Performance Modeling for Sewer Networks

Khalid Kaddoura

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______________________________ External Examiner
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______________________________ External to Program
Dr. Amr Youssef

______________________________ Examiner
Dr. Fuzhan Nasiri

______________________________ Examiner
Dr. Ashutosh Bagchi

______________________________ Admin. Supervisor
Dr. Fariborz Haghighat

Approved by ______________________________
Dr. Fariborz Haghighat, Graduate Program Director

Monday, July 16, 2018 ______________________________
Dr. Amir Asif, Dean
Faculty of Engineering and Computer Science

ABSTRACT

Performance Modeling for Sewer Networks

Khalid Kaddoura, Ph.D.
Concordia University, 2018

In spite of the pressing need to preserve sewer networks, sewer pipelines and manholes are prone to deterioration and hence to collapse. According to the American Society of Civil Engineers (ASCE) (2017), the sewer network's grade of the United States (US) is grade "D+", making it one of the worst infrastructure assets in the US. In addition, the Canadian Infrastructure Report Card (CIRC) (2016) states that more than half of their linear wastewater assets' physical condition were ranked between very poor to good states, with a total replacement value of $47-billion. Despite the enormous studies conducted in this field, many of the efforts lack a comprehensive assessment of sewer components, leading to misjudged rehabilitation decision plans and continued asset deterioration.

Improved cost-effective models that optimize sewer rehabilitation plans, given the scarcity of resources, are clearly needed. Accordingly, the paramount objective of this research is to design a decision-support system that optimizes the maintenance, rehabilitation and replacement (MRR) decisions of sewer pipelines and manholes. The first phase of the research is to identify several defects that impact the condition of sewer components and to model the erosion void defect utilizing fuzzy expert system. The model provided accuracy, true positive rate and precision values of 83%, 76%, and 80%, respectfully. The identified defects were then grouped into several robust models to study their cause and effect relationship through the application of the Decision-Making Trial Evaluation Laboratory (DEMATEL). The overall condition of the sewer pipeline is then found by integrating the DEMATEL method with the Quality Function

Deployment (QFD), while the manhole condition is calculated using the aforementioned two techniques along with the Analytic Network Process (ANP). After validating the two models with the Royal Gardens neighbourhood's sewer network in Edmonton, the average validity percentage (AVP) for the pipeline and manhole assessment models were 58.68% and 76.24%, respectively. Subsequently, Weibull distribution analysis is adopted to predict the future calculated conditions of sewer manholes and pipelines by modelling the deterioration of each.

The research establishes an approach to aggregate the condition indexes of all pipelines and manholes in the network through a criticality model to supply the overall network performance index. Accordingly, the economic factors are deemed the most important ones compared to environmental and public factors. An informative optimized model that integrates the outputs of the previously developed models is designed through the Particle Swarm Optimization (PSO) approach to maximize the sewer network performance and minimize the total costs. Different trade-off solutions are then established by varying the weights of the objective functions and considering the defined constraints. The best network performance improvement attained is 1.47 with a total cost of $1.39- million.

The comprehensive sewer network assessment performed in this research will improve current practices in sewer networks management, thereby reducing sewer network failures and avoiding catastrophic sinkholes.

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Dedicated to

My Parents

Mahmoud & Insaf

My Wife

Aya &

My Adorable Kid

Zayd

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

2D	Two-dimensional
AC	Ant Colony
AHP	Analytic Hierarchy Process
AIP	Average Invalidity Percentage
ANN	Artificial Neural Network
ANP	Analytic Network Process
APE	Actual probability of existence
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
AVP	Average Validity Percentage
CCTV	Closed Circuit Television
cdf	Cumulative Distribution Function
CI	Consistency Index
CI_M	Condition Index for Manholes at time t
CI_M_PDC	Predicted condition index of the manhole
CI_M_UDC	Updated condition index of the manhole
CI_M_M	Manhole condition after M&R
CI_P	Condition Index for Pipelines at time t
CI_P_PDC	Predicted condition index of the pipeline
CI_P_UDC	Updated condition index of the pipeline
CI_P_M	Pipeline condition after M&R

CIPP	Cured-in-place
CR	Consistency Ratio
CRI	Criticality Index
CW	Component Weight
DEMATEL	Decision-Making Trial Evaluation Laboratory
DM_M	Manhole condition improvement
DM_P	Pipeline condition improvement
EAs	Evolutionary Algorithms
EPA	Environmental Protection Agency
ES	Evolutionary Strategy
FN	False Negative
FP	False Positive
GA	Genetic Algorithm
gbest	Global Best
Gcm	Overall Component Grade
GPR	Ground Penetrating Radar
GUI	Graphical User Interface
GWT	Groundwater
HER	Hierarchal Evidential Reasoning
HOQ	House of Quality
I/I	infiltration/inflow
IDC	Ideal Deterioration Curve
IPWEA	Institute of Public Works Engineering Australasia

M&R	Maintenance and Rehabilitation
MA	Memetic Algorithm
MACP	Manhole Assessment and Certification Program
MAE	Mean Absolute Error
MAUT	Multi-Attribute Utility Theory
MSCC	Manual of Sewer Condition Classification
MSI	multi-sensor inspection
NASSCO	National Association of Sewer Service Companies
ONP	Overall Network Performance
PACP	Pipeline Assessment and Certification Program
pbest	Particle Best
PDC	Predicted Deterioration Curve
PMI	Project Management Institute
PMSN	Performance Modeling for Sewer Networks
PPR	Pipe Penetrating Radar
PSO	Particle Swarm Optimization
PVC	Polyvinyl Chloride
QFD	Quality Function Deployment
RI	Random Index
RMSE	Root Mean Square Error
RW	Relative Weights
SFL	Shuffled Frog Leaping
SRM	Sewerage Rehabilitation Manuals

SVMs	Support Vector Machines
TLCC	Total Life Cycle Costing
TN	True Negative
TP	True Positive
TPR	True Positive Rate
TQM	Total Quality Management
UDC	Updated Deterioration Curve
UK	United Kingdom
US	United States
Wf_c	Relative importance weights of the criticality factors of pipelines
Wf_{cs}	Relative importance weight of each sub-factor *s* in factor *c*
Wf_e	Relative importance weights of the criticality factors of manholes
Wf_{ed}	Relative importance weight of each sub-factor *d* in factor *e*
W_M	Relative importance weights of manholes
W_{ONP}	Importance weight of the ONP
W_P	Relative importance weight of the pipelines
WRc	Water Research Centre
W_{TLCC}	Importance weight of the parameter TLCC

Chapter One: Introduction

1.1 Overview

Assessing the condition of infrastructure assets is essential due to its backbone need for any urban city (Kaddoura 2015). Sewer systems, forming one of the most capital-intensive infrastructure systems (Wirahadikusumah et al. 1998), transfer sewage medium from private/public outlets (i.e., buildings, houses, hospitals, schools, etc.) to laterals, which are connected to main pipelines that end at sewage treatment plants or disposal areas. They are the ultimate low-profile infrastructure assets in spite of their health and environmental benefits (Kirkham et al. 2000). These systems are buried in the subsurface and are distributed in a maze of a complex infrastructure. Their low visibility stands a reason for their frequent low rehabilitation and/or maintenance (Wirahadikusumah et al. 1998). Sewers are prone to collapse and failure, imposing severe consequences on the surroundings (Kirkham et al. 2000) and resulting in costly and difficult rehabilitation (Wirahadikusumah et al. 1998). Therefore, studying the performance of the system is essential to gain knowledge about the future conditions of the sewer assets for rehabilitation (Kleiner 2001) and budget allocation purposes. The necessity of this task is deduced from the reinforcing loop shown in Figure 1.1. The higher is the condition of an asset provides a higher overall performance of the system (reinforcing relationship). The higher is the overall performance requires less rehabilitation and maintenance (balancing relationship). Therefore, the costs for repair and maintenance are less (reinforcing relationship).

Furthermore, funds will be available to enhance other assets' performance and hence the overall sewer system's performance (reinforcing relationship).

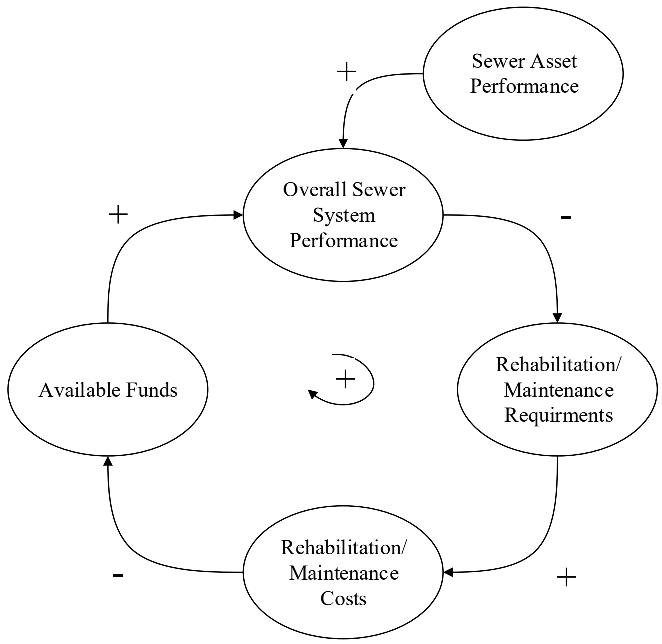


Figure 1.1 Reinforcing Loop

Several countries publish infrastructure report cards to inform the public about the condition of the infrastructure assets. In Canada, for example, the Canadian Infrastructure Report Card (2016) claimed a Very Good overall rating for the linear wastewater system. However, due to aging, these assets are subject to deterioration over time. It can be deduced from Table 1.1, which displays a history glance of the wastewater system condition in the United States (US) based on the American Society of Civil Engineers (ASCE). Since 1988, the US wastewater condition is deteriorating in spite of grades improvements in some years due to rehabilitation/replacement practices.

Table 1.1 ASCE Wastewater Grades

Year	Wastewater Grade	
1988	C	(ASCE 1988)
1998	D+	(ASCE 1998)
2001	D	(ASCE 2001)

2003	D	(ASCE 2003)
2004	D	(ASCE 2004)
2005	D-	(ASCE 2005)
2009	D-	(ASCE 2009)
2013	D	(ASCE 2013)
2017	D+	(ASCE 2017)

1.2 Problem Statement

Wastewater networks are the backbone means of transferring sewage medium. An excellent and effective wastewater system ensures a clean and sustainable environment by limiting any possible exfiltration scenarios to ground or drinking water resources. Despite the necessities in preserving sewer networks, decision-makers still confront challenges in planning for rehabilitation due to the scarcity of resources. Several types of research were conducted to assess sewer networks and enhance their performance by suggesting assessment and optimized models. Nevertheless, these efforts lack the comprehensive evaluation of sewer networks as current practices lack the integration of sewer pipelines and manholes. Hence, there is a pressing need to develop more comprehensive and extensive optimized robust tool that integrates these two assets.

Current practices does not consider erosion void as a defect when evaluating the observed distress. This is due to the fact that the literature does not model or predict the erosion void condition. Not only but also, sewer manholes received little attention by researchers although several studies reported their importance in the networks. The current assessment relies on the mean score in calculating the overall grade which does not represent the comprehensive defects detected in inspections. In fact, manhole components are considered equally important. Furthermore, the overall performance assessment of sewer networks is limited to the mean calculation of pipelines' conditions disregarding some critical factors that distinguishes the relative importance of sewer assets in the network. Also, current studies lack the cause and effect relationship evaluation of the defects in the sewer system, making it difficult for decision-makers to pinpoint the root causes of severe defects' propagation.

1.3 Research Objectives

The present research is expected to improve the current practices for condition assessment by achieving the following main objectives:

1- Identify and study different defects in sewer networks
2- Model the pipeline erosion void defect
3- Develop a sewer network overall performance index
4- Design an optimized sewer performance rehabilitation plan

1.4 Document Organization

Chapter 1 introduces the subject and provides the problem statement. It also lists the objectives of the proposed research.

Chapter 2 discusses the literature review of multiple topics such as condition assessment, deterioration modeling, decision support systems, budget allocation as well as the techniques that are used.

Chapter 3 is dedicated to the construction of the research methodology of all the models.

Chapter 4 mentions the data collection and provides samples of the questionnaires. It also describes the case study brought from the agencies.

Chapter 5 implements the models developed using the case studies.

Chapter 6 illustrates a semi-automated tool for the whole developed models.

Chapter 7 provides the conclusions reached, limitations and future work.

Chapter Two: Literature Review

2.1 Overview

This chapter provides information about the backbone elements of the proposed research and illustrates inspection techniques for sewer pipelines and manholes. The current practices most pertinent to sewer asset assessment are outlined here as well. This literature review also covers the relevant decision making models, deterioration models, criticality, and budget allocation models.

2.2 Sewer Inspection Techniques

Since sewer pipelines are major infrastructure assets, it is essential to maintain their functionality through their life cycles. Regular inspections are required to assess and plan for rehabilitation or maintenance. Closed Circuit Television (CCTV) cameras are part of an inspection technique to record the inner surfaces of buried pipelines. CCTV is used to inspect pipelines with a wide range of diameters, as many pipelines are inaccessible due to their small sizes and insecure environment. These cameras are usually mounted on top of a crawler or a float where operators control the movement of the robot and the camera from afar (Kaddoura 2015). After the camera records the environment inside the pipeline, experts review the videos to assess the condition of the pipeline based on a specific protocol. Despite the availability of several sophisticated inspection techniques, CCTV is still one of the most commonly used sewer inspection techniques as per a survey conducted by Thomson (2004). While it is true that CCTV captures defects in sewer pipelines, many researchers have listed several drawbacks of this technique (Feeney et al.

2009). One major drawback is that CCTV camera cannot record any information below the flow-line. In addition, operators confront major obstacles when reporting numeral information regarding surface damage, settled deposits and deformation defects, despite CCTV's ability to locate them. As a result, subjective conclusions may be drawn which could negatively impact some rehabiliation decisions. Therefore, it is worthwhile to consider other technologies that can lessen the drawbacks of CCTV.

One technology that helps in assessing deformation and in locating surface damage defects is the two-dimensional (2D) laser profiler. This is a sensor that can draw, detect and measure the changes in a pipeline's cross-section that occur due to excessive loading, known as deformation. The 2D laser light is composed of a ring of light that is generated from a sensor with a very high intensity. The sensor is generally paired with a CCTV camera, which can detect the laser light.

Sonar sensors are mostly used to detect and quantify grease and settled deposits below the flow-line. The technology is based on sound energy that travels through the inspected pipeline material. Once a change in material is detected, the waves get reflected.The accuracy of the sonar sensor is highly dependent on the selection of the acoustic frequency and the travel speed (Andrews 1998), as ineffective frequencies and travel speeds produce unreliable images. Selecting the optimal frequency depends on the pipeline material -- the higher the acoustic frequency, the lower the penetrating power.

Pipe-penetrating radar (PPR) is the application of ground penetrating radar (GPR) in pipeline inspection. GPR emits radio waves to detect several features in the subsurface (Daniels 2004), where an antenna produces high-frequency radio waves (Feeney et al. 2009). PPR is applied in-pipe, so the signal will penetrate the pipe's wall to the surrounding soil. The system can operate using two or three antennas that are able to detect several frequencies for evaluation purposes.

SewerVUE Surveyor is the a multi-sensor inspection (MSI) robot that incorporates several technologies, such as CCTV, laser and PPR, shown in Figure 2.1. The PPR robot is mounted on a rubber tracked robot equipped with two high frequency attennae (Ékes 2016). The PPR system can used for sewer pipelines whose diameters range between 450 mm and 900 mm (Ékes and Neducza 2012). The GPR attennae can be rotated from 9 to 3 in the clockwise direction. The information is collected by two independent channels as it flows in both in and out directions to provide information about the rebar cover, the void present outside the pipe and the pipe wall thickness (Ékes and Neducza 2012). In addition, the laser system is deployed to provide information inside the pipeline wall, such as information required to calculatethe deformation defect, shown in Figure 2.2. The CCTV technology is deployed to record the inner condition of the pipeline and may display defects such as cracks, fractures, holes, breaks, etc. Figure 2.3 shows the typical integrated analyzed inspection information for a pipeline. The sections provide information about the rebar cover, pipeline wall thickness and the recommended action.

In spite of the efforts devoted to developing SewerVUE Surveyor, this machine has not yet been extensively tested in research laboratories or by industry experts to validate the results, as stated by a supplier employee. In addition, the sensors can only be located in few clockwise positions, which may hinder the results as voids may present in uninspected sections. As each inspection can only be run on two clock positions, the inspection would need to be run again for cases where more positions are required, with the associated longer times and higher costs. Moreover, in places where deposits are attached at the wall section, voids may be difficult to detect. A further restriction is that the robot is not applicable to pipelines that are wider than 900 mm or smaller than 450 mm.

Figure 2.1 PPR Robot (Ékes 2016)

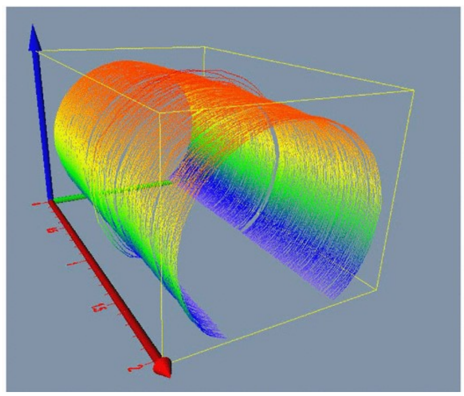


Figure 2.2 PPR Pipeline Geometrical Detection (Ékes and Neducza 2012)

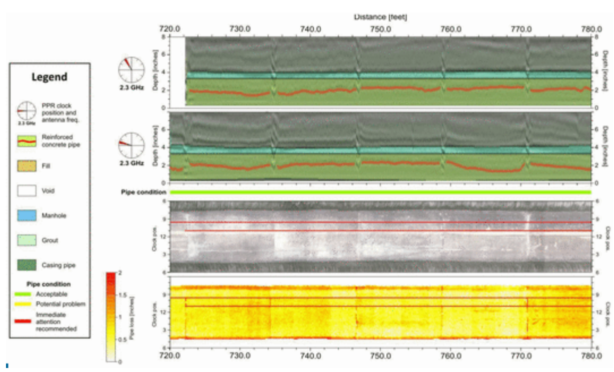


Figure 2.3 PPR Results (Ékes and Neducza 2012)

In contrast to pipelines, only a limited number of inspection techniques are utilized for sewer manholes. Man entry, so-called visual inspection, is the oldest inspection method used for manhole assets. It requires an operator to enter the manhole from an entry point "manhole opening" and visually assess the condition of the manhole sections, including the frame, chimney, channel, etc. The air quality must be checked and monitored during the operation, and operators may require ventilation. For a safer inspection atmosphere, the operator may require some or all of the following systems for safety:

- An air meter
- A fall arrest system
- Lighting
- Traffic control
- A cage around the opening

Man-entry is a rapid method for inspection and planning decisions; however, in many cases, an operator may find it difficult to access deeply inside the manhole, which could result in misleading conclusions. One of the most commonly used manhole inspection methods is the panorama camera. This type of inspection does not require man entry; it can be done from aboveground. This camera can record the images in a 360-degree view from the ground level to the channel level. The quality of the image is highly dependent on the resolution of the camera as well as on the manhole environment. The recorded panoramic images are then reviewed by an expert to understand the condition of the manhole. This technique allows the analyst to zoom in and out as well as display a panoramic image.

2.3 Condition Assessment Models

Current practices rely on a distress-based evaluation of sewer assets that is based on predeveloped sewer protocols applied to sewer pipeline inspection information. These protocols are either designed by local municipalities or by agencies' experts in the field. The protocols classify sewer defects into different sub-defects where each sub-defect has an associated specific severity value. Two of the most popular sewer protocols were developed by the Water Research Centre (WRc) in the United Kingdom (UK) for sewer assessment. The WRc developed two main protocols to systematically classify and assess sewer systems. The first is the Manual of Sewer Condition Classification (MSCC), which explains, defines and classifies defect groups and sub-defects with their corresponding codes (WRc 2013). The second protocol is the Sewerage Rehabilitation Manual (SRM) which defines the condition grades for the defects and their deduct values (WRc 2001). These protocols rely on the CCTV inspection method. The MSCC defines four main defect groups in the assessment of sewers: structural defects, service defects, construction features and miscellaneous features. The WRc considers different condition grades that range between "Acceptable Condition" to "Collapses". Each defect is represented by a deduction value using the predefined protocol. The overall defect score are usually calculated by the mean, peak and total scores. The structural condition or grade is computed considering the peak scores. A service defects group grade is concluded by selecting the maximum value between the peak score and the mean score**.**

Developed in partnership with the WRc, the Pipeline Assessment and Certification Program (PACP) of the National Association of Sewer Service Companies (NASSCO) (2003) has become the North American Standard. Many municipalities, like the city of Edmonton, Alberta, have switched from using their own standards to utilizing PACP assessment. PACP defines lower and higher rating scales for sewer pipelines, from 1 to 5 where 1 represents an excellent condition and 5 indicates that an immediate attention action is required.

Due to the lack of manhole assessment guidelines, NASSCO has developed a coding system for the defects observed in manholes. In the latest version of the Manhole Assessment and Certification Program (MACP), NASSCO proposes two different inspection protocols to assess manholes. Level1 inspection provides basic condition assessment information to evaluate the general condition of a manhole, while level 2 inspection records the detailed defects observed. In spite of the complex manhole structure, NASSCO considers a manhole as a vertical pipeline and therefore, MACP uses the established PACP coding system. The manhole condition rating is similar to that of the PACP rating scheme.

Hughes (2009) proposed a manhole condition assessment that was based on the structural degeneration and excessive infiltration/inflow (I/I) occurring in an asset. The author suggested a five-point rating system for the I/I and the structural evaluations for all manhole items except for the manhole cover inflow. Manhole cover inflow could be estimated based on a number of parameters such as the drainage area, the depth of ponding, the number of holes in a cover, its condition and its frame-bearing surface. The manhole items on which its condition is dependent upon were listed as the cover, frame seal, chimney, cone or corbel, wall, pipe seal, bench and invert or channel. Hughes (2009) suggests that these rates can be adjusted and that they are project specific. The defect flows that the author considered range between 0 and 1.6 gallons per minute. The I/I ratings are No I/I, Minor I/I (weeper), Moderate I/I (dripper), Heavy I/I (runner) and Severe I/I (gusher) as displayed in Table 2.1. The manhole structural condition was based on items similar to those of the manhole in addition to the steps. The condition rating was based on a 1 to 5 scale, in which 1 represented a Good condition while the 5 rating describes a poor condition, as indicated in Table 2.1.

Table 2.1 ASCE Condition Ratings for Manholes (Hughes 2009)

Condition Rating	I/I Observed	Structural Condition Observed
Good	No I/I	No structural defects
Fair +	Minor I/I	Minor defect identified
Fair	Moderate I/I	Multiple minor defects or moderate defect identified

Fair-	Heave I/I	Multiple moderate defects or major defect identified
Poor	Severe I/I	Major defects identified

Due to certain limitations observed in current practices, some researchers have developed models that assess sewer condition using recent inspections. Along these lines, Kaddoura et al. (2017) proposed a model that investigates the state of the pipeline considering four major defects. The authors suggested that deformation, surface damage, settled deposits and infiltration are the major sewer defects that could propagate and initiate other defects such as longitudinal cracks, breaks, roots, etc. Hence, the assessment of these major defects could provide an overview of the overall condition of a sewer asset. The main technique utilized in their assessment was the Multi-Attribute Utility Theory (MAUT). The authors adopted three different protocols to develop utility curves for deformation and settled deposits' defects considering the defects' severities from each protocol. They also investigated a structural point of view to evaluate the surface damage defect using the American Society for Testing and Materials (ASTM) guidelines. Subsequently, they developed utility curves for three different sewer pipeline materials. The infiltration defect's utility curve was developed considering the severities suggested by electro scan. However, the model did not include many of the sewer defects that can be found in inspection reports.

In another work, Daher (2015) adopted a fuzzy expert system to assess sewer assets including manholes, pipelines and pipeline joints. The author considered a number of sewer defects for each asset and formed a set of attributes related to each defect group in each asset to be used as fuzzy input variables. Each defect in the model was represented in a fuzzy membership function. The author collected the relative importance weights of the defects and sub-defect groups employing the Analytic Network Process (ANP). Hierarchal Evidential Reasoning (HER) was then utilized to integrate the defect groups' grades into one crisp index.

Angkasuwansiri and Sinha (2014) assessed sewer pipelines by suggesting a performance index that takes into consideration both structural and operational models. The structural portion of the index was evaluated after defining the external corrosion, internal corrosion, surface wear and load modules, and the operational portion of the index was calculated by considering the infiltration/exfiltration, blockage, root penetration and hydraulic modules. In each module, there were a set of criteria along with attribute values. The input of the modules were wastewater pipeline data such as depth, slope, size, proximity to trees, etc. The authors relied on CCTV, smoke test data and environmental data to extract some inputs. To compute a crisp index, two methods were adopted separately in their assessment: the fuzzy expert system and the weighted average method.

Other researchers have suggested sewer condition prediction models employing sophisticated tools such as the Artificial Neural Network (ANN), Support Vector Machines (SVMs), simulation models, multiple regressions, etc. For instance, Kulandaivel (2004) proposed a model based on a trained ANN to predict the condition of sewer pipelines depending on the historic condition assessment information. This model was subsequently tested and validated. Najafi and Kulandaivel (2005) later proposed another ANN model that uses historical data to assess sewers.

SVMs have also been utilized to assess the condition of sewer pipelines. Mashford et al. (2010) developed four SVM models. The first model uses the intrinsic characteristics of the asset such as its age, diameter, and material. The second model uses soil characteristics in addition to the first model's inputs. The third model uses the inputs of the first model and adds grade and angle information. The fourth model considers all sewer characteristics, sewer configurations, and the surrounding environment.

Condition assessment models have been developed utilizing ANNs combined with other accompanying techniques. As an example, Chae and Abraham (2001) combined the use of ANNs and fuzzy logic to accurately analyze and interpret the data for sewer pipeline condition assessment. Sousa et al. (2014) used ANN and SVM methods to predict the structural condition of sewer pipelines. They collected complete data about the pipelines, including material type, diameter, size, length, age, depth and slope, and computed the design flow velocity as a variable in their model. They grouped pipe conditions into two categories. The first category, conditions 1, 2, and 3, included "sewers that do not require immediate intervention." The second category, conditions 4 and 5, included sewers that "require immediate intervention." Sousa et al. then quantified associated uncertainties using ANNs and SVMs.

Simulation models have also been used to asses sewers. Ruwanpura et al. (2004) developed a rule-based simulation model to predict sewer condition. The simulation model included CCTV data analysis. Later, the authors developed the actual probability of existence (APE) from the collected data. The model considered the pipe characteristics, such as age, material, length, and its APE value.

Ariaratnam et al. (2001) used historical data in developing logistical models to evaluate the condition of sewers. These models proposed options to help decision makers to manage and plan for future inspections. The model probability was developed by using pipe characteristics such as age, diameter, and type of waste. They concluded that the quality of the results was highly dependent upon the quality of the data collected.

Chughtai and Zayed (2008) recommended a methodology for predicting the structural and operational condition of sewers using regression models. Historical data was used to develop models for each sewer pipeline material: concrete, asbestos cement, and Polyvinyl Chloride (PVC). Bakry et al. (2016a) used multiple regression model to construct equations that predict the structural condition and operational condition of Cured-in-place (CIPP) sewer pipelines. Several factors were taken into consideration, such as average daily traffic, diameter, pipe depth, pipe material, rehabilitation age, road type and service type. Bakry et al. (2016b) used the same approach in predicting the structural and operational condition of chemical grouted pipelines. Similar factors were considered in their evaluation. However, the multiple linear regression method assumes that the relation between the dependent variables and the independent variables is linear, and this is not the actual case for a sewer pipeline condition assessment model.

Despite the significant efforts invested in predicating sewer pipeline condition, the required input data rely heavily on huge datasets that could be difficult to attain for many municipalities. More importantly, much of the data obtained has been based on CCTV records and thus is subjective in nature.

2.4 Deterioration Models

Sewer networks are recognized as a significant part of the public health infrastructure (Duchesne et al. 2013) as they transfer sewage medium to treatment plants or special disposal areas. In fact, they form one of the most capital-intensive types of infrastructure in North America (Wirahadikusumah et al. 2001). A considerable proportion of public budgets must be reserved to enhance, repair, maintain or replace constructed sewer assets, as sooner or later, their maximum service life will be reached (Wirahadikusumah et al. 2001). Sewer assets are subject to deterioration due to ageing and other factors; therefore, it is imperative to inspect their conditions regularly to make optimum decisions to avoid any disruption. The information provided by an inspection indicates the general and current state of the assets such that reactive actions are to be taken (Baik et al. 2006) on a “fix it if and when it fails” basis (Fenner 2000). However, such a practice not only could result in comprehensive public and safety problems, it is almost guaranteed to cost a significant amount of money, ranging from two to ten times the cost of applying proactive strategies.

Therefore, predicting the future condition of infrastructure assets is crucial to the planning for proactive strategies to make the best use of the budgets allocated for maintenance and rehabilitation (M&R). A number of approaches have been utilized to model the deterioration of infrastructure assets. As per Morcous et al. (2002a), these models are composed of three groups: polynomial-type models, artificial intelligence models and stochastic or probabilistic models.

Polynomial-type models utilize continuous functions to understand the effects of different factors (explanatory variables) in a system on an asset’s condition. Chughtai and Zayed (2008) proposed a polynomial regression model to predict the condition of sewer pipelines. The authors classified the considered factors and sub-factors into structural and operational groups. Data from a municipality was then used to construct the regression models. Structural and operational grade predictions for different pipeline materials were proposed and were then used to plot the deterioration curves. In a similar work, Bakry et al. (2016a) developed a prediction model for CIPP-rehabilitated sewer pipelines and another model to predict the condition of chemically-grouted rehabilitated pipelines and manholes (Bakry et al. 2016b). The authors relied on a dataset from a local municipality to implement and validate their models. Later, the models were used to establish deterioration curves to understand the future states of the assets. One significant limitation of this technique is that the condition ratings indicate a relative ordering with no or minimal meaning assigned to the distance between the condition ratings (Scheidegger et al. 2011). Continuous functions are therefore inappropriate for representing discrete ordinal measures (Scheidegger et al. 2011).

Other researchers employed artificial intelligence models, which are information driven techniques. Usually, the outputs of the model are produced after it has learned from the available input data. Morcous et al. (2002b) proposed a case-based reasoning to model infrastructure deterioration assuming that the performance of an infrastructure asset can be predicted by the recorded performance of other assets that share similar attributes. After identifying six requirements to design their model, the developed prototype was able to predict the future condition of bridge decks. In a related work, Najafi and Kulandaivel (2005) developed a model to predict the condition of sewer pipelines based on historic condition assessment data. They used multiple variables for the ANN model, including the length, size, material type, age of sewer, depth of cover, slope and type of sewer. While artificial intelligence techniques can handle condition ratings and non-linear deterioration behavior, their main limitation is that they require a considerable amount of data to establish a robust and reliable model (Scheidegger et al. 2011).

Infrastructure deterioration has also been modeled using stochastic (probabilistic) techniques such the Markov chain model. For example, Wirahadikusumah et al. (2001) presented a Markov chain-based deterioration model for large buried combined sewers. The authors utilized an exponential model in the regression analysis to relate between the overall structural grade and the sewer age. Based on the authors; premise, the condition of a sewer does not decrease by more than one state in one year transition. The transition probabilities among five different identified states were predicted using the nonlinear optimization-based approach. Distinct deterioration models were plotted considering different combinations of factors (material, groundwater level, backfill material and depth of cover). Kleiner (2001) proposed another Markov chain-based deterioration models for water and sewer systems. That work assumed a single state transition among the condition states considered. The transition time was fitted as a random variable using Weibull distribution analysis. The author disregarded significant factors that could expedite the asset's deterioration and relied only on the age of the asset.

Continuing with stochastic techniques, Micevski et al. (2002) developed a Markov chain-deterioration model for water pipelines. They assumed multiple state transitions among the four identified states, in which the Metropolis-Hastings algorithm was used to estimate the transition probabilities. The authors claimed different deterioration rates for different pipeline categories: pipeline diameter, soil type, pipeline material and adjacency to coastline.

Baik et al. (2006) proposed a Markov chain-based deterioration model to estimate the future condition of wastewater systems. These authors assumed five different states to construct the transition probability matrix. The transition probability matrix was estimated using the concepts of an ordered probit model along with an incremental model. The variables used for the ordered probit model were the length of the pipeline, the diameter size, the type of pipeline material, the age and the slope of the pipeline. In addition, the authors applied the nonlinear optimization technique-based approach to estimate the transition probabilities before concluding that the ordered probit model approach was statistically and theoretically more robust. Nevertheless, the authors reported several limitation to their findings. Despite the comprehensive and extensive efforts accomplished by many researchers who applied Markov chain models, the technique's main limitation is its accuracy and its ability to estimating the transition probability matrix. In spite of the efforts undertaken to improve the estimation of the transition probabilities, the improvements considered did not attain satisfactory results (Baik et al. 2006).

2.5 Sewer Network Performance

The comprehensive assessment of an overall sewer network has received little attention in the literature. Although several report cards are published to inform the community about the overall grade and condition of infrastructure components, the methodology for calculating the grade is still vague. Moreover, several agencies and municipalities represent the overall sewer network performance by considering the mean value of all conditions. In addition to their limited representation, manholes are neglected in many of the overall assessments.

Developing a comprehensive approach in evaluating the sewer network is essential, as municipalities are adopting proactive and optimized approaches to manage sewer assets in the short- and long-term (Halfawy et al. 2008). The backbone objective will then be maximizing the overall performance of the sewer network as a whole, along with other objectives (i.e. to minimize the cost). This process allows effective solutions to be reached instead of relying on day-to-day activities (Halfawy et al. 2008).

In some related studies, the overall sewer network condition or performance was considered as an objective function in the optimization models, where it was a function of length (Halfawy et al. 2008 and Marzouk and Omar 2013) and a mean of all conditions (Shahata 2013). Despite the incorporation of a limited overall sewer network in the optimization models, these models were only relevant to sewer pipelines. Therefore, extensive enhancements to the current practices are required to achieve sound optimized decisions (i.e. including manholes in the evaluation and considering factors other than just the length of pipelines).

According to the Institute of Public Works Engineering Australasia (IPWEA) (2007), condition assessment and performance assessment of facilities are “inexorably” linked; deterioration of an asset causes its failure which will lead to poor performance. However, a condition by itself only reflects the physical condition of the asset, unlike the performance, which describes the reliability, availability, capacity and success at meeting customer demands and needs (IPWEA 2007). Based on some performance monitoring processes and measurements, the risks associated with asset performance are considered, along with an asset’s ability to meet occupational, health and safety regulations, public safety requirements and environmental requirements (IPWEA 2007), which is similar to the criticality definition. Theoharidou et al. (2010) defined criticality as “the contribution level of the infrastructure to the society in maintaining a minimum quality level of vital social functions, health, safety, security, and economic or social well-being of people”. Some English dictionaries describe criticality as “the quality, state, or degree of being of the highest importance.” This leads to the conclusion that an asset with extreme criticality has the highest importance; similarly, assets that are non-critical are of least importance. Therefore, the sewer network will be computed according to the relative importance weights; in other words, the criticality of each asset compared to that of the others. Assuming that a subnetwork consists of two pipelines, pipeline A and B. Pipeline A has a condition of 5 and is not critical, whereas, Pipeline B has a condition of 5 and is of extreme criticality. Therefore, in expressing the overall sewer network performance, pipeline B will have a higher weight than pipeline A.

Criticality in infrastructure has attracted several researchers in construction management. In addition to Theoharidou et al. (2010), Miles et al. (2007) expressed criticality as the consequence of the failure of an asset. In fact, Syachrani et al. (2013) defined critical assets as assets with a high probability of failure and high consequences if they do fail. Moreover, it is very important to study the criticality of one asset in relation to another in order to make the most efficient decisions. This can be accomplished by a so-called criticality assessment, which is the process of assessing the criticality level of an asset (Theoharidou et al. 2010) by considering its consequence of failure.

In assessing the criticality of infrastructure components, several studies have been conducted to serve certain objectives. In this context, Miles et al. (2007) proposed a pipeline rehabilitation priority decision matrix by considering the condition of the pipelines and their criticality criteria. The rehabilitation proprieties were set based on the available information related to the probability of failure and the consequence of failure criteria that were weighted by experts. The authors identified certain factors that could influence the probability of the failure and the consequence of failure. Under the condition category, the authors subdivided the capacity, structural and maintenance conditions into several sub-factors. Meanwhile, the criticality group was subdivided into four different sub-groups: environmental impact, size, transportation impact and ease of repair/reliability; each sub-group was composed of several factors. The authors assigned higher levels to a factor that was more critical compared to the others. The criticality rating was calculated by adopting the assigned levels to each criticality factor. However, the condition rating was computed based on the levels assigned to each condition factor and their relative importance weights. The authors concluded their decisions based on a 5 x 5 matrix that was constructed based on the condition and criticality parameters. Critical assets that required immediate actions topped their rehabilitation actions list.

Salman et al. (2011) defined criticality as the consequence of failure and proposed a risk-based model to prioritize wastewater rehabilitation decisions. The authors acquired a weighted scoring system to determine a numerical consequence of failure value for each pipe section. The risk level was computed by aggregating the consequence of failure with the probability of failure. They adopted three different models in their computations, namely: the multiplication of probability and consequence of failure, risk matrices and a fuzzy inference system. A number of factors were identified that could affect the criticality, such as the proximity to the nearest building, depth, size, number of complaints, roadway type, location, etc.

Syachrani et al. (2013) proposed a criticality-based assessment model for sewer pipeline assets. They modelled their approach based on a risk assessment that was comprised of the probability of failure and the consequence of failure. They introduced a new method using the "real age" of a pipe in estimating the probability of failure. The consequence of failure was estimated based on a semi-parametric survival analysis, based on information from a Delphi workshop. The risk level was then calculated by the multiplication factor of the probability of failure and the weighted consequence of failure.

In addition, Baah et al. (2015) proposed a risk-based model to prioritize the future inspection of uninspected wastewater pipelines in the natural and built environment. The authors computed the probability of asset failure based on estimating the grade of the sewer pipeline using a deterioration model. However, the consequence of failure for each pipeline was determined according to a weighted-sum scoring matrix system. Several factors were identified to calculate the consequence of failure such as: the roadway type, pipe size, depth, proximity to buildings, proximity to hospitals, proximity to rivers, etc. The risk of failure was then computed using the risk matrix system.

In this research, the overall sewer network performance will be a function of the criticality of each asset. The higher the criticality of an asset, the higher its contribution to the overall sewer network condition.

2.6 Decision-Making Models in Sewer Infrastructure

Optimization methods are commonly used to solve budget allocation problems in infrastructure asset management. There are four main types of optimization algorithms that are commonly used in infrastructure: linear, non-linear, integer and dynamic programming (Nunoo 2001). In the construction management domain, the budget allocation problem could be in the form of one or more objective function that shall be minimized or maximized. However, due to limited resources and diverse requirements, the objective functions are subject to constraints related to money, time, manpower, etc. As a result, defining all possible solutions while restraining the problem could be very complex (Al-Tabtabai et al. 1999). Typical mathematical programming tools are used for unconstrained problems and as a result are not applicable to constrained objective functions and very large complex problems (Wang 2013). However, evolutionary algorithms (EAs) have emerged as alternative methods to solve large-scale and complex optimization problems (Veldhuizen and Lamont 1998).

For example, in sewer infrastructure, Lin et al. (2016) designed a sewerage rehabilitation multi-objective management model to prioritize sewer pipeline rehabilitation decisions. The authors used the non-dominated sorting genetic algorithm (GA)-II to design a number of Pareto surfaces considering desirable rehabilitation methods and the substituted material. Three conflicting objectives were determined: minimizing rehabilitation costs, maximizing pipe service and minimizing traffic disruption. The model was conducted on a real case study and the authors claimed that it saved almost 20% of the rehabilitation costs determined by the experts.

Marzouk and Omar (2013) presented a model for life-cycle maintenance planning for sewer network. Prior to developing a prioritization model, the authors developed a Markov chain model to predict the future deterioration of sewer pipelines. Next, they used a multi-objective GA model to build the prioritization model. Three objective functions were considered: improving the overall network, improving the intended network service life and reducing the present value of the life-cycle maintenance cost. Six different variables with different relevant states and benefits were considered: do nothing, routine cleaning, shotcrete, CIPP, reinforced fiberglass sliplining, and dig and replace with concrete pipeline.

On the other hand, Halfawy et al. (2008) proposed an integrated approach for systemizing the sewer renewal planning procedure after utilizing a multi-objective GA model. The authors relied on three main objectives: to minimize the average condition index, minimize the average risk measure of the network and minimize the total life-cycle cost. The proposed model was claimed to support short- and long-term planning situations as well as network-level and project-level planning.

Furthermore, Yang and Su (2007) established a GA-based optimization model to supply an optimal rehabilitation plan for sewer assets. The authors considered the three most popular rehabilitation methods: renewal, renovation and excavation, and trenchless replacement. The cost associated for each method was determined by an equation that is dependent on the pipeline diameter. In addition, the authors considered the substitution materials in the decision making process. After applying the methodology on a case study, they stated that the approach could reduce the rehabilitation costs by 20% of the actual rehabilitation expense.

DeMonsabert et al. (1999) utilized the integer programming method to optimize and prioritize a sewer rehabilitation schedule. The model was developed to choose the repair method that yielded the minimum present value-cost solution over a 20-year planning period with maintenance at 5-year intervals. The objective of the approach was to select the optimal repair strategy to minimize the total cost, subject to budget constraints.

Wirahadikusumah and Abraham (2003) suggested a decision-making framework to select the appropriate M&R plan, based on dynamic programming in conjunction with a Markov chain model. Before commencing the decision-making approach, the authors designed a Markov chain-based deterioration curve to predict the future condition of the sewer pipelines. The decision making approach considered five different states from 1 to 5 for the assets, and six different alternatives corresponding to a specific state: no maintenance/rehabilitation, routine cleaning, shotcrete, CIPP, reinforced fiberglass sliplining and dig and replace with concrete pipe.

2.7 Erosion Voids in Buried Infrastructure

Sewer pipelines are one of the most common distributed underground assets in urban cities. They are installed above bedding materials in trenches at distinct depths and gradients. Later, they are buried by some type of compacted backfilling material. Aging and other factors such as ground movements, excessive overburden loads, poor bedding compaction, frost action, and chemically-induced bonds can lead to structural deterioration which may result in the collapse of the pipeline (Jaganathan et al. 2010). In fact, Davies et al. (2001) explained three common stages for a sewer pipeline's collapse process. The first stage (Figure 2.4a), is where cracks are formed due to poor construction practices or overloading disturbance. The surrounding soil remains in position supporting the pipeline. In the second stage (Figure 2.4b), due to the presence of cracks in the pipeline and the presence of groundwater, infiltration/exfiltration in the system begins due to the hydrostatic pressure, which then washes out the soil around the pipeline (Jaganathan et al. 2010 and Davies et al. 2001). This can lead to a loss of the side support in some locations, a situation that can expedite the deformation of the pipeline. As a result, cracks will develop to become fractures. The third and final stage, illustrated in Figure 2.4c, is when the sewer pipeline is prone to collapse if its side support is lost and the sides of the pipeline are further pushed to cause deformation that exceeds 10%, resulting in a pipeline collapse. It is clear that the soil surrounding a pipeline acts as a backbone support for it (MacDonald and Zhao 2001) and that void erosion is likely to cause a harmful consequence for the asset with collapse scenarios (MacDonald and Zhao 2001, Jaganathan et al. 2010, Vipulanandan and Liu 2005).

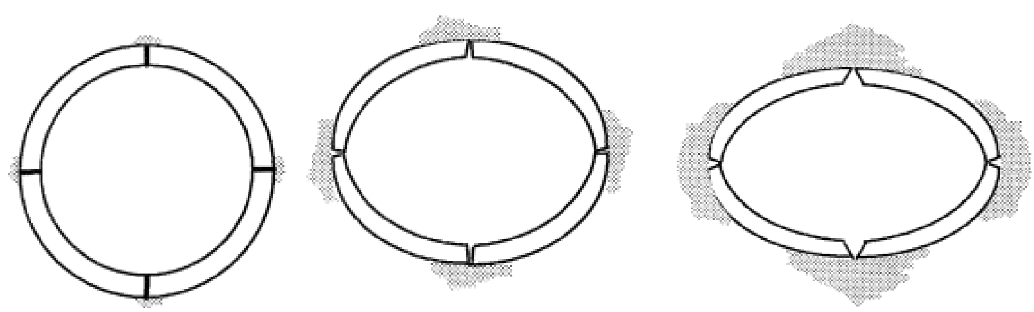


Figure 2.4 Sewer Pipeline Collapse Process (Davies et al. 2001) - a) Stage 1, b) Stage 2, c) Stage 3

Moser and Folkman (2001) stated that the formation of voids around the pipeline could cause pressure concentration against it. Several structural and geotechnical engineering studies were conducted to analyze the consequences of void formation in pipelines (Tan and Moore 2007, Kamel and Meguid 2013, Zheng and Moore 2007 and Balkaya et al. 2012) and tunnels (Meguid and Dang 2009 and Jifei et al. 2010). Most of these studies claimed that bending moments and thrust would change with the formation and growth of void sizes. For example, Tan and Moore

(2007) concluded that the critical long-term failure mechanism for concrete and vitrified clay pipelines is the erosion of the soil support surrounding a pipeline. The formation of erosion voids will induce fractures to the asset. Once fractures are present, more eroded soil will occur and even larger voids formed, which may lead to sudden collapse and surface failure known as sinkholes.

The collapse of a pipeline will result in the exfiltration of the sewage material, thereby threatening the surroundings (soil, water, public, etc.). In addition, the surface failure will have severe consequences for the public, such as the disruption of transportation routes, economic losses and in some cases death scenarios (Jaganathan et al. 2010), as sinkholes could expose the public to life-threating accidents. The authors reported several accidents that occurred in the US and which are displayed in Table 2.2.

Table 2.2 Urban Sinkhole Collapses Reported in the US (Jaganathan et al. 2009)

Location	Date	Description
Pottsville, PA	28-Jun-06	Two cars plummeted 21 m after a sinkhole opened on Route 924
New York state	28-Jun-06	Two truckers were killed after their rigs falls into sink hole on Interstate 99
Portland, OR	27-Dec-06	Maintenance truck falls into sinkhole
New York city	23-Dec-06	SUV falls into 3 m deep sinkhole; mother and two children rushed to hospital
Houston, TX	22-Jan-07	A sinkhole formed on the intersection of Braeswood and Buffalo Speedway
Orange county, FL	15-Feb-07	Three cars damaged after driving into sinkhole
Memphis, TN	8-Apr-08	Three meter dia., 15 m deep sinkhole shutdown the CNR rail line; $1 M for repair
Iowa city, IA	9-Jul-08	A 1.2 m dia., 9 m deep sinkhole forced closure of a main bridge
Albuquerque, NM	9-Jul-08	A 3 m deep sinkhole formed near a public school nearly swallowed a fire truck
Pasadena, CA	17-Jul-08	Sinkhole opened on the northbound of HW 110, shutting down highway
Huntington, W.VA	28-Jul-08	Massive sinkhole opened in a public park; repair costs = $250,000
Bethlehem, PA	7-Aug-08	A large sinkhole threatening nearby 18th century Moravian building
St. Louis, IL	11-Feb-09	Hundred and forty year old sewer collapsed swallowing a semi-trailer truck

2.8 Quality Function Deployment (QFD)

Quality Function Deployment (QFD) is a technique that is utilized to convert customer needs into technical requirements in each stage of product development (Sullivan 1986). It is conducted to attain several quality issues' objectives (Chan and Wu 2002):

1- Improve the quality of design

2- Provide a planned quality control chart before the initial production run

The method was firstly developed in Japan in 1966 by Yoji Akao, but the approach was not formalized in quality control planning until 1972 (Costa et al. 2000). Since then, QFD approach has rapidly spread across Japan and the US (Costa et al. 2000). QFD is a Total Quality Management (TQM) approach as it requires the inclusion of customer needs into project design targets apart from a projects' basic requirements (Dikmen et al. 2005). It focuses on implementing the voice of the customer, a critical step (Hofmesiter 1991), after assessing their needs, which are usually determined by interviews and/or focus groups or surveys, in order to ensure their satisfaction (Dikmen et al. 2005).

The formulation of the QFD approach starts with the determination of the product policy and the end-user needs into a basic concept. Therefore, design requirements are established to form the "WHAT's", which in turn establishes the component characteristics' "HOW's" of the product design. A matrix is then constructed to study the relationship between the HOW's and the WHAT's (Govers 1996). The absolute weights are then determined by aggregating the HOW's and the WHAT's through the use of the factors in the matrix established earlier. Consequently, the House of Quality (HOQ) is then finalized; a basic representation is depicted in Figure 2.5.

The aforementioned method is proposed as an approach to be used in the condition assessment of sewer system assets; in this research manhole components and pipelines. The method will be restructured to suit its application in infrastructure condition assessment. Thus, in the context of this research, each component is considered as follows (Alsharqawi et al. 2016):

- WHAT's are the conditions' severity. In this research, five different severities are considered: excellent, very good, fair, poor and critical. These severities rate the asset's condition;
- HOW's represent the defects considered in each asset under assessment, and do so percentagewise;
- A relationship matrix is the roof component of the QFD approach. It establishes the relationship between the defects;
- Absolute Weights are the weights of the WHAT's that are determined after aggregating the HOW's and each WHAT. In this research, five different grades are considered; and
- The HOQ represent the complete application of the QFD as shown the diagram of Figure 2.5

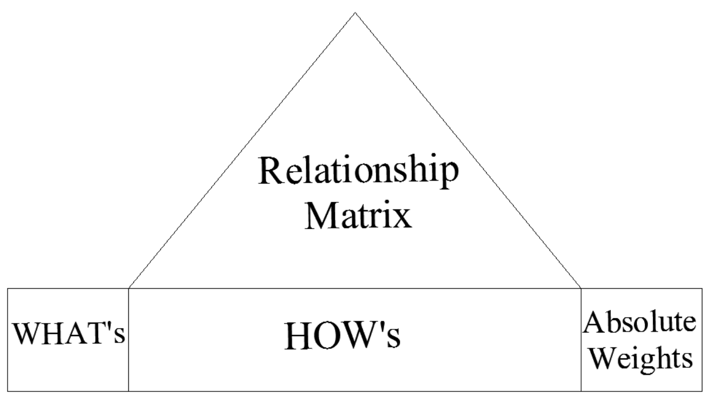


Figure 2.5 HOQ General Representation

2.9 Causality vs. Correlation

The backbone formalization of the matrix in the HOQ is based on the correlation between the associated defects. By definition, correlation describes the size and the direction between two variables; however, it fails to identify the cause and effect relationship. In general, correlation between variables is represented by a coefficient that describes the strong or weak correlation between two different variables. A higher number means a stronger correlation and a lower number indicates a weaker correlation. In addition, negative and positive relations can be depicted between two different variables through the coefficient signs. A positive sign represents a positive relationship; when one variable increases, the other increases and vice versa.

However, in project management, for example as per the Project Management Institute (PMI) (2013), plan quality management is associated with causes rather than correlations. The main concept of considering a cause and effect over a correlation is the fact that decision makers can pin-point the causes and solve them to prevent the effects. However, solving the problems will not prevent the causes from re-developing and producing the undesired effects. In the long-term, such an approach could reduce the quality costs due to the detection and the reparation of causes. In a cause and effect model, for X to cause Y, X must happen before Y. Assuming the same symbols, let X be a cause of Y within a period of time. Therefore, X_t causes Y_{t+a} where the subscript refers to time with $a > 0$. Based on this representation, Y_{t+a} cannot cause X_t since this will violate time precedence.

The PMI (2013) listed several basic quality tools to solve quality- related issues. The first is cause and effect diagrams, which are also called fishbone diagrams or Ishikawa diagrams. The problem is stated at the head of the fishbone, where the head is used to point out the root causes until possibilities are determined by asking “why” questions. Flowcharts are also called process maps as they establish a sequence of steps such that the branching of inputs transforms outputs. Checksheets, also called tally sheets, can be used as checklists when collecting data. They are mostly used to organize the facts of a potential quality issue for effective data collection. Pareto diagrams are a form of vertical bar chart that are used to identify the sources that causes most of the effects. Histograms, which are another form of a bar chart, describe the central tendency and the shape of a statistical distribution of a quality problem causes. In this research, the HOQ's top-most triangle will consider the cause and effect relationship rather than correlation factors, using the Decision-Making Trial Evaluation Laboratory (DEMATEL).

2.10 Decision-Making Trial Evaluation Laboratory (DEMATEL)

DEMATEL was developed by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva between 1972 made 1976 to solve complicated problems (Tzeng et al. 2007). The DEMATEL approach could improve the understanding of a specific *problematique* for a cluster of intertwined problems and contribute to the identification of workable solutions by means of a hierarchical structure (Tzeng et al. 2007). This method can establish an interdependency relationship between the participating variables in a cause and effect scenario to determine the causing and effecting variables (Tzeng et al. 2007) and thereby identify the central components of the problem. This technique is based on a questionnaire directed to experts. The more responses, the better the results as they multiple results allows several professional opinions in the domain to be compiled. The average influence matrix is constructed based on the responses, revealing the influence of one element in the system on the other. This influence is represented by 0, 1, 2, 3 and 4, indicating "no influence", "low influence", "medium influence", "high influence" and "extreme influence". Next, the normalized influence matrix is assembled, which in turn calculates the total influence matrix, so that the cause and effect contribution of each element in the system is attributed. These cause and affect elements are then categorized.

2.11 Analytic Network Process (ANP)

The ANP method was applied in different applications related to strategic planning, project management, fund allocation, human resources and research and development problems, and supplied satisfactory results (Daher et al. 2017). This method has also been utilized to assess several infrastructure assets, and the methodologies supplied minimal errors compared to actual values. For instance, Hawari et al. (2016) proposed a model that assessed the condition of free-flow and pressurized sewer pipelines by integrating fuzzy logic and the ANP. El Chanati et al. (2015) modeled a performance assessment methodology to assess water pipelines by aggregating several identified factors using the ANP method, and the conditions of oil and gas pipelines were evaluated using the ANP application (El-Abbasy et al. 2015). Due to the successful implementations of the ANP in infrastructure management, this study adopts it in the manhole assessment and criticality model.

The ANP is one of the most widely-used multi-criteria decision making process techniques. It is based on considering decision makers' judgments on the factors of involved in certain systems. The root of the ANP method is the Analytic Hierarchy Process (AHP), developed by Saaty in the late 1960's, and which is a general theory of measurements (Saaty and Vargas 2002). It is used to find the relative priorities on absolute scales from both discrete and continuous paired comparisons in multilevel hierarchic structures (Saaty and Vargas 2002). The comparison may be established by actual measurements or by the relative strength of preferences or feelings. Since many problems cannot be structured hierarchically, the ANP was designed to consider the interaction and the inter-dependence of elements involved in a system or network. In other words, the AHP is used to establish a comparison in a vertical direction, unlike the ANP, which considers a comparison in both vertical and horizontal directions.

The first step of the ANP method is identifying the system to be analyzed and then decomposing it through a set of hierarchies or networks. Later, paired comparison judgments in the AHP/ANP are applied to pairs of homogeneous elements. In many cases, the preferences or the judgments are established by a questionnaire given to experts. The fundamental scale of values to represent the intensities of judgments is shown in Table 2.3.

Table 2.3 Intensity of Importance Scales for AHP/ANP

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two attributes contribute equally to the objective
2	Weak	intermediate values
3	Moderate Importance	Experience and judgment slightly favour one activity over another
4	Moderate Plus	Intermediate values
5	Strong Importance	Experience and judgment strongly favour one activity over another
6	Strong Plus	Intermediate values
7	Very Strong or Demonstrated Importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, Very Strong	Intermediate values
9	Extreme Importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of Above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

Suppose that an element Z in an arbitrary system is given a relative importance of k compared to element C, then the relative importance of element C when compared to element Z is 1/k. After collecting the pairwise comparisons from experts, the unweighted matrix considering the relative importance weights is constructed. The next step is forming the weighted supermatrix to consider the interdependency among the elements in the system. At the end, the weighted supermatrix is multiplied by itself until the limit supermatrix is attained, and in which the final local priorities are reached (Yang et al. 2008).

It is very important to consider the computation of the Consistency Ratio (CR) to ensure that expert opinions are not contradicting several aspects in a system. Two parameters are considered in the computation of the CR, the Consistency Index (CI) and the Random Index (RI). The CI is computed using equation 2.2.

$$CR = \frac{CI}{Random\ Index} \qquad [2.1]$$

$$CI = \frac{\lambda - n}{n - 1} \qquad [2.2]$$

where

λ is the highest eigenvalue in the pairwise comparison matrix, and

n is the matrix size.

However, the RI depends on the number of elements in the matrix and is determined using Table 2.4, adapted from (Saaty and Vargas 2002). After determining the two values, the CR is computed accordingly. The pairwise comparison matrix is considered to be consistent if the CR is < 0.1.

Table 2.4 Random Consistency Index vs. Elements Number

n	1	2	3	4	5	6	7	8	9	10
Random Consistency Index (RI)	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

2.12 Fuzzy Set Theory

The classical set theory is developed based on the fundamental definition of "set", in which an element is either a member of a set or not (Chen and Pham 2000). For a well-defined set, there is a crisp and clear distinction between a member and a non-member in a defined set. So basically, the question may be posed as follows "is this element within the set or not?" and the answer will be either "yes" or "no" when considering well-defined sets (Chen and Pham 2000); true for many of the deterministic and stochastic cases. As a result, in classical set theory, an element is not allowed to be in a set and not in a set. However, many problems in the real-world cannot be described as a crisp value due to different problem definitions. For example, the description of people who are "old" could be different from one person to another and therefore it is not precisely measured.

In the effort to better represent the real world, fuzzy set theory, developed by Zadeh, accepts partial memberships between sets to solve many real life problems. Using fuzzy set theory, we let *S* be a non-empty set, called the universe set, which consists of the possible elements of concern in a particular problem. Each of these elements is called an element or a member of *S*. Therefore, a union of several members of elements of *S* is called a subset of *S*, and can be written as:

$s \in S$

However, if an element is not a member of subset *S*, it is represented as

$s \notin S$

Considering a set of *A* in *S*, the characteristics function X_A of subset A is defined as

$$X_A(x) = \begin{cases} 1 \; if \; x \in A \\ 0 \;\; if \; x \notin A \end{cases} \qquad [2.3]$$

which is an indicator of the members and non-members of the crisp set A. However, to generalize the concept of making a partial membership, one needs to describe the membership grade of the element in a set. Back to the example where people are categorized by the property of "old", suppose S be the set of people and let

$S_f = \{s \in S \mid s \text{ is old}\}$

where S_f is a "fuzzy subset" of *S* because of the property of "old" which is ambiguous and cannot be measured precisely. Therefore, a generalized membership function associated with S_f shall be constructed to avoid ambiguity in the decision. The subset S_f and the membership function associated with the subset is called the fuzzy subset.

2.12.1 Fuzzy Set Shapes

There are several shapes that can represent membership function fuzzy logic; nevertheless, the shapes used the most are the linear approximations: trapezoidal and triangular shapes (Dubois & Prade 1988). Figure 2.6 displays these two shapes for any membership function. The trapezoidal fuzzy set can be represented by four points (*a, b, c, d*), where *a* and *d* are the lower and upper bounds, respectively, and b and c are the lower and upper middle values, respectively. The triangular fuzzy set can be considered as a special case of the trapezoidal fuzzy set provided that $b = c$. Therefore, the membership function can be expressed as given in equation 2.4.

$$y_A(x) = \begin{cases} \dfrac{x-a}{b-a} & a < x < b \\ 1 & a \le x \le b \\ \dfrac{x-d}{c-d} & c < x < d \\ 0 & otherwise \end{cases} \quad [2.4]$$

As per equation 2.4, if $y_A(x) = 0$, this means that x has a null membership in the expressed fuzzy set A; while if $y_A(x) = 1$, it means that x has full membership in the defined fuzzy set A.

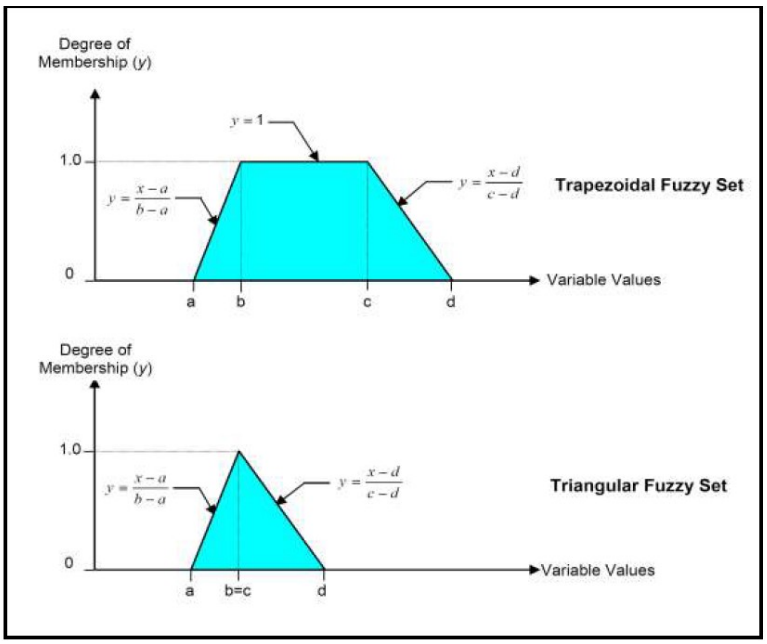


Figure 2.6 Fuzzy Sets Representation

2.12.2 Fuzzification and Defuzzification

Fuzzification and defuzzification are essential steps in formulating fuzzy logic; the end product is a crisp value that minimizes subjectivity. The fuzzification process translates raw data from linguistic terms such as very old, old, medium, young and very young into distinct membership functions, while he defuzzification process, is converts the overall membership functions into crisp values (Mamdani 1974). Several defuzzification methods are commonly used to change fuzzy values into crisp values. The following examples demonstrate the calculation of $z*$, a defuzzfied value, using different defuzzification methods (Ross 2010):

- Centroid Method: also called the centre of area method, this is the most prevalent defuzzification method and is calculated using equation 2.5 (the function is shown in Figure 2.7)

$$z^* = \frac{\int \mu c(z).z\, dz}{\int \mu c(z)\, dz} \quad \text{for all } z \in Z \qquad [2.5]$$

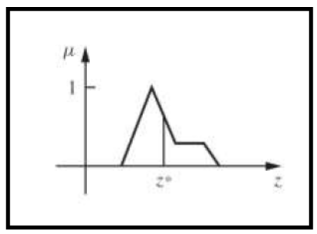


Figure 2.7 Centroid Defuzzification Method (Ross 2010)

- Weighted average method: due to its computational simplicity compared to the other methods, this approach is often preferred. The algebraic formula is shown in equation 2.6, where Σ is the algebraic sum and $\bar{z}$ is the centroid of each symmetrical membership function. This function is illustrated in Figure 2.8.

$$z^* = \frac{\sum \mu c(\bar{z}).\bar{z}}{\sum \mu c(\bar{z})} \qquad [2.6]$$

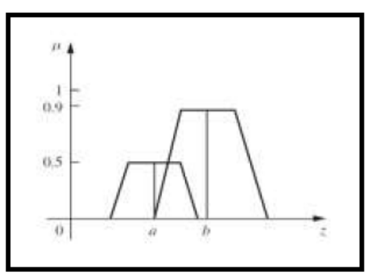


Figure 2.8 Weighted Average Defuzzification Method (Ross 2010)

- Mean-Max membership: also called the middle of maxima method. This method can be utilized when the peaked output membership function is a plateau, as shown in Figure 2.9. Equation 2.7 represents the calculation for this method.

$$z^* = \frac{a+b}{2} \qquad [2.7]$$

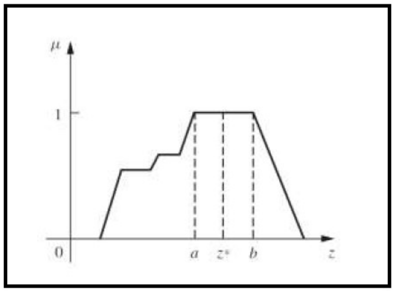


Figure 2.9 Mean-Max Membership Defuzzification Method (Ross 2010)

- Center of Sums: one of the fastest defuzzification methods. Accomplished in three steps, this defuzzification method is summarized in Figure 2.10. The defuzzified value, however, can also be calculated as shown in equation 2.8.

$$z^* = \frac{\sum_{k=1}^{n} \mu c_k(z) \ \int_z \bar{z}\, dz}{\sum_{k=1}^{n} \mu c_k(z) \ \int_z dz} \qquad [2.8]$$

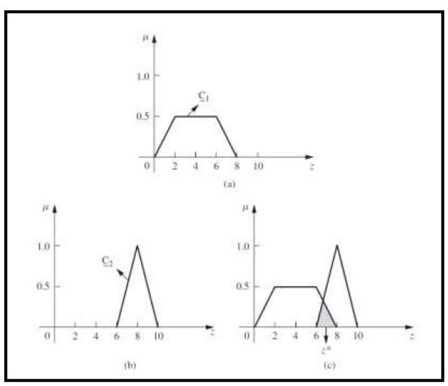


Figure 2.10 Center of Sums Defuzzification Method – a) First Membership Function; b) Second Membership Function and c) Defuzzification Step (Ross 2010)

2.13 Weibull Analysis

Weibull analysis has caught the attention of many researchers since its discovery by Waloddi Weibull (1887-1979), as indicated by the hundreds of papers on this topic (Rinne 2008). Rinne (2008) claimed that Weibull distribution is without any doubt the most popular model in modern statistics. It has been utilized by many practitioners due to its special features, as it is able to fit data from many different fields such as in engineering, health, meteorology, etc. Furthermore, Jardine and Tsang (2006) stated that Weibull analysis is the most popular technique to analyze and predict all types of failures and malfunctions.

Waloddi Weibull found that the distribution of data for a specific asset or product can be fitted by the following function:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} * e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \qquad \text{for } t > \gamma \qquad [2.9]$$

where

β is the shape factor and is greater than zero;

γ is the location factor and is greater than zero;

η is the scale factor; and t is the time.

Meanwhile, the Weibull cumulative distribution function (cdf) is described by equation 2.10, which determines the failure at any time t.

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \qquad [2.10]$$

Therefore, one can describe the reliability at time *t* as the deduction of the cdf function from one, as shown in equation 2.11:

$$R(t) = 1 - F(t) = e^{-(\frac{t-\gamma}{\eta})^{\beta}} \quad [2.11]$$

In this research, Semaan's (2011) method has been adopted to model the deterioration of assets, as historical data are scarce and this approach only requires one data point to plot the deterioration of an asset. The reliability of the asset is calculated based on its calculated condition.

2.14 Particle Swarm Optimization (PSO)

Among the many evolutionary algorithms (EAs), the Particle Swarm Optimization (PSO) method is easier to implement and has more competitive exploration and detection capabilities (Kennedy and Eberhart (2001); Parsopoulos and Vrahatis (2002). The PSO also has a faster convergence when compared to other EA methods. Several researchers have evaluated the performance of multiple optimization methods. For example, Koay and Srinivasan (2003) optimized a power plant maintenance scheduling problem using GA, Evolutionary Strategy (ES) and the PSO, and stated that the PSO method supplied better results and performance than GA and ES. Coello et al. (2004) and Baltar and Fontane (2006) utilized four distinct optimization tools to evaluate five multi-objective problems and concluded that the PSO attained faster convergence; they concluded that it is well-suited to the multi-objective optimization problem. El-Ghandour and Elbeltagi (2017) compared five different optimization techniques, the GA, PSO, Ant Colony (AC), Memetic Algorithm (MA) and Shuffled Frog Leaping (SFL) methods, on two benchmark water networks to determine the least cost for one and the least rehabilitation cost for the other. They concluded that the PSO surpassed the other algorithms in both test situations.

Comparing the application of the GA and PSO methods in solving single objective problems, Jung and Karney (2006) evaluated the performance of GA and PSO in optimizing the sizing and the selection of hydraulic devices for protection, and found that both methods provided similar results. However, they concluded that the PSO outperformed the GA method when the same number of iterations and population sizes were used. Based on these multiple positive results, the PSO method was selected for this research to solve the budget allocation problem.

The PSO method was introduced by Kennedy and Eberhart in 1995. This method was inspired by the flocking patterns of birds and fish that move in swarms to search for food. As illustrated in Figure 2.11, this method commences with an initial random pool of solutions represented by a swarm. Each swarm encompasses a number of solutions that are known as the size of the population. The swarm determines the number of solutions, with each exemplified as a particle. Following an iterative approach, the best solution is found by considering the problem at hand.

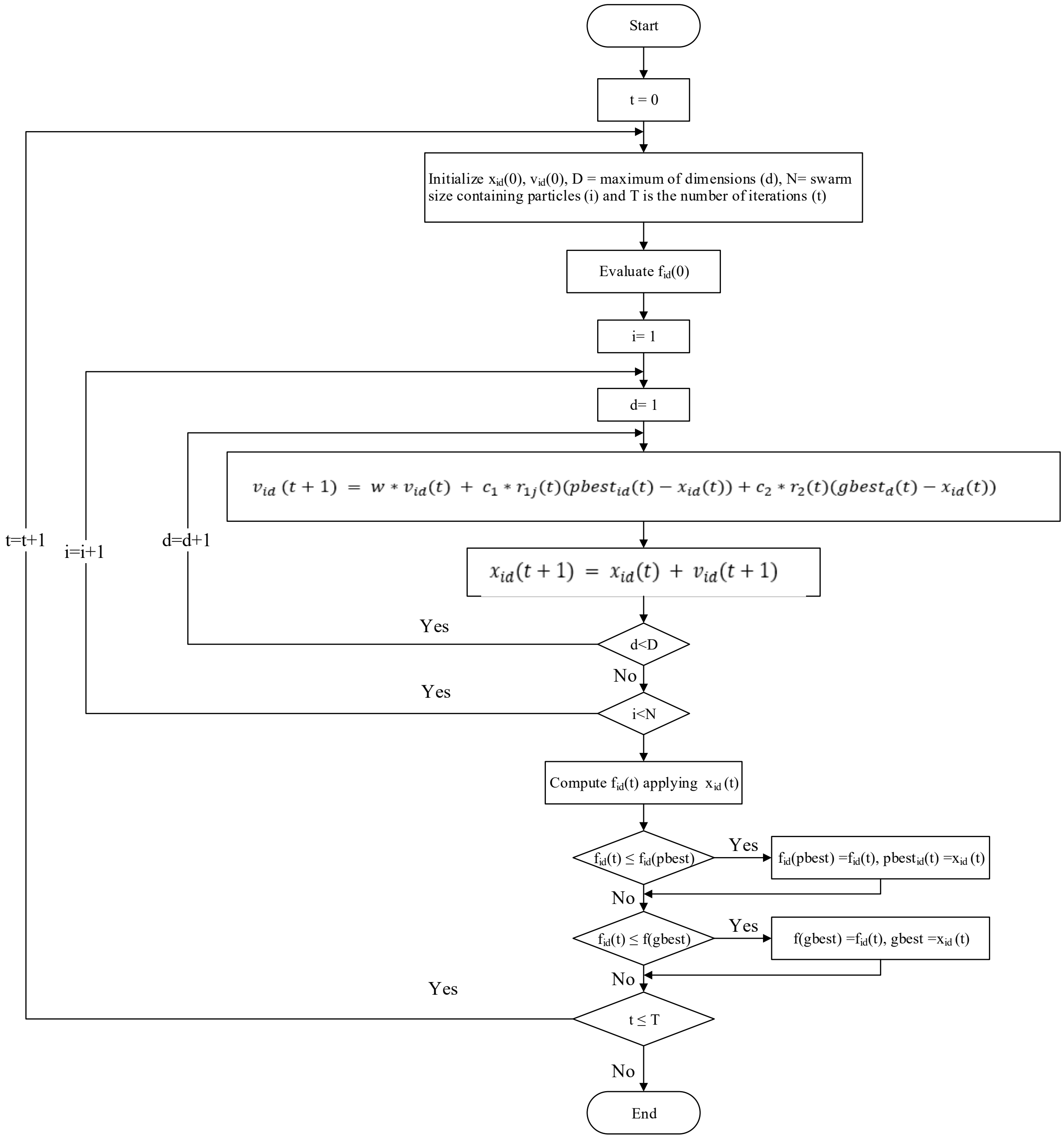


Figure 2.11 PSO Flowchart

Each particle in the swarm has a specific position. The fitness of the current position of any particle is evaluated according to a defined fitness function. Subsequently, the best fitness solution of each particle is denoted as *pbest* (particle best) and is archived and automatically updated once a better solution (position) is found. Considered as a minimization problem, the personal best of particle *i* in the subsequent step can be represented as

$$pbest_i\,(t+1) = \begin{cases} pbest_i\,(t) & if\ f(x_i(t+1)) > pbest_i\,(t) \\ x_i(t+1) & if\ f(x_i(t+1)) \leq pbest_i\,(t) \end{cases} \qquad [2.12]$$

Among the *pbest* found in each iteration, the best position among all the positions is also stored for subsequent iterations and is described as the *gbest*. The $gbest\,(t) = min\,\{pbest_i(t)\}$ is always updated whenever new better overall position is reached.

The particles in the swarm are always updated by a better position in every iteration by considering randomized values toward some directions. These changes are calculated by using the velocity. The velocity of the particle relies on three mean factors: *pbest*, *gbest* and the random function. The evaluation scheme and the modifications repeat until the termination criteria is reached. The modifications are always completed through the velocity function. Considering D elements of array A = (z_{i1}, z_{i2}, z_{i3},..., z_{iD}) as the search space, the *gbest* describes the global best particle of a swarm and $pbest_i$ denotes the archived best position of the i^{th} particle in the swarm population. Therefore, the velocity of the particle can be calculated according to equation 2.13 (Shi and Eberhart 1998). Considering the velocity values, the particle's updated position is computed using equation 2.14 (Shi and Eberhart 1998).

$$v_{id}\,(t+1) = w * v_{id}(t) + c_1 * r_{1j}(t)(pbest_{id}(t) - x_{id}(t)) + c_2 * r_2(t)(gbest_d(t) - x_{id}(t)) \qquad [2.13]$$

$$x_{id}(t+1) = x_{id}(t) + v_{id}(t+1) \qquad [2.14]$$

where

t	is the iteration;
$t+1$	is the subsequent iteration;
d	is a value from the D space ranging from 1 to D;
N	is the total number of particles in a swarm (population size);
i	particle number that ranges between 1 to N
w	is the inertia weight that is taken as a parameter;
$x_{id}(t)$	is the current position of the *i*th particle in the d dimension;
$x_{id}(t+1)$	is the new position of the ith particle in d dimension
$v_{id}(t)$	is the current position of the *i*th particle in the d dimension;
$v_{id}(t+1)$	is the new velocity of the *i*th particle in the d dimension;
$pbest_i$	is the best position of the *i*th particle stored;
$gbest_d$	is the global best position of a swarm from among all the particles;
r_1	is a uniform random number [0,1];
r_2	is a uniform random number [0,1]; and
c_1 and c_2	are acceleration coefficients.

The parameter v_{id} restrains the particle to consider its previous direction and speed, thereby allowing the particle to discover new areas in the search space. The cognitive learning rate c_1 controls the velocity of the particle's movement towards the *pbest*, while the social learning rate c_2 controls the velocity towards the *gbest*. Large numbers of c_1 and c_2 can lead to expedited particle movements toward the current *gbest* or *pbest*; a situation which could lead to premature convergence.

Particles with larger v_{id} tend to move rapidly towards the global area; but, if they are close enough to the global area, the global position may be ignored and they can move to alternative areas. Since the value of the v_{id} impacts the converging criteria to a global optimum, the global and local searches shall be restrained such that the search space is limited to $x_{id} \in [-x_{max}, x_{max}]$, $v_{max} = k * x_{max}, 0.1 \leq k \leq 1$. Nevertheless, the inertia factor w was introduced by Shi and Eberhart (1998) in order to limit the particle movement to new search areas. Keeping a value of w =1 will maintain the standard form of PSO. In general, a large value of the weight expands the range towards new areas, while lower values encourage the particles to search in closer range areas.

2.14.1 PSO Algorithm Parameters

In order to perform the PSO analysis, several parameters shall be considered before commencing the iteration process. These parameters have significant impact on the efficiency of the optimization model (Carlisle and Dozier 2001). In PSO, the basic parameters are the swarm size (number of particles or population size), the number of iterations, the velocity components and the acceleration coefficients.

2.14.2 Swarm Size

The swarm size represents the number of particles used in the evaluation. A larger number of particles allows larger parts of the search space to be reached in each iteration. The number of iterations can be reduced to reach to the near optimum solution, but then the computational time may increase when compared to that of smaller swarm size. Based on empirical studies, it has been observed that the common population considered in PSO is between 20 and 60 per swarm (van den Bergh and Engelbrecht 2002).

2.14.3 Number of Iterations

A too-low number of iterations could block the converging criteria and produce premature solution. Meanwhile, a higher number of iterations adds complexity to the model (Engelbrecht 2007).

2.14.4 Velocity Components

A particle's velocity is dependent on three main parameters that are updated in each iteration and that control the movement direction of the particle.

1. The term v_{id} is the inertia component. This component provides an archive of the previous particle direction in the space, restricting the drastic change of a particle's movement.
2. The term $c_1 * r_{1j}(t)(pbest_{id}(t) - x_{id}(t))$ is called the cognitive component. This component evaluates the performance of the particle compared to the previous archived performance. It acts as an individual memory for each particle in the search domain to ensure the particle returns to its best position.
3. The term $c_2 * r_2(t)(gbest_d(t) - x_{id}(t))$ represents the social component. This component evaluates the performance of a particle relative to the whole population size. The main aim of the social component is to drive each particle towards the best position.

2.14.5 Acceleration Coefficients

These coefficients, along with r_1 and r_2, maintain the stochastic impact of the cognitive and social components of the particle velocity equation. The factor c_1 describes the confidence of each particle in itself, while c_2 indicates the confidence level of the particle in its neighborhood (Engelbrecht 2007).

- If $c_1 = c_2 = 0$, the particles are moving at their current speed until they reach the search boundary. As a result,

  $$v_{id}\,(t+1) = v_{id} \qquad [2.15]$$

- If $c_1 > 0$ and $c_2 = 0$, the particles are independent and they do not rely on the best performance of the population. Therefore, the velocity equation becomes

  $$v_{id}\,(t+1) = w * v_{id}(t) + c_1 * r_{1j}(t)(pbest_{id}(t) \qquad [2.16]$$

- If $c_2 > 0$ and $c_1 = 0$, the velocity of the particles are attracted towards the *gbest*

  $$v_{id}\,(t+1) = w * v_{id}(t) + c_1 * r_{1j}(t)(pbest_{id}(t) - x_{id}(t)) + c_2 * r_2(t)(gbest_d(t) - x_{id}(t)) \qquad [2.17]$$

- If $c_1 = c_2$, the particles are attracted to the average of *pbest* and *gbest*
- If $c_1 > c_2$, the particles are significantly influenced by their own positions and vice versa.

2.14.6 Graphic Illustration of the PSO

The velocity of a particle is dependent on three main parameters: the inertia, the cognitive and the social components. Figure 2.12 and Figure 2.13 display the performance of one particle at t and t+1, respectively. It can be observed that the particle that was initially at x (t) moves to x (t+2) until it closely reaches to the value of *gbest*.

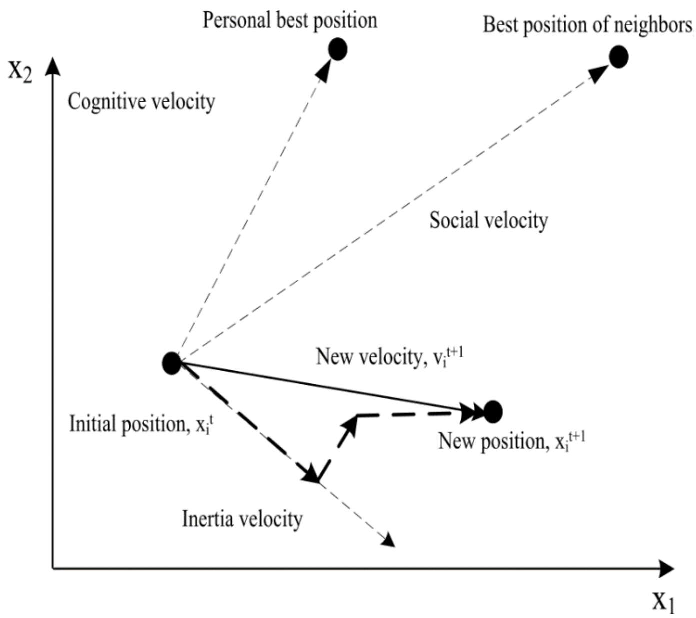


Figure 2.12 Particle Performance at t

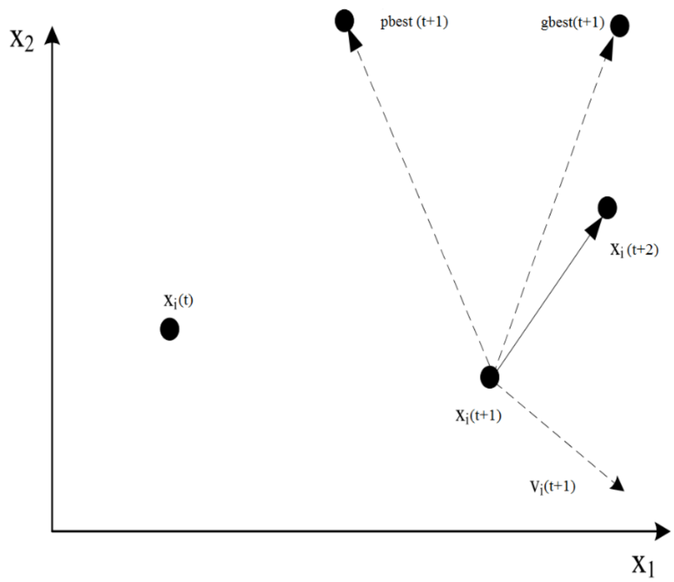


Figure 2.13 Particle Performance at t+1

The *gbest* or star topology, represented in Figure 2.14, allows each particle in the search space to connect with the other particles. This topology provides for a faster convergence as it is influenced by the *gbest* of the total population size.

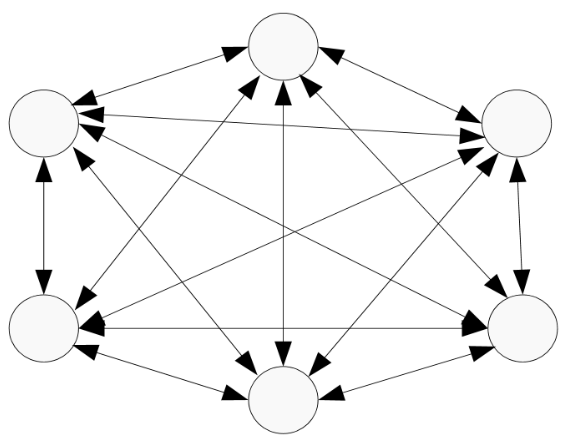


Figure 2.14 gbest (star topology)

2.15 Current Practices Limitations

Current practices rely on CCTV, the most widely-used inspection technique, to record the inner condition of pipeline assets. An overall rating is then deduced based on a specific standard used by each municipality. The overall rating is deduced using either the peak score or the mean score of all defect grades. Peak scores flatten the data and provide a vague overall rating for a pipeline (Daher 2015), as some defects are neglected. However, the overall grading deduced from the mean calculation of all defects considers common weights for all the defects, resulting in misleading conclusions for decision makers. In addition, the reviewed literature does not assess void erosion and hence does not consider it as a defect. There is no doubt that this lacunae is because there are few (if any) techniques and methodologies that can predict or assess erosion voids.

Sewer systems are not only composed of sewer pipelines, the main concern for many researchers. Manholes are important system assets to consider and maintain in good condition (Sever et al. 2013). However, many of the available standards do not consider manhole condition assessment. Surprisingly, recent manhole assessments either consider similar overall ratings as those of sewer pipelines, or they do not comprehensively assess each manhole's components.

As stated previously, sewer assets are prone to ageing and are subject to deterioration over time. If no interventions are planned, assets may fail and collapse causing severe economic and environmental consequences. Consequently, it is crucial to model the deterioration of sewer assets in order to predict their future condition. The literature shows a distinct lack of modeling for the deterioration of manhole assets in sewer systems. Some sewer pipeline deterioration modeling techniques are available, but many of the developed models utilize regression techniques or Markov Chains. These models require huge datasets, but the required inspection reports may be very difficult to obtain. In addition, they require extensive statistical analysis and mathematical calculations. Furthermore, many of them are not dynamic in nature and thus it is difficult (or impossible) to update their deterioration curves.

To date, researchers have not studied the overall assessment of sewer networks to enhance rehabilitation prioritization. According to the reviewed literature, rehabilitation prioritization is planned for sewer pipelines in sewer networks. In fact, several prioritization models' main objectives are to improve the condition of sewer pipelines, even though they disregard the enhancement of the overall sewer network performance, considering the whole assets (pipelines and manholes).

Chapter Three: Research Methodology

3.1 Overview

This chapter provides an extensive formulation and illustration of the techniques used in the research. The first part discusses the erosion void factors and the attribute values considered. It also illustrates the proposed condition assessment models for pipelines and manholes as well as the grading scale and description formats. In addition, this chapter comprehensively explains the techniques deployed in this research, including the QFD, DEMATEL, the ANP, Weibull analysis, fuzzy logic and the PSO algorithm.

3.2 Literature Review

The research begins with a review of the literature pertinent to sewer networks, conducted as per Figure 3.1. This literature is valuable for the of several available condition assessment tools, inspection techniques, sewer network overall performance, etc. Some limitations are depicted from the available literature. Based on these limitations, the research commences the modelling stage by proposing the erosion void prediction model for sewer pipelines. This model is essential, as the outputs are used in the pipeline condition assessment model.

The QFD and DEMATEL approaches are utilized to conclude an index of sewer pipelines. Next, manhole conditions are studied, after dividing the manhole into several components and finding their importance weights using the ANP method. Both assessment models are validated using actual data. After the validation model is completed, deterioration curves are constructed using the Weibull analysis tool.

Beyond the proposal stage, the research will also investigate the overall sewer network assessment process by integrating the criticality of each asset in a sewer network to determine the performance of a sewer network. In addition, the research will design an optimized decision analysis tool for rehabilitation actions that maximizes the overall sewer performance and minimizes the available budget, given some constraints.

3.3 Data Collection

This study reviewed several sewer protocols available in the industry and extracted significant information to tailor the proposed condition assessment models. The collected data is divided into several parts in which each has its own importance to the study.

The data collection relies on a questionnaire that is distributed to stakeholders and sewer system experts to help in constructing two major models (DEMATEL and ANP). The questionnaire pertinent to the DEMATEL approach contributes to finding the influence of each defect on the other; hence, establishing a cause and effect relationship among them. The questionnaire designed for the ANP approach is instead based on a pairwise comparison of the manhole's components (pavement, channel, bench, etc.) and the relative importance weights of each component. For the erosion void model, the experts are asked to provide a weightage percentage for each factor considered.

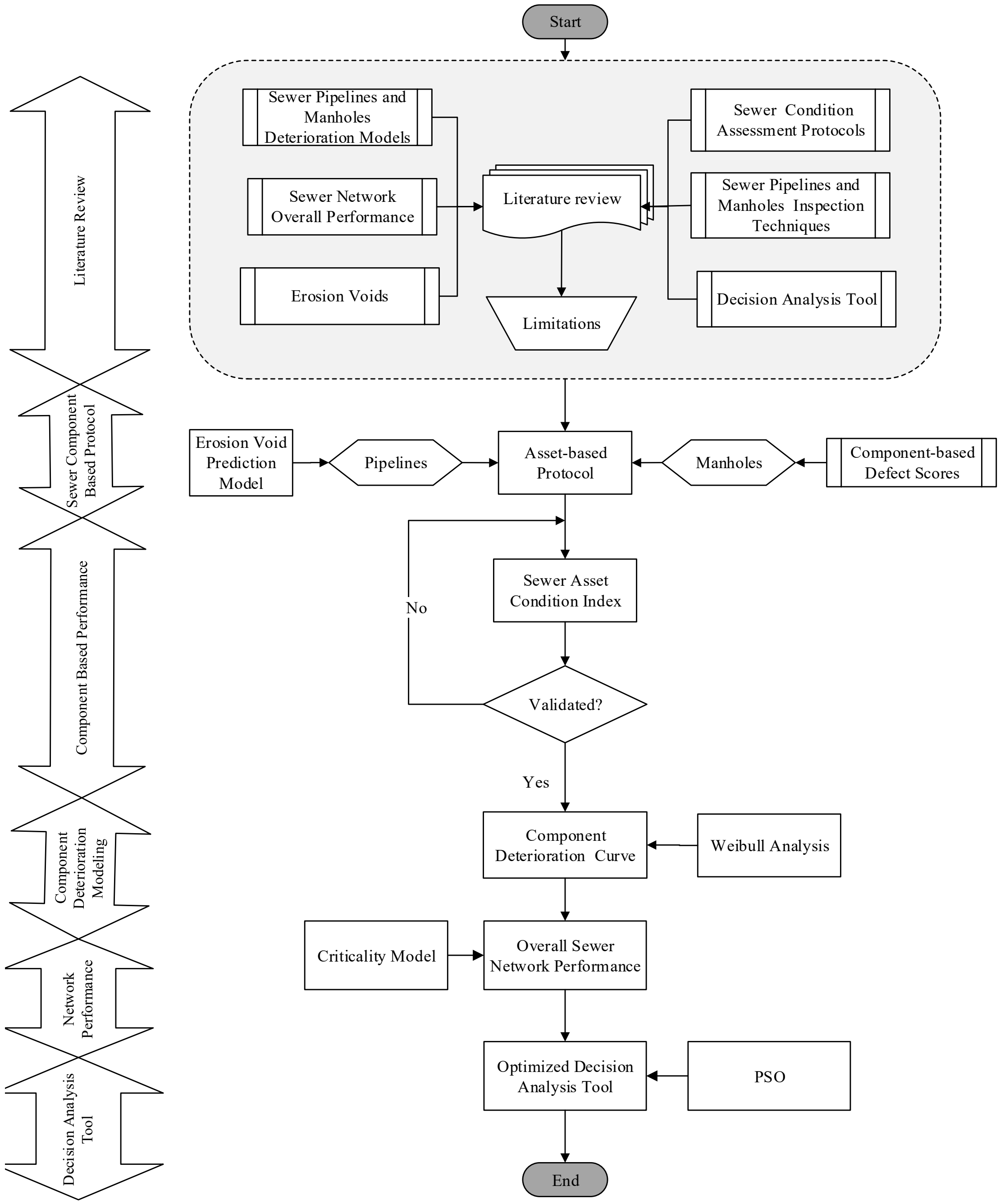


Figure 3.1 Research Methodology

3.4 Erosion Void Factors

3.4.1 Bedding Material

The stability of the pipeline is influenced by different factors such as the soil-pipe interaction and the uniformity of soil support around a pipeline. A stable foundation with consistent bedding, with attributes as presented in Table 3.1, is important for uniform longitudinal support along the pipeline. The use of unstable foundation materials, over-excavation, and the non-uniform compaction of bedding material can lead to loss of support for the invert and the haunches (Balkaya et al. 2012). Moreover, erosion voids may expand around the pipe if leakage is present due to structural defects (Balkaya et al. 2012). The fuzzy membership function established for the bedding type is based on a 95% confidence level (certainty) as the type of data used is discrete.

Table 3.1 Bedding Type Factor and Attributes Descriptions

Factor	Type	Description
Bedding	Class A	Excellent
	Class B	Good
	Class C	Fair
	Class D	Critical

3.4.2 Pipeline Depth

Pipeline depth is another factor that could influence the erosion voids surrounding the pipeline. The analysis includes the effect of the soil-structure interaction on earth pressure (Balkaya et al. 2012). Deeper pipelines provide higher static pressures as they will form higher soil interactions. In addition, O'Reilly et al. (1989) determined that the defect rate decreases with increasing pipeline depth, which may lead to a lower rate of structural defects. Based on the aforementioned explanation, the depth is categorized as displayed in Table 3.2.

Table 3.2 Depth Factor and Attributes Descriptions

Factor	Depth (m)	Description
Depth	=>5	Very Deep (Excellent)
	3.65-5	Deep (Good)
	2-3.65	Medium (Fair)
	1.25-2	Shallow (Poor)
	<1.25	Very Shallow (Critical)

3.4.3 Soil Type

Different soils are used as backfilling materials to provide soil envelopes around pipelines: sandy, silty, clayey, etc. In forming erosion voids, Guo et al. (2013) reported that the volume and diameter of erosion voids increases when finer cohesion-less soil exists due to a smaller submerged angle of repose (Fathi-Moghadam et al. 2010). The soil types are therefore classified as shown in Table 3.3. The coarser the soil type, the higher the resistance to erosion. A 95% confidence level (certainty) is assumed as the data are discrete.

Table 3.3 Soil Type Factor and Attributes Descriptions

Factor	Soil Type	Description
Soil Type	Gravel	Excellent
	Course Sand	Good
	Fine Sand	Fair
	Fine Sand and Silt	Poor
	Low Plasticity Clay	Critical

3.4.4 Pipeline Age

Sewer pipelines are prone to ageing and hence are susceptible to deterioration. This is due to the nature of many of the continuously-used items. The higher the usage, the higher the chance of losing some of its initial condition. As sewer pipelines get older, more structural defects will propagate. O'Reilly et al. (1989) found that more defects are present in older sewer pipelines. In addition to a pipeline's age, if a sewer pipeline is continuously below the groundwater table or is subject to inflow, the risk of confronting void erosion will be higher due to the presence of structural defects and the groundwater table or inflow. Therefore, pipeline age is classified into five different groups as shown in Table 3.4. The newer the pipe, the better its condition.

Table 3.4 Age Factor and Attributes Descriptions

Factor	Age (years)	Description
Age	0-15 years	New (Excellent)
	15-30 years	Young (Good)
	30-50 years	Medium (Fair)
	50-75 years	Old (Poor)
	>75 years	Very Old (Critical)

3.4.5 Groundwater Table

Water flowing through structural defects could lead to soil loss; hence, a lack of pipeline support (Davies et al. 2001). If the groundwater level exists above the sewer pipeline or above any structural defect, there is a greater chance of infiltration and soil entrance to the sewer pipeline (Davies et al. 2001). WRc (2001) has reported the effect of groundwater level on ground loss, these are categorized as per Table 3.5:

- High risk to ground loss: water table is above or close to sewer
- Low risk to ground loss: water table is below sewer

The membership function used is based on a 95% confidence level as the type of data is discrete and is in linguistic form.

Table 3.5 Groundwater Factor and Attributes Descriptions

Factor	Pipeline	Description

Location		
Groundwater	Below Pipeline	Excellent
	Above Pipeline	Critical

3.5 Pipeline Condition Assessment Model

Pipeline condition assessment is an important practice as it helps decision-makers to plan for proactive maintenance/rehabilitation. Therefore, this study develops a defect-based pipeline condition assessment model considering a cause and effect relationship between the identified defects. According to Figure 3.2, the first step is gathering defects that affect the condition of buried pipelines. In addition to the common defects discussed in many available protocols, soil loss (erosion void) is added to the model due to its importance in propagating other defects (Davies et al. 2001). The DEMATEL method is deployed to find the relative influence weight of each defect. To this end, a questionnaire was sent to sewer experts in different regions to evaluate the influence of one defect on another. An average influence matrix is established and used in the HOQ instead of the regular correlation matrix. Based on the DEMATEL and QFD integration, severity condition percentages are calculated after aggregating the severity percentages of each defect.

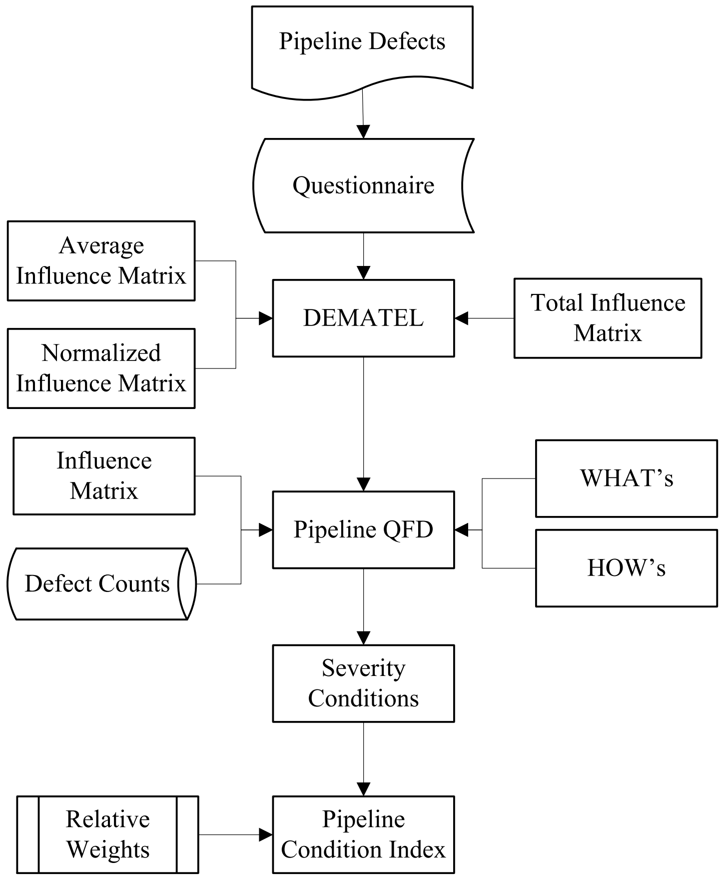


Figure 3.2 Pipeline Condition Assessment Model

3.5.1 Pipeline Defects

There are several defects that can be observed in sewer pipelines and that are categorized according to their nature. Each category has a number of defects that explain the type of the damage occurring in the pipeline. PACP (NASSCO 2003) categorizes sewer defects into four different groups:

1. Structural defects are ones that jeopardize the structural integrity of a pipe; these comprise deformation, surface damage, holes, breaks, etc. In fact, the most severe situation occurs when the pipeline collapses; hence, it requires replacement.

2. Operational defects are defects that could have an adverse effect on the flow inside a pipe. These defects include families of infiltration, settled deposits, roots, soil intrusion, etc.
3. Construction features are defects that occur during construction, such as intruding sealing material, tap, line, etc.
4. Miscellaneous defects include observations noted by inspectors, such as abandoned inspections.

Davies et al. (2001) explained the three main stages that lead to a pipeline collapse. They found that erosion voids could lead to deformation. Next, deformation defects cause longitudinal cracks. Eventually, excessive deformation can open the cracks to form fractures. In the presence of some structural defects and groundwater, water can infiltrate sewer pipelines and offer room for roots to penetrate into the system. When roots have an attractive environment, they expand. As a result, the severity of fractures can increase and could lead to some breaks and holes. In addition, as the flow runs through the pipeline, deposits get attached to the roots inside the pipeline. Over time, these deposits will accumulate and disturb the flow. Due to the inexorable relation between these defects, the system disregards the four different categories listed above to combine all defects into one system.

The present study considers twenty-two defects from structural, operational and construction features, grouped as presented in Table 3.6. Unlike many of the sewer protocols, the erosion void defect is included in the defects' list due to its importance in causing other defects to emerge. In addition, the same table ranks the severity of each defect in different grades that range between 1 and 5. The higher the grade, the more critical the defect.

Table 3.6 Sewer Pipeline Defects

Number	Pipeline Defects	Description	Grade	Grade Description		Remarks
1	Longitudinal Crack	Line is apparent but not open, running along the pipeline's axis	1	Length <75 mm		
			2	75-150 mm		
			3	>150-225		
			4	>225 - 300 mm		
			5	>300 mm		
2	Circumferential Crack	Line is apparent but not open, running at right angles to the pipeline's axis	1	1 clock positions		
			2	2 clock positions		
			3	3-4 clock positions		
			4	5-6 clock positions		
			5	>6 clock positions		
3	Multiple Crack	Combination of longitudinal and circumferential cracks	1	Length <75 mm		
			2	75-150 mm		
			3	>150-225		
			4	>225 - 300 mm		
			5	>300 mm		
4	Longitudinal Fracture	An open crack that runs along the pipeline's axis	1	Length <75 mm	Width <1.5 mm	Consider maximum grade between length and width
			2	75-150 mm	1.5 mm to 5	
			3	>150-225 mm	5 to 8 mm	
			4	>225 - 300 mm	8 to 16 mm	
			5	>300 mm	> 16 mm	
5	Circumferential Fracture	An open crack that runs at right angles to the pipeline's axis	1	1 clock positions	Width <1.5 mm	Consider maximum grade between length and width
			2	2 clock positions	1.5 mm to 5	
			3	3-4 clock positions	5 to 8 mm	
			4	5-6 clock positions	8 to 16 mm	
			5	>6 clock positions	> 16 mm	
6	Multiple Fracture	Combination of longitudinal and circumferential fractures	1	Length <75 mm	Width <1.5 mm	Consider maximum grade between length and
			2	75-150 mm	1.5 mm to	

Number	Pipeline Defects	Description	Grade	Grade Description		Remarks
					5	width
			3	>150-225	5 to 8 mm	
			4	>225 - 300 mm	8 to 16 mm	
			5	>300 mm	> 16 mm	
7	Deformation	When the cross-section of the pipeline is altered horizontally or vertically	1	Deformation < 2.5%		
			2	2.5% and < 5%		
			3	5 and <7.5%		
			4	7.5 and <15%		
			5	>= 15%		
8	Hole	A visible hole in the pipeline	3	1 clock position		
			4	2 clock positions		
			5	>=3 clock positions		
9	Break	Pieces are noticeably displaced in the pipeline wall	3	1 clock position		
			4	2 clock positions		
			5	>=3 clock positions		
10	Sag	When pipeline slope changes; this can be detected through ponds.	1	<5%		
			2	5 and <10%		
			3	10 and <25%		
			4	25 and <50%		
			5	>=50%		
11	Collapse	Loss of structural integrity of the pipeline	5	Pipeline Collapsed		
12	Surface Damage	Pipeline surface is changed from its original condition (loss of wall thickness)	1	0-10% thickness loss or increased roughness		
			2	<10%-20% or spalling		
			3	<20%-30% or aggregate visible or projecting, missing mortar		
			4	30%-<50% or aggregate missing, displaced brick		
			5	>=50% or reinforcement visible or corroded, missing brick		
13	Settled Deposits	Materials in a sewer pipeline which could cause flow turbulence and reduction of cross-	1	0-5%		
			2	<5-10%		
			3	<10-20%		
			4	<20-30%		

Number	Pipeline Defects	Description	Grade	Grade Description	Remarks
		section (i.e. debris)	5	>30%	
14	Soil Deposits	Presence of soil from pipeline inlets or surrounding ground; causing turbulence in the flow	1	0-5%	
			2	<5-10%	
			3	<10-20%	
			4	<20-30%	
			5	>30%	
15	Roots	Ingress of roots through defects	1	0-5%	
			2	<5-10%	
			3	<10-20%	
			4	<20-30%	
			5	>30%	
16	Infiltration	Ingress of groundwater through defects		<6 ml/min	
				6-500 ml/min	
				>500 ml/l-5 l/min,	
				>5 l/min 10 l/min	
				>10 l/min	
17	Obstruction	An obstacle in the drain	1	0-5%	
			2	<5-10%	
			3	<10-20%	
			4	<20-30%	
			5	>30%	
18	Offset Joint	A pipe is not concentric with the socket of the adjacent pipe	1	0 to 6% of pipe diameter	
			2	>6 -12 of pipeline diameter	
			3	>12 to 18% of pipeline diameter	
			4	>18% to 25% of pipeline diameter	
			5	>25% of pipeline diameter	
19	Open Joint	Adjacent pipelines which are longitudinally displaced at the joint	1	> 0 to 12 mm	
			2	>= 12 mm and < = 25 mm	
			3	>25mm and <= 50mm	
			4	>50mm and <=100mm	
			5	>100 mm	
20	Soil Loss (Erosion Void)	Loss of soil support around the pipeline	1	Excellent	
			2	Good	
			3	Fair	
			4	Poor	
			5	Critical	

Number	Pipeline Defects	Description	Grade	Grade Description	Remarks
21	Attached Deposits	Foreign materials are attached to the sewer pipeline and continue to accumulate	1	0-5%	
			2	<5-10%	
			3	<10-20%	
			4	<20-30%	
			5	>30%	
22	Protruding Service	Objects that have been inserted after construction	1	0-5%	
			2	<5-10%	
			3	<10-20%	
			4	<20-30%	
			5	>30%	

3.5.2 Overall Pipeline Grade

The pipeline grade is essential as it reflects the state of the pipeline inspected. The output of the model shall be an input for the decision making process. In this approach, five different percentage severities are concluded; the relative weights are then found to calculate the overall grade of the asset. The overall grade of the pipeline is found by aggregating the grades' percentages with the value of the grade condition as per equation 3.1.

$$\text{Overall Pipeline Grade} = \sum_{1}^{5} RW_i \ * \ i \qquad [3.1]$$

where

RW is the relative weight of each grade found; and

i is the weight of each condition severity. For example, Excellent is 1, Good is 2, Fair is 3, Poor is 4 and Critical is 5.

The calculated grade ranges between 1 and 5 (Excellent to Critical). The grade description is interpreted in Table 3.7. The table provides information about each condition grade with its corresponding overall grade range and description.

Table 3.7 Proposed Pipeline Overall Grades, Conditions and Descriptions

Overall Grade	Condition	Description
1.00 to <1.50	Excellent	No defects and strong soil support
1.50 to < 2.00	Good	Minor defects are observed with small to medium severities; soil support erosion started with minimal severity.
2.00 to < 3.00	Fair	Moderate defects with medium severity; soil erosion is in progress
3.00 to <4.00	Poor	Major defects with medium to high severity; void erosion is severe.
4.00 to 5.00	Critical	Severe defects are observed. Pipeline collapses or collapse is imminent. Pipeline has lost major of its surrounding soil

3.6 Manhole Condition Assessment Model

Manholes are another asset found in sewer systems; they are assumed to be vertical pipelines. Therefore, due to ageing, they are susceptible to deterioration. Nevertheless, a manhole is composed of several components in which one could be more important than another. Indeed, several defects found in a typical pipeline can be observed in manholes. In spite of its significant contribution to the sewer system, minimal attention has been given to manhole condition assessment as per the reviewed literature.

Consequently, this study develops a manhole condition assessment model, based on components and defects, that produces a condition index for manholes in order to plan for maintenance and/or rehabilitation. Figure 3.3 displays the process of the developed model. The first step in this model is to filter the twenty-two defects according to their possible availability in each component. For example, for the cover, frame and pavement components, protruding services is not considered as a defect, unlike cone and wall components.

After filtering the defects for each manhole component, each of them had its own QFD model; in total, nine models corresponding to nine components are designed. The influence matrix of each HOQ is relevant to the defects involved in each, and the values are acquired from the twenty-two average matrices analyzed previously. For example, a component in a manhole that has a deformation as a defect will share similar average influence values of the deformation in the pipeline, taking into account the other defects. It is worth mentioning that a longitudinal crack and a longitudinal fracture in a pipeline is considered as a vertical crack and a vertical fracture, respectively. Similarly, a circumferential crack and a circumferential fracture in a pipeline is expressed as a horizontal crack and a horizontal fracture, respectively.

Therefore, in order to compute the overall grade of any component of a manhole, one can use the following equation:

$$\text{Overall Component Grade } (G_{CM}) = \sum_{1}^{5} RW_i * i \qquad [3.2]$$

where

RW is the relative weight of each grade found; and

i is the weight of each condition severity. For example, Excellent is 1, Good is 2, Fair is 3, Poor is 4 and Critical is 5.

The next step is to send a questionnaire to sewer experts to compare the manhole components investigated in the study. Such a step was achieved by a pairwise comparison completed by the participants. Each participant's response is analyzed to bring forth the relative importance weights based on the ANP application, and to amalgamate the severities' percentages of all components into manhole severity percentages as indicated in Figure 3.4. The relative weights of the conditions are then computed and the final overall grade is found according to equation 3.3.

Overall Manhole Grade = $\sum_{1}^{9} CW_i * G_{CMi}$ [3.3]

where

CW is the relative component weight computed by ANP method; and

G_{CM} is the overall grade of each component.

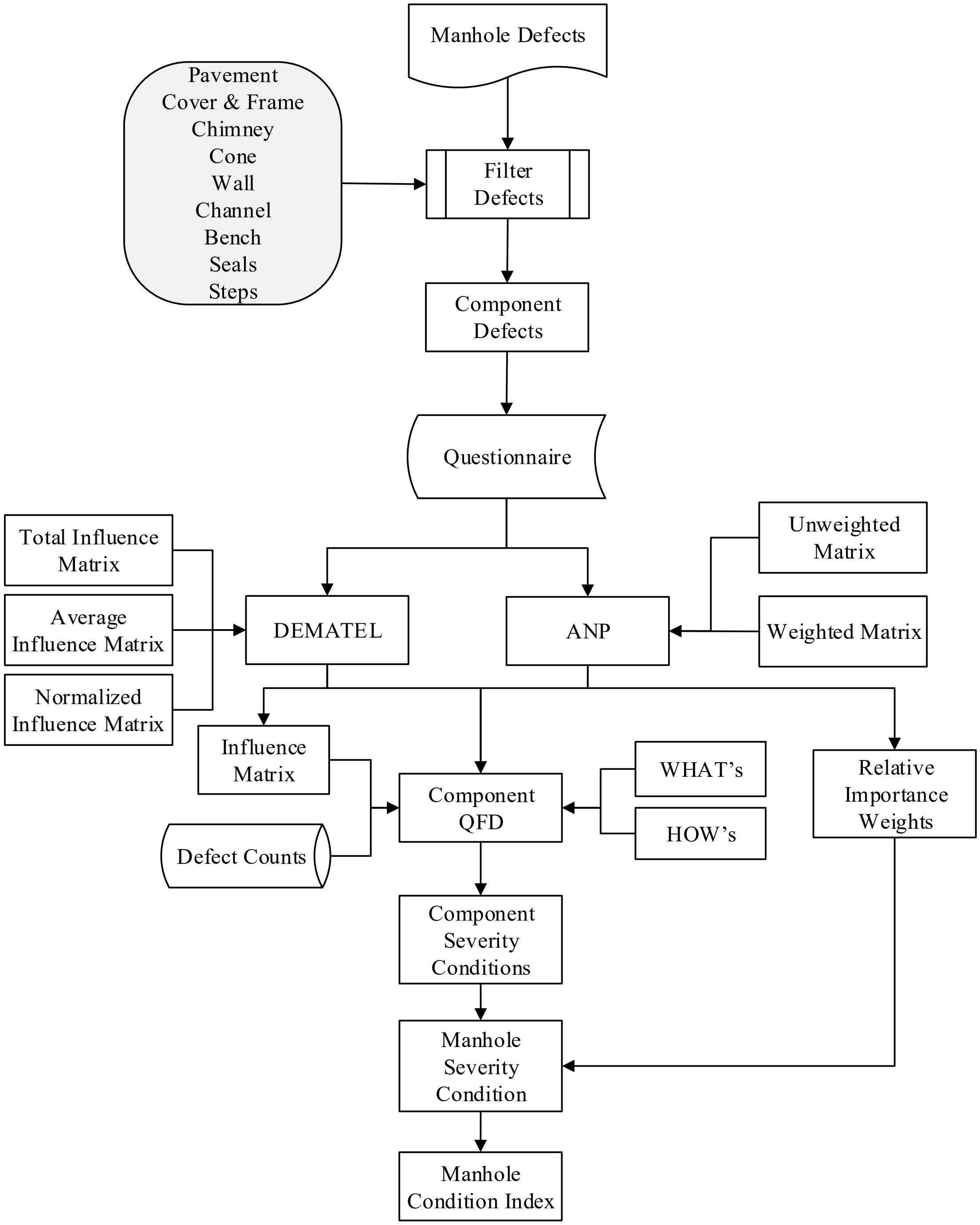


Figure 3.3 Manhole Condition Assessment Model

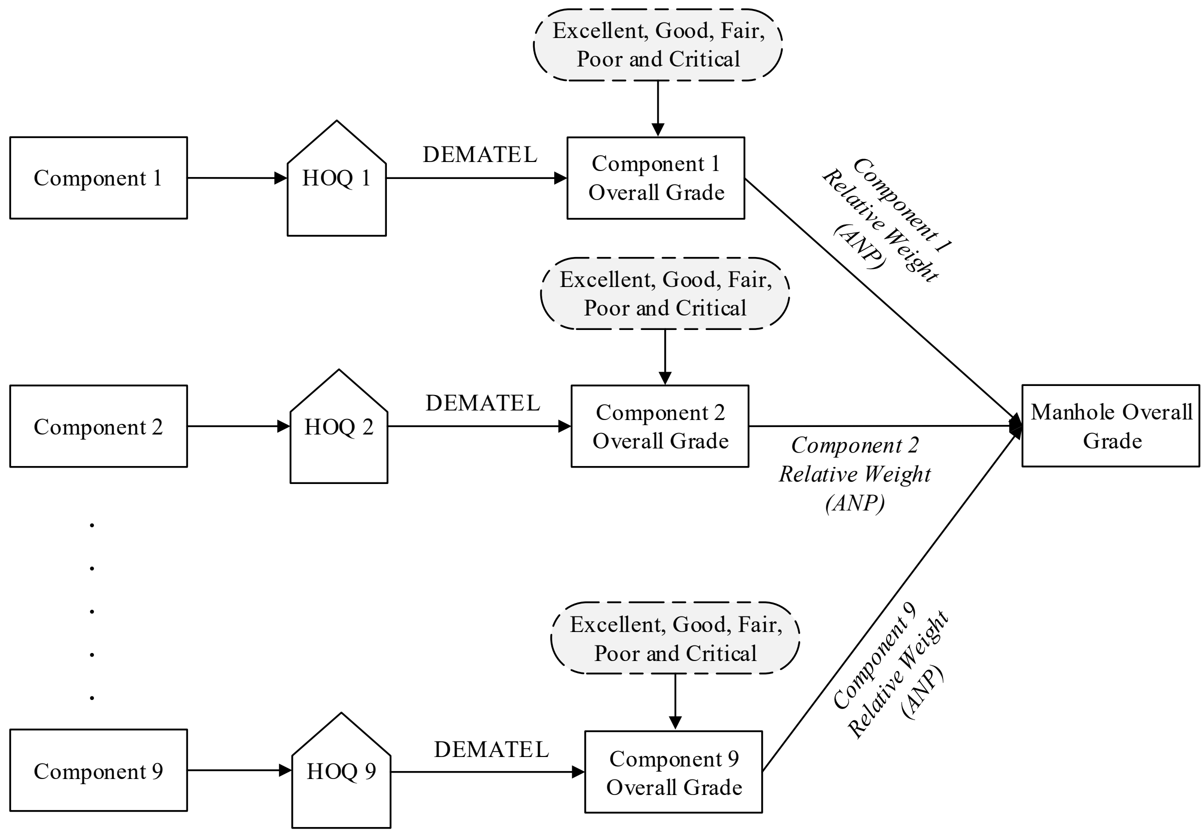


Figure 3.4 Manhole Components Aggregation Process

3.6.1 Sewer Manhole Components

Manholes are important assets in sewer systems; yet, their conditions are mostly ignored. When the researcher demanded condition ratings for sewer manholes, multiple cities did not have records for manhole assessment. As a result, this research aims to develop a comprehensive manhole assessment by decomposing manholes into multiple components. The components that are assumed to affect the condition of manholes are: pavement, cover and frame, chimney, cone, wall, channel, bench, seals and steps. These components are illustrated in Figure 3.5. This study assumes several defects in each component, depending on its location and the nature of the defects.

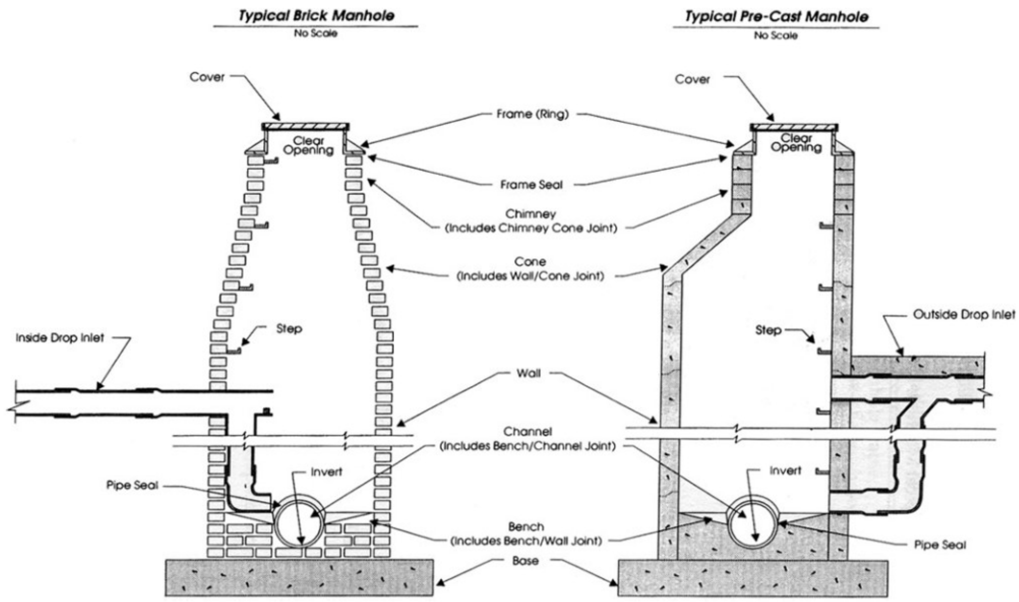


Figure 3.5 Manhole Components (Hughes 2009)

a) Pavement

Pavement is the part of the rigid or flexible pavement that surrounds the manhole cover. It is considered in the manhole assessment because damaged pavements surrounding the asset can expose other components, causing them to degrade. According to Hughes (2009), signs of voids outside the manhole structure, which can affect the manhole wall strength, can be triggered from observations of alligator cracking in asphaltic concrete, and spalling, cracking, or tipping in pavements. Therefore, the defects pertinent to pavements are based on the damaged part of the pavement.

b) Cover and Frame

The cover is the lid that provides access to the interior of the manhole, and the frame is the cast or ductile ring that supports the cover (Hughes 2009). Defects identified for these components are cracks, breaks, grades, corrosion and inflow.

c) Chimney, Cone and Wall

The chimney is the narrow vertical part built from either brick or concrete materials with adjusting rings that extend from the top of the cone to the frame and cover (Hughes 2009). The cone is the reduced section that tapers concentrically or eccentrically from the top wall joint to the chimney or from the frame and cover (Hughes 2009). The wall is the vertical barrel portion extending just above the bench joint to the cone (Hughes 2009). Defects pertinent to these components are vertical cracks, horizontal cracks, vertical fractures, horizontal fractures, deformation, holes, breaks, collapse, surface damage, roots, I/I, obstruction, attached deposits and protruding services.

d) Seals

Seals are materials or devices that prevent the intrusion of water at the joints of multiple components (Hughes 2009). Defects pertinent to seals are I/I, cracks and roots.

e) Bench

The bench is the concrete or brick floor of the manhole, generally shaped as a fillet to direct incoming flows to the outlet pipeline and minimize the accumulation of deposits (Hughes 2009). Defects pertinent to the bench component are vertical cracks and fractures, horizontal cracks and fractures, holes, breaks, collapse, surface damage, settled deposits, roots and I/I.

f) Channel

The channel is the flow-shaped way within the bench (Hughes 2009). Defects pertinent to the channel component are vertical cracks and fractures, horizontal cracks and fractures, multiple cracks and fractures, holes, breaks, collapse, surface damage, settled deposits, roots, obstruction and I/I.

g) Steps

The steps are composed of a ladder made of separated parts that are fixed to multiple components in the manhole. Steps allow inspectors to move in and out. Defects pertinent to the steps component are related to corrosion, missing and/or broken individual steps.

3.6.2 Sewer Manhole Defects and Deduct Values

This study assumes several defects in each component depending on its location and the nature of the defects, as shown in Table 3.8. In total eighteen defects are identified and filtered based on the component. According to the table, the pavement and steps each have one defect. The chimney, cone and wall share the same defects. Attached deposits are expected to emerge in components above the bench. However, settled deposits are expected to accumulate in the bench and the channel.

Table 3.8 Manhole Component Defects

Defect	Manhole Component								
	Pavement	Cover and Frame	Chimney	Cone	Wall	Seals	Bench	Channel	Steps
Damaged Pavement	●								
Crack (Vertical & Horizontal)		●	●	●	●	●	●	●	
Fractures (Vertical & Horizontal)			●	●	●		●	●	
Break		●	●	●	●		●	●	
Grade		●							

Surface Damage including corrosion	●	●	●	●		●	●	
I/I	●	●	●	●	●	●	●	
Deformation		●	●	●				
Obstruction		●	●	●			●	
Roots		●	●	●	●	●	●	
Attached Deposits		●	●	●				
Collapse		●	●	●		●	●	
Hole		●	●	●		●	●	
Protruding Service		●	●	●				
Settled Deposits						●	●	
Multiple Crack							●	
Multiple Fractures							●	
Damaged, Corroded, Missing Steps								●

Each of these defects have specific deduct values that are collected from the literature (Hughes, 2009; Nelson et al., 2010) and range between 1 and 5, where 1 is excellent and 5 is critical. These values explain the severities of the defect as displayed in Table 3.9. For example, a component with a deformation of more than 15% is critical and will have a deduct value of 5. Nevertheless, a deformation lower than 2.5% is considered as excellent, with a value of 1 is assigned.

Table 3.9 Manhole Defects' Deduct Values

Defect	Description	Defect Criteria	Deduct Value
Damaged Pavement	Damaged parts of the flexible and rigid pavements surrounding the	Pavement damage <= 25% of cover circumference	2
		Damage >25% and	3

	manhole cover	<=75%	
		Damage >75%	4
Crack	Any crack lines that are observed in the components. The severity is expressed by the number of cracks recorded	1	1
		2	2
		3	3
		4	4
		>5	5
Break	Any broken parts of the component, expressed as a percentage of material loss compared to the actual material area	>0 and <=2.5%	1
		>0 and <=5%	2
		>5% and <=10%	3
		>10% <=25%	4
		>25%	5
Grade	The location of the cover; whether it is above, below or on grade	On grade	1
		below or above	5
Corrosion	Any corrosion material observed. Expressed by the corrosion surface area	>0 and <=2.5%	1
		>0 and <=5%	2
		>5% and <=10%	3
		>10% <=25%	4
		>25%	5
I/I	The inflow of water to the manhole asset through any component	0 and <= 0.757 l/m	1
		>0.757 l/m and <=1.514 l/m	2
		>1.514 l/m and <=3.028 l/m	3
		>3.028 l/m and <=6.057 l/m	4
		>6.057 l/m	5
Deformation	When the cross section of the	Deformation < 2.5%	1
		2.5% and < 5%	2

	component is altered horizontally or vertically	5 and <7.5%	3
		7.5 and <15%	4
		>= 15%	5
Surface Damage	Surface is changed from its original condition (loss of wall thickness)	Aggregate visible, cracked mortar	2
		Chipped , wall loss < 10%,eroded mortar	3
		>=10% to <20%, missing brick, missing mortar	4
		>=20%, missing brick	5
Roots	Ingress of roots through defects	<=25% of component	3
		>25% to <=50% of component	4
		>50% of component	5
Attached Deposits	Foreign materials that are attached to the component and continue to accumulate	0-5%	1
		<5-10%	2
		<10-20%	3
		<20-30%	4
		>30%	5
Collapse	Collapse of a component	Collapsed	5
Hole	Visible hole in the component	<=5% of component	1
		>5% and <= 8.33% of component	2
		>8.33% and >= 16.6667 %	3
		>16.667% and <=25%	4
		>25% of component	5

Obstruction	Objects that block parts of the component	0-5%	1
		<5-10%	2
		<10-20%	3
		<20-30%	4
		>30%	5
Protruding Service	Objects that have been inserted after construction	0-5%	1
		<5-10%	2
		<10-20%	3
		<20-30%	4
		>30%	5
Vertical Crack	Crack line is apparent but not open, running along the manhole's axis	Length <75 mm	1
		75-150 mm	2
		>150-225 mm	3
		>225 - 300 mm	4
		>300 mm	5
Horizontal Crack	Crack line is apparent but not open, running at right angles to the axis of the manhole	Length <75 mm	1
		75-150 mm	2
		>150-225 mm	3
		>225 - 300 mm	4
		>300 mm	5
Vertical Fracture	An open crack running along the manhole axis	Length <75 mm	1
		75-150 mm	2
		>150-225 mm	3
		>225 - 300 mm	4
		>300 mm	5
Horizontal Fracture	An open crack running at right angles to the axis of the manhole	Length <75 mm	1
		75-150 mm	2
		>150-225 mm	3
		>225 - 300 mm	4

		>300 mm	5
Settled Deposits	Materials settled on the component	0-5%	1
		<5-10%	2
		<10-20%	3
		<20-30%	4
		>30%	5
Multiple Crack	Combination of vertical and horizontal cracks	Length <75 mm	1
		75-150 mm	2
		>150-225 mm	3
		>225 - 300 mm	4
		>300 mm	5
Multiple Fractures	Combination of vertical and horizontal fractures	Length <75 mm	1
		75-150 mm	2
		>150-225 mm	3
		>225 - 300 mm	4
		>300 mm	5

3.6.3 Manhole Overall Grade

After calculating the grade of each component the overall manhole grade can be interpreted according to Table 3.10. Five different conditions are described in the table, along with their corresponding overall grades. An excellent condition describes a defect-free manhole. At the other extreme, a condition between 4 and 5 could result in collapse.

Table 3.10 Proposed Manhole Overall Grades, Conditions and Descriptions

Overall Grade	Condition	Description
1.00 to <1.50	Excellent	No defects
1.50 to < 2.00	Good	Minor defects are observed with small to medium severities
2.00 to < 3.00	Fair	Moderate defects with medium severity

3.00 to <4.00	Poor	Major defects with medium to high severity
4.00 to 5.00	Critical	Severe defects are observed. Manhole/component collapses or collapse is imminent.

3.7 DEMATEL

DEMATEL is utilized to determine the influence power of each defect in a system. The backbone of this approach is to design a questionnaire and send it to experts in the field. To accomplish the DEMATEL approach and ease its integration with the QFD, several steps need to be applied (Shieh et al. 2010 and Tzeng et al. 2007):

1- Find the average matrix. The average matrix is calculated from the questionnaire responses to evaluate the direct and indirect influence between any two participating elements; herein, the defects in the system. The influence is represented by certain values which are tabulated in Table 3.11 along with their definitions. The lower the number, lower the influence and vice versa.

Table 3.11 DEMATEL Influence Values and Definitions

Influence Number	Definition
0	No Influence
1	Low Influence
2	Medium Influence
3	High Influence
4	Extreme Influence

The degree to which the respondents believe that factor *i* is affected by factor *j* is given by the notation x_{ij}. For example, if an expert assigns a value of 3 when comparing the influence of deformation to that of longitudinal crack, this means that deformation has a high influence in initiating the crack. However, for $i = j$, which are the diagonal values in a matrix, the values are set to zero. For each respondent, an $n \times n$ non-negative matrix can be established as $X^k = [x^k_{ij}]$ where k is the number of participating respondents with $1 \leq k \leq H$, and n is the number of factors. As a result, $X^1, X^2, \ldots, X^H$ are the number of matrices found from each respondent. Therefore, the values of each x_{ij} in each matrix is computed through the average, as per equation 3.4.

$$a_{ij} = \frac{1}{H}\sum_{k=1}^{H} x_{ij}^{k} \qquad [3.4]$$

The average matrix is displayed in the HOQ as the top roof triangle, which is originally the correlation matrix. Figure 3.6 shows the average influence matrix of a system comprised of four elements. Taking elements 2 and 3 as an illustration, a_{23} is the influence of element 2 on factor 3, and a_{32} is the influence of element 3 on factor 2. In fact, the zeros in the triangle are the diagonal values of the matrix, which are always zero.

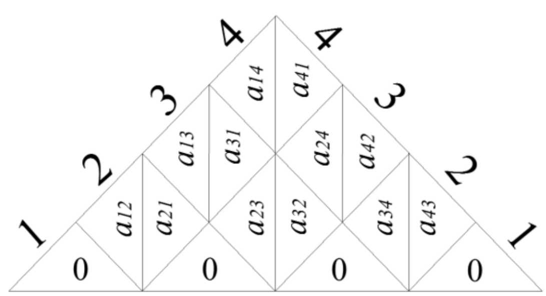


Figure 3.6 Relationship Matrix in HOQ

2- Calculate the normalized direct influence relation matrix D from the average matrix found in step 1 and according to equation 3.5. The first step is to identify the maximum value from summing the a_{ij} values in the rows and in the columns. The maximum value will be used to compute matrix D.

$$S = \frac{1}{\underset{1 \leq i \leq n}{Max} \sum_{j=1}^{n} a_{ij}} \quad [3.5]$$

3- Calculate the total relation influence matrix. The total relation influence matrix T is calculated by equation 3.6.

$$T = D\,(I - D)^{-1} \quad [3.6]$$

where I is the identity matrix. Define r and c as $n \times 1$ and $1 \times n$ vectors representing the sum of the rows and the sum of the columns of the total relation matrix T, respectively. Consider r_i as the sum of the ith row in matrix T, then r_i concludes both the direct and indirect effects given by factor i to the other factors. If c_j denotes the sum of the jth column in matrix T, then c_j shows both the direct and indirect effects of factor j on the other factors. When $j = i$, the sum $(r_i + c_j)$ shows the total effects given and received by factor u. In other words, it represents the total cause and effect relation in the whole system. However, the difference $(r_i – c_j)$ translates the net effect that factor i contributes to the system. If the value computed is positive, then the factor is a cause. On the other hand, if the calculated value is negative, then the factor is an effect.

4- Consider setting up a threshold to filter out negligible effects. Nevertheless, in this research, setting up a threshold will not be considered as all participating elements are assumed to be significant in assessing the condition of the sewer assets.

3.8 Analytic Network Process (ANP)

The ANP is one of the decision-making processes that is based on a pairwise comparison between elements in any system. This approach is utilized for the manhole condition assessment. The ANP is employed to conclude the relative importance of one component compared with that of another and with respect to a certain criteria.

1- The process is accomplished by designing a tailored questionnaire. The questionnaire shall raise a question to the participant as follows (Tzeng and Huang 2011):

   "How much importance does a criterion have compared to another criterion, with respect to another criteria?" As an example, the question for the study would be "How much importance does a bench have compared to steps, with respect to the cover and frame?"

The relative importance values that an expert selects are odd number from 1 to 9, ranging from "equal importance" to "extreme importance". The complete relative importance values and definitions can be found in Table 2.3.

2- The questionnaire is significant in forming the supermatrix, which has the following general form

$$
W = \begin{array}{cc}
 & \begin{array}{cccc} C_1 & C_2 & \cdots & C_m \\ e_{11} \cdots e_{1n_1} & e_{21} \cdots e_{2n_2} & \cdots & e_{m1} \cdots e_{mn_m} \end{array} \\
\begin{array}{cc}
C_1 & \begin{array}{c} e_{11} \\ e_{12} \\ \vdots \\ e_{1n_1} \end{array} \\
C_2 & \begin{array}{c} e_{21} \\ e_{22} \\ \vdots \\ e_{2n_2} \end{array} \\
\vdots & \vdots \\
C_m & \begin{array}{c} e_{m1} \\ e_{m2} \\ \vdots \\ e_{mn_m} \end{array}
\end{array}
& \begin{bmatrix}
W_{11} & W_{12} & \cdots & W_{1m} \\
W_{21} & W_{22} & \cdots & W_{2m} \\
\vdots & \vdots & \vdots & \vdots \\
W_{m1} & W_{m2} & \cdots & W_{mm}
\end{bmatrix}
\end{array}
$$

where C_m denotes the mth cluster, e_{mn} represents the nth element in the mth cluster and Wij is the principal eigenvector of the influence of the elements compared in the jth cluster to the ith cluster. It is worth noting that if the jth cluster has no influence on the ith cluster, then Wij shall be equal to zero (Tzeng and Huang 2011).

3- The third step is forming the weighted supermatrix by transforming all columned sums to unity exactly. This step is similar to the concept of Markov chains for ensuring that the sum of these probabilities of states is equal to one. Later, the weighted supermatrix is raised to limiting powers to obtain the global priority vectors or the relative importance weights (Tzeng and Huang 2011).

In this study, the Superdecisions software was adopted in the calculation of the relative importance weights after feeding the software with the responses from the experts.

3.9 Fuzzy Set Theory

Fuzzy set theory is utilized to minimize uncertainty in the assessment of the erosion void. After reviewing the literature and considering the unanimity decision-making process, five different parameters in the erosion void model were considered to affect the severity of the erosion void defect. These five factors are the bedding class, pipeline age, soil type, groundwater table presence and the pipeline depth. Triangular membership functions are established to translate the linguistic definitions, where applicable. Since the output of the developed model is in the form of a membership function, a defuzzification method, the weighted average method, is used to convert the fuzzy membership functions into a crisp value. The crisp value obtained from the aggregation of all the parameters is evaluated on an overall scale to include it in the HOQ of the pipeline.

3.10 Sewer Component Deterioration Models

This research proposes an evaluation scheme for sewer pipelines and manholes utilizing the DEMATEL and QFD for sewer pipelines and the DEMATEL, QFD and ANP for sewer manholes. Each model supplies an index that suggests the performance or condition of the asset. The index of each asset is then used to plot the deterioration curve which estimates its deterioration through its service life and finally determining the remaining service life of the asset. In this research, the deterioration model developed by Semaan (2011) has been adopted to construct the deterioration curves as per Figure 3.7. According to the author, there are three main curves to be constructed to form the deterioration curves: the ideal deterioration curve, the updated deterioration curve and the predicted deterioration curve. Each has a specific application as will be demonstrated in the next sub-sections.

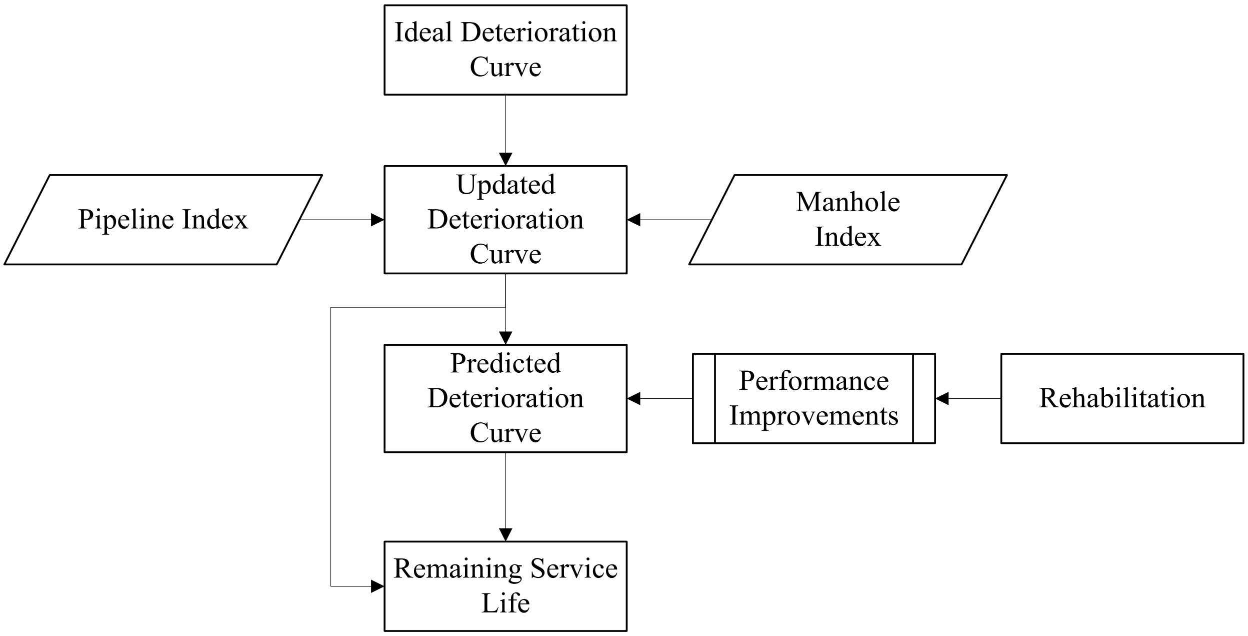


Figure 3.7 Asset Deterioration Curve Formulation Process

3.10.1 Ideal Deterioration Curve (IDC)

According to Semaan (2011), the ideal deterioration curve is constructed to overcome the difficulty in estimating the Weibull distribution factors. The reliability function starts at the maximum performance level and stays constant for a certain period of time, where the slope is equal to zero. In practice, once the asset is constructed, the asset functions properly and in excellent condition before the condition starts to deteriorate. After some time, the condition starts to deteriorate and so its reliability diminishes, which forms a negative slope. The actual scenario of the asset's deterioration can be modelled using the Weibull distribution analysis.

According to the literature review, the Weibull probability distribution function is defined as the following:

$$f(t) = \frac{\delta}{\tau}\left(\frac{t-\alpha}{\tau}\right)^{\delta-1} * e^{-\left(\frac{t-\alpha}{\tau}\right)^{\delta}} \qquad \text{for } t > \alpha \qquad [3.7]$$

where

α	is the location factor,
τ	is the scale factor,
δ	is the shape factor, and
t	is the time.

The cumulative Weibull distribution function (cdf) is described as in equation 3.8

$$F(t) = 1 - e^{-(\frac{t-\alpha}{\tau})^{\delta}} \quad [3.8]$$

So, the reliability function can be described according to equation 3.9:

$$R(t) = 1 - F(t) = e^{-(\frac{t-\alpha}{\tau})^{\delta}} \quad [3.9]$$

The Ideal Deteriroation Curve (IDC) can be described according to equation 3.10, which shares a similar shape to that of the previous equation.

$$IDC\ (t) = \alpha * e^{-(\frac{t}{\tau})^{\delta}} \quad [3.10]$$

Certain conditions are applied to construct the IDC curve (Semaan 2011):

- At time zero, the slope of the curve is zero as per the following:

$$\frac{\partial({P_I}^{IDC})}{\partial t} = {P_I}^{IDC\prime}\ (t) = 0$$

- The ideal service life of sewer pipelines and manholes is 75 years;
- The lowest performance is 0.2 (1/5);
- At $t = 0$, the reliability of the asset shall be 1.00 (excellent condition); as a result,

$$IDC\ (0) = \alpha * e^{-(0/\tau)^{\delta}} = \alpha \qquad [3.11]$$

Therefore, α = 1.00; and

- At t = 75 years, the reliability of the asset is equal to the lowest performance which is 0.2.

Therefore,

$0.20 = 1 * e^{-(75/\tau)^{\delta}}$, then

$$\tau = \frac{75}{\sqrt[\delta]{-\ln(0.2)}} \qquad [3.12]$$

The shape factor shall be greater than 1. The optimum value of δ is equal to 3, as other integers do not supply a desired deterioration curve. Considering $\delta = 3$,

$\tau = \frac{75}{\sqrt[3]{-\ln(0.2)}}$ $\tau = 64.00$

Thus, the Condition Index for Pipelines at time t (*CI_P*) is described as in equation 3.13

$$CI\_P\_IDC\ (t) = 1 * e^{-(\frac{t}{64.00})^{3}} \qquad [3.13]$$

and the Condition Index for Manholes at time t (*CI_M*) is described as in equation 3.14

$$CI\_M\_IDC\ (t)\ (Ideal) = 1 * e^{-(\frac{t}{64.00})^{3}} \qquad [3.14]$$

By using any of the two condition index equations, Figure 3.8 is plotted and thus displays the ideal deterioration of any of the two assets. When an asset is constructed, it will be in excellent condition. After 75 years, it will reach the critical condition.

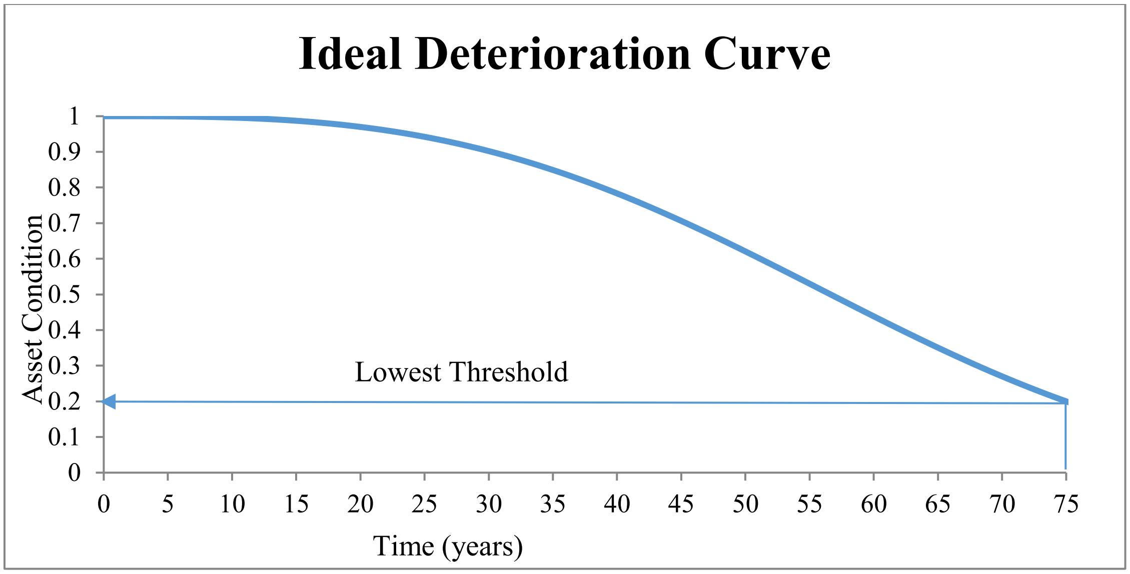


Figure 3.8 Ideal Deterioration Curve

3.10.2 Updated Deterioration Curve (UDC)

According to Semaan (2011), the IDC is constructed to understand the ideal deterioration of assets. However, not all inspected assets share similar deterioration curves and therefore, the deterioration curve shall be updated; herein called the Updated Deterioration Curve (UDC). The distribution is modified considering an input value (condition), which is used to plot the curve. Therefore, an updated service life is concluded.

The UDC for each asset can be calculated as follows

$$CI\_P\_UDC(t) = 1 * e^{\ln(CI\_P_i)(\frac{t}{t_i})^3} \qquad [3.15]$$

$$CI\_M\_UDC(t) = 1 * e^{\ln(CI\_M_i)(\frac{t}{t_i})^3} \qquad [3.16]$$

where *CI_P_UDC* is the updated condition index of the pipeline at any time t_i, *CI_M_UDC* is the updated condition index of the manhole at any time t, CI_P_i and CI_M_i are the condition indexes at any time t_i of both the pipeline and manhole, respectively. Considering the aforementioned equations, the UDC can be plotted for any asset. Figure 3.9 illustrates the UDC and the IDC of any asset. In this example, the asset is underperforming, as the updated curve is below that of the IDC.

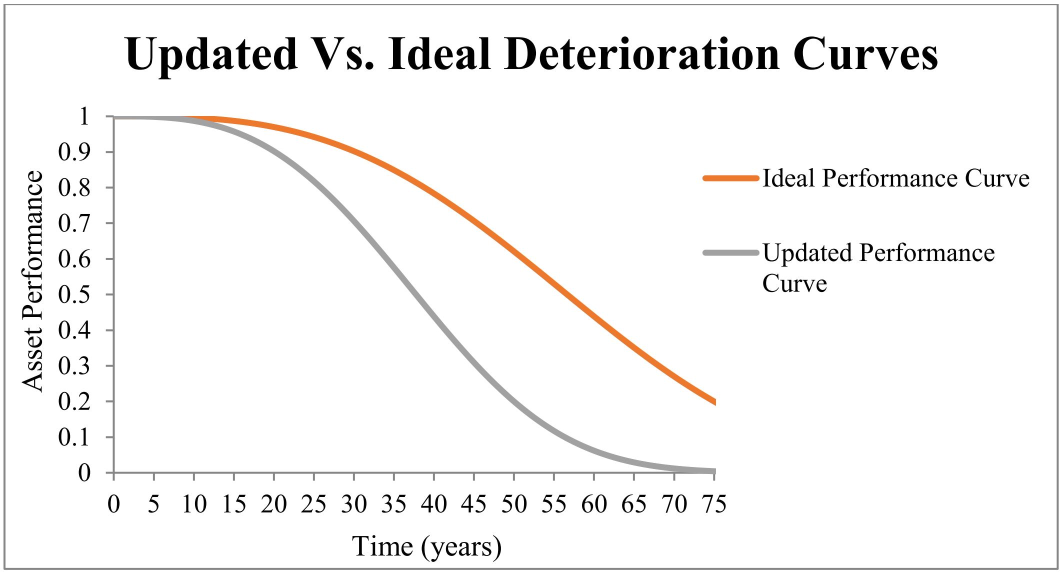


Figure 3.9 UDC vs. IDC

3.10.3 Predicted Deterioration Curves (PDC)

The last deterioration curve constructed is the Predicted Deterioration Curve (PDC) (Semaan 2011). Since assets are subject to deterioration over time, municipalities are required to allocate budgets for maintenance and rehabilitation at a specific time (t_m). These actions, once implemented, enhance the condition and the performance of the asset.

After rehabilitation, the curve can be modelled as follows (Semaan 2011):

$$CI\_P\_PDC\ (t) = CI\_P_M * e^{\ln(CI\_P_{M_i}) * (\frac{t-t_m+1}{t_i})^3} \quad [3.17]$$

$$CI\_M\_PDC\ (t) = CI\_M_M * e^{\ln(CI\_M_{M_i}) * (\frac{t-t_m+1}{t_i})^3} \quad [3.18]$$

where t_m is the time of M&R action, *CI_P_PDC (t)* is the condition of the pipeline after M&R at time t_i, and *CI_M_PDC (t)* is the condition of the manhole after M&R at time t_i. CI_P_M is the condition of the pipeline directly before M&R and CI_M_M is the condition of the manhole directly before the M&R. Subsequently, the IDC, UDC and PDC can be plotted and represented as follows. As per Figure 3.10, once the M&R actions are conducted, a spike in the asset condition is observed. The enhanced performance extends the service life of the asset.

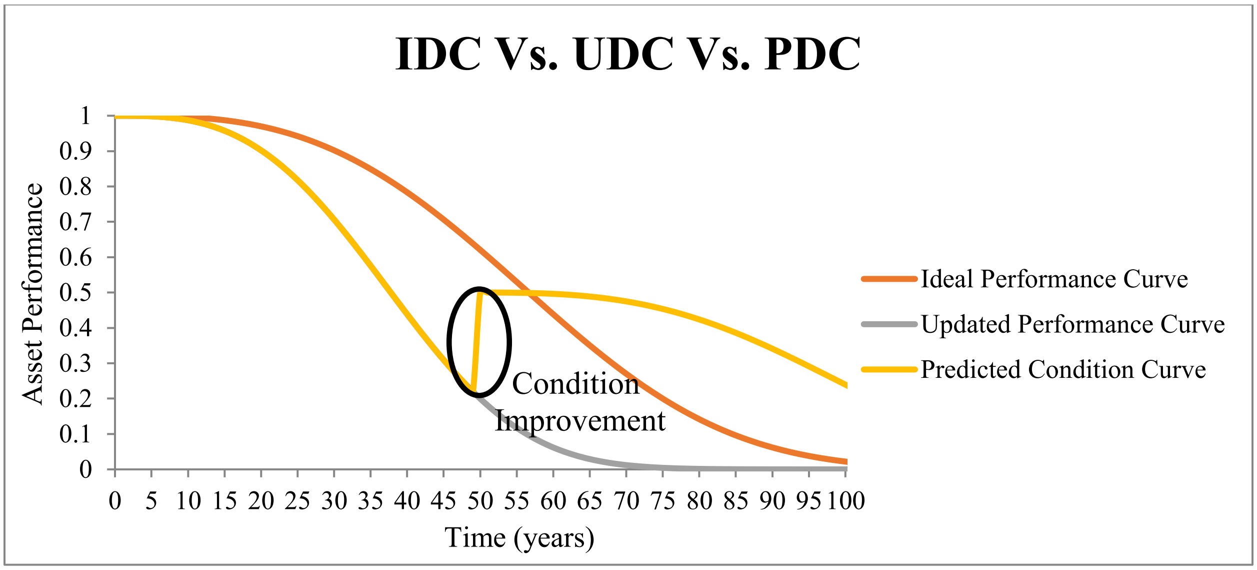


Figure 3.10 IDC vs. UDC vs. PDC

3.11 Sewer Network Performance

As illustrated earlier, the overall sewer network performance is calculated considering the relative importance weights of pipelines and manholes. This is accomplished through a criticality study for manholes and pipelines in the sewer network. Since several studies (Gallay et al. 2006, Borchardt et al. 2007, Hunt et al. 2010, Vroblesky et al. 2011, Verlicchi et al. 2012, Bradbury et al. 2013, and Meffe and de Bustamante 2014) have shown that defective sewer pipelines may cause severe environmental, public and economic impacts, the sewer network overall condition computation relies on the criticality of each asset, as shown in Figure 3.11.

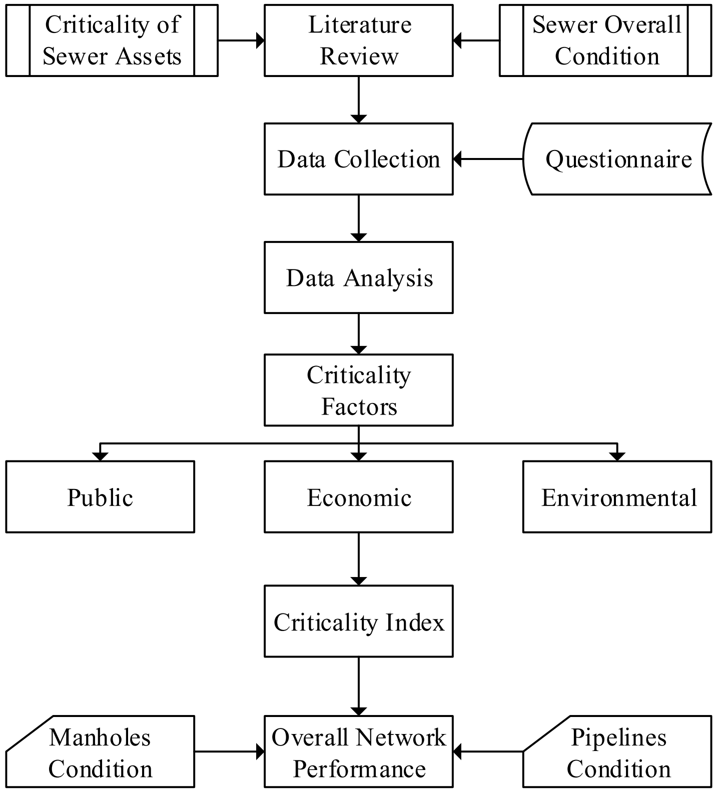


Figure 3.11 Sewer Network Performance Model

In this research, the criticality of an asset is defined according to Miles et al. (2007), who expressed it as the consequence of failure. Therefore, several factors are identified which could impact the economic, environmental and public contributions. Figure 3.12 and Figure 3.13 illustrate the factors and sub-factors considered for pipelines and manholes, respectively. Each factor is comprised of several sub-factors that could differentiate the criticality of one asset to another. The consideration of the criticality factors is highly dependent on the applicability of each. For example, the number of inlets is applicable to manholes but not to pipelines. As a result, three and five sub-factors are identified for both assets under the environmental and economic factors, respectively. However, seven sub-factors are considered for pipelines and six for manholes under the public factor.

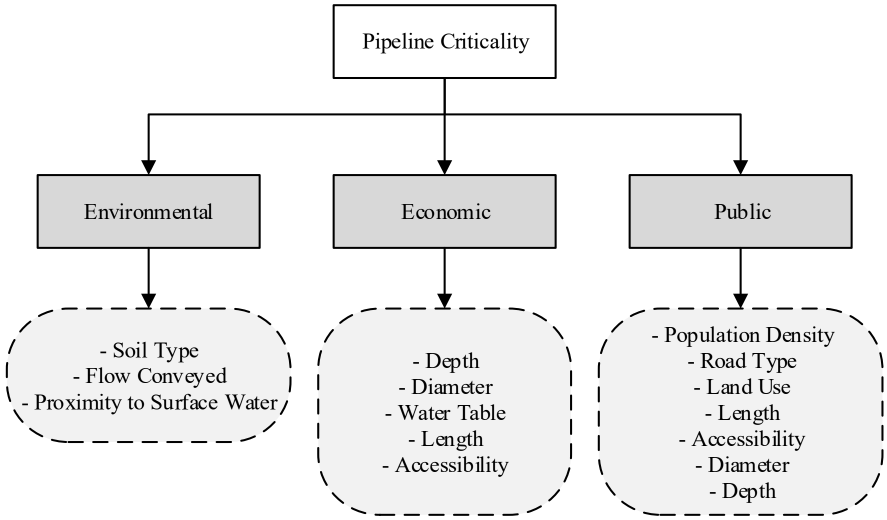


Figure 3.12 Sewer Pipeline Criticality Factors and Sub-factors

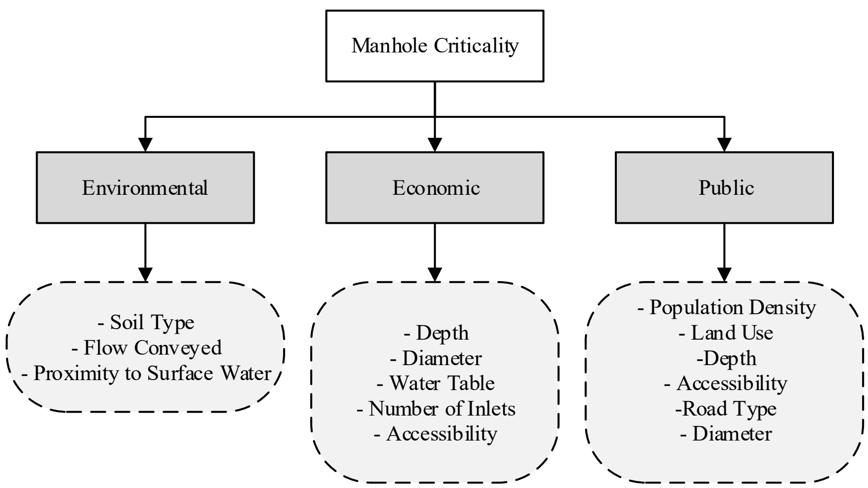


Figure 3.13 Sewer Manhole Criticality Factors and Sub-factors

Each sub-factor from the list is evaluated based on certain attribute values. The attribute values are collected from the literature and standards bodies. The attribute values range between 1 and 5, where 1 corresponds to noncritical and 5 is extreme.

3.11.1 Criticality Factors/Sub-Factors

a) Environmental Factors

These are factors that are related to the environmental consequences if assets fail. They are categorized into three different sub-factors for both pipelines and manholes.

1) Soil Type

Soil forms an envelope to the asset as it surrounds pipelines. Soil types range between fine aggregate to coarse aggregate. The finer the particle, the easier the exfiltration and vice versa. Therefore, the most critical case is when particles are the finest as they will expedite the exfiltration flow to the surroundings. Soil types are categorized and assigned their criticality values as shown in Table 3.12. Gravel soil type is Excellent while finer soils like clay and silt are worse types.

Table 3.12 Soil Type Criticality

Factor	Type	Criticality Value
Soil Type	Gravel	1
	Course Sand	2
	Fine Sand	3
	Fine Sand and Silt	4
	Clay	5

2) Flow Conveyed

The flow conveyed is determined according to the location of the pipeline or manhole from the upstream asset. The upstream asset in not as critical as the downstream asset. Any failure in the downstream asset will exfiltrate more sewer medium to the surroundings due to more flow transfer. Hence, it will increase the chance of having more significant environmental impacts upon failure. The determination of the flow conveyed factor is based on the flow direction in the network and the accumulation of the flow. The accumulation of the flow varies according to the contribution of each pipeline. The factor of each pipeline is determined according to the maximum accumulated flow. Therefore, the accumulation flow factor is determined according to equation 3.19.

$$Accumalation\ Flow\ Factor\ = \frac{flow\ conveyed}{Maximum\ Accumaltion} \qquad [3.19]$$

As an illustration, the simple network in Figure 3.14 is comprised of five pipelines and three manholes. Each pipeline will contribute to the flow by a factor of 1, assuming equal flow for each pipeline. Therefore, the accumulation flow factor may differ from one asset to another. For example, P1 will contribute by 1 to the network, and P2 will contribute the accumulation flow from P1 and from P2 itself. Based on this approach, Table 3.13 was prepared to find the accumulated flow factors for each asset.

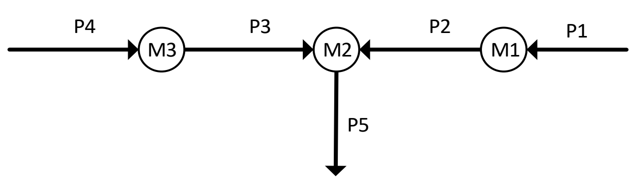


Figure 3.14 Flow Conveyed Sample

Table 3.13 Sample of Flow Conveyed Calculation

Asset	Accumulated Factor
P1	1
M1	Flow of P1 = 1
P2	Flow of P1 + P2 = 1 + 1 = 2
P4	1

P3	Flow of P3 + P4 = 1 + 1 = 2
M2	Flow of P1 +P2 + P3 + P4 = 4
P5	Flow of P1 + P2 + P3 + P4 + P5 = 5

Accordingly, since the final downstream asset will transfer all the flow received from all other assets in the network, it will be the most critical asset. Any failure in this asset will have the highest exfiltration flow compared to the other assets and hence will impact the surrounding environment. Based on this concept, five different ranges have been prepared, as shown on Table 3.14. The most critical asset will have a factor of 1.

Table 3.14 Flow Conveyed Criticality

Factor	Accumulated Flow Factor	Criticality Value
Flow Conveyed	<0.2	1
	0.2- <0.4	2
	0.4- <0.6	3
	0.6- <0.8	4
	0.8-1	5

3) Proximity to Surface Water

Any sewer exfiltration will have a negative impact on the surrounding environment. City inspectors have a higher likelihood of locating sewer overflows on land than in surface water. A sewer pipeline could cause severe consequences for the surface water as it may impact the water quality and hence the water habitats. Therefore, the nearer the asset is to surface water, the more critical the situation. The criticality is assessed based on the closest distance of the sewer asset to the surrounding surface water, as shown in Table 3.15.

Table 3.15 Proximity to Water Criticality

Factor	Accumulated Flow Factor	Criticality Value
Proximity	> = 450 m	1

to Surface Water	450 m – 215 m	2
	215 m – 120 m	3
	120 m – 45 m	4
	< = 45 m	5

b) Economic Factors

These are the factors that require financial resources once assets fail, such as repairs and costs. In this research five sub-factors are identified for both manholes and pipelines.

1) Depth

Sewer assets laid above bedding materials and surrounded by any ground soil type. Deeper assets require extensive excavation and hence are costly. Therefore, Table 3.16 is prepared for pipeline depths and Table 3.17 for manhole depths. The deeper the asset the more critical that asset compared to others.

Table 3.16 Pipeline Depth Criticality

Factor	Depth	Criticality Value
Pipeline Depth	< = 2	1
	2m to 3m	2
	<3m to 3.5 m	3
	<3.5m to 4m	4
	>4m	5

Table 3.17 Manhole Depth Criticality

Factor	Depth	Criticality Value
Manhole Depth	<= 2m	1
	2 to 5	2
	5 to 7	3
	7 to 10	4
	>=10	5

2) Diameter

Sewers' pipelines and manholes are constructed with various diameters. The decision to use a specific diameter is based on the flow that an asset is required to transfer. Bigger diameters require costlier repairs than smaller diameter assets. Abiding with this concept, bigger sizes are more critical than smaller sizes as per Table 3.18 (pipelines) and Table 3.19 (manholes).

Table 3.18 Pipeline Diameter Criticality

Factor	Diameter	Criticality Value
Pipeline Diameter	< = 300 mm	1
	300 mm to 450 mm	2
	<450 to 750	3
	<750 to 1200 mm	4
	>1200 mm	5

Table 3.19 Manhole Diameter Criticality

Factor	Diameter	Criticality Value
Manhole Diameter	< 1200 mm	1
	1200 – 1800 mm	2
	1800 – 2200 mm	3
	2200- 2800 mm	4
	> 2800 mm	5

3) Water Table

Sewer pipelines are buried underground; their laying process involves trenching, excavation, piling, backfilling, etc. In fact, sometimes, the underground water table may present and impact the installation process. Therefore, before the assets are laid, a dewatering process is required to ensure that the bottom of the excavation is in a proper state for the asset to be installed. In general, deeper sewer lines require a dewatering process (Swamee 2001), which will add to the cost and require additional financial resources. Therefore, if an asset is located below or surrounded by the groundwater table, a dewatering process is required; hence, it is more critical than that of an asset located above the groundwater table, as indicated in Table 3.20.

Table 3.20 Water Table Location Criticality

Factor	Diameter	Criticality Value
Water Table	Asset Above Water table	1
	Asset Below Water table	5

4) Length of Pipeline/Depth of Manhole

The assets are made of distinct materials that each have their own unit cost. The common practice in ordering an asset is per unit length. Therefore, the longer the asset, the higher the criticality value, as per Table 3.21.

Table 3.21 Pipeline Length Criticality

Factor	Diameter	Criticality Value
Pipeline Length	<30m	1
	30-75m	2
	<75-120m	3
	<120-150 m	4
	>150 m	5

5) Accessibility

Minimal access to failed assets could require additional resources for repair tasks. In addition, more time will be required to repair the damage. Inaccessible places include e confined areas where mega-machines cannot enter the construction site. As a result, inaccessible assets are more critical than accessible ones, as shown in Table 3.22.

Table 3.22 Accessibility Criticality

Factor	Diameter	Criticality Value
Accessibility	Accessible	1
	Moderate Accessibility	3
	Inaccessible	5

6) Number of Manhole Inlets

The number of manhole inlets depends on the number of pipelines connected to it. A higher number of inlets requires more sealing materials, time and costs. Therefore, the most critical case is when a manhole has more inlets than the others as per Table 3.23.

Table 3.23 Manhole Inlets Criticality

Factor	Number	Criticality Value
Number of Inlets	0	1
	1	2
	> 2	5

c) Public Factors

These are factors that could hinder the public or the community when failure situations occur, and include aspects such as public health, travel time, service interruption, disruption, etc. Several factors have been identified that could impact the public factor: population density, road type, land use, length, depth and accessibility.

1) Accessibility

Limited access to failed assets could impact repair tasks. According to the US Environmental Protection Agency (EPA) (2015), inaccessible areas could lead to increased impacts to the community. The agency also stated that longer repairs contribute to longer disruption. The criticality of this factor depends on the situation itself.

2) Population Density

The higher the population, the more critical the situation. When sewer assets fail, some sewer medium will be exposed to the public; therefore, it could impact public health. The higher the number of people residing in the area of a failed sewer asset, the greater the exposure to sewer medium and the greater the health impact. Therefore, the attributes are prepared in Table 3.24 based on different population linguistic criteria as High, Medium and Low.

Table 3.24 Population Density Criticality

Factor	Diameter	Attribute
Population Density	Low	1
	Medium	3
	High	5

3) Road Type

Sewer assets could be laid in different locations; in urban cities they are laid beneath roads. As a result, any failure in an asset could disturb the public as the travel time will increase. Therefore, city and municipalities need to manage the road loads by flagging to facilitate the flow of the traffic. Some road sections of will be closed due to rehabilitation tasks. The most critical situation is when an asset fails in a high capacity road, as per Table 3.25. In this research, the roads are categorized as local, collector, arterial, highway and freeway.

Table 3.25 Road Type Criticality

Factor	Diameter	Attribute
Road Type	Local	1
	Collector	2
	Arterial	3
	Highways	4
	Freeway	5

4) Land Use

The criticality of a failed sewer asset to the community differs in terms of the type of land used. For example, in an abandoned space, the criticality of a failed sewer asset is (much) lower compared to a failed sewer at an institutional location. Therefore, different criteria have been set to consider this type of social factor, as listed in Table 3.26. Based on the table, the most critical areas are when the assets fail in an institutional and health centers.

Table 3.26 Land Use Criticality

Factor	Diameter	Attribute
Land Use	Abandoned Space	1
	Agriculture	2
	Residential/Park	3
	Industrial	4
	Institutional and Health Centre	5

5) Length of Pipeline

Long failed sewer pipelines require more space for repair, leading to greater community disruption.

6) Diameter

Larger diameters require more space for repair or excavation, leading to a greater chance of disruption for the community.

7) Depth

Deeper assets require deeper trenching and excavation. To prevent the soil from caving in, the bank angle shall be considered, which in turn will require more construction area. Hence, it will increase the level of public disruption.

3.11.2 Criticality Index

The weight of each factor and its corresponding sub-factor is found through a questionnaire designed and sent to experts. The importance weights of pipelines and of manhole are investigated using the same designed questionnaire.

Therefore, the criticality index (CRI) of each pipeline can be found using equation 3.20

$$CRI_i = \sum_{c=1}^{3} Wf_c \left(\sum_{s=1}^{u} Wf_{cs} * x_{csi}\right) \qquad [3.20]$$

where

Wf_c is the relative importance weights of the criticality factors of pipelines (environmental, public and economic);

Wf_{cs} is the relative importance weight of each sub-factor *s* in factor *c*; and

x_{csi} is the attribute value for each sub-factor for each pipeline *i* in population *k*.

The *CRI* for each manhole is calculated according to equation 3.21

$$CRI_j = \sum_{e=1}^{3} Wf_e \left(\sum_{d=1}^{q} Wf_{ed} * x_{edj}\right) \qquad [3.21]$$

where

Wf_e is the relative importance weights of the criticality factors of manholes (environmental, public and economic);

Wf_{ed} is the relative importance weight of each sub-factor *d* in factor *e; and*

x_{edj} is the attribute value for each sub-factor for each manhole *j* in population *n*.

The computations of each criticality index will supply an index that ranges between 1 and 5. This index can be interpreted according to Table 3.27. The higher the index, the more critical an asset is in terms of the environmental, public and economic concerns, and vice versa.

Table 3.27 Asset Criticality Grade, Criticality Type and Description

Criticality Index	Criticality Type	Description
1.00 to <1.50	Non Critical	If failed, the asset is not critical to the environmental, economic and public
1.50 to < 2.00	Low	If failed, the asset has low criticality to the environment, economy and public
2.00 to < 3.00	Medium	Moderate criticality to the environment, economy and public
3.00 to < 4.00	High	High criticality to the environment, economy and public
4.00 to 5.00	Extreme	Asset is of extreme criticality if failed

3.11.3 Sewer Network Performance Grade

The performance of the network will be computed by considering all assets in the network along with their criticality to inform the decision-maker about the overall performance of the sewer network, utilizing equation 3.22.

$$Overall\ Network\ Performance\ (ONP) = W_P\left(\frac{\sum_{i=1}^{k} CI\_P_i * CRI_i}{\sum_{i=1}^{k} CRI_i}\right) + W_M\left(\frac{\sum_{j=1}^{n} CI\_M_j * CRI_j}{\sum_{j=1}^{n} CRI_j}\right)$$

[3.22]

where

i	is the pipeline number in population *k;*
j	is the manhole number in population *n;*
W_P	is the relative importance weight of the pipelines;
W_M	is the relative importance weights of the manholes;
CI_P	is the condition index of the pipeline *i;*
CI_M	is the condition index of the manhole *j; and*
CRI	is the criticality of the asset.

The performance grade is interpreted according to Table 3.28. The higher the performance index, the more critical an asset is to the network performance.

Table 3.28 Network Performance Grade, Condition and Description

Overall Grade	Condition	Description
1.00 to <1.50	Excellent	Sewer assets are in excellent conditions. No or only a few small defects can be expected
1.50 to < 2.00	Good	Sewer assets have minor defects that are observed with small to medium severities
2.00 to < 3.00	Fair	Sewer assets have moderate defects with medium severity
3.00 to <4.00	Poor	Sewer assets have major defects with medium to high severity

Overall Grade	Condition	Description
4.00 to 5.00	Critical	Sewer assets have severe defects

3.12 Optimized Sewer Performance Rehabilitation Plan

Urban cities have thousands of pipelines and manholes that require regular maintenance, rehabilitation and replacement decisions. Due to several constraints such as budgets and personnel, decision-makers require robust models that optimize their selections based on certain given budgets. Therefore, an optimization model is designed in this research and the overall representation is explained in Figure 3.15.

The main two objectives for this problem are ensuring that the overall sewer performance is performing above a certain threshold and that the costs of enhancements are minimized. This can be accomplished by deciding on an optimization tool that takes into account several inputs to supply optimum or near-optimum solutions. The overall outputs of the model are improved performance and better rehabilitation decisions based on defined decision variables.

Therefore, the main two objectives are:

- Maximizing the overall sewer network performance; and
- Minimizing the total costs.

This research adopts the PSO algorithm because it outperformed multiple optimization methods, as mentioned in the literature. Building a budget allocation problem utilizing the PSO requires a process to represent each particle in the swarm, setting parameters to balance the exploration in the defined search space and accommodate the PSO algorithm in the budget allocation problem.

In designing a rehabilitation plan, assets in the network are subject to any type of intervention action. Therefore, each pipeline and manhole can be considered as a project. Each project can hold different types of rehabilitation actions (decision variables) throughout the considered life cycle and could have multiple combinations over the studied number of years. In addition, each asset shall interact with the other assets in order to measure the fitness of each particle in the swarm.

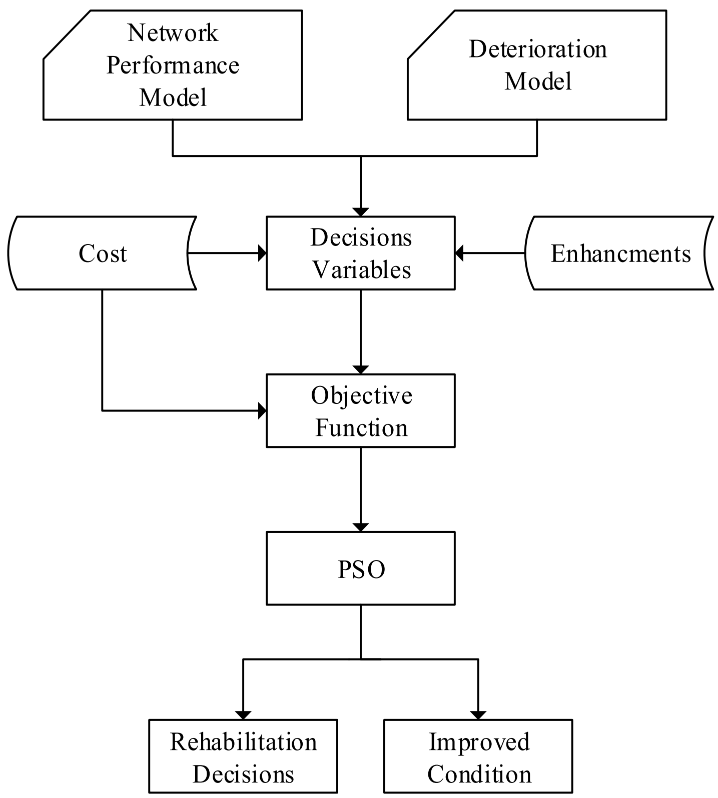


Figure 3.15 Optimized Rehabilitation Plan Model

3.12.1 Particle Encoding

Particle coding is key to facilitate solving the budget allocation problem as it impacts the initialization of the particle, fitness computation, movement and the archiving process. In this research, a particle is represented as a 2D array (n x m) to propose a solution considering predefined objective functions. It is composed of rows and columns; the rows represent the number of the assets (s) in the network, and the columns represent the number of years considered in the study, which is five years. Each element in the array is considered as a potential decision variable (q) for each asset. The decision variables considered in this research are listed in Table 3.29.

Table 3.29 Decision Variables

Decision #	Interpretation	Example	Improvement	Cost for the Pipelines (Adjusted)	Cost for Manholes Average (Adjusted)
0	Do nothing	Do nothing	-	-	-
1	Minor Rehabilitation	Chemical Grouting and sealing	Max of 1 state	\$40/m	\$40/m
2	Major Rehabilitation	Structural Liner (Cured-in-place)	Max of 3 states (Marzouk and Omar 2013)	\$1.77 (/mm/m)	\$5531.149 (Hughes 2009)
3	Replacement	Replace	Return state to 1 (Halfawy et al. 2008)	\$1943.4/m (Marzouk and Omar 2013)	\$11434 (Hughes 2009)

As a result, the 2D array of each particle will be represented as shown in Figure 3.16:

Figure 3.16 Particle Encoding

Considering *y* to be 5 and *s* as 109, then each particle will hold an array of n = 5 and m = 109. As per the array representation, q11 can be any integer value from the decision variables [0,3]. Therefore, a single particle will possess 545 random decision variables to solve the problem.

3.12.2 Initializing Particles

In the first iteration, the particles are initialized only once and then the same number of particle sizes is considered in the defined number of iterations. Each particle will represent the total population of the assets in the network and consider the same number of years studied. Each value on the array will hold a random integer value [0,3], where 0 represents do nothing and 3 calls for replacement. Since the two objective functions will be aggregated into one objective function by means of user-defined weights, there will be one swarm size and the total number of particles is the swarm size. By considering the different decision variables, each particle will be evaluated according to the defined fitness function.

3.12.3 Performance Measures

Since each particle will hold 545 random decision variables, each particle will possess a fitness value that is evaluated by the fitness function. As a minimization problem, in each iteration, the *pbest* of each particle will be stored and the updated *gbest* will be archived for the next iterations. All of the particles' updated velocities and positions will be modified according to the current *pbest* of the particle and *gbest* of the swarm. The computation will continue until it reaches either of the stopping criteria:

1- Covering the defined iteration number; or

2- Problem converges.

3.12.4 Parameters

The PSO has a number of parameters to set before the computation commences. The parameters are the swarm size, iteration number, cognitive parameter, social parameter and inertia weight. These parameters are selected by the user and can differ from one application to another. According to Kennedy (1998), the optimum summation of the cognitive and social parameter is equal to 4.0 and therefore, c_1 and c_2 are both 2.0. The population size, however, is problem-dependent. In fact, in many applications the particle size was [20,50]. In this study, the swarm size selected is 20. For a model to perform well, Shi and Eberhart (1998) suggested that the inertia weight to be between 0.9 and 1.2.

Table 3.30 PSO Parameters

Parameter	Value
Swarm size	20
Iteration	20000
Cognitive parameter	2.00
Social parameter	2.00
Inertia Weight	0.99

3.12.5 Objective Function

Each particle in swarm is evaluated based on a fitness function. In this research, the fitness function is a combination of the total cost and the ONP. The aggregation of these two parameters are based on weights that are user-defined. An equal importance for the two parameters will establish 50% weights for each. To accomplish the optimization tool, the ONP shall be maximized and the total cost shall be minimized, given several constraints.

$$Maximize\ ONP = W_P\left(\frac{\sum_{i=1}^{k} CI\_P_i * CR_i}{\sum_{i=1}^{k} CR_i}\right) + W_M\left(\frac{\sum_{j=1}^{n} CI\_M_j * CR_j}{\sum_{j=1}^{n} CR_j}\right) \quad [3.23]$$

$$Minimize\ Total\ Life\ Cycle\ Costing\ (TLCC) = \frac{1}{(1+r)^t}\sum_{t=1}^{z}\sum_{i=1}^{k} C_{ti} + \frac{1}{(1+r)^t}\sum_{t=1}^{z}\sum_{j=1}^{n} C_{tj} \quad [3.24]$$

$$r = \frac{1+interest\ rate}{1+inflation\ rate} - 1 \quad [3.25]$$

where

r is the real interest rate;

z is the period from one inspection to another (in this study it is 5 years); and

C is the cost of the intervention plan of pipeline i and manhole j at any time t.

These two functions are aggregated into a single function as follows

$$Minimize\ Fitness\ Function = W_{ONP}\left(\frac{ONP}{Max\ Performance}\right) + W_{TLCC}\left(\frac{TLCC}{Budget}\right) \quad [3.26]$$

subject to:

One decision variable per asset in the study period, such that

$$ONP_t \leq Max\ Performance \text{ and} \quad [3.27]$$

$$TLCC \leq Total\ Budget \quad [3.28]$$

where

W_{ONP} is the importance weight of the ONP parameter; and

W_{TLCC} is the importance weight of the $TLCC$ parameter. These weights are user defined. The most significant parameter will have the higher weight.

3.12.6 MATLAB CODE

3.12.6.1 ONP Function

The first objective function considered is to maximize the overall network performance at the end of the study period (in this research, it is 5). Four decision variables are considered as demonstrated earlier (do nothing, minor, major and replace). Each decision variable has an improvement if applied (except for do nothing). If the "minor" decision variable is considered, the improvement will increase by 1. For instance, if the initial pipeline condition is 2.3, applying the second decision variable will make it 1.3. However, a replacement will return the asset to condition 1. This is defined as per Figure 3.17. The total number of the population is 109, which is the sum of the pipeline and manhole population.

```
function z1 = ONP(Wp,CI,CR,decision,Age)

Sum1 = 0;
Sum2 = 0;
Sum3 = 0;
Sum4 = 0;
y = 0;

X1PP_Improvement = 0;
X2PP_Improvement = -1;                          % CHANGE BY -1
X3PP_Improvement = -3;                          % CHANGE BY -3
X4PP_Improvement = 1;                           % RESET TO 1

X1MH_Improvement = 0;
X2MH_Improvement = -1;                          % CHANGE BY -1
X3MH_Improvement = -3;                          % CHANGE BY -3
X4MH_Improvement = 1;                           % RESET TO 1

Improvement = zeros([1 109]);
Rehab = zeros([1 109]);
```

Figure 3.17 Decision Variable Improvements

The improvements for the pipelines and manholes are similar; however, the costs differ. Since the population contains 85 pipelines and 24 manholes, the improvements for the pipelines are only applied for the first 85 elements in the 2D array. The deterioration of the assets are measured by time, as explained by the IDC, UDC and PDC equations. The UDC of the pipelines are defined based on the age and the condition at a given year. However, if an improvement is suggested, the PDC will be applied, according to Figure 3.18; otherwise, the UDC will be used. The age of the pipelines and manholes are also coded as per Figure 3.19. Similarly, the conditions of manholes “CIMH” and pipelines “CIPP” are also defined in Figure 3.20.

```
if Improvement(j) ~=0
    Factor = (((6-CI(j))/5)+Improvement(j)*exp(log(0.2)*((year+Age(j)-Rehab(j)+1)/y)^3))
    if Factor > 1
        Factor = 1;
    end
    CI(j) = 6-5*Factor;
else
    CI(j) = 6 - 5*exp(log((6-CI(j))/5)*((year+Age(j))/Age(j))^3);
end
```

Figure 3.18 PDC Coding

```
AgePP = [ 53 53 53 54 53 54 54 53 54 54 54 53 53 54 54 53 53 54 54 54 54 54 54 54 ...
    54 54 54 54 54 54 50 54 54 54 54 54 54 52 52 53 54 51 54 52 52 54 54 54 54 52 ...
    53 53 53 53 53 53 53 54 53 54 53 54 53 53 53 53 53 53 53 53 53 53 53 53 50.02 ...
    54 54 54 47 31 53 32 53 53 8 ];
AgeMH = [ 53 53 54 54 54 54 54 54 54 50 50 50 50 50 53 54 54 54 54 54 54 53 54 47 ];
```

Figure 3.19 Defining Population Ages

```
CIMH = [ 1.92 2.73 2.59 2.49 2.33 2.415 2.56 2.97 3.165 2.27 1.99 2.435 ...
    2.45 2.215 1.75 1.725 1.99 1.36 2.345 1.835 1.46 2.165 1.955 1.99 ];
CIPP = [ 1.83 2.765 2.44 2.04 3.445 3.39 2.49 2.485 2.56 3.655 3.145 2.8 ...
    2.37 3.81 3.875 2.49 2.21 3.195 2.15 3.995 2.875 2.95 3.885 3.73 2.76 ...
    1.68 2.705 2.575 2.105 2.42 2.22 3.04 2.955 1.875 1.875 1.465 2.71 2.525 ...
    2.525 3.25 3.335 2.355 2.585 3.32 2.3 2.17 1.975 2.445 2.5 2.27 3.52 2.415 ...
    2.51 2.635 3.02 2.565 2.815 2.605 2.33 3.295 2.905 3.135 2.55 2.55 2.54 3.285 ...
    3.295 3.075 3.275 2.88 2.535 2.805 2.38 2.48 2.25 3.46 3.465 2.31 2.485 ...
    1.83 2.34 3.17 2.285 2.735 2.075 ];
```

Figure 3.20 Defining Population Condition Values

Therefore, the improved pipeline condition is calculated as per Figure 3.21. Similar coding is used for manholes. The improvements are changed from 0 to 1 as the PDC and UDC values are between 0 and 1.

```
for year=1:5
    for j = 1:85

        if  abs(floor(decision(year,j))) == 0
            CI(j) = CI(j) + X1PP_Improvement;
        elseif abs(floor(decision(year,j))) == 1
            CI(j) = CI(j) + X2PP_Improvement;
            Improvement(j) = 0.2;
            Rehab(j) = year + Age(j);

        elseif abs(floor(decision(year,j))) == 2
            CI(j) = CI(j) + X3PP_Improvement;
            Improvement(j) = 0.6;
            Rehab(j) = year + Age(j);

        elseif abs(floor(decision(year,j))) == 3
            CI(j) = X4PP_Improvement;
            Improvement(j) = X4PP_Improvement;
            Rehab(j) = year + Age(j);

        end
```

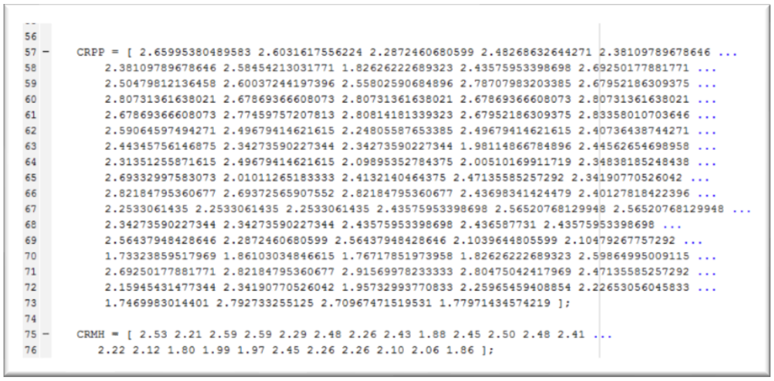
Figure 3.21 Improved Condition Coding

Therefore, the improvements that occur during the study period will affect the ONP calculated in year 5.

Figure 3.22 demonstrates the ONP computation after defining the criticality of each asset (Figure 3.23).

```

% Calculate ONP @ Year Five

for i=1:85
     Sum1 = CI(j) * CR(j) + Sum1;
     Sum2 = CR(j) + Sum2;
end

for i=86:109
     Sum3 = CI(j) * CR(j) + Sum3;
     Sum4 = CR(j) + Sum4;
end

z1 = (Wp*Sum1/Sum2) + (1-Wp)*(Sum3/Sum4);

end
```

Figure 3.22 ONP Objective Function



```
CRPP = [ 2.65995380489583 2.6031617556224 2.2872460680599 2.48268632644271 2.3810978967864‌6 ...
    2.38109789678646 2.58454213031771 1.82626222689323 2.43575953398698 2.69250177881771 ...
    2.50479812136458 2.60037244197396 2.55802590684896 2.78707983203385 2.67952186309375 ...
    2.80731361638021 2.67869366608073 2.80731361638021 2.67869366608073 2.80731361638021 ...
    2.67869366608073 2.77459757207813 2.80814181339323 2.67952186309375 2.83358010703646 ...
    2.59064597494271 2.49679414621615 2.24805587653385 2.49679414621615 2.40736438744271 ...
    2.44345756146875 2.34273590227344 2.34273590227344 1.98114866784896 2.44562654698958 ...
    2.31351255871615 2.49679414621615 2.09895352784375 2.00510169911719 2.34838185248438 ...
    2.69332997583073 2.01011265183333 2.4132140464375 2.47135585257292 2.34190770526042 ...
    2.82184795360677 2.69372565907552 2.82184795360677 2.43698341424479 2.40127818422396 ...
    2.2533061435 2.2533061435 2.2533061435 2.43575953398698 2.56520768129948 2.56520768129948 ...
    2.34273590227344 2.34273590227344 2.43575953398698 2.436587731 2.43575953398698 ...
    2.56437948428646 2.2872460680599 2.56437948428646 2.1039644805599 2.10479267757292 ...
    1.73323859517969 1.86103034846615 1.76717851973958 1.82626222689323 2.59864995009115 ...
    2.69250177881771 2.82184795360677 2.91569978233333 2.80475042417969 2.47135585257292 ...
    2.15945431477344 2.34190770526042 1.95732993770833 2.25965459408854 2.22653056045833 ...
    1.7469983014401 2.792733255125 2.70967471519531 1.77971434574219 ];

CRMH = [ 2.53 2.21 2.59 2.59 2.29 2.48 2.26 2.43 1.88 2.45 2.50 2.48 2.41 ...
   2.22 2.12 1.80 1.99 1.97 2.45 2.26 2.26 2.10 2.06 1.86 ];
```

Figure 3.23 Defining Population Criticality Values

3.12.6.2 TLCC Function

The second function to be evaluated is the total cost required to attain the improvements suggested based on a predefined budget. This function applies the real interest rate after considering the inflation rate, the cost of each improvement and the year it is applied. The four improvements for the pipelines and manholes are defined and listed in Figure 3.24. All the costs of the pipeline's improvement are defined as unit costs. Therefore, they are dependent on the asset geometry (Figure 3.25). Unlike manhole improvements, decision variables "2" and "3" are fixed costs regardless of the geometry.

```
function z2 = TLCC(r,decision,Diameter,Length)

Sum1 = 0;
Sum2 = 0;
Sum3 = 0;
Sum4 = 0;


X1PP_Cost = 0;
X2PP_Cost = 40;                          % MULTIPLY BY LENGTH
X3PP_Cost = 1.77746805659921;            % MULTIPLY BY DIA & LENGTH
X4PP_Cost = 1943.42034300741;            % MULTIPLY BY LENGTH

X1MH_Cost = 0;
X2MH_Cost = 40;                          % MULTIPLY BY DEPTH-LENGTH
X3MH_Cost = 5531.14900596961;            % FIXED COST
X4MH_Cost = 11433.8997539424;            % FIXED COST
```

Figure 3.24 Decision Variables Costs

```
LengthPP = [ 113.6 121.93 73.84 82.04 109.46 101.43 75.57 106.93 107.25 106.5 13.71 ...
    1.59 99.67 89.59 108.22 79.24 87.32 94.47 75.31 92.34 95.69 100.23 ...
    107.85 100.42 107.12 106.03 67.18 27.74 74.04 76.78 104.23 33.54 ...
    33.54 98.42 1.62 58.75 56.96 114.19 59.78 94.54 90.81 19.81 15.19 ...
    60.95 50.29 52.34 69.37 40.23 64.64 113.03 89.95 82.59 83.13 77.71 ...
    99.35 98.12 58.55 33.51 86.97 98.45 76.18 96 46.41 99.23 32 59.64 ...
    74.73 74.66 3.19 87.82 65.42 75.69 44.59 76.74 60.96 30.17 45.15 ...
    66.46 24.38 6 18.21 12.78 5.57 61.9 9.2 ];

DiaPP =[ 450 450 250 450 200 250 450 200 200 450 450 600 675 525 200 200 ...
    200 200 200 200 200 200 200 200 450 450 450 200 450 450 200 200 200 450 ...
    450 450 450 250 300 250 450 300 600 300 300 600 450 525 250 600 200 200 ...
    200 200 200 200 200 200 200 200 200 200 200 200 200 200 200 200 250 200 ...
    375 450 675 600 300 250 250 300 300 750 375 250 450 100 300 ];

DepthMH = [ 4.89 6.635 7.292 7.526 6.521 3.199 3.707 3.165 2.926 4.89 4.89...
    4.89 3.506 4.89 7.424 3.679 3.438 3.477 3.53 3.686 4.028 10.712 2.857 4.16 ];

DiaMH = [ 1200 1200 1200 1200 1200 1200 1200 1200 1200 1200 1200 1200 1200 1200 ...
    1200 1200 1200 1200 1200 1200 1200 1200 1200 1200 ];
```

Figure 3.25 Defining Population Geometry

The total life cycle costing is the summation of the costs incurred as if they were returned to year zero (present value). As per Figure 3.26, the costs for the first set are synchronized to the pipeline population and those for the second set are connected to the manhole population.

```
for year=1:5
    for i = 1:85
        if  abs(floor(decision(year,i))) == 0
            CT(year, i) = CT(year, i) + X1PP_Cost / (1+r)^year;
        elseif abs(floor(decision(year,i))) == 1
            CT(year, i) = CT(year, i) + X2PP_Cost*Length(i) / (1+r)^year;
        elseif abs(floor(decision(year,i))) == 2
            CT(year, i) = CT(year, i) + X3PP_Cost*Length(i)*Diameter(i) / (1+r)^year;
        elseif abs(floor(decision(year,i))) == 3
            CT(year, i) = CT(year, i) + X4PP_Cost*Length(i) / (1+r)^year;
        end
    end

        for i = 86:109
        if  abs(floor(decision(year,i))) == 0
            CT(year, i) = CT(year, i) + X1MH_Cost / (1+r)^year;
        elseif abs(floor(decision(year,i))) == 1
            CT(year, i) = CT(year, i) + X2MH_Cost*Length(i) / (1+r)^year;
        elseif abs(floor(decision(year,i))) == 2
            CT(year, i) = CT(year, i) + X3MH_Cost / (1+r)^year;
        elseif abs(floor(decision(year,i))) == 3
            CT(year, i) = CT(year, i) + X4MH_Cost / (1+r)^year;
        end
        end

end
```

Figure 3.26 TLCC Objective Function

3.12.6.3 PSO Code

After defining the two functions required for the tool, they are aggregated and evaluated based on a fitness function considering user-defined weights as per Figure 3.27. Therefore, each particle in the swarm will be evaluated based on the defined fitness function. The "Wonp" and the "Woco" are the user defined weights for each of the objective functions.

```
    % Evaluation
Maxcost = TLCC(r,particle(i).Position,Diameter,Length);
particle(i).Objective = Wonp*(ONP(Wp,ConditionIndex,Criticality,particle(i).Position, Age)-1)/5 + Woco*(TLCC(r,particle(i).Position,Diameter,Length)/Budget);
```

Figure 3.27 Fitness Function

The PSO parameters are also a main part of the tool and are defined according to Figure 3.28. These parameters are user-defined and dependent on the complexity of the problem. The budget definition acts as a constraint so that the TLCC does not exceed the defined budget. The parameters "c1" and "c2" have values of 2 and the inertia weight is taken as 0.99.

```
%============== Parameters of PSO ================%

Budget = %user defined;
Wonp = %use defined;
Woco = %user defined;

MaxIt = %user defined;           % #Iterations
nPop = %user defined;            % Total Swarm Size


wdamp = 0.99;                    % Damping ratio of Inertia Coefficient
c1 = 2;                          % cognitive Acceleration Coefficient
c2 = 2;                          % Social Acceleration Coefficient
```

Figure 3.28 PSO Parameters

Since the lower bound of the decision variables is 0 and the upper bound is 3, the maximum and minimum velocities are defined according to Figure 3.29, where the *k* factor is taken as 1. Therefore, the maximum value of the velocity is 3 and the minimum velocity is -3.

```
MaxVelocity = (VarMax-VarMin);
MinVelocity = -MaxVelocity;
```

Figure 3.29 Velocity Lower and Upper Bounds

Each particle will be defined according to its position, velocity, objective value, best position and best objective value. The template of each particle is defined according to Figure 3.30. According to the same figure, each particle is represented as an array of 5x109, where 5 is the number of years and 109 represents the population of the assets. In the first iteration, each particle initializes at distinct positions; however, the initial velocity is set to zero. These values are updated according to subsequent iterations. The same figure codes, from line 219 to 231, the first constraint that is pertinent to the number of decision variables applied for each asset. Based on the constraint, if any decision variable other than "do nothing" is applied in any year, the remaining years will be the "do nothing" decision variable.

```
% Particles Template
empty_particle.Position = [];
empty_particle.Velocity = [];
empty_particle.Objective = [];

empty_particle.Best.Position = zeros(5,nVar);
empty_particle.Best.Objective = zeros(5,nVar);


% Population Array
particle = repmat(empty_particle, nPop, 1);

% Initialize Personal Best --> Change to manual value!!
for  i = 1:nPop
 particle(i).Velocity = zeros(VarSize);
GlobalBest.Objective = inf;
GlobalBest.Position = zeros(5,nVar);
particle(i).Best.Objective = inf;
% Generate Random Solution
particle(i).Position = floor(unifrnd(VarMin, VarMax, VarSize));
end



for it = 1:MaxIt
% Asset visited once
    for i = 1:nPop
       currentX = particle(i).Position;

                    for j = 1:length(Length)
                      for year = 1:5
                           if particle(i).Position(year,j) > 0
                            for k = year+1:5
                               particle(i).Position(k,j) = 0;
                            end
                           end

                      end
                    end

```

Figure 3.30 Particle Encoding

In Figure 3.31, the velocity of each particle is defined according to the parameters defined earlier and based on the calculated *pbest*, *gbest* and the current position. After calculating the velocity of each particle, the updated position of the particle is computed. To restrain the particles in the domain, the upper and lower bounds are defined as well.

```
for i=1:nPop

% Update Velocity
 particle(i).Velocity = w*particle(i).Velocity ...
 + c1*(rand(VarSize)).*(particle(i).Best.Position - particle(i).Position) ...
+ c2*(rand(VarSize)).*(GlobalBest.Position - particle(i).Position);

% Apply Velocity Limits
particle(i).Velocity = max(particle(i).Velocity, MinVelocity);
particle(i).Velocity = min(particle(i).Velocity, MaxVelocity);


% Update the position

particle(i).Position = particle(i).Position + particle(i).Velocity;

% Apply Lower and Upper Bound Limits
particle(i).Position = max(particle(i).Position, VarMin);
particle(i).Position = min(particle(i).Position, VarMax);
```

Figure 3.31 Velocity and Position Equations

As per Figure 3.32, each iteration will contain the *pbest* of each particle and the *gbest* based on the evaluated fitness function. Therefore, the position and the velocities are updated accordingly. The best position in each iteration will be called the "GlobalBest" and is evaluated based on the minimum fitness value of all particles in the same iteration.

```

        % Update Personal Best
            if particle(i).Objective < particle(i).Best.Objective
                particle(i).Best.Position = particle(i).Position;
                particle(i).Best.Objective = particle(i).Objective;
                % Update Global Best
                if particle(i).Best.Objective < GlobalBest.Objective
                    GlobalBest = particle(i).Best;
                end
            end

    end

        % Store the Best Cost Value
        BestObjective(it) = GlobalBest.Objective;

        % Display Iteration Information
        if ShowIterInfo
            disp(['Iteration ' num2str(it) ': Best Objective = ' num2str(BestObjective(it))]);
        end

    % Damping Inertia Coefficient
    w = w * wdamp;

end
```

Figure 3.32 *pbest* and *gbest* Updates

Chapter Four: Data Collection

4.1 Overview

One significant part of this research work is to design questionnaires and send it to experts in the infrastructure field and more specifically in sewer systems. These questionnaires are essential in completing the research objectives by including experts' opinions in the study. This research designed a questionnaire that was divided into several parts. The first part collected weights of factors that are correlated to erosion void in sewer pipelines. These weights are significant in aggregating the multiple factors into a condition to understand the soil support loss occurring around pipelines.

The second part is pertinent to the deployment of the DEMATEL method in concluding influencing factors between several elements in different systems. Another part of the questionnaire is to compute the relative importance weights of the manhole components through a pairwise comparison to establish the ANP approach and find the relative weight of each component. In addition, a questionnaire is also designed for the criticality model to compute the considered factors' weights.

The last phase of the data collection is concerned with the case studies. These samples are used to implement and validate the developed models. The validation implemented in this research is based on comparing and verifying the results obtained with the case studies brought from a third party. The first case study is pertinent to sewer pipelines samples that are tested for erosion void existence. The second case study is related to an actual sewer network brought from the city of Edmonton, Canada.

4.2 Questionnaire 1

More than 115 questionnaires were distributed as a hard copy and a softcopy, with the help of social media engines, in different regions. Fortunately, 27% of the distributed questionnaires were received; in specific, 32 experts from four different areas, North America (Canada and US), Middle East, Europe and China, participated. The respondents' number of years of experience were categorized into five different groups as per Table 4.1. Based on Table 4.1 and Figure 4.1, the highest number of responses were participants having experience between 9 and 15 years. However, the lowest number of responses were participants having experience between 3 and 6 years. In addition, participants from North America were the highest participating region among the other regions; while the Middle East region respondents were the lowest participants as per Figure 4.2. This was expected since sewer condition assessment practice and trenchless technology in the Middle East is not as popular as in the other regions.

Table 4.1 Respondents Years of Experience

Years of Experience	Responses
1-3 years	6
3 - 6 years	4
6 - 9 years	7
9 - 15 years	9
15+ years	6
Total	**32**

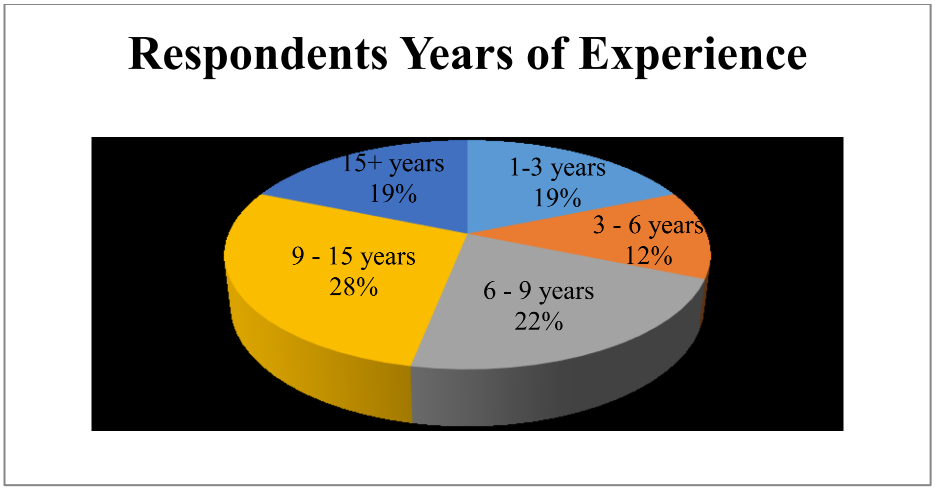


Figure 4.1 Respondents Years of Experience

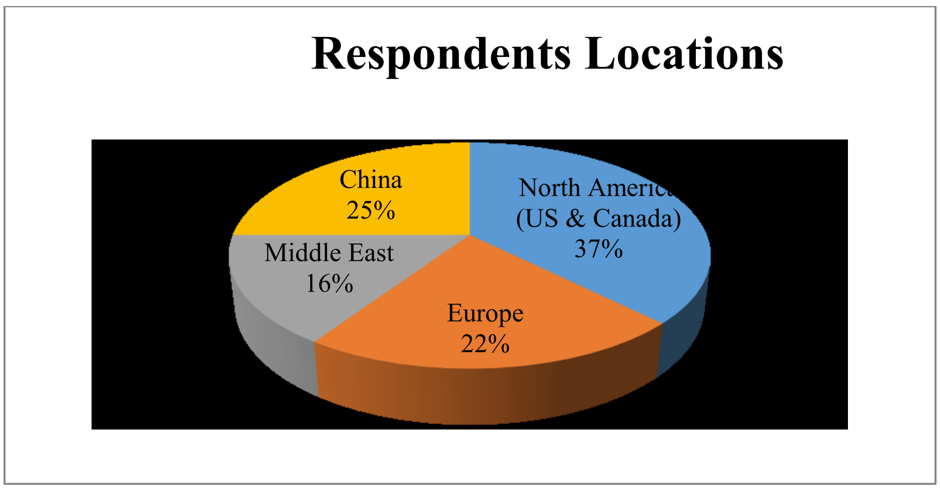


Figure 4.2 Respondents Locations

4.2.1 HOQ Influence Matrix

As mentioned earlier, the generalized form and the widely used matrix in the HOQ, in the QFD method, is the correlation between the elements in the system. However, in this research, the influence matrix is utilized to suggest the cause and effect relationship between the elements and in this research are the defects in each asset assessed. Therefore, a questionnaire was designed and distributed to experts. The questionnaire included general defects found in pipelines and manholes. In total, 22 defects were used in the questionnaire. Figure 4.3 is a sample of a questionnaire distributed to experts. Each table, in the figure, represents two different defects.

The expert shall select the influence of X on Y and the influence of Y on X considering the 0, 1, 2, 3 and 4 factors.

X	No Influence	Low Influence	Medium Influence	Extreme Influence	High Influence	Y
Fracture	0	1	2	3	4	Infiltration
	→					
	←					
	4	3	2	1	0	
X	High Influence	Extreme Influence	Medium Influence	Low Influence	No Influence	Y

X	No Influence	Low Influence	Medium Influence	Extreme Influence	High Influence	Y
Roots	0	1	2	3	4	Infiltration
	→					
	←					
	4	3	2	1	0	
X	High Influence	Extreme Influence	Medium Influence	Low Influence	No Influence	Y

Figure 4.3 HOQ Influence Questionnaire Sample

After reviewing each response, the average influence matrix was calculated and the same average values were used for the different HOQs of the sewer assets and components.

4.2.2 Manhole Components Relative Weights

According to this research, several components were considered when computing the condition of the manhole such as the pavement surrounding the cover, manhole cover and frame, chimney, cone, wall, channel, bench, seals, and steps. However, the contribution of each component's condition is distinct due to the relative importance of one component to the other. As a result, this study examined the components that impact the condition of the manhole. ANP method was considered in finding the relative importance weights of the elements of the system as it depicts the interdependencies among the elements involved in the system. The respondents of this part were similar to those of the previous questionnaire. Thirty-two responses were gathered and each was analyzed separately. Table 4.2 shows a sample of a questionnaire that helped in completing the ANP deployment. The respondents filled the tables comparing component X and Y with respect to Z.

Table 4.2. Sample of Manhole Relative Importance Questionnaire

Degree Of Importance										
X	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Y
(Z) Cone										
Cover										Pavement
										Chimney
										Wall
										Steps
										Seals
										Channel
										Bench
(Z) Cover										
Chimney										Pavement
										Cone
										Wall
										Steps
										Seals
										Channel
										Bench
(Z) Seals										
Channel										Pavement
										Cone
										Wall
										Steps
										Cover
										Chimney
										Bench
(Z) Pavement										
Wall										Seals
										Cone
										Pavement
										Steps
										Cover
										Channel
										Bench

According to the data collected, thirty-two experts responded to the questionnaire, and therefore, the relative importance weights were computed using the “Superdecisions” software. The results are shown in Table 4.3. The table shows the average relative weight of each component, the standard deviation, the minimum and maximum value, the 95% confidence intervals and the percentage difference between the average value and any of the confidence interval bounds.

Table 4.3 Manhole Component Weights and Statistics

Component	Average	Standard Deviation	Min	Max	95% Confidence Interval		Difference% (Average and Bounds)
					Lower Bound	Upper Bound	
Bench	6.21%	0.0283	2.85%	11.23%	5.23%	7.19%	15.81%
Channel	11.10%	0.0529	6.58%	29.94%	9.27%	12.93%	16.52%
Chimney	11.52%	0.0120	9.39%	14.60%	11.10%	11.93%	3.62%
Cone	15.46%	0.0222	11.14%	18.43%	14.69%	16.23%	4.97%
Cover & Frame	15.13%	0.0282	11.08%	20.83%	14.15%	16.10%	6.45%
Pavement	4.70%	0.0241	2.12%	9.64%	3.87%	5.54%	17.75%
Seals	14.44%	0.0274	8.71%	19.03%	13.49%	15.39%	6.57%
Steps	3.83%	0.0068	3.01%	5.78%	3.59%	4.07%	6.17%
Wall	17.61%	0.0308	12.69%	23.73%	16.54%	18.68%	6.07%

By consulting the table, it can be observed that there are differences between the respondents' opinions. The extreme minimum and maximum values show apparent discrepancies among the experts in signifying the importance of one component to another. This can be observed in the channel and wall components. As per the data collection chapter, the responses were collected from four different regions around the world and therefore, not all experts are homogenous in thinking and judgment.

However, the 95% confidence level ranges are not far from the average value calculated for each component. Based on the difference percentage calculated between the average relative importance weight of each defect and the lower or upper bound of the confidence interval value, it can be observed that the percentage difference ranges between 3% and 18%.

4.2.3 Erosion Voids Factors

The factors that are expected to explicitly influence the formation of the erosion voids have been identified. The questionnaire in Table 4.4 asked the respondents to rate the factors from 0-100, which explains the strength of the factor contributing to the condition of the void erosion in pipelines.

Table 4.4 Erosion Void Factors Sent Questionnaire

#	Factor	Percentage
1	**Bedding Material**	
2	**Pipeline Depth**	
3	**Soil Type**	
4	**Pipeline Age**	
5	**Groundwater Table**	
Total		100%

Accordingly, the weights of each factor were collected and averaged to use it in calculating the severity or condition of the erosion void defect. The average weights collected are summarized in Table 4.5. In addition, the lower and upper bounds of the 95% confidence interval were calculated. As per displayed, the weights are different, and this is depicted from the maximum and the minimum values for each factor weights. This explains the different opinions by the participants in distinct regions.

Table 4.5 Erosion Void Factors Weights and Statistics

Factor	Average	Standard Deviation	Min	Max	95% Confidence Interval		Difference %
					Lower Bound	Upper Bound	
Bedding Type	12.03	5.9378	5	20	9.974	14.089	17.10%
Pipeline Depth	12.66	5.8177	5	20	10.641	14.672	15.93%
Soil Type	21.09	4.8749	10	30	19.405	22.783	8.01%
Pipeline Age	24.69	5.2267	15	35	22.877	26.498	7.34%
Groundwater	29.38	8.4003	20	50	26.464	32.286	9.91%

4.3 Questionnaire 2

Unlike Questionnaire 1, only sixteen responses were gathered from three regions (North America, Europe, and China). The years of experience of the participants are categorized according to Table 4.6. Fifteen percent of the participants were located in North America, and around 31% of the participants were located in China.

Table 4.6 Respondents Years of Experience

Years of Experience	Responses
1-3 years	1
3 - 6 years	2
6 - 9 years	4
9 - 15 years	5
15+ years	4
Total	**16**

The criticality of one asset shall differ from another in the network based on several aspects. These aspects rely on the impacts of the failed asset to the environment, economic and public. Nevertheless, the effect of the factors differs from one to another. The research deployed the ANP technique to find out the weights of each factor and sub-factor. The questionnaire included the factors and sub-factors considered in this research for pipelines as per Table 4.7 and manholes as per Table 4.8. In addition, it collected the percentages of the manholes and pipelines that contribute to the condition of the overall sewer network as shown in Table 4.9.

Table 4.7 Pipeline Criticality Questionnaire

Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Sewer PIPELINES Criticality										
Economic Factors										Environmental Factors
										Social Factors
Environmental Factors										Social Factors
Environmental Factors										
Soil Type										Flow Conveyed
										Proximity to Surface Water
Flow Conveyed										Proximity to Surface Water
Economic Factors										
Depth										Diameter
										Water Table
										Length
										Accessibility
Diameter										Water Table
										Length
										Accessibility
Water Table										Length
										Accessibility
Length										Accessibility
Public Factors										
Population Density										Road Type
										Land Use
										Length
										Accessibility
										Diameter
										Depth
Road Type										Land Use
										Length
										Accessibility
										Diameter
										Depth
Land Use										Length
										Accessibility
										Diameter
										Depth
Length										Accessibility
										Diameter
										Depth
Accessibility										Diameter
										Depth
Diameter										Depth
Economic Factors										
Environmental Factors										Public Factors
Environmental Factors										
Public Factors										Economic Factors
Public Factors										
Environmental Factors										Economic Factors

Table 4.8 Manhole Criticality Questionnaire

Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Sewer MANHOLE Criticality										
Economic Factors										Environmental Factors
										Social Factors
Environmental Factors										Social Factors
Environmental Factors										
Soil Type										Flow Conveyed
										Proximity to Surface Water
Flow Conveyed										Proximity to Surface Water
Economic Factors										
Depth										Diameter
										Water Table
										Number of Inlets
										Accessibility
Diameter										Water Table
										Number of Inlets
										Accessibility
Water Table										Number of Inlets
										Accessibility
Number of Inlets										Accessibility
Public Factors										
Population Density										Road Type
										Land Use
										Depth
										Accessibility
										Diameter
Road Type										Land Use
										Depth
										Accessibility
										Diameter
Land Use										Depth
										Accessibility
										Diameter
Depth										Accessibility
										Diameter
Accessibility										Diameter
Economic Factors										
Environmental Factors										Public Factors
Environmental Factors										
Public Factors										Economic Factors
Public Factors										
Environmental Factors										Economic Factors

Table 4.9 Pipelines vs. Manholes Questionnaire

Which is more important to the SEWER network Condition?	
Asset	**Percentage**
Pipelines	
Manholes	

4.3.1 Pipeline Criticality Weights

Each questionnaire was analyzed taking into account the consistency of the responses. The weights of each response was recorded, and the statistical parameters were calculated: average, minimum, maximum 95% confidence interval upper and lower bounds. Table 4.10 summarizes the results of the weights computed along with the statistical parameters for the pipeline criticality factors. The table suggests the different opinions among the experts in the field. As per the table, the economic factors had the highest average weight compared to the other two factors. In fact, the accessibility sub-factor under the economic factor scored the highest average global weight compared to the other factors. On the other hand, the same sub-factor under the public factor had the minimum average global weight.

Table 4.10 Pipeline Criticality Weights

Pipelines Factor/Sub factor	Average	Standard Deviation	Min	Max	95% Confidence Interval	
					Lower Bound	Upper Bound
Environmental	28.44%	8.58%	19.21%	51.34%	24.23%	32.64%
Economic	39.27%	10.85%	20.54%	62.32%	33.96%	44.59%
Public	32.29%	8.82%	18.04%	55.59%	27.97%	36.61%
			Environmental			
Soil Type	35.82%	9.62%	20.12	54.22	31.11%	40.53%
Flow Conveyed	26.49%	6.96%	13.85	37.35	23.08%	29.90%
Proximity to Surface Water	37.69%	11.75%	20.54	60.87	31.93%	43.45%
			Economic			

Depth	25.56%	4.71%	16.07%	32.10%	23.26%	27.87%
Diameter	21.58%	5.11%	13.04%	30.24%	19.07%	24.08%
Water Table	8.24%	5.05%	1.36%	18.70%	5.76%	10.72%
Length	16.88%	4.65%	10.09%	24.33%	14.60%	19.16%
Accessibility	27.74%	7.98%	15.85%	41.34%	23.83%	31.66%
			Public			
Population Density	27.99%	7.07%	16.00%	40.20%	24.53%	31.45%
Road Type	29.44%	6.21%	19.07%	39.08%	26.40%	32.49%
Diameter	13.44%	3.72%	6.05%	19.07%	11.61%	15.26%
Length	8.54%	4.18%	1.40%	17.04%	6.49%	10.59%
Depth	8.55%	4.66%	3.67%	16.04%	6.27%	10.83%
Accessibility	3.56%	2.58%	1.09%	10.06%	2.30%	4.83%
Land Use	8.47%	6.43%	2.04%	23.31%	5.33%	11.62%

4.3.2 Manhole Criticality Weights

In addition, the weights for manhole criticality factors and subfactors were calculated along with their statistical parameters. Based on Table 4.11, the environmental factor's average weight was the least while the highest was for the economic factors. In the context of the subfactors, the highest average global weight was the proximity to surface water under the environmental category. However, the lowest average global weight was for the depth under the public category. Based on the results, the experts had different overviews regarding the criticality of the two assets.

Table 4.11 Manhole Criticality Weights

Manhole Factor/Sub-factor	Average	Standard Deviation	Min	Max	95% Confidence Interval	
					Lower Bound	Upper Bound
Economic	37.80	15.27	20.00	60.00	30.32	45.28
Environmental	28.81	10.31	17.00	60.00	23.76	33.87
Social	33.39	16.15	6.00	61.00	25.47	41.30
			Environmental			
Soil Type	37.53	13.30	20.00	60.00	31.01	44.04
Flow Conveyed	24.91	11.87	11.00	49.00	19.09	30.72
Proximity to water	37.57	13.01	20.00	64.00	31.19	43.95

Economic						
Depth	30.00	7.06	17.21	36.12	26.54	33.46
Diameter	22.94	5.41	16.15	36.03	20.29	25.59
Accessibility	28.19	5.97	21.01	39.00	25.26	31.11
Water Table	12.48	6.57	2.40	24.20	9.26	15.70
Number of Inlets	6.40	3.75	0.89	14.30	4.56	8.23
Public						
Population Density	22.38	5.83	13.31	32.00	19.52	25.24
Land use	20.58	5.53	10.00	31.00	17.87	23.29
Depth	6.21	3.05	3.00	13.40	4.71	7.70
Road Type	20.07	8.19	9.60	34.00	16.06	24.08
Accessibility	14.77	8.50	3.14	33.10	10.60	18.93
Diameter	15.99	8.65	6.40	30.10	11.76	20.23

4.3.3 Pipelines vs. Manholes

The questionnaire also collected the percentage importance of one asset to the other when deciding the network condition (Table 4.12). The results show that pipelines are more important than manholes according to the experts' opinions. Perhaps, all experts shared similar thoughts by providing higher percentages to the pipelines when compared to manholes. The average percentage of the pipelines was 65.31% while the percentage for the manholes was 34.69%.

Table 4.12 Manhole vs. Pipelines Weights

Asset	Average	Standard Deviation	Min	Max	95% Confidence Interval	
					Lower Bound	Upper Bound
Pipelines	65.31%	6.94%	55%	75%	61.91%	68.72%
Manholes	34.69%	6.94%	25%	45%	31.28%	38.09%

4.4 Erosion Void Case Study

The first case study consists of sixteen pipelines obtained from a contractor that conducts sinkhole and void detection surveys using GPR. The pipelines are located in distinct regions in North America. Due to the high confidentiality of the information, the locations were scarce. The contractor used antennas with lower frequencies (< 250 megahertz) for potential detection of deeper voids. However, higher frequencies were used to detect shallower voids. The report included the inputs required for the developed model. The information is pertinent to the five factors identified in this study. The bedding types were Classes A, B, and C. However, the depths ranged between 1.50 m to 6.00 m. The average age of the pipelines was 51.19 years, where the youngest was 21 years and the oldest was 140 years. The soils surrounding the pipelines were in the categories of fine sand and silt, fine sand, course sand, and gravel. From the sixteen pipelines, five were below the groundwater table. Besides, the conditions by the inspection results were provided in three different linguistic grades: acceptable, moderate and inadequate. The grading, according to the report, was based on the analyzed hyperbolas of each GPR inspection. Acceptable means that no voids were detected. Yet, moderate explains that minor voids were observed; while inadequate represents significant voids. The number of pipelines in acceptable, moderate and inadequate grades were nine, five and two, respectively. To accommodate the application of the case study and for the validation purposes, the five proposed severities were restructured according to the three severities in the case study. Therefore, acceptable was considered as excellent and good; moderate was fair; inadequate was poor and critical.

4.5 City of Edmonton Case Study

This research obtained the Royal Gardens' sewer network from the city of Edmonton, shown in Figure 4.4. Royal Gardens, a residential area, is located in the Petrolia subdivision of south-central Edmonton with a population of 3,500.

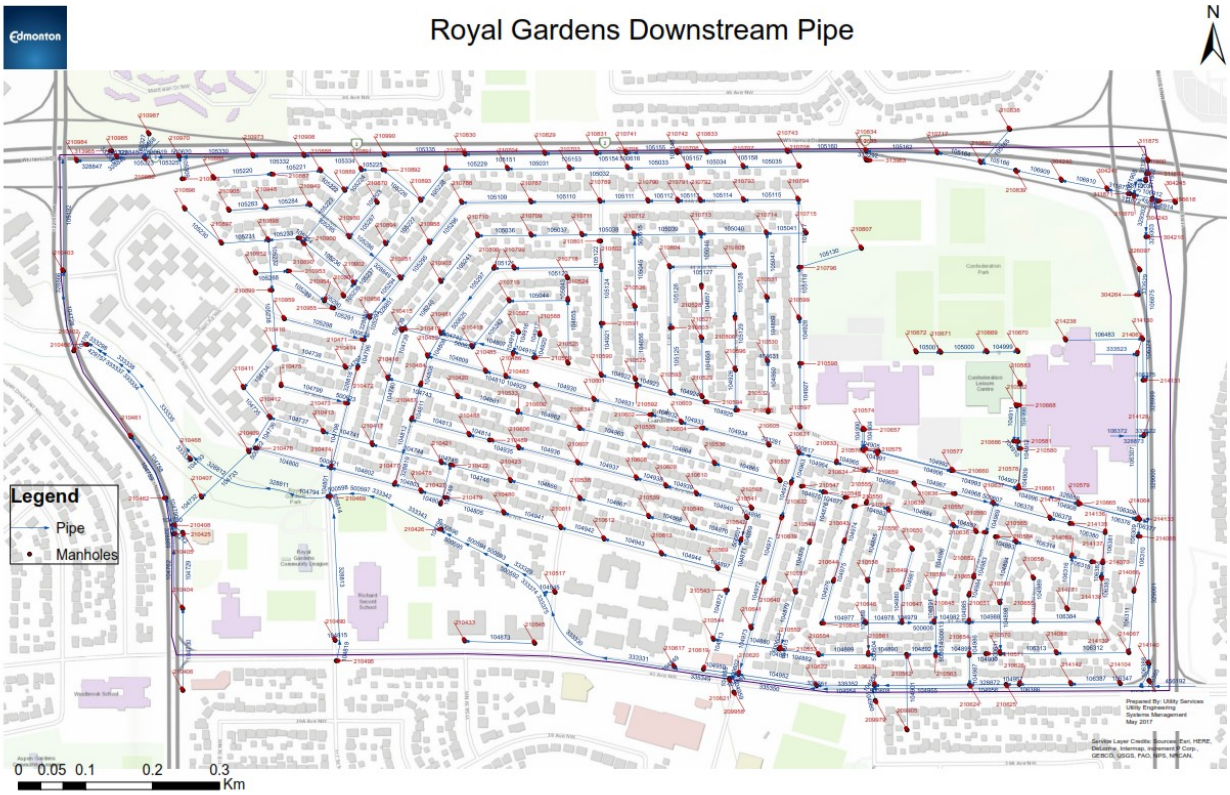


Figure 4.4 Royal Gardens Sewer Network

4.5.1 General Information

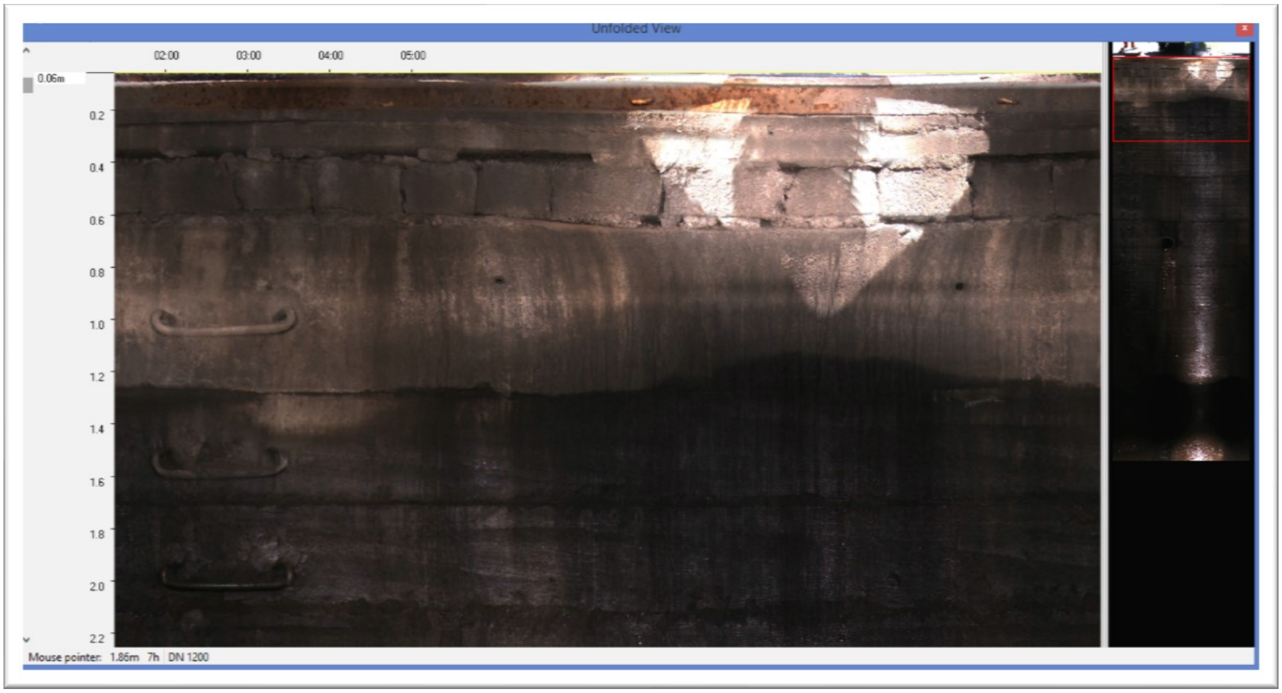
The information obtained was for sewer pipelines and some of the network's manholes. Extensive manhole condition information was difficult to obtain due to their scarcity in the city of Edmonton. The information received consisted of 481 sewer pipelines and 370 manholes. The database for the pipelines included general information about the pipelines such as the year of construction, depth, material type, etc. Besides, 4067 defects/observations are reported in the database according to PACP coding system. Borehole sample result is used to locate the groundwater table and obtain soil distribution. Comparing the depth of the pipeline with the borehole information, soil type and pipeline location with respect to the groundwater table are obtained.

On the other hand, the manhole database consisted of information about the defects and general manhole information such as the age, shape, location (longitude and latitude). In addition, the city provided some ".ipf" format files for manholes inspection as per Figure 4.5. PipeTech View software was used to run the manhole inspection files. A 360-degree view of each manhole was acquired with the help of the software; zoom in and out as well as pan and tilt views were accessible. In this context, 24 extensive manhole reports were supplied by the city. Due to the lack of the actual data, the reports were re-evaluated by an expert as shown in Table 4.13.

Table 4.13 Manholes Conditions

Manhole #	Condition	Manhole #	Condition	Manhole #	Condition
1	3	9	4	17	2
2	4	10	4	18	1
3	3	11	2	19	2
4	3	12	2	20	3
5	3	13	4	21	2
6	2	14	2	22	3
7	2	15	3	23	2
8	4	16	2	24	3

a)


Unfolded View
02:00
03:00
04:00
05:00
0.06m
0.2
0.4
0.6
0.8
1.0
1.2
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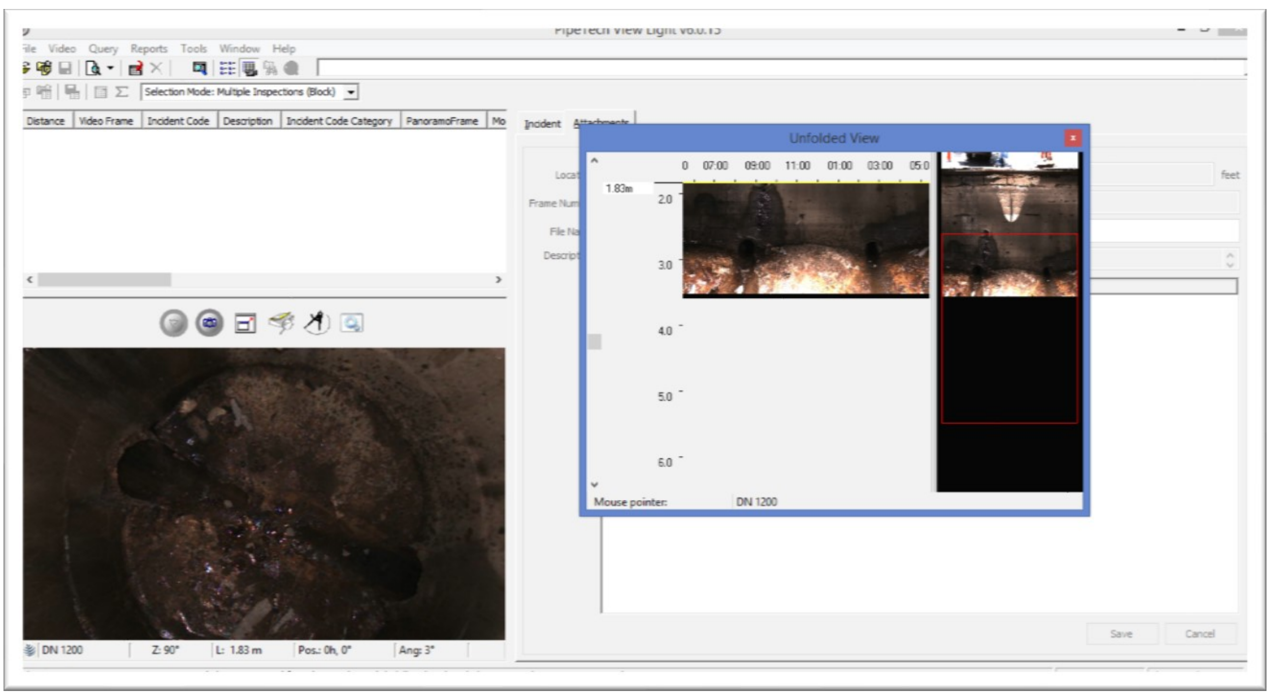
1.6
1.8
2.0
2.2
Mouse pointer: 1.86m 7h DN 1200

b)


File Video Query Reports Tools Window Help
Selection Mode: Multiple Inspections (Block)
Distance
Video Frame
Incident Code
Description
Incident Code Category
PanoramoFrame
Incident
Unfolded View
1.83m
2.0
3.0
4.0
5.0
6.0
Mouse pointer:
DN 1200
feet
Save
Cancel
DN 1200
Z: 90°
L: 1.83 m
Pos.: 0h, 0°
Ang: 3°

c)

Figure 4.5 Manhole Inspection Snapshots (a,b and c)

4.5.2 Royal Gardens Sewer Network Information

- Bedding Class
    - Some bedding types were missing. With the collaboration with an engineer in the City of Edmonton, the engineer suggested using Class A for larger pipes. The researcher examined the pipelines in the database and observed that pipelines that were 900 mm and lower were in class B; more than 900 mm, Class A was considered. Therefore, for any unknown pipeline with a diameter of 900 mm and above will be assigned to Class A and the rest as Class B. Therefore, the distribution of the bedding classes are as per Figure 4.6. As per the figure, the majority of the beddings were Class B.

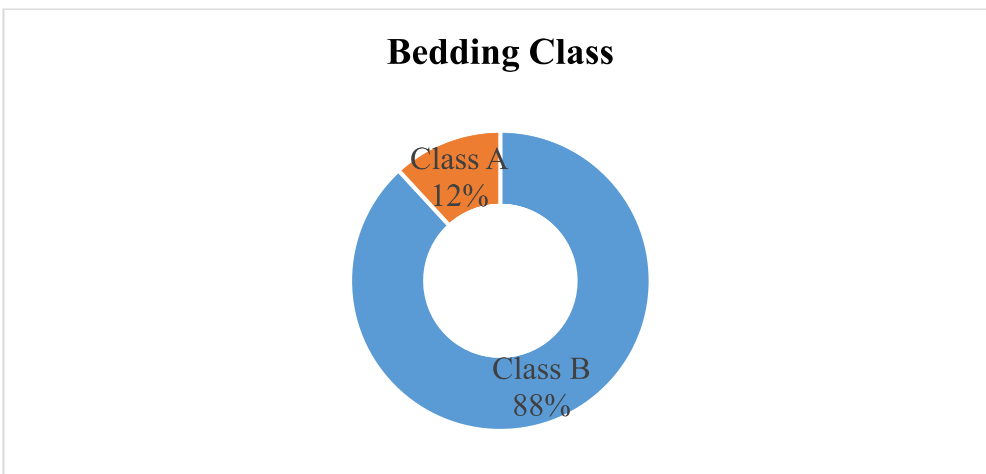


Figure 4.6 Bedding Class

- Pipeline Age
    - Seventeen pipelines had an unknown year of construction. Therefore, the average age of the known pipelines was calculated and assigned to the pipelines with an unknown year of construction. The average of known ages was 50.02 years. As per Figure 4.7, the majority of the pipelines' ages were 50 years and older.

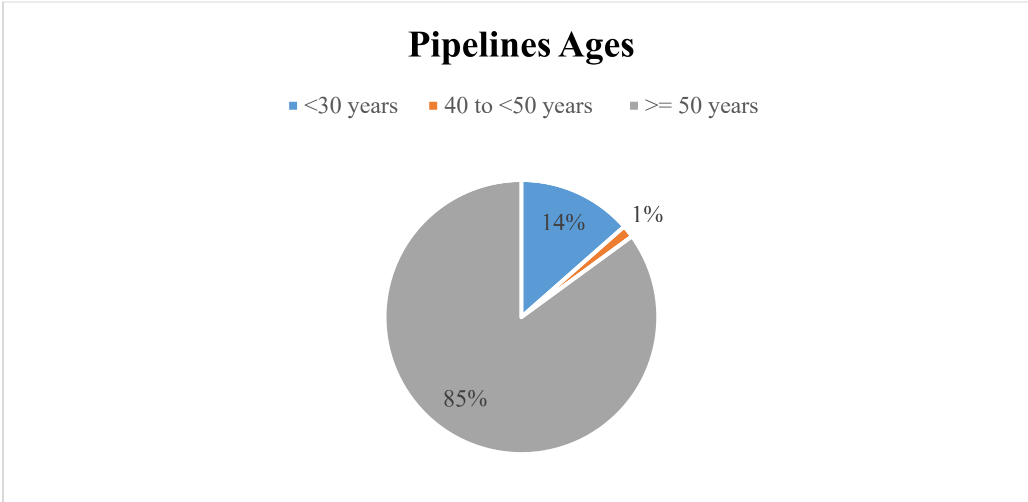


Figure 4.7 Pipeline Ages

- Pipeline Depth
  - The average depth of the upstream and downstream depths was calculated and considered in the evaluation. For the unknown depths, the average of the known depths was calculated and considered for the missing ones. The average depth was found to be 4.74 m. From Figure 4.8, the majority of the pipelines' depths were between 3 m and 4 m.

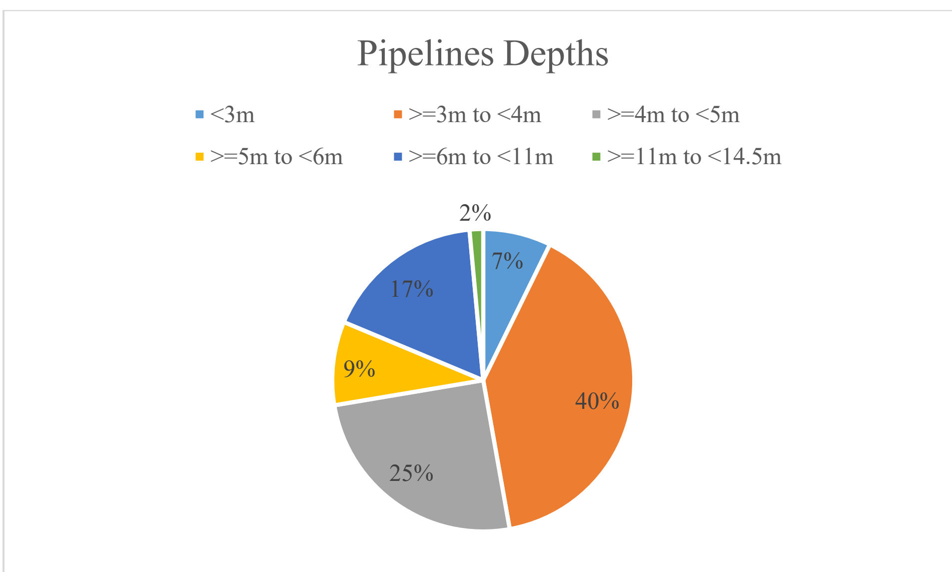


Figure 4.8 Pipelines Depths

- Groundwater Level

- The city provided one test hole for the Royal Gardens area. The groundwater (GWT) level was 3.60 m measured from the surface. Therefore, the average depths of the pipeline was compared with the depth of the groundwater level to decide on whether the pipeline was above or below the water level. As per Figure 4.9, the majority of the pipelines were located above the GWT.

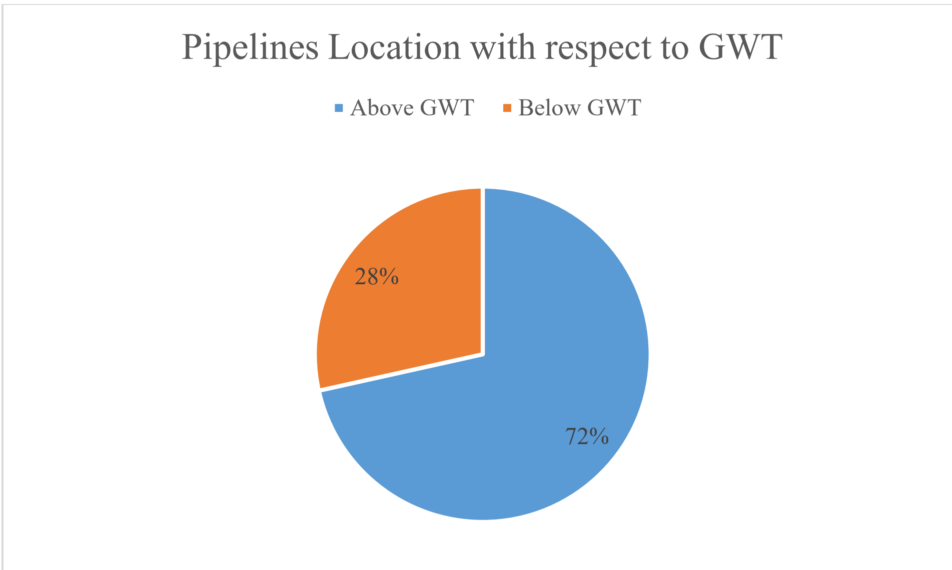


Figure 4.9 Pipeline Location with respect to GWT

- Soil Type
  - One borehole test was provided and was reviewed with the soil distribution in the hole. The soil layers were made of gravel, silt, sand, and clay. Comparing the depths of soils and the pipelines, the soil type surrounding the pipelines were determined. As per Figure 4.10, most of the pipelines were surrounded by fine sandy soil.

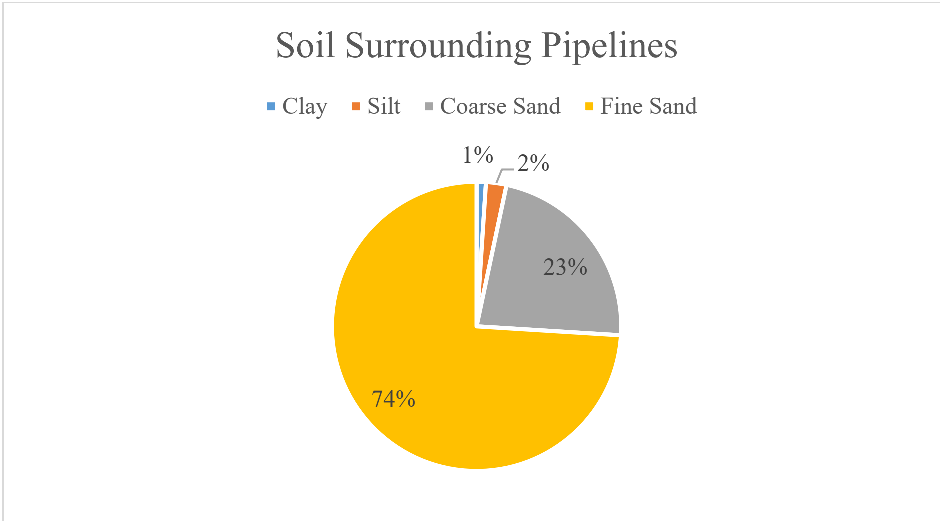


Figure 4.10 Soil Surrounding Pipelines

- General Manhole Information

The general dimensions for the manholes were 1200 mm as per the database. Besides, the database included the ages for the sanitary manholes. The years of construction ranged between 1962 and 2010. However, the majority of the manholes were constructed in 1964 and 1965 as shown in Figure 4.11. Nevertheless, 16 of the manholes year of construction were unknown. Excluding the unknown manhole ages, the average year of construction for the manholes was in 1968 years.

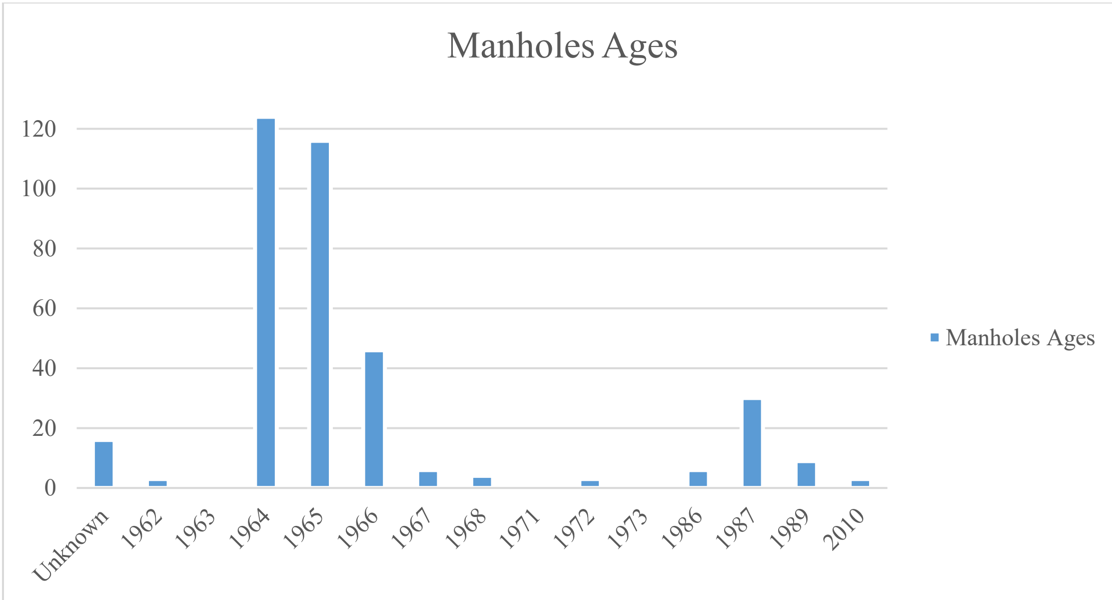


Figure 4.11 Manholes Year of Construction

Chapter Five: Model Implementation & Validation

5.1 Overview

This research consisted of several parts, each part dedicated to accomplish a specific objective. The first part implemented a fuzzy-based assessment of the erosion void surrounding sewer pipelines. The second part proposed a condition assessment model for sewer pipelines and manholes. Nine different models were developed assessing manholes, which were then aggregated together to produce a manhole condition index. A number of techniques were used to accomplish these tasks. The DEMATEL approach was adopted to study the influence of different defects on the asset or component being analyzed. Later, a QFD model was built for each asset and component. Since manhole assessment utilized nine different models, relative importance weights were computed using the ANP method to aggregate the severity percentages of each component. The results of the condition assessment models were used to determine the overall sewer network performance using the criticality model. Based on the calculated network performance, rehabilitation decisions were suggested by applying the PSO tool.

5.2 Erosion Void Model

The erosion void model was developed using five different factors extracted from the literature and suggested by experts. The five parameters are the bedding type, soil type, groundwater presence and pipeline age. The strength of each factor contributing to soil loss were collected from questionnaires from different regions. The scale that was adopted for this model ranged from Excellent to Critical according to certain values, as shown in Table 5.1.

Table 5.1 Void Erosion Condition Scale

Condition	Range
Excellent	0-1
Good	1-2
Fair	2-3
Poor	3-4
Critical	4-5

5.2.1 Membership Functions

5.2.1.1 Bedding Material

Soil type interaction is significant for a pipeline; a stable foundation and consistent bedding along the pipeline lessen and slow the growth of an erosion void around a pipeline. Using unstable foundation or bedding could hinder the soil support at the invert level and at the haunches, allowing an erosion void defect to propagate and lead to serious implications such as sinkholes. The membership functions for bedding material are displayed in Figure 5.1 and they are discrete. A confidence level of 95% (certainty) is assumed. The type of data used for the membership construction are linguistic and based on bedding classes: Class A (Excellent), Class B (Good), Class C (Fair) and Class D (Poor).

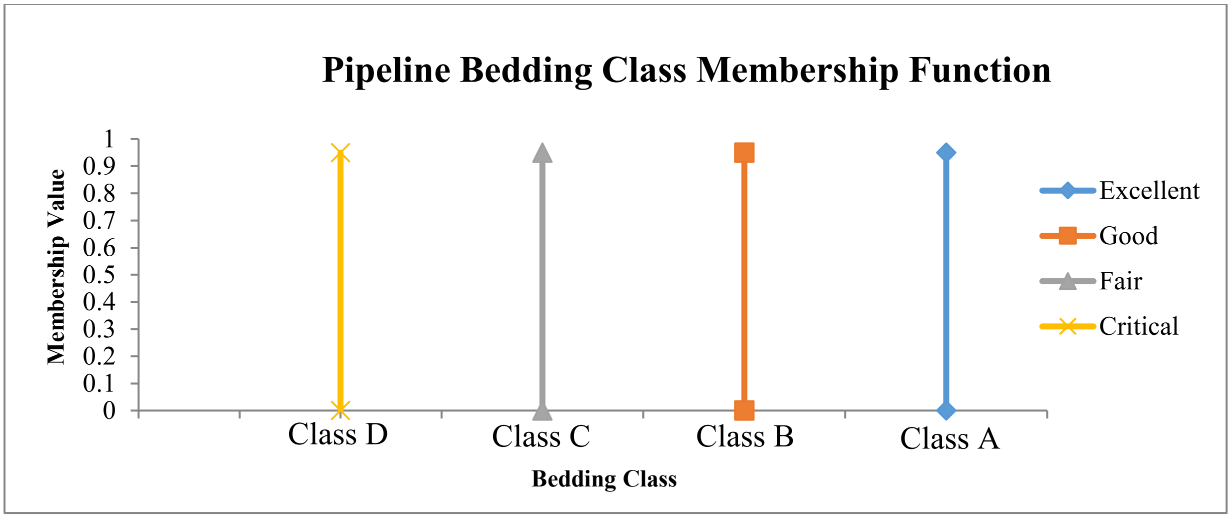


Figure 5.1 Bedding Class Membership Function

5.2.1.2 Pipeline Depth

Pipeline depth is another factor that is considered to impact the severity of the erosion void around a buried pipeline. The soil interaction with a pipeline is important to ensure a stable environment around it. Accordingly, the deeper a pipeline is in the ground, the greater the soil interaction, due to the effect of the soil-structure interaction on the earth pressure. Therefore, the membership function was developed for five different linguistic categories as very deep, deep, medium, shallow and very shallow, as shown in Figure 5.2. The input values are extracted from Pipeline depth is another factor that could influence the erosion voids surrounding the pipeline. The analysis includes the effect of the soil-structure interaction on earth pressure (Balkaya et al. 2012). Deeper pipelines provide higher static pressures as they will form higher soil interactions. In addition, O'Reilly et al. (1989) determined that the defect rate decreases with increasing pipeline depth, which may lead to a lower rate of structural defects. Based on the aforementioned explanation, the depth is categorized as displayed in Table 3.2.

Table 3.2.

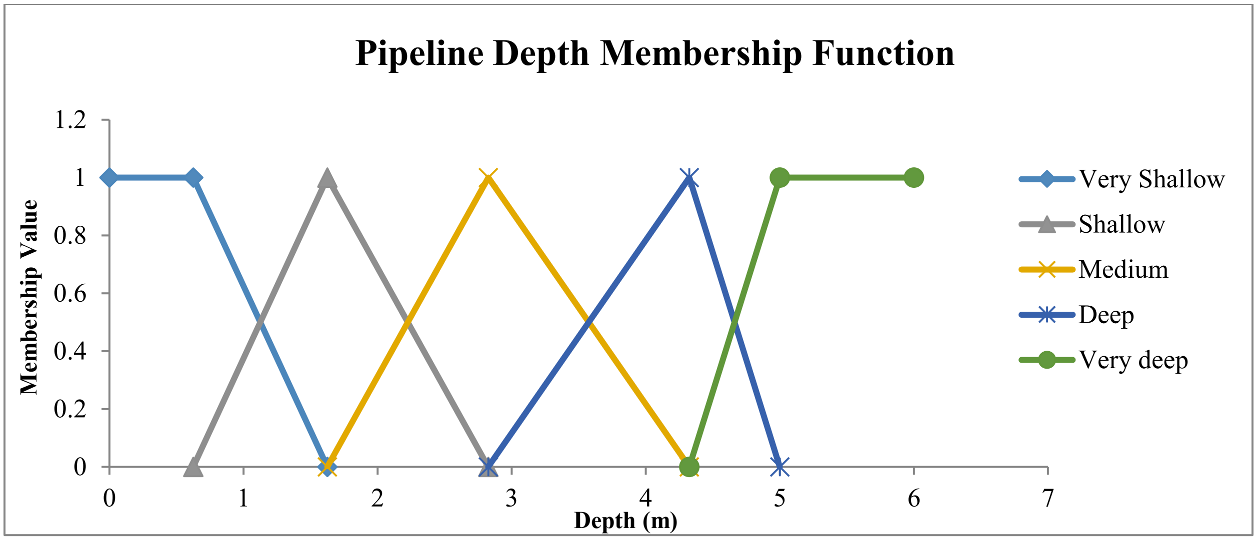


Figure 5.2 Pipeline Depth Membership Function

5.2.1.3 Soil Type

According to the reviewed literature, in the presence of the groundwater table, finer soil particles are more prone to flow inside a pipeline that presents some structural defects. As a result, the finer the soil composition around a pipeline, the more critical the situation. The membership functions are displayed in Figure 5.3 and they are discrete. A 95% confidence level (certainty) is assumed. The type of data used for the membership construction are linguistic and based on soil type: excellent, good, fair, poor and critical.

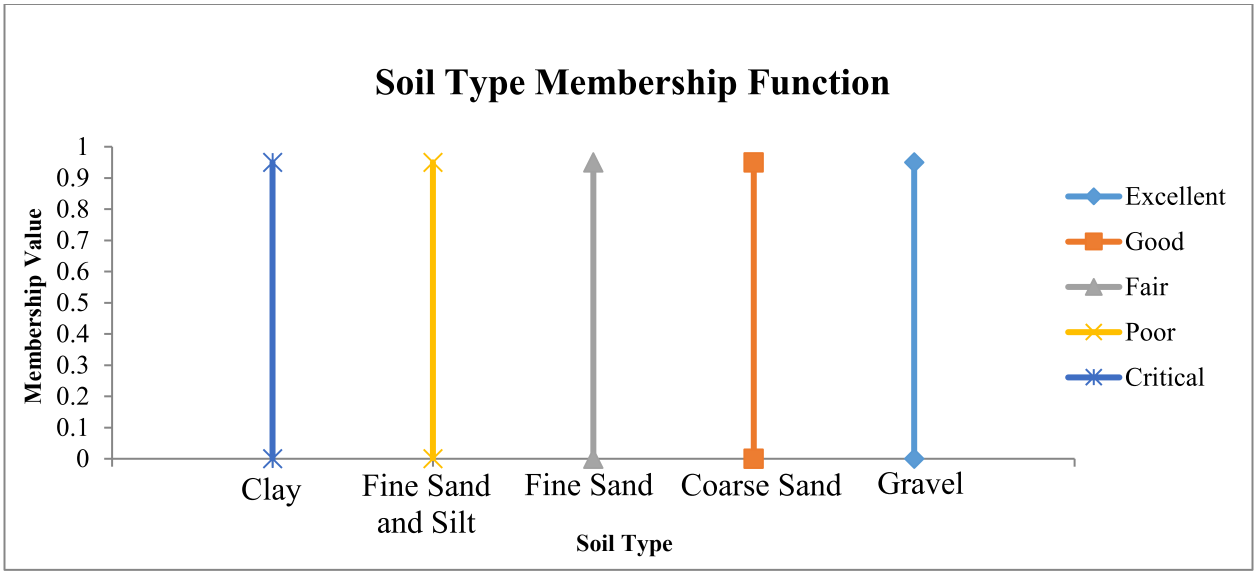


Figure 5.3 Soil Type Membership Function

5.2.1.4 Pipeline Age

Sewer pipelines are prone to deterioration due to ageing; structural defects initiate and eventually evolve to critical ones. Defective sewer pipelines that are continuously below the groundwater table or subject to inflow have higher risks of confronting erosion voids. Therefore, five different categories are used to represent the pipeline age parameter: new, young, medium, old and very old. The membership functions representing the age parameter are shown in Figure 5.4. The older the pipe, the more critical is the need to assess and prevent erosion void.

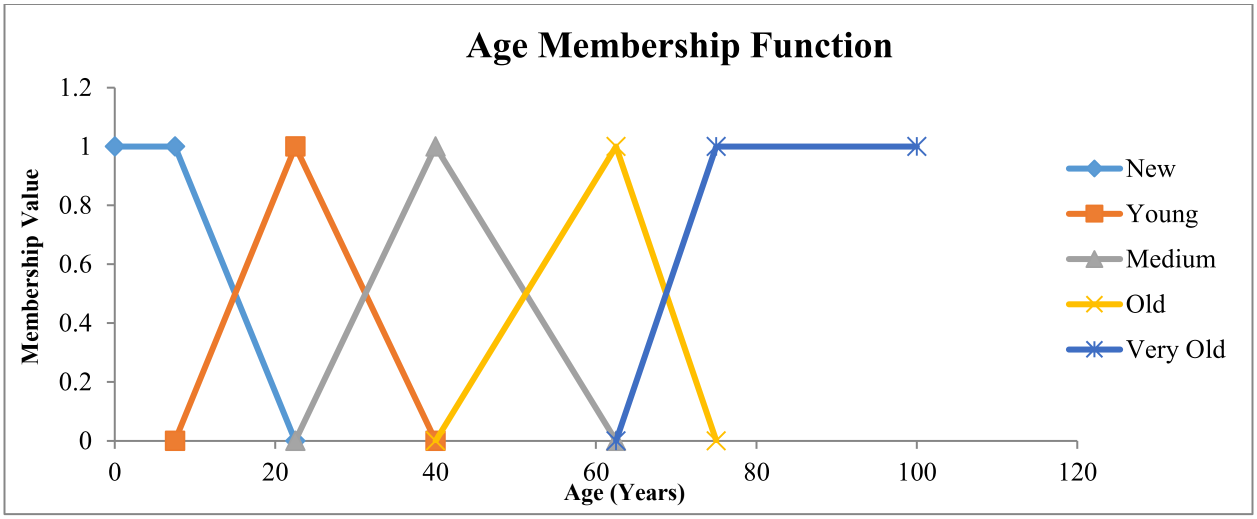


Figure 5.4 Pipeline Age Membership Function

5.2.1.5 Ground Water Table

The formation of voids around pipelines depends on the presence of the inflow or infiltration. Therefore, the most critical situation for a pipeline with erosion void is when the pipeline is below the groundwater table (and vice versa). The membership functions are displayed in Figure 5.5 and they are discrete. A 95% confidence level (certainty) is assumed. The type of data used for the membership construction are linguistic and based on the presence of the groundwater table, with the pipeline below or above.

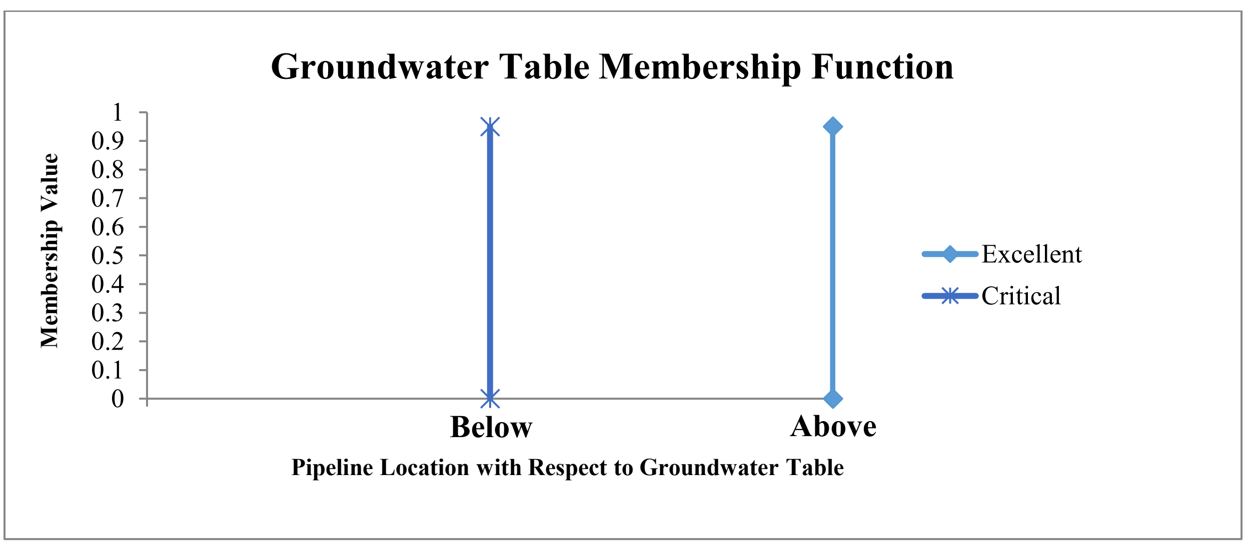


Figure 5.5 Pipeline Location w/r to Groundwater Table Membership Function

5.2.1.6 Grading Scale

To represent the overall condition of the void erosion model, Table 5.1 is used to determine the condition grading scale considering the fuzzy outputs obtained earlier. If the condition of the void erosion is Excellent, the ranges would be from 0 to 1. If the condition of the void erosion is critical, then the range would be from 4 to 5. The fuzzy output membership function of the proposed condition grading is displayed in Figure 5.6 and the outputs are used as a percentage for the pipeline condition assessment as a HOW. For example, if the crisp value of the defuzzified overall output was 2, this means that the condition of the void erosion is 0.5 good and 0.5 fair. As a result, in the HOQ of the pipeline, 50% of the Good condition and 50% of the Fair condition of the void erosion defect will be used.

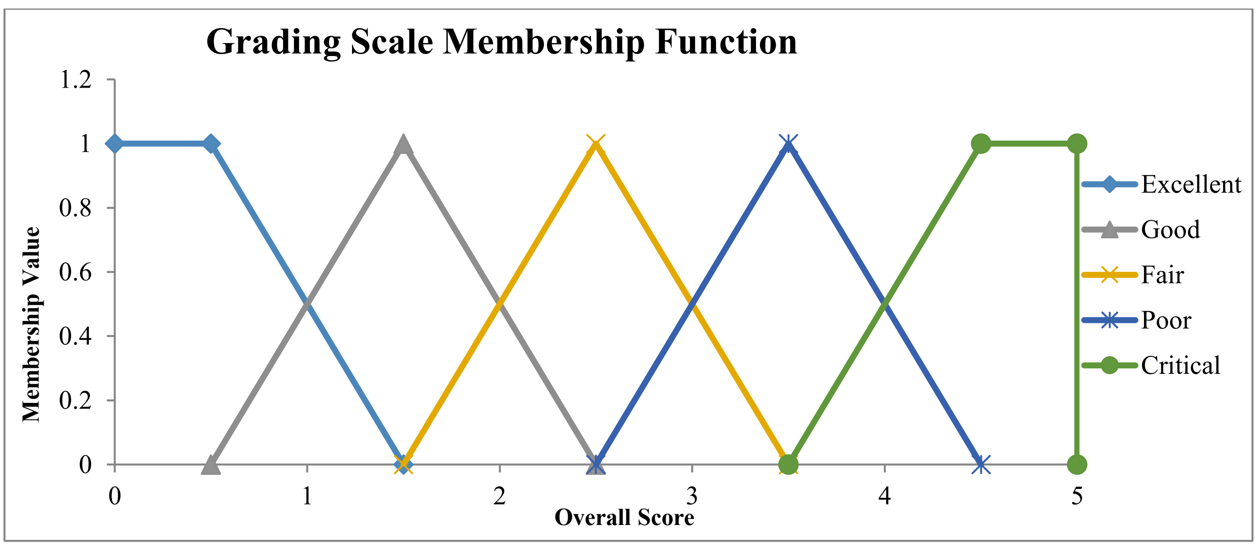


Figure 5.6 Membership Function Grading Scale

5.2.2 Erosion Void Implementation & Validation – a GPR Case Study

Sixteen collected pipelines were used to calculate the crisp index of the erosion voids considering the fuzzy membership functions and the factors' weights. After restructuring the five severities, the outputs will be either acceptable, moderate or inadequate. Thus, a value that is lower or equal to two is acceptable; but a value that is larger than three is inadequate. The resulting computations are summarized in Figure 5.7.

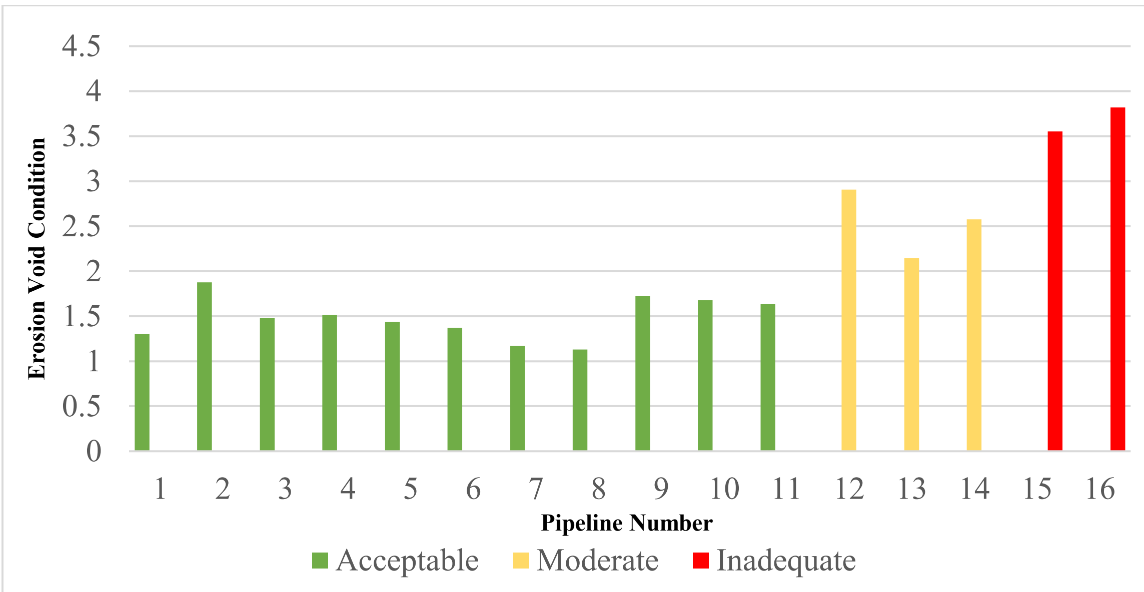


Figure 5.7 GPR Case Study - Erosion Voids

According to the calculated indexes, eleven pipelines were predicted as acceptable, three were predicted as moderate and two as inadequate. Table 5.2 summarizes the results and compares the case study data with the predicted data; this will facilitate forming the confusion tables for each severity to compute the three indicators, which are the accuracy, true positive rate (TPR) and the precision as per equations 5.1, 5.2 and 5.3, respectively.

Table 5.2 Case Study 1 - Erosion Void Results

Severity	Case Study

		Acceptable	Moderate	Critical
Predicted	Acceptable	8	3	0
	Moderate	1	2	0
	Critical	0	0	2

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad [5.1]$$

$$TPR = \frac{TP}{TP + FN} \quad [5.2]$$

$$PPV = \frac{TP}{TP + FP} \quad [5.3]$$

This type of validation was considered as the case study data is in a linguistic form and lacks numeral indexes. The three indicators were calculated after finding the true positive (TP), true negative (TN), false positive (FP) and false negative (FN) of each severity from each confusion table. The TP presents the number of times that the model correctly predicted each category when compared with the case study data (predicted: acceptable; case study: acceptable). The FP indicator describes the incorrect prediction of the model (predicted: moderate; case study: acceptable or inadequate), and the FN represents the number of times that the model failed to predict the severity even though the severity was observed (predicted: moderate or critical and case study: acceptable). The higher the values of the TPR, the more reliable a model is in classifying the erosion void severities, and vice versa. Similarly, higher values of accuracy and precision denote an accurate and precise model. The confusion matrix for each severity can be used to find the three indicators.

Table 5.3 GPR Case Study - Confusion Matrix

Samples	**Condition Positive**	**Type**	**Samples**	**Condition Negative**	**Type**	**Samples**
Positive Predicted	TP	Acceptable Classification	8	FP	Acceptable Classification	3

Condition		Moderate Classification	2		Moderate Classification	1
		Critical Classification	2		Critical Classification	0
Negative Predicated Condition	FN	Acceptable Classification	1	TN	Acceptable Classification	4
		Moderate Classification	3		Moderate Classification	10
		Critical Classification	0		Critical Classification	14

The three indicators can thus be calculated to test the applicability of the model. The results of the three indicators are summarized in Table 5.4.

Table 5.4 Case Study 1 - TPR, Precision and Accuracy Values

Category	TPR	Precision	Accuracy
Acceptable	89%	73%	75%
Moderate	40%	67%	75%
Critical	100%	100%	100%

According to Table 5.4, the TPR of the moderate group was the lowest percentage, as the model predicted three pipelines in acceptable condition while the case study data graded those pipelines to be in moderate condition. However, for these three pipelines, the calculated indexes were closer to 2. On the contrary, the accuracy in predicting the three categories was high, with an average accuracy of 83%. The average precision was 80% and the TPR was 76%. Therefore, the model has the capability of predicting the presence of erosion voids based on the proposed fuzzy expert model. Since the actual erosion void data from the city of Edmonton is scarce, the developed erosion void model was used as validation and the results were satisfactory.

5.2.3 Erosion Void Implementation – City of Edmonton Case Study

Since the previous case study attained satisfactory results, the erosion void model is used to predict potential soil support loss in the Royal Gardens neighborhood of Edmonton. The input data for all the network's pipelines are used so that the conditions can later be used for the pipeline assessment model. Based on the implementation, the conditions ranged between 1 and 3.5. Since the outputs of this model will be the inputs for the HOQ for the pipeline condition assessment model, the crisp value shall be interpreted using the overall fuzzy membership grading scale, shown in Figure 5.6. Therefore, the output of the model shall be in the form of Condition_1, Percentage_1 and Condition_2, Percentage_2. As an example, a crisp value of 1.82 is interpreted as Good, 68% and Fair, 32%. The conditions and their corresponding percentages are used in the HOQ to further calculate the pipeline condition. , The summarized results based on this case study are displayed in Figure 5.8, where three condition groups were concluded. Detailed percentages are shown in Figures Figure 5.9, Figure 5.10 and Figure 5.11. Based on the results, almost half of the pipelines of the neighborhood have a condition of Good to Fair. The remaining are classified such that 28% are considered Fair to Poor and 26% are in Excellent to Good condition. No critical scenarios are triggered, as 71.5% of the population are buried above the groundwater table. In addition, the bedding types and surrounding soils for most of the pipelines are adequate to prevent void erosion situations. Therefore, the results suggest that the pipelines are all in a condition wherein collapses or sinkholes are not imminent. This conclusion is confirmed with the senior infrastructure engineer who claimed that no sinkholes were reported in the neighborhood.

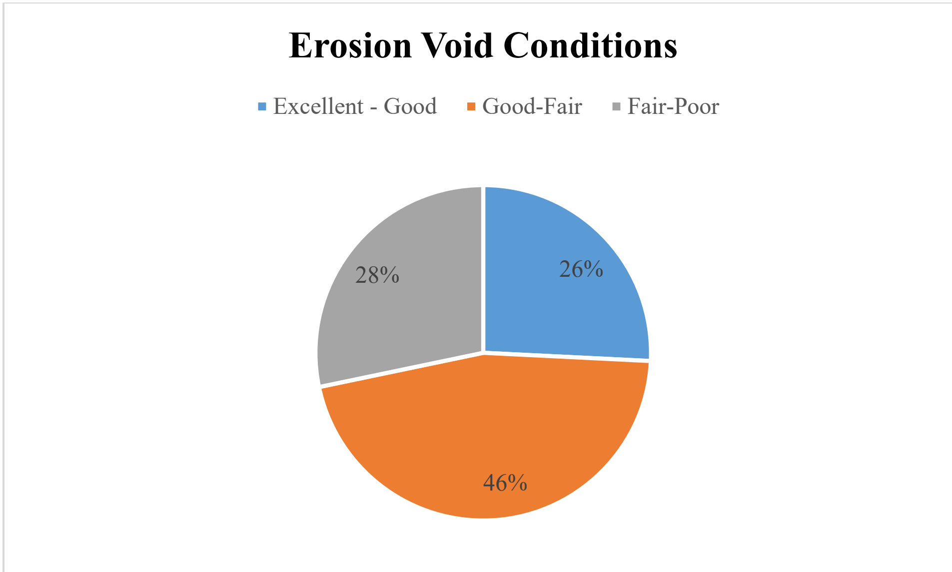


Figure 5.8 Royal Gardens Pipelines Erosion Void Conditions - Summary

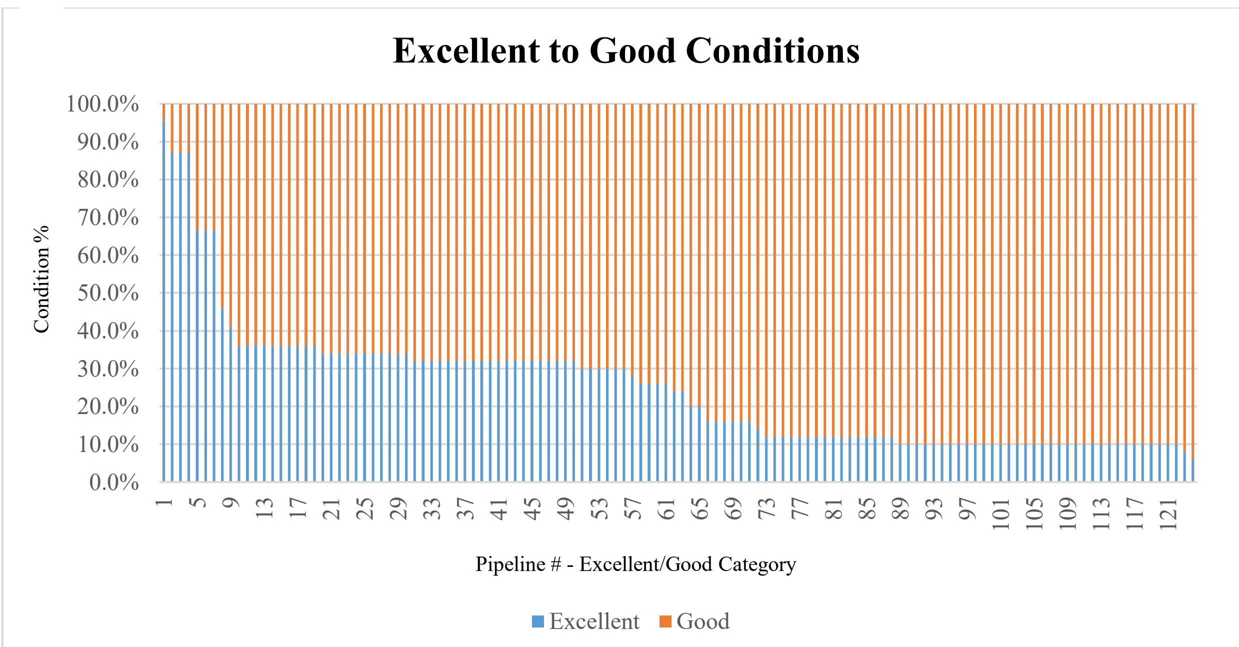


Figure 5.9 Royal Gardens Pipelines Erosion Void Conditions - Excellent to Good Conditions

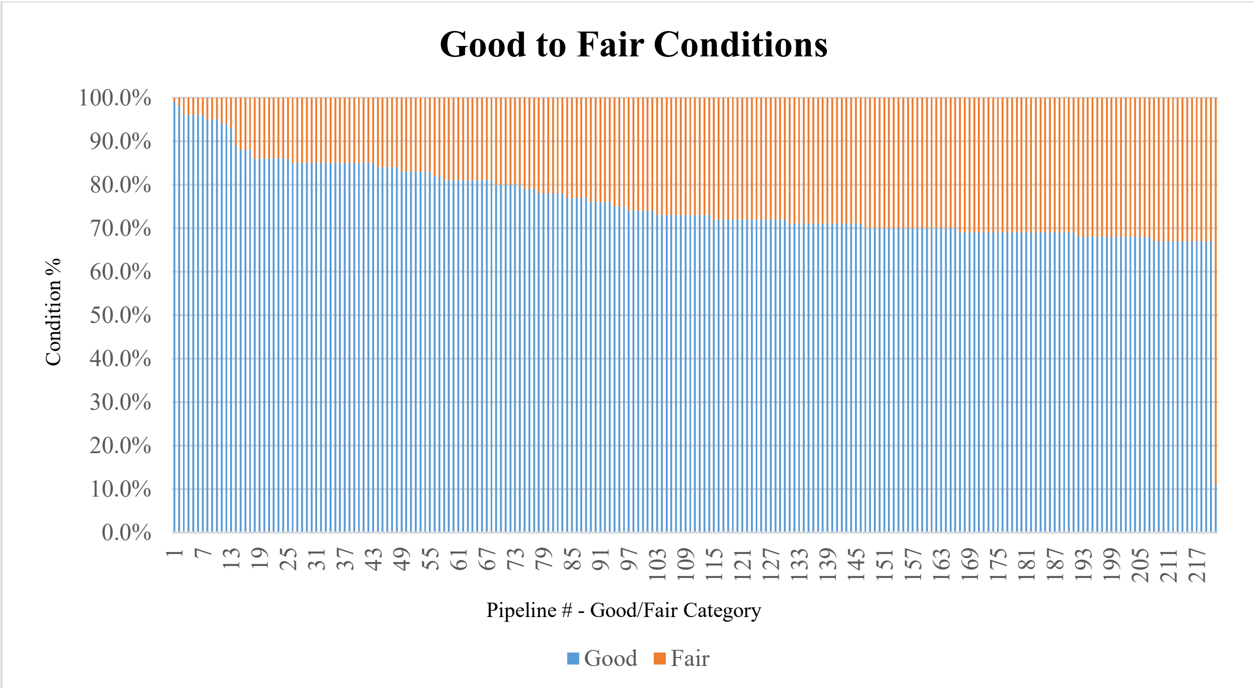


Figure 5.10 Royal Gardens Pipelines Erosion Void Conditions - Good to Fair Conditions

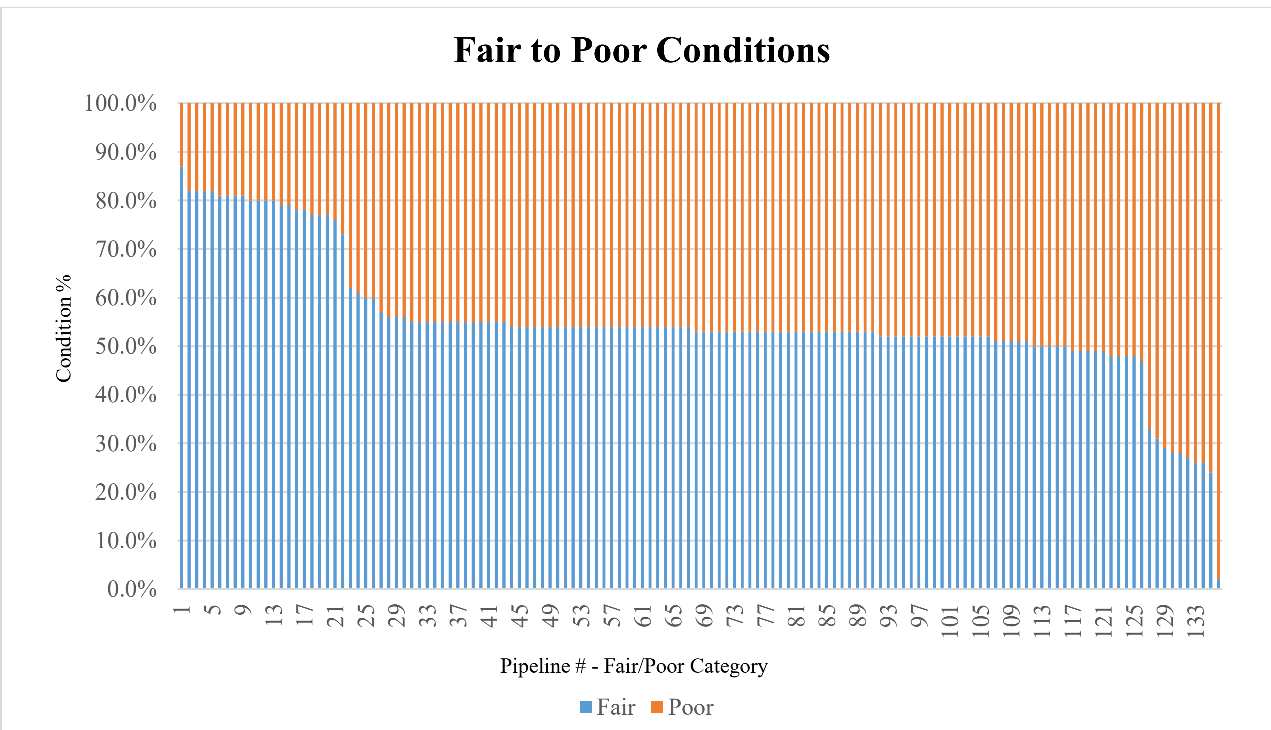


Figure 5.11 Royal Gardens Pipelines Erosion Void Conditions - Fair to Poor Conditions

5.3 Pipeline Condition Assessment Model

The pipeline condition assessment model relied on two methods: DEMATEL and QFD. The DEMATEL method was used to establish an influence matrix in the QFD model, where the WHAT's and HOW's were identified accordingly. The WHAT's represented the five different severity conditions: Excellent, Good, Fair, Poor and Critical, and the HOW's were the defects percentages computed from actual reports after considering the defect counts for each defect. Twenty-two defects were considered to evaluate a sewer pipeline's condition, a mix of operational, structural and construction feature defects. They were sorted as one group to study the influence of each one on the other and to determine the cause and effect relationships.

5.3.1 QFD

Based on the questionnaire received from thirty two experts, the influence matrix in the HOQ of the pipeline was developed and is shown in Figure 5.12. For example, defect number 1, longitudinal crack, had an influence of 0.03 on defect number 7 (deformation); however, the deformation defect (7) had an influence of 3.98 on longitudinal cracks. This shows that the deformation defect has a very strong influence on the propagation of a longitudinal crack. However, a longitudinal crack had minimal to no influence on causing a deformation, according to the average influence matrix. On the other hand, when comparing defect number 2 (circumferential crack) with defect number 7, the deformation defect had an influence of 1.82 on the propagation of the circumferential crack, which was obviously lower than the influence of deformation on the longitudinal crack. This is inherently true, because longitudinal cracks initiate due to structural consequences; however, circumferential cracks propagate due to construction faults and so are not as critical as longitudinal cracks.

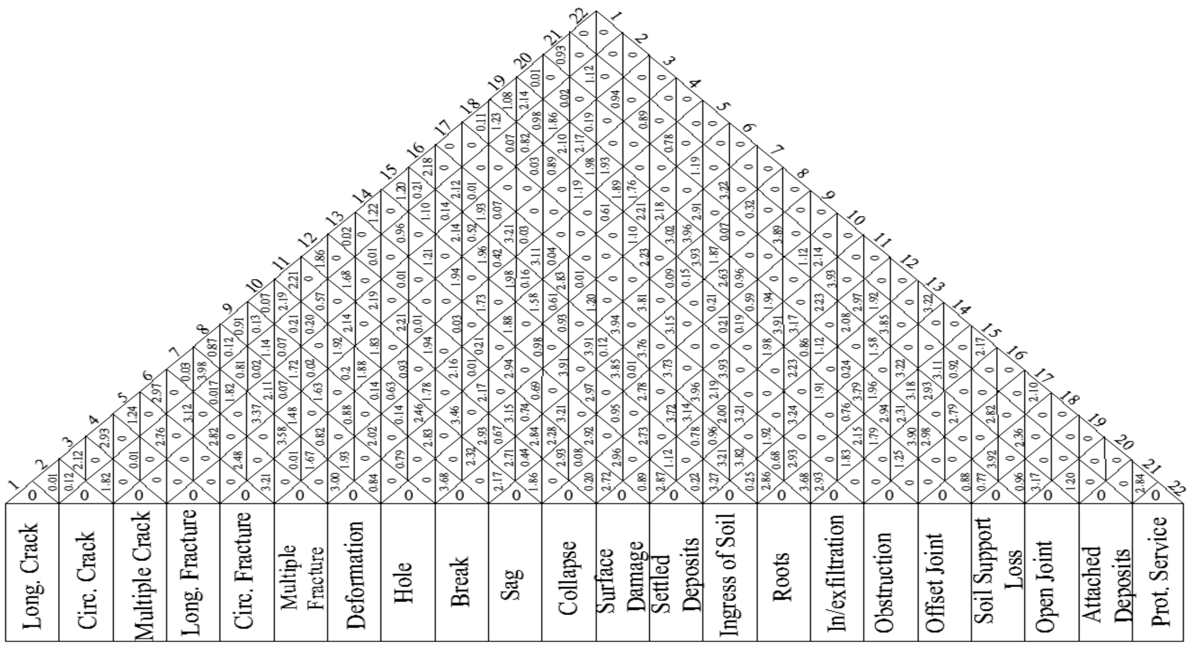


Figure 5.12 Influence Matrix

After finding the average influence matrix, the normalized influence matrix was computed after comparing the maximum summation of each column and row. The highest number was taken and was divided by the values in the average influence matrix. The resulting normalized influence matrix is shown in Table 5.5:

Table 5.5 Average Influence Matrix

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0.000	0.000	0.047	0.065	0.027	0.065	0.001	0.019	0.020	0.002	0.049	0.041	0.001	0.027	0.026	0.048	0.000	0.002	0.024	0.000	0.021	0.000
2	0.003	0.000	0.040	0.000	0.061	0.069	0.000	0.018	0.025	0.005	0.013	0.037	0.000	0.021	0.024	0.047	0.000	0.002	0.022	0.000	0.025	0.000
3	0.000	0.000	0.000	0.000	0.000	0.063	0.000	0.047	0.038	0.000	0.047	0.048	0.000	0.027	0.047	0.043	0.000	0.001	0.046	0.004	0.021	0.000
4	0.000	0.000	0.000	0.000	0.000	0.055	0.000	0.033	0.036	0.004	0.040	0.049	0.000	0.043	0.043	0.071	0.000	0.000	0.044	0.000	0.020	0.000
5	0.000	0.000	0.000	0.000	0.000	0.071	0.000	0.018	0.019	0.003	0.021	0.043	0.001	0.038	0.044	0.069	0.000	0.000	0.042	0.000	0.017	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.043	0.045	0.003	0.039	0.048	0.005	0.041	0.035	0.062	0.000	0.000	0.049	0.000	0.026	0.000
7	0.088	0.040	0.074	0.079	0.037	0.066	0.000	0.019	0.017	0.062	0.076	0.048	0.065	0.022	0.021	0.026	0.000	0.049	0.067	0.064	0.071	0.000
8	0.003	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.065	0.069	0.015	0.086	0.086	0.087	0.084	0.002	0.087	0.002	0.007	0.000
9	0.003	0.002	0.000	0.000	0.000	0.000	0.000	0.081	0.000	0.000	0.060	0.063	0.071	0.065	0.085	0.083	0.069	0.000	0.058	0.000	0.086	0.000
10	0.048	0.004	0.042	0.041	0.014	0.054	0.000	0.051	0.048	0.000	0.041	0.065	0.064	0.021	0.061	0.082	0.000	0.005	0.013	0.000	0.025	0.000
11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.010	0.000	0.000	0.004	0.065	0.060	0.082	0.087	0.087	0.000	0.086	0.000	0.087	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.016	0.050	0.002	0.060	0.000	0.020	0.025	0.017	0.044	0.000	0.000	0.019	0.000	0.065	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.063	0.000	0.005	0.071	0.000	0.000	0.000	0.000	0.000	0.085	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.072	0.000	0.006	0.015	0.000	0.000	0.084	0.000	0.000	0.000
15	0.005	0.003	0.011	0.009	0.004	0.013	0.000	0.003	0.000	0.000	0.069	0.021	0.084	0.063	0.000	0.081	0.000	0.047	0.065	0.070	0.069	0.000
16	0.000	0.000	0.002	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.048	0.071	0.042	0.065	0.065	0.000	0.000	0.000	0.086	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.071	0.000	0.040	0.000	0.000	0.000	0.000	0.000	0.062	0.000
18	0.027	0.018	0.020	0.026	0.013	0.024	0.000	0.003	0.005	0.004	0.044	0.049	0.042	0.017	0.039	0.028	0.000	0.000	0.019	0.086	0.052	0.000
19	0.047	0.041	0.048	0.043	0.039	0.048	0.087	0.041	0.021	0.043	0.070	0.025	0.005	0.043	0.051	0.066	0.000	0.017	0.000	0.021	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.049	0.046	0.035	0.071	0.065	0.062	0.000	0.000	0.070	0.000	0.026	0.000
21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.047	0.000	0.042	0.000	0.000	0.020	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.071	0.000	0.048	0.000	0.046	0.000	0.000	0.000	0.063	0.000

Later, the total direct influence matrix was found; the matrix resulting from this operation is shown in Table 5.6.

Table 5.6 Direct Influence Matrix

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0	0	0.05	0.07	0.03	0.08	0.01	0.04	0.04	0.01	0.08	0.07	0.03	0.06	0.06	0.09	0.01	0.01	0.07	0.01	0.05	0
2	0.01	0	0.05	0	0.06	0.08	0.01	0.03	0.04	0.01	0.04	0.06	0.02	0.05	0.06	0.08	0.01	0.01	0.06	0.01	0.05	0
3	0.01	0	0.01	0.01	0	0.07	0.01	0.06	0.05	0.01	0.08	0.08	0.03	0.06	0.08	0.08	0.02	0.01	0.09	0.01	0.05	0
4	0.01	0	0.01	0.01	0	0.06	0.01	0.05	0.05	0.01	0.07	0.08	0.03	0.08	0.08	0.11	0.01	0.01	0.08	0.01	0.05	0
5	0.01	0	0.01	0.01	0	0.08	0.01	0.03	0.03	0.01	0.05	0.07	0.03	0.07	0.07	0.1	0.01	0.01	0.08	0.01	0.04	0
6	0.01	0	0.01	0.01	0	0.01	0.01	0.05	0.05	0.01	0.07	0.07	0.03	0.07	0.07	0.1	0.01	0.01	0.09	0.01	0.05	0
7	0.1	0.05	0.09	0.1	0.05	0.11	0.01	0.05	0.05	0.08	0.14	0.12	0.11	0.09	0.1	0.11	0.02	0.06	0.14	0.08	0.13	0
8	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.1	0.1	0.06	0.12	0.13	0.13	0.09	0.01	0.13	0.02	0.05	0
9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.09	0.01	0.01	0.1	0.1	0.12	0.11	0.14	0.13	0.09	0.01	0.11	0.01	0.13	0
10	0.05	0.01	0.05	0.05	0.02	0.07	0.01	0.07	0.06	0.01	0.09	0.11	0.1	0.07	0.12	0.14	0.02	0.01	0.07	0.01	0.07	0
11	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.02	0.01	0.03	0.04	0.1	0.09	0.12	0.12	0.09	0.01	0.12	0.01	0.12	0
12	0	0	0	0	0	0	0	0.03	0.05	0.01	0.08	0.02	0.04	0.05	0.04	0.07	0.01	0	0.05	0	0.09	0
13	0	0	0	0	0	0	0	0	0	0.01	0.01	0.07	0.01	0.02	0.08	0.01	0	0	0.01	0.01	0.1	0
14	0.01	0	0.01	0.01	0	0.01	0.01	0.01	0	0.01	0.01	0.01	0.08	0.01	0.02	0.03	0	0	0.09	0	0.01	0
15	0.01	0.01	0.02	0.02	0.01	0.03	0.01	0.01	0.01	0.01	0.1	0.06	0.12	0.1	0.05	0.12	0.01	0.05	0.11	0.08	0.1	0
16	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.07	0.09	0.07	0.09	0.09	0.03	0.01	0.01	0.12	0.01	0.03	0
17	0	0	0	0	0	0	0	0	0	0	0.01	0.01	0.08	0.01	0.05	0.01	0	0	0.01	0	0.07	0
18	0.03	0.02	0.03	0.03	0.02	0.04	0.01	0.02	0.02	0.01	0.08	0.08	0.07	0.05	0.08	0.07	0.01	0.01	0.06	0.09	0.08	0
19	0.06	0.05	0.07	0.06	0.05	0.08	0.09	0.07	0.04	0.06	0.13	0.08	0.06	0.1	0.11	0.14	0.02	0.03	0.07	0.04	0.05	0
20	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.08	0.07	0.06	0.1	0.09	0.09	0.01	0.01	0.1	0.01	0.05	0
21	0	0	0	0	0	0	0	0	0.01	0.05	0.01	0.05	0.01	0.01	0.03	0.01	0	0	0.01	0	0.01	0
22	0	0	0	0	0	0	0	0	0	0	0.01	0.01	0.08	0.01	0.06	0.01	0.05	0	0.01	0	0.08	0

As a result, the contribution of each element in terms of its cause and effect in the system was found by summing up the column of each defect with the row of the same defect. This information is displayed in Table 5.7.

Table 5.7 DEMATEL Method Results

Number	Sum of Columns	Sum of Rows	C+R	R-C	Weight
1	0.87	0.36	1.23	0.51	0.035
2	0.73	0.20	0.93	0.53	0.026
3	0.81	0.45	1.26	0.36	0.035
4	0.80	0.41	1.22	0.39	0.034
5	0.70	0.31	1.01	0.39	0.028
6	0.74	0.78	1.52	-0.05	0.043
7	1.79	0.23	2.02	1.55	0.057
8	1.04	0.68	1.72	0.36	0.048
9	1.22	0.56	1.79	0.66	0.050
10	1.21	0.34	1.55	0.87	0.044
11	0.97	1.44	2.41	-0.47	0.068
12	0.56	1.45	2.02	-0.89	0.057
13	0.35	1.34	1.69	-0.98	0.047
14	0.34	1.40	1.74	-1.06	0.049
15	1.05	1.74	2.78	-0.69	0.078
16	0.70	1.78	2.48	-1.08	0.070
17	0.25	0.51	0.76	-0.25	0.021
18	0.89	0.25	1.14	0.64	0.032
19	1.66	1.47	3.13	0.19	0.088
20	0.75	0.45	1.20	0.31	0.034
21	0.21	1.47	1.68	-1.26	0.047
22	0.33	0.00	0.33	0.33	0.009

Based on this table, the value of C+R of each defect represents the impact of each element in the system considering its cause and effect powers. Consequently, the "Weight" column is basically the relative total influence of the defect in the system, computed from the C+R column. According to Table 5.7 , voids present outside pipelines had the greatest weight. This reflects the reality, as when soil voids present, pipelines are subject to deformation and critical structural defects. More cracks and fractures will propagate with leakage, causing other defects to initiate as explained earlier. The cumulative influence of all defects influenced by the soil void is amalgamated in the relative influence weight. The least relative weight was that for a protruding service. The reason for such a low value is that protruding services only exist in the system due to design and construction faults. Based on the questionnaires, a protruding service can cause defects such as settled deposits, ingress of soil, roots, obstruction and attached deposits; however, no defects contribute to the protruding service.

The R-C column in the table distinguishes defects in terms of influencing defects and influenced defects. Any value that is less than zero is considered as an influenced defect, while any value that is greater than zero suggests that a defect is an influencing defect. Figure 5.13 scatters the R-C values of each defect number. Based on the results and as shown in Figure 5.14, the influencing defects' percentage in the system was 59%, including cracks in all their patterns, longitudinal and circumferential fractures, deformation, hole, broken, sag, offset joint, open joint, erosion void and protruding services; the remaining 41% were the defects that were influenced by defects in the system.

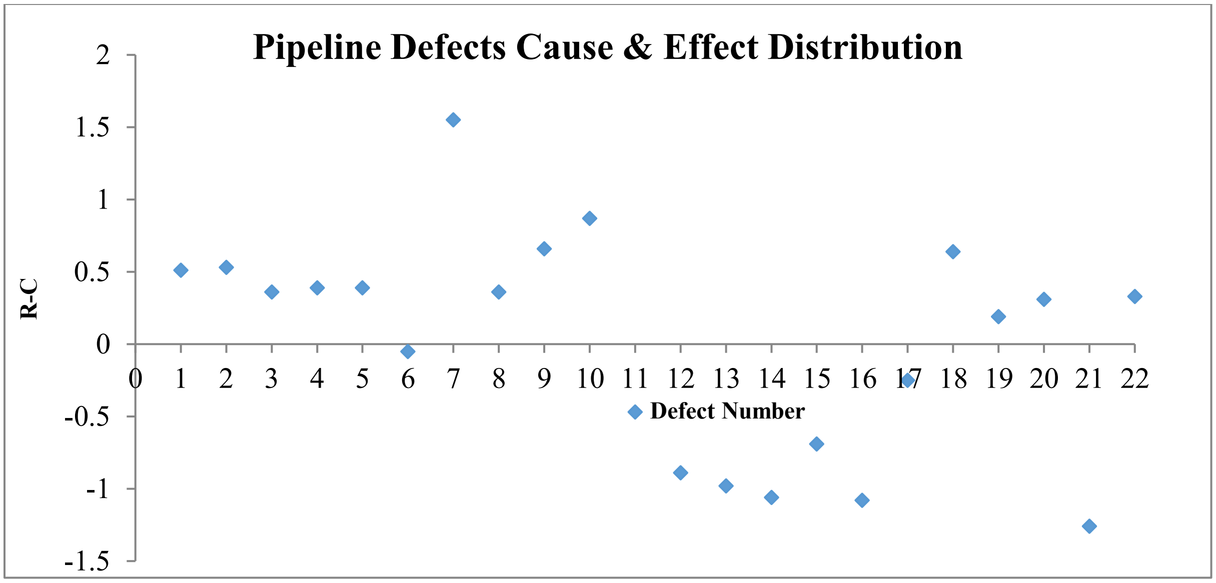


Figure 5.13 Influencing Defects vs. Influenced Defects

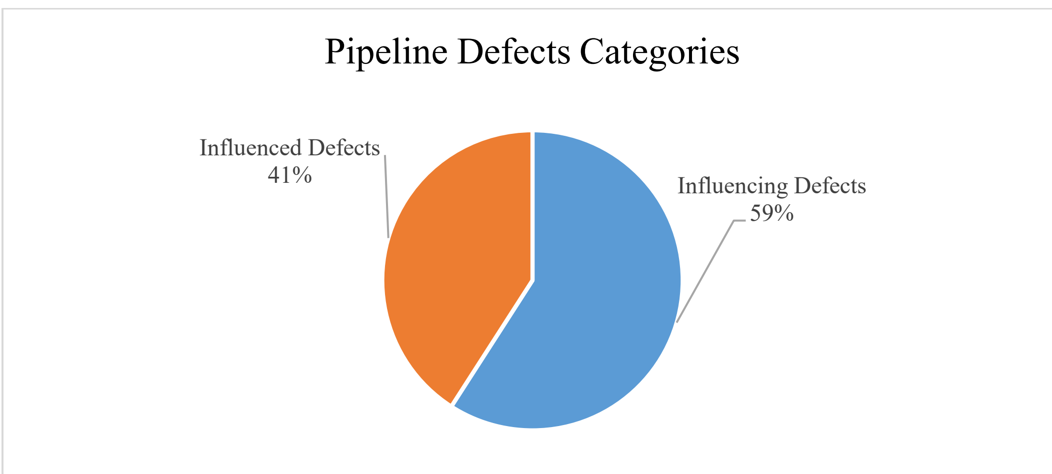
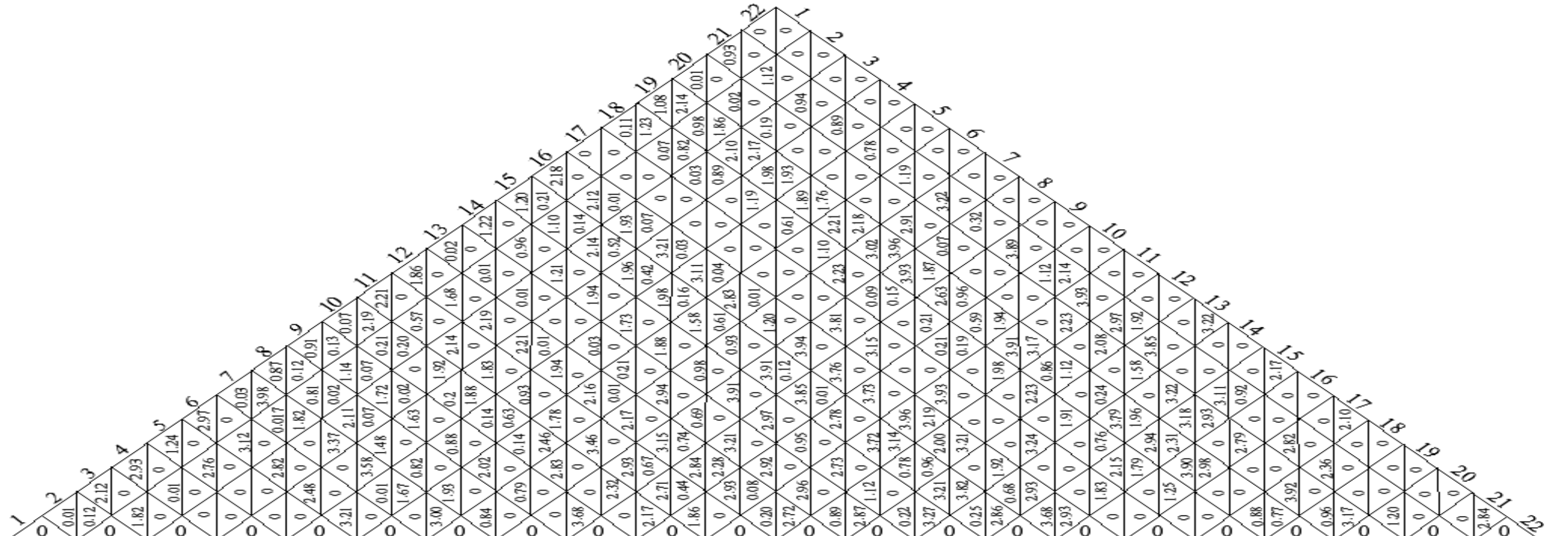


Figure 5.14 Pipeline Defects Summary - Influencing vs. Influenced

After studying the influence impact of each defect, the HOQ model was completed after considering the relative influence weights found in Table 5.7. Figure 5.15 shows an example of implementing the HOQ condition assessment model.



Severity	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
		Long. Crack	Circ. Crack	Multiple Crack	Long. Fracture	Circ. Fracture	Multiple Fracture	Deformation	Hole	Break	Sag	Collapse	Surface Damage	Settled Deposits	Ingress of Soil	Roots	In/exfiltration	Obstruction	Offset Joint	Soil Support Loss	Open Joint	Attached Deposits	Prot. Service
		1.23	0.93	1.26	1.22	1.01	1.52	2.02	1.72	1.79	1.55	2.41	2.02	1.69	1.74	2.78	2.48	0.76	1.14	3.13	1.20	1.68	0.33
	Relative Influence Weight	0.035	0.026	0.035	0.034	0.028	0.043	0.057	0.048	0.050	0.044	0.068	0.057	0.047	0.049	0.078	0.070	0.021	0.032	0.088	0.034	0.047	0.009
Excellent	1	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Good	2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	85.00%	0.00%	0.00%	0.00%
Fair	3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	15.00%	0.00%	0.00%	0.00%
Poor	4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Critical	5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Excellent	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Good	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	85	0	0	0
Fair	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0
Poor	4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Critical	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.15 Pipeline HOQ Implementation

The inputs of the model are the defect counts for a pipeline which are inserted in the second table of the same figure. The percentages of each severity is then calculated based on the aggregation of the same severity by the relative influence weight of each defect. The resulting five different severities of the pipeline are thereby calculated. For example, for pipeline segment number 7, the report indicated that two defects were observed and the PACP grade was 2.50. The first one was settled deposits and the second was a circumferential fracture. Based on the information provided in the report, each defect's severity was compared with the defect information proposed in this research. Therefore, for the circumferential crack, a grade 1 was considered. However, for the settled deposits, a grade 4 was considered. Since the reports did not evaluate the erosion void defect, the severity of the aforementioned defect was incorporated from the erosion void model outputs. In summary, Table 5.8 displays the information obtained and the assigned grades, with the position of the defect reported in the clockwise direction, showing the PACP grade and the grade based on the research evaluation. It can be observed that the void erosion defect was 85% Good and 15% Fair. The circumferential fracture grade was 1 since it was located between the 1 and 2 clock positions. The information listed in the table was transferred to the HOQ and automatically translated to percentages.

Table 5.8 Sample Pipeline Defects, Actual Grades & Research Grades

Defect	Value	From (Clock Position)	To (Clock Position)	PACP Grade	Research Grade
Circumferential Fracture	NA	1	2	2	1
Settled Deposits	30%	6	NA	4	4
Erosion Void	NA	NA	NA	NA	85% Good & 15% Fair

The relative influence weights were used to aggregate each severity grade separately, considering the defect counts and the information. Table 5.9 shows the severity grade percentage calculated for the considered pipeline. The pipeline had five severity grades with different percentages. Since the Good grade for erosion void was 85% and knowing that the relative influence weight for this defect was the highest, the aggregated grade percentage for Good was the highest among the other grades. The relative weights of the condition grade percentages were then found to calculate the overall grade for the pipeline on a scale of 1 to 5. As a result, the overall grade can be found as follows:

Overall Grade = 1*0.1728 + 2* 0.4567 + 3*0.0806 + 4*0.2900 + 5*0.00 = 2.49

Table 5.9 Sample Pipeline Condition Grades and Overall Grade

Grade	Condition Grade %	Condition Grade Relative Weight %	Overall Grade
Excellent	2.83%	17.28%	2.49
Good	7.48%	45.67%	
Fair	1.32%	8.06%	
Poor	4.75%	29.00%	
Critical	0.00%	0.00%	

The remaining pipeline conditions were calculated following the aforementioned methodology. From the 481 sewer pipelines obtained, 85 contained defects and observations. Therefore, 85 HOQs were designed and the overall grades calculated accordingly. Table 5.10 displays the resulting grade percentages as well as the calculated overall grades.

Table 5.10 Pipelines Actual and Calculated Overall Grades

Pipeline #	Excellent	Good	Fair	Poor	Critical	PACP Grade	Estimated Grade
1	17.02%	82.98%	0.00%	0.00%	0.00%	2.00	1.83
2	13.85%	47.04%	13.59%	0.00%	25.52%	1.86	2.76
3	0.00%	55.96%	44.04%	0.00%	0.00%	2.00	2.44
4	12.75%	70.64%	16.61%	0.00%	0.00%	1.40	2.04

Pipeline #	Excellent	Good	Fair	Poor	Critical	PACP Grade	Estimated Grade
5	0.00%	42.42%	14.14%	0.00%	43.44%	5.00	3.44
6	0.00%	32.56%	31.71%	0.00%	35.73%	2.33	3.39
7*	17.28%	45.67%	8.06%	29.00%	0.00%	2.50	2.49
8	12.41%	26.61%	60.98%	0.00%	0.00%	1.67	2.49
9	0.00%	43.95%	56.05%	0.00%	0.00%	3.00	2.56
10	0.00%	25.88%	19.99%	16.77%	37.36%	2.71	3.66
11	0.00%	48.59%	19.96%	0.00%	31.45%	1.86	3.14
12	6.79%	49.58%	22.10%	0.00%	21.52%	1.00	2.80
13	6.79%	49.55%	43.66%	0.00%	0.00%	1.00	2.37
14	0.00%	23.59%	24.02%	0.00%	52.39%	2.60	3.81
15	6.29%	10.50%	17.86%	20.24%	45.11%	2.38	3.87
16	0.00%	50.94%	49.06%	0.00%	0.00%	2.00	2.49
17	0.00%	79.25%	20.75%	0.00%	0.00%	2.00	2.21
18	0.00%	33.42%	40.10%	0.00%	26.48%	2.33	3.20
19	0.00%	85.06%	14.94%	0.00%	0.00%	2.00	2.15
20	0.00%	21.05%	9.02%	19.41%	50.53%	2.50	3.99
21	0.00%	37.00%	38.24%	24.75%	0.00%	1.00	2.88
22	0.00%	35.06%	35.06%	29.89%	0.00%	2.00	2.95
23	0.00%	0.00%	37.23%	37.00%	25.76%	4.00	3.89
24	14.56%	0.00%	23.51%	21.71%	40.23%	2.40	3.73
25	23.19%	38.68%	7.71%	0.00%	30.42%	2.29	2.76
26	31.90%	68.10%	0.00%	0.00%	0.00%	2.00	1.68
27	18.65%	51.68%	0.00%	0.00%	29.66%	2.25	2.70
28	0.00%	42.65%	57.35%	0.00%	0.00%	3.00	2.57
29	6.27%	76.92%	16.81%	0.00%	0.00%	2.00	2.11
30	18.72%	49.79%	9.62%	14.37%	7.50%	1.83	2.42
31	5.34%	75.64%	10.65%	8.36%	0.00%	2.00	2.22
32	0.00%	26.29%	43.21%	30.50%	0.00%	2.25	3.04
33	0.00%	35.08%	34.42%	30.50%	0.00%	2.00	2.95
34	27.30%	58.00%	14.70%	0.00%	0.00%	1.75	1.87
35	27.30%	58.00%	14.70%	0.00%	0.00%	4.00	1.87
36	53.63%	46.37%	0.00%	0.00%	0.00%	1.86	1.46
37	23.61%	40.16%	7.06%	0.00%	29.17%	2.73	2.71
38	0.00%	47.42%	52.58%	0.00%	0.00%	2.90	2.53
39	0.00%	47.42%	52.58%	0.00%	0.00%	3.00	2.53
40	0.00%	0.00%	74.91%	25.09%	0.00%	2.33	3.25
41	0.00%	0.00%	66.37%	33.63%	0.00%	3.00	3.34
42	0.00%	64.39%	35.61%	0.00%	0.00%	1.00	2.36

Pipeline #	Excellent	Good	Fair	Poor	Critical	PACP Grade	Estimated Grade
43	0.00%	41.47%	58.53%	0.00%	0.00%	2.00	2.59
44	0.00%	0.00%	68.17%	31.83%	0.00%	1.00	3.32
45	0.00%	70.00%	30.00%	0.00%	0.00%	3.00	2.30
46	0.00%	82.95%	17.05%	0.00%	0.00%	1.00	2.17
47	24.35%	53.70%	21.94%	0.00%	0.00%	1.33	1.98
48	0.00%	55.67%	44.33%	0.00%	0.00%	3.00	2.44
49	0.00%	49.92%	50.08%	0.00%	0.00%	1.00	2.50
50	0.00%	73.04%	26.96%	0.00%	0.00%	2.00	2.27
51	0.00%	12.06%	43.76%	24.37%	19.82%	2.52	3.52
52	28.46%	15.82%	41.57%	14.15%	0.00%	1.88	2.41
53	39.17%	0.00%	31.63%	29.20%	0.00%	1.00	2.51
54	21.76%	37.94%	17.83%	0.00%	22.46%	2.70	2.63
55	16.15%	14.01%	39.83%	11.75%	18.25%	2.21	3.02
56	20.96%	16.40%	47.98%	14.66%	0.00%	2.04	2.56
57	22.16%	18.48%	28.97%	16.52%	13.86%	2.13	2.81
58	33.24%	18.48%	16.44%	17.97%	13.86%	1.88	2.61
59	27.53%	43.48%	9.34%	7.88%	11.77%	2.00	2.33
60	0.00%	19.06%	32.31%	48.63%	0.00%	2.18	3.30
61	13.15%	26.29%	36.30%	5.39%	18.87%	2.39	2.91
62	0.00%	32.55%	44.54%	0.00%	22.92%	2.00	3.13
63	0.00%	45.18%	54.82%	0.00%	0.00%	3.00	2.55
64	0.00%	45.18%	54.82%	0.00%	0.00%	3.00	2.55
65	0.00%	45.84%	54.16%	0.00%	0.00%	3.00	2.54
66	0.00%	0.00%	71.35%	28.65%	0.00%	3.00	3.29
67	0.00%	0.00%	70.69%	29.31%	0.00%	3.00	3.29
68	0.00%	32.40%	47.69%	0.00%	19.91%	2.80	3.07
69	4.94%	39.78%	14.32%	4.94%	36.02%	2.20	3.27
70	0.00%	60.18%	15.80%	0.00%	24.02%	3.00	2.88
71	0.00%	46.49%	53.51%	0.00%	0.00%	3.00	2.54
72	17.85%	27.54%	26.92%	11.66%	16.03%	2.23	2.80
73	0.00%	62.17%	37.83%	0.00%	0.00%	1.00	2.38
74	0.00%	52.06%	47.94%	0.00%	0.00%	1.00	2.48
75	0.00%	75.00%	25.00%	0.00%	0.00%	3.00	2.25
76	0.00%	0.00%	53.98%	46.02%	0.00%	3.00	3.46
77	0.00%	0.00%	53.52%	46.48%	0.00%	3.00	3.46
78	0.00%	68.98%	31.02%	0.00%	0.00%	3.00	2.31
79	0.00%	51.56%	48.44%	0.00%	0.00%	3.00	2.48
80	16.94%	83.06%	0.00%	0.00%	0.00%	2.00	1.83

Pipeline #	Excellent	Good	Fair	Poor	Critical	PACP Grade	Estimated Grade
81	6.77%	79.57%	0.00%	0.00%	13.67%	3.50	2.34
82	0.00%	0.00%	82.84%	17.16%	0.00%	3.00	3.17
83	7.67%	56.01%	36.32%	0.00%	0.00%	3.00	2.29
84	24.13%	18.28%	37.54%	0.00%	20.05%	3.14	2.74
85	33.80%	33.33%	24.20%	8.67%	0.00%	2.53	2.08

*Pipeline used for illustration

According to Table 3.7, the 85 pipelines are categorized according to their grading category as shown in Figure 5.16. The figure suggests that the majority of the calculated overall grades (62%) were in Fair condition ranging between 2 and 3. However, 30% of the calculated overall grades were in Poor conditions and 7% of the calculated overall grades for the pipelines were in Good condition. Nevertheless, 1% of the estimated overall grades of the pipelines were in Excellent condition. Based on the results, none of the pipelines were in critical condition.

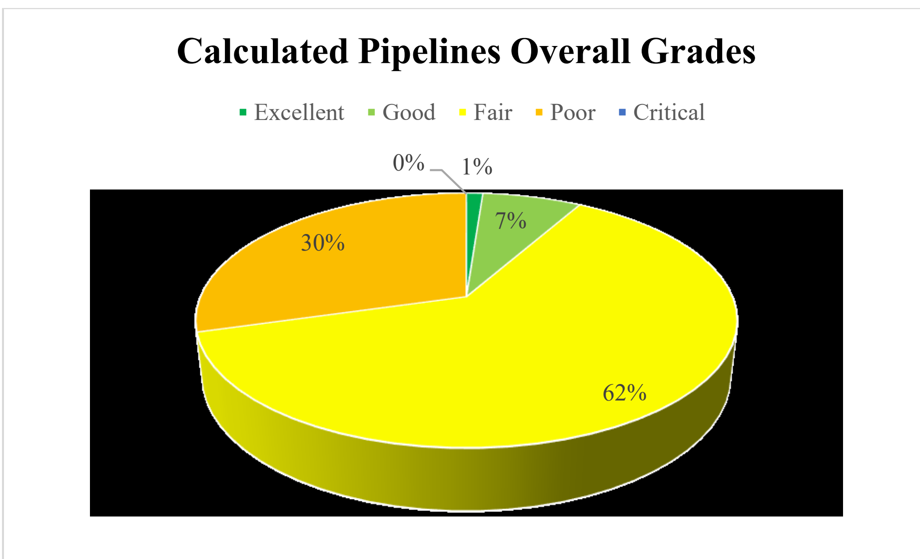


Figure 5.16 Royal Gardens Overall Pipeline Conditions

5.3.2 Model Validation

The condition assessment model was validated (verified) with the actual values obtained from the city of Edmonton reports. Therefore, this section shall signify the efficiency of the proposed model compared to the actual results. Equations 5.4 and 5.5 show the average invalidity percentage (AIP) and the AVP as a means to check the accuracy of the estimated overall grade. The closer the AIP is to 0.00, the more the model is considered sound. In addition, the root mean square error (RMSE) and the mean absolute error (MAE) are estimated according to Equations 5.6 and 5.7, respectively. If their values are close 0, the model is sound and vice versa. The fitness function (f_i) can be calculated as per equation 5.8. If the value of f_i is closer to 1000, the developed model is fit for the validation data and vice versa.

Table 5.11 summarizes the results based on the equations below. The AVP was calculated as 58.68%; RMSE was 0.89; MAE was 0.73 and f_i was 578.16. These results suggest that there were deviations from the actual values. This was as expected, as the model suggests a new methodology to assess the pipeline condition considering relative influence weights. In addition, the model took into account an essential defect, void erosion, which is not considered by many of the existing protocols.

$$AIP = \frac{\sum_{i=1}^{n} \left|1-\left(\frac{E_i}{C_i}\right)\right|}{n} * 100 \quad [5.4]$$

$$AVP = 100 - AIP \quad [5.5]$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(C_i - E_i)^2}{n}} \quad [5.6]$$

$$MAE = \frac{\sum_{i=1}^{n}|C_i - E_i|}{n} \quad [5.7]$$

$$f_i = \frac{1000}{1+MAE} \quad [5.8]$$

Table 5.11 Pipeline Condition Assessment Model Validation Results

Parameter	Value
AIP	41.32%
AVP	58.68%
MAE	0.73
f_i	578.16
RMSE	0.89

5.4 Manhole Condition Assessment

Manhole condition assessment is the other part of the condition assessment model developed in this research. The difference between the two assets is that the manhole is composed of several parts that are expected to affect its condition, and so these components must be taken into account when computing the condition of the manhole. These components are pavements, cover and frame, seals, chimney, cone, wall, bench, channel and steps. The aggregated manhole condition index was found by utilizing the ANP relative importance weights. Not all of these components share the same defects. Utilizing the information available in the literature, the defects were allocated based on the expected defect propagation in each component.

The QFD model was also utilized, with similar and different WHAT's and HOW's being shared, depending on the number of associated defects. An HOQ was thus constructed for each defect and the influence matrix values for the defects involved were acquired from the questionnaires.

5.4.1 DEMATEL and Defects' Influence

The DEMATEL method was adopted to measure the influencing power of the defects involved in each manhole component. Therefore, the influence matrix in each HOQ was constructed based on the questionnaires and the resulting average influence matrix. Based on the severities suggested for each component, pavement and steps did not acquire an influence matrix as they do not share more than one defect.

5.4.1.1 Cover and Frame

This component of the manhole had five defects that could affect its condition: cracks, break, grade, corrosion and inflow.

i. Influence Matrix

An influence matrix was built for this component, as shown in Figure 5.17. Further analysis based on the average influence matrix was conducted to verify the influence power for each defect.

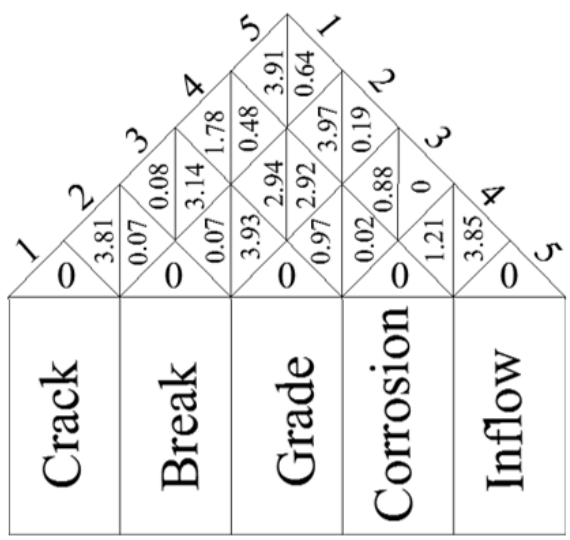


Figure 5.17 Cover and Frame Influence Matrix

ii. Normalized Influence Matrix

The normalized influence matrix was calculated after summing the columns and rows for each defect. The maximum value of the aforementioned result was used to form the normalized matrix illustrated in Table 5.12

Table 5.12 Cover & Frame Normalized Influence Matrix

Defect Number	1	2	3	4	5
1	0.00	0.35	0.01	0.16	0.36
2	0.01	0.00	0.01	0.27	0.37
3	0.29	0.36	0.00	0.09	0.08
4	0.04	0.27	0.00	0.00	0.11
5	0.06	0.02	0.00	0.35	0.00

iii. Total Average Matrix

The total average matrix was the final major computation of the DEMATEL approach (Table 5.13). From the resulting matrix, one can determine the influencing power of each defect after evaluating the C+R displayed in Table 5.14. In addition, R-C should categorize the defects in the system as influencing or influenced defects (Table 5.14) as explained in previous sections. According to Table 5.14, the highest influencing power was corrosion, and the least influencing power was the grade. According to Figure 5.18, there were two influencing defects: cracks and grade; however, three defects were influenced: break, corrosion and inflow. As a result, 40% of the system was based on influenced defects and 60% was based on influencing defects, as shown in Figure 5.19.

Table 5.13 Cover & Frame Total Average Matrix

Number	1	2	3	4	5
1	0.07	0.54	0.01	0.55	0.65
2	0.06	0.17	0.01	0.51	0.51
3	0.35	0.63	0.01	0.49	0.49
4	0.07	0.36	0.01	0.21	0.29
5	0.09	0.18	0.00	0.47	0.15

Table 5.14 Cover & Frame DEMATEL Results-Weights, Influencing and Influenced Defects

Number	Columns	Rows	C+R	R-C	Weight
1	1.82	0.64	2.46	1.175115	17.88%

Number	Columns	Rows	C+R	R-C	Weight
2	1.26	1.88	3.14	-0.61865	22.78%
3	1.96	0.04	2.00	1.926171	14.51%
4	0.95	2.24	3.19	-1.28927	23.14%
5	0.90	2.09	2.99	-1.19336	21.69%

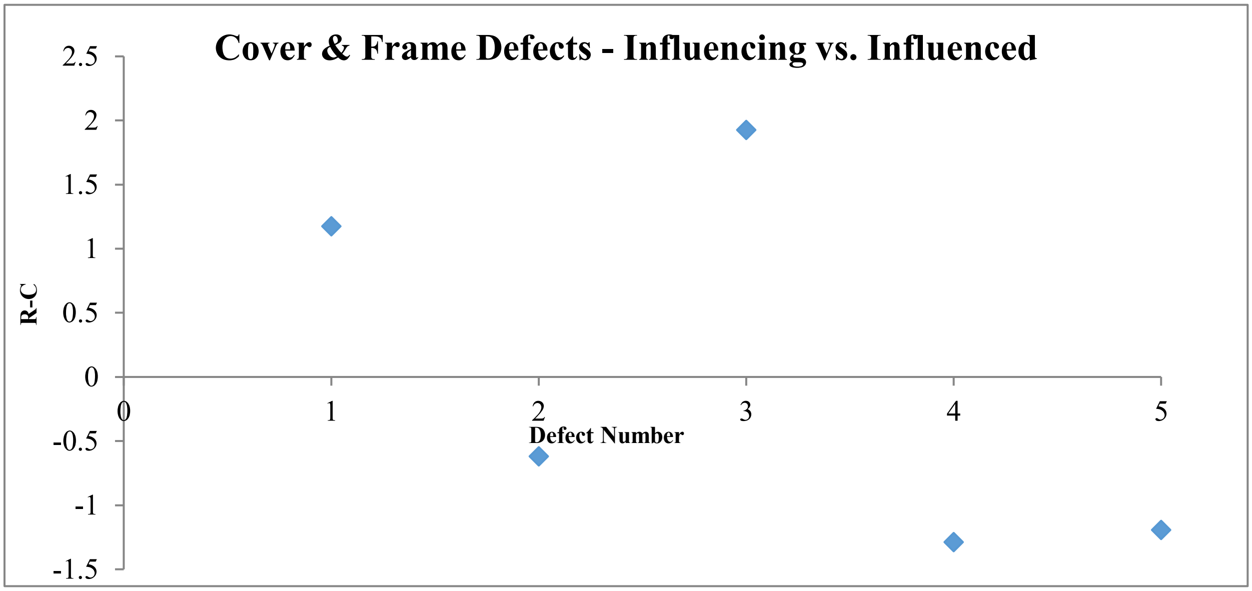


Figure 5.18 Cover and Frame Defects - Influencing vs. Influenced

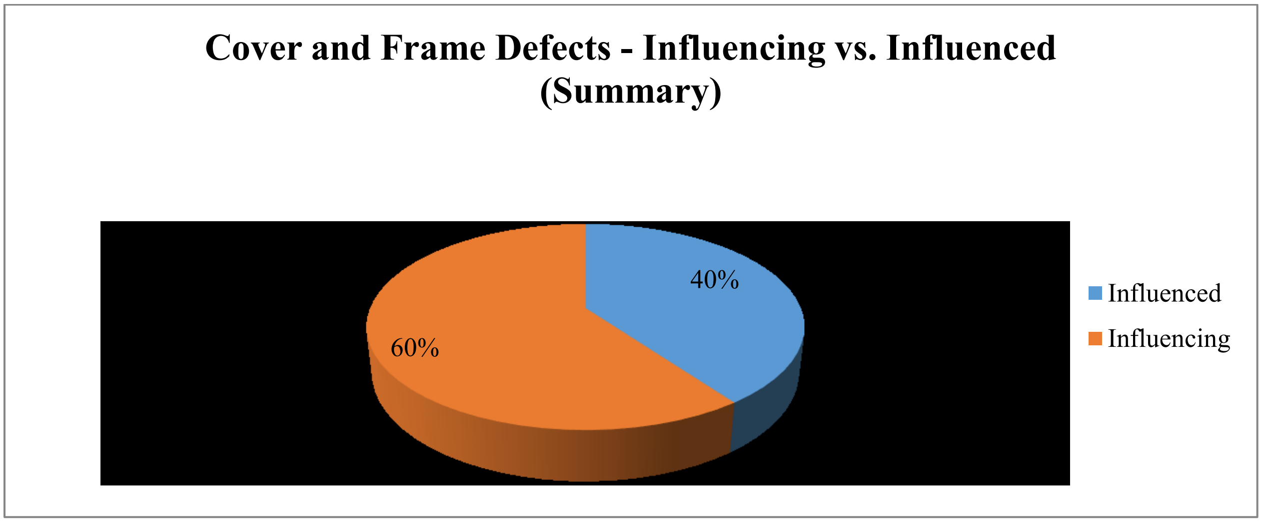


Figure 5.19 Cover and Frame Defects - Influencing vs. Influenced (Summary)

5.4.1.2 Seals

This manhole component had three defects that could affect its condition: inflow/infiltration, crack/deteriorated and roots.

i. Influence Matrix

Accordingly, the influence matrix built for this component is shown in Figure 5.20. Further analysis on the average influence matrix was conducted to determine the influence power for each defect.

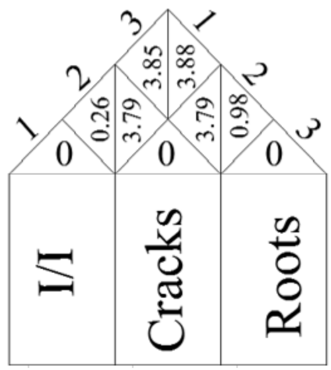


Figure 5.20 Seals Influence Matrix

ii. Normalized Influence Matrix

The normalized influence matrix was calculated after summing the columns and rows for each defect. The maximum value of the aforementioned result was used to form the normalized matrix.

Table 5.15 Seals Normalized Influence Matrix

Defect Number	1	2	3
1	0.00	0.03	0.50
2	0.49	0.00	0.49
3	0.51	0.13	0.00

iii. Total Average Matrix

The total average matrix was the final major computation of the DEMATEL approach. From the resulting matrix, one can determine the influencing power of each defect after evaluating the

C+R which is displayed in Table 5.17. In addition, R-C values categorized the defects in the system as influencing or influenced defect (

Table 5.17), as explained earlier. According to that table, the highest influencing power was the roots, and the least influencing power was the crack/deteriorated. According to Figure 5.21, there was only one influencing defect, crack/deteriorated; however, there are two influenced defects: inflow/infiltration and roots. As a result, 67% of the system was based on influenced defects and 33% was based on influencing defects, as shown in Figure 5.22.

Table 5.16 Seals Total Average Matrix

Defect Number	1	2	3
1	0.50	0.16	0.83
2	1.19	0.19	1.19
3	0.91	0.23	0.57

Table 5.17 Seals DEMATEL Results-Weights, Influencing and Influenced Defects

Number	C	R	C+R	R-C	Weight
1	1.48	2.59	4.08	-1.11	35.39%
2	2.57	0.58	3.15	1.99	27.31%
3	1.71	2.58	4.30	-0.87	37.30%

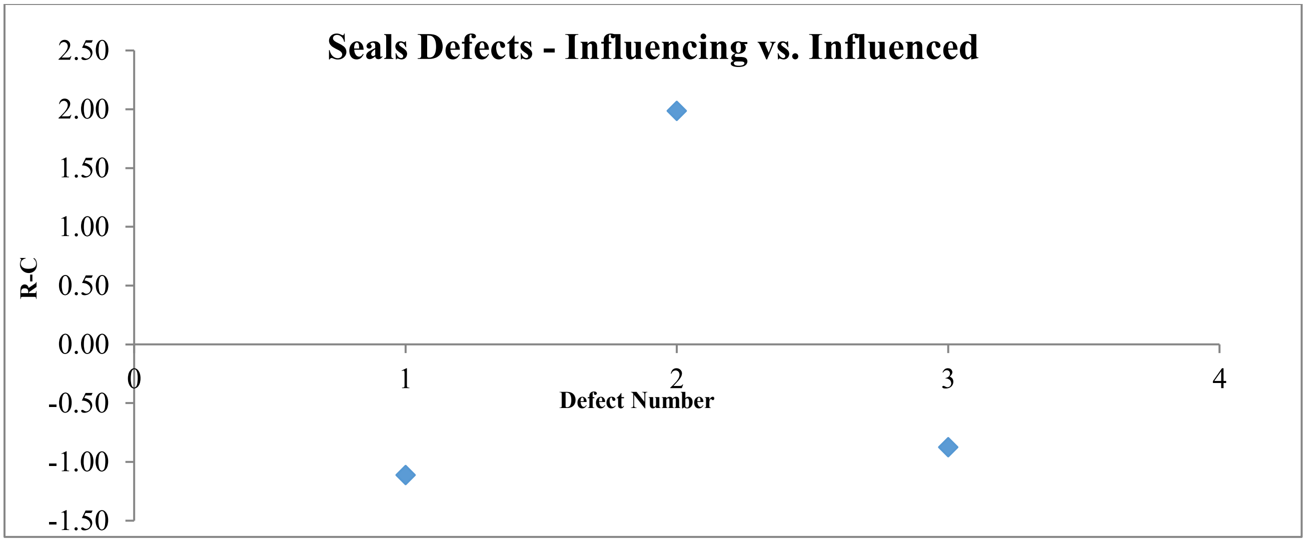


Figure 5.21 Seals Defects - Influencing vs. Influenced

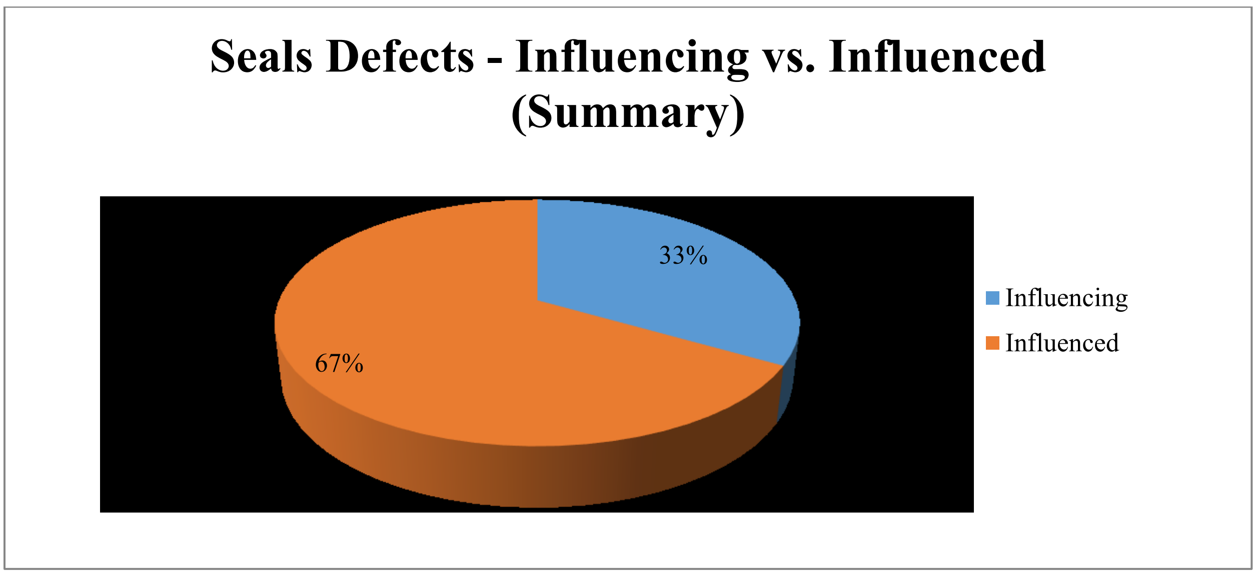


Figure 5.22 Seals Defects - Influencing vs. Influenced (Summary)

5.4.1.3 Chimney, Cone and Wall

These manhole components share similar defects; a total of fourteen defects that could affect their conditions. These were longitudinal crack, circumferential crack, longitudinal fracture, circumferential fracture, deformation, hole, break, collapse, surface damage, roots, inflow/infiltration, obstruction, attached deposits and protruding service.

i. Influence Matrix

Accordingly, the influence matrix that was built for each component is shown in Figure 5.23. Further analysis on the average influence matrix was conducted to evaluate the influence power for each defect.

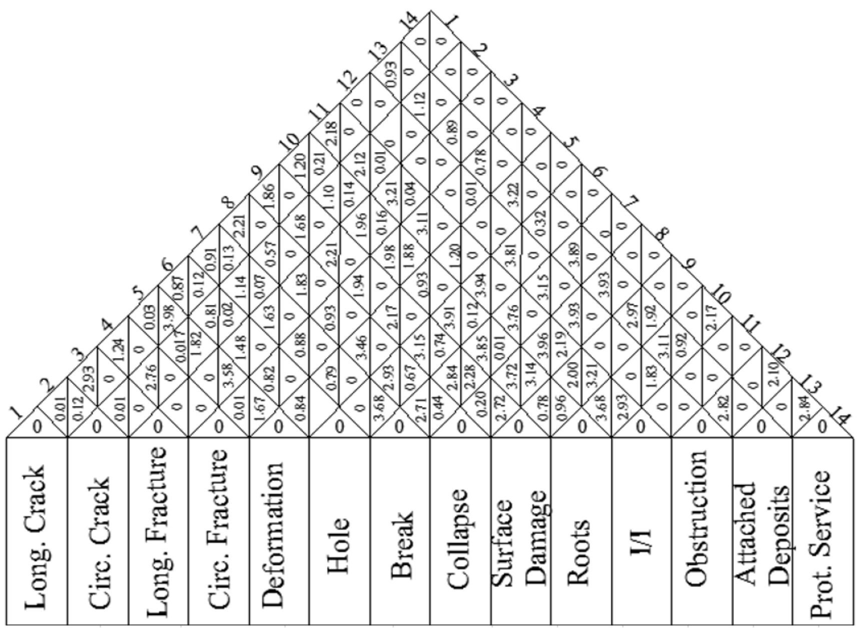


Figure 5.23 Chimney, Cone and Wall Influence Matrix

ii. Normalized Influence Matrix

The normalized influence matrix (Table 5.18) was calculated after summing the columns and rows for each defect. The maximum value of the aforementioned result was used to form the normalized matrix.

Table 5.18 Chimney, Cone and Wall Normalized Influence Matrix

Defect Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.000	0.000	0.100	0.043	0.001	0.030	0.031	0.076	0.064	0.041	0.075	0.000	0.032	0.000
2	0.004	0.000	0.000	0.095	0.001	0.028	0.039	0.020	0.058	0.038	0.073	0.000	0.038	0.000
3	0.000	0.000	0.000	0.000	0.000	0.051	0.056	0.063	0.076	0.067	0.110	0.000	0.031	0.000
4	0.000	0.000	0.000	0.000	0.000	0.028	0.030	0.032	0.067	0.068	0.107	0.000	0.027	0.000
5	0.136	0.062	0.123	0.057	0.000	0.029	0.027	0.119	0.074	0.032	0.041	0.000	0.110	0.000
6	0.004	0.001	0.000	0.000	0.000	0.000	0.000	0.100	0.108	0.134	0.135	0.131	0.011	0.000
7	0.004	0.002	0.000	0.000	0.000	0.126	0.000	0.093	0.097	0.132	0.129	0.108	0.133	0.000
8	0.000	0.000	0.000	0.000	0.000	0.023	0.015	0.000	0.007	0.128	0.136	0.135	0.135	0.000
9	0.000	0.000	0.000	0.000	0.000	0.025	0.078	0.093	0.000	0.027	0.069	0.000	0.102	0.000
10	0.007	0.005	0.014	0.005	0.000	0.004	0.000	0.108	0.033	0.000	0.126	0.000	0.107	0.000
11	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.075	0.110	0.100	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.063	0.000	0.000	0.097	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.066	0.032	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.074	0.000	0.072	0.097	0.000

iii. Total Average Matrix

The total average matrix (Table 5.19) was the final major computation of the DEMATEL approach. From the resulting matrix, one can determine the influencing power of each defect after evaluating C+R displayed in Table 5.20. In addition, R-C values categorized the defects in the system as influencing or influenced defect (Table 5.20) as explained earlier. According to Table 5.20, the highest influencing power was the roots, and the least influencing power was the protruding services. Based on Figure 5.24, there were eight influencing defects and six influenced defects. As a result, 43% of the system was based on influenced defects and 57% was based on influencing defects, as shown in Figure 5.25.

Table 5.19 Chimney, Cone and Wall Total Average Matrix

Defect Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.001	0.001	0.102	0.043	0.001	0.049	0.049	0.125	0.110	0.102	0.141	0.028	0.085	0
2	0.005	0.001	0.002	0.096	0.001	0.041	0.051	0.059	0.095	0.083	0.121	0.019	0.077	0
3	0.001	0.001	0.002	0.001	0.000	0.066	0.067	0.113	0.119	0.124	0.167	0.031	0.084	0
4	0.001	0.001	0.002	0.001	0.000	0.038	0.039	0.072	0.099	0.108	0.148	0.019	0.066	0
5	0.138	0.063	0.139	0.070	0.000	0.060	0.058	0.191	0.148	0.121	0.146	0.040	0.189	0
6	0.006	0.002	0.004	0.002	0.000	0.010	0.014	0.153	0.146	0.193	0.195	0.154	0.084	0
7	0.007	0.004	0.004	0.002	0.000	0.137	0.016	0.163	0.160	0.216	0.211	0.150	0.213	0
8	0.001	0.001	0.003	0.001	0.000	0.029	0.020	0.041	0.049	0.173	0.174	0.146	0.181	0
9	0.001	0.001	0.002	0.001	0.000	0.040	0.083	0.126	0.038	0.079	0.115	0.031	0.146	0
10	0.008	0.005	0.016	0.007	0.000	0.012	0.009	0.135	0.067	0.046	0.161	0.021	0.141	0
11	0.001	0.001	0.003	0.002	0.000	0.008	0.012	0.106	0.125	0.127	0.042	0.017	0.044	0
12	0.001	0.000	0.001	0.000	0.000	0.001	0.001	0.010	0.011	0.069	0.011	0.002	0.107	0
13	0.000	0.000	0.001	0.000	0.000	0.003	0.006	0.013	0.070	0.038	0.013	0.003	0.014	0
14	0.001	0.000	0.001	0.001	0.000	0.001	0.001	0.012	0.013	0.087	0.014	0.074	0.117	0

Table 5.20 Chimney, Cone and Wall DEMATEL Results-Weights, Influencing and Influenced Defects

Number	Sum of Columns	Sum of Rows	C+R	R-C	Weight
1	0.84	0.17	1.01	0.67	5.18%
2	0.65	0.08	0.73	0.57	3.74%
3	0.78	0.28	1.06	0.49	5.42%
4	0.59	0.23	0.82	0.37	4.21%
5	1.36	0.00	1.36	1.36	6.99%
6	0.96	0.49	1.46	0.47	7.46%
7	1.28	0.43	1.71	0.86	8.76%
8	0.82	1.32	2.14	-0.50	10.95%
9	0.66	1.25	1.91	-0.59	9.81%
10	0.63	1.57	2.19	-0.94	11.23%
11	0.49	1.66	2.15	-1.17	10.99%
12	0.21	0.73	0.95	-0.52	4.86%
13	0.16	1.55	1.71	-1.39	8.76%
14	0.32	0.00	0.32	0.32	1.65%

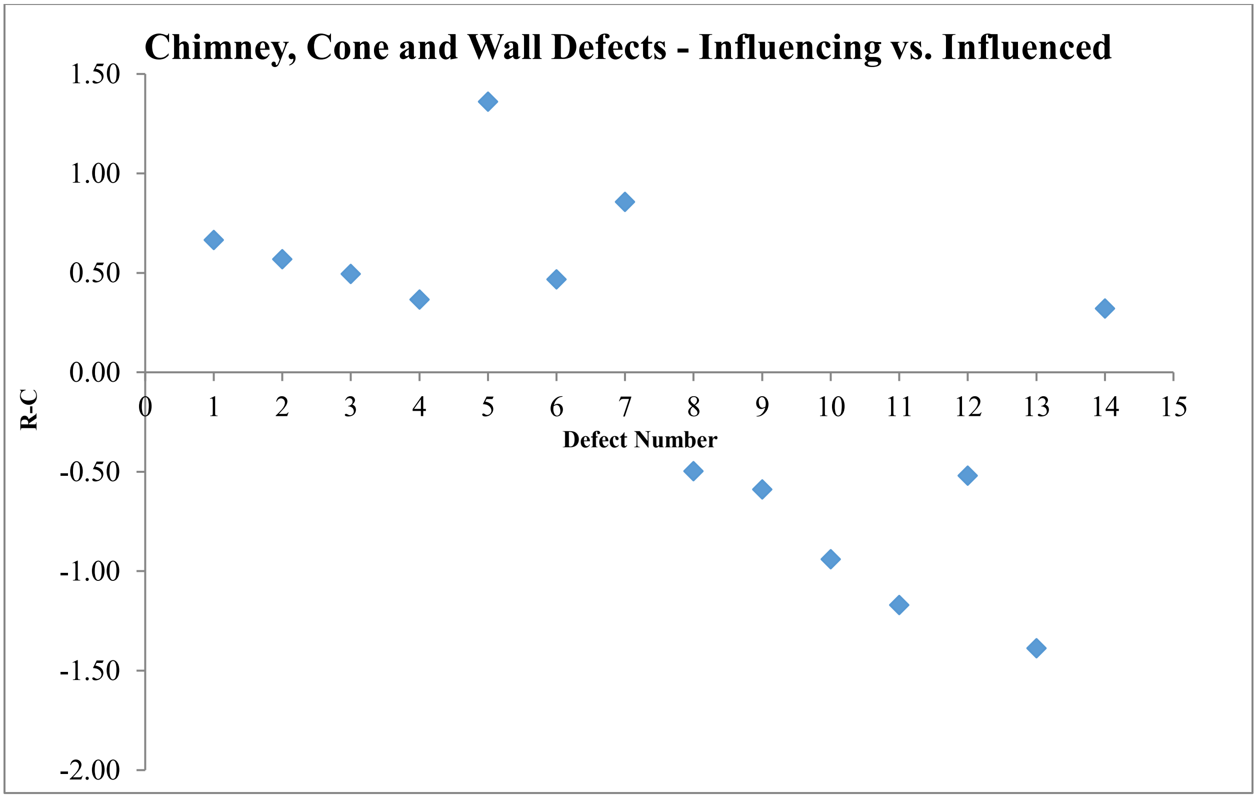


Figure 5.24 Chimney, Cone and Wall Defects - Influencing vs. Influenced

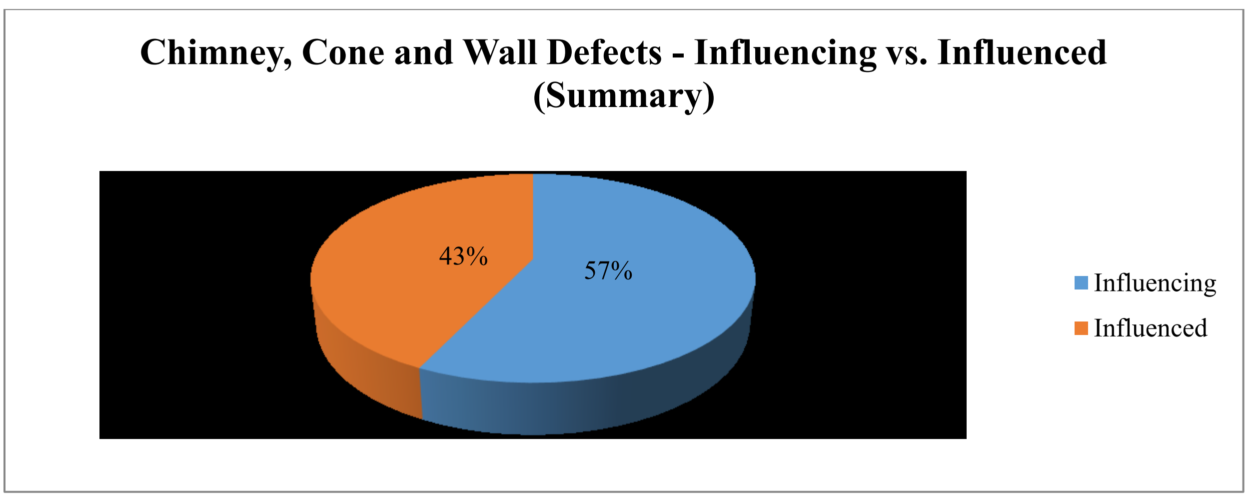


Figure 5.25 Chimney, Cone and Wall Defects - Influencing vs. Influenced (Summary)

5.4.1.4 Bench

This manhole component had eleven defects that could affect its condition: longitudinal crack, circumferential crack, longitudinal fracture, circumferential fracture, hole, break, collapse, surface damage, settled deposits, roots and inflow/infiltration.

i. Influence Matrix

Accordingly, the influence matrix that was built for such a component is shown in Figure 5.26. Further analysis on the average influence matrix was conducted to evaluate the influence power for each defect.

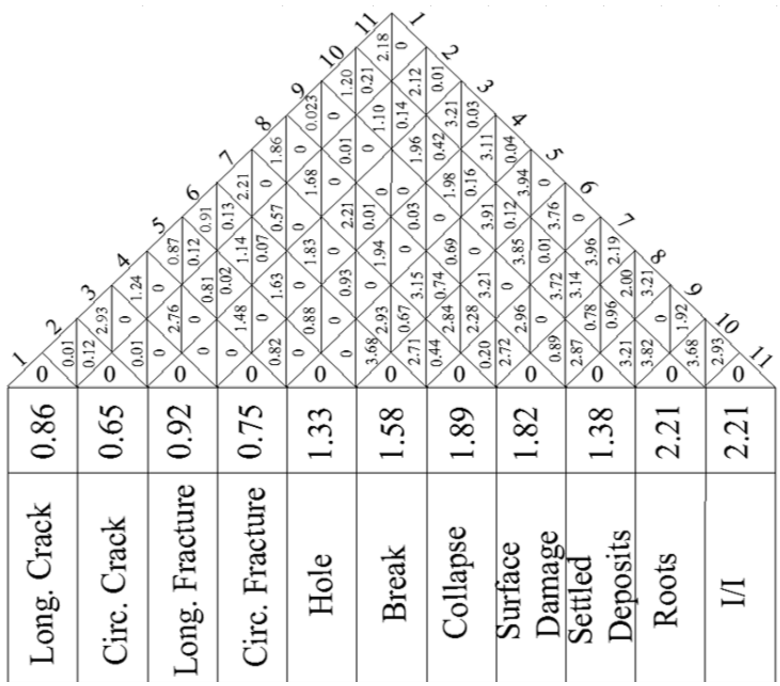


Figure 5.26 Bench Influence Matrix

ii. Normalized Influence Matrix

The normalized influence matrix (Table 5.21) was calculated after summing the columns and rows for each defect. The maximum value of the aforementioned result was used to form the normalized matrix.

Table 5.21 Bench Normalized Influence Matrix

Defect Number	1	2	3	4	5	6	7	8	9	10	11
1	0.000	0.000	0.105	0.044	0.031	0.033	0.079	0.067	0.001	0.043	0.078
2	0.004	0.000	0.000	0.099	0.029	0.041	0.020	0.060	0.000	0.039	0.076
3	0.000	0.000	0.000	0.000	0.053	0.058	0.065	0.079	0.000	0.070	0.115
4	0.000	0.000	0.000	0.000	0.029	0.031	0.033	0.069	0.001	0.071	0.111
5	0.004	0.001	0.000	0.000	0.000	0.000	0.105	0.113	0.025	0.140	0.141
6	0.005	0.003	0.000	0.000	0.132	0.000	0.097	0.102	0.115	0.138	0.134
7	0.000	0.000	0.000	0.000	0.024	0.016	0.000	0.007	0.106	0.133	0.142
8	0.000	0.000	0.000	0.000	0.026	0.082	0.097	0.000	0.032	0.028	0.072
9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.103	0.000	0.115	0.000
10	0.008	0.005	0.015	0.006	0.004	0.000	0.112	0.034	0.137	0.000	0.132
11	0.000	0.000	0.001	0.001	0.000	0.000	0.078	0.115	0.069	0.105	0.000

iii. Total Average Matrix

The total average matrix (Table 5.22) was the final major computation of the DEMATEL approach. From the resulting matrix, one can determine the influencing power of each defect after evaluating C+R, which is displayed in Table 5.23. In addition, the R-C value categorized the defects in the system as influencing or influenced (Table 5.23), as explained earlier. According to Table 5.23, the highest influencing power was the roots, and the least influencing power was the horizontal (circumferential) crack. According to Figure 5.27, there were six influencing defects and five influenced defects. As a result, 45% of the system was based on influenced defects and 55% was based on influencing defects, as shown in Figure 5.28 .

Table 5.22 Bench Total Average Matrix

Defect Number	1	2	3	4	5	6	7	8	9	10	11
1	0.001	0.001	0.107	0.045	0.052	0.052	0.134	0.117	0.052	0.111	0.152
2	0.005	0.001	0.002	0.100	0.044	0.053	0.064	0.100	0.039	0.090	0.129
3	0.002	0.001	0.002	0.001	0.069	0.071	0.121	0.126	0.057	0.135	0.179
4	0.001	0.001	0.002	0.001	0.040	0.042	0.078	0.106	0.045	0.117	0.157
5	0.006	0.002	0.004	0.002	0.012	0.016	0.163	0.158	0.091	0.203	0.207
6	0.007	0.004	0.005	0.002	0.145	0.018	0.176	0.176	0.193	0.236	0.227
7	0.002	0.001	0.003	0.002	0.031	0.022	0.047	0.057	0.154	0.186	0.185
8	0.001	0.001	0.002	0.001	0.043	0.087	0.134	0.040	0.079	0.087	0.123
9	0.001	0.001	0.002	0.001	0.006	0.010	0.030	0.116	0.028	0.131	0.033
10	0.008	0.005	0.017	0.007	0.013	0.011	0.146	0.081	0.177	0.066	0.174
11	0.001	0.001	0.003	0.003	0.009	0.014	0.115	0.141	0.110	0.146	0.050

Table 5.23 Bench DEMATEL Results-Weights, Influencing and Influenced Defects

Number	Sum of Columns	Sum of Rows	C+R	R-C	Weight
1	0.82333	0.036	0.86	0.7874	5.51%
2	0.62728	0.018	0.65	0.6089	4.14%
3	0.76522	0.15	0.92	0.6151	5.87%
4	0.58982	0.165	0.75	0.4253	4.84%
5	0.86223	0.463	1.33	0.3994	8.50%
6	1.18855	0.395	1.58	0.7931	10.16%
7	0.68694	1.207	1.89	-0.52	12.14%
8	0.59727	1.218	1.82	-0.621	11.64%
9	0.3598	1.025	1.38	-0.665	8.88%
10	0.70589	1.506	2.21	-0.8	14.18%
11	0.5924	1.615	2.21	-1.022	14.15%

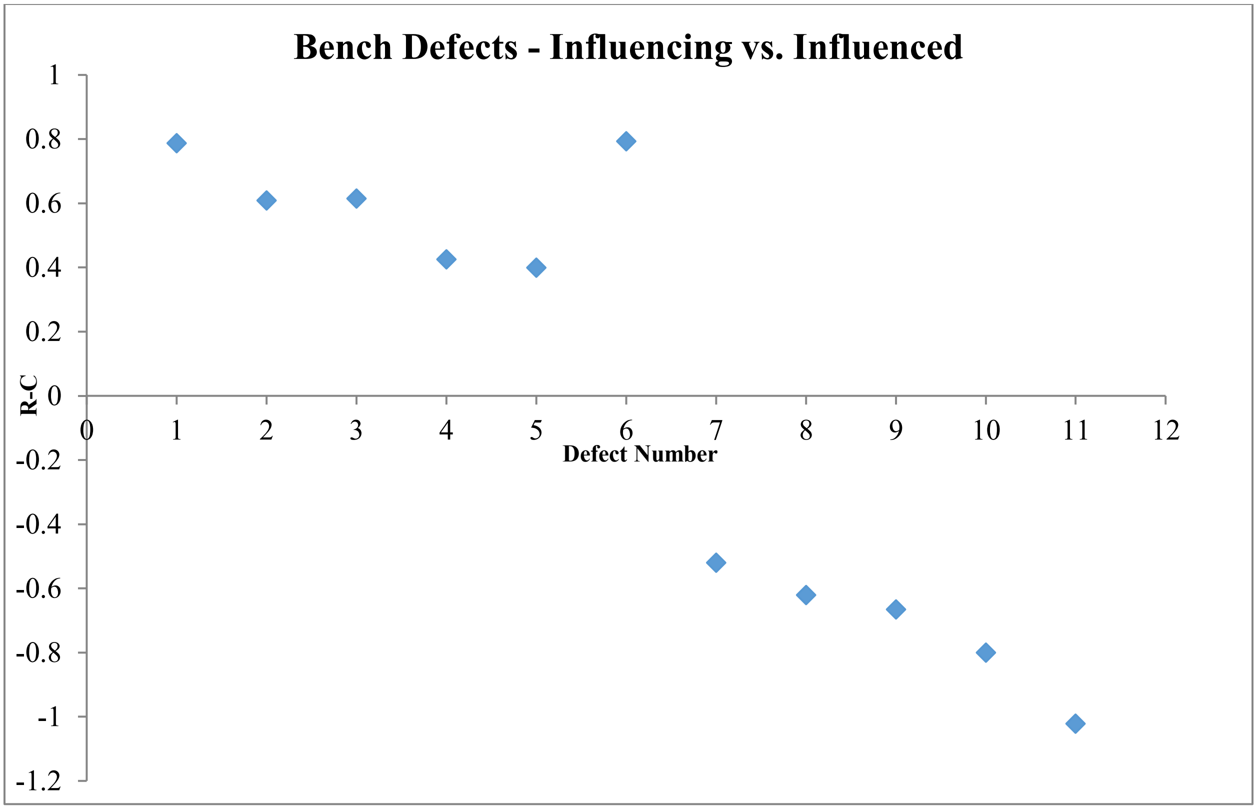


Figure 5.27 Bench Defects - Influencing vs. Influenced

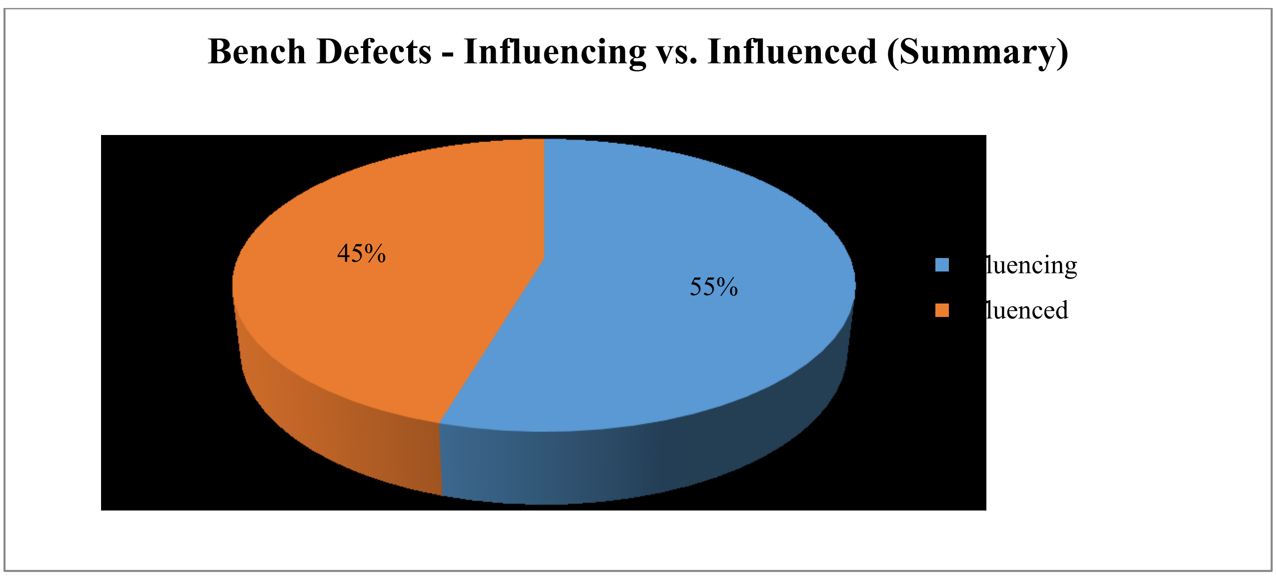


Figure 5.28 Bench Defects - Influencing vs. Influenced (Summary)

5.4.1.5 Channel

This component had fourteen defects that could affect its condition. Since the common channel component is formed like a pipeline (half a pipeline), many of its defects were similar to those of pipelines. Therefore, the defects that could affect the channel condition were longitudinal crack, circumferential crack, multiple crack, longitudinal fracture, circumferential fracture, multiple fracture, hole, break, collapse, surface damage, roots, inflow/infiltration, and obstruction.

i. Influence Matrix

Accordingly, the influence matrix that was built for such a component is shown in Figure 5.29 Further analysis on the average influence matrix was conducted to evaluate the influence power for each defect.

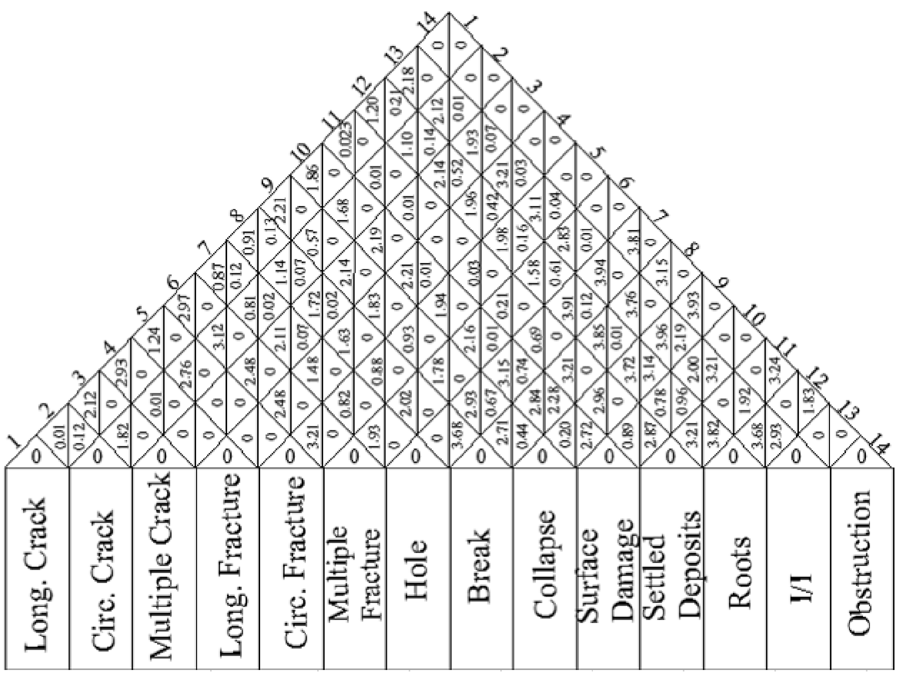


Figure 5.29 Channel Influence Matrix

ii. Normalized Influence Matrix

The normalized influence matrix (Table 5.24) was calculated after summing the columns and the rows for each defect. The maximum value of the aforementioned result was used to form the normalized matrix.

Table 5.24 Channel Normalized Influence Matrix

Defect Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.000	0.000	0.065	0.090	0.038	0.091	0.027	0.028	0.068	0.057	0.001	0.037	0.067	0.000
2	0.004	0.000	0.056	0.000	0.084	0.095	0.025	0.035	0.017	0.051	0.000	0.034	0.065	0.000
3	0.000	0.000	0.000	0.000	0.000	0.087	0.064	0.053	0.065	0.067	0.000	0.065	0.059	0.000
4	0.000	0.000	0.000	0.000	0.000	0.076	0.045	0.050	0.056	0.068	0.000	0.060	0.098	0.000
5	0.000	0.000	0.000	0.000	0.000	0.098	0.025	0.027	0.028	0.059	0.001	0.061	0.095	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.059	0.062	0.054	0.066	0.006	0.048	0.086	0.000
7	0.004	0.001	0.002	0.000	0.000	0.000	0.000	0.000	0.090	0.096	0.021	0.119	0.120	0.116
8	0.004	0.002	0.001	0.000	0.000	0.000	0.112	0.000	0.083	0.087	0.098	0.118	0.115	0.096
9	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.013	0.000	0.006	0.090	0.114	0.121	0.120
10	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.070	0.083	0.000	0.027	0.024	0.061	0.000
11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.088	0.000	0.098	0.000	0.000
12	0.006	0.004	0.016	0.013	0.005	0.019	0.004	0.000	0.096	0.029	0.117	0.000	0.112	0.000
13	0.000	0.000	0.002	0.001	0.001	0.000	0.000	0.000	0.067	0.098	0.059	0.090	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.099	0.056	0.000	0.000

iii. Total Average Matrix

The total average matrix (Table 5.25) was the final major computation of the DEMATEL approach. From the resulting matrix, one can determine the influencing power of each defect after evaluating C+R which is displayed in Table 5.26. In addition, the R-C value should categorize the defects in the system as either influencing or influenced. According to same table, the highest influencing power was the roots, and the least influencing power was the circumferential fracture. According to Figure 5.30, there were eight influencing defects and six influenced defects. Therefore, 43% of the system was based on influenced defects and 57% was based on influencing defects (Figure 5.31).

Table 5.25 Channel Total Average Matrix

Defect Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.001	0.001	0.067	0.091	0.039	0.109	0.054	0.053	0.121	0.108	0.044	0.101	0.138	0.026
2	0.005	0.001	0.058	0.002	0.085	0.111	0.047	0.055	0.063	0.095	0.035	0.085	0.121	0.018
3	0.001	0.001	0.003	0.002	0.001	0.090	0.083	0.067	0.112	0.107	0.046	0.120	0.119	0.030
4	0.001	0.001	0.002	0.002	0.001	0.079	0.062	0.064	0.101	0.107	0.045	0.113	0.152	0.026
5	0.001	0.001	0.002	0.002	0.001	0.101	0.040	0.041	0.068	0.094	0.037	0.102	0.139	0.017
6	0.001	0.001	0.002	0.001	0.001	0.002	0.072	0.070	0.094	0.100	0.048	0.097	0.132	0.026
7	0.005	0.001	0.006	0.003	0.001	0.005	0.009	0.012	0.131	0.129	0.081	0.171	0.167	0.134
8	0.006	0.003	0.005	0.003	0.002	0.005	0.122	0.013	0.138	0.140	0.164	0.193	0.180	0.128
9	0.001	0.001	0.003	0.002	0.001	0.004	0.025	0.018	0.033	0.043	0.137	0.158	0.151	0.129
10	0.001	0.000	0.001	0.001	0.001	0.002	0.034	0.073	0.108	0.028	0.061	0.066	0.096	0.024
11	0.001	0.000	0.002	0.002	0.001	0.003	0.004	0.007	0.021	0.097	0.020	0.109	0.023	0.004
12	0.007	0.005	0.018	0.014	0.006	0.024	0.013	0.010	0.122	0.066	0.147	0.050	0.145	0.017
13	0.001	0.001	0.004	0.003	0.002	0.003	0.007	0.010	0.092	0.116	0.088	0.118	0.035	0.013
14	0.000	0.000	0.001	0.001	0.000	0.002	0.001	0.001	0.009	0.013	0.109	0.070	0.010	0.001

Table 5.26 Channel DEMATEL Results-Weights, Influencing and Influenced Defects

Number	Sum of Columns	Sum of Rows	C+R	R-C	Weight
1	0.95	0.03	0.99	0.92	5.26%
2	0.78	0.02	0.80	0.76	4.25%
3	0.78	0.17	0.95	0.61	5.09%
4	0.75	0.13	0.88	0.63	4.71%
5	0.64	0.14	0.78	0.50	4.19%
6	0.65	0.54	1.19	0.11	6.33%
7	0.85	0.57	1.43	0.28	7.61%
8	1.10	0.49	1.60	0.61	8.52%
9	0.71	1.21	1.92	-0.51	10.25%
10	0.50	1.24	1.74	-0.74	9.27%
11	0.29	1.06	1.35	-0.77	7.23%
12	0.64	1.55	2.20	-0.91	11.73%
13	0.49	1.61	2.10	-1.12	11.22%
14	0.22	0.59	0.81	-0.37	4.34%

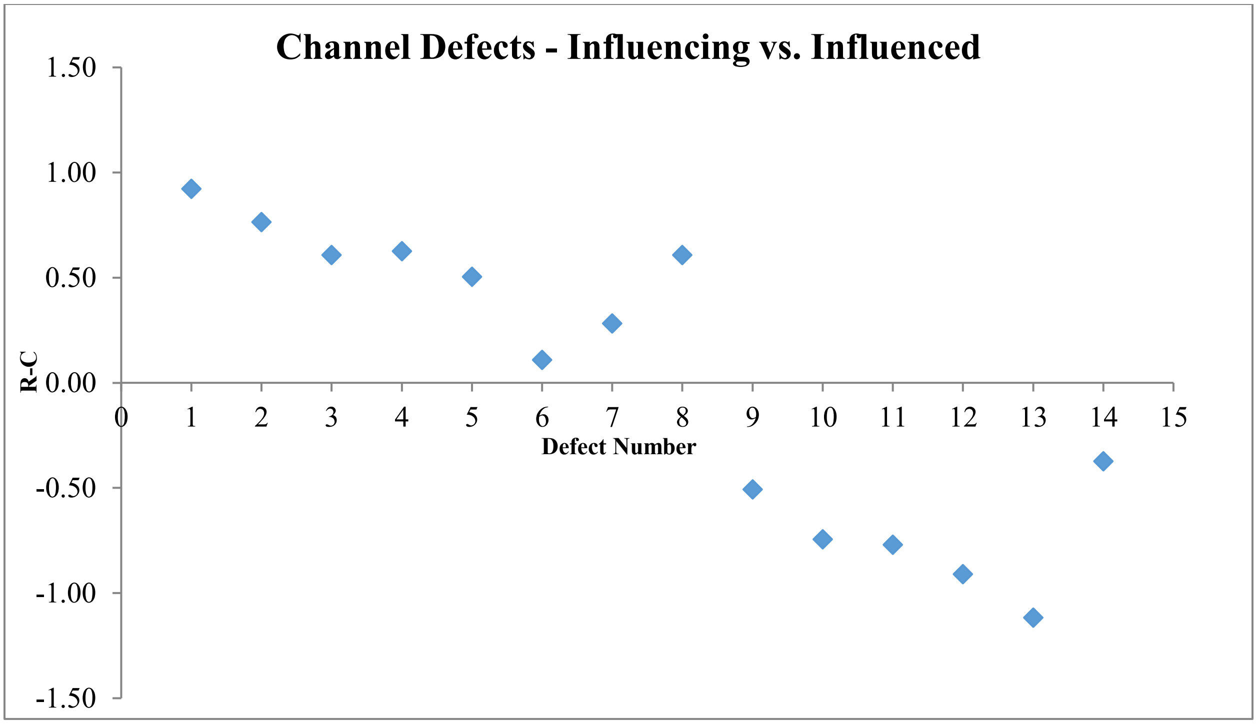


Figure 5.30 Channel Defects - Influencing vs. Influenced

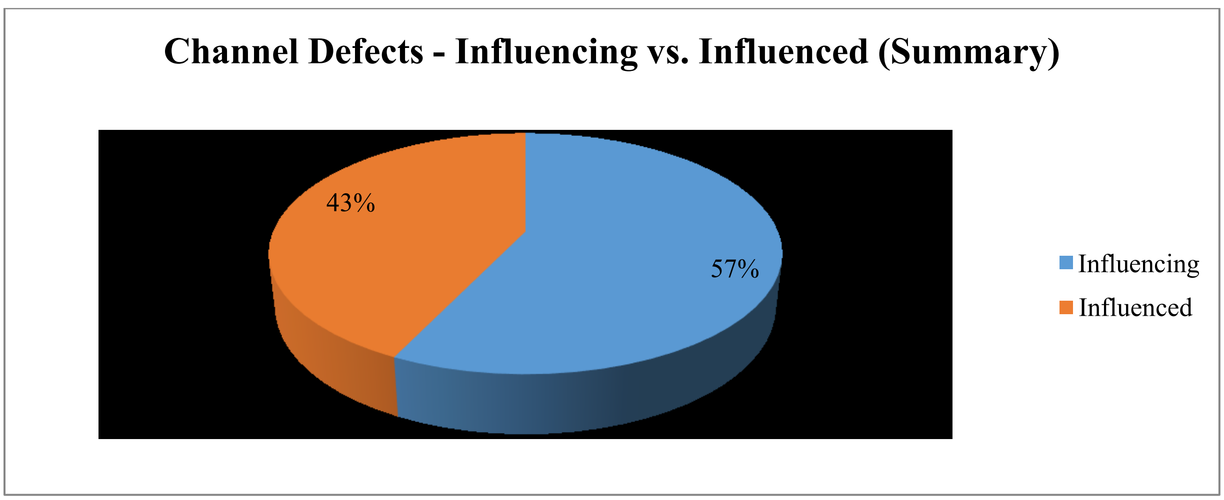


Figure 5.31 Channel Defects - Influencing vs. Influenced (Summary)

5.4.1.6 Discussion

The DEMATEL approach was conducted to study the cause and effect of the defects involved in sewer assets (pipelines and manholes). The manholes were composed of multiple components in which each had its own analysis. The highest and the lowest influence powers among the defects were calculated. In addition, the influencing and influenced defects were displayed in scattered plots.

Table 5.27 displays the results found from the DEMATEL approach on pipelines and manholes. Based on the results, most of the assets have higher influencing defect percentages, except for the manholes' seals' component. This is due to the fact that the defects that are defined for this component were crack/deteriorated, roots and inflow/infiltration. Based on these defects, it was obvious that a crack or a deterioration in the seals lead to the root penetration and/or inflow/infiltration. However, other assets and components involved a higher number of defects in which each system had its own influencing and influenced defects based on the experts' opinions. The erosion void in the pipeline had the highest relative influence power, as is a major contribution in developing other defects; such as excessive deformation, fractures, infiltration, etc. (Davies et al 2001). It is worth noting that the defects that propagate due to void erosion are also influencing the development of other defects. In addition, roots' defects emerged to be a significant defect that has a great influencing power in multiple manhole components. According to Schrock (1994), roots can expand an existing opening in a sewer causing weakening in the structure and ultimately leading to breakage and collapse. Hence, the accumulated effect of root intrusion on other defects resulted in a higher influence power compared to other defects. On the other hand, the most-repeated defect found in multiple parts was protruding services, and which represented the lowest influence power. This was as expected, as protruding services present in the sewer system due to construction and design faults and are not caused by other sewer defects. Therefore, the accumulation of influence power was restricted resulting in a low weight.

Table 5.27 Summary of DEMATEL Approach

<table>
<tr><th colspan="2">Asset</th><th>Highest Influence Power</th><th>Lowest Influence Power</th><th>Influencing %</th><th>Influenced %</th></tr>
<tr><td colspan="2">Pipeline</td><td>Erosion Void</td><td>Protruding services</td><td>55</td><td>45</td></tr>
<tr><td rowspan="7">Manhole</td><td>Cover & Frame</td><td>Corrosion</td><td>Grade</td><td>60</td><td>40</td></tr>
<tr><td>Seals</td><td>Roots</td><td>Cracks/Deteriorated</td><td>33</td><td>67</td></tr>
<tr><td>Chimney</td><td>Roots</td><td>Protruding services</td><td>57</td><td>43</td></tr>
<tr><td>Cone</td><td>Roots</td><td>Protruding services</td><td>57</td><td>43</td></tr>
<tr><td>Wall</td><td>Roots</td><td>Protruding services</td><td>57</td><td>43</td></tr>
<tr><td>Bench</td><td>Roots</td><td>Horizontal Crack</td><td>55</td><td>45</td></tr>
<tr><td>Channel</td><td>Roots</td><td>Circumferential Fracture</td><td>57</td><td>43</td></tr>
</table>

5.4.2 QFD

The QFD was utilized in preparing the top-most roof triangle of each HOQ of each component. Further analysis was implemented to find the relative influence power of each defect to compute the final weights that represents the final WHAT's in each HOQ. The aggregated severity percentage was based on the HOW's of each defect that were extracted from actual reports. The following demonstrates an evaluation methodology for one of the report's manholes.

5.4.2.1 Pavement

The pavement condition was checked using the Pipetech View software. Based on the images, the manhole was located in a green area where no pavement was available. In such a case, the pavement condition was taken as Excellent. Therefore, the local pavement condition was 1.00 as shown in Table 5.28.

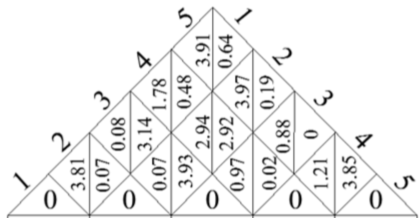
Table 5.28 Pavement Condition

<table>
<tr><th>Condition</th><th>Pavement Condition %</th><th>Pavement Overall Condition</th></tr>
<tr><td>Excellent</td><td>100.00%</td><td rowspan="2">1.00</td></tr>
<tr><td>Good</td><td>0.00%</td></tr>
</table>

Condition	Pavement Condition %	Pavement Overall Condition
Fair	0.00%	
Poor	0.00%	
Critical	0.00%	

5.4.2.2 Cover & Frame

The information for this manhole component was checked using the Pipetech View software. Accordingly, the defect counts were considered and used to construct the HOQ as per Figure 5.32 and to calculate the condition of the component as shown in Table 5.29. Subsequently, the relative percentage for each grade was found and used to compute the overall component's grade, which was 1.67.



		2.46	3.14	2.00	3.19	2.99
		Crack	Break	Grade	Corrosion	Inflow
Condition	**Defect Number**	1	2	3	4	5
	Score/Weight	17.88%	22.78%	14.51%	23.14%	21.69%
Excellent	1	0.00%	100.00%	100.00%	50.00%	0.00%
Good	2	100.00%	0.00%	0.00%	0.00%	0.00%
Fair	3	0.00%	0.00%	0.00%	0.00%	0.00%
Poor	4	0.00%	0.00%	0.00%	50.00%	0.00%
Critical	5	0.00%	0.00%	0.00%	0.00%	0.00%
Excellent	1	0	1	1	1	0
Good	2	1	0	0	0	0
Fair	3	0	0	0	0	0
Poor	4	0	0	0	1	0
Critical	5	0	0	0	0	0

Figure 5.32 Cover and Frame HOQ

Table 5.29 Cover and Frame Conditions

Condition	Cover & Frame Condition %	Relative % Condition	Cover & Frame Overall Condition
Excellent	48.860%	62.39%	1.67
Good	17.877%	22.83%	
Fair	0.000%	0.00%	
Poor	11.572%	14.78%	
Critical	0.000%	0.00%	

5.4.2.3 Seals

The seals condition was computed after checking the PipeTech View software for the manholes and the information in the database. Accordingly, the defect counts were considered and used to construct the HOQ as shown in Figure 5.33 and to calculate the condition of the component as listed in Table 5.30. Subsequently, the relative percentage for each grade was found and used to compute the overall component's grade, which was 1.27.

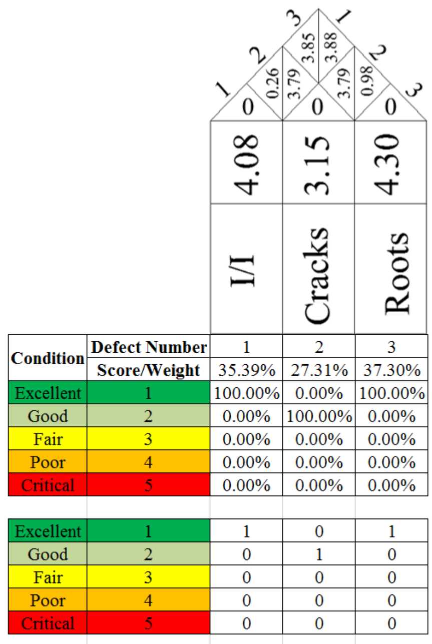


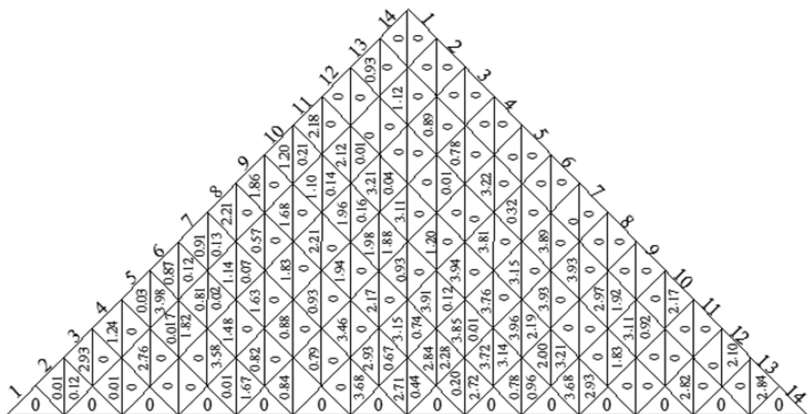
Figure 5.33 Seals HOQ

Table 5.30 Seals Conditions

Condition	**Seals Condition %**	**Relative % Condition**	**Seals Overall Condition**
Excellent	72.69%	72.69%	1.27
Good	27.31%	27.31%	
Fair	0.00%	0.00%	
Poor	0.00%	0.00%	
Critical	0.00%	0.00%	

5.4.2.4 Chimney

The chimney condition was computed after checking the PipeTech View software for the manholes and the information in the database. Accordingly, the defect counts were considered and used to construct the HOQ as illustrated in Figure 5.34 and to calculate the condition of the component as shown in Table 5.31. Subsequently, the relative percentage for each grade was found and used to compute the overall component's grade, which was 2.08.



		Long. Crack	Circ. Crack	Long. Fracture	Circ. Fracture	Deformation	Hole	Break	Collapse	Surface Damage	Roots	I/I	Obstruction	Attached Deposits	Prot. Service
		1.01	0.73	1.06	0.82	1.36	1.46	1.71	2.14	1.91	2.19	2.15	0.95	1.71	0.32
Condition	**Defect Number**	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Score/Weight	5.18%	3.74%	5.42%	4.21%	6.99%	7.46%	8.76%	10.95%	9.81%	11.23%	10.99%	4.86%	8.76%	1.65%
Excellent	1	71.43%	100.00%	20.00%	16.67%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Good	2	0.00%	0.00%	0.00%	16.67%	100.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fair	3	0.00%	0.00%	80.00%	33.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Poor	4	28.57%	0.00%	0.00%	16.67%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Critical	5	0.00%	0.00%	0.00%	16.67%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Excellent	1	5	1	1	1	0	0	0	0	0	0	0	0	0	0
Good	2	0	0	0	1	1	0	0	0	1	0	0	0	0	0
Fair	3	0	0	4	2	0	0	0	0	0	0	0	0	0	0
Poor	4	2	0	0	1	0	0	0	0	0	0	0	0	0	0
Critical	5	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure 5.34 Chimney HOQ

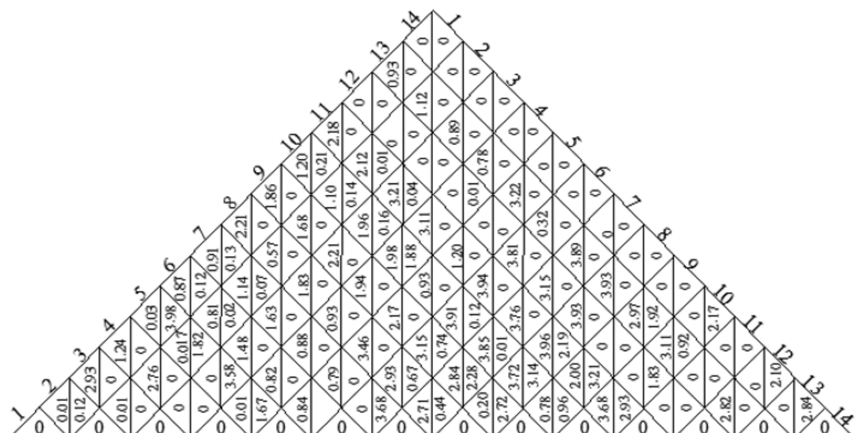
Table 5.31 Chimney Condition

Condition	Chimney Condition %	Condition Relative %	Chimney Overall Condition
Excellent	9.22%	26.10%	2.08
Good	17.50%	49.52%	
Fair	5.74%	16.23%	

Poor	2.18%	6.17%	
Critical	0.70%	1.98%	

5.4.2.5 Cone

The cone condition was computed after checking the PipeTech View software for the manholes and the information in the database. Accordingly, the defect counts were considered and used to construct the HOQ as shown in Figure 5.35 and to calculate the condition of the component as indicated in Table 5.32. Subsequently, the relative percentages for each grade were found and utilized to compute the overall component's grade, which was 2.00.



Condition	Defect Number	Long. Crack	Circ. Crack	Long. Fracture	Circ. Fracture	Deformation	Hole	Break	Collapse	Surface Damage	Roots	I/I	Obstruction	Attached Deposits	Prot. Service
		1.01	0.73	1.06	0.82	1.36	1.46	1.71	2.14	1.91	2.19	2.15	0.95	1.71	0.32
	Score/Weight	5.18%	3.74%	5.42%	4.21%	6.99%	7.46%	8.76%	10.95%	9.81%	11.23%	10.99%	4.86%	8.76%	1.65%
Excellent	1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Good	2	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fair	3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Poor	4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Critical	5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Excellent	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Good	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Fair	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Poor	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Critical	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0

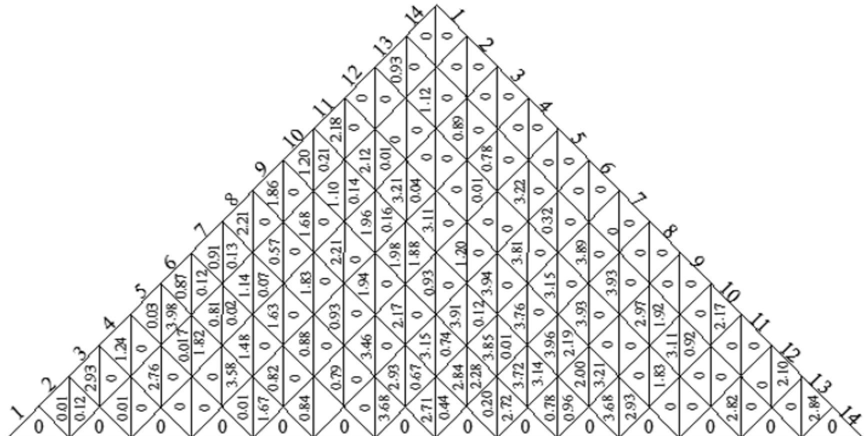
Figure 5.35 Cone HOQ

Table 5.32 Cone Condition

Condition	Cone Condition %	Condition Relative %	Cone Overall Condition
Excellent	0.00%	0.00%	2.00
Good	6.99%	100.00%	
Fair	0.00%	0.00%	
Poor	0.00%	0.00%	
Critical	0.00%	0.00%	

5.4.2.6 Wall

The wall condition was computed after checking the PipeTech View software for the manholes and the information in the database. The defect counts were considered and used to construct the HOQ as per Figure 5.36 and to calculate the condition of the component as shown in Table 5.33. Subsequently, the relative percentages for each grade were found and used to compute the overall component's grade, which was 2.04.



Condition	Defect	Long. Crack	Circ. Crack	Long. Fracture	Circ. Fracture	Deformation	Hole	Break	Collapse	Surface Damage	Roots	I/I	Obstruction	Attached Deposits	Prot. Service
		1.01	0.73	1.06	0.82	1.36	1.46	1.71	2.14	1.91	2.19	2.15	0.95	1.71	0.32
	Defect Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Score/Weight	5.18%	3.74%	5.42%	4.21%	6.99%	7.46%	8.76%	10.95%	9.81%	11.23%	10.99%	4.86%	8.76%	1.65%
Excellent	1	20.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Good	2	20.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fair	3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Poor	4	60.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Critical	5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Excellent	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Good	2	1	0	1	1	1	0	0	0	5	0	0	0	0	0
Fair	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Poor	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0
Critical	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0

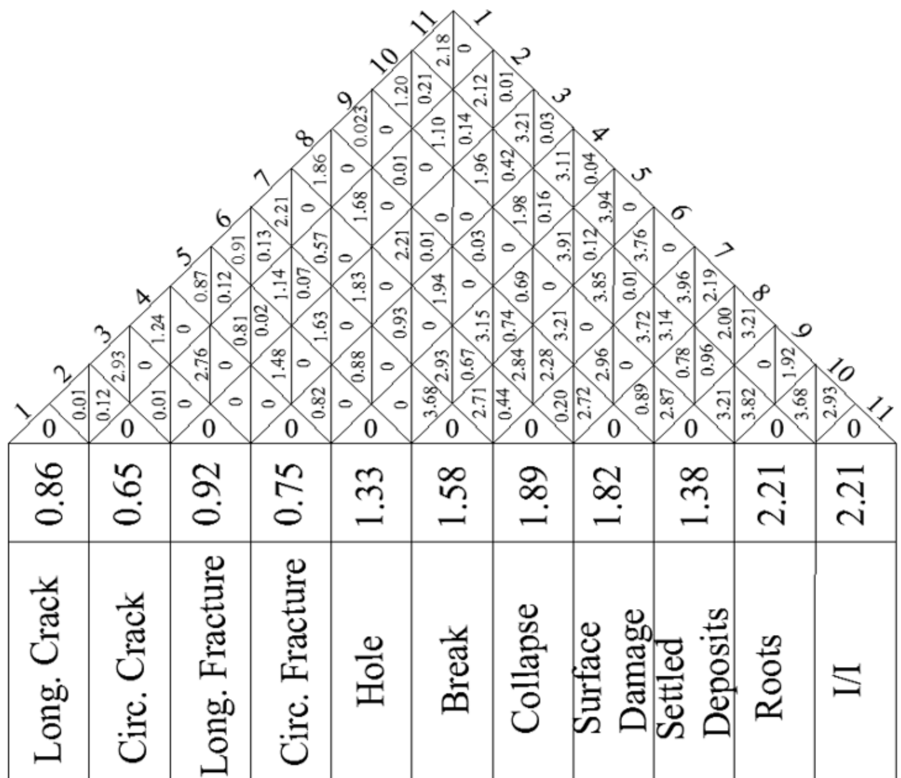
Figure 5.36 Wall HOQ

Table 5.33 Wall Condition

Condition	Wall Condition %	Condition Relative %	Wall Overall Condition
Excellent	4.78%	13.52%	2.04
Good	27.46%	77.70%	
Fair	0.00%	0.00%	
Poor	3.11%	8.79%	
Critical	0.00%	0.00%	

5.4.2.7 Bench

The wall condition was computed after checking the PipeTech View software for the manholes and the information in the database. Accordingly, the defect counts were considered and used to construct the HOQ as per Figure 5.37, and to calculate the condition of the component as shown in Table 5.34. Subsequently, the relative percentages for each grade were found and used to compute the overall component's grade, 2.07.



Condition	Defect Number	1	2	3	4	5	6	7	8	9	10	11
	Score/Weight	5.51%	4.14%	5.87%	4.84%	8.50%	10.16%	12.14%	11.64%	8.88%	14.18%	14.15%
Excellent	1	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	14.29%	100.00%	0.00%	0.00%
Good	2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	28.57%	0.00%	0.00%	0.00%
Fair	3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	14.29%	0.00%	0.00%	0.00%
Poor	4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	42.86%	0.00%	0.00%	0.00%
Critical	5	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Excellent	1	0	1	1	1	0	0	0	1	2	0	0
Good	2	0	0	0	0	0	0	0	2	0	0	0
Fair	3	0	0	0	0	0	0	0	1	0	0	0
Poor	4	0	0	0	0	0	0	0	3	0	0	0
Critical	5	1	0	0	0	0	0	0	0	0	0	0

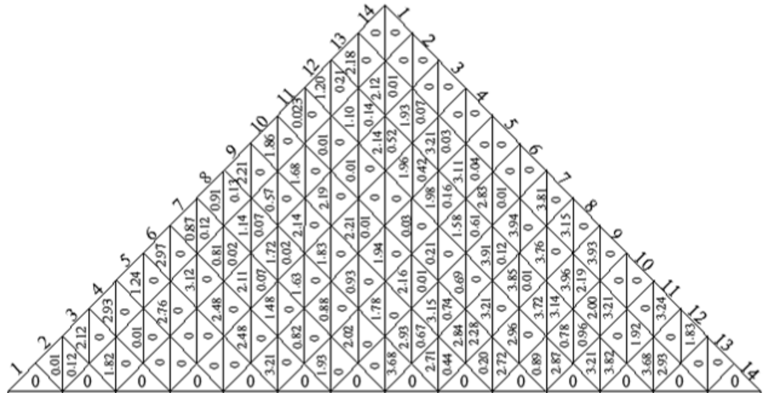
Figure 5.37 Bench HOQ

Table 5.34 Bench Condition

Condition	Bench Condition %	Condition Relative %	Bench Overall Condition
Excellent	25.39%	62.11%	2.07
Good	3.33%	8.14%	
Fair	1.66%	4.07%	
Poor	4.99%	12.20%	
Critical	5.51%	13.48%	

5.4.2.8 Channel

The channel condition was computed after checking the PipeTech View software for the manholes and the information in the database. Accordingly, the defect counts were considered and used to construct the HOQ as per Figure 5.38, and to calculate the condition of the component as shown in Table 5.35. Subsequently, the relative percentages for each grade were found and used to compute the overall component's grade: s 2.71.



		0.99	0.80	0.95	0.88	0.78	1.19	1.43	1.60	1.92	1.74	1.35	2.20	2.10	0.81
		Long. Crack	Circ. Crack	Multiple Crack	Long. Fracture	Circ. Fracture	Multiple Fracture	Hole	Break	Collapse	Surface Damage	Settled Deposits	Roots	I/I	Obstruction
Condition	**Defect Number**	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Score/Weight	5.26%	4.25%	5.09%	4.71%	4.19%	6.33%	7.61%	8.52%	10.25%	9.27%	7.23%	11.73%	11.22%	4.34%
Excellent	1	100.0%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Good	2	0.00%	66.67%	100.0%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fair	3	0.00%	33.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.0%	0.00%	0.00%	0.00%
Poor	4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.0%	0.00%	0.00%	0.00%	0.00%
Critical	5	0%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Excellent	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Good	2	0	2	2	0	0	0	0	0	0	0	0	0	0	0
Fair	3	0	1	0	0	0	0	0	0	0	0	1	0	0	0
Poor	4	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Critical	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.38 Channel HOQ.

Table 5.35 Channel Condition

Condition	Channel Condition %	Condition Relative %	Channel Overall Condition
Excellent	5.26%	16.90%	2.71
Good	7.93%	25.49%	
Fair	8.65%	27.80%	
Poor	9.27%	29.81%	
Critical	0.00%	0.00%	

5.4.2.9 Steps

The steps condition was computed after checking the PipeTech View software for the manholes and the information in the database. Accordingly, the defect counts were considered and used to measure the HOWs in the HOQ as per Table 5.36, and to calculate the overall condition of the component as shown in Table 5.36, which was 2.63.

Table 5.36 Steps Condition

Condition	Score/Weight	Defect Counts	Defect Percentage	Condition
Excellent	1	0	0.00%	2.63
Good	2	4	50.00%	
Fair	3	3	37.50%	
Poor	4	1	12.50%	
Critical	5	0	0.00%	

5.4.3 Manhole Overall Grade

This research considered nine different components for each manhole. Each component has its own defects and defect grades. The WHAT's of each component were similar; however, the HOW's were different based on the reports provided by the city of Edmonton. Using the relative influence weights of the defects involved in each model, the aggregated overall grade for each component was calculated. In order to determine the overall condition of the manhole, all of the components' grades were taken into account. The aggregation of all the components' grades was accomplished by utilizing the weights of the ANP operation. In the example demonstrated earlier, all component weights were computed and summarized as presented in Table 5.37.

Table 5.37 Manhole Components Conditions Summary

Component Overall Condition	Condition	Percentage	Overall Local Condition	Weight

Component Overall Condition	Condition	Percentage	Overall Local Condition	Weight
Pavement	Excellent	100.00%	1.00	4.70%
	Good	0.00%		
	Fair	0.00%		
	Poor	0.00%		
	Critical	0.00%		
Cover & Frame	Excellent	48.86%	1.67	15.13%
	Good	17.88%		
	Fair	0.00%		
	Poor	11.57%		
	Critical	0.00%		
Seals	Excellent	72.69%	1.27	14.44%
	Good	27.31%		
	Fair	0.00%		
	Poor	0.00%		
	Critical	0.00%		
Chimney	Excellent	9.22%	2.08	11.52%
	Good	17.50%		
	Fair	5.74%		
	Poor	2.18%		
	Critical	0.70%		
Cone	Excellent	0.00%	2.00	15.46%
	Good	6.99%		
	Fair	0.00%		
	Poor	0.00%		
	Critical	0.00%		
Wall	Excellent	4.78%	2.04	17.61%
	Good	27.46%		
	Fair	0.00%		
	Poor	3.11%		
	Critical	0.00%		
Bench	Excellent	25.39%	2.07	6.21%
	Good	3.33%		
	Fair	1.66%		
	Poor	4.99%		
	Critical	5.51%		
Channel	Excellent	5.26%	2.71	11.10%
	Good	7.93%		

Component Overall Condition	Condition	Percentage	Overall Local Condition	Weight
	Fair	8.65%		
	Poor	9.27%		
	Critical	0.00%		
Steps	Excellent	0.00%	2.63	3.83%
	Good	50.00%		
	Fair	37.50%		
	Poor	12.50%		
	Critical	0.00%		

The aggregated conditions of all components are found using the ANP weights as follows:

Manhole Overall Grade = 1.00 * 0.047 + 1.67 *0.1513 + 1.27*0.1444 + 2.08 * 0.1152+ 2.00*0.1546 + 2.04 * 0.1761 + 2.07 * 0.0621 + 2.71*0.111 + 2.63*0.0383 = 1.92

Based on the results, the overall manhole grade is 1.92 and its condition is Good, meaning that minor defects were observed with small to medium severities. The remaining 23 manhole conditions were calculated following the same steps. Each manhole condition was computed considering the nine models illustrated earlier, with the results as displayed in Table 5.38. The table shows the overall grade for each component and the overall grade of each manhole. In addition, the MACP grades are indicated in the last column and were used to validate the results.

Table 5.38 Royal Gardens Manhole Conditions

Manhole #	Overall Component Grade									Manhole Overall Grade	Actual
	Pavement	Cover & Frame	Seals	Chimney	Cone	Wall	Bench	Channel	Steps		
1	1	1.67	1.27	2.08	2	2.04	2.07	2.71	2.63	1.92	3
2	1	2.41	1.27	2.56	3.14	3.51	2.92	3.78	3.54	2.73	4
3	4	2.2	1	1.74	3.69	2.94	3.26	2.71	3.46	2.59	3
4	2	2.26	1.18	2.29	3.39	2.5	3.4	2.89	3.29	2.49	3
5	5	1.55	1.28	3.04	2.2	2.22	3.07	2.61	2.79	2.33	3
6	3	2.32	1.28	3.27	2.45	2.38	3.11	2.41	2.67	2.41	2
7	3	2.95	1.18	3.42	2.47	2.47	3.49	2.31	3.1	2.56	2
8	5	2.84	1	3.71	2.64	2.74	4.15	4.1	3.44	2.97	4
9	5	3.63	1.27	4.21	2.49	2.55	4.23	4.3	3.57	3.16	4
10	1	1.69	1.31	2.57	2.1	2.13	3.58	4.12	2.67	2.27	4
11	1	2	1	2.2	2.47	2.31	2.45	1.87	2.44	1.99	2
12	3	2.31	1	3.64	1.74	2.44	3.18	3.41	2.81	2.44	2
13	1	1.41	1.12	3.17	1.86	3.37	3.74	3.89	3.12	2.45	4
14	2	1.65	1	1.85	1.1	3.56	3.4	3.47	3.12	2.21	2
15	1	1	1	3.12	1.21	2.05	2.16	2.25	3	1.75	3
16	1	1	1	3.59	1.13	1.97	2.03	2.04	2.51	1.73	2
17	1	1.21	1	2.95	1.37	2.97	2.52	2.69	2.19	1.99	2
18	3	1.12	1	1.31	1.03	1.45	2.03	1.21	2.1	1.36	1
19	5	1.34	2.34	3.67	1.56	2.59	2.34	1.67	3.12	2.35	2
20	2	1	1	3.86	1.21	1.69	2.17	2.36	3.1	1.83	3
21	1	1	1	1.23	1.19	1.13	3.22	2.41	3.21	1.46	2
22	2	1.12	1	3.54	2.15	3.64	1.32	1.54	3.19	2.16	3
23	5	1	1	3.66	1.18	1.14	2.68	2.96	3.28	1.96	2
24	1	1	1	3.58	1.51	2.64	2.19	2.51	3.21	1.99	3

To better represent the results, they are represented in pie-chart form in Figure 5.39. Based on that figure, 4% of the manholes are rated as Poor, 54% are rated as Fair,34% of the manholes are in Good condition, and 8% of the manholes are in Excellent condition. According to the assessment, no critical condition is depicted.

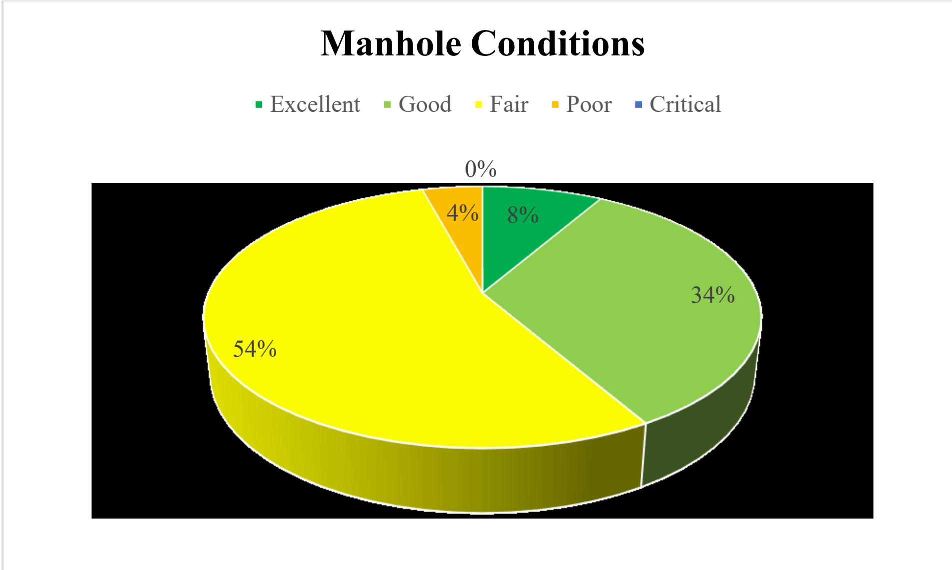


Figure 5.39 Royal Gardens Manholes Conditions Categories

5.4.4 Model Validation

The manhole condition assessment model was validated with the MACP values obtained from an expert. This section indicates the efficiency of the proposed model compared to the actual results. Equations 5.1 to 5.5 were adopted to validate the results.

Considering the validation equations, Table 5.39 summarizes the results. The AVP is calculated as 76.24%; RMSE is 0.84; MAE is 0.69 and f_i is 591.72. The results suggested that there were some deviations from the actual values. This was expected, as the model suggested a new methodology for assessing the manhole condition considering relative influence weights and relative importance weights.

Table 5.39 Manhole Condition Assessment Model Validation Results

Equation	Value
AIP	23.76%
AVP	76.24%
MAE	0.69
f_i	591.72
RMSE	0.84

5.5 Sewer Pipeline Deterioration

The proposed research designed a novel approach for estimating the condition of sewer pipelines and manholes by including major defects that can be observed in the asset. More importantly, the assessment model involved the void erosion defect, a key defect that is neglected by current practices. All of the defects were displayed in a unique HOQ which represented the WHAT's and HOW's of the system. Instead of using the correlation between the defects, the cause and effect relationship between the defects was established through a questionnaire. The results of the questionnaire were analyzed using the DEMATEL approach to aggregate every condition grade. Later on, a condition index considering all condition grades was calculated based on a 1 to 5 scale. The condition index supplied by the condition assessment model was used to construct the UDC of the pipeline to understand how the pipeline will behave over future years.

In this context, the deterioration model was established for the same pipeline used for the condition assessment estimation. The pipeline's calculated grade was 2.49 and its age was 54 years since construction. Figure 5.40 displays the IDC and the UDC of the pipeline. According to the figure, the pipeline is functioning better than the ideal condition. Based on the results, the pipeline is expected to reach to a critical condition at the age of 89 to 90 years. A decision maker can follow the curve plotted for the UDC and estimate the CI_P_UDC at time t_i. For example, at 60 years, the asset condition based on the UDC curve is 0.62, which is 2.90 on a scale of 1 to 5.

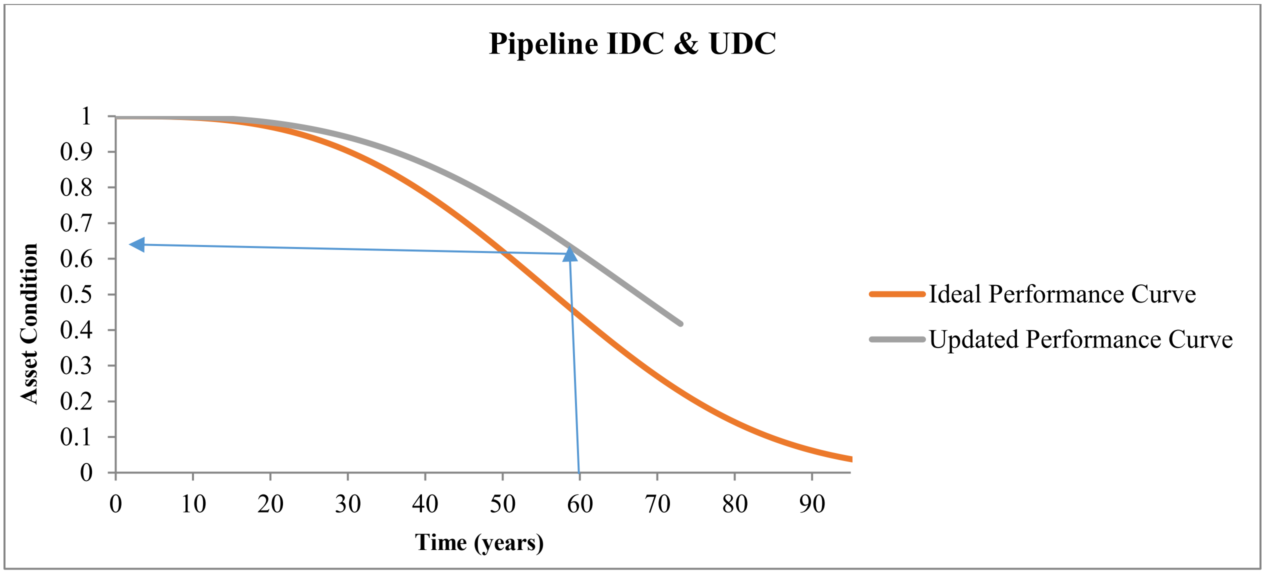


Figure 5.40 IDC and UDC of a Royal Gardens Pipeline

The rest of the pipelines' deterioration curves were modeled and can be found in the Appendix. Table 5.40 summarizes the results found for each pipeline in terms of the age and the year when the pipeline is predicted to reach condition 5 without any intervention. Similar results are also shown in Figure 5.41. According to the table and the figure, the average year when a pipeline is expected to reach condition 5 is at 2049, where the average age of is 84. The minimum age of a pipeline reaching a condition 5 is after 15 years since construction (at year 2025). Meanwhile, the maximum age of a pipeline reaching a condition of 5 is after 137 years since construction (in year 2101).

Table 5.40 Royal Gardens Pipelines Deterioration Prediction

Pipe #	Estimated Condition	Condition (0-1)	Year Of Construction	Age	Age at Condition 5	Year at Condition 5
1	1.830	0.834	1965	53	109	2074
2	2.763	0.647	1965	53	82	2047
3	2.440	0.712	1965	53	89	2054
4	2.039	0.792	1964	54	102	2066
5	3.445	0.511	1965	53	72	2037
6	3.389	0.522	1964	54	73	2037

Pipe #	Estimated Condition	Condition (0-1)	Year Of Construction	Age	Age at Condition 5	Year at Condition 5
7	2.488	0.702	1964	54	89	2053
8	2.486	0.703	1965	53	88	2053
9	2.560	0.688	1964	54	87	2051
10	3.656	0.469	1964	54	69	2033
11	3.143	0.571	1964	54	76	2040
12	2.799	0.640	1965	53	81	2046
13	2.369	0.726	1965	53	95	2060
14	3.812	0.438	1964	54	67	2031
15	3.874	0.425	1964	54	66	2030
16	2.491	0.702	1965	53	87	2052
17	2.208	0.758	1965	53	95	2060
18	3.195	0.561	1964	54	76	2040
19	2.149	0.770	1964	54	99	2063
20	3.994	0.401	1964	54	65	2029
21	2.877	0.625	1964	54	81	2045
22	2.948	0.610	1964	54	80	2044
23	3.885	0.423	1964	54	66	2030
24	3.730	0.454	1964	54	68	2032
25	2.758	0.648	1964	54	83	2047
26	1.681	0.864	1964	54	120	2084
27	2.703	0.659	1964	54	85	2049
28	2.573	0.685	1964	54	87	2051
29	2.105	0.779	1964	54	100	2064
30	2.421	0.716	1964	54	91	2055
31	2.220	0.756	1968	50	91	2059
32	3.042	0.592	1964	54	78	2042
33	2.954	0.609	1964	54	80	2044
34	1.874	0.825	1964	54	109	2073
35	1.874	0.825	1964	54	109	2073
36	1.464	0.907	1964	54	137	2101
37	2.710	0.658	1964	54	84	2048
38	2.526	0.695	1966	52	85	2051
39	2.526	0.695	1966	52	85	2051
40	3.251	0.550	1965	53	73	2038
41	3.336	0.533	1964	54	74	2038
42	2.356	0.729	1967	51	88	2055
43	2.585	0.683	1964	54	87	2051

Pipe #	Estimated Condition	Condition (0-1)	Year Of Construction	Age	Age at Condition 5	Year at Condition 5
44	3.318	0.536	1966	52	71	2037
45	2.300	0.740	1966	52	90	2056
46	2.170	0.766	1964	54	98	2062
47	1.976	0.805	1964	54	105	2069
48	2.443	0.711	1964	54	90	2054
49	2.501	0.700	1964	54	89	2053
50	2.270	0.746	1966	52	91	2057
51	3.520	0.496	1965	53	70	2035
52	2.414	0.717	1965	53	90	2055
53	2.509	0.698	1965	53	87	2052
54	2.635	0.673	1965	53	84	2049
55	3.020	0.596	1965	53	77	2042
56	2.563	0.687	1965	53	86	2051
57	2.814	0.637	1965	53	81	2046
58	2.607	0.679	1964	54	87	2051
59	2.329	0.734	1965	53	92	2057
60	3.296	0.541	1964	54	74	2038
61	2.906	0.619	1965	53	79	2044
62	3.133	0.573	1964	54	77	2041
63	2.548	0.690	1965	53	86	2051
64	2.548	0.690	1965	53	86	2051
65	2.542	0.692	1965	53	87	2052
66	3.287	0.543	1965	53	73	2038
67	3.293	0.541	1965	53	73	2038
68	3.074	0.585	1965	53	76	2041
69	3.273	0.545	1965	53	73	2038
70	2.879	0.624	1965	53	80	2045
71	2.535	0.693	1965	53	87	2052
72	2.805	0.639	1965	53	81	2046
73	2.378	0.724	1965	53	90	2055
74	2.479	0.704	1965	53	88	2053
75	2.250	0.750	1967.98	50.02	83	2051
76	3.460	0.508	1964	54	72	2036
77	3.465	0.507	1964	54	72	2036
78	2.310	0.738	1964	54	94	2058
79	2.484	0.703	1971	47	78	2049
80	1.831	0.834	1987	31	64	2051

Pipe #	Estimated Condition	Condition (0-1)	Year Of Construction	Age	Age at Condition 5	Year at Condition 5
81	2.342	0.732	1965	53	91	2056
82	3.172	0.566	1986	32	45	2031
83	2.287	0.743	1965	53	93	2058
84	2.736	0.653	1965	53	82	2047
85	2.077	0.785	2010	8	15	2025

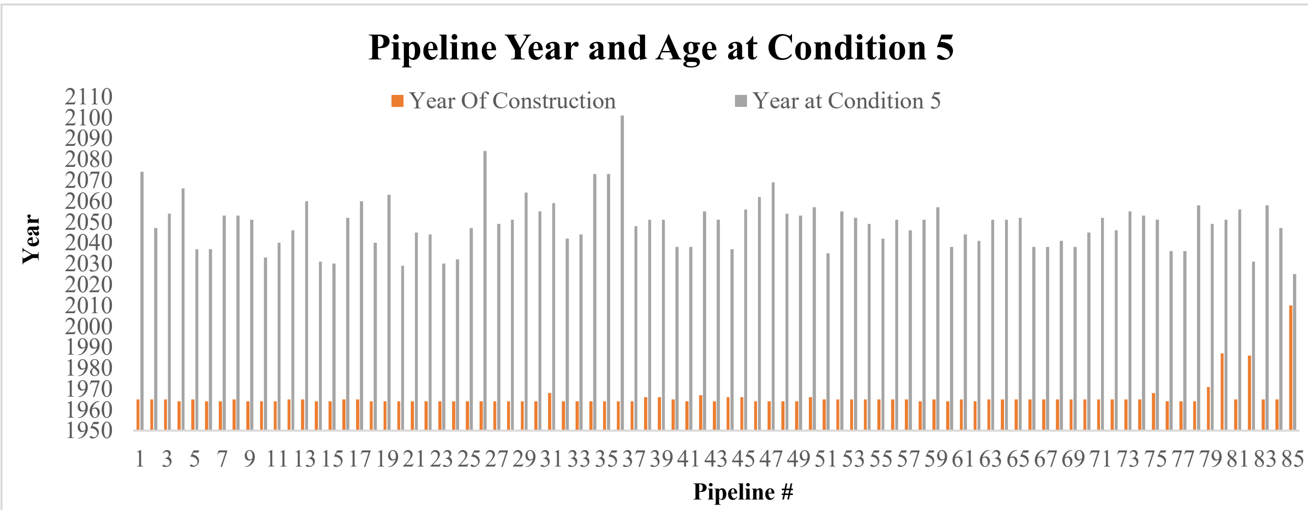


Figure 5.41 Royal Gardens Pipelines Age at Condition 5

5.6 Sewer Manhole Deterioration

The proposed research designed a novel approach to estimating the condition of sewer manholes by including major defects that can be observed in the different manhole components. The considered defects for each manhole component were displayed in unique HOQs that represented the WHAT's and HOW's of the systems. Instead of using the correlation between the defects, the cause and effect relationship between the defects was established. The results of the questionnaire were analyzed using the DEMATEL approach to aggregate every condition grade and finally to represent each component by its condition. Subsequently, all component conditions were aggregated after implementing the ANP approach. The condition index supplied by the condition assessment model is used to construct the UDC of the manhole to understand how it will behave throughout the years.

In this context, the deterioration model was established for one of the manholes used for the condition assessment model implementation. The overall calculated manhole grade was 3.16 and its age 54 years since construction. Figure 5.42 displays the IDC and the UDC of the manhole. Based on the two curves, the UDC is approximately behaving similar to the IDC distribution. Based on the results, the manhole is expected to reach to the critical condition at the age of 76. For example, a decision maker can follow the curve plotted for the UDC and estimate the CI_M_UDC at time t_i. For example, at age of 60 years, the asset condition based on the UDC curve is 0.46, which is 3.7 on a scale of 1 to 5.

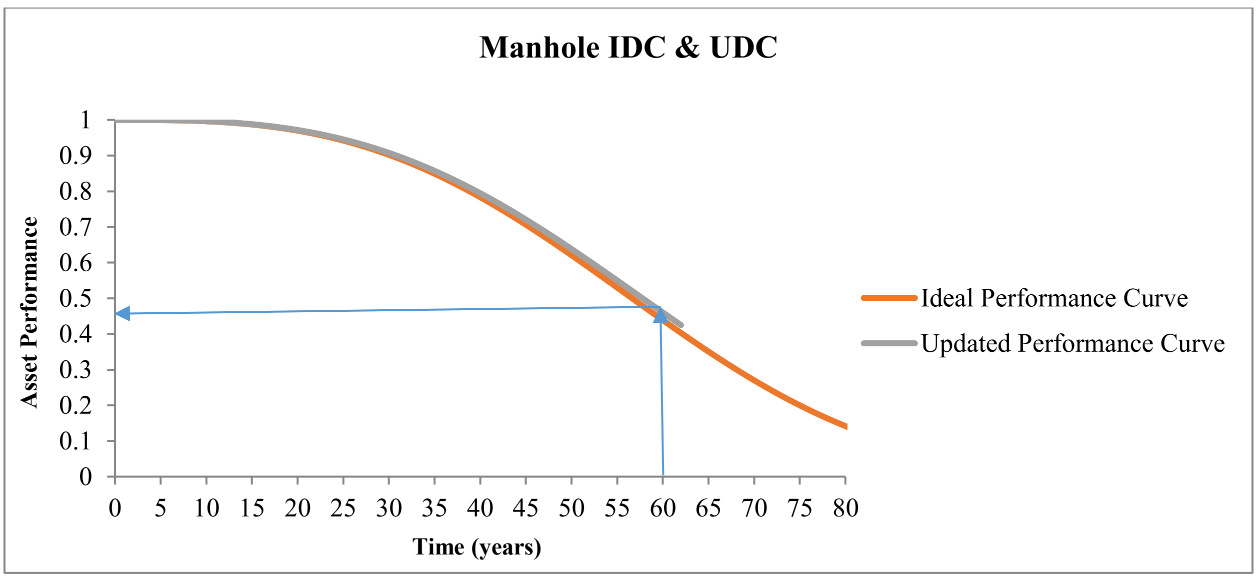


Figure 5.42 IDC and UDC for a Royal Gardens Manhole

The rest of the manholes' deterioration curves were modeled and can be found in the Appendix. Table 5.41 summarizes the results found for each manhole in terms of the age and the year when the pipeline is predicted to reach condition 5. Similar results are also shown in Figure 5.43. According to the table and the figure, the average year in which pipeline are expected to reach condition 5 is in 2063, where the average age of is 98. The minimum age of a pipeline reaching a condition 5 is 76 years since construction (at year 2040). Nevertheless, the maximum age of a pipeline reaching a condition of 5 is at 138 years since construction (at year 2102).

Table 5.41 Royal Gardens Manhole Deterioration Prediction

Manhole #	Estimated Condition	Condition (0-1)	Year of Construction	Age	Age at Condition 5	Year at Condition 5
1	1.920	0.816	1965	53	106	2071
2	2.730	0.654	1965	53	83	2048
3	2.590	0.682	1964	54	87	2051
4	2.490	0.702	1964	54	89	2053
5	2.330	0.734	1964	54	94	2058
6	2.414	0.717	1964	54	91	2055
7	2.560	0.688	1964	54	88	2052
8	2.972	0.606	1964	54	80	2044
9	3.163	0.567	1964	54	76	2040
10	2.270	0.746	1968	50	88	2056
11	1.989	0.802	1968	50	97	2065
12	2.437	0.713	1968	50	84	2052
13	2.452	0.710	1968	50	84	2052
14	2.214	0.757	1968	50	90	2058
15	1.749	0.850	1965	53	114	2079
16	1.727	0.855	1964	54	117	2081
17	1.988	0.802	1964	54	105	2069
18	1.361	0.928	1964	54	138	2102
19	2.346	0.731	1964	54	93	2057
20	1.834	0.833	1964	54	112	2076
21	1.458	0.908	1964	54	138	2102
22	2.164	0.767	1965	53	97	2062
23	1.956	0.809	1964	54	106	2070
24	1.991	0.802	1971	47	91	2062

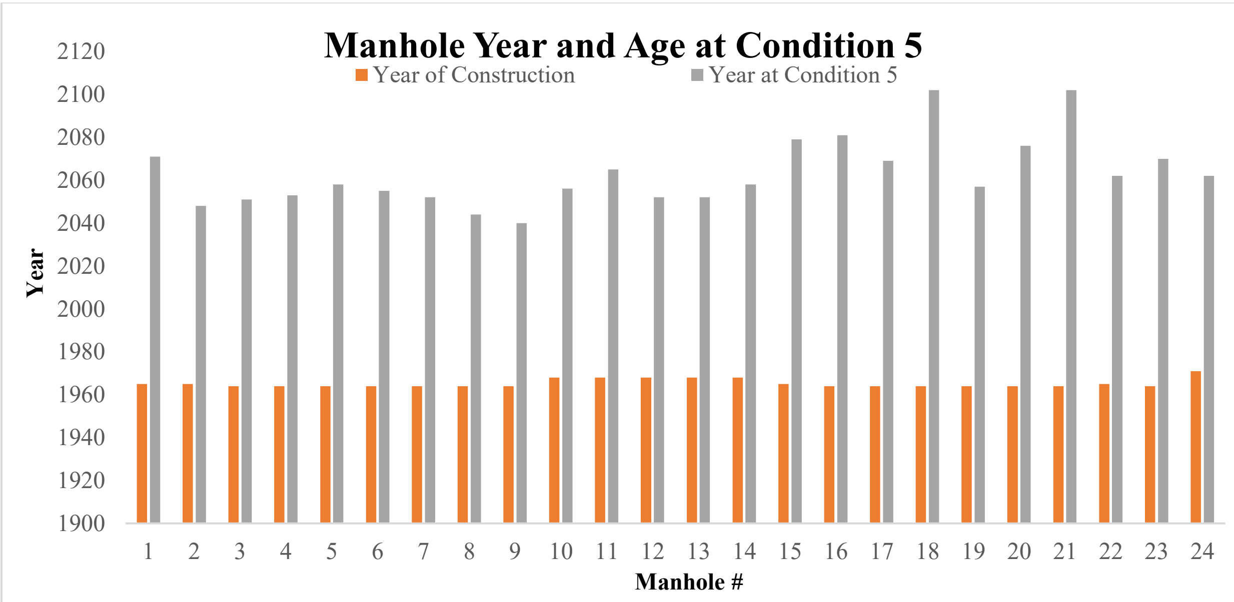


Figure 5.43 Royal Gardens Manholes Age at Condition 5

5.7 Pipelines Criticality

The pipeline data was almost comprehensive, with minimal missing information. The criticality model was implemented on 85 pipelines. Based on the information provided in the database, each sub-factor was analyzed and an attribute value from 1 to 5 was assigned. Later, the criticality value was aggregated using the weights obtained from the ANP and from the questionnaires. Table 5.42 displays the assigned attribute values and the criticality values for each pipeline.

Based on the results, none of the pipelines were of high and extreme criticality. In addition, no pipeline was found to be completely noncritical. The results suggest that 89% of the pipelines are of medium criticality and 11% are of low criticality, as shown in Figure 5.44. It is worth mentioning that the sewer network in the city of Edmonton is actually a residential area and lacks any proximity to surface water. In addition, the implemented case study was not comprehensive, as other pipeline information were missing.

Table 5.42 Royal Gardens Pipelines Criticality

Pipe #	Environmental			Economic					Public							Criticality
	Soil Type	Flow Conveyed	Proximity to Surface Water	Depth	Diameter	Water Table	Length	Accessibility	Population Density	Road Type	Diameter	Length	Depth	Accessibility	Land Use	
	0.102	0.075	0.107	0.100	0.085	0.032	0.066	0.109	0.092	0.095	0.043	0.028	0.028	0.013	0.024	
1	2	3	1	5	2	1	3	3	1	4	2	3	5	3	3	2.66
2	2	1	1	5	2	1	4	3	1	4	2	4	5	3	3	2.60
3	3	1	1	5	1	1	2	3	3	1	1	2	5	3	3	2.29
4	2	2	1	5	2	1	3	3	3	1	2	3	5	3	3	2.48
5	3	1	1	5	1	1	3	3	3	1	1	3	5	3	3	2.38
6	3	1	1	5	1	1	3	3	3	1	1	3	5	3	3	2.38
7	3	2	1	5	2	1	3	3	3	1	2	3	5	3	3	2.58
8	3	1	1	4	1	1	3	1	1	1	1	3	4	1	3	1.83
9	3	1	1	4	1	1	3	3	5	1	1	3	4	3	3	2.44
10	3	1	1	5	2	1	3	3	5	1	2	3	5	3	3	2.69
11	3	1	1	5	2	1	1	3	5	1	2	1	5	3	3	2.50
12	2	3	1	5	3	1	1	3	1	4	3	1	5	3	3	2.60
13	2	2	1	5	3	1	3	1	3	3	3	3	5	1	3	2.56
14	3	1	1	4	3	1	3	3	5	2	3	3	4	3	3	2.79
15	3	1	1	3	1	5	3	5	5	1	1	3	3	5	3	2.68
16	3	1	1	5	1	1	3	5	5	1	1	3	5	5	3	2.81
17	3	1	1	4	1	1	3	5	5	1	1	3	4	5	3	2.68
18	3	1	1	5	1	1	3	5	5	1	1	3	5	5	3	2.81
19	3	1	1	4	1	1	3	5	5	1	1	3	4	5	3	2.68
20	3	1	1	5	1	1	3	5	5	1	1	3	5	5	3	2.81
21	3	1	1	4	1	1	3	5	5	1	1	3	4	5	3	2.68
22	3	1	1	3	1	5	3	5	5	2	1	3	3	5	3	2.77
23	3	1	1	4	1	5	3	5	5	1	1	3	4	5	3	2.81
24	3	1	1	3	1	5	3	5	5	1	1	3	3	5	3	2.68
25	2	1	1	5	2	1	3	5	5	1	2	3	5	5	3	2.83
26	2	1	1	5	2	1	3	3	5	1	2	3	5	3	3	2.59
27	2	1	1	5	2	1	2	3	5	1	2	2	5	3	3	2.50
28	3	1	1	4	1	1	1	3	5	1	1	1	4	3	3	2.25
29	2	1	1	5	2	1	2	3	5	1	2	2	5	3	3	2.50
30	2	1	1	5	2	1	3	3	3	1	2	3	5	3	3	2.41
31	3	1	1	3	1	5	3	3	3	3	1	3	3	3	3	2.44
32	3	1	1	3	1	5	2	3	5	1	1	2	3	3	3	2.34
33	3	1	1	3	1	5	2	3	5	1	1	2	3	3	3	2.34
34	2	1	1	5	2	1	3	1	1	1	2	3	5	1	3	1.98
35	2	4	1	5	2	1	1	3	3	1	2	1	5	3	3	2.45
36	2	1	1	5	2	1	2	3	3	1	2	2	5	3	3	2.31
37	2	1	1	5	2	1	2	3	5	1	2	2	5	3	3	2.50
38	3	1	1	5	1	1	3	1	1	2	1	3	5	1	5	2.10
39	3	1	1	5	1	1	2	1	1	2	1	2	5	1	5	2.01
40	3	1	1	3	1	5	3	3	3	2	1	3	3	3	3	2.35
41	3	1	1	4	2	5	3	3	5	1	2	3	4	3	3	2.69
42	3	1	1	5	1	1	1	3	1	1	1	1	5	3	3	2.01
43	3	3	1	5	3	1	1	1	1	3	3	1	5	1	5	2.41
44	3	1	1	4	1	5	2	3	5	1	1	2	4	3	3	2.47
45	3	1	1	4	1	1	2	3	5	1	1	2	4	3	3	2.34
46	3	1	1	5	3	1	2	3	5	2	3	2	5	3	3	2.82
47	3	1	1	5	2	1	2	3	5	2	2	2	5	3	3	2.69
48	3	1	1	5	3	1	2	3	5	2	3	2	5	3	3	2.82
49	3	1	1	4	1	1	2	3	5	2	1	2	4	3	3	2.44
50	3	1	1	5	3	1	3	1	1	3	3	3	5	1	3	2.40
51	3	1	1	3	1	5	3	3	3	1	1	3	3	3	3	2.25
52	3	1	1	3	1	5	3	3	3	1	1	3	3	3	3	2.25
53	3	1	1	3	1	5	3	3	3	1	1	3	3	3	3	2.25
54	3	1	1	4	1	1	3	3	5	1	1	3	4	3	3	2.44
55	3	1	1	4	1	5	3	3	5	1	1	3	4	3	3	2.57
56	3	1	1	4	1	5	3	3	5	1	1	3	4	3	3	2.57
57	3	1	1	3	1	5	2	3	5	1	1	2	3	3	3	2.34
58	3	1	1	3	1	5	2	3	5	1	1	2	3	3	3	2.34
59	3	1	1	4	1	1	3	3	5	1	1	3	4	3	3	2.44
60	3	1	1	3	1	5	3	3	5	1	1	3	3	3	3	2.44
61	3	1	1	4	1	1	3	3	5	1	1	3	4	3	3	2.44
62	3	1	1	5	1	1	3	3	5	1	1	3	5	3	3	2.56
63	3	1	1	5	1	1	2	3	3	1	1	2	5	3	3	2.29
64	3	1	1	5	1	1	3	3	5	1	1	3	5	3	3	2.56
65	3	1	1	5	1	1	2	3	1	1	1	2	5	3	3	2.10
66	3	1	1	4	1	5	2	3	1	1	1	2	4	3	3	2.10
67	3	1	1	3	1	5	2	1	1	1	1	2	3	1	3	1.73
68	3	1	1	5	1	1	2	1	1	1	1	2	5	1	3	1.86
69	3	1	1	5	1	1	1	1	1	1	1	1	5	1	3	1.77
70	3	1	1	4	1	1	3	1	1	1	1	3	4	1	3	1.83
71	3	1	1	5	2	1	2	3	5	1	2	2	5	3	3	2.60
72	3	1	1	5	2	1	3	3	5	1	2	3	5	3	3	2.69
73	3	1	1	5	3	1	2	3	5	2	3	2	5	3	3	2.82
74	3	1	1	5	3	1	3	3	5	2	3	3	5	3	3	2.92
75	3	1	1	5	1	1	2	3	5	4	1	2	5	3	5	2.80
76	3	1	1	4	1	5	2	3	5	1	1	2	4	3	3	2.47
77	3	1	1	3	1	5	2	3	3	1	1	2	3	3	3	2.16
78	3	1	1	4	1	1	2	3	5	1	1	2	4	3	3	2.34
79	3	1	1	5	1	1	1	1	1	3	1	1	5	1	3	1.96
80	3	1	1	5	3	1	1	1	1	4	3	1	5	1	1	2.26
81	2	1	1	5	2	1	1	3	1	3	2	1	5	3	3	2.23
82	3	1	1	2	1	5	1	1	1	4	1	1	2	1	1	1.75
83	2	3	1	5	2	1	1	3	5	3	2	1	5	3	5	2.79
84	3	1	1	5	1	1	2	3	5	3	1	2	5	3	5	2.71
85	3	1	1	4	1	1	1	1	1	3	1	1	4	1	1	1.78

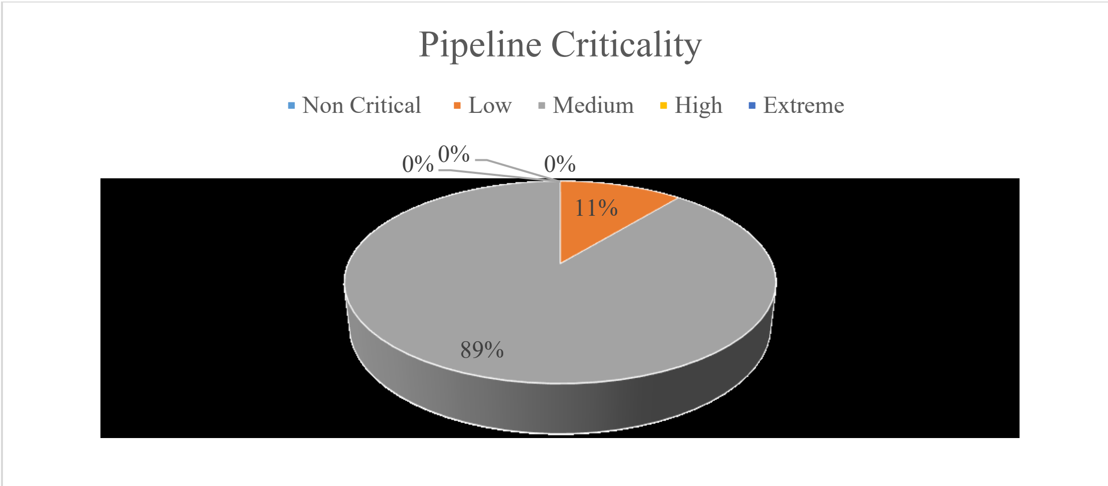


Figure 5.44 Royal Gardens Pipelines Criticality Classification

5.8 Manhole Criticality

The manhole data is not comprehensive, as much of the manholes' information was missing. Therefore, the criticality model was implemented on 24 manholes. Based on the information provided in the database, each sub-factor was analyzed and an attribute value from 1 to 5 was assigned. Later, the criticality value was aggregated using the weights obtained from the ANP and the questionnaires. Table 5.43 displays the assigned attribute values and the criticality values for each manhole.

Based on the results, none of the manholes was of high or extreme criticality. However, there were no pipelines that were non critical. The results suggests that 86% of the manholes are of medium criticality and 14% are of low criticality, as highlighted in Figure 5.45. It is worth noting that the sewer network brought in the city of Edmonton is actually a residential area and most of the manholes are not in critical zones. For example, most of the assets are far from surface water, a sub-factor with one of the highest weights.

Table 5.43 Royal Gardens Manholes Criticality

Manhole #	Environmental			Economic					Public						Criticality
	Soil Type	Flow Conveyed	Proximity to Surface Water	Depth	Diameter	Accessibility	Water Table	Number of Inlets	Population Density	Land Use	Depth	Road Type	Accessibility	Diameter	
	0.108	0.072	0.108	0.113	0.087	0.107	0.047	0.024	0.075	0.069	0.021	0.067	0.049	0.053	
1	3	1	1	2	2	3	1	2	5	5	2	3	3	2	2.53
2	2	1	1	3	2	3	1	2	3	3	3	2	3	2	2.21
3	2	1	1	4	2	5	1	2	3	3	4	1	5	2	2.59
4	2	1	1	4	2	5	1	2	3	3	4	1	5	2	2.59
5	2	1	1	3	2	3	1	2	5	3	3	1	3	2	2.29
6	3	1	1	2	2	3	5	3	5	3	2	1	3	2	2.48
7	3	1	1	2	2	3	1	2	5	3	2	1	3	2	2.26
8	3	1	1	2	2	3	5	1	5	3	2	1	3	2	2.43
9	3	1	1	2	2	1	5	1	1	3	2	2	1	2	1.88
10	3	3	1	2	2	3	1	4	5	3	2	1	3	2	2.45
11	3	4	1	2	2	3	1	3	5	3	2	1	3	2	2.50
12	3	4	1	2	2	3	1	2	5	3	2	1	3	2	2.48
13	3	1	1	2	2	1	5	2	5	5	2	3	1	2	2.41
14	3	1	1	2	2	1	1	2	5	5	2	3	1	2	2.22
15	2	2	1	4	2	1	1	3	3	3	4	2	1	2	2.12
16	3	1	1	2	2	1	1	2	3	3	2	1	1	2	1.80
17	3	1	1	2	2	1	5	2	3	3	2	1	1	2	1.99
18	3	1	1	2	2	1	5	1	3	3	2	1	1	2	1.97
19	3	1	1	2	2	3	5	2	5	3	2	1	3	2	2.45
20	3	1	1	2	2	3	1	2	5	3	2	1	3	2	2.26
21	3	1	1	2	2	3	1	2	5	3	2	1	3	2	2.26
22	2	1	1	5	2	1	1	3	1	3	5	3	1	2	2.10
23	3	1	1	2	2	1	5	2	3	3	2	2	1	2	2.06
24	3	2	1	2	2	1	1	2	1	3	2	3	1	2	1.86

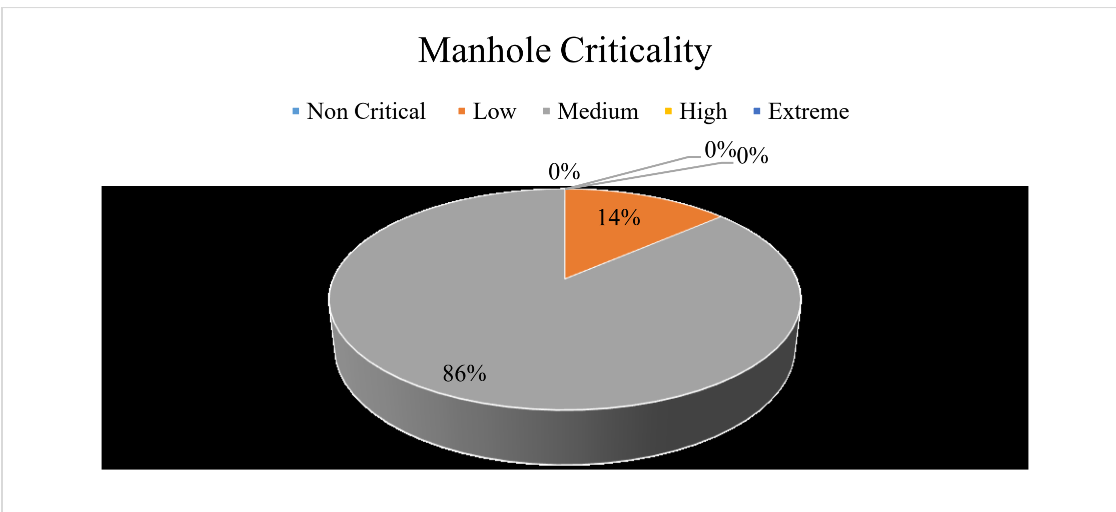


Figure 5.45 Royal Gardens Manholes Criticality Classifications

5.9 Royal Gardens Sewer Network Performance

The overall pipeline conditions were determined by considering the criticality of each pipeline and its condition. It is computed by dividing the summation of the product of the criticality and the condition by the summation of all criticalities. Based on this operation, the overall pipelines' condition is found to be 2.71. According to the proposed scale, the overall pipelines' condition is

Fair. The overall manholes' condition is determined by considering the criticality of each manhole and its condition. It is computed by dividing the summation of the product of the criticality and the condition by the summation of all criticalities. Based on this operation, the overall manholes' condition is found to be as described in Section 2.23. According to the proposed scale, the overall manholes' condition is Fair.

The overall network performance is estimated based on a weighted average method considering the abovementioned values and the importance weight of each asset. According to the survey, with regards to the importance of the asset in computing the network condition, the pipelines' percentage was 65.313% and the manholes' percentage was 34.688%. These weights are significant so that the overall pipelines and manholes' conditions can be aggregated. Doing so, the overall sewer network condition was computed as 2.54. Based on the proposed scale, the network condition is Fair.

5.10 Budget Allocation Model

The budget allocation model is implemented to provide two main outputs for decision makers: the total cost required to enhance the performance of the sewer network as well as the decision variable (interventions) needed in the study period. The model utilizes the PSO tool to solve the budget allocation problem.

5.10.1 Decision variables

The decision variables considered in this research are four per asset: do nothing, minor, major and replacement. The improvements of the decision variables are similar in both assets; however, the costs differ from one type to the other. Since the study period is five years, real interest rate is considered, by incorporating the inflation rate. The considered real interest rate is 3%. The optimization problem in this study involves minimizing the total cost and maximizing the ONP. A specific maximum budget is taken into account so that the interventions do not exceed the allocated budget. As a result, the overall budget is taken as $1.5-million distributed over five years. This amount is considered as the number of assets forming the network is low.

Municipalities are required to maintain proper ONP to avoid any malfunction or exfiltration. Therefore, the initial relative importance weight of the ONP is set as 60%. However, the study will also generate additional trade-off solutions between available budgets and improvements by varying the weights to plot the near-optimum Pareto Frontier. As a result, decision makers can select any of the solutions that satisfy their minimum ONP and total costs (constraints). However, further investigations are required should any of the solutions be selected. This will allow decision-makers to list the interventions required for each asset along with the costs involved.

5.10.2 Model Outputs

Based on the considered relative importance weights for objective functions (60% ONP and 40% TLCC), the number of iterations required to attain the solution was 1255 (Figure 5.46). As shown in Figure 5.46, eight different *gbest* particles in the swarm led to the convergence. Global PSO has the ability to widely explore for solutions in a domain space. Each particle influences the whole swarm and directs them to the best solutions in each iteration. Therefore, the first few iterations are expected to drop (minimization problem) significantly, as the particles are still very much exploring. However, before convergence, minimal changes are observed, because the particles will be exploiting the advantages. Although the results were not compared with other

EA optimization methods, PSO is well-known for its fast convergence compared to other methods. Based on the results, the fitness function was 0.554 and hence, the total budget required was 1.126-million. Based on the total predicted budget, the ONP attained at the end of the fifth year was 2.11. According to Table 5.44, the MRR budget was distributed in the first four years while no costs were incurred in the last year. The highest incurred costs were in the first year and the least incurred costs were in year four. Most of the TLCC portion was dispensed in the first year, since 44 assets were rehabilitated or replaced that first year. More specifically, 13 assets were replaced and 31 assets were rehabilitated. The detailed near-optimum decisions selected are displayed in Table 5.45, which shows the decision variables for each asset during the five-year period. Most of the interventions were performed on pipelines, due to their higher weight in the ONP calculation. Accordingly, 13 pipelines were selected to be replaced; with nine replacements slated for in the first year. However, 17 major rehabilitations for pipelines are to be accomplished in the first 3 years, while 21 minor rehabilitations for pipelines are predicted for the first four years. On the other hand, only 5 manholes will be replaced, four in the first year and one in the fourth year. Furthermore, five major rehabilitations shall be performed for five manholes during the study period.

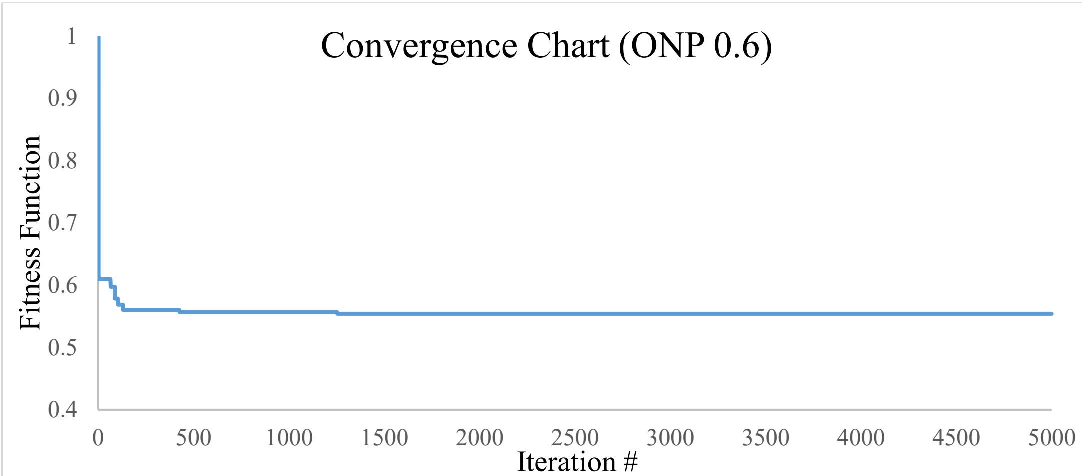


Figure 5.46 Convergence Chart (ONP Weight 0.6)

Table 5.44 Total Costs Incurred (ONP Weight 0.6)

Year	Total Cost ($)	Decision Variable			
		0	1	2	3
1	904,370	65	16	15	13
2	160,510	99	2	6	2
3	46,339	105	2	1	1
4	14,767	106	1	0	2
5	-	109	0	0	0
TLCC	$1,125,986				

Table 5.45 Assets Decision Variables (ONP Weight 0.6)

Pipeline #	Year 1	2	3	4	5
1	0	0	3	0	0
2	1	0	0	0	0
3	0	0	0	0	0
4	0	2	0	0	0
5	0	0	0	0	0
6	0	0	0	0	0
7	2	0	0	0	0
8	0	0	0	0	0
9	0	0	1	0	0
10	3	0	0	0	0
11	2	0	0	0	0
12	3	0	0	0	0
13	0	0	2	0	0

Pipeline #	Year 1	2	3	4	5
44	1	0	0	0	0
45	0	0	0	0	0
46	1	0	0	0	0
47	2	0	0	0	0
48	1	0	0	0	0
49	3	0	0	0	0
50	0	0	0	0	0
51	0	0	0	0	0
52	0	0	0	0	0
53	0	0	0	0	0
54	0	1	0	0	0
55	0	2	0	0	0
56	1	0	0	0	0

Manhole#	Year 1	2	3	4	5
1	3	0	0	0	0
2	0	0	0	0	0
3	3	0	0	0	0
4	3	0	0	0	0
5	0	0	0	0	0
6	3	0	0	0	0
7	0	0	0	0	0
8	0	2	0	0	0
9	0	0	0	0	0
10	2	0	0	0	0
11	2	0	0	0	0
12	2	0	0	0	0
13	2	0	0	0	0

14	0	2	0	0	0	**57**	0	0	0	0	0
15	0	3	0	0	0	**58**	0	0	0	0	0
16	1	0	0	0	0	**59**	1	0	0	0	0
17	0	2	0	0	0	**60**	3	0	0	0	0
18	3	0	0	0	0	**61**	1	0	0	0	0
19	2	0	0	0	0	**62**	1	0	0	0	0
20	3	0	0	0	0	**63**	0	0	0	0	0
21	0	1	0	0	0	**64**	2	0	0	0	0
22	2	0	0	0	0	**65**	0	0	0	0	0
23	2	0	0	0	0	**66**	0	0	0	0	0
24	1	0	0	0	0	**67**	0	0	0	0	0
25	1	0	0	0	0	**68**	0	0	0	0	0
26	1	0	0	0	0	**69**	0	0	0	0	0
27	0	0	1	0	0	**70**	0	0	0	0	0
28	0	0	0	0	0	**71**	0	0	0	1	0
29	0	3	0	0	0	**72**	3	0	0	0	0
30	1	0	0	0	0	**73**	2	0	0	0	0
31	0	0	0	3	0	**74**	3	0	0	0	0
32	0	0	0	0	0	**75**	0	2	0	0	0
33	0	0	0	0	0	**76**	2	0	0	0	0
34	0	0	0	0	0	**77**	0	0	0	0	0
35	1	0	0	0	0	**78**	0	0	0	0	0
36	0	0	0	0	0	**79**	0	0	0	0	0
37	3	0	0	0	0	**80**	0	0	0	0	0
38	0	0	0	0	0	**81**	0	0	0	0	0
39	0	0	0	0	0	**82**	0	0	0	0	0
40	0	0	0	0	0	**83**	1	0	0	0	0
41	1	0	0	0	0	**84**	2	0	0	0	0
42	0	0	0	0	0	**85**	0	0	0	0	0
43	2	0	0	0	0						

14	0	0	0	0	0
15	0	0	0	0	0
16	0	0	0	0	0
17	0	0	0	0	0
18	0	0	0	0	0
19	0	0	0	3	0
20	0	0	0	0	0
21	0	0	0	0	0
22	0	0	0	0	0
23	0	0	0	0	0
24	0	0	0	0	0

The PDC of each asset can then be established to predict their future conditions. For instance, Pipeline #7 will reach condition 5 at an age of 89 if no M&R interventions take place. In fact, the optimization tool suggested that major rehabilitation shall be performed for this pipeline. Consequently, at age 54, the condition will be updated to 1 as the decision variable improves the old condition by a maximum reduction of 3, as per Figure 5.47 Pipeline #7 Deterioration Curves (ONP Weight 0.6). The figure suggests that with this rehabilitation, the pipeline will reach condition 5 at an age of 143. The selected decision variable can thus extend the service life of the pipeline by 54 years.

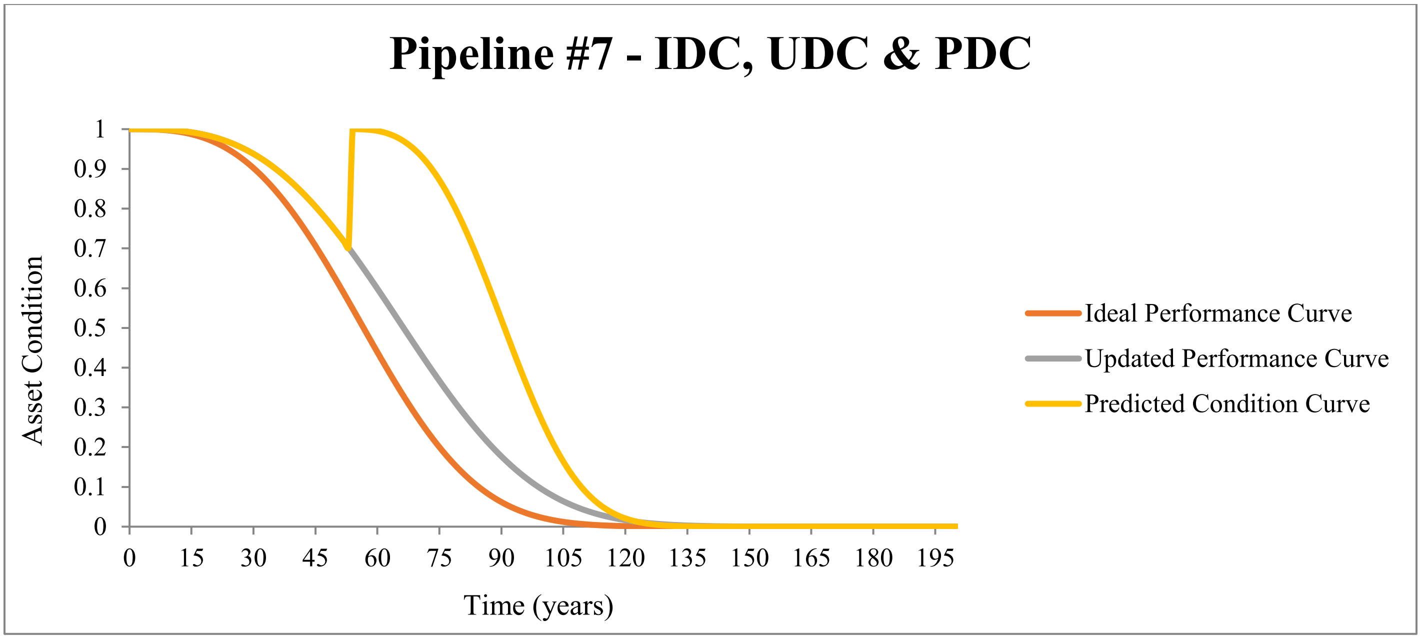


Figure 5.47 Pipeline #7 Deterioration Curves (ONP Weight 0.6)

A Pareto frontier was established to aid decision makers to select the solution that best that fits their constraints. Figure 5.48 was established after changing the relative importance weights of ONP and TLCC. Based on this near-optimum Pareto frontier, seven non-dominated solutions were depicted based on the lowest fitness function from each combination of weights. It is obvious that setting the weight of the ONP to zero shall attain a total cost of 0. Hence, the ONP will reach its maximum deterioration at the end of the fifth year, which is 3.83. Meanwhile, setting the weight of the TLCC to be zero will provide the best ONP in the fifth year, which is 1.47 with a total cost of 1.39-million.

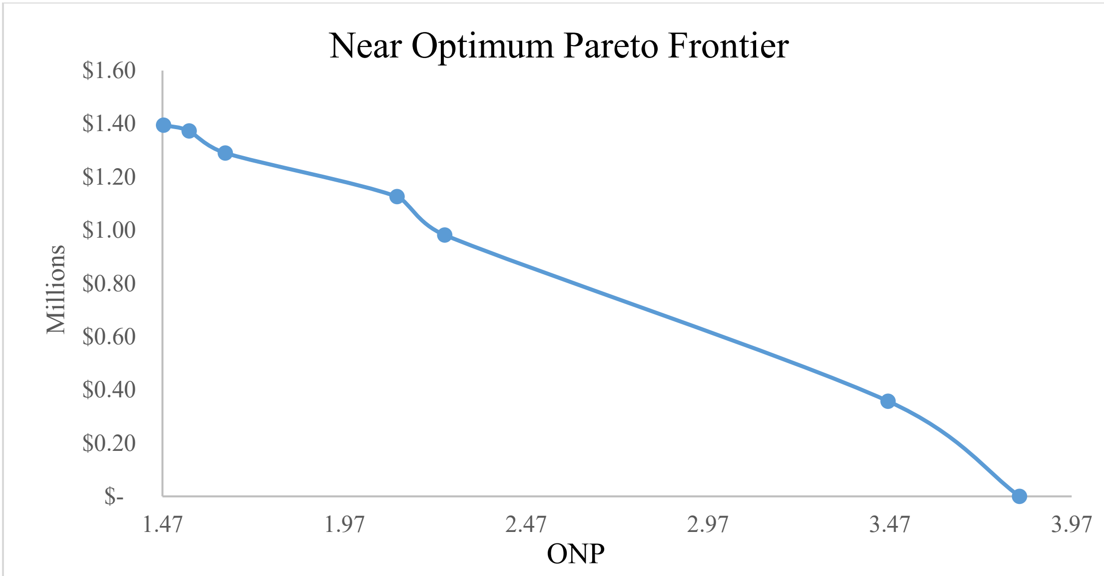


Figure 5.48 Near Optimum Pareto Frontier

Chapter Six: Semi-Automated Tool

6.1 Introduction

This chapter demonstrates the features of the semi-automated tool for the Performance Modeling for Sewer Networks (PMSN). The tool links the excel-sheets developed for each model with the Graphical User Interface (GUI) developed in this research. These models are the erosion void assessment, pipeline/manhole assessment, deterioration curves, network performance and finally the budget allocation.

6.2 Main Page

The main page, shown in Figure 6.1, consists of five different options corresponding to each of the developed models. Each of these buttons is linked to the excel sheet used to input the data required to obtain the results.

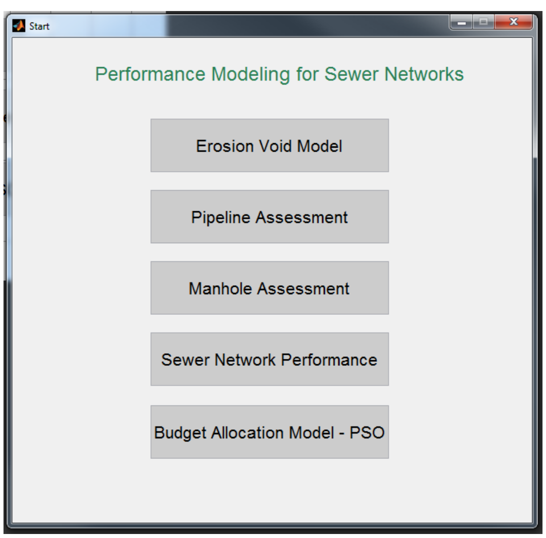


Figure 6.1 Main Page

6.2.1 Erosion Void Model

The erosion void model predicts the soil loss surrounding sewer pipelines. As mentioned earlier, five different factors were considered in the assessment. Therefore, the user can input the data in each of the columns as shown in Figure 6.2. Subsequently, the same excel file will provide the fuzzy membership values of each of the inputs.

Bedding	Pipeline Depth	Pipeline Location to GW	Age	Soil	Bedding-Fuzzy	Pipeline Depth-Fuzzy	Pipeline Location-Fuzzy	Age-Fuzzy	Soil Type-Fuzzy
A	9.4105	Above	55	Coarse Sand	0.475	0.5	0.475	3.17	1.425
B	6.81	Above	53	Coarse Sand	1.425	0.5	0.475	3.08	1.425
B	6.808	Above	53	Coarse Sand	1.425	0.5	0.475	3.08	1.425
B	7.164	Above	54	Coarse Sand	1.425	0.5	0.475	3.12	1.425
B	6.993	Above	54	Coarse Sand	1.425	0.5	0.475	3.12	1.425
B	5.4505	Above	53	Fine Sand	1.425	0.5	0.475	3.08	2.375
B	5.7105	Above	53	Coarse Sand	1.425	0.5	0.475	3.08	1.425
B	6.0725	Above	54	Coarse Sand	1.425	0.5	0.475	3.12	1.425
B	5.6885	Above	54	Coarse Sand	1.425	0.5	0.475	3.12	1.425
B	4.3765	Above	53	Fine Sand	1.425	1.42	0.475	3.08	2.375
B	3.918	Above	54	Fine Sand	1.425	1.77	0.475	3.12	2.375
B	4.0155	Above	54	Fine Sand	1.425	1.71	0.475	3.12	2.375
B	5.064	Above	54	Fine Sand	1.425	0.5	0.475	3.12	2.375
B	3.723	Above	53	Fine Sand	1.425	1.9	0.475	3.08	2.375
B	3.916	Above	54	Fine Sand	1.425	1.77	0.475	3.12	2.375
B	4.7605	Above	54	Fine Sand	1.425	0.85	0.475	3.12	2.375
B	4.852	Above	54	Fine Sand	1.425	0.72	0.475	3.12	2.375
B	5.4635	Above	54	Fine Sand	1.425	0.5	0.475	3.12	2.375
B	4.1435	Above	46	Fine Sand	1.425	1.62	0.475	2.77	2.375
A	12.482	Above	56	Coarse Sand	0.475	0.5	0.475	3.21	1.425
B	13.3085	Above	53	Coarse Sand	1.425	0.5	0.475	3.08	1.425
A	14.3835	Above	56	Coarse Sand	0.475	0.5	0.475	3.21	1.425
B	3.1585	Below	54	Fine Sand	1.425	2.28	4.275	3.12	2.375

Figure 6.2 Input Data/Fuzzy Outputs

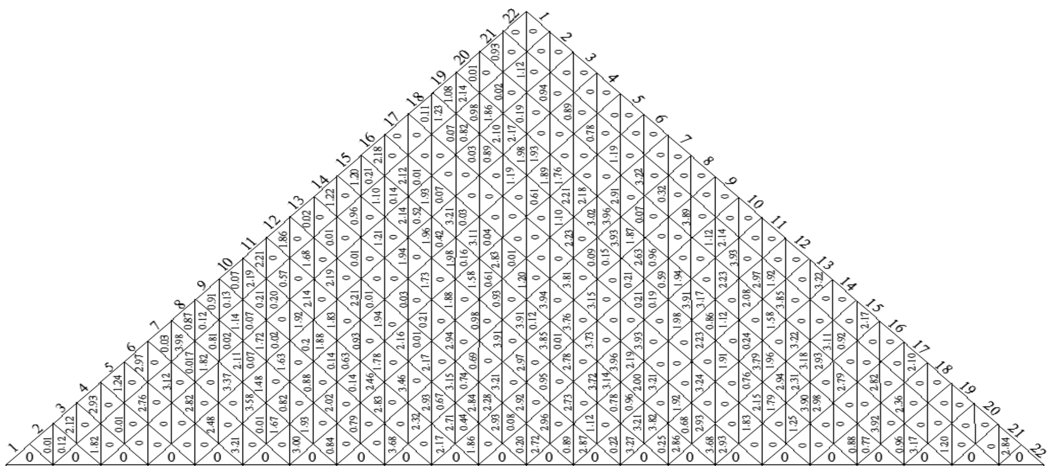
The fuzzy values are then aggregated to supply a grade that suggests the condition of the soil loss as per Figure 6.3. Each grade will then be fuzzified so that it can later be used in the pipeline assessment model. For example, erosion void condition of 1.34 means that the pipeline erosion void condition is 32% excellent and 68% good.

Erosion Void Condition	Condition	Percentage	Condition	Percentage
1.34	Excellent	32.0%	Good	68.0%
1.44	Excellent	12.0%	Good	88.0%
1.44	Excellent	12.0%	Good	88.0%
1.45	Excellent	10.0%	Good	90.0%
1.45	Excellent	10.0%	Good	90.0%
1.64	Good	86.0%	Fair	14.0%
1.44	Excellent	12.0%	Good	88.0%
1.45	Excellent	10.0%	Good	90.0%
1.45	Excellent	10.0%	Good	90.0%
1.75	Good	75.0%	Fair	25.0%
1.81	Good	69.0%	Fair	31.0%
1.80	Good	70.0%	Fair	30.0%
1.65	Good	85.0%	Fair	15.0%
1.81	Good	69.0%	Fair	31.0%
1.81	Good	69.0%	Fair	31.0%
1.69	Good	81.0%	Fair	19.0%
1.67	Good	83.0%	Fair	17.0%
1.65	Good	85.0%	Fair	15.0%
1.70	Good	80.0%	Fair	20.0%
1.35	Excellent	30.0%	Good	70.0%
1.44	Excellent	12.0%	Good	88.0%
1.35	Excellent	30.0%	Good	70.0%
2.99	Fair	51.0%	Poor	49.0%
2.98	Fair	52.0%	Poor	48.0%

Figure 6.3 Erosion Void Grades

6.3 Pipeline/Manhole Assessment Model

The pipeline assessment model developed by integrating QFD and DEMATEL techniques. Besides the two techniques, ANP model was also used for the manhole assessment. The inputs of the models are extracted from inspection reports. Defect counts are considered in the assessment besides the erosion void that was calculated previously for the pipelines. Therefore, the second button in the main page shall open the excel sheet for the user so that s/he can input the defect counts for each pipeline similar to the one displayed in Figure 6.4. However, the third button links the sheet for the manhole assessment and will display similar QFD model for each component.



		Long. Crack	Circ. Crack	Multiple Crack	Long. Fracture	Circ. Fracture	Multiple Fracture	Deformation	Hole	Break	Sag	Collapse	Surface Damage	Settled Deposits	Ingress of Soil	Roots	In/exfiltration	Obstruction	Offset Joint	Soil Support Loss	Open Joint	Attached Deposits	Prot. Service
		1.23	0.93	1.26	1.22	1.01	1.52	2.02	1.72	1.79	1.55	2.41	2.02	1.69	1.74	2.78	2.48	0.76	1.14	3.13	1.20	1.68	0.33
	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Severity	Relative Influence Weight	3.45%	2.62%	3.54%	3.43%	2.83%	4.27%	5.68%	4.82%	5.02%	4.36%	6.76%	5.66%	4.75%	4.88%	7.82%	6.97%	2.14%	3.20%	8.80%	3.36%	4.72%	0.92%
Excellent	1	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Good	2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	85.00%	0.00%	0.00%	0.00%
Fair	3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	15.00%	0.00%	0.00%	0.00%
Poor	4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Critical	5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Excellent	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Good	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	85	0	0	0
Fair	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0
Poor	4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Critical	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6.4 Pipeline Assessment Model

As a result, each pipeline will possess five different grades and will be aggregated to 1-5 scale. As shown in Figure 6.5. The first columns provide the percentages for each grade while the last columns denote the asset index.

Excellent	Good	Fair	Poor	Critical	Estimated Condition
17.02%	82.98%	0.00%	0.00%	0.00%	1.83
13.85%	47.04%	13.59%	0.00%	25.52%	2.76
0.00%	55.96%	44.04%	0.00%	0.00%	2.44
12.75%	70.64%	16.61%	0.00%	0.00%	2.04
0.00%	42.42%	14.14%	0.00%	43.44%	3.44
0.00%	32.56%	31.71%	0.00%	35.73%	3.39
17.28%	45.67%	8.06%	29.00%	0.00%	2.49
12.41%	26.61%	60.98%	0.00%	0.00%	2.49
0.00%	43.95%	56.05%	0.00%	0.00%	2.56
0.00%	25.88%	19.99%	16.77%	37.36%	3.66
0.00%	48.59%	19.96%	0.00%	31.45%	3.14
6.79%	49.58%	22.10%	0.00%	21.52%	2.80
6.79%	49.55%	43.66%	0.00%	0.00%	2.37
0.00%	23.59%	24.02%	0.00%	52.39%	3.81
6.29%	10.50%	17.86%	20.24%	45.11%	3.87
0.00%	50.94%	49.06%	0.00%	0.00%	2.49
0.00%	79.25%	20.75%	0.00%	0.00%	2.21
0.00%	33.42%	40.10%	0.00%	26.48%	3.20

Figure 6.5 Pipeline Assessment Model Output

6.4 Network Performance

Sewer network performance was developed using a criticality-based model. The criticality model considered several factors and subfactors related. The user can, therefore, use the fourth button to provide the inputs to the excel sheet. The same excel sheets shall supply the criticality indexes for each pipeline and manhole. After inputting the data, the criticality grades will automatically be calculated. The user has the option to investigate each asset's criticality in details; yet, the sheet will provide pie charts of the criticalities as shown in Figure 6.6.

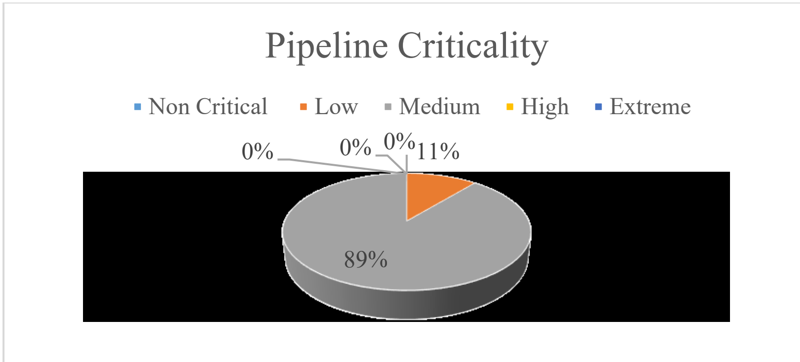


Figure 6.6 Criticality Model Output

6.5 Budget Allocation Model

PSO was used to develop the budget allocation model, where the coded program was developed using MATLAB and was discussed in Chapter 3. The deterioration formulas adopted in this research was also programmed to consider the deterioration of each asset. Therefore, the two main inputs of this model are the total cost required to enhance the network performance as well as the MRR intervention plan in the considered study period. After running the MATLAB code, the convergence curve will be displayed as shown in Figure 6.7. The horizontal axis represents the number of iteration; yet, the vertical axis shows the fitness value. Besides, the cost incurred in each year is also displayed as an output as shown in Figure 6.8. In addition, the decision variables applied within the study period can also be displayed, as shown in Figure 6.9, after selecting the “GlobalBest.Position”.

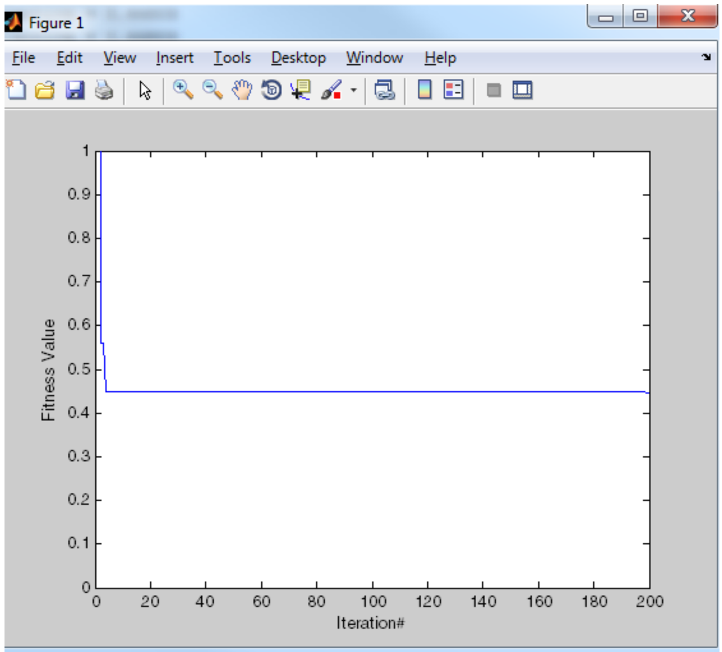
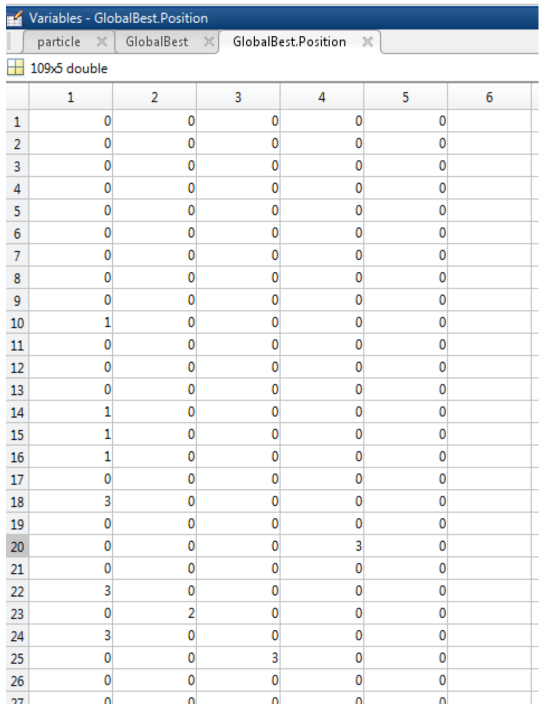


Figure 6.7 PSO Output - Convergence Curve

```
Year1Cost =

   7.3589e+05

Year2Cost =

   1.7351e+05

Year3Cost =

   2.3283e+05

Year4Cost =

   1.6701e+05

Year5Cost =

     0
```

Figure 6.8 PSO Output - Cost per Year


Variables - GlobalBest.Position
particle | GlobalBest | GlobalBest.Position
109x5 double

	1	2	3	4	5	6
1	0	0	0	0	0	
2	0	0	0	0	0	
3	0	0	0	0	0	
4	0	0	0	0	0	
5	0	0	0	0	0	
6	0	0	0	0	0	
7	0	0	0	0	0	
8	0	0	0	0	0	
9	0	0	0	0	0	
10	1	0	0	0	0	
11	0	0	0	0	0	
12	0	0	0	0	0	
13	0	0	0	0	0	
14	1	0	0	0	0	
15	1	0	0	0	0	
16	1	0	0	0	0	
17	0	0	0	0	0	
18	3	0	0	0	0	
19	0	0	0	0	0	
20	0	0	0	3	0	
21	0	0	0	0	0	
22	3	0	0	0	0	
23	0	2	0	0	0	
24	3	0	0	0	0	
25	0	0	3	0	0	
26	0	0	0	0	0	
27	0	0	0	0	0	

Figure 6.9 PSO Output - Decision Variables

Chapter Seven: Conclusions, Contributions and Recommendations

7.1 Conclusions

This study comprehensively researched wastewater buried infrastructure management starting from analyzing inspection reports up to the selection of rehabilitation techniques for sewer networks improvements. The studied assets were manholes and pipelines. Before assessing these assets, the study developed a fuzzy expert system to evaluate the erosion voids in sewer pipelines and validated it on two case studies. Subsequently, a defect-based method was established, incorporating structural and operational defects, in one system to analyze the causality relationship among the defects. The integrated QFD-DEMATEL approach categorized the defects into influencing and influenced defects. The other developed assessment model was pertinent to manholes. The component and defect-based approach classified potential defects in each component of the manholes. The approach utilized ANP, QFD and DEMATEL approaches to supply an overall condition grade. Later, the sewer network performance was calculated based on a criticality-based model. Manhole and pipeline criticality models were suggested after identifying environmental, economic and public factors and sub-factors. The sewer network performance was then calculated after aggregating the criticality values of all assets through weights found from ANP. The final stage of this research was implementing the PSO tool to select the near optimum decisions to enhance the performance of sewer network with constrained budgets.

This study concluded the following:

- Presence of groundwater table above pipelines is the most important factor contributing to erosion void defects with a weight of 0.294. Yet, the least importance factor was the bedding type with 0.120 weight.
- The most important component of the manhole was the wall section with an importance weight of 0.176; however, the least important component was the steps with a weight of 0.0383.
- The most important criticality factor for pipelines and manholes was the economic factor compared with the public and environment. In addition, the same questionnaire indicated that pipelines are more important than manholes with an approximate ratio of 2:1.
- The fuzzy expert system model is capable of classifying the severity of the erosion voids defect with an average TPR, precision and accuracy of 76%, 80% and 83%, respectively. The model also confirmed that no critical erosion voids conditions are found in Royal Gardens neighborhood. The majority of the pipelines had Good to Fair erosion voids condition.
- The causality model for pipelines confirmed that erosion voids had the highest causing and effect power with a weight of 0.088. In addition, the model suggested that 59% of the pipelines defects are influencing defects and the rest are influenced defects.
- The pipeline assessment model confirmed that no critical pipelines were found in the Royal Gardens area. However, 30% of the pipelines were in poor conditions and 62% were in fair conditions.
- Roots emerged to be a significant defect in many of the manhole’s components. Besides, the percentage of the influencing defects in many of the components was higher.

- The manhole assessment model confirmed that no critical manholes were depicted in the network while the majority of the manholes were in fair condition.
- In a scale of 1 to 5, 89% of the pipelines were classified as medium criticality, whereas, 11% were of a low criticality. However, 86% of the manholes' criticalities were medium while the criticalities of the remaining population were low.
- PSO had the capability of supplying near-optimum solutions for infrastructure budget allocation without computational complexities. With a maximum budget of $1.5-million, the best ONP attained was 1.47 with a total cost of $1.39-million.

7.2 Contributions

This research is constituted of several objectives that are expected to add to field of construction management. The objectives are as follows:

1. Modeled the erosion void defect;
2. Developed a pipeline condition assessment model;
3. Built a component-based manhole condition assessment model ;
4. Suggested a criticality model for sewer pipelines and manholes;
5. Developed an integrated condition index for sewer network systems;
6. Proposed a rehabilitation prioritization model for sewer network assets; and
7. Coded the PSO and implement it on sewer budget allocation.

7.3 Research Limitations

The current study developed three condition assessment models: erosion voids, pipeline assessment model, and manhole assessment model. In addition, it introduced the application of the PSO tool for infrastructure budget allocation and specifically for sewer networks after considering the criticality model to aggregate the whole assets. Although the validation produced satisfactory results, the outcomes can be further improved if the following is accomplished:

- ✓ Erosion Void Model
    - The erosion voids weights collected are based on the average of the percentages considered by the responses. The interdependency was not studied and this can be accomplished by deploying ANP method.
    - The validation of the erosion void model was conducted on only sixteen dataset in which many of them were in acceptable condition. Therefore, the accuracy and precision in classifying the other category shall be further examined by additional case studies.
    - The margin of error was not calculated for the weights obtained.
- ✓ Pipeline & Manhole Assessment Models
    - The model relied on common defects that are observed in sewer manholes and pipelines; however, most of the pipelines' defects are applicable to reinforced concrete. In addition, defects for rehabilitated pipelines and manholes were not considered.
    - The margin of error was not calculated for the influence of weights obtained.
    - The DEMATEL approach can be further improved if the influence matrix was calculated for each response.
- ✓ Criticality Model
    - The margin of error was not considered for the weights calculated.

- Other critical weights could be added to the model and based on environmental measures.

✓ Budget Allocation Model

- The multi-objective problem was solved using the weighted method which could be bias in nature.
- Decision variables could be narrowed down to include applicable trenchless technology methods.
- The same improvement of the decision variables could differ from one asset to another based on surrounding factors.
- The model was not implemented using other methods to conclude its reliability.

7.4 Recommendations & Future Work

As the main objective is to design a budget allocation model for sewer rehabilitation intervention, the model can be extended by completing the following:

7.4.1 Model Enhancement

- Consider increasing the sample size of the questionnaire. As a result, the reliability of the responses will increase.
- Use a study period of more than five years for better longer planning period.
- Other factors in erosion voids can be incorporated such as pipeline material, water table pressure, if any, etc. In addition, ANP approach could be used to study the interdependency of the factors identified.
- Consider defects pertinent to post-rehabilitation such as lining condition after placing.

- Apply other sophisticated methods to solve multi-objective problems such as the vector evaluated PSO. The generated results from the PSO can be further validated using other sophisticated optimization models.
- The consistency of the responses in the DEMATEL approach shall be investigated.
- The developed model can be further applied and validated in a pilot study.

7.4.2 Recommendation for Future Work

- The semi-automated tool can be further enhanced to make a fully automated tool. This can be accomplished by designing a coded program that integrates all the models into one user-friendly platform.
- It is recommended to design a scheduling model for rehabilitation by integrating the optimization tool designed with other constraints and parameters.
- Consider sewer defects with the applicable trenchless technology method. This shall lessen the number of decision variables for each asset. For example, CIPP method can be neglected in case pipelines have deformation of more than 10%.
- This research used the normal conditions to assess the assets. However, future considerations to resilience of assets can be implemented to understand the ability of assets to restore their conditions after abnormal conditions such as earthquake.
- A hydraulic model can accompany the generated model with the resilience of the assets to capture the full image and not rely on the structural state of the asset.

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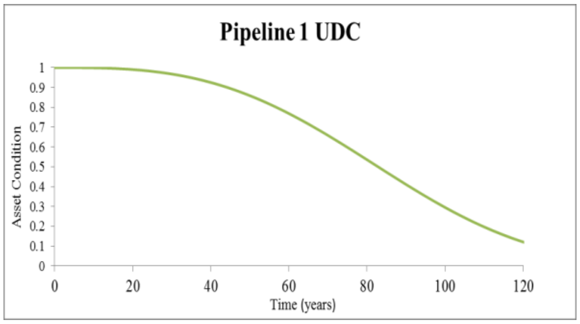
Appendix



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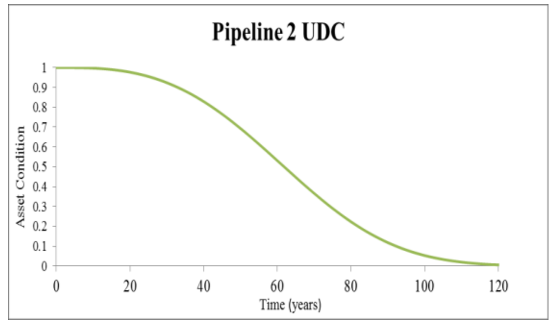

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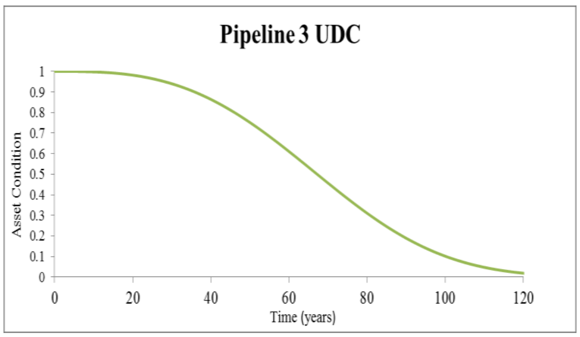

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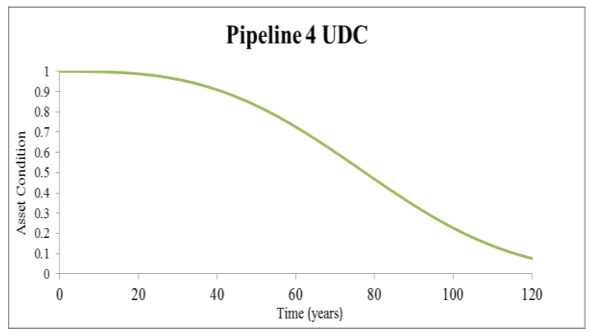

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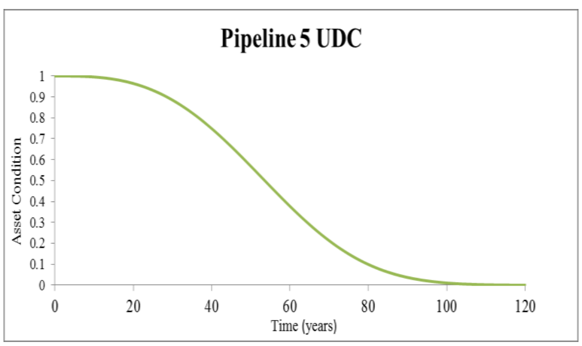

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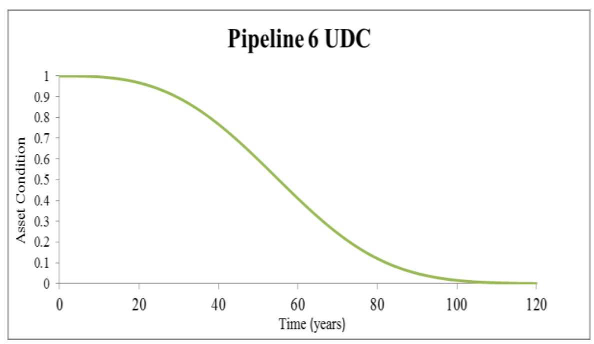

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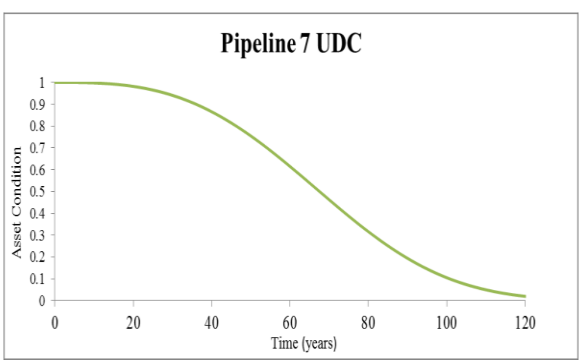

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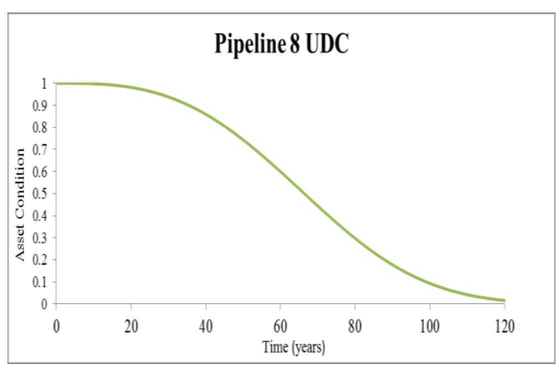

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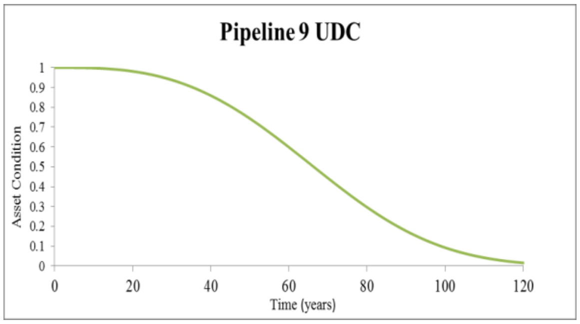
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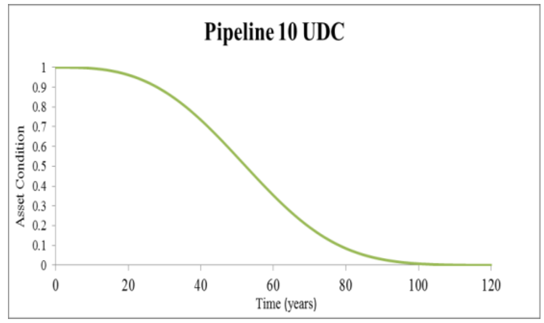
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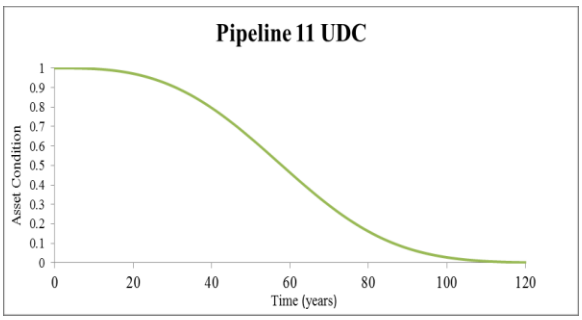
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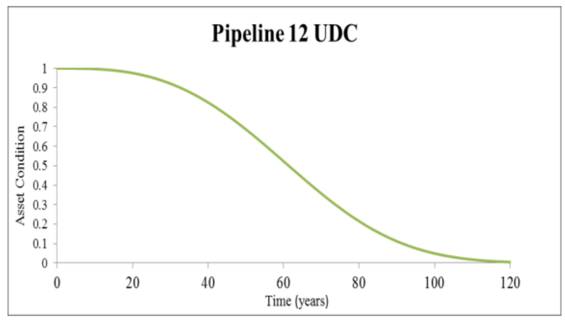
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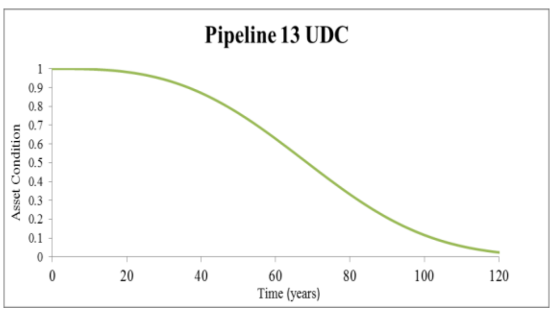
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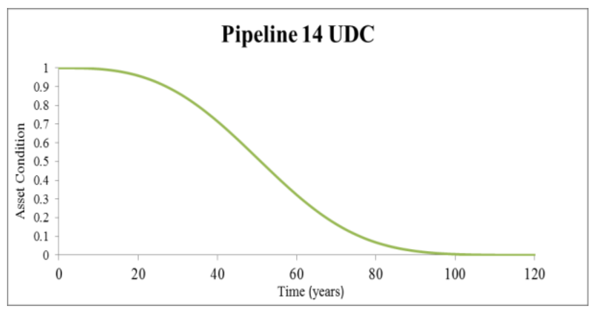
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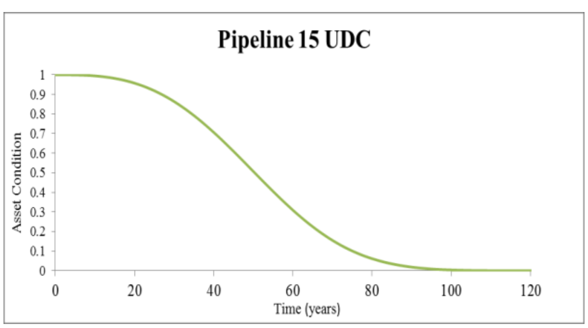
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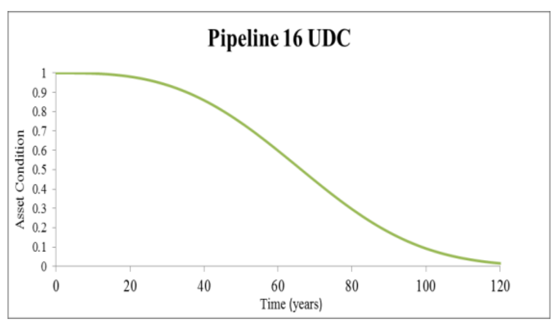
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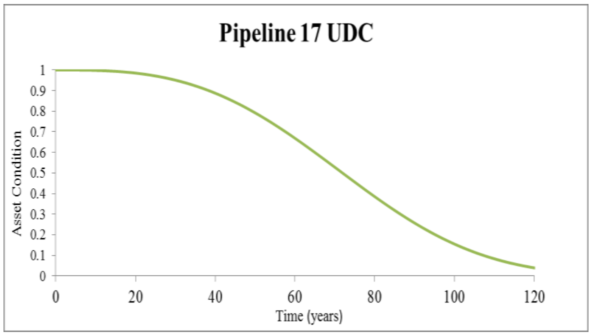
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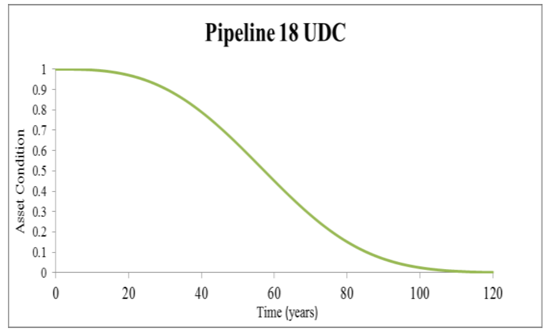
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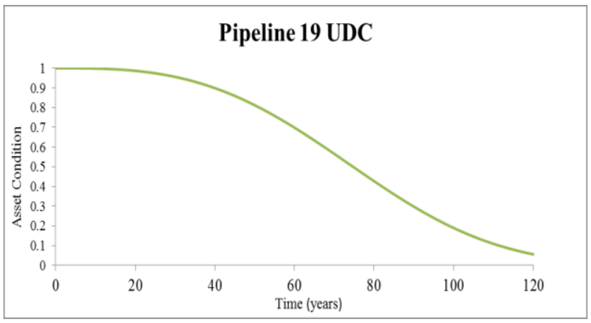
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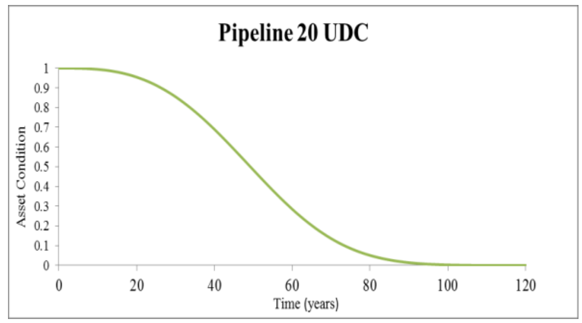
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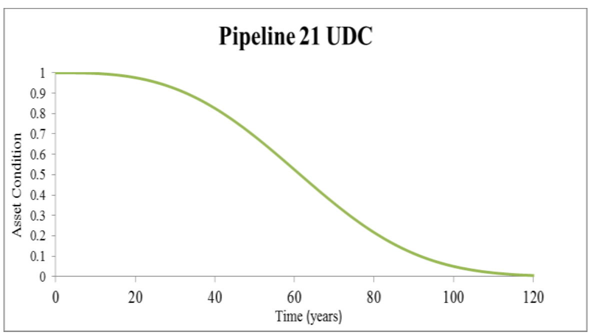
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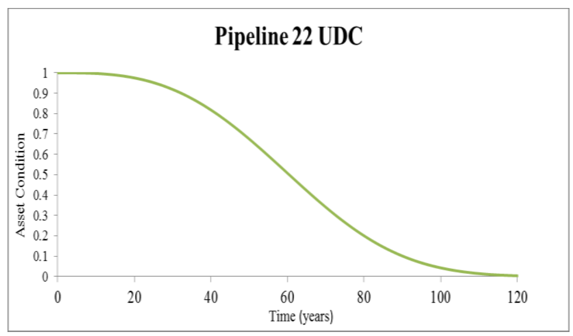
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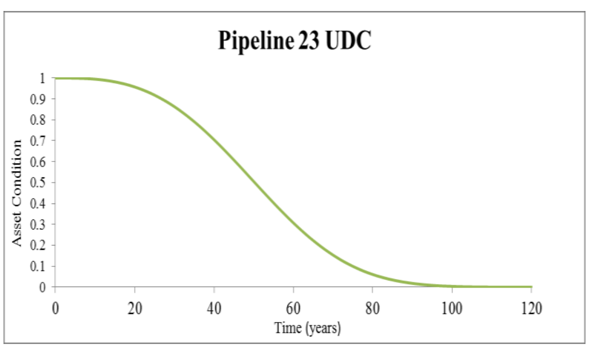
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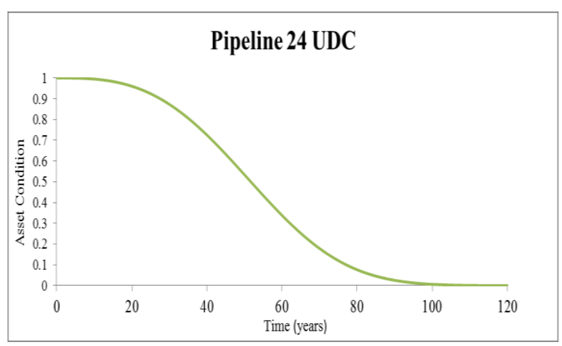
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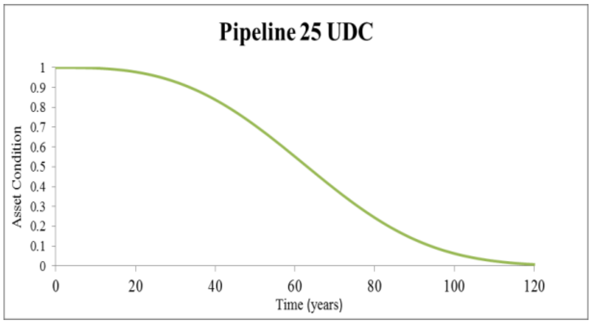
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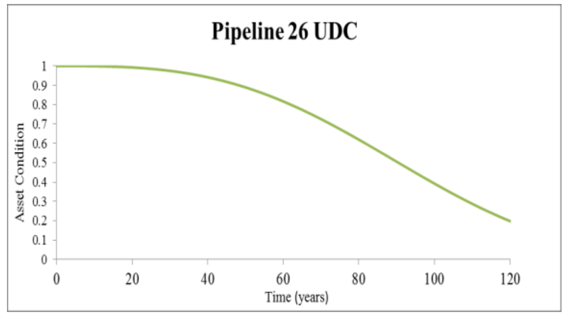
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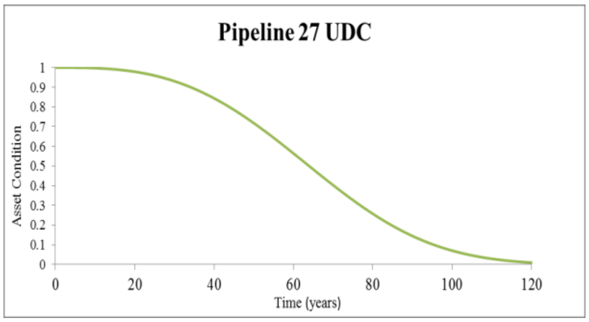
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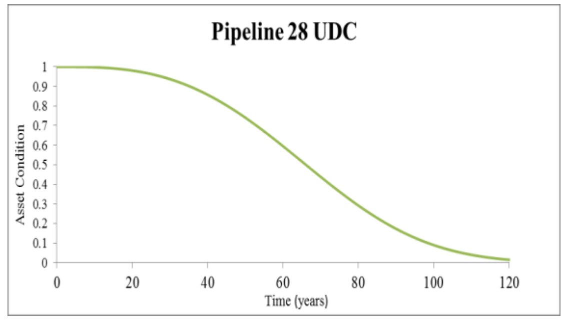
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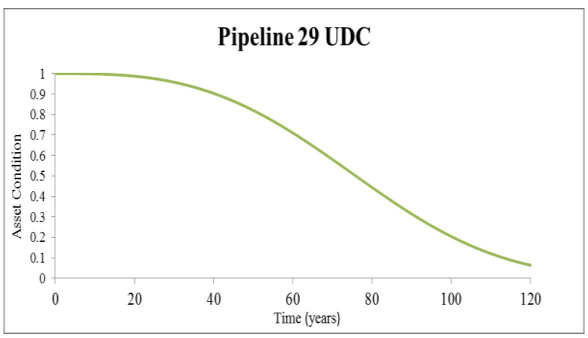
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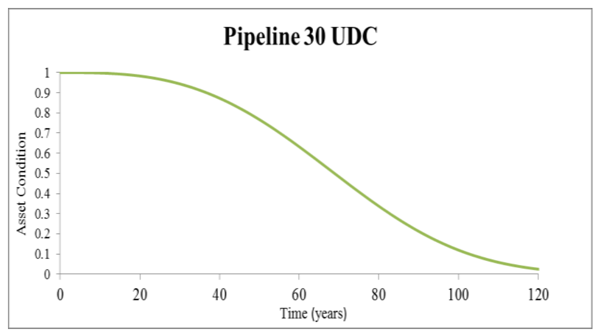
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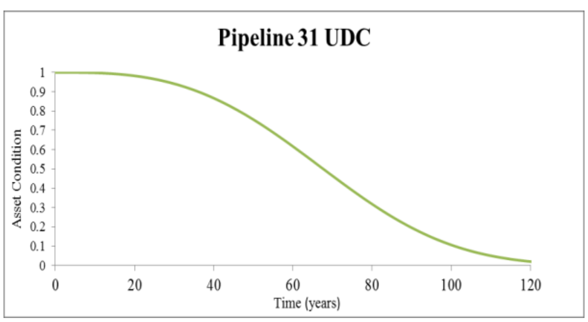
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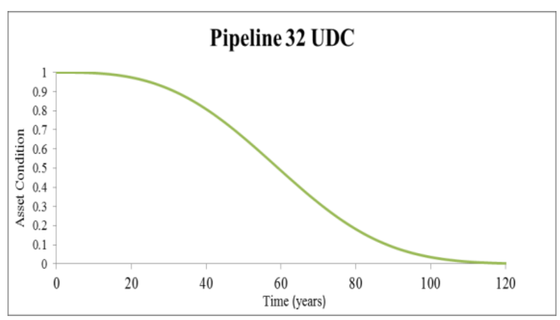
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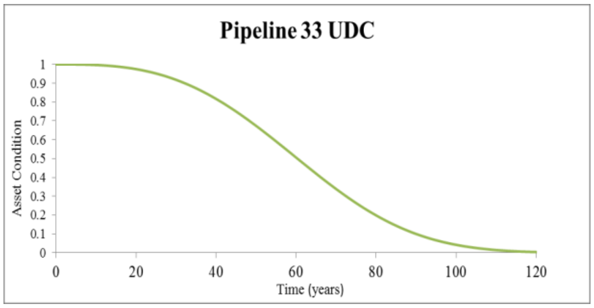
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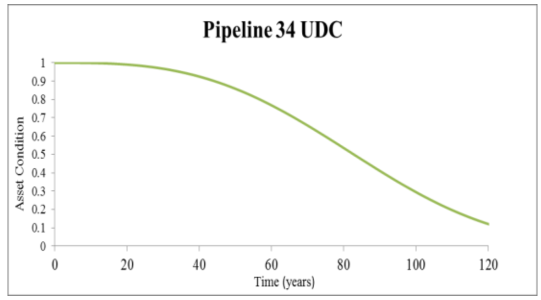
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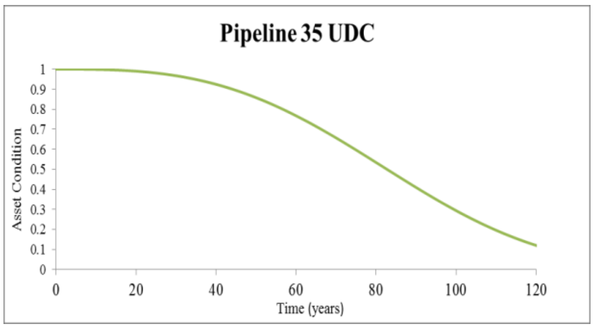
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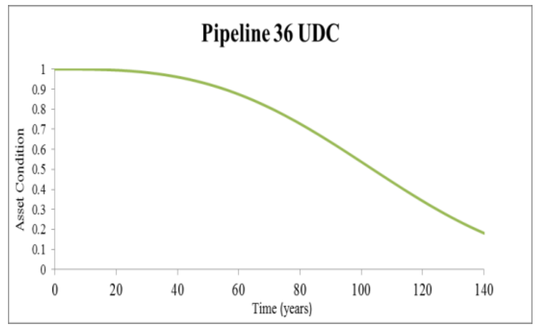
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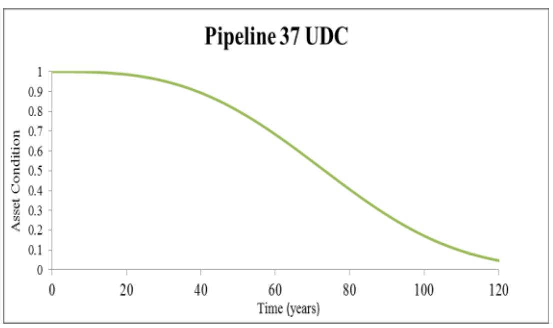
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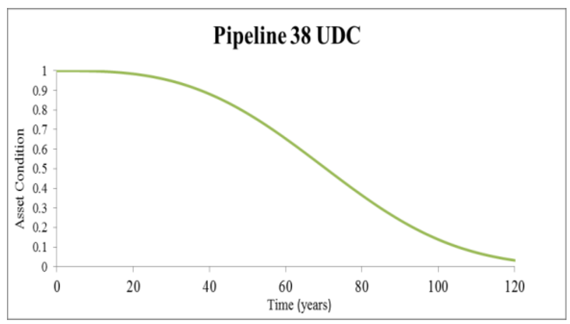
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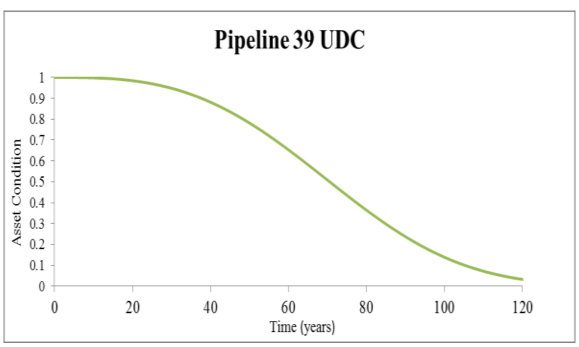
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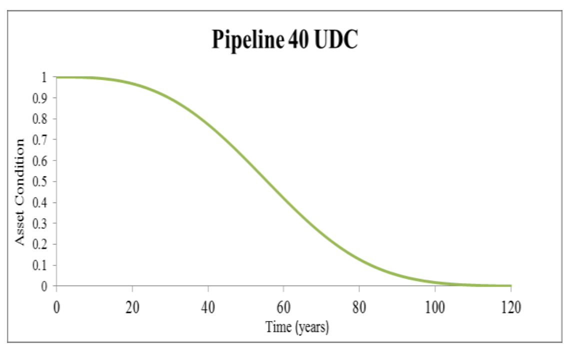
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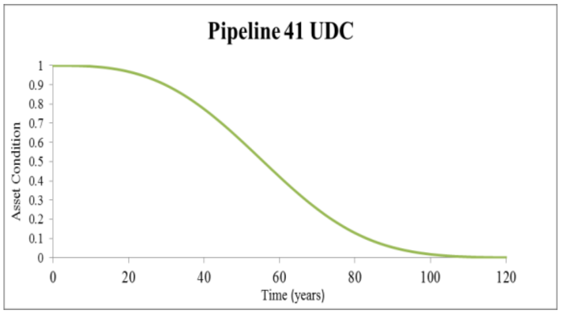
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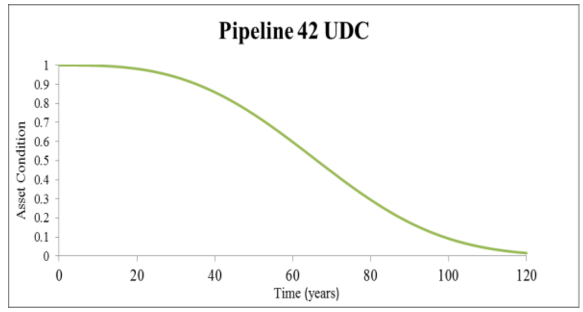
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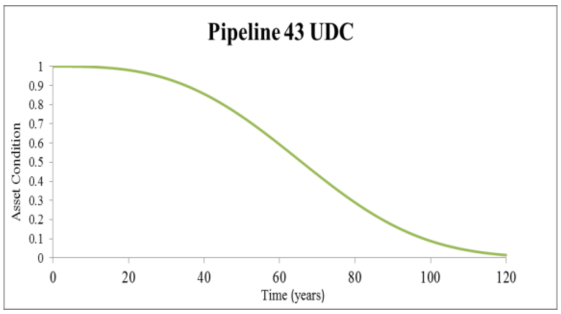
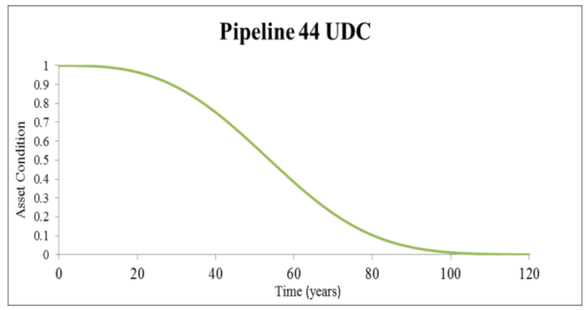
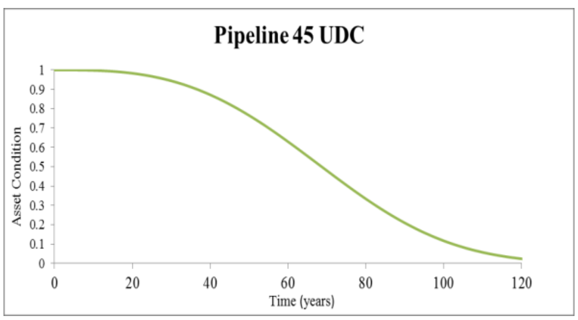
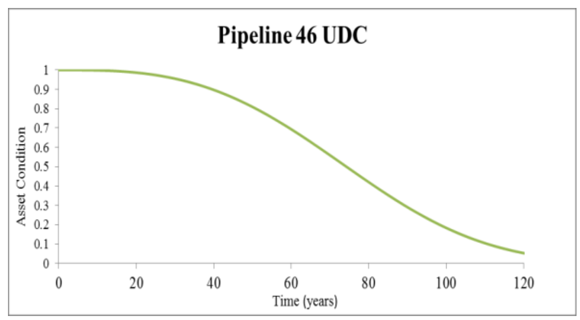
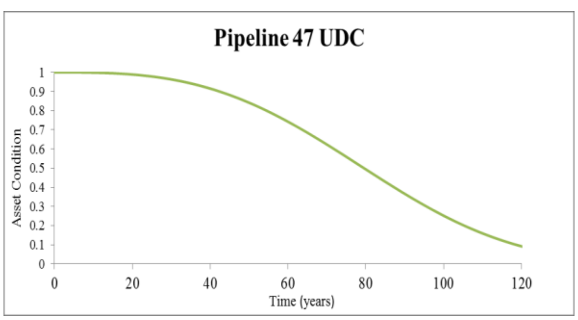
Asset Condition
Time (years)

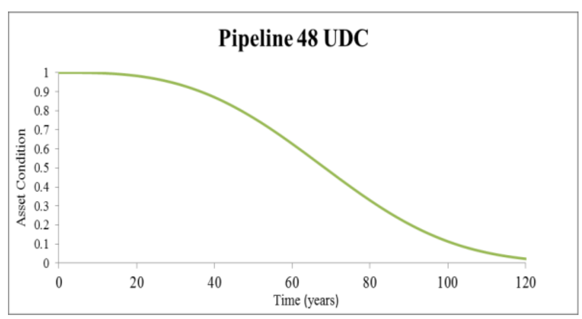

Pipeline 43 UDC
Asset Condition
Time (years)

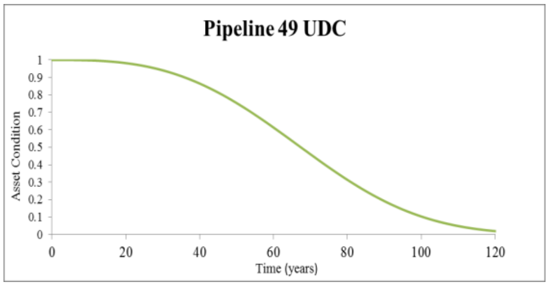

Pipeline 44 UDC
Asset Condition
Time (years)

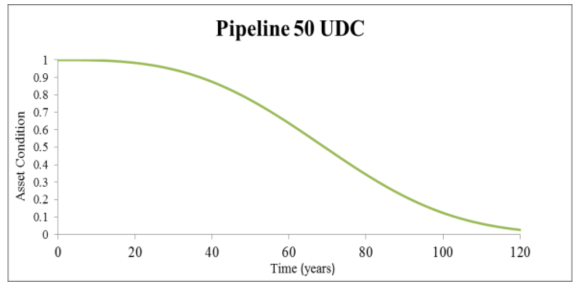

Pipeline 45 UDC
Asset Condition
Time (years)

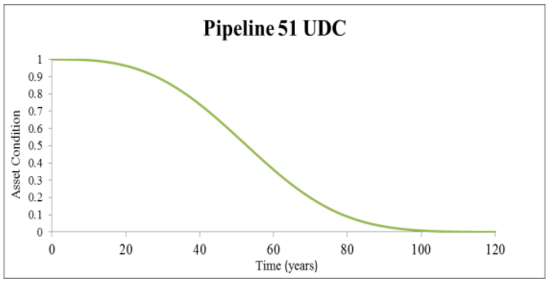

Pipeline 46 UDC
Asset Condition
Time (years)

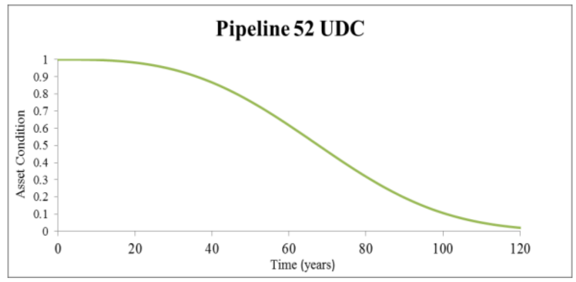

Pipeline 47 UDC
Asset Condition
Time (years)

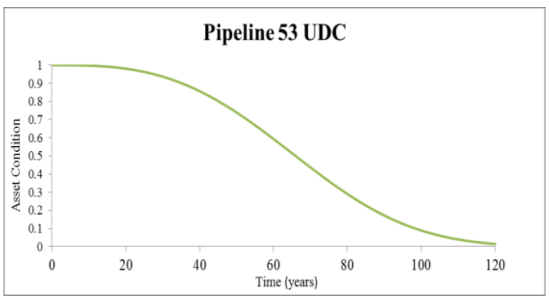

Pipeline 48 UDC
Asset Condition
Time (years)

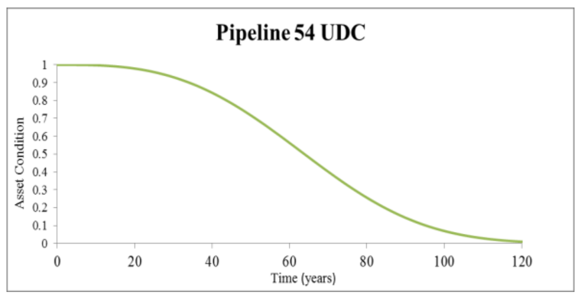

Pipeline 49 UDC
Asset Condition
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
Time (years)

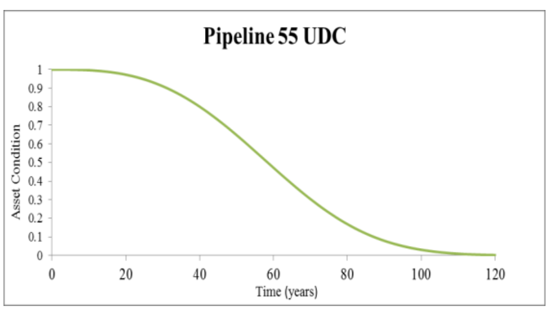

Pipeline 50 UDC
Asset Condition
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
Time (years)


Pipeline 51 UDC
Asset Condition
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
Time (years)


Pipeline 52 UDC
Asset Condition
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
Time (years)


Pipeline 53 UDC
Asset Condition
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
Time (years)


Pipeline 54 UDC
Asset Condition
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
Time (years)


Pipeline 55 UDC
Asset Condition
1
0.9
0.8
0.7
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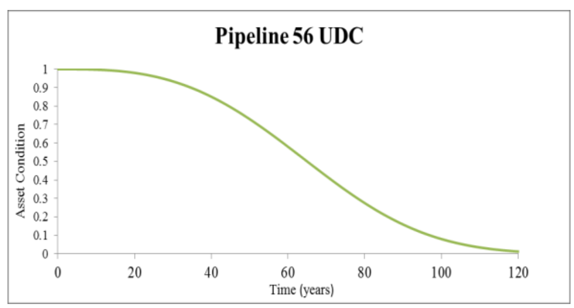
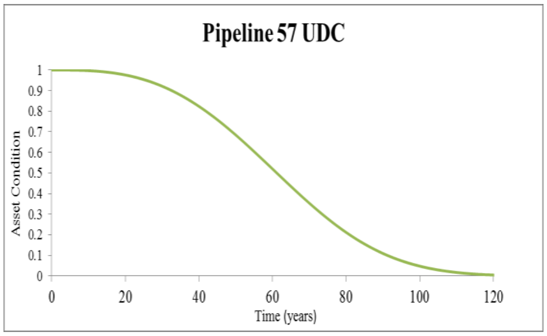
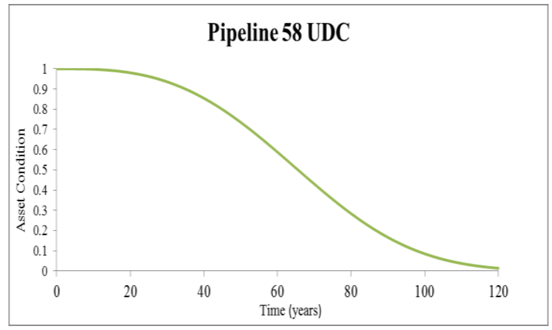
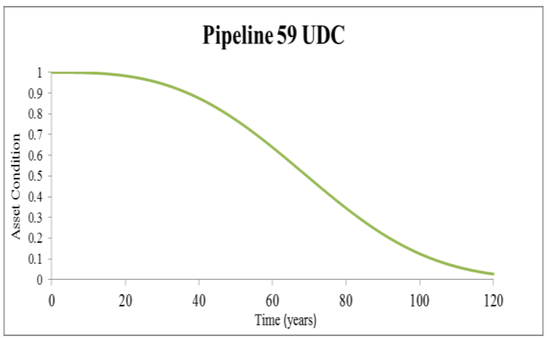
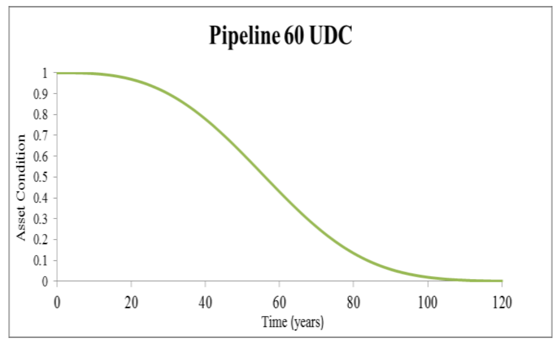
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
Time (years)

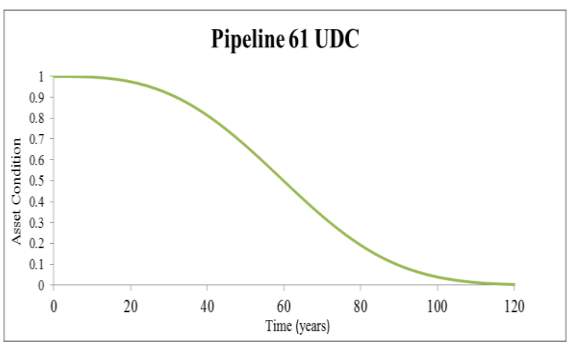

Pipeline 56 UDC
Asset Condition
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
Time (years)

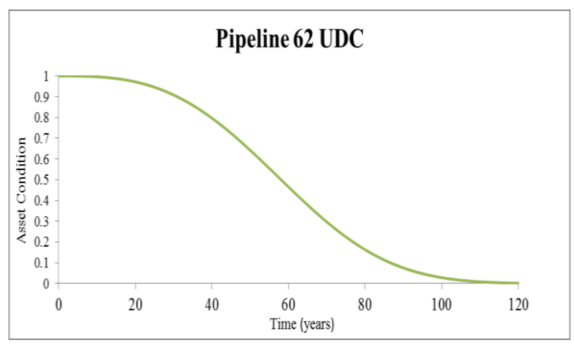

Pipeline 57 UDC
Asset Condition
Time (years)

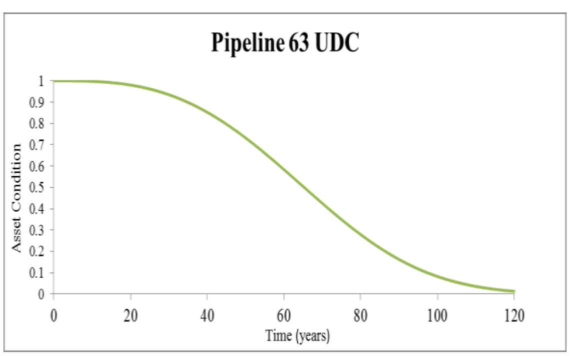

Pipeline 58 UDC
Asset Condition
Time (years)

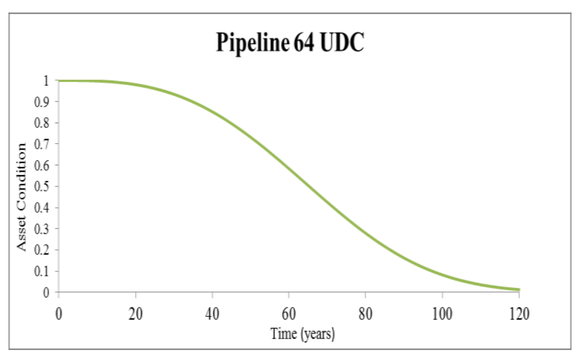

Pipeline 59 UDC
Asset Condition
Time (years)

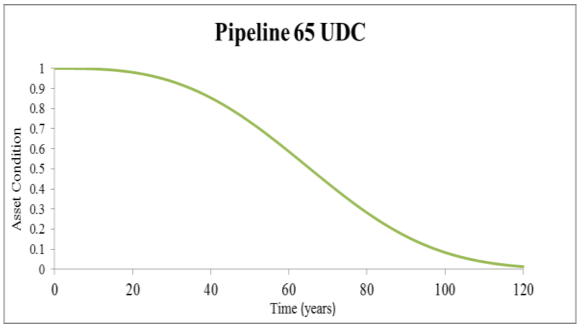

Pipeline 60 UDC
Asset Condition
Time (years)

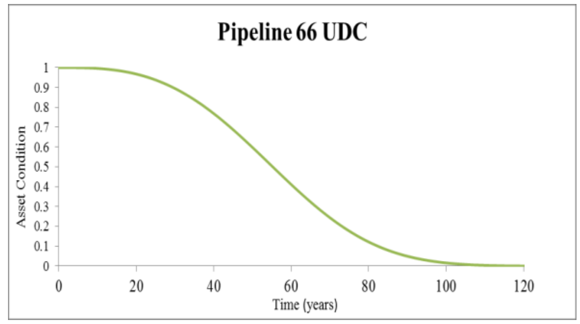

Pipeline 61 UDC
Asset Condition
Time (years)

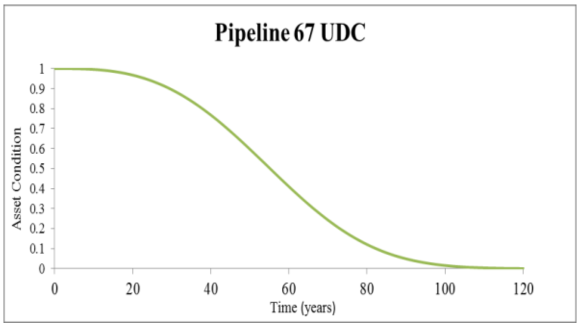

Pipeline 62 UDC
Asset Condition
Time (years)

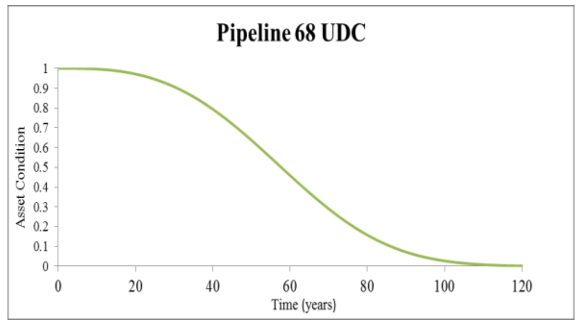

Pipeline 63 UDC
Asset Condition
Time (years)

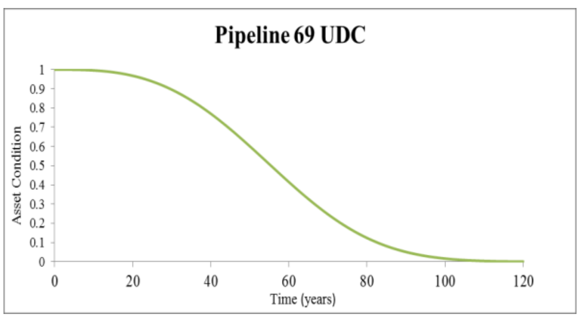

Pipeline 64 UDC
Asset Condition
Time (years)

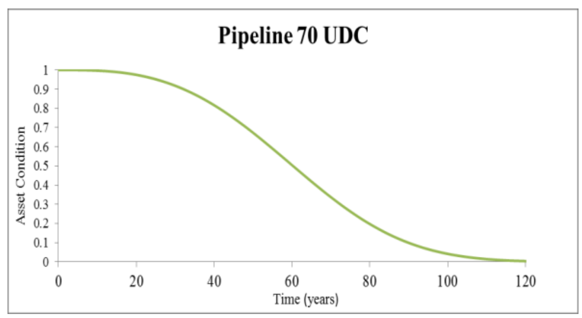

Pipeline 65 UDC
Asset Condition
Time (years)

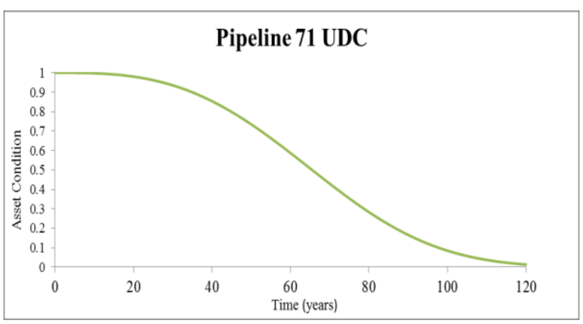

Pipeline 66 UDC
Asset Condition
Time (years)

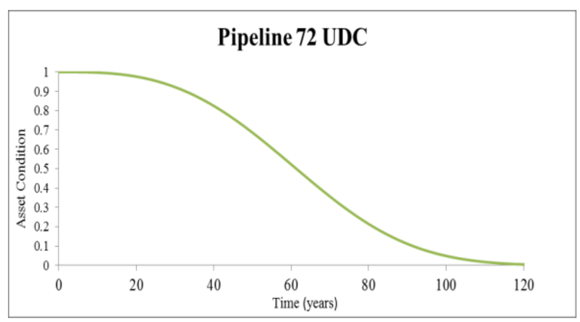

Pipeline 67 UDC
Asset Condition
Time (years)

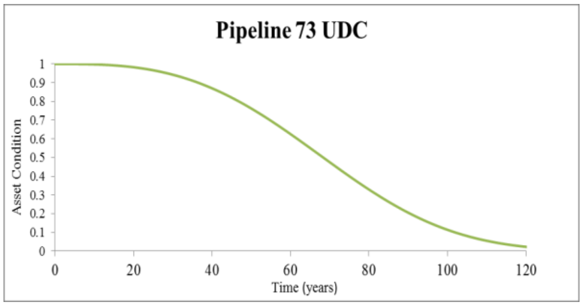

Pipeline 68 UDC
Asset Condition
Time (years)


Pipeline 69 UDC
Asset Condition
Time (years)

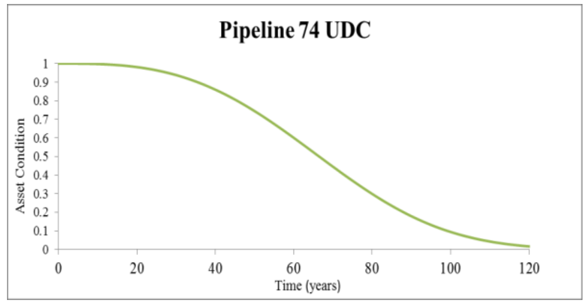

Pipeline 70 UDC
Asset Condition
Time (years)


Pipeline 71 UDC
Asset Condition
Time (years)

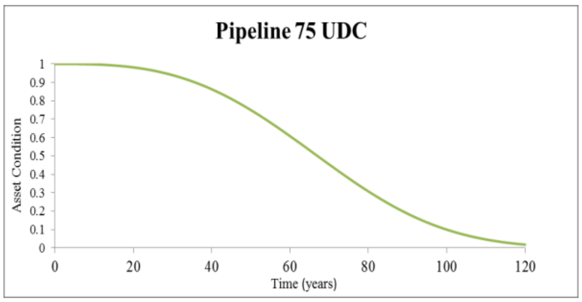

Pipeline 72 UDC
Asset Condition
Time (years)



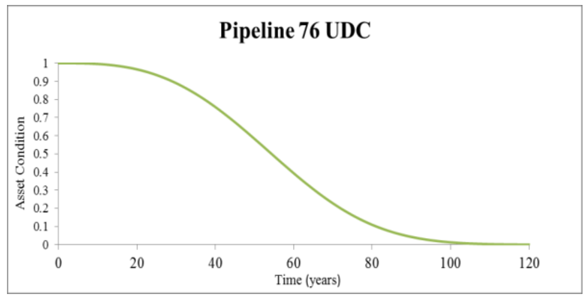
Pipeline 73 UDC
Asset Condition
Time (years)



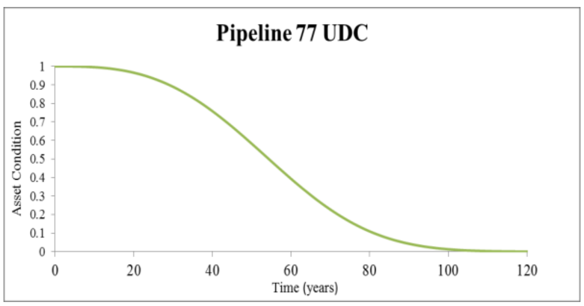
Pipeline 74 UDC
Asset Condition
Time (years)



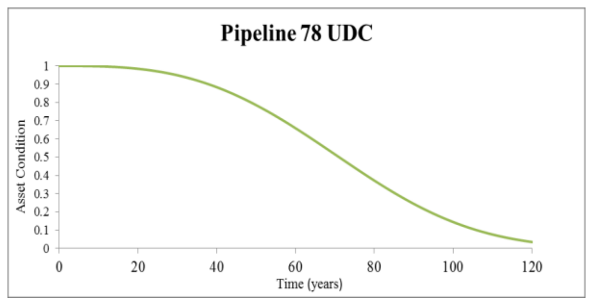
Pipeline 75 UDC
Asset Condition
Time (years)



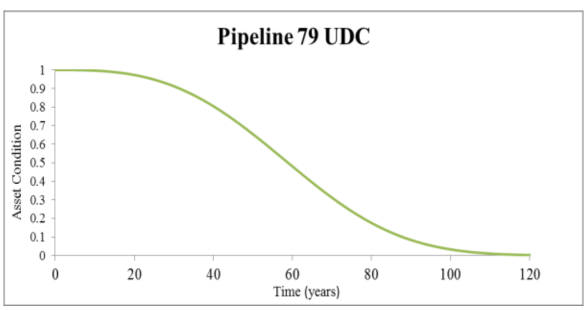
Pipeline 76 UDC
Asset Condition
Time (years)



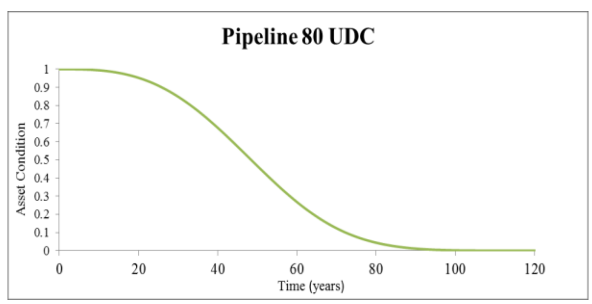
Pipeline 77 UDC
Asset Condition
Time (years)



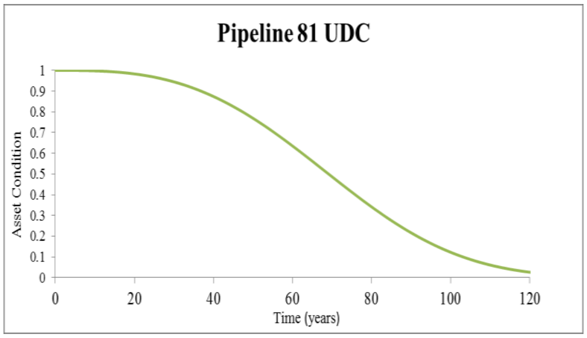
Pipeline 78 UDC
Asset Condition
Time (years)

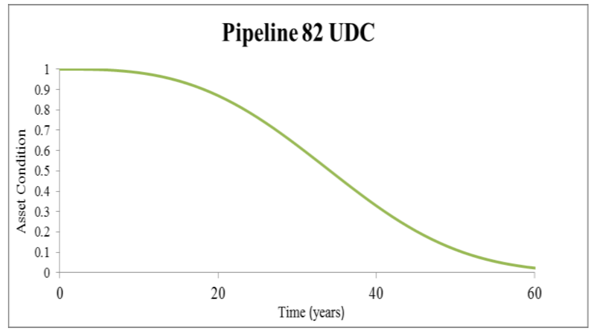


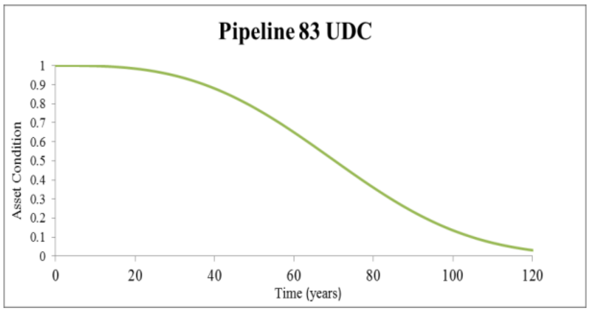
Pipeline 79 UDC
Asset Condition
Time (years)

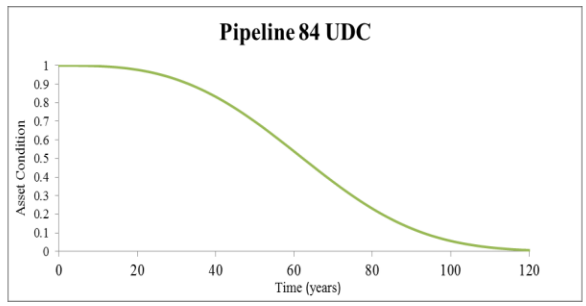


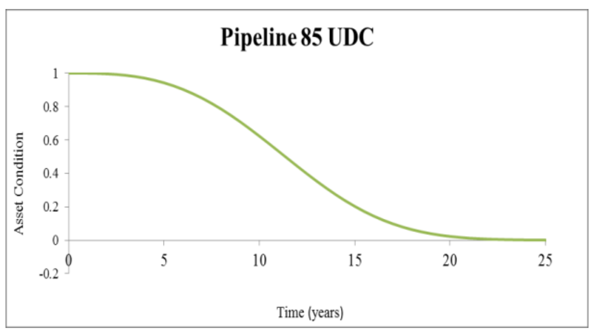
Pipeline 80 UDC
Asset Condition
Time (years)

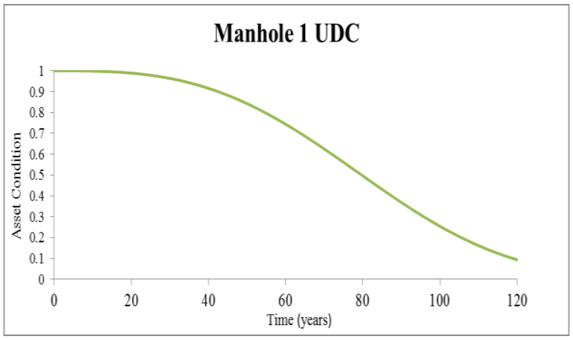

Pipeline 81 UDC
Asset Condition
Time (years)

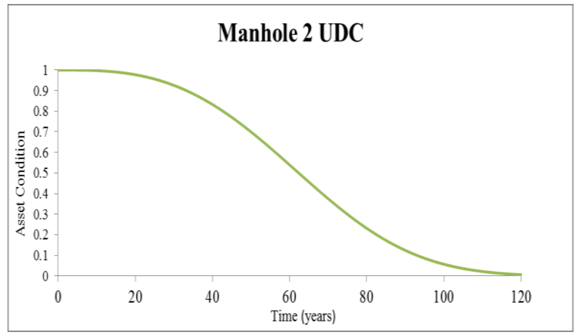

Pipeline 82 UDC
Asset Condition
Time (years)

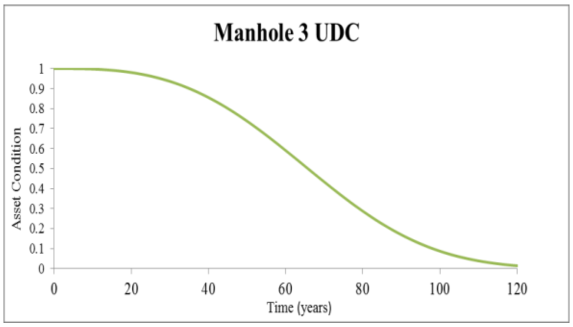

Pipeline 83 UDC
Asset Condition
Time (years)

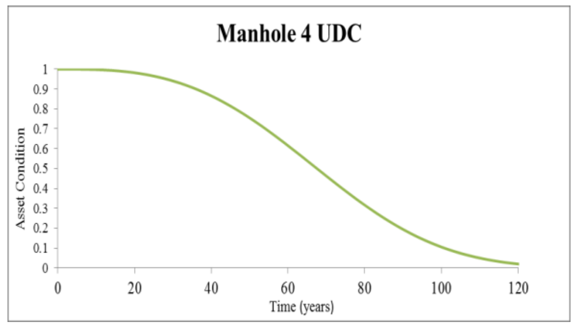

Pipeline 84 UDC
Asset Condition
Time (years)

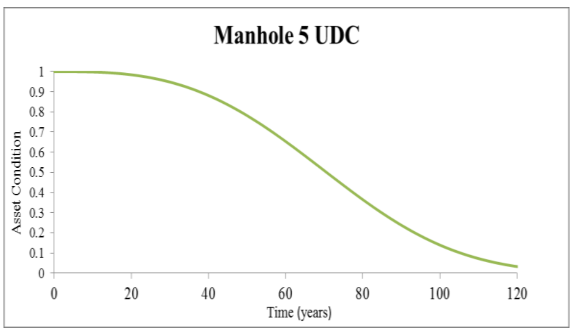

Pipeline 85 UDC
Asset Condition
Time (years)

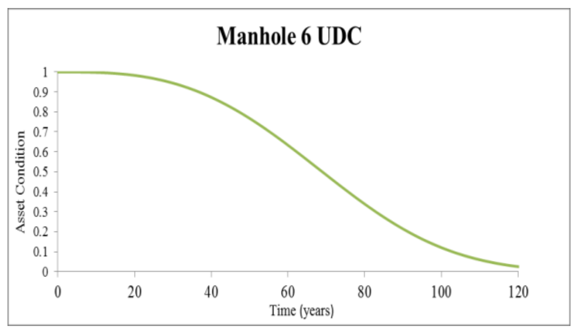

Manhole 1 UDC
Asset Condition
Time (years)

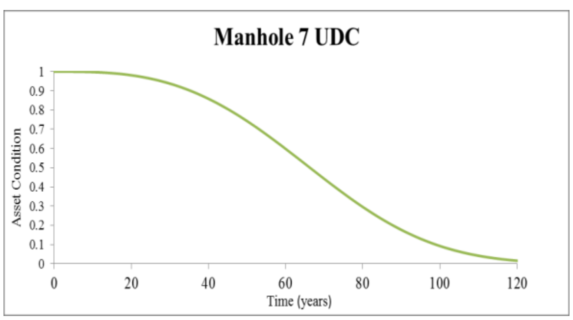

Manhole 2 UDC
Asset Condition
Time (years)

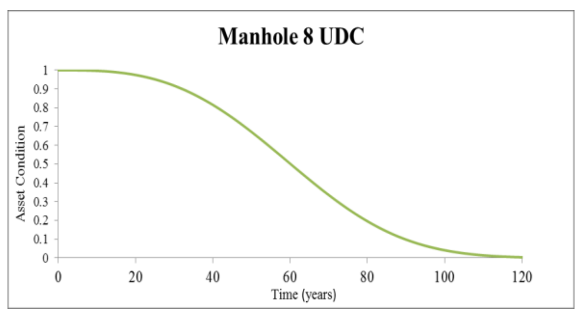

Manhole 3 UDC
Asset Condition
Time (years)

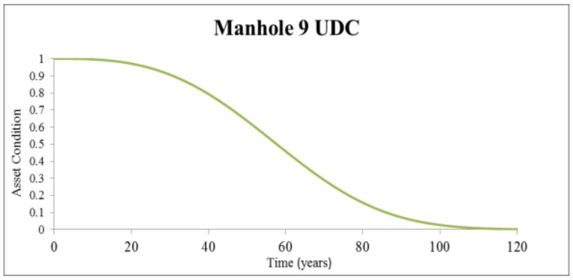

Manhole 4 UDC
Asset Condition
Time (years)

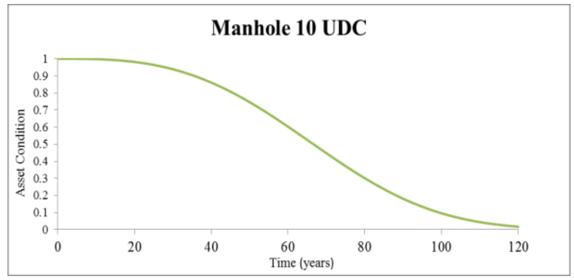

Manhole 5 UDC
Asset Condition
Time (years)

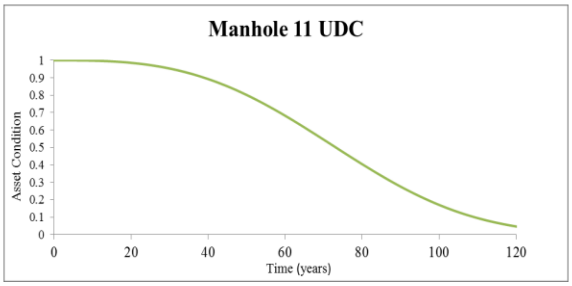

Manhole 6 UDC
Asset Condition
Time (years)

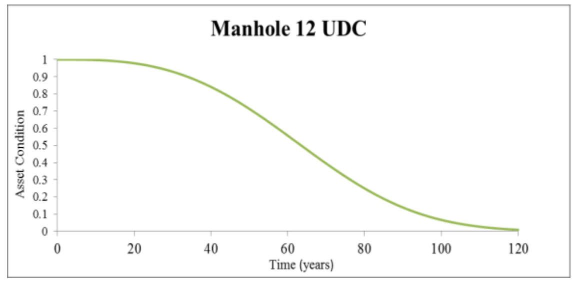

Manhole 7 UDC
Asset Condition
Time (years)

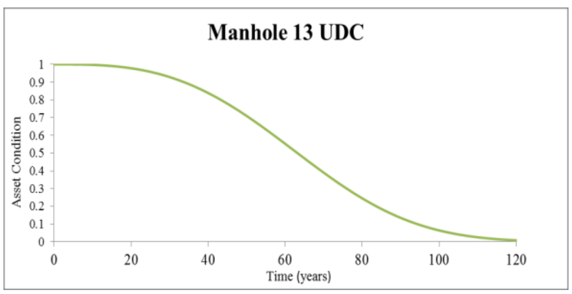

Manhole 8 UDC
Asset Condition
Time (years)

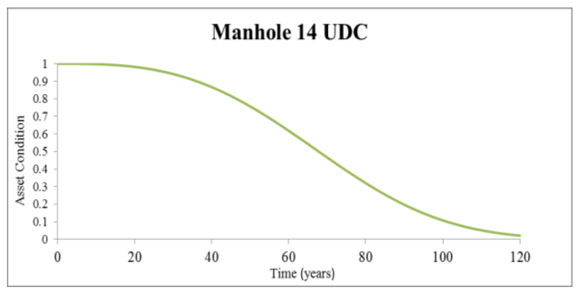

Manhole 9 UDC
Asset Condition
Time (years)

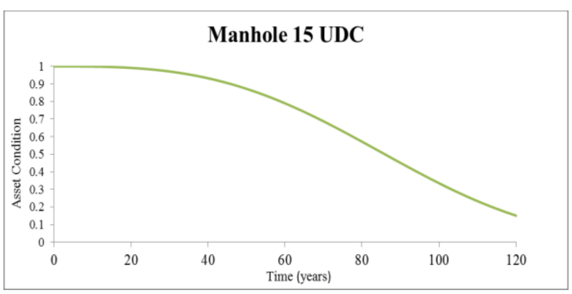

Manhole 10 UDC
Asset Condition
Time (years)

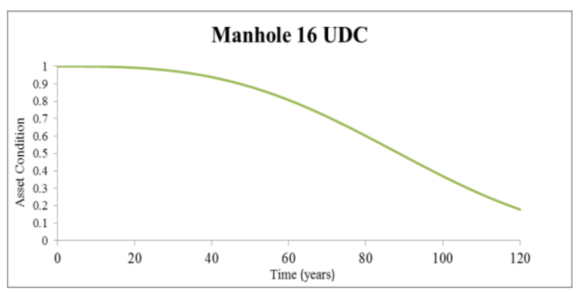

Manhole 11 UDC
Asset Condition
Time (years)

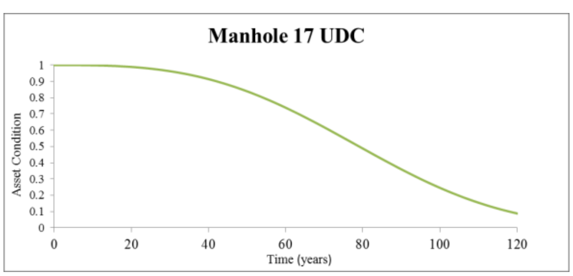

Manhole 12 UDC
Asset Condition
Time (years)

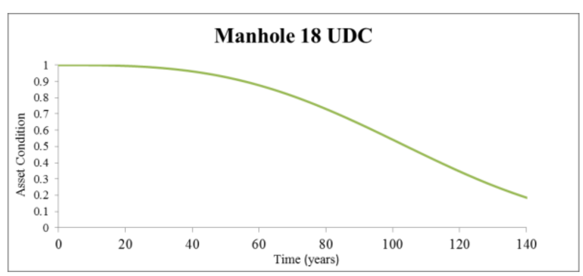

Manhole 13 UDC
Asset Condition
Time (years)

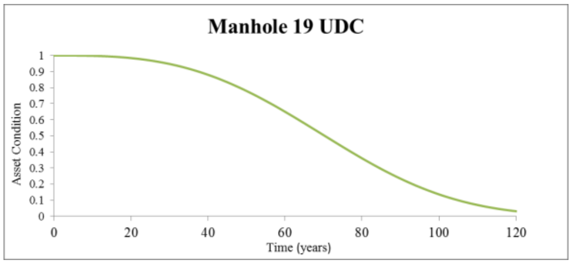

Manhole 14 UDC
Asset Condition
Time (years)

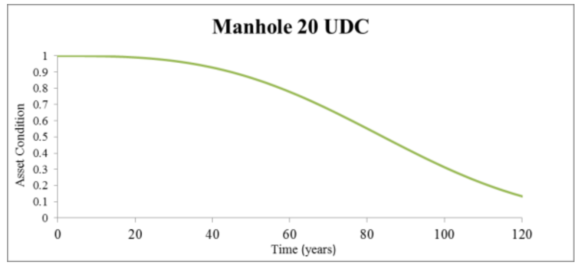

Manhole 15 UDC
Asset Condition
Time (years)

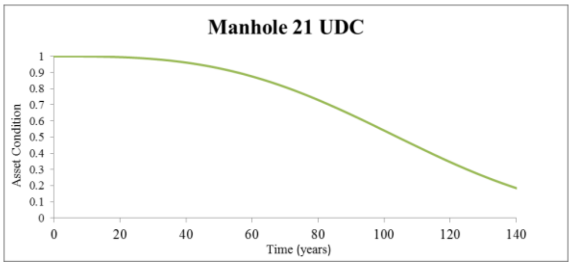

Manhole 16 UDC
Asset Condition
Time (years)

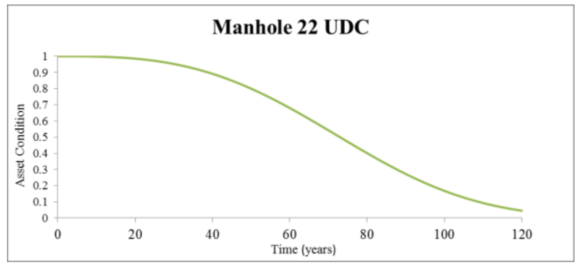

Manhole 17 UDC
Asset Condition
Time (years)

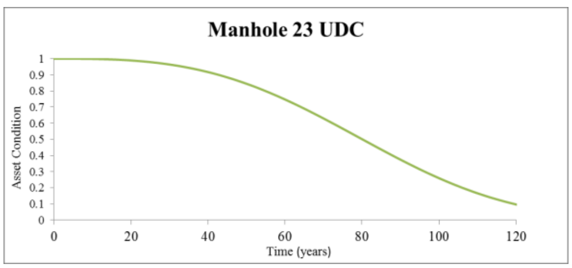

Manhole 18 UDC
Asset Condition
Time (years)

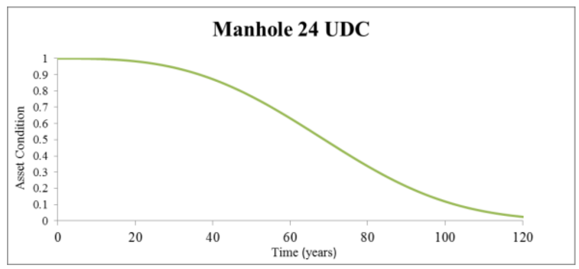

Manhole 19 UDC
Asset Condition
Time (years)


Manhole 20 UDC
Asset Condition
Time (years)


Manhole 21 UDC
Asset Condition
Time (years)


Manhole 22 UDC
Asset Condition
Time (years)


Manhole 23 UDC
Asset Condition
Time (years)


Manhole 24 UDC
Asset Condition
Time (years)