bursting replaces the old pipe with a new one at the exact location as the old pipe; Pipe Jacking and Microtunneling presses or tunnelling new pipe at the location of choice.

2.6.2.1 Pipe Bursting

Pipe Bursting is a trenchless method to replace pipes with a new one, with the ability to use the same, less, or larger dimensions. A bursting head with a larger diameter is pushed through the old pipe and breaks it. As the bursting head moves through the old pipe, a new pipe, commonly PE, is put in place. Pipe bursting is most commonly used to rehabilitate main pipes, pressure pipes, or service (lateral) pipes (SSTT, 2021e). The advantages are the possibility to change the pipe's diameter, it is fast and can be applied in many situations and that it is trenchless, i.e. no excavation is needed. The disadvantages are that there is a need for temporary wastewater service during the installation period. Further, the method is ineffective when the pipe segment includes numerous service pipes.

2.6.2.2 Pipe Jacking & Microtunneling

Pipe Jacking is often used to install steel or plastic gravity pipes in clay. The pipe is pressed through the soil with a steering device in the front. The method is usually used for new or re-installation. The main advantages are that no excavation is necessary, and that the groundwater table is not affected, which minimises the risk of settlements. However, if obstacles occur in the installation process, excavations may be needed (SSTT, 2021d).

Microtunneling is a trenchless method where a remote-controlled drilling robot penetrating its way through the soil or rock from manhole-to-manhole, and the pipe, usually concrete, is successively installed. The advantages are that it is precise and can handle various diameters. However, the technique does not work adequately in clay (SSTT, 2021d).

2.6.3 Maintenance & Repair

Jetting is a hydraulic cleaning method using high-velocity water sprayed on the pipe walls. Jetting can remove roots or FOG from the pipe, recreating the entire cross-sectional area and increasing the hydraulic capacity (WEF, 2009).

Mechanical cleaning uses, e.g. scrapes or brushes, to remove roots, debris and FOG that the jetting cannot remove. Mechanical cleaning can damage flexible pipes, i.e. plastic pipes (WEF, 2009).

Chemical root control can be used after mechanical or jetting maintenance to ensure no regrowth will be present (WEF, 2009).

Grouting is a non-structural repair type. Grouting is usually made of polyurethane formulations, and the purpose of grouting repair is to reduce the permeability of the soil in the trench, external grouting, or to seal openings or holes inside the pipe, internal grouting (WEF, 2009).

When addressing structural repairs, the *open-cut* method is the oldest one. The method includes excavating where the defect is located and repair in place or replacing it. More modern types of restoration are *Robotic Localised Repair*. The method comprises a Robot controlled by CCTV cameras inserting epoxy material in voids, holes or defect joints (WEF, 2009).

2.7 Condition assessment

The definition of condition assessment by USEPA (2009) is:

".. the collection of data and information through the direct inspection, observation, and investigation and in-direct monitoring and reporting, and the analysis of the data and information to make a determination of the structural, operational and performance status of capital infrastructure assets."

Condition assessment in this thesis will mainly regard CCTV inspections. In Figure 2-25 a schematic view of the condition assessment process presented by Zhao et al. (2001) is presented.

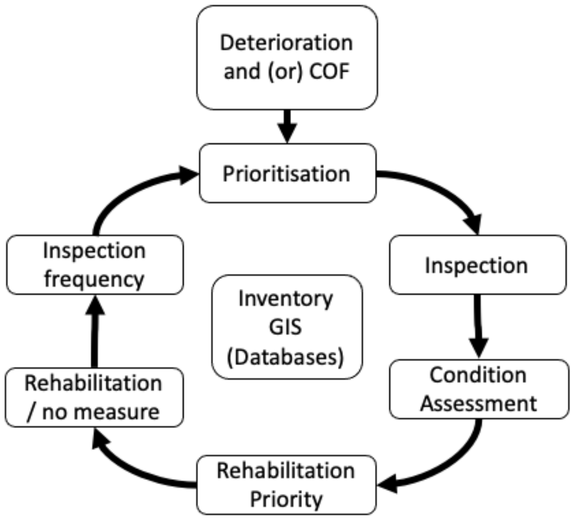


Figure 2-25: Condition assessment process. Adopted from (USEPA, 2009; Zhao et al., 2001)

2.7.1 Closed-Circuit Television (CCTV)

Closed-Circuit Television (CCTV) is the most used inspection type to determine wastewater pipe condition. As the name implies, CCTV inspections deliver data in the form of video or frames from inside the pipe. In Sweden, CCTV inspections was introduced in the 1960s, and in 1985, Swedish Water and Wastewater Association (SWWA) published the first guidelines for CCTV inspections. In 1994 the condition assessment protocol Kortbetyg (KB) was introduced. Further, CCTV technology has developed through the years with better frame quality (SWWA, 2006). The traditional CCTV inspection generally follows the following steps (Liu and Kleiner, 2013):

i. CTTV apparatus is mounted on a carrier and introduced via an access point (e.g. a manhole).
ii. The CCTV is operated to capture video frames that can represent the condition of the pipe.
iii. Video data is analysed with a condition assessment protocol.

The quality of CCTV inspection depends on several factors. The most important are the quality of observation, the water level in the pipe, picture quality, analysis of the data, and water level in the pipe.

Zoom Cameras, like traditional CCTV, collects still images and (or) video data. The difference is that the Zoom Camera is mounted on a stationary mount. Hence, the technology is suitable for inspection in manholes and screening for more thorough CCTV inspections. The disadvantages compared to traditional CCTV is the range of the inspection, while the advantages are that it is less costly and time-consuming (Selvakumar et al., 2014).

Digital scanning is similar to traditional CCTV; a digital scanner is mounted on a carrier and operated inside the pipe. The main difference is that Digital Scanning uses one or two high-resolution (HD) cameras with wide angles lenses resulting in 360d spherical images, i.e. it is fair to say that Digital scanning is the state-of-the-art CCTV method. The main disadvantage compared to CCTV is higher costs (Liu and Kleiner, 2013).

2.7.1.1 Obtained data and analysis from CCTV inspections

From CCTV inspections, various defects are evaluated, where the primary defects considered in CCTV inspection are:

Operational defects

- Root intrusion.
- Debris & Encrustation.
- Sediment.
- I & I.
- Settled & Attached deposits.

Structural defects

- Cracks.
- Breaks/Collapse/Fractures.
- Deformation.
- Joint displacements.
- Surface Damage.

The analysis of the CCTV inspections is evaluated with a condition assessment protocol. The protocols generally use weights to determine how severe the spotted defects are, where the combination or sum of the weights adds up to a structural or operational grade. In Sweden, KB is used to grade the condition of the pipes. The most used international standards (discussed in 4.4) are Water Research Centers (WRCs) MSCC5, The Pipeline Assessment and Certification Program (PACP), and Large Sewer Condition Coding and Rating (LSCCR).

The grading and observed defects differ from condition assessment protocols. However, the significant defects evaluate are similar. In the following sections, observations and grading from the Swedish KB system perspective according to the guidelines presented by Bäckman et al. (2005); SWWA (2006)

The defect codes are used to determine the structural condition of the pipe. In the Nordic systems, each defect's grade is a grade between 1 to 4, where one is a minor defect, and four is a severe defect. Defects regarding the dimension or cross-sectional area uses the threshold values in Table 2-7.

Table 2-7 Percentual change in dimension or cross-sectional area. Adopted from: (Bäckman et al., 2005)

Grade	*Defect [%]*
1	< 5%
2	5% - 15 %
3	15% - 30 %
4	> 30%

2.7.1.2 Deformation

Deformations are grade according to Table 2-7 and characterised as; vertical, the pipe's height is reduced; Horizontal, the pipe's width is reduced; Point deformation, the change is centralised at a point. In Figure 2-26, CCTV inspection of deformation is presented at the top and the bottom, percentual deformation with associated grade.

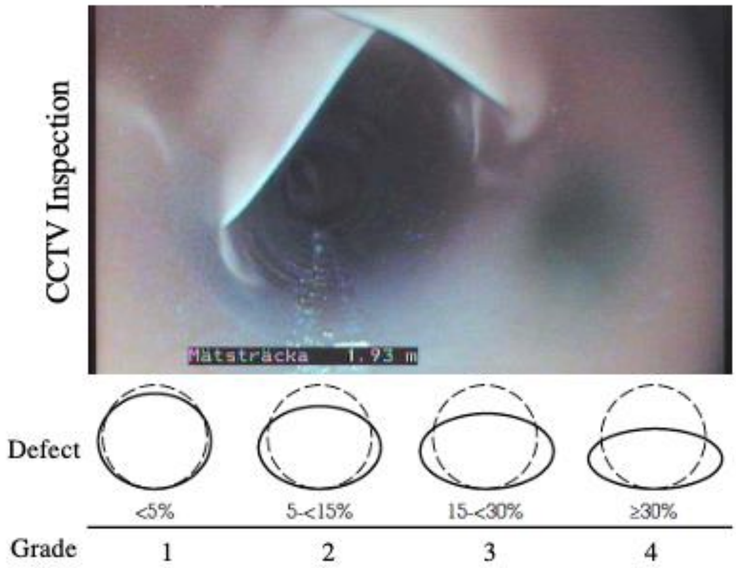


Figure 2-26. CCTV inspection representing deformation grade 4. In the bottom, percentual deformation with associated grade. Retrieved from: (STVF, 2012)

2.7.1.3 Fissures/Cracks

Fissures, translation from (Bäckman et al., 2005), or Crack, as international term, are characterised as a longitudinal, circumferential, or complex fracture. Cracks are graded between 1 and 3 where:

1. Cracks are only visible at the surface.
2. Cracks are present on the pipe wall.
3. Open cracks in the pipe wall.

Further, if cracks are severe, instead of grade them with a four, they are graded as breakage (collapse).

In Figure 2-27 a CCTV inspection of a collapse is presented to the left, and to the right, a longitudinal fissure/crack.

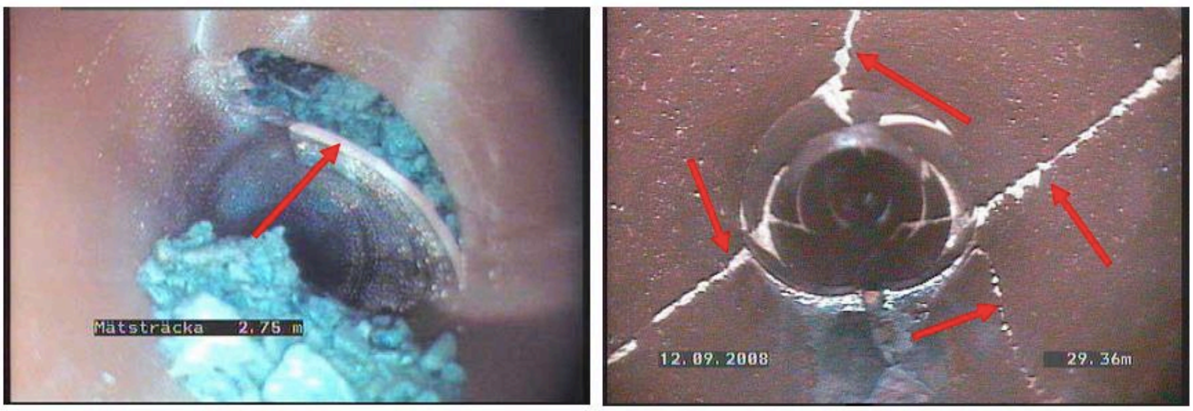


Figure 2-27. CCTV inspection of Fissures. To the right, a pipe collapse and to the left, a longitudinal fissure. Retrieved from: (STVF, 2012)

2.7.1.4 Break/Collapse

Collapse is the ultimate breakage. Breakage is defined as when chunks are missing or displaced, and collapse is defined when the shape has deformed to the degree where the pipe's structural integrity is lost. Pipe breaks are graded as:

1. Not used.
2. Displaced chunks of pipe but no loss of pipe wall.
3. Chunks are missing from the pipe wall.
4. Collapse.

2.7.1.5 Surface damage

Surface damage refers to the inner pipe walls condition. The condition can be affected by mechanical process, e.g. erosion, or chemical process, where the most common are corrosion in iron pipe and MIC in concrete pipes. Surface damages are graded as:

1. Increased roughness.
2. Further increased roughness, aggregate in concrete is present.
3. Aggregate is missing, or reinforcement is present.
4. Chunk(s) of the pipe wall is missing.

In Figure 2-28 a CCTV inspections of surface damage is presented, where a concrete pipes aggregate is present to the left and to the right, a chunk of the pipe wall is missing.

Figure 2-28. CCTV inspection of surface damages. To the left, aggregate is present. To the right, a piece of the pipe wall is missing. Retrieved from: (STVF, 2012)

2.7.1.6 Intruding connections and sealing material

Intruding connection is a lateral (service) pipe that decreases the cross-sectional area. Intruding sealing material occurs when the sealing ring is displaced. Intruding sealing material both reduce the condition of the pipe and the operation status, i.e. infiltration or exflow can occur. Intruding connection and sealing material are graded according to a percentual reduction in the cross-sectional area according to Table 2-7. Intruding connections does not necessarily influence the hydraulic function (decreased cross-sectional area) of the pipes, but there is a risk for infiltration with this type of defects.

2.7.1.7 Displaced joints

Joint displacements can occur due to angular, radial or longitudinal movements. Joint displacements are graded as:

1. Displacements are less than ½ pipe wall thickness.
2. Displacements are between ½ and the wall thickness.
3. Displacements are between wall thickness and two times wall thickness.
4. Displacements are more than two times wall thickness.

In Figure 2-29 CCTV inspection of displaced joints are presented.

Figure 2-29. CCTV inspection of displaced joints. Retrieved from: (STVF, 2012)

2.7.1.8 Operational defect codes

Root intrusion, attached deposits, settled deposits, and other obstacles are all graded according to the percentual reduction in cross-sectional area, according to Table 2-7.

Infiltration is graded by the amount of water infiltrated from surrounding soil and graded by:

1. Sweating.
2. Dropping.
3. Streaming.
4. Pouring.

In Figure 2-30 CCTV inspections of operational defects are presented, where attached deposits (to the left) and root intrusion (to the right) is presented.

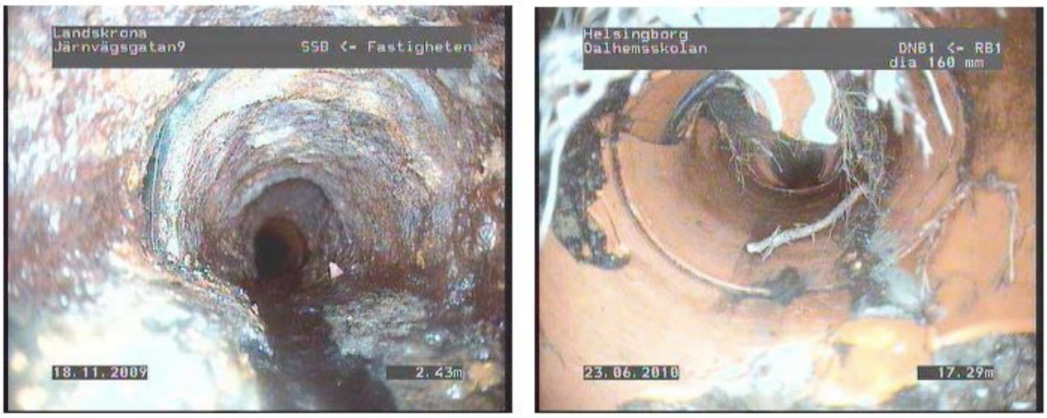


Figure 2-30. CCTV inspections of operational defects. To the left, attached deposits and to the right, root intrusion. Retrieved from: (STVF, 2012)

2.7.2 Other inspections technologies

Although CCTV is the most used technology, other technologies are on the market with various purposes. In the following sections, some of these technologies will be summarised.

2.7.2.1 Laser Profiling

Laser inspection follows the same category as CCTV, Zoom Camera, and Digital scanning, i.e. visual inspections. There are numerous types of Laser inspection technologies. However, laser profiling's main advantages are the ability producing 3D scanned profiles of the pipes profile with an accuracy of 0.03% (Selvakumar et al., 2014). Further, the scanned profile is compared to a reference profile of the pipe.

2.7.2.2 Acoustic Technologies

Acoustic inspection technologies in the category of inspection types using vibrations and (or) sound waves. Generally, there are three types of acoustic inspection types:

i. Leak detectors.
ii. Acoustic monitoring systems.
iii. Sonar and Ultrasonic.

Leak detectors can identify leaks, even tiny ones, using microphones over and under the waterline (aquaphones), where the sounds are analysed manually or with more advanced computer-based software (USEPA, 2009).

Acoustic monitoring has usually been used on prestressed concrete cylinder pipes (PCCPs) and can provide continuous monitoring of deterioration. The technology analyses the condition of the pipe with acoustic signals and can detect breaks and corrosion. However, no individual defects are analysed. Hence, the technology is mainly used as a screening technology.

Sound Navigation and Ranging (Sonar) scanning uses high-frequency ultrasonic sound waves that reflect on the pipe walls and can recognise defects such as pipe geometry, defects on pipe walls and cracks. Sonar used under the waterline can identify debris and sediment. It should be noted that Sonar is often used in combination with CCTV inspections (Liu and Kleiner, 2013; USEPA, 2009).

2.7.2.3 Electrical & Electromagnetic techniques

As the name implies, *electrical and electromagnetic* currents are used in this category of technologies. Standard methods are Eddy Current Testing (ECT), Remote Field Eddy Current (RFEC) and Magnetic Flux Leakage (MFL) inspections. These methods are often used in CI or DI pipes.

3 Conceptual model

The conceptual model is divided into the parameters influencing POF and COF. In Figure 3-1, the most significant parameters accelerating the deterioration process is presented. The model can be summarised as including; the physical properties of the pipes, e.g. age, diameter, material and length; environmental parameters such as soil type, vertical loads, groundwater table, wastewater content and bedding condition; operational information, including, e.g. blockages, sediment, debris and root intrusion.

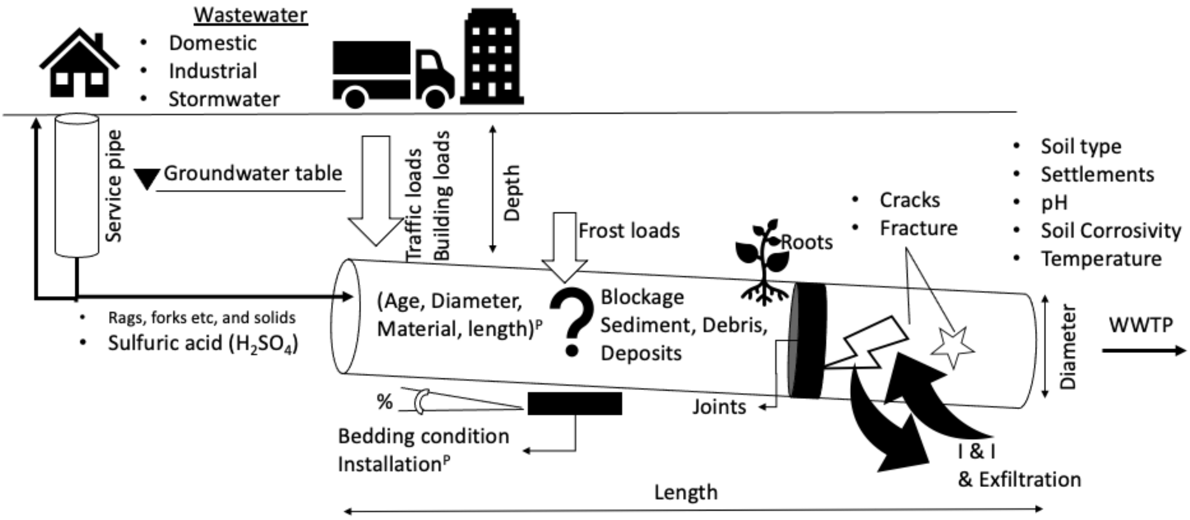


Figure 3-1: The conceptual model for POF including parameters accelerating the deterioration process.

In Figure 3-2, the parameters influencing COF with the associated hazardous event is presented. The hazardous events can be summarised as exflow, CSOs, SSOs, backup flooding's, and adjacent object or land areas where wastewater failure and exflow would significantly have economic, social and (or) environmental consequences.

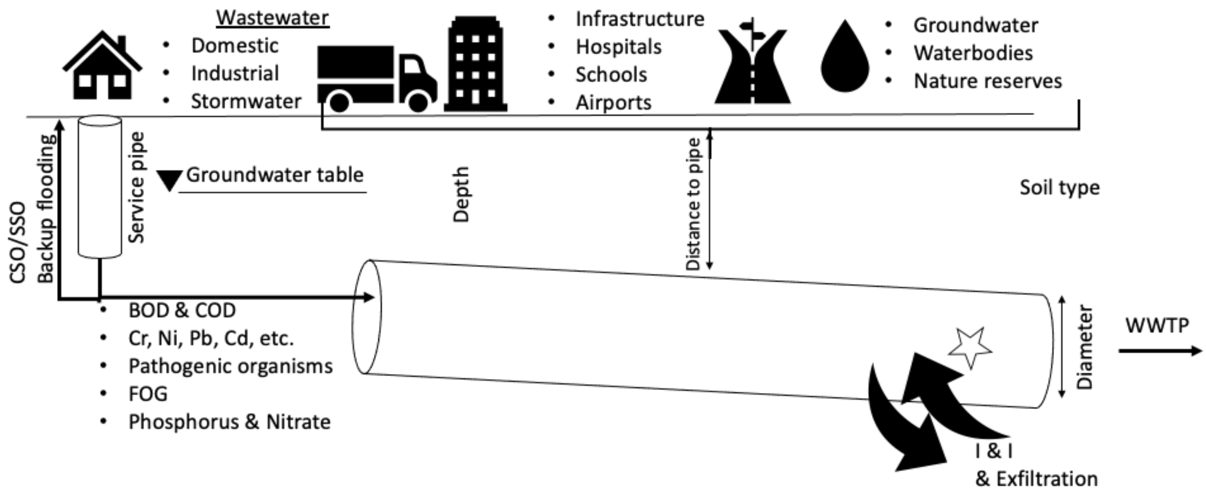


Figure 3-2: The conceptual model for COF including hazardous events due to wastewater pipe failure and associated parameters influencing the magnitude of COF.

4 Review of risk-based methods

This section of the thesis aims to review available research, methods and strategies applicability in a risk-based rehabilitation model.

The literature review has been conducted using the following keywords in Scopus: *"wastewater" AND "rehabilitation" OR "deterioration" OR "optimization" AND "sewer" OR "pipe" AND "risk" OR "risk assessment" OR "risk management" OR "asset management" OR "Condition assessments" AND "probability" OR "consequences" OR "decision making" OR "failure"*. Further, cross-references from essential articles, dissertations and reports have been used to get an overall picture.

A schematic view of the various methods to determine probability of failure (POF) and consequences of failure (COF) are presented in Figure 4-1.

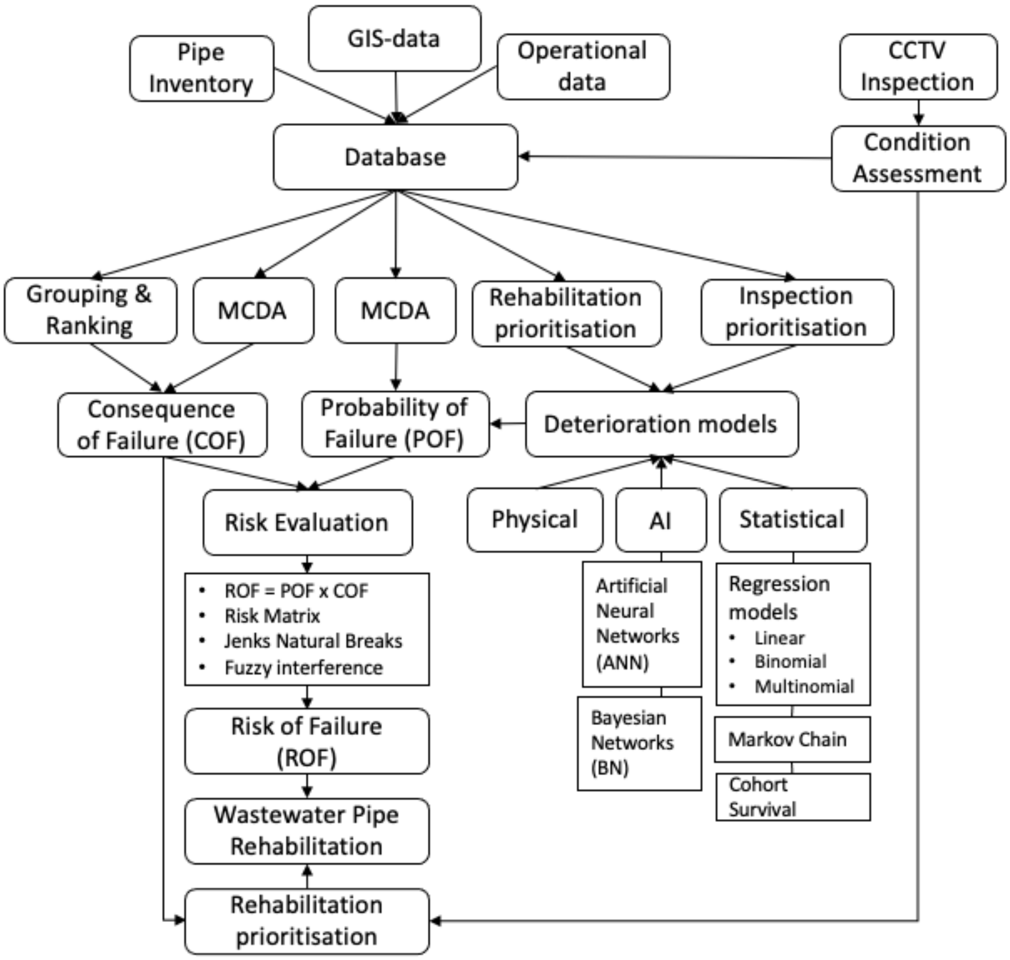


Figure 4-1: Schematic view of the literature reviews most significant findings.

The different steps in Figure 4-1 can be described as the most significant findings in the literature review, where the following steps can summarise the essence of the studied methods:

i. The data used in the reviewed literature the consists of a combination of GIS data, Operational information, pipe inventory and CCTV inspections.
ii. The data is used to predict COF and POF, where POF has been assessed by predicting the deterioration process using physical methods, artificial intelligence, Multi-Criteria Decision Analysis (MCDA), or statistical models to either set up at rehabilitation or inspection priority. COF has mainly been based on environmental data, e.g. objects or land areas where a pipe failure would significantly impact the society regarding the economy, public health, environment and infrastructural assets. Further, to evaluate COF, MCDA methods have been used frequently, along with more straightforward ranking and grouping of consequence levels.
iii. Risk evaluation determines ROF using the combination or product of COF and POF.
iv. The wastewater pipe rehabilitation has been evaluated using ROF or by combining CCTV Inspections (Condition assessment protocols) with COF.

4.1 Databases

In all literature reviewed regarding COF, POF, and deterioration models, the data (or) databases are essential. Data utilised in the databases can be broken into four categories:

i. Pipe inventory.
ii. Operational data.
iii. Geographic information system (GIS).
iv. CCTV inspections.

Pipe inventory is the data connected to the pipe's physical properties such as installation date (age and era), material, length, slope, burial depth and diameter.

Operational data is including, e.g. customer complaints, basement flooding's, CSOs and SSOs and I&I.

GIS-data have been used to estimate POF by collecting geographical information that affects the pipe condition, e.g. soil type, soil corrosivity, and water table. Moreover, to evaluate COF, GIS data is essential. In the reviewed literature, the practice is to measure the distance between the pipe and objects or land areas, which would suffer unwanted consequences in case of wastewater pipe failure. In Figure 4-2, a schematic illustration of the use of GIS data is presented, where the object can be a road, waterbody, or others.

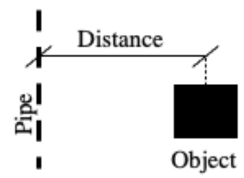


Figure 4-2. Schematic view of the use of GIS data and determine COF

CCTV inspections have been practised in two ways in the reviewed literature. Where the first is to use the structural and (or) operational graded, discussed in 4.2, to evaluate the condition and directly, among other factors, evaluate risk and rehabilitation priorities. The second way is using the structural and (or) operational grade to build deterioration models, which will be discussed further in section 4.2.2 and 4.2.3.

4.2 Probability of failure (POF) & deterioration models

From a risk-based perspective, evaluating the probability of failure (POF) is essential. From previous research, POF is often evaluated as the state of deterioration or as a product of condition assessment. Further, in the reviewed literature, two main reasons for designing deterioration models were found:

i. Rehabilitation prioritisation
ii. Inspection prioritisation

Rehabilitation prioritisation models give decision-support for renovation and replacement, and *inspection prioritisation models* for a strategically inspection plan.

Two comprehensive reviews have been written about deterioration and deterioration models regarding buried wastewater pipes (Hawari et al., 2020; Mohammadi et al., 2019). These two, and several other articles forms the base of this review. Further, Mohammadi et al. (2020) reviewed factors influencing the condition of wastewater pipes. These factors are summarized in Table 4-1.

Table 4-1. Factors influencing the condition of wastewater pipes. Adopted from (Malek Mohammadi et al., 2020)

Physical (pipe) parameters	***Environmental parameters***	***Operational parameters***
	Bedding material	
Installation (method)	Ground movement	Blockages, Burst &
Pipe age	Ground movement	Maintenance history (failure
Pipe depth	Root interference	records)
Pipe diameter	Groundwater level	Debris
Pipe length	Road (type, characteristics, and	Flow velocity
Pipe material	flow), or another surface type	Hydraulic condition
Pipe shape	Soil corrosivity	Infiltration/Exfiltration
Start & End elevation	Soil type	Pipe type
	Surface type	Sediment level

In the following sections physical, artificial intelligence, MCDA and statistical models will be reviewed.

4.2.1 Physical models

Physical and deterministic models combine the pipes physical characteristics (e.g. material) with the deterioration process in-situ by internal and external stresses (e.g. traffic loads or frost loads). Rajani and Kleiner (2001) review physical models, where individual components such as: frost loads, pipe-soil interaction, residual structural resistance, and corrosion index are evaluated. Further, Rajani and Kleiner (2001) discuss deterministic physical models where, e.g., mathematical relationships of corrosion depth and pipe age predict the pipe's remaining wall thickness.

Physical deterministic models are, in general, more correct in describing the deterioration process than statistical or artificial intelligence models when only one parameter (e.g., corrosion) and one type of breakage or failure type (e.g., longitudinal fractures) is considered (Hawari et al., 2020). However, there are shortcomings of the models. Corrosion models are usually specific for only one type of pipes (e.g., ductile iron), based on laboratory tests, or only take, e.g. vertical loads or displacements, into consideration (Rajani and Kleiner, 2001).

4.2.2 Artificial Intelligence (AI) models

In this thesis, two AI models for predicting deterioration are reviewed, Bayesian Networks (BNs) and Artificial Neural Networks (ANNs). First, a brief description of the differences between statistical and AI and (or) Machine Learning (ML) models are explained. Firstly, AI models and Statistical models have been distinguished in the review literature. Secondly, statistical models describe the relationship between the dependent variable (outcome) and the independent variables by minimising the means squared error. In contrast, AI and ML models are not designed to prove relationships between variables but mainly about predicting the outcome (Stewart, 2019). To summarise, statistical models' strengths are the ability to show relationship and significance between variables and AI models to solve complex and non-linear problems but are not always explainable.

4.2.2.1 Bayesian networks

Bayesian networks (BNs), also referred to as Bayesian Belief Networks (BBNs) or causal network, are used to graphicly simulate system with incomplete understanding and uncertainties. The base of BNs is Bayes theorem (Equation 4-1):

$$P(A|B) = \frac{P(A)P(A|B)}{P(B)}$$ *Equation 4-1*

Where *P(A)* is the probability of event A, *P(B)* is the probability of the event *(B)*, and $P(A|B)$ is the probability of A given the event B. BNs are built on nodes and with links connecting them. Each node represents a variable, continuous, e.g., age (years) or diameter (mm) or discrete like material, e.g., PVC or concrete (Nielsen and Verner Jensen, 2007). In Figure 4-3, a schematic view of a BN is presented. A and B represent a continuous or discrete variable, C is the event resulting, given A and B. Further, event D is the resulting event if C occurs.

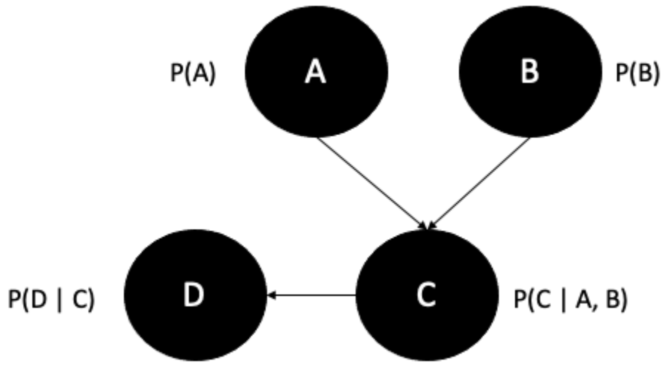


Figure 4-3: A schematic view of a Bayesian Network with links and nodes.

Anbari et al. (2017) used BNs to calculate POF as a function of either structural or operational failure. The study was conducted as a basis for prioritising CCTV inspections. The study's data consisted of 513 pipes in a separate wastewater pipe system with 200 – 600 millimetres diameter. The material consisted of PVC and asbestos cement with age between 5 - 40 years. Further, various failure event data, CCTV reports, GIS maps and expert opinions were used. 752 datasets were available for the study, where 70% was used to train the model and 30% for validation. The BN was conducted with the software Hugin, which predicts the relationships between variables using the Expectation-Maximization (EM) algorithm. The parameters used in the model is presented in Table 4-2.

Table 4-2. *Failure type, deterioration process, and parameters used. (Anbari et al., 2017)*

Failure type	***Deterioration process***	***Parameters***
Structural	Erosion & corrosion	Age, material, velocity, cathodic protection, cover and coating
	Deformation	Age, material, diameter, and burial depth, traffic
	Cracks or fractures	Age, diameter, burial depth, GW-level, and traffic
Hydraulic	Leakage	Age, material, connections, GW-level
	Blockages (sediments or roots)	Trees, age material, diameter, velocity, (separate/combined)

The POF was presented on a 0 – 100 scale (to fit COF) and grouped into classes: very low (0 – 20), low (20 - 40), moderate (40 – 60), moderate to high (60 – 80), and high (80 – 10). The model's accuracy was 64.5% for the whole network, 52.1% for the failure events and 68% for the non-failure events.

Ghavami et al. (2020) used a similar BN to calculate POF, using; pipe characteristics: age, material, diameter, and burial depth; and CCTV reports, GIS maps, failure event databases, and interviews with experts. Further, 70% of the collected data was used to learn the model and the rest for validation. The BN's accuracy was 83.33% for all pipes, 40.68% for failure pipes, and 99.98% for non-failure pipes.

Elmasry et al. (2018) used a defect-based BN divided into a; static analysis, where the condition at present was evaluated; and a dynamic analysis that predicted the condition in the prospect. The data used in the model were CCTV inspections, including structural grading, operational condition grading, and overall condition grading (WRC protocols). Pipe characteristics such as age diameter, length, material, and street category were also used. The BN was designed according to WRCs condition assessment protocols' defects, where structural and operational failure is considered. The BN is presented in Figure 4-2.

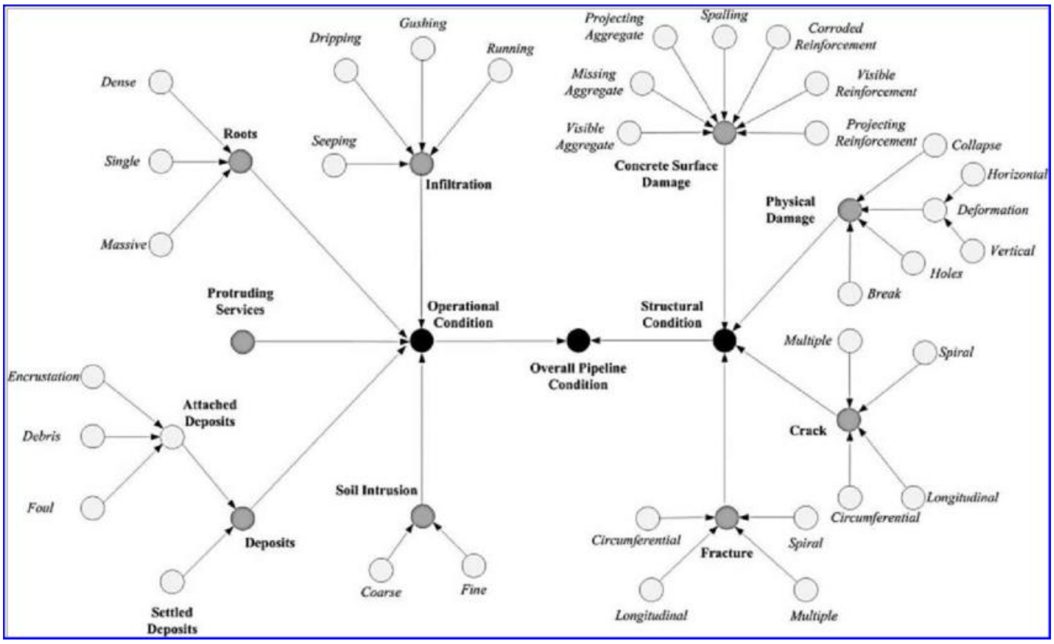


Figure 4-4: The defect based Bayesian Network, based on Water Research Centres (WRCs) condition assessment protocol. Adopted from:(Elmasry et al., 2018)

Further logistic regressions were used to predict the operational and structural deterioration process and when a pipe transfers to undesirable operational or structural condition. The results showed that the BN overestimated low structural, operational and total condition grades and overestimated higher grades. The BN was validated with a randomly chosen dataset from the collected data. The validation was performed applying Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) with values of 0.67, 1.06, 0.56 and 1.05, 1.60, 0.95 for structural, operational, and overall conditions, respectively.

4.2.2.2 Artificial neural networks

Artificial neural networks (ANNs) are based on the human brain structure, i.e., an ANN takes in information and learns how the input data relates to and affects the output data. A typical ANN design is shown in Figure 4-5, where the input layer is information put into the ANN. The hidden layer consists of neurons that summarise the input data with weights for each line connecting the neurons with input data. The output is then calculated using an activation function, often the sigmoid function. Further, the ANN calibrates under supervised learning, where the error in estimated output calibrates the neuron (Lek and Guegan, 2000).

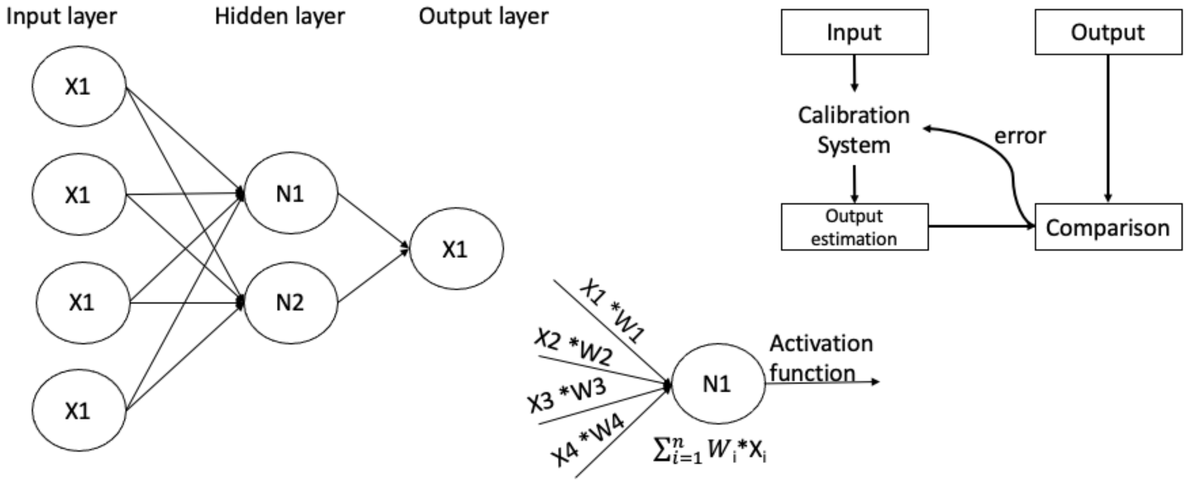


Figure 4-5 To the left, a schematic view of a typically Artificial Neural Network (ANN). In the middle, the neuron in the hidden layer receiving input from the input layer and activated by the activation function. To the right, the process scheme of ANNs.

Kerwin et al. (2020) used ANN to predict failure of water pipes. In the case study, the average pipe age was 33 years and with a variety of material; cast iron (CI), ductile iron (DI) and polyethene (PE). The data used in the ANN consisted of; pipe characteristics such as material, diameter, age, and length; and failure reports and GIS data. The study found that the following parameters were affecting the condition: previous failures was the primary influence, followed by age, soil type (silt), and the pipe material DI.

Sousa et al. (2014) compared ANNs, logistic regression and Support Vector Machines (SVMs) in a case study consisting of 120 km pipes. Data used in the study was material, age, length, burial depth, and slope. As the output, two condition categories were developed based on the WRC condition assessment protocol. Category 1 considered pipes that did not require immediate rehabilitation and equal WRC grades of 1, 2 and 3. Category 2 regarded pipe where rehabilitation considered necessary and equal WRC grade 4 and 5. The study showed that ANNs had the best prediction rate of 73% to 81%.

The advantages of using ANNs are that they can evaluate deterioration and probability of failure when the relationship between input variables and output are unclear and can identify non-linear processes. The disadvantages are that they depend on big datasets and that design of ANNs is a complex process (Hawari et al., 2020).

4.2.3 Statistical models

In deterioration models, three main statistical models have been used (Hawari et al., 2020; Mohammadi et al., 2019; Mohammadi et al., 2020):

i. Regression models.
ii. Markov Chains.
iii. Cohort survival.

4.2.3.1 Regression models

Three regression models have been evaluated in the review literature (Fahrmeir et al., 2013; Salman, 2010):

i. Linear regression.
ii. Binomial logistic regression.
iii. Multinomial logistic regression.

Linear regression is the simplest form of regression models, with the general for presented in Equation 4-2.

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots \beta_n X_n + \in \qquad \textit{Equation 4-2}$$

Where; Y is the dependent value; $X_1, X_2, \ldots, X_n$ are independent variables; α = intercept at y-axis; $\beta_1, \beta_2, \ldots, \beta_n$ are regressions coefficients; $\in$ = error term.

Further logistic regression can be used when the dependent variable does not continuously respond to the independent variables. In binomial logistic regression, the dependent variable takes values of $Y \in \{0|1\}$, e.g., non-failure or failure. The general form is presented in Equation 4-3.

$$\log(Y) = \ln \frac{P(Y=1)}{1 - P(Y=1)} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots \beta_n X_n = LE \qquad \textit{Equation 4-3}$$

And the probability of P(Y=1), is given by Equation 4-4.

$$P(Y|X_1, X_2 \ldots X_n) = \frac{1}{1 + e^{\alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots \beta_n X_n}} \qquad \textit{Equation 4-4}$$

Where the Logistic Equation (LE) is the linear predictor, summarising the intercept, independent variables (α, X_i, β_i). The linear regression and logistic regression are presented in Figure 4-6 where the linear regression (to the left) forms an approximate linear relationship between the independent variable x and the dependent variable y. To the right the logistic regression is presented where the scatter are the predictions for the binary outcome (Equation 4-4).

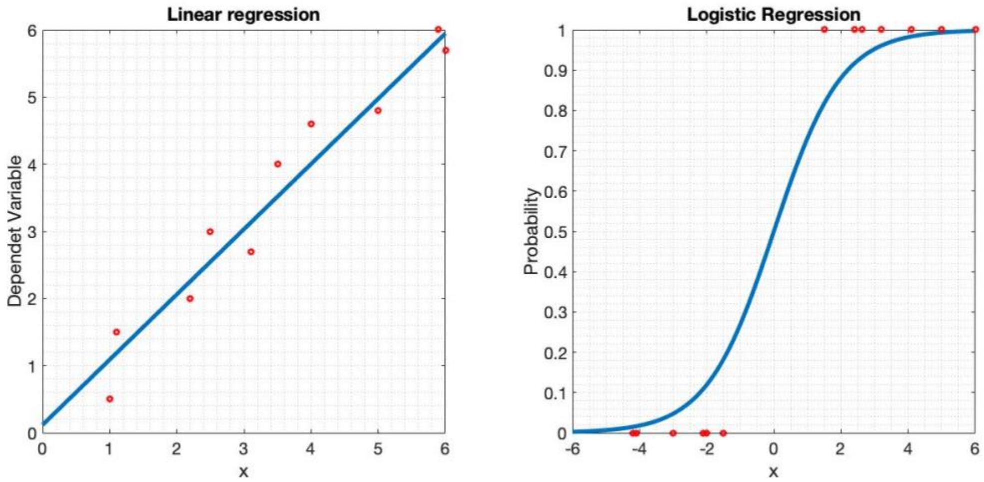


Figure 4-6: To the left, the linear regression for the dependent variable y and independent variable x. To the right the logistic regression with the probability on the y-axis and independent variable x on the x-axis

Gadem et al. (2016) used linear regressions to evaluate the structural grade of wastewater pipes. The dependent value was based on CCTV inspection grades where the following state of condition (dependent variable) was used: Excellent (1), Good (2), Fair (3), Poor (4), and Bad (5). Further, the independent variables consisted of the following pipe characteristics: material, diameter, age, and burial depth. The linear regression proved that age and the constant held the highest significance, accompanied by burial depth. The R-squared was equal to 0.87, i.e. the independent variables can explain 87% of the variance. The final model suggested by Gadem et al. (2016) to predict pipes' condition is presented in Equation 4-5.

$$Pipe\ Index\ =\ 0.678 +\ 0.092 * age\ +\ 0.00095 * burial\ depth$$ *Equation 4-5*

Ariaratnam Samuel et al. (2001) used binary logistic regression to evaluate the condition of wastewater pipes. Further, as the dependent variable, PACP (WRC) grades were used. Structural grade 1, 2 3 was considered acceptable, and grade 4 and 5 indicated the need for rehabilitation. The data used consisted of pipe characteristic: age, diameter, burial depth, material, and type of wastewater pipe system. The binary regression model used Equation 4-6 to determine the pipe condition.

Equation 4-6

$$\log(\frac{\pi}{1-\pi}) = a\ + \beta_1 X_1\ +\ \beta_2 X_2 + \ldots \beta_n X_n$$

The results showed that the constant age, diameter, and wastewater pipe system (combined or separate) was significant, while burial depth and material had low significance. Further analysis of the results showed that with every added year in age, the deficiency in condition increase by 2.62%, and with 100mm increased diameter, the deficiency increase by 32.3%

Chughtai and Zayed (2008) used multinomial regression to determine operational and structural grades, according to the WRC condition assessment protocol. The data used in the model was based on environmental data, pipe characteristics, and CCTV inspections, where the WRC grading 1 – 5 (acceptable to critical) was used as the dependent variable. Parameters used as independent variables in the model to estimate the dependent variable for structural grade (based on WRC grade) was; age, length, diameter, burial depth, bedding condition, and pipe material. Further, parameters used as independent variables to estimate operational grade was: material, age, length, diameter, and slope. The data were divided into training data (80%) and validation data (20%).

Chughtai and Zayed (2008) regression models resulted in four equations were Equation 4-10 predicted operational grade and Equation *4-7*, Equation *4-8*, and Equation 4-9 predicted structural grade for asbestos cement, concrete, and PVC, respectively. Further, the regressions models statistical validity was investigated using R-squared. For asbestos cement (Equation *4-7*), concrete (Equation *4-8*), and PVC (Equation 4-9), the R-squared was 72.7%, 82.4% and 81.8%, respectively. For the operational condition (Equation 4-10), R-squared was equal to 87.9%.

Asbestos cement (AC)

$$Structural\ Grade = \sqrt{20.9 + 542\frac{\log Diameter}{Length} + 0.207Age - 0.742AC - 14.8Diameter}$$

Equation 4-7

Concrete (C)

$$Structural\ grade = (3.94 + 0.592\frac{logDiameter}{Length} - 0.00681e^{StreetCategory} - 3.22log10depth - 1.6\frac{logAge}{C} + 6.92\frac{Logdepth}{Bedding\ factor} - 5.75\frac{1}{Beddingfactor})^{-1}$$

Equation 4-8

PVC

$$Structural\ grade = (2.25 - 0.00642Age - 1.89Length^{0.01} - 0.0302Beddingfactor - 0.0405StreetCategory - 0.0000(Diameter)^{0.3}(depth)^{4}$$

Equation 4-9

Operational (AC), (C), PVC

$$Operational\ grade = (\frac{0.308 + 0.567\frac{Age}{Diameter}Lentg^{slope}}{Age})^{\frac{1}{0.63}}$$

Equation 4-10

Salman and Salem (2012) used a risk-based approach to identify pipes with a high risk of failure (ROF) using the product of the POF and COF. To determine the POF, binary logistic regression and multinomial logistic regression was used, with numerical variables: diameter, length, slope, age and depth, and categorical variables: material, roadway type, and wastewater pipe type. PACPs condition grades was used as the dependent variable and transformed to the fit the multinomial logistic- and logistic regression models (Table 4-3).

Table 4-3. Transformation from PACP condition grades to dependent in Salman (2010); Salman and Salem (2012)

Multinomial regression	***Binary logistic***	***PACP – Condition rating***
1	0	0 -1
2		2 – 3
3	1	4 - 5

Further, Salman (2010) used binary and multinomial regression models in a case study consisting of 1,373 wastewater pipes. The material where mainly vitrified clay (51.61%) and concrete (22.98%). The mean age was 78.72 years with a standard deviation equal to 28.77 years. Classification tables were used to evaluate the accuracy of the models. The results are presented in Table 4-4, where the white diagonal a correct predictions and blue cells (under estimations) and red cells (over estimations) incorrect predictions.

Table 4-4. Classification tables used to evaluate the regression models in Salman (2010); Salman and Salem (2012)

Multinomial logistic regression				
Observed	Predicted			Percent correct predicted
	1	2	3	
1	2254	216	845	68.0%
2	1063	254	1238	9.9%
3	594	200	2434	75.4%

Binary logistic regression			
	Predicted		
Observed	0	1	Percent correct predicted
0	4683	1187	79.8%
1	1612	1616	50.1%

The multinomial regression model predicted condition grade 1 and 3 quite well (PACP grade 0 to 1, and 4 to 5). However, for pipes in condition class 2, only 9.9% was predicted by the model. The binary logistic model observed non-failure pipes well, 79.8%. However, for failure pipes, 50.1% was correctly predicted.

Linear regression models are considered relatively easy to develop, and they visualize how the independent variables relate to the dependent variable. However, the linear relationship to describe POF has been criticised for not representing the non-linear deterioration process (Mohammadi et al., 2019). Logistic regression models, on the other hand, is better to predict POF. Logistic regression also has the advantage that no assumptions are needed for independent values and doesn't require any advanced computer resources. The main disadvantage is the need for a lot of complete data (Hawari et al., 2020).

4.2.3.2 Markov Chains & Cohort survival

Markov Chains are a stochastic model with the aim to describe the deterioration process. Markov Chains are built on a transition matrix (Hawari et al., 2020), Equation 4-11 and Equation 4-12.

$$= \begin{pmatrix} P11 & \cdots & P1m \\ \vdots & \ddots & \vdots \\ Pm1 & \cdots & Pmm \end{pmatrix}$$ *Equation 4-11*

$$\sum_{j=1}^{m} P_{ij} = 1(for\ i\ =\ 1,2,3,\ldots m)$$ *Equation 4-12*

Where; Pij is the probability of pipe to be in condition j, at the current state i. Markov chains assume that the present condition determines the following condition, e.g. a pipe with condition P_1 moves to P_{12} in the next step.

Cohort Survival models are similar to Markov Chains because both describe the deterioration process and use a transition function. Baur and Herz (2002) presented Equation 4-13 to predict deterioration.

$$R(t) = \frac{(A+1)}{A+e^{B(t-C)}}$$ *Equation 4-13*

Where R(t) = percentage of pipe in same condition class at time t, A = vector of ageing, B = vector of transition parameter, and C = vector of resistance.

Further, for different pipe groups, e.g., material, A, B, and C must be calculated. Cohort survival models are easy to use and can predict the transition time between different condition grades. However, to build a solid model, there is a need for a significant amount of sequential CCTV inspections.

Markov Chains advantages are that they can model complex and non-linear process. Markov Chains are also dependent on CCTV inspections, and the transition matrix can be hard to determine (Hawari et al., 2020).

4.2.4 Multi-Criteria Decision Analysis (MCDA)

In the articles reviewed, Vladeanu (2018) estimated POF using Triple Bottom Line (TBL) and Analytical Hierarchy Process (AHP), discussed in 0, where the following categories and parameters were included; Pipe characteristics including: age, material, diameter, length, and shape; External conditions including: burial depth, soil type, traffic load, corrosivity, seismic zone, groundwater level; Hydraulic & other factors including: PACP scores, flow, inflow, pipe surcharge, and repair history. In this paper, the AHP framework set the weights, a Multi-Criteria Decision Analysis (MCDA) method, where stepwise comparison of each parameter affects consequences (Triantaphyllou, 2000). Further Consistency Index (CI) and Consistency Ratio (CR) are calculated to verify the expert opinions consistency in the matrix's grading.

Further, a comprehensive review has been written by Tscheikner-Gratl et al. (2017) regarding the applicability of MCDA models in rehabilitation prioritisation of buried pipes (water, wastewater and gas). The authors distinguished three different MCDA models compared against each other where:

i. The value measured models: Use scoring for each alternative, where weights are assigned to each parameter and criteria (AHP and WSM).
ii. Goals, ambition and reference, oriented models: Determines how the alternatives stand against the aims from expert and (or) stakeholders (TOPSIS).
iii. Outranking models: Compares alternatives through pairwise comparison, finding the alternatives' strengths and weaknesses (ELECTRE and PROMETHEE).

Tscheikner-Gratl et al. (2017) stated that AHP had been the most common method used in determine POF (28.3% of review articles) for water and wastewater assets. With the advantages of highlighting CI and CR, and the use of qualitative and quantitative criteria. The disadvantages are that the stepwise comparison between alternatives can lead to compensation effects and that application can be complicated. The simplest MCDA tool, Weighted Sum Method (WSM), was used in 3.8% of the articles. The AHP and WSM method will be discussed further in section 0.

As the second category MCDA models, Technique for order preference by similarity (TOPSIS) was the least used (1.9% of reviewed articles). TOPSIS aim to determine the alternative closest to the ideal and far from the most negative associated alternative.

The third category of MCDA models included ELECTRE from the French, Elimination Et Choix la realite, used in 15.1% of the reviewed articles, and Preference Ranking Organisation Methods for Enrichment Evaluations (PROMETHEE), used in 13.2%, where both represent the outranking methods.

The study was performed in a small municipality, all MCDA methods discussed above were implemented, and the difference in results was examined to evaluate variations between the methods.

The pipe criteria were divided into three categories of influencing parameters; Condition, including diameter, material, age, and hydraulic capacity; Importance, including sewer type and economy, where the economic criteria are the depreciation; Street level, including the number of manholes and connections. The different parameters were assigned a performance value between 0 and 100, where 0 was the best-case scenario and 100 the worst-case. The various models' ranking was examined by looking at the standard deviation of ranking between the models. The results are presented in Table 4-5.

Table 4-5. Comparison of MCDA models. Adapted from (Tscheikner-Gratl et al., 2017)

σ	*AHP*	*WSM*	*ELECTRE*	*PROMETHEE*	*TOPSIS*
AHP	X	2.94	6.00	3.30	2.81
WSM		X	4.72	4.38	4.27
ELECTRE			X	5.10	7.10
PROEMTHEE				X	4.31
TOPSIS					X

The study concluded that the different MCDA models performed varying outcomes due to the difference in scoring algorithms. It couldn't be said which model provided the most accurate results, just that the simple models such as AHP and WSM were as consistent as more complex methods such as PROMETHEE. Further, the authors suggested that the AHP and WSM models are not preferable when dealing with many criteria. AHP, WSM, and TOPSIS methods are also more straightforward to implement using, e.g., EXCEL, and no programming is necessary.

4.2.5 Summary of POF

To summarise the reviewed models, their advantages and disadvantages, the following conclusion can be concluded:

- Physical models can be used to evaluate one deterioration process at a time, e.g. corrosion rate or live loads. However, with the knowledge that deterioration processes for wastewater pipes are affected by many parameters, physical models suffer limitations.
- Cohort survival and Markov chains advantages and disadvantage is the ability to predict the condition of groups of pipes. Further, the models require sufficient data to indicate transition condition.
- Regression models have shown to be an adequate tool to estimate the condition of wastewater pipes. Generally, CCTV gradings have been used as the dependent variable and pipe characteristics and environmental data as independent variables. Further, the relationships between dependent and independent variables can be determined with different tools to show significance.
- AI models have been as good as regression models to estimate condition. The models can handle numerous data and non-linear problems. The disadvantages are the complexity of building the models and understand the relationship between variables.
- MCDA models are depended on how the weighting is performed and which model is used. Different models have their strength and weaknesses; the model chosen should be in terms of the experience using the model and awareness of the disadvantages.

As a supplement to the conclusions, the parameters used in the literature review and in Hawari et al. (2020); Malek Mohammadi et al. (2020); Mohammadi et al. (2019) reviews are ranked based on the level of usage (Table 4-6).

Table 4-6. Summation of the most frequently used parameters evaluating POF. Adapted from: (Hawari et al., 2020; Mohammadi et al., 2019; Mohammadi et al., 2020)

Level of usage	***Parameters***
High	Age, Material, Diameter, Burial depth, Sewer type
Moderate	Soil type, Slope, Flow, Groundwater level, Traffic volume, Road or street category, Bedding type, Soil corrosivity, Flow, Installation year, Expert opinions
Low	Land use, Repair history, Number of connections, Number of trees, Shape

4.3 Consequences of failure (COF)

In the conceptual model of the literature review of rehabilitation strategies, Multi-Criteria Decision Analysis (MCDA) is commonly used to determine COF. MCDA models are used when several criteria in a decision-making process are evaluated. Further, MCDA is useful when criteria conflicting with each other or criteria are expressed in different units (Triantaphyllou, 2000). Besides MCDA, direct grouping or scoring have been used to determine COF.

4.3.1 Weighted Sum Model (WSM)

The Weighted Sum Model (WSM), Equation 4-14, is one of the most common used MCDA models.

$$A_{WSM} = \sum_{j=1}^{n} W_j \times a_{ij}, \quad \text{for } i = 1, 2, 3, \ldots, m$$

Equation 4-14

Where: A_{WSM} = weighted score, the alternatives, i = 1, 2, 3, ...m, Wj equals the number of weights for j = 1, 2, 3, ...n, and a_{ij} the sub-criteria value for the j-th criteria and the i-th alternative.

Zhao et al. (2001), as a part of National Research Council Canadas (NRCs) guidelines for Large Sewer Condition Coding and Rating (LSCCR), used WSM to evaluate COF using five identified impact factors: pipe location, embedment soil, diameter, burial depth, pipe system, and seismic zone, with weights (Wj) of 0.2, 0.16, 0.16, 0.16, 0.16, 0.6 respectively. For each impact factor, a sub-criteria value (a_{ij}) assigned between 1.0 (low), 1.5 (medium), and 3.0 (high) depending on severeness.

Salman and Salem (2012) used WSM model based on geographical data (GIS). Sixteen parameters were identified with the help of expert opinions. The parameters were divided into three categories; economic impact, factors equal to direct costs, e.g. operation, maintenance or replacement costs; environmental impact, factors where wastewater discharge would impact, e.g., waterbodies or nature in general; Social impact, factors that could disturb, e.g., infrastructure or roads. Weights (Wj)between 1 -10 and sub-criteria values (a_{ij}) from 0 to 100 were set for: roadway type, distance to the railway, location in the city centre, the function of the pipe section, landslide potential in the area, type of consumer, burial depth, lateral connection, diameter, complaints, and proximity to rivers and streams, parks and recreational areas, and downstream of wastewater pipes.

Baah et al. (2015) used WSM to evaluate COF with the following consequence parameters: Roadway type, proximity to railway tracks, pipe diameter, burial depth, pipes located in the city centre, adjacent building, and proximity to; hospitals, schools, rivers, parks or recreational areas. The data was collected using ArcGIS. The total COF was calculated as the sum of weights and sub-criteria values. Further, Baah et al. (2015) used Jenks natural breaks classification to minimise the deviation in the same class and maximize the variation between classes. The COF was then presented on a 1 to 5 scale: very low, low, medium, high, and very high. The model was used in a case study with 4656 pipes, where 6% received high to very high COF.

Anbari et al. (2017) used WSM to evaluate COF, with weights between 0 and 10, and sub-criteria values (a_{ij}) between 0 and 100. The weights and sub-criteria values were a product of expert opinions. The parameters used to determine the COF were; Cost of pipe repair as a function of diameter and material; Wastewater origin, e.g., from industries or hospital; Proximity to public infrastructure such as airports, subways, and hospitals; Roadway type included freeway, ringway; Proximity to buildings, hospitals, and significant commercial and public centres; and pipes located within the influence radius of wells. Further, the sum of weighted scores was divided into COF categories: very low (0 – 20), low (20 – 40), moderate (40 – 60), moderate to high (60 – 80), and high (80 – 100).

4.3.2 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a method where decision-makers or experts pairwise compare various alternatives (Saaty, 1990). In Figure 4-7 a 4x4 matrix illustrates the alternatives pairwise compared and the rank of importance value.

	A_1	A_2	A_3	A_4
A_1	1	a	b	c
A_2	1/a	1	e	d
A_3	1/b	1/e	1	f
A_n	1/c	1/d	1/f	1

Rank of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values

Figure 4-7. AHP grading matrix and rank of importance. Adapted from: (Saaty, 1990)

Where the diagonal is equal to one, due to A_i compared to A_i are of equal importance. In the example, A_1 compared to A_2 is equal to (a), A_1 compared to A_3 is equal to (b), A_1 compared to A_4 is equal to (c), and so forth. Where a, b, and c can take any number from 1/9 to 9.

Further, the matrix is normalized by the sum of each column. The weights are then calculated by sum the rows and divided them by the number of rows. The weights and sum of weights are then used to calculate the eigenvalue, λ. Saaty (1990) developed the Condition Index (CI), to evaluate the consistency in ranking the matrix, Equation 4-15.

$$CI = \frac{\lambda max - n}{n - 1}$$ *Equation 4-15*

Where n equals the number of alternatives. Further, the Consistency Ratio (CR) is calculated with Equation 4-16.

$$CR = \frac{CI}{RCI} < 0.1$$ *Equation 4-16*

Where CR < 0.1 equals consistent grading, and the Random Consistency Index (*RCI*) equal to the number of alternative (n-th alternatives) value in Table 4-7.

Table 4-7. Random Consistency Index (RCI) for nth alternatives. Adapted from: (Vladeanu, 2018)

n	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Vladeanu and Matthews (2019) estimated COF using TBL where the following categories and parameters were included; economic cost including: age, length, burial depth, access, distance to laterals, soil type, and seismic zone; social cost including: proximity to infrastructure and laterals, traffic; environmental cost including: proximity to infrastructure, distance to water bodies, and land use. In this paper, the AHP framework set the weights, where stepwise comparison of each parameter affects consequences (Triantaphyllou, 2000). Further CI and CR are calculated to verify the expert opinions consistency in the matrix's grading.

Ghavami et al. (2020) used a 9 x 9 AHP matrix to evaluate weights for the following criteria; Roadway type, diameter, burial depth; and adjacent to health centres, educational areas, residential areas, streams, green spaces and water pipes. The CR value of the AHP model was 0.08, with the highest weight assigned to Burial Depth. Further, the AHP scoring was combined with Data Envelopment Analysis (DEA) in order to quantitively rank the pipes within the dataset.

4.3.3 Other Methods

Besides from the MCDA methods WSM and AHP other methods to evaluate COF have been used. Firstly, WRC classifies the COF into three categories, A to C, where:

A. Represents pipes where the cost of pipe failure would imply the highest costs, and the social impact of loss in service would be significant.
B. Represents pipes where the economic and social consequence is high but lower than category A.
C. Represents pipes where the economic and social costs are less than both categories A and B.

All categories take diameter, road type, and proximity to essential infrastructure such as hospitals, educational or industrial areas into consideration (Rahman and Vanier, 2004; WRC, 1984).

Further, the Swedish Water and Wastewater Association (SWWA, 2021) have suggested a scoring system where the following parameters are giving a score of 1 or 0; separate system, combined system, water pipe located under wastewater pipe (risk for pollution), the risk for exflow to protected water areas, proximity to water bodies (<10 m), proximity to roads, pressure pipe over 200 mm, repeated complaints, proximity to essential infrastructure and pipes with burial depth over 5 meters. The scoring of each parameter is used to evaluate the consequence on a 1 to 5 scale, where one is the lowest consequence and five the highest. The thresholds for each consequence group are presented in Table 4-8.

Table 4-8: Consequence scoring system recommend according to SWWA

SWWA Scoring system					
Parameter Score	0	0	0	$0 < x < 3$	$3 <= x$
Consequence Group	1	2	3	4	5
Impact	Low	...	...	...	High

4.3.4 Summary of COF

To summarise the literature review regarding evaluating COF, the following conclusion can be drawn:

- The consequences of wastewater pipe failure are complex and multicriteria problems. Generally, in the literature review, MCDA has been used, and WSM or AHP models in particular.
- The COF is generally divided into three categories of consequences where:
    - Economic consequences represent the direct cost of failure, e.g. replacement or renovation.
    - Social consequences are the consequences affecting infrastructure, such as closed roads due to reparation work.
    - Environmental consequences are, e.g. contaminated soil or water bodies.
- The majority of the reviewed literature uses some form of GIS software to collect information.

Further, to complement the summary, the parameters used to determine COF is ranked by level of usage in Table 4-9.

Table 4-9. Summation of the most frequently used parameters evaluating COF.

Level of usage	***Economic***	***Social***	***Environmental***
High	Diameter, burial depth (access to pipe)	Proximity to; Roads; Railway; Hospitals; Business areas; Educational areas	Proximity to; Lakes (water bodies); Nature reserves etc.
Moderate	Material, Length, Soil type, Seismic Zone*	Average daily traffic	Embedment soil
Low	Age, Proximity to critical laterals	Proximity to critical laterals.	Proximity to other laterals

4.4 Condition assessment guidelines & protocols for CCTV inspections

CCTV inspections are used to evaluate the structural and operational condition of wastewater pipes. The advantages of CCTV inspections compared to deterioration models are that CCTV inspections give more accurate information about the pipe condition. In this section, the Swedish condition assessment protocol KB, will be compared with Water Research Centres (WRC), The Pipeline Assessment and Certification Programs (PACP), and National Research Council Canadas (NRC) system.

4.4.1 Kortbetyg (KB)

Kortbetyg (KB) is a CCTV defect coding system developed by Nilsson and Stahre (1994), mainly used in Sweden. The system is divided into structural and operational grading protocols. When evaluating the structural grade, the matrix in Table 4-10 is used. Each defect for the CCTV inspections is graded between 1 – 4, with a given weight ranging between 0 and 100.

Table 4-10: Kortbetyg grading matrix for Structural grade. 1: Abbreviations are in Swedish. Adopted from: (Nilsson and Stahre, 1994)

Defect[1]	***Grade 1***	***Grade 2***	***Grade 3***	***Grade 4***
Fissure/Cracks (SPR)	3	6	24	
-circumferential (SPC	2	4	16	
-longitudinal (SPL	3	6	20	
-multiple (SPU)	4	8	24	
Break/Collapse (RBR)	36	54	75	100
Deformation (DEF)	6	18	54	100
Surface damage (YTS)	0.1	6	54	100
Displaced Joints				
- Radial (TFK)	0.01	1	18	36
- Longitudinal (LFK)	0.01	8	24	24
- Angular (RIA)	0.1	1	1	1
Blocking Service Pipe (INH)	0.01	3	9	24
Blocking Joint (INT)	1	6	18	18
Hole (HÅL)	1	6	6	6

Further Total Score, Average Score, And Peak Score are evaluated using Equation *4-17*, Equation *4-18*, and Equation *4-19*, where r_i is the associated weight.

$$Total\ Score = \sum_{i=1}^{n} r_i \qquad \text{Equation 4-17}$$

$$Average\ Score = \sum_{i}^{n} \frac{r_i}{L} \qquad \text{Equation 4-18}$$

Where: L = pipe length [m]

$$Peak\ Score = Max(r_i) \qquad \text{Equation 4-19}$$

The Total, Average and Peak Score are then evaluated by the thresholds given in Table 4-11. The highest structural grade is dominating, i.e. if the Total Score and Average Score equals two and the Peak Score equals three, the grade for the whole pipe will be three.

Table 4-11: Total Score, Average Score and Peak Score thresholds for structural grades. Adapted from: (Nilsson and Stahre, 1994)

Structural grade	***Total Score***	***Average Score***	***Peak Score***
1	< 20	< 0.5	< 5
2	20 – 100	0.5 – 3.0	5 – 35
3	> 100	> 3.0	> 35

The operational score is evaluated in the same way as the structural grade. The matrix for operational scoring is shown in Table 4-12.

Table 4-12: Kortbetyg grading matrix for Operational grade. 1: Abbreviations are in Swedish. Adopted from: (Nilsson and Stahre, 1994)

Defect[1]	***Grade 1***	***Grade 2***	***Grade 3***	***Grade 4***
Debris (ANS)	1	1	1	1
Other Obstacles (FRF)	1	1	1	1
Blockage/Obstacles (HIN)	0.1	1	9	24
Infiltration (INL)	0.01	3	24	60
Encrustation (PBG)	0.1	1	9	24
Root (R)	0.1	3	24	60
Settled deposits (SED)	0.1	3	12	60
Attached deposits (UTF)	0.1	1	9	24

Further, Equation *4-17*, Equation *4-18* and Equation *4-19* are applied, and the grading thresholds in Table 4-13 sets the grade.

Table 4-13. Total Score, Average Score and Peak Score thresholds for Operational grades. Adapted from: (Nilsson and Stahre, 1994)

Operational grade	***Total Score***	***Average Score***	***Peak Score***
1	< 20	< 0.5	< 5
2	20 – 100	0.5 – 3.0	5 – 15
3	> 100	> 3.0	> 15

4.4.2 WRC (PACP)

The British WRC initiated a five-year research program in 1978 to investigate over 250 wastewater pipe failure that had collapsed. From this research, WRC published the Sewerage Rehabilitation Manual (SRM). SRM is divided into two parts where; the first part discusses deterioration and why pipes collapse, hydraulics, survey techniques, and how to maintain wastewater pipes; the second part gives information about wastewater rehabilitation techniques (Rahman and Vanier, 2004; WRC, 1984). Further, the American National Association of Sewer Service Companies (NASSCO) condition assessment protocol, Pipeline Assessment and Certification Program (PACP), is based on WRCs guidelines. The WRC grading matrix is presented in APPENDIX A.

4.4.3 NRC

The NRCs condition assessment guidelines are called Large Sewer Condition Coding and Rating (LSCCR), developed by Zhao et al. (2001). LSCCR grades operational and structural defects and in combination with the failure impact evaluation discussed in section 0. The grading protocol is presented in APPENDIX A. The operational protocol takes the following defects into consideration roots (R), debris (DE), encrustation (E), Protruding services (P), and Infiltration (I) with weights between 2 and 10, where each defect type has the same sub-criteria as the structural grade, i.e. light, moderate and severe. The system consists of weights for each defect and severity. Further, the Peak Score (Equation *4-19*) determines the structural condition grade due to the thresholds in Table 4-14.

Table 4-14: NRC (LSCCR): Peak Score ranges for Structural Grade. Adapted from (Zhao et al., 2001).

Peak Score	***Structural Grade***
0	0
1 – 4	1
5 – 9	2
10 – 14	3
15 - 19	4
20	5

4.4.4 Rehabilitation & Priority

The different condition assessment protocols evaluate the grades differently, i.e. what does the structural and operational grade mean and what rehabilitation measures should be taken.

4.4.4.1 Kortbetyg (KB)

Nilsson and Stahre (1994) summarise the KB system as a *rough valuation system,* where the final grade ranges from one to three, where; grade one represents good condition; two, poor condition; and three, very poor condition. Unlike the WRC and NRC, KB does not give any further recommendations on rehabilitation measures.

4.4.4.2 WRC

WRC uses the structural peak score and operational grading in Table 4-15 to evaluate the condition of the pipes. Where 1 is an acceptable condition and 5 is a collapse at hand.

Table 4-15. WRC thresholds for Structural and Operation score to determine Condition grade. Adapted from: (Daher, 2015)

Grade	***Description***	***Structural Peak Score***	***Operational Peak Score***	***Operational Mean Score***
1	Acceptable condition	< 10	< 1	< 0.5
2	The probability for a collapse is minimal, but deterioration is present	10 – 39	1 – 1.9	0.5 – 0.9
3	The probability for a collapse is unlikely shortly, but further deterioration	40 – 79	2 – 4.9	1 – 2.4
4	The probability for a collapse is likely	80 – 164	5 – 9.9	2.5 – 4.9
5	Collapse is at hand	> 165	> 10	> 5

4.4.4.3 NRC

Zhao et al. (2001) and NRC system LSCCR suggested combining the structural grade and failure impact rating, COF, to evaluate a rehabilitation priority, presented in section 4.3. The grading is then used to set a rehabilitation priority. The rehabilitation priority is presented in Table 4-16.

Table 4-16 LSCCR: Prioritisation for rehabilitation through a function of structural grade and failure impact evaluation (Zhao et al., 2001).

Structural grade	***Description***	***Failure Impact factor (COF)***	***Rehabilitation priority***
5	Failed, or failure at hand	1 - 5	Immediate
4	- Very poor condition - High probability for structural failure	5 1 - 4	Immediate High
3	- Poor condition - Moderate probability for structural failure	4 – 5 1 – 3	Medium Low
2	- Fair condition - Low probability for structural failure	1 – 5	Low
1 – 0	- Good or excellent condition	1 - 5	Not required

4.4.5 Inspection frequency.

Zhao et al. (2001) also recommends the frequency of inspections concerning structural grade (LSCCR) and failure impact rating (COF). In Table 4-17 suggested re-inspection based on structural grade from WRC and NRC, with associated rehabilitation priority is presented (Rahman and Vanier, 2004). Category A and B refers to WRCs COF system, and the one-to-five scale to NRCs COF system (discussed in 0).

Table 4-17: Summary of rehabilitation priority and re-inspection recommendation based on Structural Grade and COF for WRC and NRC. 1: Medium refers to COF 4 – 5. 2: Low refers to COF 1 – 3. Adopted from (Rahman and Vanier, 2004; USEPA, 2009; Zhao et al., 2001)

Structural Grade		***COF***		***Re-inspection frequency***		***Rehabilitation priority***	
WRC	NRC	WRC	NRC	WRC	NRC	WRC	NRC
5	5	A B	1-5	- -	-	Immediate	Immediate
4	4	A B	5 1 - 4	- 5	- 2 – 6	Immediate	Immediate High
3	3	A B	5 1 - 4	3 15	3 5 - 10	Medium Low	Medium (4-5)[1] Low (1-3)[2]
2	2	A B	5 1 - 4	5 20	5 10 - 15	Medium Low	Low
0 - 1	0 - 1	A B	5 1 - 4	10 20	10 15 - 25	Not required	Not required

4.4.6 Summary & analysis of condition assessment protocols

When comparing the condition assessment protocols provided by KB, WRC (PACP) and NRC, the evaluation of defects are similar. However, there are some semantic differences, and some defects are unique for the specific system. Further, KB uses threshold values for Mean Score, Average Score and Peak Score while NRC uses Peak Score for one-metre pipe and WRC exclusively Peak Score. Table 4-18 summarises the most common and severe structural defects in KB, WRC, and NRC by Peak Weight and Relative Weight. The relative weight was determined by dividing the specific weight with the highest weight within the condition assessment protocol.

Table 4-18 Comparison between weights and relative weights for Kortbetyg, WRC and NRC. 1: Relative Weight is defined as the individual grade divided by the maximum weight within the condition assessment protocol. 2: Fractures are not explicitly defined in KB, Fractures and Collapse are assumed to be in the same category of defects.

	KB		***WRC***		***NRC***	
Defect	Peak Weight	Relative Weight[1] [%]	Peak Weight	Relative Weight [%]	Peak Weight	Relative Weight [%]
Cracks	24	24%	10	6%	10	50%
- Circumferential	26	26%	10	6%	5	25%
- Longitudinal	20	20%	40	24%	5	25%
- Multiple	24	24%	40	24%	5	25%
Fractures[2]	100	100%	80	48%	20	100%
Collapse	100	100%	165	100%	20	100%
Deformation	100	100%	165	100%	15	75%
Surface damage	100	100%	-	-	15	75%
Hole	6	6%	165	100%	15	75%
Joint displacement	36	36%	165	100%	15	75%
Joint Opening	24	24%	165	100%	15	75%

When analysing Table 4-18, collapse and deformation are the two most severe defects in all protocols. Defects in joints are evaluated lower in the KB system with a relative weight between 24 to 36%, where WRC and NRC hold 100% and 75%, respectively. Holes in the KB protocol are rated less than in WRC and NRC. However, if holes are large, they can be graded under surface damages in KB. Further for WRC and NRC uses Peak Score to evaluate structural grade. Hence, it is easy to evaluate which defects from the protocols are equivalent to the structural grades. On the other hand, KB can reach high grade by Total Score, Average Score and Peak Score. The structural grade equivalent to Peak Score can easily be found in Table 4-10. Further, for the Total Score and Average Score, structural grade 3 can be reached with defects equal Peak Score 1, i.e. several moderate defects can give high structural grade.

4.5 Determine ROF & Rehabilitation priority

In the reviewed articles that explicitly evaluates risk, ROF has been assessed as the product of POF and COF (Baah et al., 2015; Salman, 2010; Salman and Salem, 2012; Vladeanu, 2018). Further, Jenks' natural breaks have been used to divide COF, POF and ROF into classes where the deviation within classes is minimised, and the deviation between classes is maximised (Baah et al., 2015; Salman, 2010). Fuzzy inference system has been used (Baah et al., 2015; Salman, 2010) to evaluate the membership of COF, POF, and ROF. Fuzzy inference systems are used to visualise the degree of membership for each class of, e.g., ROF. With evaluated COF and POF, risk matrixes have been used to visualise how COF and POF contribute to levels of ROF. In Figure 4-8, the risk matrix used by Salman (2010) is presented, with COF on the x-axis and POF on the y-axis and ROF depended on how COF and POF are weighted in the risk matrix.

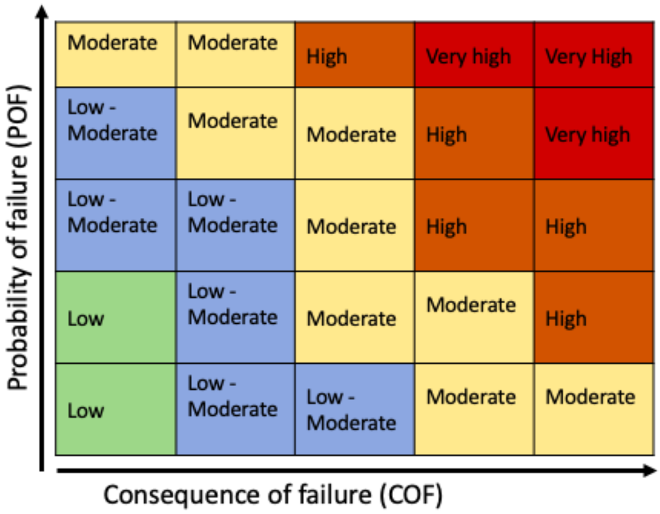


Figure 4-8: Risk matrix. adopted from (Salman, 2010)

NRC and WRC (WRC, 2020; Zhao et al., 2001) use priority or probability tables based on structural grade and (or) COF and operational grade. The NRC table can be seen as a risk matrix where the structural grade is equivalent to POF.

5 The Risk-based model

In Figure 5-1 the risk-based model is presented. The model can be divided into seven steps, where:

i. Summarise the available information within the water utility, regarding; pipe inventory; including material, age, length, diameter; GIS data, including data of objects where pipe failure would significantly impact economic, social or environmental factors; and CCTV inspections of the wastewater pipe network.

ii. Sort the available data into parameter affecting deterioration and consequence impact parameters. Deterioration parameters include physical, environmental and operational data to predict the condition of the pipe. Consequence impact parameters include parameters influencing social, environmental, and economic consequences.

iii. POF and COF

   a. Evaluate the probability of failure (POF) for the pipes within the wastewater pipe network. Methods used are Multi-Criteria Decision Analysis (MCDA) and Regression models. POF is based on a combination of parameters that are most likely to influence and accelerate the deterioration process of the pipes. POF should strive to represent the condition of individual pipes within the Wastewater pipe network.

   b. Evaluate COF by setting up social, environmental and economic consequence groups. Social consequences include events where infrastructure, such as railway tracks, roads and roads for emergency vehicles, is disrupted due to wastewater pipe failure or when customer service is affected. Environmental consequence summarises events where undesired exflow of wastewater spreads to sensitive or protective areas. Economic consequence summarises the direct cost of replacing, renovating or repairing wastewater pipes.

iv. Evaluate ROF using the results from the COF and POF in a risk matrix to determine the most critical pipes within the wastewater pipe network. From the evaluated ROF, a CCTV inspection priority is formed to determine the condition of the high-risk pipes.

v. The new CCTV inspections are evaluated and graded using a condition assessment protocol.

vi. The structural grade from CCTV inspections is used in combination with COF to set up a rehabilitation priority and a re-inspection priority.

vii. The new CCTV inspections should update the database and re-evaluate the assumptions and methods used in the POF model to execute more reliable estimations in the future.

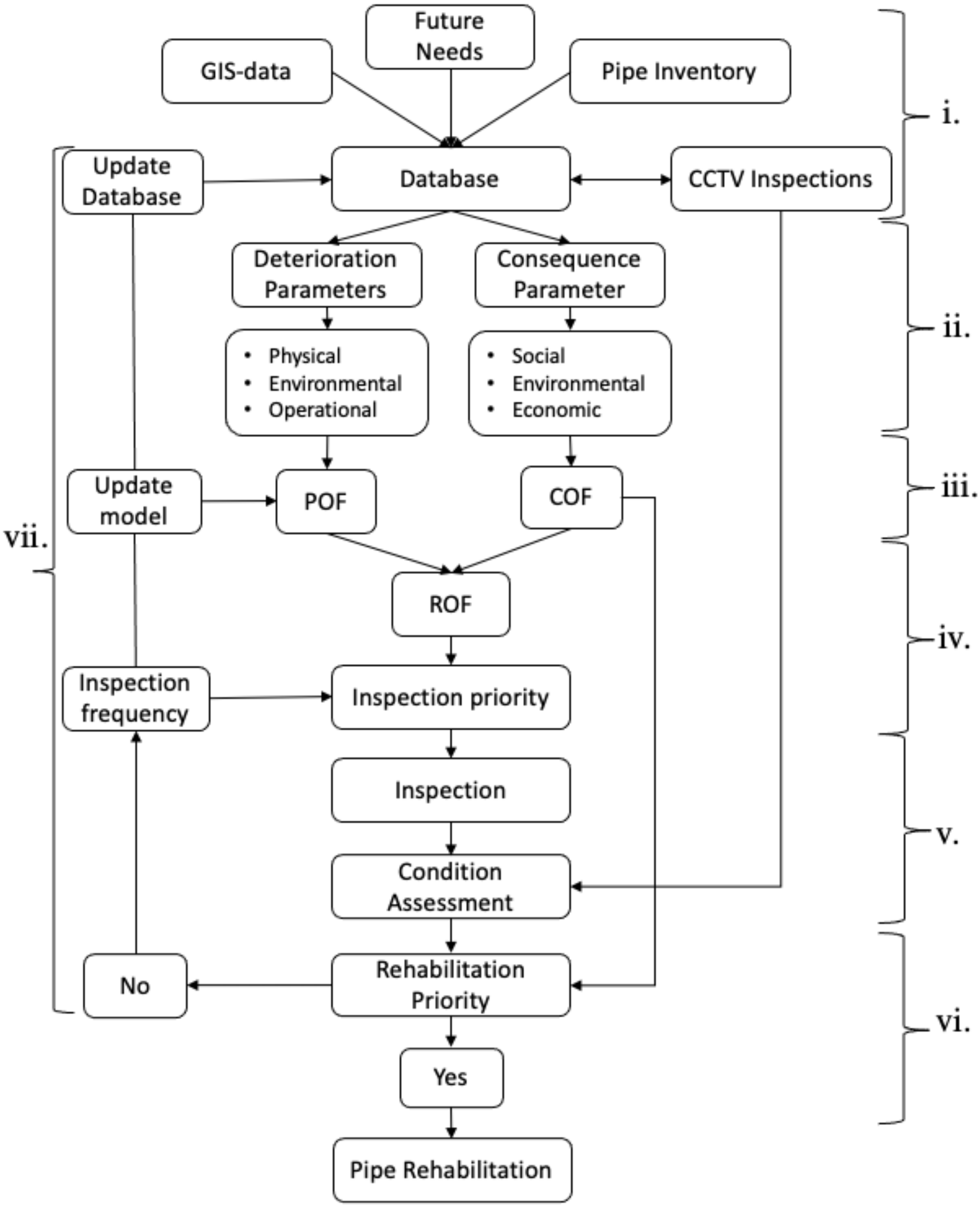


Figure 5-1: The Risk-based model for rehabilitation of Wastewater pipes

5.1 Methods of Choice

In this section the methods used for POF, COF and ROF will be described:

- Multi-Criteria Decision Analysis (MCDA) using the Weighted Sum Method (WSM)
- Logistic regression
- Risk matrix

The WSM method is used to evaluate COF, and the WSM method and Logistic regression evaluate POF. Regarding COF, the WSM method has been used frequently in the reviewed literature. Mainly due to the simplicity and that its practical to solve multi-criteria problems.

The motivation for using logistic regression and the WSM method for evaluating POF is twofold; The first is the relative simplicity of the models, which conceivably make it feasible for water agencies to adopt them; the second is that statistical regression models return statistical information about the pipe network, which can be helpful in decision making and future development. In contrast, MCDA models take the expert knowledge and experience within the water utility into account. Further, for both COF and POF, the WSM method is qualitative, taking advantage of experts' knowledge and competence within the water utility. Logistic regression is a quantitative method where the model can be tested for its accuracy and reliability.

The Risk matrix was used to evaluate ROF, using the combination of COF and POF. Further, the logistic regression model was discarded due to the inability to identifying high-risk pipes. The arguments for rejecting the model will be further discussed in section 6.4.1.1.

5.2 Multi-Criteria Decision Analysis (MCDA)

Multi-Criteria Decision Analysis (MCDA) is the umbrella term of different methods to evaluate different sets of alternatives and criteria to make the best possible decision (Triantaphyllou, 2000). When implementing MCDA, from a risk assessment perspective, the essential steps are; defining objectives and criteria; determine weights to each criterion; coordinate the weights with stakeholders; and evaluating the result (IEC 31010, 2019).

5.2.1 Weighted Sum Model (WSM)

The Weighted Sum Method (WSM) is the most frequently used model under the MCDA umbrella. The WSM method is generally used to choose between different alternatives with differential attributes. The base of the WSM method is the decision matrix with a finite set of alternatives, $A = \{A_{i,}\ i = 1, 2, 3, \ldots, m\}$, representing the rows and Criteria (Cj) with associated weights, $W = \{W_j,\ j = 1, 2, 3, \ldots, n\}$ representing the columns (Triantaphyllou, 2000). However, implementing WSM to evaluate COF and POF is not about making decisions but rather ranking and classifying the numerous pipes in the wastewater pipe network based on identified criteria with associated sub-criteria. Hence, A can represent the number of pipes in the wastewater pipe network, and the decision matrix can be termed the classification matrix. The classification matrix with the pipes within the wastewater pipe network (A), Criteria (Cj), with associated Weights (Wj) and Sub-Criteria Value (SCV_{ij}) is presented in Table 5-1.

Table 5-1. The decision matrix (termed classification matrix) Matrix. Adopted from (Triantaphyllou, 2000)

	C_1	C_2	C_3	…	C_n
Pipe.	**(W_1**	W_2	W_3	…	**W_n)**
A_1	SCV_{11}	SCV_{12}	SCV_{31}	…	SCV_{1n}
A_2	SCV_{21}	SCV_{22}	SCV_{32}	…	SCV_{2n}
A_3	SCV_{31}	SCV_{23}	SCV_{33}	…	….
…	….	….	…	…	….
A_m	SCV_{m1}	SCV_{m2}	SCV_{m3}	…	SCV_{mn}

Further, Wj is the weight associated with the j-th criteria placed in the j-th column, and SCV_{ij} is the Sub-Criteria Value for the i-th pipe and the j-th criteria. The total COF or POF is calculated using Equation 5-1.

$$COF\ /\ POF = \sum_{j=1}^{n} SCV_{ij} \times W_j, \qquad for\ i = 1,\ 2,\ 3, \ldots,\ m. \tag{Equation 5-1}$$

Where the sum of Wj usually sums up to one, and consequently, the value of SCV_{ij} determines the maximum value of COF or POF, and Wj takes values between 0 and 1 (Equation 5-2).

$$\sum_{j=1}^{n} W_j = 1, \qquad W_j \in (0,1) \tag{Equation 5-2}$$

Further, the Wj was calculated by assigning each criterion an *Importance Score* (*IS*) between 1 and 10, where 1 represents the lowest influence on COF or POF and 10 the most significant influence on COF or POF. The Wj was calculated by dividing the individual *IS* for each criterion by the sum of *IS* for all criteria (Equation 5-3). *IS* were set based on information from the literature review and consultation with Kungsbacka municipality's water utility.

$$Wj = \frac{IS_j}{\sum_{j=1}^{n} IS_j} \tag{Equation 5-3}$$

The SCV_{ij} associated with each criterion was set based on former studies and in dialogue with Kungsbacka municipality's water utility.

5.2.1.1 Sensitivity analysis

The WSM method is a qualitative approach to solve multi-criteria problems. Therefore, much of the uncertainty in the results of the WSM model can be derived from the subjective weighting. However, Vladeanu (2018) performed a sensitivity analysis on the AHP model by step-by-step changing the weights and evaluating the percentage difference between the original AHP model and the new weighted AHP model. The sensitivity analysis was performed by changing the original weights with -50%, -25%, -10%, 10%, 25% and 50%. Since the Wj in the AHP method sums up to one, and this study used WSM where the Wj summed up to one, this approach could be adapted.,

If the sum of the weights equals one (Equation 5-2), $k_i = \{0.5, 0.75, 0.9, 1.1, 1.25, 1.5\}$, and the criteria with associated Wj for $j = 1, 2, 3, \ldots, N$. The change of the first weight is calculated using Equation 5-4.

$$W_1^* = \sum W_1 \times k_i \qquad \textit{Equation 5-4}$$

Where the new weight (W_1'), based on the first change in weight (W_1^*), is calculated using *Equation 5-5*.

$$W_1' = \frac{W_1^*}{W_1^* - W_1 + \sum_{j=1}^{n} W_j} \qquad \textit{Equation 5-5}$$

And the resulting weights ($W'j$) based on the change in the first weight (W_1') is calculated by *Equation 5-6*.

$$W_j' = \frac{W_j}{W_1^* - W_1 + \sum_{j=1}^{n} W_j} \qquad \textit{Equation 5-6}$$

Hence the number of new scenarios for the WSM model due to the change in weight for all criteria equals the number of elements in k_i times the number of criteria. Further, the sensitivity is calculated as the percentual difference between the original WSM model and the newly weighted WSM model using *Equation 5-7*.

$$\Delta COF/POF = \frac{\sum_{j=1}^{n} W_j \times SCV_{ij} - \sum_{j=1}^{n}(W_j' + W_1') \times SCV_{ij}}{\sum_{j=1}^{n} W_j \times SCV_{ij}} \times 100\ [\%] \qquad \textit{Equation 5-7}$$

Further, for every scenario analysed in the sensitivity analysis, all weights will change. Hence, if W_1 increases by 50%, the resulting weights (Wj') will decrease. The exact weights and change of weights used in the sensitivity analysis are presented in APPENDIX DAPPENDIX D

5.3 Logistic regression

Logistic regression is suitable for problems where the dependent variable does not continuously respond to the independent variables.

In binomial logistic regression, the dependent variable takes values of $Y \in \{0|1\}$, e.g., yes/no, or in the case of wastewater pipe failure, failure/no-failure. The general form is presented in *Equation 5-8* (Garson, 2016) .

$$\log(Y) = \ln \frac{P(Y=1)}{1 - P(Y=1)} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \dots \beta_n X_n \qquad \textit{Equation 5-8}$$

Where $X_1, X_2, \dots, X_n$ represents the independent variables for n =1, 2, 3, ...N, α is the intercept and β_1, β_2 , ..., β_n the regression coefficients for associated independent variable (X_i). The probability for P(Y=1), i.e. the POF, is given by *Equation 5-9*.

$$P(Y|X_1, X_2 \dots X_n) = \frac{1}{1 + e^{-(\alpha + \beta_1 X_1 + \beta_2 X_2 + \dots \beta_n X_n)}} \qquad \textit{Equation 5-9}$$

P(Y=1) can take any value from 0 to 1, representing the probability for the binary outcome equal to one.

Multinomial regression is used when there are more than two dependent variables, often used as a non-numeric categorical outcome. Further, if k dependent categorical variables are used, the number of regression equations used equals, $i = k$-1. Since i regression equations are used, one of the dependent variables are used as a reference level. The general form is presented in Equation *5-10* (Garson, 2016).

$$log(Y) = ln\frac{(P(Y = i|X_1, X_2..., X_n))}{(P(Y = k|X_1, X_2..., X_n))} = \alpha + \beta_1 X_1 + X_2 + ... \beta_n X_n \qquad \textit{Equation 5-10}$$

Where X, α, β are the same as for binomial regression. The probability for the dependent reference variable is calculated according to Equation *5-11*.

$$P(Y = k) = \frac{1}{1 + \sum_{i=1}^{k-1} e^{\alpha + \beta_1 X_1 + \beta_2 X_2 + ... \beta_n X_n}} \qquad \textit{Equation 5-11}$$

Further, if the sum of the intercept, regression coefficient and independent variables, $\alpha + \beta_1 X_1 + \beta_2 X_2 + ... \beta_n X_n$, is denoted x, and x ranges from [-6 , 6], the probability for binomial and multinomial regression can be plotted as $\langle x|Equation$ 5-9$\rangle$ and $\langle x|Equation$ 5-11$\rangle$, respectively (see Figure 5-2) Where the shape of the curve behaves as the S-Shaped Sigmond function.

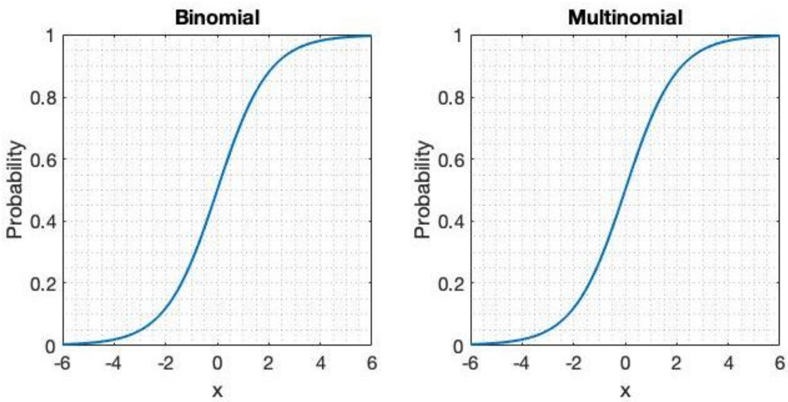


Figure 5-2 The probability function for Binomial and Multinomial regression.

5.4 Risk Matrix

The risk matrix divides the POF and COF into levels of n points, where n usually consists of three, four or five levels, consequently forming an n times n matrix, where the estimated risk levels usually are coloured and numbered to highlight the magnitude of the estimated risk. Further, the estimated level of risk does not necessarily need to be a product of COF and POF but rather an estimate of how COF and POF contribute to the relative ROF. Consequently, the risk matrix can be weighted to enhance the contribution of either POF or COF to the final ROF. Usually, is COF concerned with contributing more major to ROF even when POF is relatively low, from the decision-makers perspective. In Figure 5-3, a five times five matrix from the IEC 31010 (2019) guidelines is presented, where the matrix is somewhat weighted to enhance the contribution of COF

Consequence of failure (COF)					
a	III	III	IV	V	V
b	II	III	III	IV	V
c	I	II	III	IV	V
d	I	I	II	III	IV
e	I	I	II	III	IV
	1	2	3	4	5
	Probability of failure (POF)				

Figure 5-3: Risk matrix. Lowest risk (I) to highest risk (V). Adapted from: (IEC 31010, 2019)

6 Results

In the following sections, the risk-based model will be implemented on the Kungsbacka municipalities wastewater pipe network, following the steps presented in section 5.

6.1 Summarise Kungsbacka wastewater pipe network data (i)

Kungsbacka is a mid-size Swedish municipality located in Halland County, south of Gothenburg. In 2019 the population was 84,395, making it the twenty-sixth biggest municipality in Sweden, and the population growth is approximately 1,000 people per year (Kungsbacka, 2021).

6.1.1 Kungsbacka Wastewater pipe network.

There are five WWTPs in Kungsbacka with 65,000 people connected (Kungsbacka, 2017). The data analysed consisted of 15,044 unique pipe IDs with a total length of 571.3 kilometres. The system is separate, i.e. wastewater (domestic and industrial) is transported in different pipes than stormwater runoff. In Figure 6-1, the build-up of Kungsbacka municipalities wastewater network per material and decade is presented.

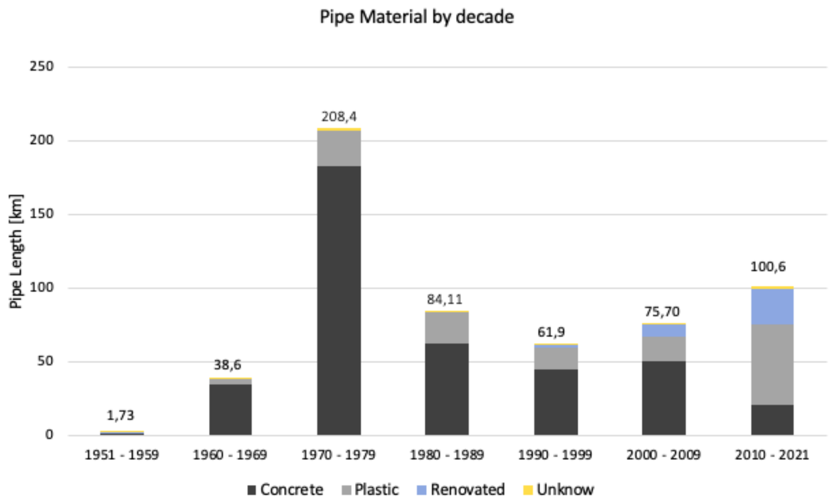


Figure 6-1. Annual build-up of Kungsbacka municipalities Wastewater network in kilometres.

As observed in Figure 6-1, the most significant part of the network was built between 1960 - 1970. Until 2010 the most used pipe material was concrete. At the start of the 21st century, plastic pipes were introduced, and the renovation of pipe started.

Further, the age distribution of the individual pipes is presented in Figure 6-2, where the blue dashed line represents the median age, equal to 31.75 years, and the black dashed line, the 5th and 95th percentile, equal to 4.25 and 54.8 years, respectively. Since new pipes are installed yearly, the lowest age observed was 0.1 years and the oldest 70 years.

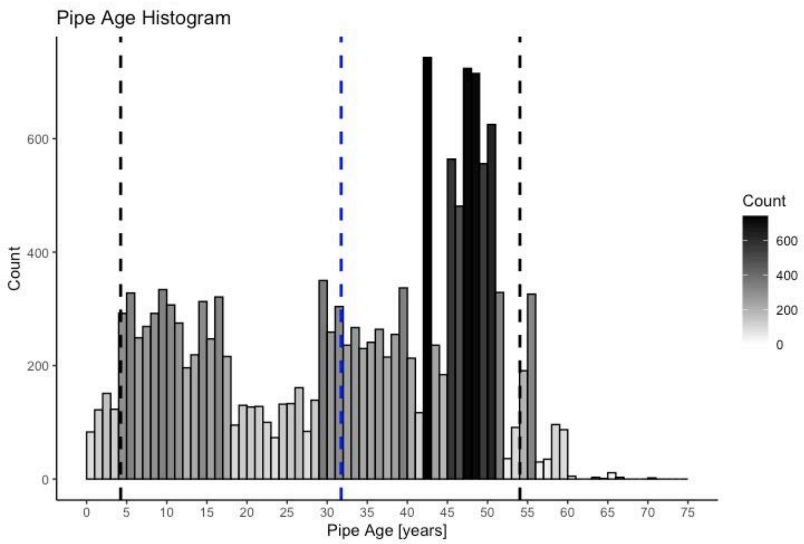


Figure 6-2: Histogram of Pipe Age [years] for the entire dataset. The black dashed lines represent the 25th and 75th quantile, the blue dashed line the median.

The distribution of length is presented in Figure 6-3. The blue-dashed line represents the mean length, equal to 38m, and the black dashed lines, the 5th and 95th percentile, equal to 3.75 and 77.2m, respectively. The shortest length observed was 0.2m, and the most extensive length 425m.

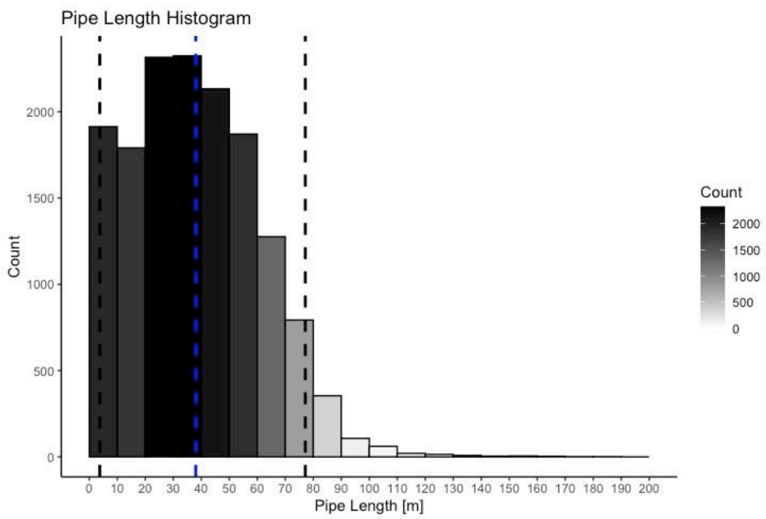


Figure 6-3. Histogram of Pipe Length [m] for the entire dataset. The black dashed lines represent the 25th and 75th quantile, the blue dashed line the median.

The distribution of diameter is presented in Figure 6-4. The blue-dashed line represents the mean, equal to 231.8mm, and the black dashed lines, the 5th and 95th percentile, equal to 150 and 400mm, respectively. The smallest diameter in the dataset was 40mm, and the largest 1000mm.

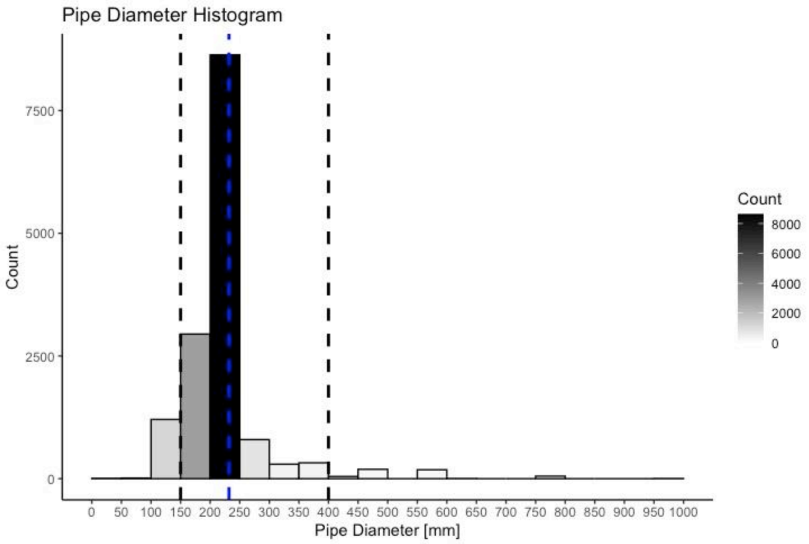


Figure 6-4. Histogram of Diameter [mm] for the entire dataset. The black dashed lines represent the 25th and 75th quantile, the blue dashed line the median.

6.1.2 CCTV Inspections

Kungsbacka has a relatively high number of CCTV inspected pipes. Approximately one-fifth of the wastewater pipe network has either (or) both structural and operational grades, using the condition assessment protocol KB. In the following sections, when CCTV inspections are referred to, the structural and operational grades are based on the KB condition assessment protocol. The distribution of different grade and percentage of the networks total pipes is presented in Table 6-1. It should be noted that some of the unique pipe IDs have several inspections. In case of several inspections, the last inspection was used in the analysis.

Table 6-1: Structural and Operational graded pipes within Kungsbacka municipalities Wastewater Network. Where the counts of each grade and percentage of total pipe ID is presented.

	Structural		***Operational***	
Grade	Count [#]	[%] of Unique ID	Count [%]	[%] of Unique ID
0	1357	9.0%	954	6.3%
1	843	5.6%	1366	9.1%
2	540	3.6%	398	2.6%
3	144	1.0%	166	1.1%
Sum	2884	19.2%	2884	19.2%

The diameter for structural and operational grade did not significantly differ from each other or within the grades. However, the mean diameter for both structural and operational grade was 225mm.

Further, the time between inspections (termed inspection age) is presented in Figure 6-5, i.e. the amount of year since the last CCTV inspection. The blue dashed line represents the mean age, equal to 3.9 years, and the black dashed lines represent the 5th and 95th percentile equal to 0.57 and 7.95 years, respectively.

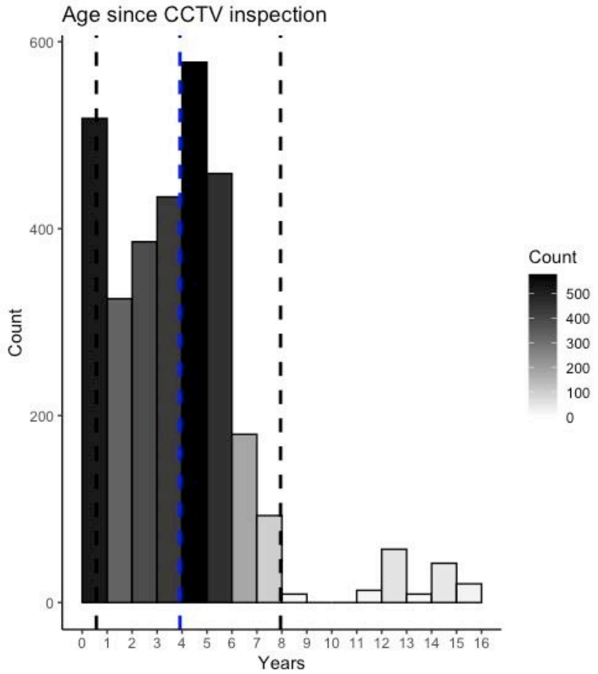


Figure 6-5. Histogram of time since inspection for the CCTV inspected pipes. The black dashed lines represent the 25th and 75th quantile, the blue dashed line the median.

6.1.3 Missing values

In Table 6-2, the missing values for the entire dataset and the CCTV inspected dataset is presented.

Table 6-2. Missing values for the entire dataset and the CCTV inspected dataset

Entire dataset			***CCTV inspected dataset***		
Parameter	**Count [#]**	**Missing values**	**Parameter**	**Count [#]**	**Missing values [% CCTV pipe ID]**
Diameter	324	2.15%	Diameter	443	14.6%
Material	339	2.25%	Material	17	0.6%
Installation Year	43	0.29%	Structural Grade	146	4.8%
			Operational Grade	146	4.8%

Further, when analysing POF, COF and ROF pipes with missing data have been excluded from the analysis.

6.2 Sort data for COF & POF (ii)

In this section the data used to evaluate COF and POF will be presented.

6.2.1 COF

In this case study, the parameters identified to evaluate COF were based on the types of consequence parameters used in the literature review and the data available in Kungsbacka municipalities GIS software. In essence, the consequence parameters used can be derived into three categories of consequences:

i. The economic cost for replacing, repairing or acquiring access to the pipe.
ii. The social impact of pipe failure, e.g. disturbing infrastructures such as roads or railway tracks.
iii. The environmental impact of undesired exflow of wastewater in sensitive or protected areas.

In the reviewed literature, the distance between the pipe and the consequences parameter has been used as a sub-criteria value. In this case study, a buffer around the consequence parameter was used instead. The consequence parameters with the associated buffer (if required), the consequence groups and counts are presented in Table 6-3.

Table 6-3:Summarised Consequence parameter per category, with count and Buffer. 1: Priority highways refers to roads frequently used by emergency vehicles.

Consequence Category	***Consequence Parameter***	***Wj***	***Count***	***Buffer***
Social	- Motorway/Highways	$W_{M/H}$	27	20 meters
	- Highway	$W_{M/H}$	1,319	12 meters
	- Priority highways[1]	W_{PH}	292	12 meters
	- Railway tracks	W_{RT}	128	30 meters
Economic	- Buildings	W_B	329	1 meter
	- Burial depth >= 5m	W_{BD}	25	-
Environmental	- Water bodies	W_{WB}	123	10 meters & diameter >= 150 mm
	- Water protection areas	W_{WPA}	135	10 meters
Diameter	Diameter	$W_{Diameter}$	14,718	-

Further, in the reviewed literature, the consequence parameter *Diameter* has ordinarily been seen as an economic consequence. However, after discussion with the Kungsbacka municipalities water utility, the *Diameter* was set to form an individual consequence category. When analysing the COF for wastewater networks, the diameter affects economic, social and environmental impact. Accordingly, a large diameter pipe will be more expensive to replace. It is usually more critical in terms of capacity, i.e. more consumers are affected by interruptions, and a large diameter pipe failure will significantly impact the environment due to more exflow of wastewater. Furthermore, *Motorway* and *Highways* were combined to form one consequence parameter, *Motorway/Highways*, mainly due to the similarity in importance regarding COF, and because Motorways only was within the buffer to 27 pipes.

6.2.2 POF

The data used in the WSM model and logistic regression model were pipe age, length diameter and material. Where the material was classified into four categories; Renovated pipe, including Close-Fit, CIP and sliplining; Plastic pipes including PE, PP, PEL, PEM, PEH, PEL and PVC; Concrete, separated into pipes installed before 1970 (<=1970) and after 1970 (>1970) due to the substantial improvement in quality during the 1970s (Lidström, 1996; Malm et al., 2011b).

6.2.2.1 Data used for evaluating POF

In this section, the data used for evaluating POF is presented. The data presented will take advantage of the CCTV inspections graded according to KB, with the assumption that the grades represent the pipes' actual condition.

In Figure 6-6 boxplots for structural and operational grade against age and length is presented. The blue boxes' boundaries represent the 25th and 75th quantile (equals 1Q), black dashed lines with brackets the maximum values or 1.5 times Q, and the black circle's potential outliers

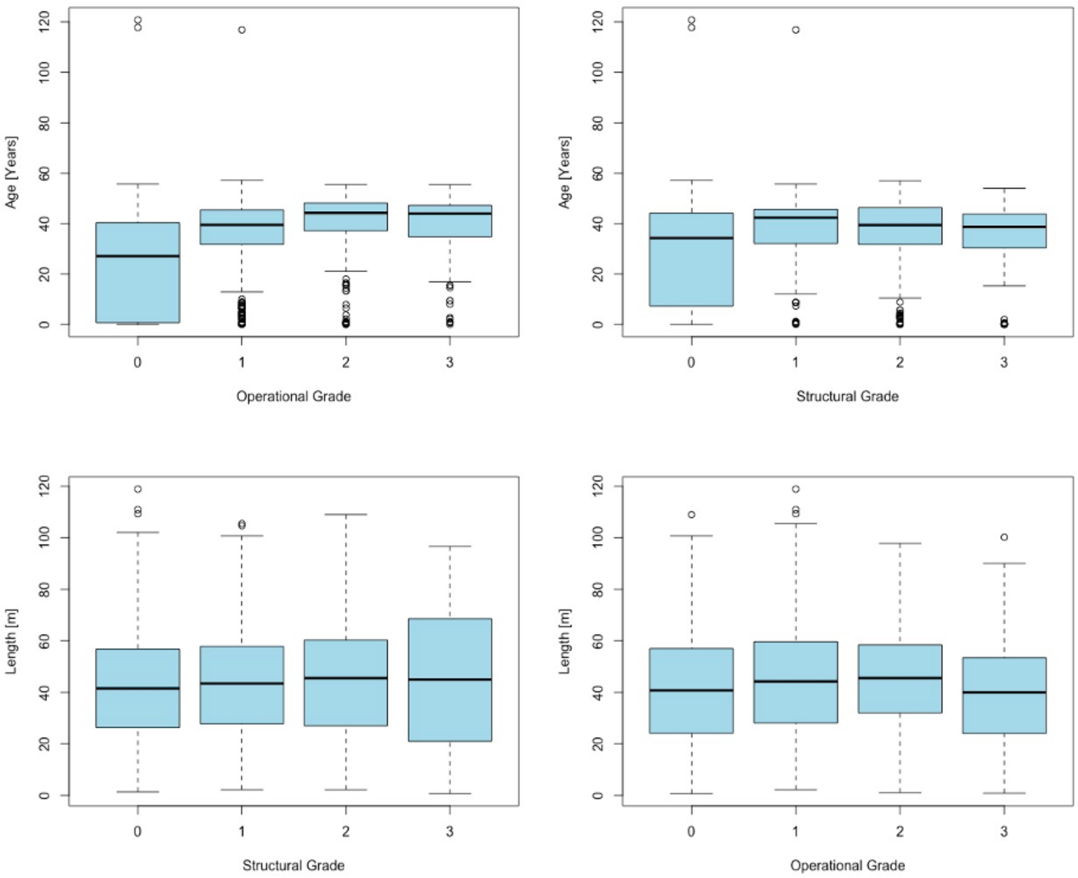


*Figure 6-6. Boxplot for Structural and Operational grade as a function of age and length. The blue box represents the thresholds for the 25th and 75th quantile equal QR. The dashed line with bracket is the maximum value or 1.5*QR. The black dots are potential outliers.*

Further, in Table 6-4, material per structural and operational grade is presented. Plastic pipes are overrepresented in structural grades 2 and 3, with 187 pipes (54%) and 62 pipes (18%). On the other hand, plastic pipes perform best in operational grade, where the distribution for grades 2 and 3 is 21 pipes (6%) and five pipes (5%), respectively. Concrete pipes installed before (or) 1970, was in section 2.4.2.1.2 identified as a material that potentially would increase POF. The distribution of these pipes for structural grade 2 and 3 was 114 pipes (28%) and 18 pipes (4%). The concrete pipes installed after 1970 performed well, with 215 pipes (13%) in structural grade 2 and 25 pipes (1%) in structural grade 3. Renovated pipes were only present in structural grade 0 - 1.

Table 6-4 Material and age distribution per Structural and Operational Grade. 1: Age.a represents the average age.

	Concrete<1970		*Concrete>1970*		*Plastic*		*Renovated*	
Operational Grade	# Count	Age.a[1]	# Count	Age.a	# Count	Age.a	# Count	Age.a
0	67 (17%)	49.5	329(21%)	32.0	185(56%)	28.5	26 (40%)	21.8
1	216 (54%)	50.5	892 (57%)	34.5	106(32%)	32.6	17(16,1%)	16.1
2	82 (20%)	50.9	228 (15%)	38.8	21(6%)	33.9	4 (6%)	18.9
3	36 (9%)	51.5	105 (7%)	39.0	17(5%)	20.4	18 (28%)	7.5
Sum	401 (100%)		1556 (100%)		336 (100%)		65 (100%)	
Structural Grade	# Count	Age.a	# Count	Age.a	# Count	Age.a	# Count	Age.a
0	129 (31%)	50.3	809 (47%)	35.0	85 (24%)	29.4	50 (96%)	18.4
1	152 (37%)	50.3	661 (39%)	36.4	14 (4%)	33.1	2 (40%)	47.2
2	114 (28%)	50.8	215 (13%)	36.7	187 (54%)	29.1	-	
3	18 (4%)	52.1	25 (1%)	37.3	62 (18%)	37.1	-	
Sum	413(100%)		1710 (100%)		348(100%)		52(100%)	

Further analysis of the structural grade per material is presented as a boxplot in Figure 6-7, with the structural grade on the x-axis and age on the y-axis. For Concrete =< 1970, increased age follows the structural grade relatively well. For Concrete > 1970 age does not follow the structural grade as well, and for Plastic pipes, structural grade 3 have the highest age. However, both Concrete > 1970 and Plastic pipes have possible outliers within the data.

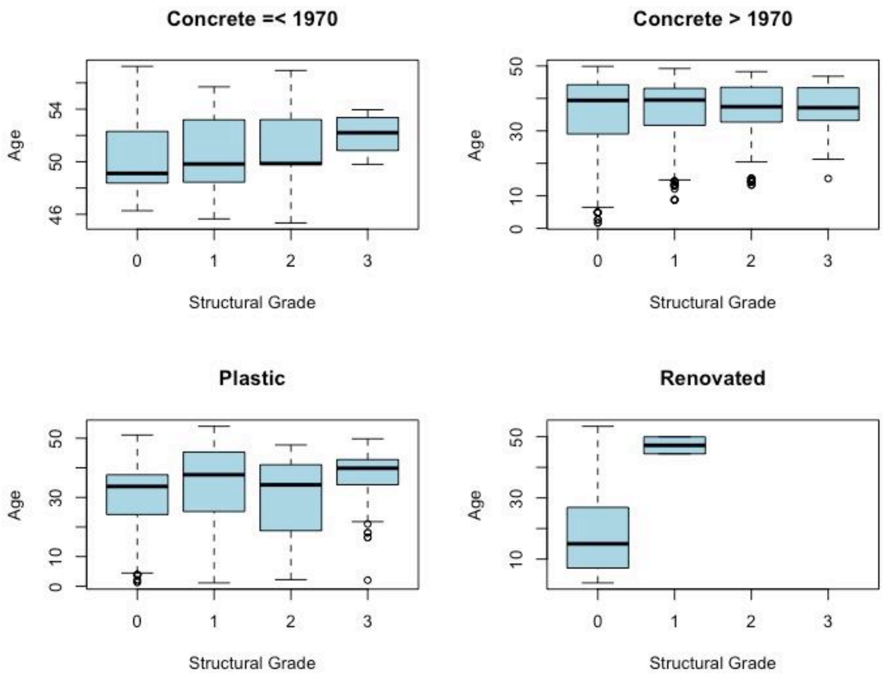


*Figure 6-7: Boxplot for age based on Structural Grade for Concrete, Plastic, and Renovated Pipes. The blue box represents the thresholds for the 25th and 75th quantile equal QR. The dashed line with bracket is the maximum value or 1.5*QR. The black dots are potential outliers.*

6.2.2.2 Logistic Regression

To set up the data to evaluate POF using Logistic Regression the first step was determine the dependent variable. In this case, the dependent variable was determined to be represented by the structural grade. The structural grade has commonly been used in the reviewed literature and is assumed to represent the pipes' condition best. Furthermore, the structural grade was transformed to fit the models; for the multinomial regression, three dependent variables were suggested, where P(Y=1), P(Y=2) and P(Y=3), representing structural grade 0 – 1, 2 and 3, respectively; in the binomial model, P(Y=1) was equal to the structural grade 3 and P(Y=0) structural 0 – 1 and 2. In Table 6-5, the suggested dependent variables and material distribution is presented.

Table 6-5: Pipe material for Kortbetyg 0 - 1, 2 and 3. Including Binomial and Multinomial categories.1: Concrete pipes installed before or in 1970. 2: Concrete pipes installed after 1970.

Structural grade	***Binomial***	***Multinomial***	***Concrete =<1970[1]***	***Concrete >1970[2]***	***Plastic***	***Renovated***	***Sum***
0-1	0	1	281 (68%)	1470 (86%)	99 (28%)	52 (100%)	1902
2		2	114 (28%)	215 (13%)	187 (54%)	-	516
3	1	3	18 (4%)	25 (1%)	62 (18%)	-	105
Sum			413 (100%)	1710 (100%)	348 (100%)	-	

6.3 Evaluating COF (iii, a)

The first step in implementing the WSM method to determine COF was to determine the criteria and sub-criteria. Within each consequence group, some of the consequence parameters conflicted with each other. To exemplify, a pipe can theoretically be adjacent to both a water body and water protection area or adjacent to buildings and have a burial depth over 5 meters. Therefore, a global weighting model with weights for each consequence group and *SCVs* for each consequence parameter was discarded. Instead, all eight identified consequence parameters were seen as a unique criterion with an associated weight.

Further, four sub-criteria for diameter were identified based on the size. The chosen intervals were set to pipes with diameter; over or equal to 1,000 mm; under 1,000 mm, and over 600 mm; under 600mm and over 400 mm; under 400 mm. The sub-criteria for the consequence parameters in the consequence categories Environmental, Social and Economic were set to act as a binary sub-criterion, which gives a binary *SCV*. A schematic view of the WSM model used is presented in Figure 6-8.

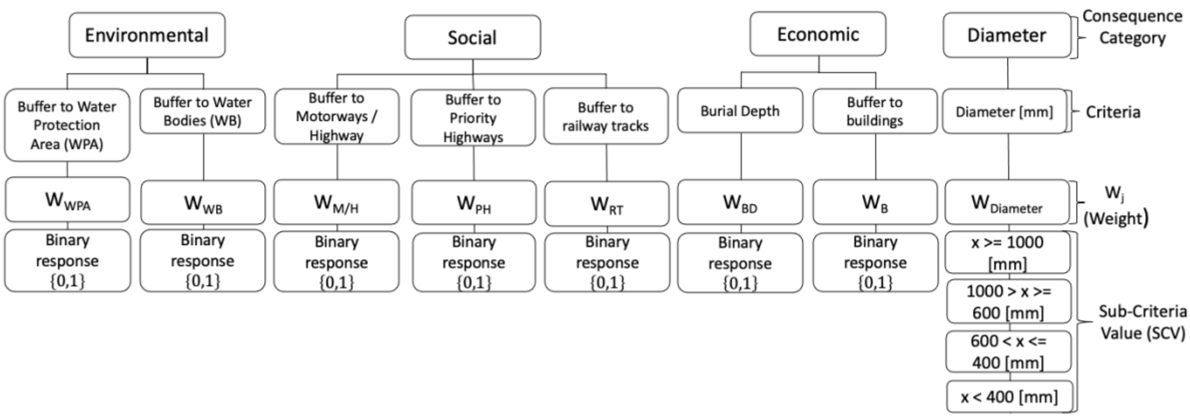


Figure 6-8: Schematic view of the WSM method implemented to evaluate COF.

The next step was to score the criteria with an *Importance Score* (*IS*) between 1 and 10, where 10 represented a high impact on COF and 1 low impact on COF. All criteria, including the sub-criteria for diameter, was given an *IS* with the consultation of Kungsbacka municipalities water utility. The *Wj* for each criterion was calculated using Equation 5-3. For the criteria *diameter*, the highest *IS* was set to represent the criterion.

The *SCVs* were decided to range from >0 to 5, where the criteria with binary sub-criteria were given an *SCV* equal to 5. The *SCV* for *diameter* was determined by dividing the *IS* for each sub-criteria with the maximum *IS* within the criterion times five. Since the maximum *IS* for diameter was equal to 5, the *SCVs* for diameter was equal to the *IS* for each sub-criterion. The *Wj* for each criterion with associated SCV_{ij} is presented in Table 6-6.

Table 6-6; IS score for each consequence parameter, the maximum IS within each category the resulting weights and SCV.

Consequence Group	Criteria	IS	IS per Criteria	Wj	Sub-Criteria	SCV
Diameter	Diameter	5	5	0.11	x >= 1000	5
		4			1000 < x <=600	4
		2			600 < x <= 400	2
		1			< 400 x	1
Economic	Burial Depth	2	2	0.05	{0,1}	5
	Buffer to Building	4	4	0.09	{0,1}	5
Social	Buffer to Motorway/ Highway	4	4	0.09	{0,1}	5
	Buffer to Priority Highway	5	5	0.11	{0,1}	5
	Buffer to Railway Tracks	7	7	0.16	{0,1}	5
Environmental	Buffer to Water Protection Area	10	10	0.23	{0,1}	5
	Buffer to Water Bodies	7	7	0.16	{0,1}	5
Sum			**44**	**1**		

Finally, COF was calculated using Equation 5-1, where *i* equals the number of analysed pipes = 1, 2, 3, ..., 14,718, and *j* =1, 2, 3, ..., 8, representing the eight criteria. Since the maximum value of *SCV* is 5 and the sum of *Wj* equals 1, COF ranges from >0 to 5.

6.3.1 Interpretation of results

The WSM model was implemented on all pipes within the dataset with a specified diameter, equalling 14,718 unique pipe IDs. Since the sum of *Wj* equalled one and the maximum value of *SCV* was five, the COF could take values between > 0 and 5. However, when analysing the results, the highest value of COF was 2.046. When analysing this pipe, it is close to a water protection area, the criteria with the highest associated *Wj*. Further, when analysing the COF scoring for the 14,718 pipes, all pipes were influenced by the criteria diameter. With further analysis and observing Table 6-3 , the economic, social and environmental consequence parameters are not influencing COF for all pipes. Consequently, for a pipe to receive the highest value, equal to five, it should be influenced by all criteria for a pipe to reach the maximum COF value. Since the pipe with the highest score was seen as very high COF, it would be insufficient to regard the highest scored pipe as low or moderate COF impact. In Table 6-7 the *SCV* and COF score for some selected pipes are presented, where the highlighted red row is the highest scored pipe and the blue some of the lowest scored pipes.

Table 6-7: SCV, COF and COF Category (COF.Cat) for selected pipes. The blue rows are the lowest scored pipes and the red row the highest scored pipe within the Wastewater pipe network. WPA: Water Protection Areas. WB: Water Body. H/M: Highway/Motorway. PH: Priority Highway. RT= Railway Track. B: Adjacent to Building. BD: Burial depth >= 5m.

Pipe ID	WPA [SCV]	WB [SCV]	H/M [SCV]	PH [SCV]	RT [SCV]	B [SCV]	Diameter [SCV]	BD [SCV]	COF	COF.Cat
3	-	-	-	-	-	-	1.0	-	0.113636363636364	1.0
4	-	-	-	-	-	5.0	1.0	-	0.568181818181818	3.0
6	-	-	5.0	-	-	-	1.0	-	0.568181818181818	3.0
29	-	-	5.0	-	-	-	1.0	-	0.568181818181818	3.0
30	-	-	-	5.0	-	-	1.0	-	0.681818181818182	3.0
65	-	-	-	5.0	-	-	1.0	-	0.681818181818182	3.0
80	-	-	-	-	-	-	1.0	-	0.113636363636364	1.0
160	-	-	-	5.0	-	-	1.0	-	0.681818181818182	3.0
183	-	-	-	5.0	-	-	1.0	-	0.681818181818182	3.0
190	-	-	-	-	-	-	4.0	-	0.454545454545455	3.0
884	-	-	-	-	-	-	1.0	-	0.113636363636364	1.0
2888	-	5.0	-	-	-	-	1.0	-	0.909090909090909	4.0
4909	5.0	-	-	-	-	-	1.0	-	1.25	5.0
4913	5.0	5.0	-	-	-	-	1.0	-	2.04545454545454	5.0
10922	-	-	-	-	-	-	1.0	-	0.113636363636364	1.0
11130	-	-	-	-	-	-	1.0	-	0.113636363636364	1.0
12591	-	-	-	5.0	-	-	1.0	-	0.681818181818182	3.0
14089	-	-	-	-	-	5.0	1.0	-	0.568181818181818	3.0
14989	-	-	-	-	-	-	1.0	-	0.113636363636364	1.0
15043	-	-	-	-	-	-	1.0	-	0.113636363636364	1.0

To solve this problem, Jenks Natural Breaks was used. The methods have been used by, e.g. Baah et al. (2015); Salman (2010), and it is a tool to divide data into classes where the variation within classes are as small as possible and the variation between classes as high as possible. However, when using the method, the data are divided into classes solely according to the variation within and between classes. Consequently, if the assumption that the highest value of COF is a very high consequence is true, the Jenks Natural Breaks can estimate the relative COF based on the highest COF value. Jenks Natural Breaks was calculated with the RStudio package BAMMtools (Robsky et al., 2019). In Table 6-8, the results are presented.

Table 6-8: Evaluated COF and linguistic impact description, category, score, and counts.

Impact	***COF category***	***COF score***	***Counts***
Low (L)	1	0 – 0.114	11970
Moderate (M)	2	0.114 – 0.228	398
Moderate-to-high (MH)	3	0.228 – 0.682	1861
High (H)	4	0.682 – 1.364	303
Very High (VH)	5	> 1.364	186
Sum			14718

Further the distribution of COF with the breaks at 0.114, 0.228, 0.682. and 1.364 is presented as a histogram in Figure 6-9. Since COF category ranges between COF score 0 – 0.114 and these pipes are only influenced by the diameter < 400 mm (Table 6-7), a majority of the pipes in Figure 6-9 are in COF category 1.

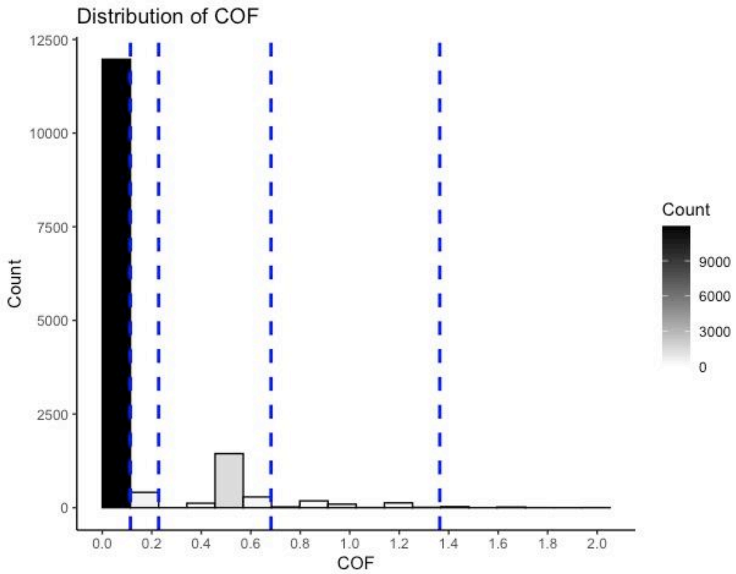


Figure 6-9: Distribution of COF with breaks from Jenks Natural Breaks (Blue dashed lines)

Further analysis is presented in APPENDIX B. The table shows that the COF categories essentially include:

1. Pipes with a diameter under 400 mm and no other consequence parameters.
2. Pipes with diameters over 400 mm and under 600 mm, and small diameter pipes with burial depth greater than five meters.
3. Pipes with a small diameter under roads and railway tracks.
4. Pipes with a larger diameter under roads and railway tracks and small diameter pipe adjacent to water bodies.
5. Pipes with larger diameter adjacent to water bodies, pipe adjacent to water protection areas and combinations of consequence parameters.

From this information, a linguistic impact grading was associated with each COF category (see Table 6-8).

6.4 Evaluating POF (iii, b)

In the following sections POF will be evaluated using:

i. Logistic Regression.
ii. WSM.

6.4.1 Multinomial Logistic Regression.

When developing the model, the first step was to sort the data according to the following steps:

i. A data set from Kungsbacka municipality water utility consisting of Structural and Operational grade was used.
ii. Duplicate pipe IDs was removed from the dataset.
iii. Pipes that did not have specified age, material, length, or diameter were removed from the dataset.
iv. The age of the pipe was set as the time between installation and observation.
v. Pipes with age under one year was removed from the dataset, mainly to exclude inspection to confirm the quality of installation or pipes that had been damaged during installation.
vi. Outliers such as a few pipes with installation data 1900-01-01 or small material categories such as DI, CI, PHLOMAX was removed from the dataset.

The advantages of binomial regression are that the outcome returns a value between one and zero, where the value can directly represent POF. However, the structural grade 2 is a broad category that indicates "poor condition". Consequently, a problem occurs when structural grade 2 is categorised as P(Y=0), non-failure. Therefore, a multinomial model was considered to represent problem formulation and input data more adequately. Further, renovated pipes were only present in structural grade 0 – 1 and discarded from the model. Three dependent variables were used, where P(Y=1), P(Y=2) and P(Y=3) represents structural grade 0 - 1, 2 and 3, respectively. Further, P(Y=3) was used as the reference level.

The multinomial logistic regression models was derived from Equation *5-10* with the used independent variables. The models are presented in Equation 6-1 and Equation *6-2* and denoted as *Multinomial Equation* (*ME*) 1 and 2.

$$\ln\frac{(P(Y=1|X_1,\ X_2\ldots,X_n))}{(P(Y=3|X_1,\ X_2\ldots,X_n))} = \alpha_1 + \beta_{1.Length}X_{Length} + \beta_{1Age}X_{Age} + \beta_{1.Diameter}X_{Diameter} + \beta_{1.BTG=<1970}Z_{BTG=<1970} + \beta_{1.BTG>1970}Z_{BTG>1970} + \beta_{1.Plastic}Z_{Plastic} = ME1$$

Equation 6-1

$$\ln\frac{(P(Y=2|X_1,\ X_2\ldots,X_n))}{(P(Y=3|X_1,\ X_2\ldots,X_n))} = \alpha_2 + \beta_{2.Length}X_{Length} + \beta_{2.Age}X_{Age} + \beta_{2.Diameter}X_{Diameter} + \beta_{2.BTG=<1970}Z_{BTG=<1970} + \beta_{2.BTG>1970}Z_{BTG>1970} + \beta_{2.Plastic}Z_{Plastic} = ME2$$

Equation 6-2

Where X_i are continuous variables taking values for i = 0,1,2, ... N, and Z binary "dummy" variables for material, equal to $Z_i \in \{0|1\}$, where 0 represents that the material is not present for that particular pipe, and 1, that the material is present. Further, *ME1* and *ME2* represents the $i = k - 1$ equations. The probability for P(Y=3), P(Y=2) and P(Y=1) was derived from Equation *5-11* and calculated using Equation *6-3*, Equation *6-4*, and Equation *6-5*.

$$P(Y = 3) = \frac{1}{1 + e^{ME1} + e^{ME2}} \qquad \textit{Equation 6-3}$$

$$P(Y = 2) = \frac{e^{ME2}}{1 + e^{ME1} + e^{ME2}} \qquad \textit{Equation 6-4}$$

$$P(Y = 1) = \frac{e^{ME1}}{1 + e^{ME1} + e^{ME2}} \qquad \textit{Equation 6-5}$$

Further each pipe was evaluated in terms of P(Y=3), P(Y=2) and P(Y=1), and the most probable *Multinomial Category* for each pipe is determined by Equation *6-6*.

$$Multionomial\ Category = max(P(Y = 3), P(Y = 2), P(Y = 1)) \qquad \textit{Equation 6-6}$$

The multinomial logistic regression model was performed analysed in RStudio, using the *nnet* package (Ripley and Venables, 2021). In Table 6-9, the results from the multinomial regression model are presented, and the calculation process is presented in APPENDIX C.

Table 6-9: Results from the Multinomial regression. Where ß is the regression coefficient, std.error the standard error, z is used for the two-tailed Z test, where the p-value is the significance. p = 0.000 indicates p-values less than 0.001.: Diameter in ME1 is not significant.*

	Intercept [α]	***Length [m]***	***Diameter [mm]***	***Age [yrs]***	***C =< 1970***	***C > 1970***	***Plastic***
ME1							
ß	4.551	-0.023	-0.002	-0.050	2.361	3.044	-0.854
exp(ß)	94.756	0.977	0.998	0.951	10.604	20.989	0.426
Std.error	0.508	0.005	0.002	0.012	0.333	0.228	0.178
z	8.952	-4.411	-1.360	-4.004	7.087	13.372	-4.797
p	0.000	0.000	0.174*	0.000	0.000	0.000	0.000
ME2							
ß	4.290	-0.014	-0.007	-0.042	2.082	1.778	0.429
exp(ß)	72.947	0.986	0.993	0.959	8.022	5.919	1.536
Std.error	0.522	0.005	0.002	0.012	0.339	0.234	0.177
z	8.216	-2.696	-3.734	-3.420	6.140	7.614	2.421
p	0.000	0.007	0.000	0.001	0.000	0.000	0.015

The regression coefficients ($ß_i$) for *ME1* and *ME2* are based on P (Y=3). To exemplify, the continuous variable age associated with *ME1* and *ME2* is equal to -0.05 and - 0.042, respectively. If inserting these values in Equation *6-3*, it is rational that the probability P(Y = 3) increases for each added year since Euler's number raised to the power of negative value results in a number below one. Further, the exp($ß_i$) tells the odds for a pipe to stay in the multinomial category P(Y=2) or P(Y=1). Taking the example with age for *ME1* and *ME2* again, the odds changes with 0.951 and 0.959 for each additional year in age for the pipe to stay in P(Y=1) and P(Y=2). In Figure 6-10 the $ß_i$ values for each independent variable for *ME1* and *ME2* is plotted with a break at $ß_i$ equal to one. Hence, the independent variables to the left of the dashed lines increase the probability for P(Y=3) and the variables to the right decrease the probability for P(Y=3).

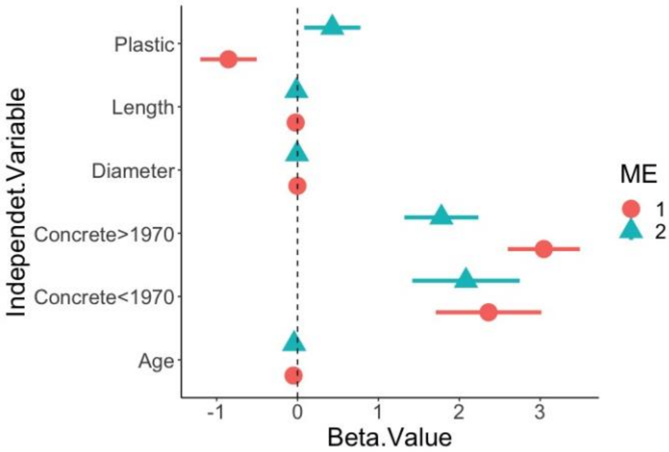


Figure 6-10: Coefficient estimates for the Multinomial Model. The orange dots representing the independent variables for ME1, the turquoise triangles the independent variables for ME2. The lines representing the lower and upper limit within confidence interval.

Further, the p value in Table 6-9 represent the significance of the parameter, where statistical significance is equal to $p < 0.05$, i.e. the null hypothesis can be rejected. Observing Table 6-9, the β^* for *Diameter* in *ME1* is not significant.

The model was then evaluated using the log-likelihood ratio test that compares the whole model with a restricted model built on solely the intercept (α). The null hypothesis is that the restricted model is more adequate in predicting the dependent variable than the full model. In Table 6-10, the test results are presented where the difference between the models is 554.10 and significant according to the chi-squared distribution. In other words, the difference between estimated and observed values are less in the full model at a significantly level that cannot be described by random (Garson, 2016; Salman, 2010).

Table 6-10: Log-likelihood ratio test for multinomial model.

Model	***-2 log likelihood***	***Degrees of freedom***	***Chi-Square***	***Sig.***
Only α	-1,675.29			
Full model	-1,398.24	10.00	554.10	0.000

Further, the model's ability to predict the dependent variables, was evaluated using a classification table (Table 6-11). In the table, the x-axis represents the predicted multinomial categories and the y-axis the observed. The diagonal (white) shows the correct predictions while the red (overestimated) and blue (underestimated) are incorrect predictions. The model predicts pipes in multinomial category 1 very well (95%). However, for category 2 and 3, the accuracy is 34% and 12%, respectively. Hence, the model consistently underestimates pipes in Multinomial category 2 and 3.

Table 6-11: Classification table for Multinomial model. White boxes are true predictions, red boxes false positives and blue boxes false negatives.

	Predicted			
Observed	1	2	3	Correct [%]
1	1753	94	3	95%
2	331	178	7	34%
3	44	48	13	12%
Sum	2128	320	23	79%

Further, in APPENDIX E, probability curves for P(Y=1), P(Y=2) and P(Y=3) for each material concerning increasing age are presented. The analysis shows that the model highly predicts Plastic pipe into multinomial category 2 and 3 compared to the concrete pipes.

6.4.1.1 Conclusion from the Multinomial Logistic Regression model

The first conclusion from the multinomial logistics model is that it consistently underestimates multinomial categories 2 and 3, where the prediction accuracy was 34% and 12%, respectively. Hence, it is fair to say that most of the significance of the model can be credited to the reliability of predicting multinomial category 1. However, some interesting results can be derived. *Age* and *length* were significant in both *ME1* and *ME2*, where an increase in either age or length enhanced the probability of P (Y = 3), which is also consistent with the reviewed literature. The multinational model also shows that *plastic* pipes are a risk factor, followed by *concrete pipes installed before 1970*, and the material with the most negligible impact for pipes to be relocated from P(Y=2) or P(Y=1) to P (Y = 3) was *concrete installed after 1970*. Further, the regression model shows a tendency for larger *diameters* to increase the probability of P (Y = 3). However, it should be added that *diameter* was only significant for one of the regression equations.

Based on the conclusions from the Multinomial Logistic Regression model, it was discarded for further evaluation of ROF. Mainly due to the model's inability to identify high-risk pipes.

6.4.2 The Weighted Sum Method (WSM)

The MCDA method chosen was WSM, with the motivation discussed in section 5.1. The WSM model was built on the same parameters as the multinomial regression, with the difference that *Renovated* pipe was included. A schematic view of the WSM model is presented in Figure 6-11.

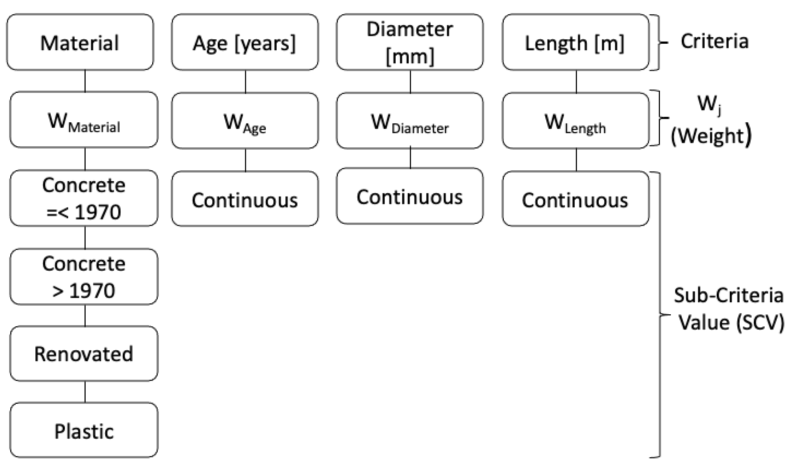


Figure 6-11 Schematic view of the WSM model to evaluate POF.

Further to sort the data used for evaluating POF using WSM followed the following steps:

i. The full dataset from Kungsbacka municipality was used consisting of 15,044 unique pipe IDs.
ii. Pipes that did not have specified age, material, length, or diameter were removed from the dataset.
iii. The age of the pipe was set as the time between installation date and 2021-01-01.
iv. Outliers such as a few pipes with installation data 1900-01-01 or small material categories such as DI, CI, PHLOMAX was removed from the dataset.

The first step in evaluating POF was score all four criteria with a *IS*. The motivation for the *IS* for each criterion where:

- Age is a vital parameter for deterioration. Further, age has been a significant parameter in most reviewed literature and is the foundation in concept models describing the deterioration processes (section 2.4.1).
- Material has shown a significant parameter in many deterioration models. Different materials have varying deterioration processes. The materials condition can also be affected by when and where they were produced.
- Diameter is theoretically a significant factor, smaller diameters have less resistance to bending forces. The diameter has been a significant factor in some of deterioration models discussed in section 2.4.2.3.
- Higher lengths are theoretically more vulnerable for ground movements. The length has also been a significant factor in some studies reviewed in section 2.4.2.4.

The *Wj* was calculated using Equation 5-3 and the result is presented in Table 6-12.

Table 6-12: IS and Wj for the WSM model (POF).

Criteria	***IS***	***Wj (linguistic)***	***Wj***
Material	5	$W_{Material}$	0.28
Age	10	W_{Age}	0.56
Length	1	W_{Length}	0.06
Diameter	2	$W_{Diameter}$	0.11
Sum	18		1

The next step was to set the *SCV* for each criterion. The *SCV* for age was chosen to be represented as a continuous function. In the two MCDA implementations reviewed in section 4 by Tscheikner-Gratl et al. (2017); Vladeanu (2018) used a non-linear scale. Further, studying the schematic conceptual models in section 2.4.1, deterioration process is described as a non-linear function of time. Consequently, the *SCV* for age were set exponentially. The maximum age in the data used for evaluating POF was approximately 70 years. Hence, a pipe with the age of (or over) 70 years was given an *SCV* equal to 5. For pipes with an age less than 70 years, the *SCV* was set to increase exponentially with age to the power of 1.5. The *SCV* as a function of year is presented in Figure 6-12.

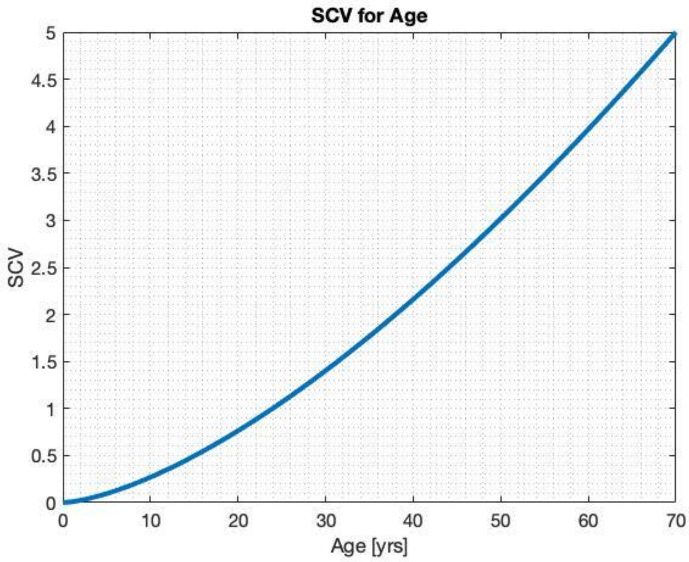


Figure 6-12: SCV as a function of age [years]

For the length, an *SCV* equal to 5 was given to pipes equal to or longer than 100 meters, assuming that longer pipes are more exposed to ground movements. For pipes with a length of less than 100 meters, *SCV* was set as a linear function of length (Figure 6-13).

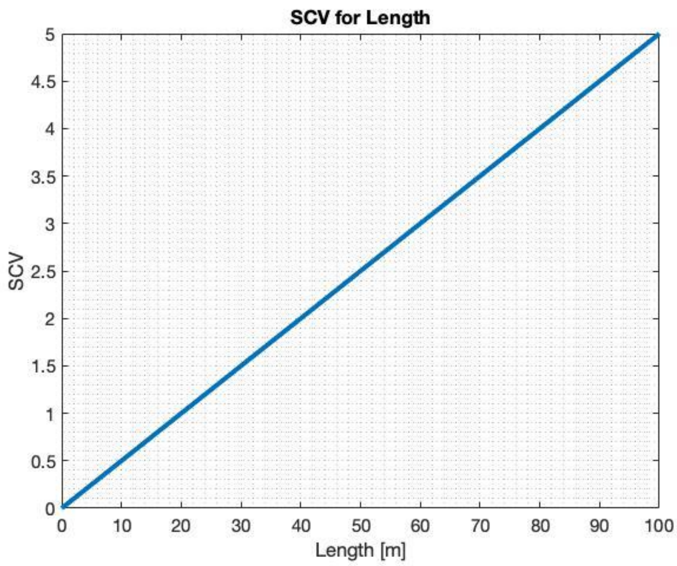


Figure 6-13: SCV as function of length [m]

For the diameter, most research suggesting higher POF for a smaller diameter. However, some research implying higher POF for very large diameter pipes. The maximum diameter within the dataset was 1000 mm, which is not considered a very large diameter. Hence, the diameter was divided into the following sub-criteria; 0 to 250 mm, 250 - 500 mm, 500 - 750 mm, and >750 mm, with the following associated *SCV*; 5, 3.75, 2.5 and 1.25, respectively. *SCV* per diameter sub- criterion is presented in Figure 6-14.

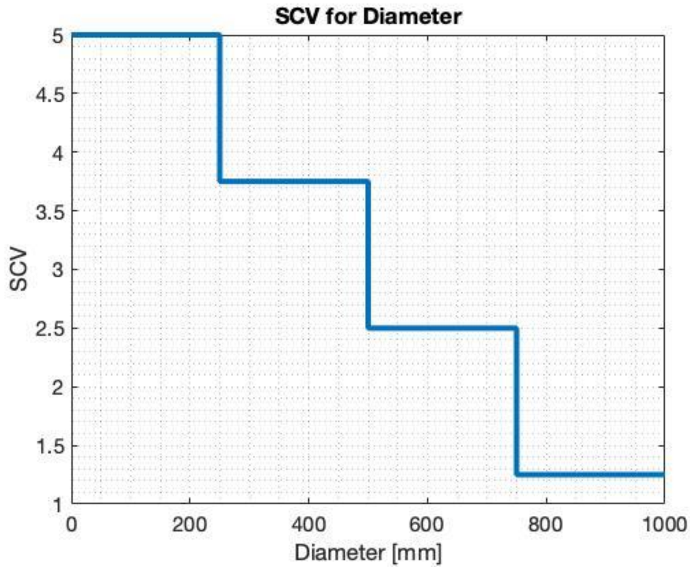


Figure 6-14: SCV as a function of diameter [mm]

For the two studies by Tscheikner-Gratl et al. (2017); Vladeanu (2018) that used MCDA methods to evaluate POF, the *SCV* for concrete was rated 2.5 – 4 times higher than plastic pipes. Section 2.4.2.1.1 declared that the main advantages of plastic pipes are the weight, easier to transport and install, resistance against galvanic or sulphide acid corrosion, and that modern plastic pipe have a theoretical long useful lifetime. Further, plastic pipes, mainly PE and PP, is the most common material in new installations. However, when the sorted data presented in section 6.2 suggest that plastic pipes are performing worse than concrete pipes in terms of structural grade. Possible explanations for plastic pipes poor structural performance are assumed to be explained by one or a combination of the following factors. For the first, plastic pipes are flexible, i.e. they creep. Within the category of plastic pipes, PE and PP pipes creep most, followed by PVC pipes and GRP pipes, which are most rigid. Since PE and PP are the most common material in the new installation, this, combined with deep burial depth, might be a factor, i.e., high vertical loads on the pipe. Further, the quality of installation might be a factor. Inadequate side support resulting in increasing vertical loads on the pipe. As expected, for concrete pipes, there are more frequently structural grade 2 and 3 for concrete =< 1970 than for concrete > 1970. Renovated pipes performed well according to the structural grade. After discussions with the Kungsbacka municipalities water utility, this might be due to when infiltration in concrete pipes is detected, and the solution is to renovate the concrete pipe using CIP, Sliplining or Close-Fit, the infiltration may not necessarily affect the structural condition, and consequently, the result is a fair structural condition concrete pipe with a new plastic pipe within it.

The final SCV for the different materials was set to:

- Plastic pipes received an SCV of 5 due to poor structural performance.
- Concrete pipes installed before 1970 received an SCV of 4 due to the relatively poor structural performance and the literature indicating a poor condition quality of pipes installed before 1970.
- Concrete pipes installed after 1970 performed well according to the CCTV inspections, and compared to other materials in the specified dataset, many pipes have been inspected. Therefore, this material group received an SCV of 2.
- According to the CCTV inspection, renovated pipes performed best in terms of structural performance and therefore given an SCV of 1.

In Table 6-13 the Wj and SCV for each criterion is presented.

Table 6-13: Summary of Wj and SCVij for evaluating POF

Material [$W_{Material}$ = 0.28]	
Sub-criteria	SCV
BTG =< 1970	4
BTG > 1970	2
Plastic	5
Renovated	1
Age [W_{Age} = 0.56]	
Sub-criteria	SCV
x >= 70	5
x < 70	$\frac{(Pipe\ Age)^\wedge 1{,}5}{117.13}$
Length [W_{Length} = 0.06]	
Sub-criteria	SCV
x >=100	5
x < 100	$\frac{Pipe\ Length}{20}$
Diameter [$W_{Diameter}$ = 0.11]	
Sub-criteria	SCV
0 x < 250	5
250=< x < 500	3.75
500 <= x <750	2.5
750 <= x <=1000	1.25

Further, Equation 5-1 was used to evaluate POF for the individual pipes, where i equals the analysed pipes, i =1, 2, 3, ... 14,633, and j equals the four-criterion material, age, length and diameter.

6.4.2.1 Interpretation of results

The WSM model was implemented on all pipes within the dataset with specified diameter, age, length and material, resulting in evaluating POF for 14,633 unique pipe IDs. The highest and lowest POF was 4.45 and 0.62, respectively. A more detailed analysis of the WSM model was performed through a test in which a newly installed plastic pipe, i.e. the material with the highest *SCV* with an age of zero years, with the most typical diameter, 225 mm, and a regular length of 20 m was evaluated. The test scoring resulted in a POF equal to 2. Hence, this test result was set as a baseline scenario for POF category 1. Consequently, POF category one was set to range from 0 - 2.0. The following POF categories 2, 3, 4 and 5 were set to range evenly distributed up to five, resulting in the categories 2 - 2.75, 2.75 - 3.5, 3.5 - 4.25 and 4.25 - 5.0 for POF category 2, 3, 4 and 5, respectively. The distribution of POF with breaks is presented as a histogram in Figure 6-15.

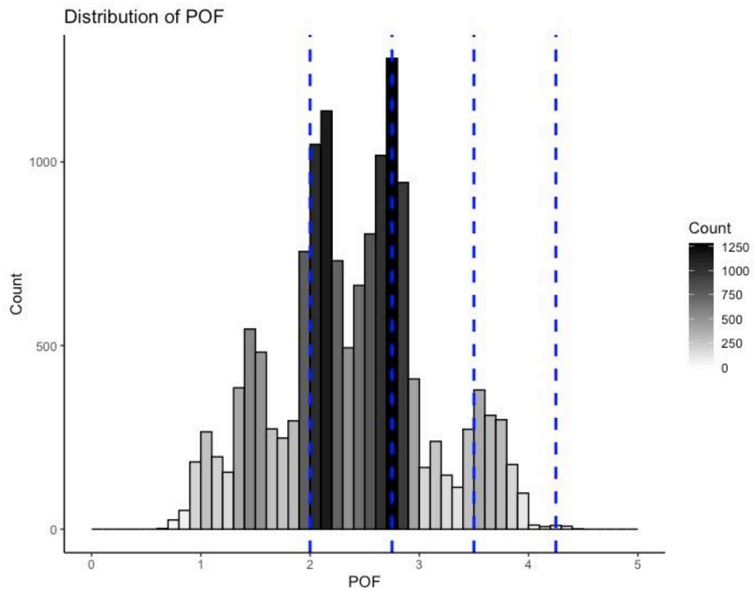


Figure 6-15. Histogram of distribution of POF with the POF category breaks at 2.0, 2.75, 3.5 and 4.25

Further analysis is presented APPENDIX B. The table presents that POF Category:

1. Total of 3,862 pipes, where the material concrete > 1970 dominating the category. The average age for pipes in this category was 15 years.
2. Total of 6,568 pipes with an average age of 31.7 years. The category included Plastic pipes with an average age of 11.8 years, Concrete > 1970 with an average age 40.1 years and renovated pipes with an average age of 46.7 years.
3. Total of 2,905 Pipes with an average age of 44.6 years. All material was included.
4. Total of 1,285 pipes with an average age of 53.2 years, consisting of Plastic and concrete < 1970.
5. Total of 13 pipes consisting of 12 concrete < 1970 with an average age of 65.3 years and one plastic pipe with an age of 59 years.

The results are presented in Table 6-14. where the POF score, the POF category and the linguistic impact description are presented.

Table 6-14: Evaluated POF and linguistic impact description, category, score and counts.

Impact	***POF category***	***POF score***	***Counts***
Low (L)	1	0 – 2.0	3862
Moderate (M)	2	2.0 – 2.75	6568
Moderate-to-high (MH)	3	2.75 – 3.5	2905
High (H)	4	3.5 – 4.25	1285
Very High (VH)	5	4.25 – 5.0	13
Sum			14633

6.5 ROF & Inspection prioritisation (iv)

ROF was evaluated using a risk matrix. Since COF and POF were set to range between >0 to 5, a 5 X 5 matrix was used. The advantages of the risk matrix are the possibility of visualising risk levels, its relative simplicity, and the flexibility in evaluating ROF. It is possible to adopt stakeholder and expert judgment and set the matrix to either enhance COF or POF influence. The process of sorting the data used in the risk matrix was:

i. The COF and POF data were combined.
ii. The pipe IDs with structural grade was removed from the dataset.

Further, after consultation with Kungsbacka municipality, it was determined that the matrix should be weighted so COF would have more influence on ROF than POF. The motivation for this decision was twofold; The first was that there are pipes and locations where a failure within the wastewater pipe network would have high consequences, which were regarded more critical than solely pipe failure; Secondly, there are more uncertainties within the POF, the COF was evaluated using spatial GIS data and pipe characteristic. Hence, there are few uncertainties where the consequences are high. The estimation of POF was based on assumptions about how pipe-characteristic data contributes to the deterioration process of wastewater pipes. Hence, POF resulting in higher uncertainties.

The Risk matrix is presented in Figure 6-16, where the x-axis represents COF from 1 to 5, the y-axis POF from 1 – 5, and the numbers within the matrix referring to ROF, where 1 is the lowest and 5 the highest. The design and weighting of the risk matrix were adopted in dialogue with Kungsbacka municipality. In APPENDIX F more detailed analysis of the risk matrix is presented.

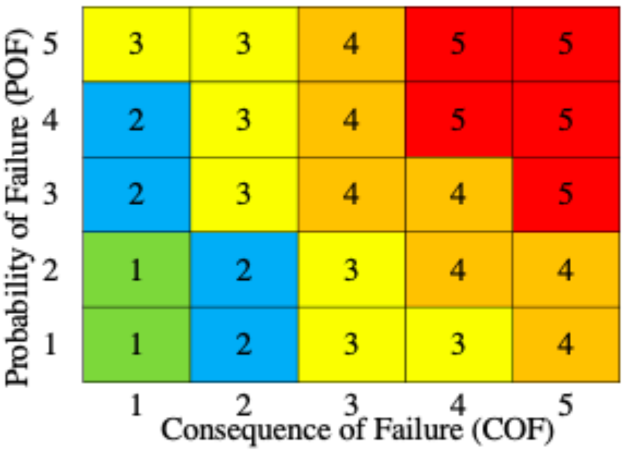


Figure 6-16: Risk Matrix. The x-axis represents COF and the y-axis the POF. The matrix is weighted to enhance COF impact on ROF.

All unique Pipe IDs within each ROF Category were summed, and the CCTV-inspection priority groups were based on the reverse ROF category, i.e. ROF category five was CCTV inspection priority one. The results are presented in Table 6-15.

Table 6-15: Evaluated ROF and CCTV-Inspection priority groups

Impact	***ROF Category***	***CCTV-Inspection Priority Group***	***Counts***
Low (L)	1	5	7,111
Moderate (M)	2	4	2,875
Moderate-to-high (MH)	3	3	1,152
High (H)	4	2	685
Very High (VH)	5	1	42
Sum			11,865

The last step in the CCTV-Inspection priority was to rank all individual pipe IDs within each Inspection group by COF as decision support for CCTV inspection.

Figure 6-17 presents an example of the result in the city centre of Kungsbacka (GIS), where pipes are highlighted with colours to represent ROF.

Figure 6-17. The results from ROF evaluation, visualised in GIS.

6.6 Inspection & Condition assessment (v)

In this case study, the inspection and KB used were already existing in the Kungsbacka municipalities database. Hence, no inspections have been performed for this thesis or with the guidelines from the risk-based method.

6.7 Rehabilitation priority & Inspection frequency (vi)

The rehabilitation priority and re-inspection priority was based on the research and guidelines from NRC and WRC, where the assessed CCTV inspections are combined with COF. As discussed in section 0, the most severe defects are treated similarly in NRC, WRC and KB condition assessment protocol. Further, NRC uses a WSM model to evaluate COF, while WRC uses fixed group, A, B and C. In Table 4-17, the rehabilitation priority and re-inspection frequency for WRC and NRC are summarised. The evaluated rehabilitation priority and inspection frequency presented in Table 6-16 is based on those guidelines.

In this step, the pipes that have been assessed with a KB using CCTV are included. The first step in establishing a rehabilitation priority was to combine the structural grade, based on the condition assessment protocol KB, with the corresponding COF (evaluated in section 6.3), resulting in 2,854 matching pipe IDs. In Figure 6-18, a 4 x 5 matrix is presented with structural grade 0, 1, 2 and 3 on the vertical axis and COF category 1, 2, 3, 4 and 5 on the x-axis. The values within the cells represent the number of pipes, where the colours indicating rehabilitation priority; (red) Immediate, (orange) High, (yellow) Moderate-to-high, (blue) Moderate and (green) Not required. Unlike the risk matrix used to determine ROF (Figure 6-16), the rehabilitation priority is based on the assessed condition from the CCTV inspection, where a higher structural grade results in higher rehabilitation priority.

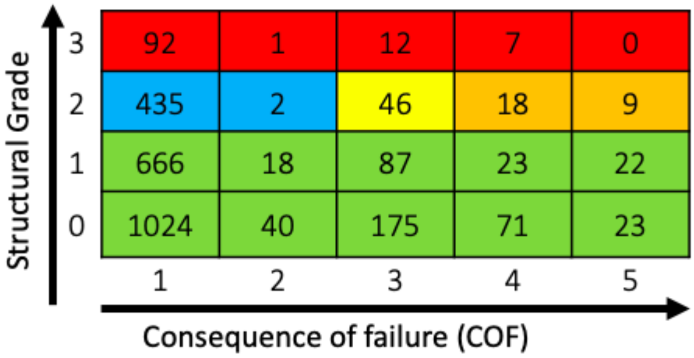


Figure 6-18: Distribution of COF per Structural grade. Green represents low frequency and red high frequency

The final rehabilitation and re-inspection plan are presented in Table 6-16. The overall strategy is based on that higher structural grade means more defects present in the pipe following an increased deterioration rate, which urges a higher rehabilitation priority or more frequent inspections to avoid undesired social, economic or environmental consequences.

KB grade 3 is assumed to represent NRC and WRC grade 5. Consequently, the priority for structural grade 3 with COF between 2 – 5 should immediately be rehabilitated, while a COF of 1 can be rehabilitated immediate or be re-inspected within 0 – 2 years due to the low COF. Rehabilitation priority and re-inspection frequency for structural grade 2 are more complicated to evaluate due to the broad span defects. However, the defects in structural grade 2 are not assumed to be so severe that immediate rehabilitation is needed. Instead, the category is treated as NRC and WRC grade 2, 3 and 4, where the COF sets rehabilitation and re-inspection priority.

Further, a pipe with KB grade 2 and high COF and, if rehabilitation is rejected, should be more frequently inspected than a pipe with KB grade 2 with lower COF. Accordingly, KB grade 2 with high COF should be rehabilitated first, while a lower COF results in lower priority. The lowest rehabilitation priority is assigned to pipes with KB grade 0 and 1.

Table 6-16: Suggested rehabilitation and re-inspection plan for the Risk-based model.

Kortbetyg (Structural grade)	***COF***	***Rehabilitation priority***	***"or"***	***Next inspection***	***Counts***
3	2 – 5	Immediate	-	-	20
	1	Immediate	or	0 - 2 years	92
2	4 - 5	High	or	6 years	27
	3	Moderate-to-high	or	6 – 10 years	46
	1 - 2	Moderate	or	10 – 15 years	437
0 – 1	3 – 5	Not required	->	15 – 20 years	401
1	1 – 2	Not required	->	20 – 25 years	684
0	1 – 2	Not required	->	25 years	1064
Sum					2771

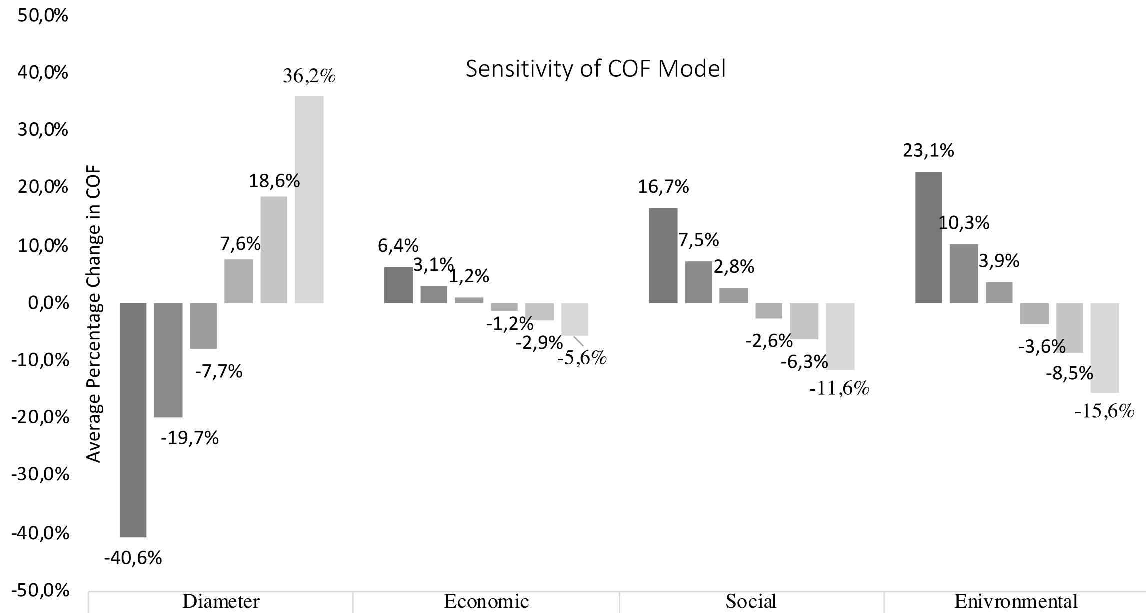
Further, unlike the risk matrix (Figure 6-16) used to evaluate ROF the rehabilitation priority is based on to summarise the rehabilitation priority, there are 20 pipes that should be rehabilitated immediately and 92 pipes that should be rehabilitated immediately or re-inspected within 2 years. Within rehabilitation priority *high*, *Moderate-to-high*, and *moderate*, 27, 46 and 437 pipes are included. Since, as mentioned, structural grade 2 is broad category, no *low* priority has been assigned.

6.8 Update and re-evaluate assumptions and database (vii)

In this case study, the evaluating COF and POF is based on and thus heavily dependent on the available data in Kungsbacka municipality and the expert judgements done by the involved representatives from water utility. Since no new inspections have been conducted according to the risk-based model, no re-evaluation of assumptions or updating of the database has been performed.

6.9 Sensitivity analysis of POF and COF

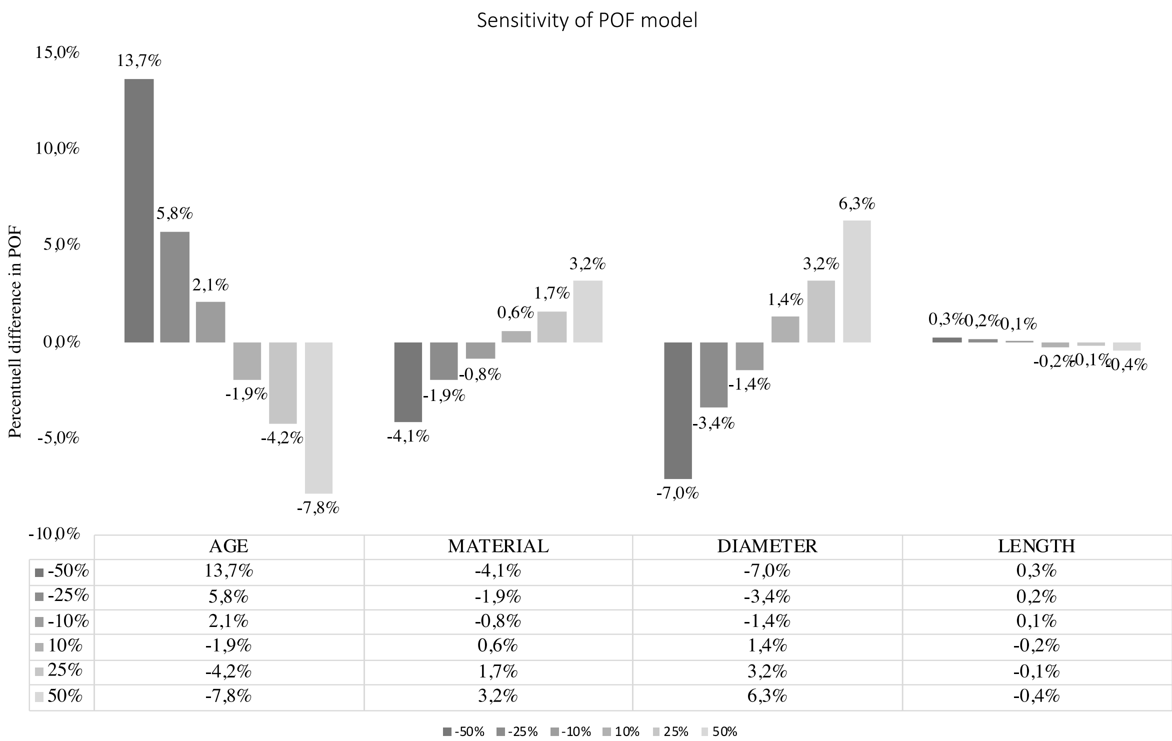
The sensitivity analysis was performed by changing the weights according to the step presented in section 5.2. POF was analysed by changing the weights for the criterion Age, Material, Diameter and Length step-by-step. COF was analysed by changing the weights of the criteria within the consequence group Economic, Social, Environment and Diameter. For example, when the weights for the Environmental consequence group were analysed, both the weight for the criteria Water protection area (WPA) and Waterbody (BD) where changed at the same time. The results from the sensitivity analysis is presented in Figure 6-19 and Figure 6-20, where the change in weight range from -50%, -25%, -10%, 10%, 25%, and 50%.



	Diameter	Economic	Social	Enivronmental
-50%	-40,6%	6,4%	16,7%	23,1%
-25%	-19,7%	3,1%	7,5%	10,3%
-10%	-7,7%	1,2%	2,8%	3,9%
10%	7,6%	-1,2%	-2,6%	-3,6%
25%	18,6%	-2,9%	-6,3%	-8,5%
50%	36,2%	-5,6%	-11,6%	-15,6%

Figure 6-19: Sensitivity analysis of COF. With step-by-step change in weight for the criteria within the Diameter, Economic, Social and Environmental consequence group.

COF is very sensitive to changes in the weight of the Diameter (Figure 6-19), where a 50% decrease changes the results by 40.6%. Further, it is notable that changes or indirect changes in the criterion Diameter have the highest impact on the COF model. When the weight for diameter increases, the weights for other criteria will decrease, and the total COF increase. Contrary, when the weights for economic, social or environmental criteria increases, the weight for diameter will decline and, consequently, COF decrease.



	AGE	MATERIAL	DIAMETER	LENGTH
-50%	13,7%	-4,1%	-7,0%	0,3%
-25%	5,8%	-1,9%	-3,4%	0,2%
-10%	2,1%	-0,8%	-1,4%	0,1%
10%	-1,9%	0,6%	1,4%	-0,2%
25%	-4,2%	1,7%	3,2%	-0,1%
50%	-7,8%	3,2%	6,3%	-0,4%

Figure 6-20: Sensitivity analysis of POF. With step-by-step change in weight for the criteria Age, Material, Diameter and Length.

The POF (Figure 6-20) is most sensitive for changes in *Age*, where a 50% lower weight changes the results by 13.7%. Further changes decrease in the weight A*ge* resulting in higher POF, while a decrease in *Material* and *Diameter* results in lower POF. Changes in the weight for *Length* resulting in very small changes in POF. Generally, changes for weights with initially high weights will result in more significant variations in COF or POF.

In order to evaluate how the WSM model used to evaluate POF respond to changes in *diameter*, *length* and *age*, three scenarios were evaluated for the four material groups *Plastic*, *Concrete=<1970*, *Concrete>1970* and *Renovated pipes*. In Table 6-17, the three scenarios are presented, where the median diameter, length and age (presented in section 6.1) is stepwise used as fixed variables.

Table 6-17: Scenarios for evaluating the behaviour of the WSM model for evaluating POF

	Change in Variable	***Fixed median values***		
Scenario	***Continuous variable***	***Diameter [mm]***	***Length [m]***	***Age [yrs]***
i	Diameter	-	38.0	31.75
ii	Length	231.8	-	31.75
iii	Age	231.8	38.0	-

In Figure 6-21, scenario **i** is presented where the diameter changes continuously from 0 to 1,000 mm with a fixed median value for length and age. The red dashed lines represent the thresholds for the POF categories.

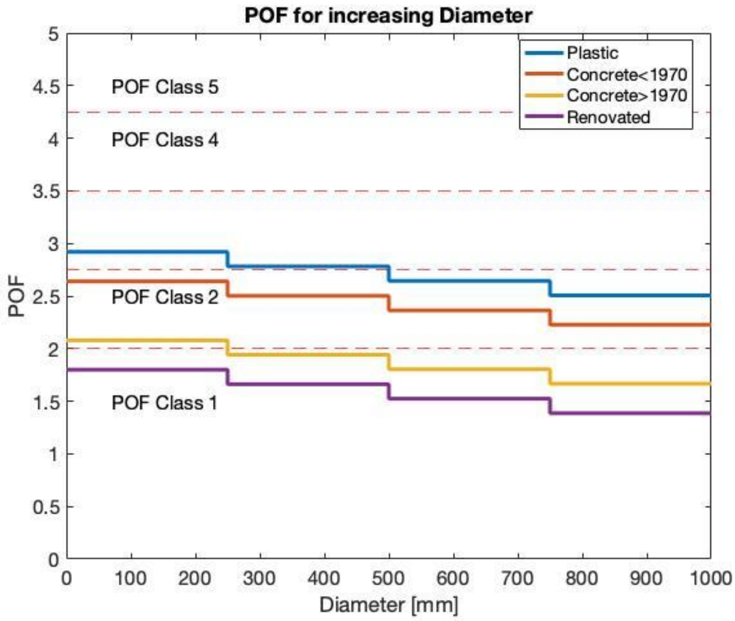


Figure 6-21: Change in POF with continuously change in Diameter with fixed age and length.

Further, in Figure 6-22, scenario **ii** is presented where the length changes continuously from 0 to 100 meters with a fixed median value for diameter and age.

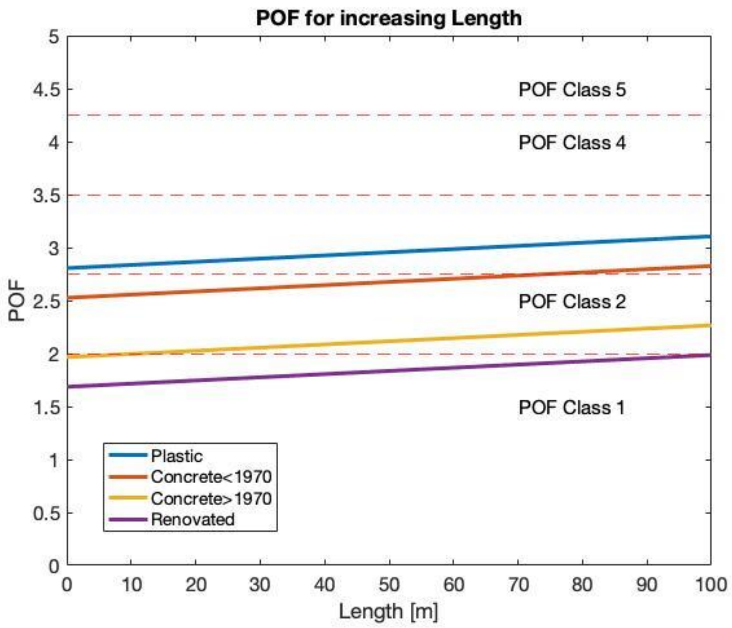


Figure 6-22: Change in POF with continuously change in Length with fixed age and diameter.

The final scenario **iii** is presented in Figure 6-23, where the age continuously changes from 0 – 70 years with a fixed median value for diameter and length.

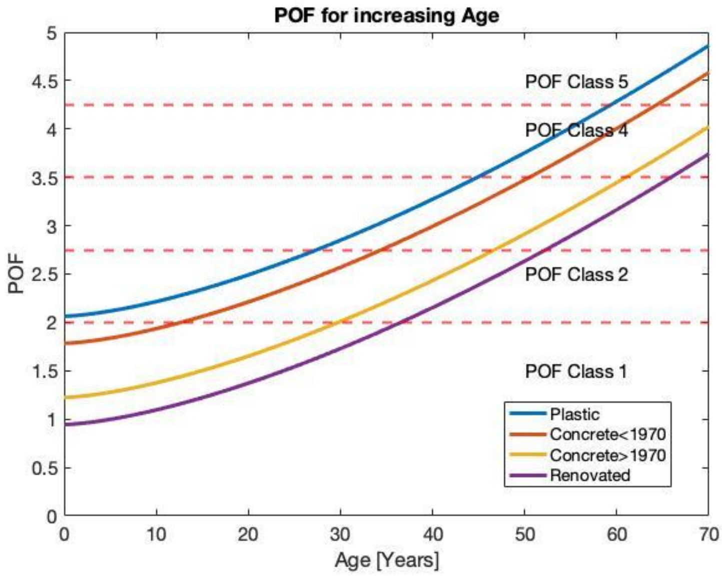


Figure 6-23: Change in POF with continuously change in Age with fixed diameter and length.

7 Discussion

In the following section the results presented in this thesis will be discussed with respect to (i) findings from the literature review, (ii) the general Risk-based method, and (iii) implementation of the risk-based model in Kungsbacka municipality.

7.1 The literature review of risk-based methods

7.1.1 POF

In the literature review, the evaluation of POF was mainly addressed as deterioration models, i.e. a model to predict the condition for a pipe at present based on the properties of the pipes. A summary of conventional parameters is presented in Table *4-1*, and the most frequently used in the literature review in Table 4-6. Further, it is customary to describe the deterioration process as a non-linear process (e.g. (Davies et al., 2001; Lidström, 1996; Misiunas, 2008)); therefore, most of the successful models in the literature are based on non-linear models such as BNs, ANNs or Logistic Regression. In all of these models, the output or dependent variable was based on condition assessments and CCTV inspections in particular, where the input or independent variables consisted of; pipe characteristics, environmental and operational data. Hence, the models take advantages of the pipes that are graded with condition assessment protocol and uses the properties of those pipes to predict the condition of pipes that have not been inspected. The accuracy of these models varies between 40% and 80%. These results can be seen as relatively good if one considers, e.g. a CCTV priority, where the water utility could inspect the most critical pipes in terms of condition with a precision of 40% - 80%. When combining this with COF, the water utility can identify high-risk pipes within the wastewater pipe network and target rehabilitation efforts to reduce the overall risk.

Further, the POF or deterioration process has been described as a function of time. If considering the process as the bat-tub curve presented in Figure 2-18 , the POF is highest at the installation and end of the useful lifetime. Additionally, it has been well described that the deterioration process accelerates when defects are present due to more movements around the pipe caused by infiltration, exflow and decreasing bearing capacity. Therefore, if regarding the deterioration process proposed in Figure 7-1 , POF is a function of time, and T_N is the predicted useful lifetime during normal conditions, where the acceleration in POF is determined by the natural degradation process of the pipe material. Additionally, T_X is the time when the first significant defect is present at the pipe, which accelerates the deterioration process. Consequently, two curves describe the deterioration process, where the blue line describes the natural deterioration under normal conditions and the red line the deterioration accelerated by present defects. In conclusion, POF and the deterioration process is complex to model.

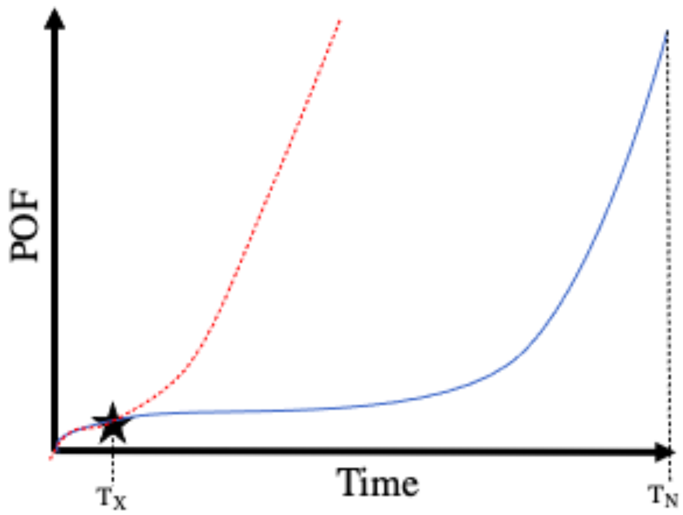


Figure 7-1: Alternative deterioration process for wastewater pipes, where POF is a function of time. The red dashed line represents the deterioration process after a severe defect. The blue line represents the deterioration process under good conditions.

The MCDA methods used to evaluate POF are harder to evaluate concerning accuracy. However, the most critical step is evaluating the criteria with associated weights, and if using experts, weights and criteria should strive against consistency. However, Tscheikner-Gratl et al. (2017) showed no significant difference between MCDA models and Vladeanu (2018) suggested using sensitivity analysis to evaluate how the results vary by change in weight.

Further, all studies within the literature review have been case studies, i.e. the methods have been developing using the data from specific cities, municipalities, or regional water utilities to build up the models. The accuracy has then been validated using, e.g. training and tests data, classification tables, r-squared etc. Hence, there is no evidence that a deterioration model could be used in another arbitrary wastewater pipe network. Furthermore, no studies have described if there has been a previous strategy for CCTV inspections. If there has been a strategy, or if only already defective pipes have been inspected, the inspected pipes properties can be biased.

7.1.2 COF

COF has mainly been evaluated using the pipes diameter and additional spatial GIS data to determine social, economic, and environmental consequences. The most used parameters are presented in Table *4-1*. Further, the COF has mainly been used using MCDA, particularly the WSM or AHP method or WRCs fixed groups. The advantages of using an MCDA method is the flexibility for the water utility to set up the COF model with the competence and stakeholder values within the organisation. However, this approach also makes the COF models tailored for the specific wastewater pipe network. Hence, water utilities should be careful to adopt these models straight away. On the other hand, the fixed COF categories presented by, e.g. WRC, are more general. Hence, having, e.g. national guidelines for COF gives results more accessible to compare between water agencies.

7.1.3 Condition assessment protocols

The reviewed condition assessment WRC and NRC can not directly be converted to the KB system. However, it is fair to say the maximum grades are similar (Table 4-18, page 57). Further, NRC gives detailed recommendation regarding inspection frequency and rehabilitation priority (Zhao et al., 2001). Further, the scale 1 (0 -1) to 5 is a more detailed condition assessment protocol, giving more decision support for water utilities regarding the type of rehabilitation or inspection priority the grade implies.

7.2 The Risk-based model

The general risk-based model (presented in Figure 5-1) strives to be a general process to set up a risk-based rehabilitation plan. The model is based on evaluating POF and COF to identify high-risk pipes within the wastewater pipe network. In order to evaluate POF and COF, several methods have been reviewed in section 4. For this reason, the presented risk-based model should be seen as a general model that offers a structured approach to renewing wastewater pipe networks. Consequently, water utilities should choose methods depending on resources, competence, experience and available data. Still, some general recommendations for the risk-based model can be summarised as:

i. Summarise the available data within the water utility.
ii. Sort the available data into parameters influencing deterioration and economic, social and environmental consequences.
iii. Evaluate COF and POF using the available data.
iv. Combine POF and COF to identify the high-risk (ROF) pipes within the wastewater pipe network.
v. Use ROF to set up a CCTV inspection (or other inspection methods) priority.
vi. Use the CCTV inspections and evaluated COF as decision support for rehabilitation measures.
vii. Update the database and assumptions in the POF and COF models when new knowledge from the inspections are available.

7.2.1 Limitations of the Risk-based model

The risk-based model is in some way dependent on CCTV inspection. The motivation for designing the model this way are; CCTV inspections and condition assessment protocols are recognised as the most common way to evaluate the structural and operational condition of wastewater pipes; CCTV inspection provides the opportunity to develop a model based on the grade for the individual pipe with associated pipe properties. The most noticeable limitation is that the condition assessment depends on the workmanship of the actual grading of the defects. Another limitation that should be addressed is that one of the problems that are high on the water utility agenda is I & I. Since CCTV inspections are not tailored to spot infiltration and inflow into wastewater pipes, there is a risk that some of these problems may be neglected. However, it should be noted that many of the defects observed in CCTV inspections will influence I & I, e.g. joint displacements, cracks and fractures. If the CCTV inspections have been made in dry weather condition in a pipe over the groundwater level, the infiltration might be absent. However, the situation can be another in case of high precipitation. Further, in the reviewed literature, there have been non or very little focus on modelling and predict I & I, where one reason is that there is no standard to grade I & I as there is for CCTV inspections.

7.3 Implementation of the risk-based model.

The discussion of the implementation of the risk-based model will follow the steps presented in section 5.

7.3.1 Summarising and sorting the data (i & ii)

The model was implemented on Kungsbacka municipality wastewater pipe network with 15,044 unique pipe IDs. Within the dataset, the parameter diameter was relatively homogenous, where the most significant of the diameters of the pipes were between 200 - 250 mm. Further, the wastewater pipe network build-up in Kungsbacka municipality was mainly concentrated in the 1960s - 1970s.

7.3.2 Evaluating COF and POF (iii)

The methods of choice implemented in the risk-based model for this case study were the WSM for POF and COF, and the multinomial regression for evaluating POF.

7.3.2.1 COF (a)

The COF was evaluated setting up economic, social, and environmental consequences and using GIS data highlighting pipes within a buffer to critical objects or land areas. Using a buffer instead of the distance between the pipe and the consequence parameters eliminates the opportunity of setting the *SCV* as a function of distance. In Figure 7-2, this is presented. However, there has been no real motivation for using the distance in the literature review instead of a buffer. Hence, no actual conclusion of which methods is most accurate can be made. Further, it is fair to say soil type might influence the consequence more than the distance in terms of permeability and risk for settlements.

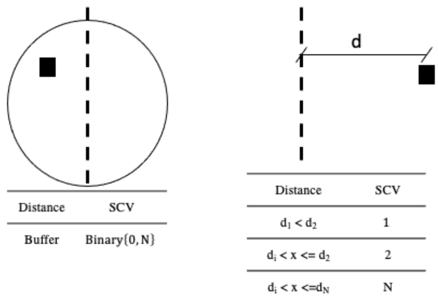


Figure 7-2: Using buffer or the distance between the pipe and consequence object/parameter.

The weight and criteria were evaluated using knowledge from the literature review (e.g. (Anbari et al., 2017; Baah et al., 2015; Salman, 2010) and consultation with Kungsbacka municipalities water utility. The model's design resulted in that the maximum value of COF was approximately 2.05, and since COF theoretically could range between value larger than zero and smaller than five, this became a problem in setting the COF categories. To divided the data into a one-to-five scale, Jenks Natural Breaks was used. Hence, using this method, one should be aware that the classes are just divided according to the variation between the data, which implies that further analysis of the resulting classes is needed. In this case, the analyse of the pipes included in each class showed apparent differences between the classes regarding severeness of consequence (APPENDIX B). However, it should be noted that the WSM model used with Jenks Natural Breaks also makes the model tailored for Kungsbacka municipality's wastewater pipe network. Therefore, one should be careful about adopting the model straight off. The results were five classes of COF with the linguistic impact description; (1) Low, (2) Moderate, (3) Moderate-to-high, (4) High and (5) Very High.

7.3.3 POF (b)

The WSM model used for evaluating POF was built on the criteria; age, material, length, and diameter, where the highest weight was given to age followed by material. Further, the weights and criteria in the WSM model were based on the finding in the literature review, statistical data and consultation with Kungsbacka municipality water utility. The most conspicuous decision was to give plastic pipes the highest *SCV*. The motivation for this decision was that all data indicated that plastic was in worse condition than concrete or renovated pipes, which can appear quite strange since concrete pipes have been outrivalled by plastic pipe, mainly PE and PP, during the last decades. One theory why plastic pipes perform worse than concrete pipes in terms of structural condition is that PE and PP pipes creep under loads (Malm et al., 2011b). If the burial depth is too deep, the vertical loads might be too high; additionally, the installation might also impact if the side support is inadequate (Lidström, 1996). Further, since the creep for plastic pipes does not necessarily impact the structural condition, and if the high structural grade is mainly based on the defect *deformation*, one explanation could be that CCTV grading and condition assessment protocols are more customised for defects in rigid pipes. Hence, if vertical deformation is present in rigid pipes, there will most definitely be defects such as cracks, the same deformations in plastic pipe could be ductile deformations that do not significantly influence the structural integrity (Rahman, 2010). The results from the WSM model for evaluating POF was divided into five categories with the same linguistic impact description as COF.

Further, the multinomial logistic regression model used to evaluate POF was inadequate in predicting pipes with structural grade two and, in particular structural grade three. However, some interesting findings were observed. The independent variables age and length behaved as expected based on section 2.4.2 , i.e., increased age and length increased the probability of defective condition. Further, there were clear indications that pipes made of plastic had a higher, and possibly unreasonable high, probability of being in poor condition than concrete pipes, according to the regression model and the analysis in APPENDIX E. However, this model was implemented in a mid-size municipality, and still, some valuable findings were noted. Consequently, it is fair to say that more advanced models might be attractive for larger municipalities with more data available. Using a regression model, or other advanced models (e.g. BN, ANN) to identify high POF pipes based condition assessment protocols, is also less expensive and time-consuming than CCTV inspections.

7.3.4 Evaluation of ROF & Inspection priority (iv)

The ROF was evaluated using a risk matrix, customised with consultation by Kungsbacka municipality water utility. The matrix was weighted to enhance the influence of COF on the total ROF. The COF was considered to have the highest impact on ROF, and that there were fewer uncertainties in the COF model. The main advantages of using the risk matrix were the flexibility and possibility of taking the expertise within the water utility. The evaluation of ROF resulted in that 97.3% of all pipes within Kungsbacka municipalities wastewater network was assigned a ROF on a one-to-five scale. After the pipes with associated KB was removed, 11,865 pipes were used to set the inspection priority. The pipes that could not be analysed missed either specified installation date, material specification or dimension. The ROF was classed into the linguistic impact categories; (1) Low, (2) Moderate, (3), Moderate-to-high, (4) High and (5) Very High. The CCTV inspection priority was set to address the Very High ROF pipes first, the High secondly and so forth. Consequently, the most critical pipes will be inspected regarding their criticality.

7.3.5 Rehabilitation priority & Re-inspection frequency (**vi** & **vii**)

The rehabilitation priority and re-inspection frequency were mainly based on WRC and NRC guidelines and the assumptions that pipes with more severe defects have a higher likelihood to fail, and pipes with high COF can cause significant consequences. However, some difficulties were observed using KB for rehabilitation purposes since the grading scale is considerably rough and that there is no real explanation of what the grade implies, except that the one-to-three scales linguistic description; (1) Good, (2) Poor and (3) Very Poor. Comparing this grading with the detailed grades by NRC and WRC made it necessary to make more rough approximations of rehabilitation prioritisation. The rehabilitation priority was set in a manner where KBs structural grade three represented WRCs and NRCs grade of five. This was made due to that the comparison in Table 4-18 showed similarities between the grades. Further, KB structural grade two was set to represent WRCs and NRCs two, three and four, where the rehabilitation priority was set based on the COF. Further, the re-inspection priority was based on the assumption that deterioration accelerates with present defects and, combined with high COF, increases the overall risk. Therefore, if rehabilitation is rejected, the re-inspection frequency should be more regular for pipes with high rehabilitation priority to follow the pipes deterioration process and minimise the risks.

7.4 Uncertainties and Sensitivity analysis.

There are uncertainties using the guidelines from NRC and WRC to set up the rehabilitation and inspection priority. It was concluded that the highest grade in KB, NRC and WRC were similar. However, within the lower grades, it is more challenging to compare the condition assessment protocols. Hence, for KB grade 0, 1 and 2, there are approximate estimations within the rehabilitation and inspection priority.

The WSM method, a qualitative approach, was used to evaluate both POF and COF. The weights and *SCV* values were set based on knowledge from the literature review, data concerning Kungsbacka wastewater pipe network and consultation with Kungsbacka water utility. Hence, most uncertainties can be derived from the subjective weighting of the different criteria. However, the sensitivity analysis in section 0 gives some insights into how changes in the different weight influence the results. Generally, since the sensitivity model changes the weights with a factor of 0.5 to 1.5, the most significant changes occur when changing the highest initial weights.

For the POF, the most significant change in results occurs when decreasing the weight A*ge* with -0.5, where the average POF increase by 13.7%. Further, when increasing the weight *Age*, the average POF reduces. Since the *SCV* for *Age* was exponential, the average *SCV* for Age is relatively low compared to *Diameter* and *Materia*l. Consequently, when the weight for *Age* decreases, the resulting weights increases, resulting in higher POF.

The COF model was very sensitive to adjusted weights. The most significant change in COF occurs when changing the weight for D*iameter* with a factor of -0.5, where the percentual change in COF was- 40.6%. As noted, the COF model is mainly influenced by the criterion *Diameter*, since the other criteria are not affecting all pipe IDs. Hence, decreases in *Economic*, *Social* and *Environmental* weights will increase the weight for *Diameter*, and consequently higher COF. Since the Jenks Natural Breaks was used to set the one-to-five categories, the analysis of uncertainties gets more complex; due to the unsureness of how the Jenks Natural Breaks would class the newly weighted data.

Further, the sensitivity analysis implies that the results in POF and COF could change significantly, which could impact the final rehabilitation priority. However, some factors should be addressed. Firstly, as already mentioned, the initial scoring and weighting were subjective, based on the literature review and consultation with Kungsbacka municipalities water utility. Secondly, the risk matrix was tailored for this specific case study, and with different POF and COF categories, the matrix could have been weighted differently. Consequently, it fair to say that the WSM model is sensitive to changes in weights and specially to changes in the COF model. However, it is harder to say that the changes in weights would impact the final rehabilitation and inspection priority since both the WSM and risk matrix are based on a qualitative method.

8 Conclusions

The overall aim and objectives for this thesis was to review risk-based strategies, set up a risk-based model and implement the model in a case study. The main conclusion were:

- In the literature review, probability of failure (POF) has been assessed by combining physical, environmental and operational data using Multi-Criteria Decision Analysis (MCDA), Bayesian Networks (BNs), Artificial Neural Networks (ANNs) or Regression models to evaluate POF. The deterioration process is complex and the choice of a POF assessment method should be based on local preconditions, given that there is no definite evidence that one method should be more reliable than the other.

- In the literature review, the practice for estimating consequence of failure (COF) is to combine parameters influencing economic, social and environmental consequences, and by using GIS data and MCDA, evaluate the most critical pipes.

- The presented risk-based model provides a structured approach for identifying high-priority wastewater pipes with respect to POF and COF and strives to provide decision-support for water utilities renewal planning.

- All water utilities can adapt the risk-based model and the structured approach, but the methods should be adjusted based on the resources, competence, available data.

- The Multinomial Logistic Regression model was ineffectual in predicting critical pipes. However, Logistic Regression and more advanced models have been shown being effective in evaluating POF and should not be rejected.

- POF and COF were evaluated using a qualitative Weighted Sum Method (WSM) model with the benefits of being relatively simple to implement and the advantage of taking the competence and experience within the water utility into consideration.

- The case study resulted in that 97.3% of the pipes within the wastewater pipe network could be evaluated in terms of risk of failure (ROF). Further, a Closed-Circuit Television (CCTV) inspection priority could be provided, including 11,865 pipes. Using the CCTV inspection and COF, a rehabilitation priority was established, including 2,854 pipes, with priority and re-inspection frequency recommendations.

- The uncertainties are essential in a risk assessment process. In this case study, a qualitative WSM model was used. Hence, uncertainties can be derived from subjective weighting. Further, the sensitivity analysis showed that the results were sensitive to changes in criteria with initial high weights. Additionally, the design of the COF model resulted in high sensitivity due to changes in the weighting.

- No re-evaluation of the COF and POF model assumptions were made in this case study since no inspections were performed based on the results from the risk-based model. However, this step is essential in the risk-based model to constantly develop competence, provide updated information on pipe condition and make more adequate decisions regarding the unique wastewater pipe network

9 Recommendations for the Swedish wastewater utilities

The presented risk-based model is a structural approach to identify high-risk pipes within the wastewater pipe network. In this thesis, various methods for evaluating COF and POF have been presented. However, water utilities should carefully choose applicable methods based on resources and competence within the organisation. Therefore, the main question for water utilities should be; Which pipes have the highest likelihood to fail; and where do we want to avoid failures? Hence, starting from these matters, implementing the risk-based model does not have to be advanced. A start can be to base POF on age and focus on areas and pipes where the water utility wants to avoid failures. Consequently, evaluation of COF and POF should be seen as a structural approach where the methods used are subordinate. However, the following methods (with progressing complexity) are recommendations for estimate POF:

1. Brainstorming and local expertise to identify pipes with high POF
2. Structural MCDA models based on data and parameter accelerating the deterioration process.
3. More advanced models such as Logistic Regression, BNs or ANNs.

To evaluate COF, the following recommendations (with progressing complexity) can be used:

1. Focus on main pipes and highlight areas based on where the water utility and stakeholders want to avoid failure
2. Structural MCDA model based on GIS data, where the water utility combined with stakeholder values can evaluate COF.

Further, there can be an advantage with national guidelines in evaluating COF considering comparing consequence levels between water utilities, cities or regions.

Evaluating ROF, a risk matrix is recommended, mainly due to the relative simplicity and the flexibility and possibility in incorporate expertise within the water utility and stakeholder values. Further, the risk-based model gives recommendations on how to set up a CCTV inspection priority. The graded CCTV inspections should also be seen as a resource in improving the method for estimating POF, i.e. the condition assessments can be used to make new assumptions and decisions when more information is available.

The rehabilitation priority presented in the model was based on guidelines from NRC and WRC. In this step, there is room for flexibility and need to develop the KB system to incorporate more detailed guidelines for what the grades indicate regarding the likelihood of failure and recommendation on rehabilitation priority.

10 Recommendations for further work

Based on the findings in this thesis, further discussions, development and research in the following topics would provide more favourable conditions for developing the use of a risk-based rehabilitation approach.

- The condition assessment protocol Kortbetyg would favour more detailed grades with an associated description of how the defects affect the structural condition, rehabilitation priority and, if possible, recommendations of rehabilitation method.

- The more advanced POF models (e.g. BNs, ANNs and Logistic Regression) should be tested on arbitrary wastewater pipe networks to see if any common conclusions can be dawn.

- More research should be performed regarding the consequence of failure (COF) for wastewater pipes, i.e. evaluate the direct economic, social, and environmental consequences and judge whether they can be quantified.

- Further research regarding predicting I & I is necessary. With new tools such as leak detectors and others, predicting I & I by combining the amount of I & I with parameters (input or independent variables) such as soil type, permeability, land use, permeability, groundwater level and CCTV inspections (defects) could be used to set up models.

11 References

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APPENDIX A Condition Assessment Protocols

WRC – MSCC5 for structural grade

MSCC5 Defect	*MSCC5 Code*	*Description (Short)*	*Score*
		Medium	1
	OJ M	Large	2
Open joint	OJ L	>5% of diameter	1
	OJ	5 – 10% of diameter	80
		> 10% of diameter	165
		Medium	1
		Large	2
	JD M	1 – 1.5 x thickness	1
Joint Displacement	JD L	> 1.5 x thickness or 5% of diameter	2
	JD	5 – 10% of diameter	40
		10 – 20% of diameter	80
		> 20% of diameter	165
	CC	Circumferential	10
Crack	CL	Longitudinal	10
	CM	Multiple	40
	CS	Spiral	40
	FC	Circumferential	40
Fracture	FL	Longitudinal	40
	FM	Multiple	80
	FS	Spiral	80
Broken	B		80
Hole	H	< $3/12^{th}$ of circumference	80
	H	> $3/12^{th}$ of circumference	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	Projecting from surface	120
Corroded reinforcement	SRC		120
Corrosion products	SCP	Presence evidence of corrosion (galvanic/acids)	5
Sealing ring - Intruding - Broken - Other	 SR SRB SO		5
Defective Repair, missing wall	RXM	<$3/12^{th}$ circumference >$3/12^{th}$ circumference	80 165
	WXL	Longitudinal	40
Weld failure (plastic)	WXC	Circumferential	40
	WXS	Helical	80
	WXL	Longitudinal	10
Weld failure (steel)	WXC	Circumferential	10
	WXS	Helical	40
		0 – 5%	20
Deformed	D	6 – 10%	80
		>10%	165

NRC - LSCCR		
Defect type	***Unit of measure***	***Weight***
Fracture Longitudinal		
- Light (<10 mm wide)	Metre	5
- Moderate (10 – 25mm wide, or 2-4 fractures)	Metre	10
- Severe (> 25mm wide, >5 fracture)	Metre	15
Fracture Circumferential (FC)		
- Light (<10 mm wide)	Metre	5
- Moderate (10 – 25mm wide, or 2-4 fractures)	Metre	10
- Severe (> 25mm wide, >5 fracture)	Metre	15
Fracture Diagonal (CL)		
- Light (<10 mm wide)	Metre	5
- Moderate (10 – 25mm wide, or 2-4 fractures)	Metre	10
- Severe (> 25mm wide, >5 fracture)	Metre	15
Fractures-Multiple (FM)	Metre	20
Crack Longitudinal (CL)		
- light (up to 3 cracks, no leakage)	Metre	3
- moderate (> 3 cracks, leakage)	Metre	5
Crack Circumferential (CC)		
- light (up to 3 cracks, no leakage)	Metre	3
- moderate (> 3 cracks, leakage)	Metre	5
Crack Diagonal (CD)		
- light (up to 3 cracks; no leakage)	Metre	3
- moderate (> 3 cracks, leakage)	Metre	5
Cracks Severe (CS) severe (multiple cracks, leakage)	Metre	10
Deformation (D)		
- Light <5% change in diameter	Metre	5
- moderate 5 – 10% change in diameter	Metre	10
- severe 11 – 25% change in diameter	Metre	15
Collapse (X)	Each	20
Broken pipe (B)	Each	15
Joint Displacement (JD)		
-light (<1/4 wall thickness)	Each	3
- moderate (1/4 – ½ wall thickness)	Each	10
- severe (>1/2 – wall thickness	Each	15
Joint Opening (JO)	Each	
- Light (< 10mm)	Each	3
- moderate (10 – 50 mm)	Each	10
- severe (> 50 mm)	Each	15
Surface Damage (H)		
- Light (< 5 mm wall thickness)	Metre	3
- Moderate (5 – 10 mm wall thickness)	Metre	10
- Severe (> 10 mm wall thickness)	Metre	15
Sag (S)		
- Light (<50 mm)	Metre	4
- Moderate (50 – 100 mm)	Metre	10
- Severe (>100 mm)	Metre	15

APPENDIX B POF & COF Analysis

Analys of COF

				Water Protection Area		Water Bodies		Highway		Motorway		Priority Highway		Railway Track		Buildings		Burial Depth		Diameter [avg. mm per Quantile]				
COF Range	Grade	Count	COF.avg	Count	D.Avg [mm]	Count	D.Avg [mm]	Count	D.avg [mm]	Count	D.Avg [mm]	Count	D.Avg [mm]	Count	D.Avg [mm]	Count	D.Avg [mm]	Count	D.Avg [mm]	min	25th	50th	75th	max
0 - 0.114	1	11970	0,114	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	40	200	225	225	390
0.114 - 0.228	2	398	0,227	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	400	400	400	500	586
0.228 - 0.682	3	1861	0,578	0	-	0	-	1225	237,3	25	292,1	201	240,4	0	240,4	273	224,9	19	526,9	63	219	225	250	1000
0.682 - 1.1364	4	303	0,936	0	-	99	268,7	46	425,5	1	250,0	60	585,4	87	585,4	30	329,0	5	705,0	40	225	315	560	1000
1.1364 - 5	5	186	1,345	132	191,6	14	488,2	23	263,8	0	-	26	321,7	38	321,7	14	274,6	1	400,0	40	167,5	219	225	800
Sum		14718		132		113		1294		26		287		125		317		25		0	1	2	3	4

COF. Avg: Average COF Values. D.Avg: Average Diameter

Analysis of POF

		Total			Concrete=<1970					Concrete>1970					Plastic					Renovated				
Range	Class	Count	POF.avg	Age [yrs].avg	Count	POF.avg	Age [yrs].avg	L [m].avg	D [mm].avg	Count	POF.avg	Age [yrs].avg	L [m].avg	D [mm].avg	Count	POF.avg	Age [yrs].avg	L [m].avg	D [mm].avg	Count	POF.avg	Age [yrs].avg	L [m].avg	D [mm].avg
0 - 2.0	1	3862	1,530	15,01	0	-	-	-	-	2623	1,59	18,54	37,67	233,29	455	1,94	3,96	15,44	256,25	784	1,09	9,61	43,57	235,51
2.0 - 2.75	2	6568	2,375	31,68	0	-	-	-	-	4475	2,44	40,90	38,28	244,14	2081	2,24	11,77	35,36	200,14	12	2,44	46,70	31,18	213,92
2.75 - 3.5	3	2905	2,978	44,60	201	3,39	51,61	28,75	365,42	1620	2,84	48,54	47,49	229,61	1080	3,11	37,34	34,35	199,00	4	2,98	57,04	38,63	216,00
3.5 - 4.25	4	1285	3,699	53,15	887	3,71	54,99	46,46	234,13	0	-	-	-	-	398	3,67	49,03	45,05	211,62	0	-	-	-	-
4.25 - 5.0	5	13	4,326	64,80	12	4,33	65,28	58,75	225,00	0	-	-	-	-	1	4,26	59,04	60,21	200,00	0	-	-	-	-
Sum		14633			1100					8718					4015					800				

POF.avg: Average POF Values. Age.avg: Average age. L.avg: Average length. D.avg: Average Diameter.

FIGURE APPENDIX 1: Summary of COF and POF

APPENDIX C RStudio

Multinomial Model

```
library(jmv)
library(nnet)

descriptives(Data, vars = vars(Length, Diameter, Age, Concrete1, Concrete2, Plastic, Renovated), freq = TRUE) #Analysing data

Data$S_G_M3 <- relevel(as.factor(Data$S_G_M), ref = 3) # S_G_M (Structural Grade Multionomial) setting grade three as reference level.

Multinomial_Model <- multinom(S_G_M3 ~ Length + Diameter + Age + Concrete1 + Concrete2 + Plastic, data = Data ,model=TRUE) # Setting up the Multinomial data.

Multionomial_Intercept <- multinom(S_G_M3 ~ 1, data = KORT_REN) # Multinomial model with only intercept

library(lmtest)

lrtest(Multinomial_Intercept, Multinomial_Model) # log-likelihood test

Model <- summary(Multinomial_Model) # Summary of Multinomial model
z <- Model$coefficients/Model$standard.errors # Calculating z-values
p <- (1 - pnorm(abs(z), 0, 1))*2 # two-tailed z-test
e <- exp(coef(multi_mo3)) # Odds ratio for regression coefficients
Result_tabell <- rbind(Modelt$coefficients[1,], e[1,] ,output$standard.errors[1,],z[1,],p[1,]
)
rownames(Result_tabell) <- c("Coefficient","exp(B)" ,"Std. Errors","z stat","p value")
tabell <- knitr::kable(Result_tabell)
print(tabell)

library(summarytools)
Classfication_tabell <- table(Data$S_G_M3,predict(Multinomial_Model)) #Building classification tabel
Classfication_tabell
```

Evaluating COF using Jenks Natural Breaks

```
library(BAMMtools)
getJenksBreaks(COF, 5) # Dividing COF data into five classes.
```

APPENDIX D Sensitivity analysis

SENSITIVITY FOR POF								
		PERCENTUELL CHANGE IN WEIGHT						
Changed Weight	***CRITERIA***	***-50%***	***-25%***	***-10%***	***Original***	***10%***	***25%***	***50%***
AGE	Age	0,385	0,484	0,529	0,556	0,579	0,610	0,652
	Material	0,385	0,323	0,294	0,278	0,263	0,244	0,217
	Diameter	0,154	0,129	0,118	0,111	0,105	0,098	0,087
	Length	0,077	0,065	0,059	0,056	0,053	0,049	0,043
	SUM	1,000	1,000	1,000	1,000	1,000	1,000	1,000
MATERIAL	Material	0,161	0,224	0,257	0,278	0,297	0,325	0,366
	Diameter	0,129	0,119	0,114	0,111	0,108	0,104	0,098
	Length	0,065	0,060	0,057	0,056	0,054	0,052	0,049
	Age	0,645	0,597	0,571	0,556	0,541	0,519	0,488
	SUM	1,000	1,000	1,000	1,000	1,000	1,000	1,000
DIAMETER	Diameter	0,059	0,086	0,101	0,111	0,121	0,135	0,158
	Length	0,059	0,057	0,056	0,056	0,055	0,054	0,053
	Age	0,588	0,571	0,562	0,556	0,549	0,541	0,526
	Material	0,294	0,286	0,281	0,278	0,275	0,270	0,263
	SUM	1,000	1,000	1,000	1,000	1,000	1,000	1,000
LENGTH	Length	0,029	0,042	0,050	0,056	0,061	0,068	0,081
	Age	0,571	0,563	0,559	0,556	0,552	0,548	0,541
	Material	0,286	0,282	0,279	0,278	0,276	0,274	0,270
	Diameter	0,114	0,113	0,112	0,111	0,110	0,110	0,108
	SUM	1,000	1,000	1,000	1,000	1,000	1,000	1,000

SENSITIVITY FOR COF								
		PERCENTUEL CHANGE IN WEIGHT						
CHANGE IN CONSEQUENCE GROUP	***CRITERIA***	***-50%***	***-25%***	***-10%***	***Original***	***10%***	***25%***	***50%***
DIAMETER	Diameter	0,060	0,088	0,103	0,114	0,124	0,138	0,161
	Burial depth	0,048	0,047	0,046	0,045	0,045	0,044	0,043
	Adjacent Buildng	0,096	0,094	0,092	0,091	0,090	0,088	0,086
	Highway/Motorway	0,096	0,094	0,092	0,091	0,090	0,088	0,086
	Priority highway	0,120	0,117	0,115	0,114	0,112	0,110	0,108
	Railway	0,169	0,164	0,161	0,159	0,157	0,155	0,151
	WPA	0,241	0,234	0,230	0,227	0,225	0,221	0,215
	Waterbody	0,169	0,164	0,161	0,159	0,157	0,155	0,151
	SUM	1,000	1,000	1,000	1,000	1,000	1,000	1,000
ECONOMIC	DJUP	0,024	0,035	0,041	0,045	0,049	0,055	0,064
	Adjacent Buildng	0,049	0,071	0,083	0,091	0,099	0,110	0,128
	Highway/Motorway	0,098	0,094	0,092	0,091	0,090	0,088	0,085
	Priority highway	0,122	0,118	0,115	0,114	0,112	0,110	0,106
	Railway	0,171	0,165	0,161	0,159	0,157	0,154	0,149
	WPA	0,244	0,235	0,230	0,227	0,224	0,220	0,213
	Waterbody	0,171	0,165	0,161	0,159	0,157	0,154	0,149
	Diameter	0,122	0,118	0,115	0,114	0,112	0,110	0,106
	SUM	1,000	1,000	1,000	1,000	1,000	1,000	1,000
SOCIAL	Highway/Motorway	0,056	0,075	0,085	0,091	0,096	0,104	0,115
	Priority highway	0,069	0,094	0,106	0,114	0,121	0,130	0,144
	Railway	0,097	0,131	0,149	0,159	0,169	0,182	0,202
	WPA	0,278	0,250	0,236	0,227	0,219	0,208	0,192
	Waterbody	0,194	0,175	0,165	0,159	0,154	0,146	0,135
	Diameter	0,139	0,125	0,118	0,114	0,110	0,104	0,096
	Burial depth	0,056	0,050	0,047	0,045	0,044	0,042	0,038
	Adjacent Buildng	0,111	0,100	0,094	0,091	0,088	0,083	0,077
	SUM	1,000	1,000	1,000	1,000	1,000	1,000	1,000
ENVIRONMENTAL	WPA	0,141	0,189	0,213	0,227	0,241	0,259	0,286
	Waterbody	0,099	0,132	0,149	0,159	0,168	0,181	0,200
	Diameter	0,141	0,126	0,118	0,114	0,109	0,104	0,095
	Burial depth	0,056	0,050	0,047	0,045	0,044	0,041	0,038
	Adjacent Buildng	0,113	0,101	0,095	0,091	0,088	0,083	0,076
	Highway/Motorway	0,113	0,101	0,095	0,091	0,088	0,083	0,076
	Priority highway	0,141	0,126	0,118	0,114	0,109	0,104	0,095
	Railway	0,197	0,176	0,165	0,159	0,153	0,145	0,133
	SUM	1,000	1,000	1,000	1,000	1,000	1,000	1,000

FIGURE APPENDIX 2: Sensitivity analysis for COF and POF with changes in weight.

APPENDIX E Probability curves for the multinomial regression model

Further analysis of the multinomial regression models was conducted using the regression coefficients for *ME1* and ME2, with the average diameter and length for the three material groups; *concrete installed before 1970*, *concrete pipes installed after 1970* and *plastic* pipes as a function of time. Hence, using these parameters, probability curves could be assessed with the properties presented in TABLE APPENDIX 1.

TABLE APPENDIX 1:Scenarios for analysis of the Multinomial Logistic Regression in terms of age.

Material	*Length [m]*	*Diameter [mm]*	*Age [Yrs]*
Concrete<1970	44.4	253.3	0 - 200
Concrete>1970	43.9	233.8	0 – 200
Plastic	45.1	215.9	0 - 200

Further, the probability equations for P(Y=1), P(Y=2) and P(Y=3) was used on each material with the average length and diameter as a function of age. The results are presented in FIGURE APPENDIX 3, where the red area represents the probability.

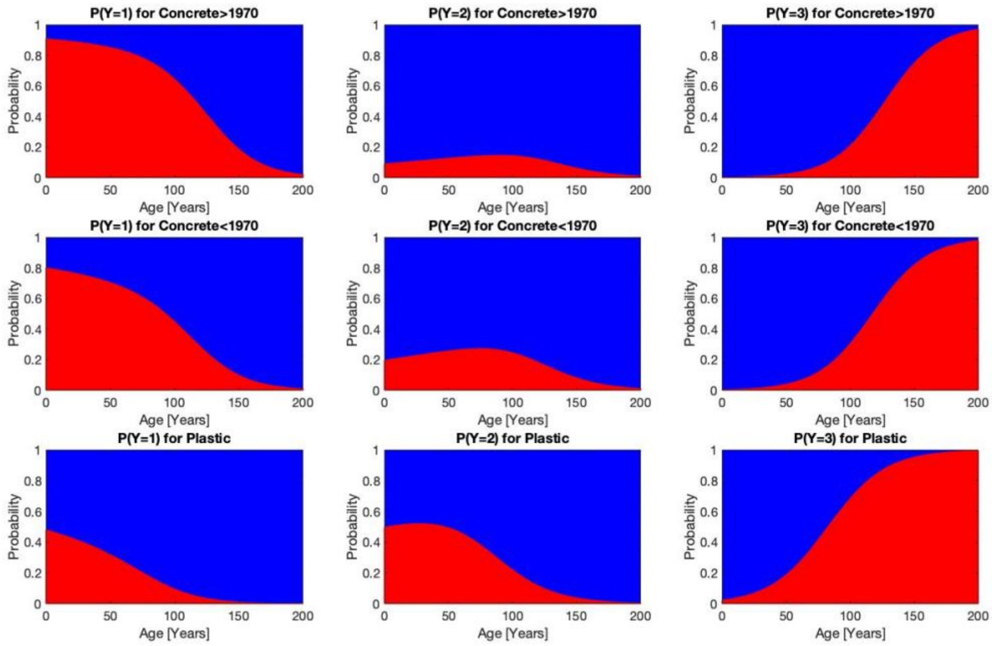


FIGURE APPENDIX 3: Probability curves for Concrete>1970, Concrete =<1970 and Plastic pipes.

From the figure, it can be noted that for the two concrete material, the probability for P(Y=1) is higher than P(Y=2) in most cases, and the probability for P(Y=3) increases as most after ages of approximately 100 to 150 years. Further, the plastic pipes are predetermined to P(Y=2), even for young ages. Furthermore, observing all three graphs for P(Y=1) shows that the red probability areas are greater for concrete pipes than for plastic pipes. Contrary, the read probability area for P(Y=3) for plastic pipes is greater than the concrete pipes. Hence, most of the pipes categorised in multinomial category 2 and 3 will be plastic pipes, and pipes made of concrete, especially concrete pipes installed after 1970, will be categorised in a multinomial category 1.

APPENDIX F The Risk Matrix

The Risk Matrix used to evaluate ROF is presented in FIGURE APPENDIX 4. The numbers within the cells represents the ROF category.

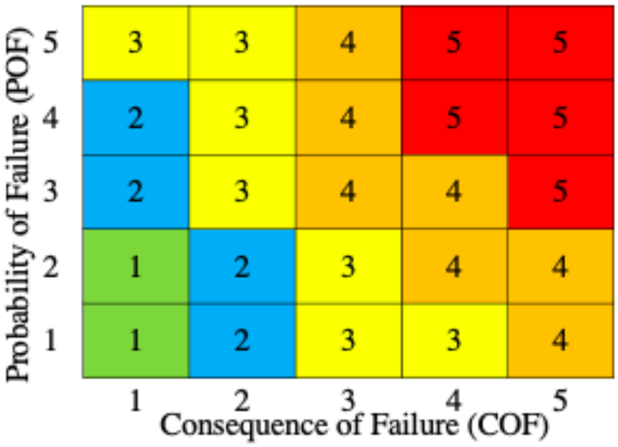
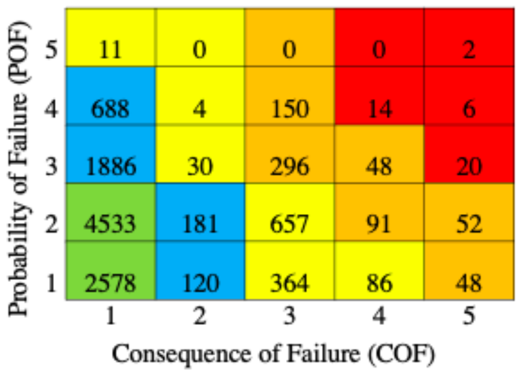


FIGURE APPENDIX 4: The Risk Matrix used.

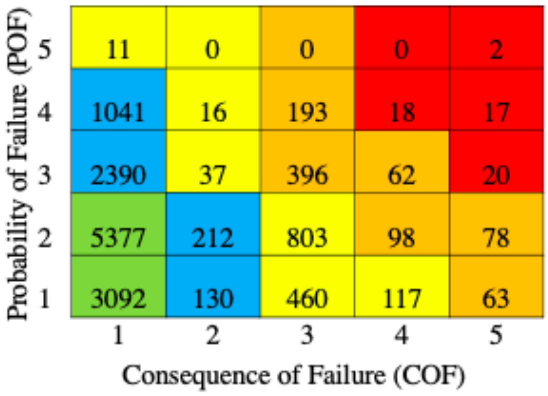
The Risk Matrix used to evaluate ROF and inspections priority is presented in FIGURE APPENDIX 5, where the pipes with associated CCTV inspections was removed. The numbers within the cells represents the counts of pipe for each combination of COF and POF.



ROF	Count
5	42
4	685
3	1152
2	2875
1	7111
Sum	11865

FIGURE APPENDIX 5: The Risk Matrix without CCTV inspections

Further, in FIGURE APPENDIX 6, the Risk Matrix with all pipes within given diameter, material, length and age is presented. The numbers within the cells represents the counts of pipes for each combination of COF and POF.



ROF	Count
5	57
4	890
3	1444
2	3773
1	8469
Sum	14633

FIGURE APPENDIX 6: Risk matrix with CCTV inspections

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