Defect-based Condition Assessment Model and Protocol of Sewer Pipelines

by

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ABSTRACT

Defect-based Condition Assessment Model and Protocol of Sewer Pipelines

Infrastructure serves as the backbone of the city and hence plays a significant role in its urban structure. Therefore, it is of utmost importance to monitor its performance and assure its compliance with the growth in demand. Due to their hidden and passive nature, sewer pipelines are neglected making it essential to assess their conditions and address their associated problems to maintain quality productivity and avoid high social costs. Currently, 30% of the Canadian Infrastructure has been evaluated to be in fair to very poor conditions with a cost of $39 billion for infrastructure repair (Felio et al. 2012).In 2008, it was stated that the capital investment needs in the United States are $15 billion annually for the coming 20 years totaling to $298 billion. Moreover, the pipelines in the U.S represent 3/4th of the total needs marking the largest capital need (ASCE 2013). The current condition assessment protocols are limited to several issues including poor accuracy caused by uncertain human judgments and imprecise assessments due to the consideration of the peak score (worst defect) as the total condition score. Therefore, the development of a sound condition assessment protocol with a unified classification of distress indicators regardless of the inspector's expertise is needed to ensure safety and quality service to the public.

The objective of this research is to develop a defect-based condition assessment model as well as a protocol for sewer pipelines. This model aims to cover the structural, operational, and installation / rehabilitation defects that are associated with the pipelines, joints, and manholes of each pipe length / segment. This Fuzzy Synthetic Evaluation model consists of the Analytic Network Process (ANP) model which covers the interdependencies between the components and their defects in order to deduce their

relative importance weights. The second model utilizes the defects' severities to develop fuzzy membership functions based on a predefined linguistic condition grading scale that would precisely indicate the degree of distress. This model quantifies the distress indicators and encodes their condition linguistically (states) and numerically (scores). Furthermore, a robust aggregation model based on the Hierarchical Evidential Reasoning (HER) and Dempster-Shafer (D-S) theory is created to integrate the defects' conditions and to evaluate the overall condition of the sewer pipeline. Also, the main grading scale in this model was developed using the K-Means clustering technique. The final condition grade is represented as a crisp value calculated by the weighted average defuzzification method. The data utilized in this research was obtained from sewer condition classification manuals, previous research, and questionnaires distributed to professionals in Qatar and Canada. Also, a sewer protocol was developed, calibrated, and verified by experts' feedback. The fruit of this fusion was also presented in a user-friendly automated tool (SPCAT). The developed model was implemented in 29 case studies from Montreal and Qatar. The predicted results of 15 inspected pipelines in Montreal, Canada, resulted in mean absolute error values for structural and operational defects of *0.533* and *0.267* respectively with correlation coefficients of *0.846* and *0.934*. The second batch of 14 inspected pipe segments in Qatar, resulted in a mean absolute error of *0.643* and a correlation coefficient of 0.60 between the predicted and real values .The results are justified throughout the research body.This model helps in minimizing the inaccuracy of sewer condition assessment through the application of severity, uncertainty mitigation, and robust aggregation. It also benefits asset managers by providing a precise condition overview for maintenance, rehabilitation, and budget allocation purposes.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CCTV	Closed Circuit Television
C.P	Clock Positions
HER	Hierarchical Evidential Reasoning
MCDM	Multiple Criteria Decision Making
NAAPI	North American Association of Pipeline Inspectors
NASSCO	National Association of Sewer Service Companies
PACP	Pipeline Assessment and Certification Program
SPCAT	Sewer Pipeline Condition Assessment Tool
SRM	Sewer Rehabilitation Manual
SRM	Sewer Risk Management
WRc	Water Research Centre

CHAPTER ONE: INTRODUCTION

1.1 Overview

A healthy infrastructure contributes to the development and wellbeing of the economy. Any community should be granted its basic infrastructural needs such as transportation, sanitation, water, communication, and energy to valuably impact the daily productivity and eventually boost the country's economic growth. It is important to sustain such social and environmental needs to maintain a quality system. Statistics show that 30% of the municipal infrastructures in Canada rank in a range of fair to very poor conditions (Felio et al. 2012). Additionally, sewer collection networks play an important role in transferring sewage from residential and commercial buildings to treatment plants where it will then be transferred to disposal areas using trunk sewers. However, sewer pipelines are mostly hidden underground rendering them passive among other infrastructural assets. It has been found that 30.1% of the sewer pipes and 40.3 % of wastewater treatment plants, pumping stations and storage tanks range between fair and very poor conditions as well (Felio et al. 2012). In consequence, it will cost $39 billion to repair the wastewater infrastructure in such conditions (Felio et al. 2012). According to the Canadian Infrastructure Report 2012, sewers have a long service life of 80-100 years or even more. This makes monitoring and maintaining those sewers crucial to maintain a good quality of service level. Moreover, sewer pipelines are deteriorating due to aging and several environmental factors. The consequence of this deterioration of sewer pipelines can have a massive impact with a high social and environmental cost in the absence of premature interference. It is therefore necessary to incorporate proactive measures in dealing with sewer pipeline deterioration to ensure a high quality of performance, a safe environment, a protected infrastructure and to avoid service disruption.

A wide range of pipeline inspection techniques have been used in practice to investigate pipeline condition. The common practice for conducting sewer pipeline investigation nowadays is using the Closed Circuit Television (CCTV). However, this inspection technique requires the intervention and expertise of humans to classify the distress indicators and determine their conditions. Various sewer condition assessment protocols have been created in several cities and municipalities. In 1978, Water Research Centre (WRc) created the so-called "embryo code" of sewer condition assessment called Sewerage Rehabilitation Manual (SRM) (Thornhill and Wildbore 2005), and many others have followed. Condition assessment is an inevitable step in managing any asset, and it is of great importance that it be reliable, accurate, credible, and efficient. An effective condition score should also be relevant and interpretable (Opila and Attoh-Okine 2011). Most sewer condition assessment techniques available in the market nowadays rely on peak or mean score defects which results in flattening the data and having an incomplete representation of the pipeline's condition. Therefore, there is a need for a comprehensive, vigorous and standardized sewer condition assessment approach that would represent the effect of distress indicators and defects in an objective and credible manner.

1.2 Problem Statement

Most of the current available protocols deduce the defects and their corresponding severities through CCTV surveys. Utilizing this inspection technique results in a subjective defect assessment and performance evaluation of the pipe segment since it depends on the inspector's CCTV image interpretation skills. Therefore, a defect that might be evaluated as "good" by one inspector might be assessed as "fair" by another, resulting in an uncertain interpretation. As a consequence, it is noticed that the current condition assessment protocols suffer from several limitations such as poor accuracy, and uncertain judgments resulting from human subjectivity. The results of defect evaluation and severity determination depend on human findings and vary across different inspectors relative to their experience in the field. This limitation requires the development of a firm; and accurate condition assessment protocol that would result in the same classification of a particular defect and its severity regardless of the inspector.

Also, the classification of defects and their corresponding weights vary between different protocols and manuals. Moreover, the condition scoring scales in the existing protocols are finite with certain ranges. "The difficulty in predicting pipe condition typically results in implementation of discrete, finite scales of relatively limited ranges"(Opila and Okine 2011). Also, the distribution of the structural defects and the impact of structural defects on the operational defects are not considered in some protocols.

In terms of determining the condition score of a certain segment, most protocols take the peak or mean scores as an indication. The peak scores flatten the data and provide an incomplete representation of the pipe segment. Furthermore, these peak or mean scores are translated into simple scales (1 to 5). The simple scale would result in grading a certain collapsed segment equally to a segment that suffers from high deterioration (but not collapsed) resulting in a misrepresentation of the pipe's condition. Therefore, a comprehensive pipeline condition index is in need of not only precisely representing the pipeline condition but also integrating the effects of structural, operational, and installation defects through robust aggregation.

1.3 Research Objectives

The main objective of this research is to create a comprehensive sewer pipeline assessment protocol that covers the uncertainty in the current protocols. The sub-objectives can be summarized as follows:

- To identify and study the different defect types in a sewer pipeline and their severities.
- To model and assess sewer pipeline condition based on defects.
- To develop a new condition grading scale
- To design a sewer pipeline assessment protocol.
- To develop an automated tool for model implementation.

1.4 Research Methodology

The aim of this research is to create a comprehensive sewer pipeline condition assessment model that overcomes the limitations found in current practices by fulfilling the above-mentioned objectives. To achieve this goal, a literature review inclusive of the current practices, protocols (available in markets and municipalities), expert opinions, available mathematical tools, and decision-making methods was conducted. Figure 1.1 shown below represents a flow chart of the research methodology that was implemented to achieve the predefined objectives. The scope of this research commences with the literature review, explains the collected data, discusses the developed model, analyzes its results, and finally it presents the developed automated tool.

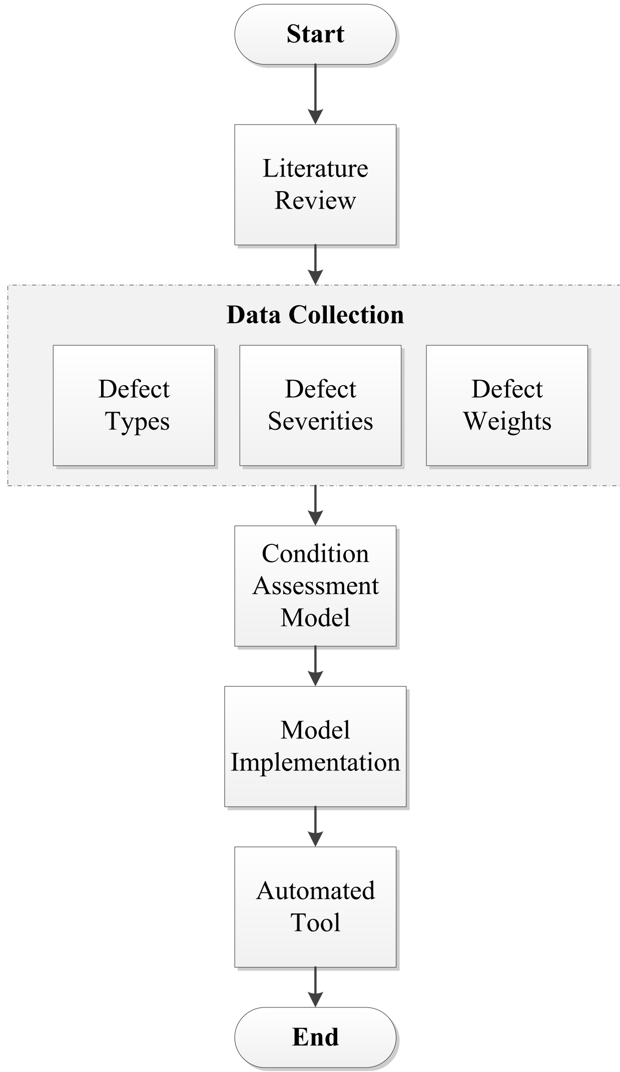


Figure 1.0.1 Research Methodology Flow Chart

The following steps describe the research methodology in details:

- Review the work done on sewer condition assessment both academically and industrially in addition to the current practices.
- Determine the different defect families, types, and sub-categories that affect the integrity of sewer pipelines, joints, and manholes.
- Create a defect hierarchy that portrays the above-mentioned defect categories with regards to their components and defect families.

- Develop a severity scale for each defect and create a set of criteria corresponding to each defect category to be used as "Fuzzy Input Variables" in an attempt to minimize subjectivity and uncertainty.
- Assess the condition of pipeline, joints, and manholes using the Analytic Network Process (ANP) to determine the relative weights of various components (considering their interdependencies), defect families, and defect types.
- Build a comprehensive condition index including the structural, operational, and installation / rehabilitation conditions with the three components integrated using the Hierarchical Evidential Reasoning Model (HER) as a robust aggregation technique.
- Create a new condition assessment scale using the K-Means Clustering technique.
- Develop a sewer condition assessment protocol that would tie condition scores to protective and proactive actions.

Data was collected from existing manuals for defect types and categories determination, and using the aid of experts to determine the relative importance weights of several components and their corresponding defects. To determine the relative importance weights, a survey was conducted both online (website) and offline (hard copies) in both Canada and Qatar. The developed tool is then applied to a network of sewer pipelines in Qatar and Canada, and the results were presented and compared with those of the current practices. In conclusion, to make this tool a user-friendly one, an automated tool was developed using Visual Basic and Excel Sheets. This tool can be used by asset managers, municipalities, subcontractors, or any person performing a CCTV survey for sewer pipelines.

1.5 Thesis Organization

The following paper consists of seven chapters in which each one is explained in details.

Chapter 1 is an introduction to the thesis topic in which an overview of the subject is provided through reflecting the importance of sewer pipelines history, maintenance, statistics, inspection techniques, and available practices. Also, the problem is stated, and the research objectives are set. Moreover, a brief workflow of the research is provided to show where the research is heading.

Chapter 2 includes a comprehensive literature review of the research topic. The literature consulted first were the current practices of sewer pipelines condition assessment, utility management, and inspection techniques. These methodologies are studied carefully to obtain an overall understanding of the algorithm behind assessing the condition of the sewer pipeline and its performance. Also, previous academic studies in the field were also reviewed to have an overview of what has been done in the topic. Moreover, asset management tools were studied to understand the manners through which an asset is managed, maintained, and rehabilitated to maintain the required performance and quality. Furthermore, several Multiple Criteria Decision Making (MCDM) techniques were reviewed. These techniques include Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Fuzzy Logic and Fuzzy Systems, Hierarchical Evidential Reasoning, and K-Means Clustering. Other several techniques were also studied to determine the most suitable one that serves the purpose of this research.

Chapter 3 provides a detailed explanation of the research model. Firstly, the sewer pipeline components, defect families, defect parts, and defect sub-categories are identified. After that, a verified defect hierarchy is created and presented. Moreover, the fuzzy membership model to transform the linguistic assessment into a numerical one is presented. K-Means Clustering is used to create a unique general condition assessment scale of the given asset taking into consideration the available scales. Additionally, the Analytic Network Process in collaboration with the Hierarchical Evidential Reasoning Approach is used for aggregation purposes to determine a crisp value that represents the whole asset. Finally, the sewer condition protocol is presented to portray the possible actions that match each score and defect types.

Chapter 4 delivers the data collection methodology. In this research, three data baskets were collected. Defect types were collected using existing manuals and sewer condition assessment and rehabilitation protocols. Components and defect weights were collected through a survey that was conducted both on-line and in hard copy distribution in both Canada and Qatar. Furthermore, the defect severities were collected from available research and existing protocols. Other types of data such as grading scales and aggregation methods were also collected.

Chapter 5 illustrates the implementation of the resulting model on 29 case studies for pipelines located in Canada and Qatar. Structural, operational, installation/rehabilitation conditions for each of the pipeline's segment, joints, and manholes were calculated for each pipe. Also, the predicted results were compared with the real values corresponding to the protocol utilized in these case studies.

Chapter 6 describes and portrays the developed automated tool.

Chapter 7 wraps up the thesis with conclusions, research contributions, limitations and future recommendations.

CHAPTER TWO: LITERATURE REVIEW

2.1 Overview

Chapter two consists of an extensive review in the literature related to this topic. A review of sewer pipeline condition assessment practices, as well as MCDM approaches is presented in this chapter. Figure 2.1 is an organization chart representing the workflow of the literature review.

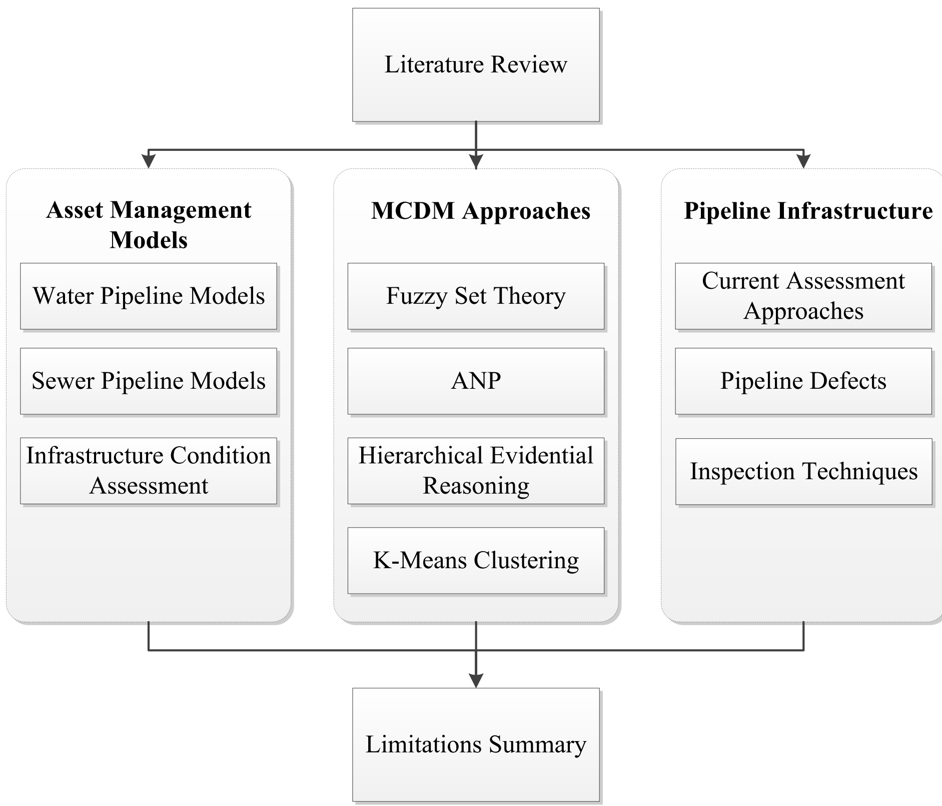


Figure 2. 1 Literature Review Flow Chart

2.2 Sewer Pipeline Inspection Techniques

Condition assessment is performed through several inspection techniques each of which has its uses, advantages, disadvantages, and technical challenges. Buried infrastructures are known for their hidden characteristics. Performing destructive testing on them would have a high impact on the social cost. Therefore, non-destructive testing techniques are favorable but are also accompanied by challenges. Pipeline inspection techniques vary between visual, electromagnetic, acoustic, and several other technologies. A flowchart that shows the different techniques used in pipeline inspection is shown in Figure 2.2. Also, most of the mentioned techniques are explained throughout this chapter.

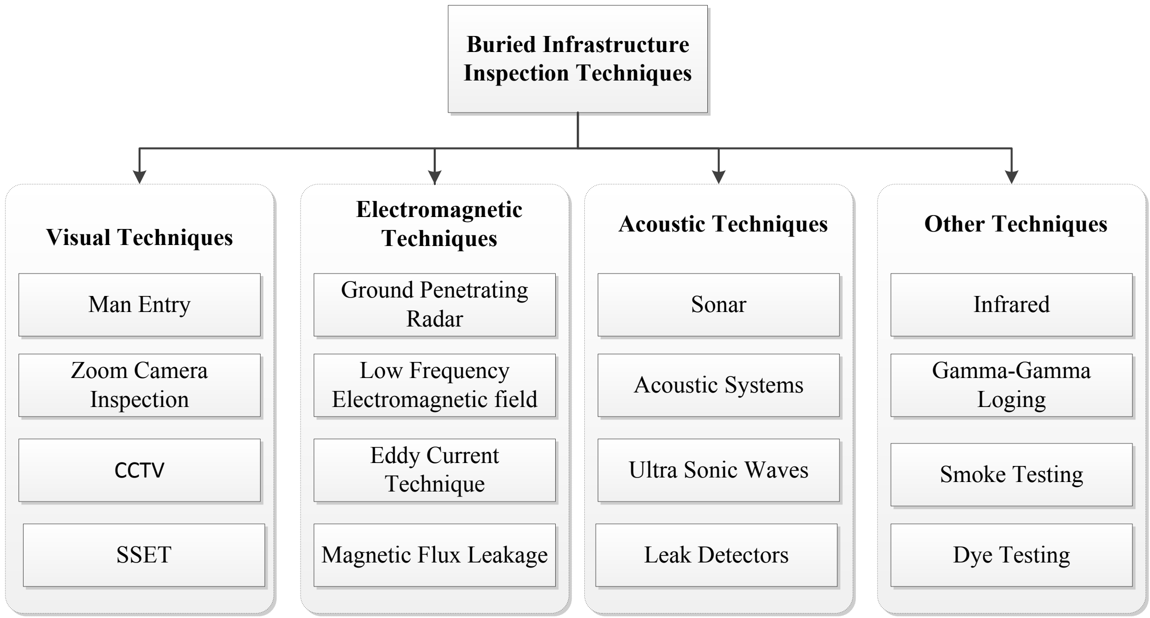


Figure 2. 2 Inspection Techniques for Buried Infrastructure

2.2.1 Visual Techniques

The primitive fashion of pipeline inspection was through sending inspectors into the pipes to check the pipeline's integrity. This method was efficient and accurate in determining the internal condition of the pipeline. However, it puts the manpower in an unsafe and unhealthy environment. It is also impractical to be applied to a set of pipelines and networks. Other forms of inspection techniques were developed to solve this problem as discussed below.

(i) Closed-Circuit Television (CCTV)

Closed-Circuit Television was first used in the 1960s to inspect the pipelines (Hao et al. 2012). The CCTV technique works by inserting a camera-mounted robot to the pipeline segment from an access hole where it can be controlled remotely by an inspector. The cost of using CCTV inspection ranges between $1.75/m to $14/m (Zhao 1998). This technique is extensively used in the industry due to its ability to provide the user with lit up images from the interior of the pipe. Another advantage is that this technique does not require man entry, and it also allows the operator to investigate the interior of the pipe in details through zooming in and out of defective areas. On the contrary, several disadvantages accompany the utilization of this technique. CCTV images can only be taken above the water level. This drawback enforces the need to pre-drain and/or clean the sewer, which adds to the inspection cost. Also, the CCTV is only able to provide the operator with images without delivering any details in terms of defect measurement. These difficulties add to its subjectivity in quantifying the defect. It also cannot determine whether a crack or a void extends to the outside surface of the pipe. This adds to the lack of confidence in determining the type of defect and its severity. In conclusion, CCTV inspection helps the inspector but is slow, subjective, and highly dependent on the image quality and the inspector's CCTV proficiency. Figure 2.3 shows a CCTV image of a complex (multiple) fracture extracted from the Euro Code ((CEN (European Committee for Standardization) 2003). It can be inferred from this image that the ability to determine the defect type and its severity is highly dependent on the camera's visibility, image quality, and the inspector's expertise. As a result, the inspector is responsible for examining the defects properly before judging the condition of the pipeline. This is related to the uncertainty and subjectivity of the current approaches in both inspection and condition assessment of sewer pipelines.

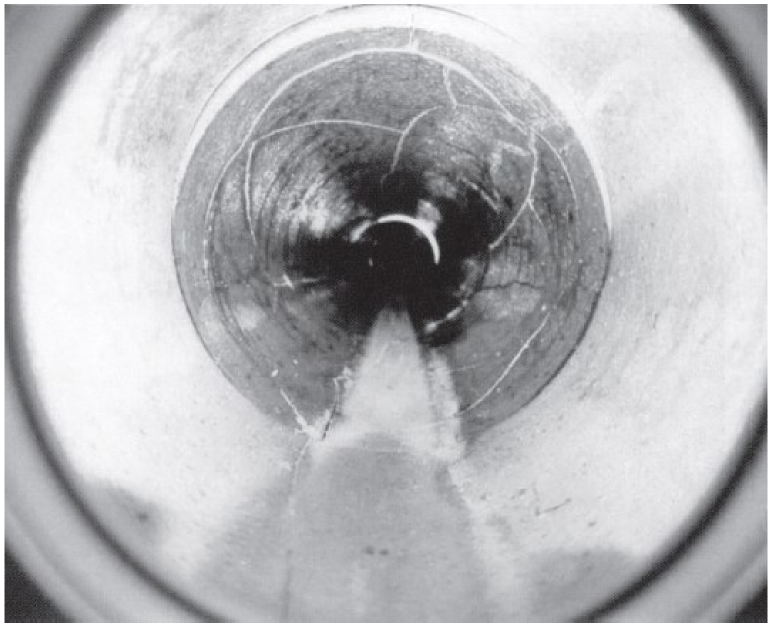


Figure 2. 3 Example of fissure (fracture-complex) (EN 13508-2, 2003)

(ii) Sewer Scanner and Evaluation Technology (SSET)

The SSET was created in an attempt to enhance the CCTV. The SSET is a multi-sensor technique that conducts its inspection throughout the pipe length without having to stop at each defect to examine it. This characteristic makes the SSET more practical and efficient than the CCTV. Also, the defects' investigation is done after the device's journey inside the pipe is over. The data interpretation in this technique is manual which calls for a well experienced operator since the defects cannot be examined in details. One advantage of the SSET is that it can scan the entire diameter of the pipe in 360 degrees coverage of the pipe's diameter and can measure horizontal and vertical pipe deflections (Allouche and Freure 2002).

2.2.2 Electromagnetic Techniques

(i) Magnetic Flux Leakage (MFL)

Magnetic Flux Leakage technique is used to inspect metallic pipelines through injecting a gauge throughout the pipeline length. Metal loss defects such as corrosion are usually detected by the MFL technique (Hao et al. 2012). It is also effective in detecting pitting defects in bad conditions (Hao et al. 2012).

(ii) Eddy Current Technique

Eddy Current technique is used for the inspection of small diameter metal pipes that have a diameter of 100 mm (Hao et al. 2012). This technique works by activating magnetic field in the pipeline and uses alternating current and magnetic coil to create an electric current. This current also produces other magnetic fields. The opposition of these magnetic fields with the previous ones creates impedance through which a person can detect pipe information.

(iii) Ground Penetrating Radar (GPR)

Ground Penetrating Radar is a nondestructive technique that uses electromagnetic waves to detect subsurface materials (Daniels 2005). There are several types of GPR technologies such as spatial domain, frequency domain and time domain types (Hao et al. 2012). Voids and pipeline collapses can be detected by traditional GPR and in-pipe GPR. Also, leak detection can be done using GPR technologies (Hao et al. 2012).

2.2.3 Acoustic Techniques

(i) Sonar

The Sonar technique is an inspection technique that depends on sound waves to develop a sonar image of the pipeline's interior. In 1987, WRc was the first to use sonar for pipelines' inspection (Feeney 2009). The sonar works by sending sound waves of high frequency through the pipe. The signals then change if there is any change in the material. This results in a profile of the pipe wall under the water level which enables the user to detect defects. Several defects such as corrosion, voids, cracks, deflections as well as the of deposits (debris, grease, silt) can be detected using the sonar (Feeney 2009). Also, it can be used in areas of poor visibility in which the usage of CCTV is not effective (Feeney 2009).

(ii) Leak Detectors Technique

This technique is used to detect leakages in pipelines through identifying their noises in pressurized sewers (Feeney 2009). It works by calculating the delay in time on the basis of wavespeed estimates (Hao et al. 2012). There are several methods to detect pipeline leakages such as using listening rods, underwater microphones, leak noise correlators, and in-line devices (Feeney 2009).

2.2.4 Other Techniques

(i) Infrared

Infrared technology is used to detect leakages through identifying voids by using energy from gases and fluids. Infrared can detect voids in the pipeline but cannot detect their sizes or causes. There are several ways to conduct an infrared survey such as performing manual inspection by an operator or by installing the infrared device on a platform / vehicle. Also, the cost of infrared inspection is about $5/m (Boshoff et al. 2009). The combination of infrared with other inspection techniques can also provide more accurate results.

(ii) Smoke Testing

Smoke Testing technique was used in the 1960s to detect leaks through injecting smoke in the pipeline (Allouche and Freure 2002).This technique works by injecting smoke into the manhole and then uses a blower to push the smoke through the cracks, voids, or impairments. Leakages and defects will be detected when the smoke appears from the pipe segment.

2.3 Current Practices

Asset management and condition assessment of infrastructure is the municipalities' concern nowadays. Inspection of sewer systems is a primary task in the process of determining the condition of the asset and setting maintenance programs. Condition assessment is also used in the decision-making process, and in setting rehabilitation priorities to extend the remaining service life of the available assets. Therefore, several protocols and codes were generated in different municipalities and cities to attain this goal. One of the condition assessment modes is the distress based evaluation type that is based on a predefined protocol. In this field, different protocols are used to classify the defects and determine their severity according to each municipality's needs. The Water Research Centre (WRc), one of the main protocols, was created in UK as a standard for sewerage condition assessment. Other protocols include NASSCO (PACP) from USA, CERIU for Quebec, Canada, European Standard EN 13508-2, New Zealand Pipe Inspection Manual, and many others that are tailored to serve the needs of each and every municipality. Figure 2.4 represents the generation of the sewer defect codes across the years. In 1977, the U.K generated a National Assessment report called Sewer and Water Mains which addressed the infrastructure management. This resulted in the methodology developed by the Water Research Centre (WRc) to manage and maintain the sewer pipelines internal condition (Thornhill and Wildbore 2005). After that, sewer condition classification manuals such as the MSCC and the SRM were created to identify the conditions and comprehend their complications. Consequently, WRc's MSCC codes were revised in 1980 and 1988 and the Australian code was created in 1991. In the United States and North America, Asia, and Europe (NAAPI, CERIU, NASSCO, Euro Code) and many other municipal codes were created based on the WRc condition assessment manual. It is important to mention that many characteristics such as the clock reference method and defect definitions are inherited from the first code.

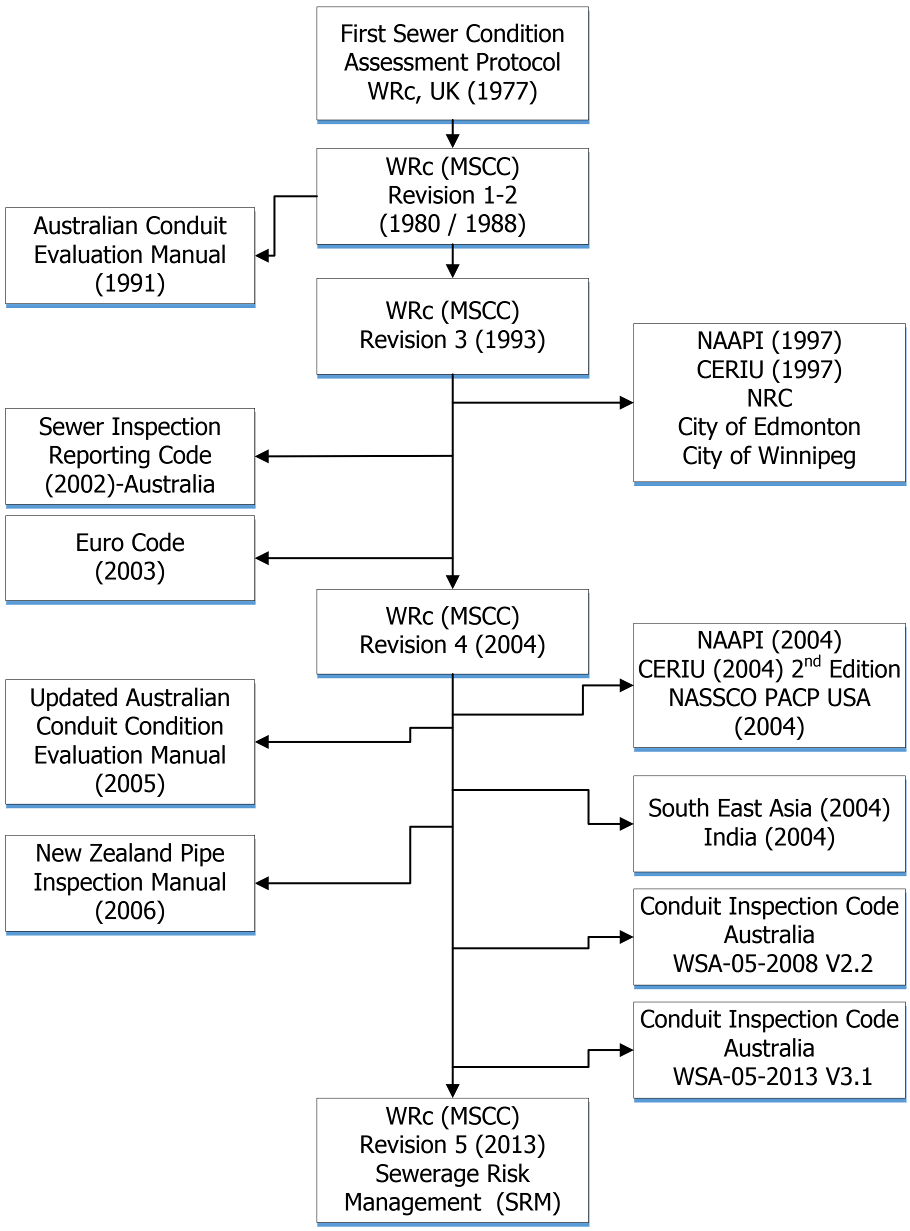


Figure 2. 4 Sewer Defect Codes

2.3.1 Water Research Centre (WRc)

Two manuals were created under the umbrella of the WRc to determine the condition of a sewer pipeline. The first manual is the Manual of Sewer Condition Classification (MSCC) which comprises of the CCTV observation convention and the defect codes. The other one is the Sewerage Rehabilitation Manual (SRM) which includes the condition grades and deduct values.

The Manual of Sewer Condition Classification is created by WRc to represent most of the structural and operational defects by defect codes. The MSCC 5th edition (2013) is based on CCTV inspection and discusses the location of the defects as well as its representation. It discusses the clock reference method to describe defects and notes that the defect should be indicated in a clockwise manner. If the defect is located on a single point, one clock reference is needed. If it is continuous, then a clock reference range should be given. The defect code in WRc can be of two or three letters having the first representing the defect type, the second representing the direction or severity, and the third describing the severity. Also, the quantification of the feature can be either by dimensions, percentages or bands as (Medium or Large) depending on the type of the feature. The (MSCC, 2013) takes the sewer length to be as “Distance between exit and entry faces in consecutive manholes/nodes”. Also, the MSCC classifies the defects into single and continuous defects where continuous defects are split into truly continuous or point defects. Truly continuous defects are ones that continue along the length of the pipe. However, point defects are regularly repeated along the length of the pipe. Also, it is stated that all what is to be seen is to be noted down without limiting it to the worse defect.

The condition grades vary from “Acceptable Structural Condition” to “Collapsed” (1 to 5) depending on the defect score. Each defect is given a deduct value according to the predefined protocol, and the defect score is calculated by calculating the mean, peak, and total scores. The structural defect grade is given upon the peak score. However, operational defect grade is given upon either peak or mean score whichever is worse. If more than one defect occur in 0.1 m of length, the deduct values are summed and treated as a single number. Also, the WRc has introduced the clock reference method to locate the defect throughout the pipe diameter. Table 2.1 presents the internal condition thresholds of structural and operational scores as well as their corresponding description and internal condition grade. It is noticed that the structural range is between (0-165) whereas the operational score is between (0-10).

Table 2. 1 SRM 4 Grading Thresholds

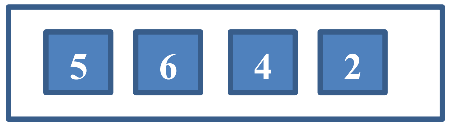
Internal Condition Grade	Description	Structural Peak Score Thresholds	Operational Peak Score Thresholds	Operational Mean Score Thresholds
1	Acceptable structural condition	<10	<1	<0.5
2	Minimal collapse likelihood in short term but potential for further deterioration	10-39	1 – 1.9	0.5 – 0.9
3	Collapse unlikely in near future but further deterioration likely	40-79	2 – 4.9	1 – 2.4
4	Collapse likely in foreseeable future	80-164	5 – 9.9	2.5 – 4.9
5	Collapsed or collapse imminent	165+	10 +	5+

2.3.2 Pipeline Assessment and Certification Program (PACP)

NASSCO (National Association of Sewer Service Companies), found in 1976, created Pipeline Assessment and Certification Program (PACP) to modify the WRc SRM so it can be used in the United States. It differs from the SRM in the sewer systems, materials and different terminologies used. The PACP code is used to code defects in a CCTV inspection and represent the pipeline's condition by a score. To indicate and code the defects, the PACP uses the clock reference technique. The PACP defects are divided into four sections which are structural, operational / maintenance, construction features, and miscellaneous defects. The structural defects include cracks, fractures, breaks, holes, deformations, collapses, offset joints, surface damages, and lining failures. According to the PACP, there are three stages in the deterioration process. The first phase is the initiation of the defect (can be created during the construction of the pipeline). Examples of first phase defects are cracks due to vertical loads, leaking joints, and excavation damages. The second phase commences when the same defect's condition gets worse due to its deterioration. If a defect is not treated, water and soil particles can seep through it creating voids which would in turn cause the support to be loose due to loss of supporting soil resulting in deformation and a weak structure. Collapse represents the third stage and it is the result of continuous deterioration.

The PACP evaluates the pipeline defects through determining their severity and assigning them a score. It also depends on their number of occurrences. It also assigns defects scores as an indication of severity on a scale of (1-5) with 1 being the best and 5 being the worst condition. Also, it provides pipelines failure estimates without considering the age of the pipe. The PACP has several rating systems such as the quick rating and the structural and operational and maintenance condition indices. The quick score, consisting of four characters, indicates the number of defects with maximum severity in the pipeline.

For Example, a (5642) quick score indicates the following.



- First Character: Maximum severity score within a pipeline
- Second Character: Number of occurrences of the maximum score
- Third Character: Second highest severity score within a pipeline
- Fourth Character: Number of occurrences of the second highest score

The second rating system represents the pipeline by an index for structural and operational defects. The indices are calculated using the following steps.

1. Write down the counts of each defect (e.g. 2 defects of FL)
2. Assign a grade to each defect
3. Calculate the segment score of each grade through the summation of the product of Defect counts and Defect Grades of a certain grade e.g: Grade 2
4. Calculate the pipe rating through the summation of segment scores
5. Calculate the Structural Pipe Rating Index, which is the result of (step 4) divided by the summation of defect counts.

For the continuous defects, the PACP transfers the continuous defect into a point defect by dividing the length of the defect by *1.5* for the metric system and derives the number of defects eventually. Table 2.2 presents the PACP's grading system in which the five grades are mapped into five linguistic conditions. Also, the level of deterioration and defect types are linked to each grade to represent the severity of the pipeline's condition. Moreover, the probability of failure is also mentioned through providing the estimated time of failure.

Table 2. 2 PACP Grading System

Grade	Condition	Description	Failure
1	Excellent	Minor Defects	Unlikely in near future
2	Good	Defect deterioration commenced	>20 Years
3	Fair	A moderate defect with continuous deterioration	10-20 Years
4	Poor	Severe defect	5-10 Years
5	Immediate Attention	Defect that has to be treated immediately	Failed or will fail in 5 Years

2.3.3 Le Centre D'expertise et De Recherche en Infrastructures Urbaines (CERIU)

Unlike the WRc and PACP, CERIU deals with the assessment of the sewer pipeline's condition in a different way. CERIU gives a number from a scale of (1 to 5) to each defect in the pipeline. This scale is used to identify whether or not interference or rehabilitation is needed rather than giving an overall condition grade that would represent the whole pipeline. The CERIU manual is divided into four main sections covering the structural defects, hydraulic defects, infiltration, and connection conditions. Table 2.3 shows the CERIU severity scale and its description. The description is provided in terms of the extent of action required to maintain the pipeline's condition.

Table 2. 3 CERIU Severity Grades

Condition Grade	Description
1	Action required without intervention
2	Minor Action Required
3	Action Required
4	Action Required Urgently
5	Action Required Immediately

2.3.4 New Zealand Pipe Inspection Manual

The New Zealand Inspection Manual considers the structural and service defects. It also assesses the pipe's condition in a similar mechanism as the WRc and the PACP.

Assessment of the pipeline's condition state, the indication of potential problem areas, and the indication of intervention or rehabilitation plans are the deliverables of this protocol. Condition Rating is represented by the number of defects and their severity for each pipeline. The three linguistic severities utilized in this protocol (S, M, L) are explained in Table 2.4.

Table 2. 4 Basis of Severity Scores (New Zealand Water and Wastes Association Inc)

Severity Code	Severity Score
S	Defects which should cause no problem in the foreseeable future and/or could have the potential for deterioration in the long-term (10 years plus). Generally scoring fewer than 10 points
M	Defects for which there is a minimal short-term failure risk, but potential for failure in the long term (10 years). They may need attention, but not urgently. They generally score between 10 and 25 points
L	Defects for which there is immediate or short-term risk of pipe failure or severe loss of service. They generally score 30 points or more

The scoring method of this manual consists of the following steps.

1. Assign weighted scores to defects
2. Assign severity ratings
3. Calculate mean score
4. Calculate peak score
5. Compare against thresholds and determine the condition of the pipe

Tables 2.5 and 2.6 present the structural and operational condition grading thresholds based on the New Zealand assessment protocol. This manual uses both intermediate and simple scales in representing the general condition of the pipe. The usage of two scales in this manual gives it an advantage over the other protocols in a sense that the pipelines' conditions can be compared more accurately using the intermediate scales. This would help in budget allocation and prioritization of inspection and maintenance works.

Table 2. 5 Structural Condition Grading Thresholds (New Zealand Water and Wastes Association Inc)

Grading	Peak Score		Mean Score	
	Initial	Intermediate	Initial	Intermediate
1.0 Excellent	0 to 2.0	0 to 2.0	0 to 0.50	0 to 0.50
2.0 Good	2.1 to 15.0	2.1 to 15.0	0.51 to 0.90	0.51 to 0.90
3.0 Moderate	15.1 to 30.0	15.1 to 20.0	0.91 to1.70	0.91 to 1.18
3.4		20.1 to 25.0		1.19 to 1.44
3.8		25.1 to 30.0		1.45 to 1.70
4.0 Poor	>30.1 to 50.0	30.1 to 34.0	1.71 to 3.00	1.71 to 1.97
4.2		34.1 to 38.0		1.98 to 2.23
4.4		38.1 to 42.0		2.24 to 2.49
4.6		42.1 to 46.0		2.50 to 2.74
4.8		46.1 to 50.0		2.76 to 3.00
5.0 Fail	>50.0	50.1 to 60.0	>3.00	3.01 to 30.0
5.2		60.1 to 70.0		30.1 to 60.0
5.4		70.1 to 80.0		60.1 to 90.0
5.6		80.1 to 90.0		90.1 to 110.0
5.8		>90.0		>110.0

Table 2. 6 Service Condition Grading Thresholds (New Zealand Water and Wastes Association Inc)

Grading	Peak Score		Mean Score	
	Initial	Intermediate	Initial	Intermediate
1.0 Excellent	0 to 3.0	0 to 3.0	0 to 0.50	0 to 0.50
2.0 Good	3.1 to 7.0	3.1 to 7.0	0.51 to 1.0	0.51 to 1.0
3.0 Moderate	7.1 to 15.0	7.1 to 10.3	1.1 to 2.0	1.10 to 1.40
3.4		10.4 to 13.5		1.41 to 1.80
3.8		13.6 to 15.0		1.81 to 2.00
4.0 Poor	>15.1 to 30.0	15.1 to 18.0	2.1 to 5.00	2.10 to 2.60
4.2		18.1 to 21.0		2.61to 3.20
4.4		21.1 to 24.0		3.21 to 3.80
4.6		24.1 to 27.0		3.81 to 4.40
4.8		27.1 to 30.0		4.41 to 5.00
5.0 Fail	>30.0	30.1 to 40.0	>5.00	5.01 to 5.60
5.2		40.1 to 50.0		5.61 to 6.20
5.4		50.1 to 60.0		6.21 to 6.80
5.6		60.1 to 70.0		6.81 to 7.40
5.8		>70.0		>7.40

2.3.5 European Standard EN 13508-2

The European Code – Part1 only uses codes to record the observations from a CCTV survey. It does not include the assessment of the pipelines. This protocol uses a uniform standard coding that consists of codes and letters to represent and describe the defects in a pipe segment. All the individual observations start with "B" for the "Main Code" and then the other letters can describe the characterization, quantification, circumferential location, and defects within joints for the secondary codes. Also, the main codes start with "BA" for defects representing the pipeline fabric, "BB" for defects representing the pipeline operation, "BC" as inventory codes, and "BD" for other codes. For Example, BAA represents deformation and BAB represents fissure. It also consists of a coding system for the manholes and inspection chambers.

2.3.6 Other Protocols

Many cities edited the current WRc condition assessment manual to fit and cope with their municipality needs. Therefore, different protocols with different characteristics and methodologies were created. Some of these protocols are presented in this chapter.

(i) National Research Canada (NRC)

The NRC code for condition assessment of sewer pipelines was issued as the "Guidelines for Condition Assessment and Rehabilitation of Large Sewers" (Zhao et al. 2001).This guideline provides the user with a condition assessment and rehabilitation manual based on structural and serviceability defects for both sewers and access holes. The NRC guideline also discusses the rehabilitation extents, actions, and techniques in its manual. Table 2.7 presents the NRC's grading system involving both structural and operational score thresholds and their description both linguistically and numerically.

Table 2. 7 NRC Grading System

Condition Rating	Description	Structural Peak Score Thresholds	Operational Peak Score Thresholds
0	Excellent	0	0
1	Good	1-4	1-2
2	Fair	5-9	3-4
3	Poor	10-14	5-6
4	Bad	15-19	7-8
5	Failure/Imminent Failure	20	9-10

(ii) City of Edmonton (COE)

The City of Edmonton created its sewer condition assessment protocol named (Standardized Sewer Condition Rating System Report) and (Sewer Physical Condition Classification Manual) in 1996 taking the WRc's second edition as its basis. The COE provides the user with a comprehensive rating system for both structural and operational defects. It also calculates the mean score, peak score, and total score in which the code takes the highest rating upon them into consideration as shown in Table 2.8.

Table 2. 8 City of Edmonton Grading System

Condition Grade	Structural Peak Score Thresholds	Structural Mean Score Thresholds	Structural Total Score Thresholds
1	<1.0	<0.5	<100
2	1.0-2.0	0.5 – 0.99	100 – 149
3	2.1-3.0	1.0 – 1.49	150 – 199
4	3.1-5.0	1.5 – 2.49	200 – 249
5	>5.0	>2.5	>250

(iii) City of Winnipeg

The City of Winnipeg also created its own sewer condition assessment manual based on the WRc's SRM second edition. This protocol contains defect values that range between 0.1-165 and condition grades that range from 1-5. Table 2.9 shows the defects deduct values' thresholds for peak, mean, and total scores.

Table 2. 9 City of Winnipeg Grading System

Condition Grade	Structural Peak Score Thresholds	Structural Mean Score Thresholds	Structural Total Score Thresholds
1	<10	<0.3	<20
2	10-59	0.3 – 1.49	20-99
3	60-99	>1.5	>100
4	100-149	-	-
5	>150	-	-

2.3.7 Protocols' Comparison

The following section provides a comparison between the defect codes, the structural deduct values, and condition grades of several protocols. The codes used for this comparison were the two main ones (WRc, and PACP) along with the New Zealand protocol.

(i) Defect Codes

Different condition codes are provided for various defects. Also, each protocol has its own set of defect codes that represent each distress indicator. The defect code usually consists of the basic code that can be accompanied by secondary elements which in turn would describe the characteristics of the defect, its severity, and/or its cause as shown in Tables 2.10 & 2.11. Table 2.10 compares the structural defect codes whereas Table 2.11 compares the operational defect codes.

Table 2. 10 Structural Defect Codes Comparison

Structural Defects	Description	Defect Codes		
		WRc	PACP	NewZealand
Crack (C)	Longitudinal	CL	CL	CL
	Circumferential	CC	CC	CC
	Multiple	CM	CM	CM
	Radiating	CR	-	-
	Spiral	CS	CS	-
Fracture (F)	Longitudinal	FL	FL	-
	Circumferential	FC	FC	-
	Multiple	FM	FM	-
	Radiating	FR	-	-
	Spiral	FS	FS	-
Broken	Broken Pipe	B	B	PB
	Broken Soil Visible		BSV	
	Broken Void Visible		BVV	
Hole	Hole in Sewer	H	H	PH
	Hole Soil Visible		HSV	
	Hole Void Visible		HVV	
Deformed	Deformed Sewer	D	D	DF
	Vertical	DV	DV	
	Horizontal	DH	DH	
Collapsed	Collapsed Sewer	XP	XP	PX
Joint Displaced	Joint Displaced	JD	-	JD
	Joint Displaced/Offset Medium	JDM	JOM	
	Joint Displaced/Offset Large	JDL	JOL	
Open Joint	Open Joint	OJ	-	JO
	Open Joint Medium	OJM	JSM	
	Open Joint Large	OJL	JSL	
	Joint Angular Medium	-	JAM	
	Joint Angular Large	-	JAL	
Surface Damage (S)	Surface Damage	-	-	SD
	Increased Roughness/Surface Wear Slight	SW	SRI	
	Roughness Increased Chemical	-	SRIC	
	Roughness Increased Mechanical	-	SRIM	
	Roughness Increased Unknown	-	SRIZ	
	Spalling	SS	SSS	
	Spalling Chemical	-	SSSC	
	Spalling Mechanical	-	SSSM	
	Spalling Unknown	-	SSSZ	
	Internal Blister or Bulge	SB	-	
	Aggregate Visible	SAV	SAV	
	Aggregate Visible Chemical	-	SAVC	

Table 2. 10 Structural Defect Codes Comparison (continued)

Structural Defects	Description	Defect Codes		
		WRc	PACP	NewZealand
	Aggregate Visible Mechanical	-	SAVM	
	Aggregate Visible Unknown	-	SAVZ	
	Aggregate Projecting from Surface / Surface Wear Medium	SAP	SAP	
	Aggregate Projecting Chemical	-	SAPC	
	Aggregate projecting Mechanical	-	SAPM	
	Aggregate Projecting Unknown	-	SAPZ	
	Surface Damage Aggregate Missing	-	SAM	
	Surface Aggregate Missing Chemical	-	SAMC	
	Surface Aggregate Missing Mechanical	-	SAMM	
	Surface Aggregate Missing Unknown	-	SAMZ	
	Reinforcement Visible	SRV	SRV	
	Aggregate is missing reinforcement visible chemical	-	SRVC	
	Aggregate is missing reinforcement visible mechanical	-	SRVM	
Surface Damage (S)	Aggregate is missing reinforcement visible unknown	-	SRVZ	SD
	Reinforcement projecting from surface	SRP	SRP	
	Aggregate missing and reinforcement is projecting chemical	-	SRPC	
	Aggregate missing and reinforcement is projecting mechanical	-	SRPM	
	Aggregate missing and reinforcement is unknown	-	SRPZ	
	Reinforcement Corroded	SRC	SRC	
	Reinforcement Corroded Chemical	-	SRCC	
	Reinforcement Corroded Mechanical	-	SRCM	
	Reinforcement Corroded Unknown	-	SRCZ	
	Corrosion Products	SCP	SCP	
	Other damage	SZ	SZ	
	Other damage Chemical	-	SZC	
	Other damage Mechanical	-	SZM	
	Other damage Unknown	-	SZZ	

Table 2. 11 Operational Defect Codes Comparison

Operational Defects	Description	Defect Codes		
		WRc	PACP	NewZealand
Roots	Fine	RF	-	RI
	Root Fine Barrel	-	RFB	
	Root Fine Lateral	-	RFL	
	Root Fine Connection	-	RFC	
	Root Fine Joint	-	RFJ	
	Tap	RT	-	
	Root Tap Barrel	-	RTB	
	Root Tap Lateral	-	RTL	
	Root Tap Connection	-	RTC	
	Root Tap Joint	-	RTJ	
	Mass	RM	-	
	Root Ball Barrel	-	RBB	
	Root Ball Lateral	-	RBL	
	Root Ball Connection	-	RBC	
	Root Ball Joint	-	RBJ	
	Root Medium Barrel	-	RMB	
	Root Medium Lateral	-	RML	
	Root Medium Connection	-	RMC	
	Root Medium Joint	-	RMJ	
Infiltration	Seeping	IS	-	IP
	Infiltration Stain	-	IS	
	Dripping	ID	ID	
	Running	IG	IG	
	Gushing	IR	IR	
	Infiltration Weeper	-	IW	
Attached Deposits (DE)	Encrustation	DEE	DAE	ED
	Fouling	DEF	-	-
	Grease	DEG	DAGS	-
	Ragging	-	DAR	-
	Other	DEZ	DAZ	-
Settled Deposits (DE)	Fine (Silt)	DES	DSF	-
	Coarse /Gravel	DER	DSGV	-
	Hard or Compacted	DEC	DSC	-
	Other	DEX	DSZ	-
Ingress of Soil	Ingress of Soil	ING	-	-
	Sand	INGS	DNF	-
	Peat	INGP	-	-
	Fine Material	INGF	-	-
	Gravel	INGG	DNGV	-
	Other	INGZ	DNZ	-

Table 2. 11 Operational Defect Codes Comparison (Continued)

Operational Defects	Description	Defect Codes		
		WRc	PACP	NewZealand
Exfiltration	Exfiltration	EX	-	-
Other Obstacles	Brick or Masonry in Invert	OBB	OBB	OT
	Pipe Material in Invert	OBM	OBM	
	Other Object in Invert	OBX	-	
	Obstacle Protruding through Wall	OBI	OBI	
	Obstacle through Connection/Junction	OBC	OBC	
	External Pipe or Cable	OBP	OBP	
	Obstacle Built into Structure	OBS	OBS	
	Other	OBZ	OBZ	
	Obstruction Wedged in Joint	-	OBJ	
	Obstruction Construction Debris	-	OBN	
	Obstruction Rocks	-	OBR	
Water Level	Water Level	WL	MWL	-
	Water Level Sag	-	MWLS	-
	Water Mark	-	MWM	-
	Clear Water	WLC	-	-
	Turbid Water	WLT	-	-
Line	Deviates Left	LL	LL	-
	Line Left Down	-	LLD	-
	Deviates Right	LR	LR	-
	Line Right Up	-	LRU	-
	Deviates Up	LU	LU	-
	Line Left Up	-	LLU	-
	Deviates Down	LD	LD	-
	Line Right Down	-	LRD	-

It is clear that the New Zealand code provides a shallow description of defects when it indicates their occurrence. However, the WRc and the PACP provide a more detailed description of each distress indicator. The WRc code considers the radiating fissures that are not considered by the PACP. However, the PACP code is more comprehensive than the WRc as it considers the cause of the defect (chemical, mechanical, etc.). It also considers the visibility of soil unlike WRc that just mentions the defect (Broken Soil

Visible, Broken). In conclusion, it can be deduced that different protocols have different representations of defects. Also, some of the defects are considered in more details in the PACP when compared to others.

(ii) Deduct Values

Different protocols have different deduct values depending on the range of their thresholds. For example, the WRc has deduct values that range from (0-165), whereas the PACP has deduct values of (1-5). The WRc provides defect scores based on the description of the defect i.e. (Longitudinal, Circumferential). On the other hand, the PACP provides scores based on descriptions and clock positions in some cases. Moreover, some defects are given defect scores that are 1.25% of the maximum score in WRc, whereas the same defect is given a score that is 20% of the maximum in the PACP such as the (Displaced Joint) and (Open Joint) defects. The same issue is represented by deformation as <5 % deformation is given a score of 25% of the maximum by WRc where it is given a score of 80% of the maximum by the PACP. These differences raise a red flag in which these scores have to be studied further to provide an accurate and unified assessment of defects. An advantage that the PACP has over the WRc is that it distinguishes between (Broken) and (Broken Soil Visible). The same procedure is applied to (Hole) and (Hole Soil Visible). It is also noticed that unlike the PACP, the WRc does not mention any scores for infiltration. The above discussion can be better viewed in Table 2.13 that compares the structural deduct values between the WRc, PACP, and New Zealand sewer condition assessment protocols.

Table 2. 12 Structural Deduct Values Comparison

Structural Defects	Description	Defect Scores/Grades		
		WRc	PACP	NewZealand (S,M,L)
Crack (C)	Longitudinal	10	2	3,15,30
	Circumferential	10	1	2,15,30
	Multiple	40	3	10,20,40
	Radiating	-	-	-
	Spiral	40	2	-
Fracture (F)	Longitudinal	40	3	-
	Circumferential	40	2	-
	Multiple	80	4	-
	Radiating	-	-	-
	Spiral	80	3	-
Broken	Broken Pipe	80	1 C.P=3 2 C.P= 4 >3 =5	15,30,75
	Broken Soil Visible	-	5	-
	Broken Void Visible	-	5	-
Hole	Hole	-	1 C.P=3 2 C.P= 4 >3 =5	5,25,40
	Radial Extent <1/4	80	-	-
	Radial Extent >1/4	165	-	-
	Hole Soil Visible	-	5	-
	Hole Void Visible	-	5	-
Deformed (%)	<5	20	4	-,25,65
	6-10	80	4	-
	>10	165	5	-
Collapsed	Collapsed Sewer	165	5	100
Joint Displaced	Joint Displaced	-	-	0,15,45
	Joint Displaced/Offset Medium <1* Pipe Thickness	1	1	-
	Joint Displaced/Offset Large >1*Pipe Thickness	2	2	-
	>10% diameter & Soil Visible	80	-	-
Open Joint	Open Joint	-	-	0,5,25
	Open Joint Medium	1	1	-
	Open Joint Large	2	2	-
	If soil visible grade as a hole	165	-	-
	Joint Angular Medium	-	1	-
	Joint Angular Large	-	2	-

Table 2.13 compares the score ranges (thresholds) of the structural and operational defects throughout several protocols. It can be noticed that each and every protocol has its own range of scores. Also, the maximum deduct value of the structural defects differ from that of the operational defects for the same protocol with the maximum operational score being less than that of the structural. These issues make it hard for companies and practitioners using different protocols to compare their work or at least map it. Therefore, it is essential to have a unified range of defect scores.

Table 2. 13 Structural and Operational Score Ranges Comparison

Protocols	WRc	PACP	New Zealand	CERIU	COE	NRC	City of Winnipeg
Structural Defects	1-165	1-5	1-100	1-5	1-115	1-20	0.1-165
Operational Defects	1-20	1-5	1-70	1-5	1-3	1-10	-

Table 2.14 compares the condition grading of the segment among different protocols.The condition grades consist of numerical values that are deduced from the severities of defects and their impact on the pipeline. These values are also deduced from the deduct values of structural and operational defects. It is inferred from this comparison that most of the protocols have a condition grading range of (1-5).

Table 2. 14 Comparison of Condition Grades

Protocols	WRc	PACP	New Zealand	CERIU	COE	NRC	City of Winnipeg
Condition Grade	1-5	1-5	1-5	1-5	1-115	1-5	1-5

2.4 Previous Research

As the need for a standardized sewer condition assessment protocol that can sustain and maintain this infrastructure was increasing in importance, several papers were published to fulfill this need. (Khan et al. 2009) utilized the artificial neural network technique to study the structural performance of a sewer pipeline based on its parameters such as diameter, buried depth, material, length, and age. Also, (Moselhi and Shehab-Eldeen 2000) created an automated model that detects and classifies defects in sewer pipelines utilizing the neural networks technique. Vani Kathula predicted the deterioration rate of sewer pipelines through developing a structural deterioration preliminary model (Kathula 2001). Also, (Chae and Abraham 2001) used the neuro-fuzzy approach to develop an automated data interpretation system for sewer pipes. Additionally,(Najafi and Kulandaivel 2005) predicted the condition of sewer pipes on the basis of historical condition assessment using the Artificial Neural Network (ANN). Also, (Najafi and Kulandaivel 2005; Le Gauffre et al. 2007) proposed a condition scoring method that assigns a grade of (1-4) with 4 being worst to the pipe segment through comparing the densities of the defects to three predefined thresholds. Moreover, a combined condition index of structural and operational conditions was created by (Chughtai and Zayed 2011) to provide a single condition index of sewer pipelines. (Chughtai and Zayed 2011) also developed a unified protocol by converting CERIU code into WRc using unsupervised neural network technique in an attempt to obtain a standard sewer pipeline condition assessment protocol. In addition to that, they assessed the structural condition of sewer pipelines using historical data through utilizing the multiple regression technique. In a paper published by (Ennaouri and Fuamba 2011), the structural and hydraulic factors were combined incorporating 15 factors and their relative importance weights that were derived using the analytic hierarchical process technique. (Khazraeializadeh 2012) performed a comparative analysis among four of the sewer condition assessment protocols such as (PACP, WRc, COE, COE revised) in which the limitations, reliability, and accuracy of each protocol were presented. Moreover, (Ahmadi et al. 2014) proposed a condition scoring methodology (RERAU) that encodes the defects into a score by multiplying its level of seriousness by its extent (taken as defect's length). Several probabilistic models were also built in an attempt to predict and assess the condition of the pipeline such as Markov Chain Models.

2.5 Multi-Criteria Decision Making

In infrastructure asset management, many multi-criteria decision-making techniques have been used to deliver a sound decision. The common foundation of the decision-making techniques remains in combining technical information with experts' point of view. These techniques work by combining the values and weights of several alternatives and eventually aggregating the results of each to result in a single index that would represent the asset's condition (Kabir et al. 2014).

2.5.1 The Fuzzy Set Theory

A wide range of problems that are faced in real life require to be solved in an objective manner to have credible results. Such problems usually involve physical processes that are accompanied by vagueness. Human intervention in solving these problems comprises of imprecision due to uncertainty in assessing the situation, and the experts' judgment and expertise. Since classes of objects in real life problems do not have a specific membership, these problems require the use of human judgment in the decision-making process.

(i) Fuzzy Relations

In a set of information, a classical set is defined as one that has certain defined boundaries without uncertainty. On the other hand, the fuzzy set, introduced by Zadeh in 1965, is defined as a set that has vague boundaries due to its uncertain properties. The transition of an element in a classical set is well defined. However, the transition of an element in a fuzzy set is through a membership with a defined function that would portray the ambiguity in the element's properties. In a fuzzy set, the same element may be a member of another fuzzy set in the same universe since there is incomplete information, unlike the classical set in which elements would have a complete membership i.e (0 or 1). Some of the standard fuzzy operations are the union, intersection, and the complement of the fuzzy sets.

(ii) Fuzzification and Defuzzification

In order to deduce quality information from vague situations, the uncertain information in a universe set is transformed into fuzzy sets. A membership function has several terms to describe its characteristics. Speaking of that, the core of a membership function is the area in which the elements in the universe have a full membership i.e.:$\mu A(x) = 1$. Moreover, the support is the area in which the elements in a certain fuzzy set have a membership not equal to 0 i.e: $\mu A(x) > 0$. Also, the boundaries are the areas in which the elements have a membership in a certain fuzzy set is greater than 0 but not equal to one i.e.: $0 < \mu A(x) < 1$.

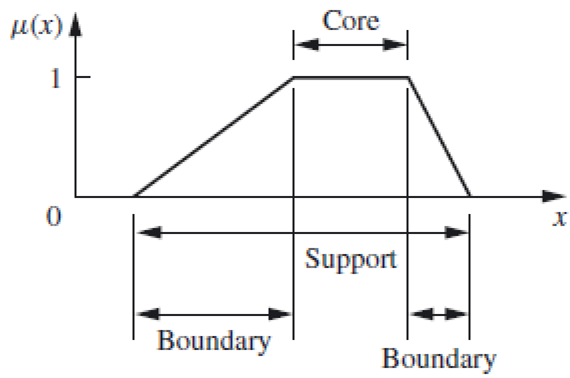


Figure 2. 5 Core, support, and boundaries of a fuzzy set (Ross 2010)

A normal fuzzy set is one in which one or more elements in the universe have a complete membership in a particular fuzzy set. Another fuzzy set, named the convex set, is defined as a fuzzy set in which the membership values are increasing, decreasing, or increasing then decreasing (Ross 2010).

Defuzzification is the process of changing a fuzzy number into a crisp precise number that would represent the encountered problem. There are several methods that are used to defuzzify a fuzzy set. The max membership method is based on determining the element in the universe that has the maximum height. The centroid method is based on determining the center of gravity of the fuzzy sets. The weighted average method is based on weighting the output of each fuzzy set and multiplying it by its maximum value, and it is considered to be computationally efficient (Ross 2010). Several other methods are also used such as the mean max membership, the center of sums, the center of the largest area, and first/last of maxima.

2.5.2 The Analytic Network Process

Multi-criteria decision-making tools are used to help the decision maker in attaining an accurate decision especially when the information available might be uncertain or ambiguous. When comparing between alternatives or when trying to determine the importance of certain factors of a certain asset, the decision maker can judge effectively the factors according to intuition or expertise and therefore obtain fine results using the MCDM tools.

The Analytic Hierarchy Process, introduced by Saaty in the late 1960's, is a decision-making tool that can account for qualitative information (Büyükyazıcı and Sucu 2003). The AHP method utilizes a pairwise comparison matrix to result in ratio scales and therefore priorities based on the decision maker's judgments (Büyükyazıcı and Sucu 2003). It also models the problem as a single directional hierarchy in which interdependencies between different factors are not accounted. The Analytic Network Process (ANP), also introduced by Saaty, is a generalization of AHP that accounts for interdependencies and interaction between elements and alternatives in which a hierarchical structure is not a must. In AHP/ANP, pairwise comparisons between different elements or criteria belonging to the same group are performed using expert judgments. The importance of one factor over the other with respect to a main criterion or a common property is measured through individual judgments that can be done by experts or decision-makers. The ANP method works by first decomposing the problem and modeling it through a set of hierarchies or feedback networks. After deconstructing the problem, the method performs pairwise comparisons that result in the relative importance weights of the utilized elements. Local priorities can be determined through the pairwise comparison of the homogeneous elements with respect to their common property or criterion. After that, an unweighted supermatrix including the relative importance weight of each criterion is created. Furthermore, the ANP is extended from the AHP to include the weighted supermatrix to allow for interdependencies among different elements in the network. Finally, the weighted supermatrix is multiplied by itself until the limit supermatrix is reached where the final local priorities corresponding to the global ones are attained (Yang et al. 2008).

To determine the pairwise comparison, a questionnaire has to be distributed based on Saaty's (1-9) scale shown in the Table 2.15 below.

Table 2. 15 Pairwise Comparison - Saaty's Fundamental Scale

Importance	Degree of Importance	Explanation
1	Equal Importance	Two attributes with equal contribution to the objective
3	Moderate Importance	Judgment slightly favors one activity over the other
5	Strong Importance	Judgment strongly favors one activity over the other
7	Very Strong Importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme Importance	The evidence favouring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values that signify (Weak, Moderate Plus, Strong Plus, and (Very, Very Strong).	
Reciprocals	If activity *i* is given one of the above numbers representing its importance over another activity *j*, then *j* has the reciprocal value when compared with *i*.	

In performing the pairwise comparison, the reciprocal property in the AHP/ANP states that if an element x is given an importance of "j" when compared to element y, then element y can be given an importance of 1/j when compared to element x with respect to a common property. In performing the pairwise comparisons, it is important to check for the consistency property through calculating the consistency index (CI) and then the consistency ratio (RI) to test the judgments. The pairwise comparison matrix is said to be consistent if the CR is <0.1.

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

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

Where λmax is the largest eigenvalue in the pairwise comparison matrix and n is the matrix size.

The following table shows the average random consistency index values recommended by (Saaty et al. 2012).

Table 2. 16 Average random consistency index (R.I.) (Saaty et al. 2012)

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Random consistency index (R.I.)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

2.5.3 The Evidential Reasoning

Reasoning systems were created in an attempt to solve the drawbacks of probabilistic problems that are accompanied by ambiguity and incomplete information. Therefore, the certainty factor was created where it was applied to medical problems (Gordon and Shortliffe 2008). In order to manage problems with incomplete information presented in a hierarchical format, “A Mathematical Theory of Evidence” was started by Dempster and continued by Shafer resulting in the Dempster-Shafer (D-S) theory.

(i) The Dempster-Shafer Theory

The D-S theory surpasses other reasoning methods in its ability to conclude a problem and accumulate sources of evidence through studying and aggregating sets of hypothesis. It plays a significant role in handling and managing problems with uncertainty and incomplete information. The D-S theory of evidence comprises of the attribution of beliefs to the model's elements and the rule of combination to aggregate several pieces of evidence and information. In contrast to the Bayesian theory that would assign equal probabilities to the elements, the D-S approach tolerates assigning beliefs to elements in a manner similar to human reasoning in order to differentiate between uncertainty and incomplete information. Starting with the theory of evidence, a frame of discernment (Θ) is defined to be a set of mutually exclusive pieces of the hypothesis. The basic probability assignment (BPA) is an extended function of the probability mass distribution. The BPA is a number that ranges between (0, 1) representing the degree in which certain evidence supports a particular hypothesis in the frame of discernment (Gordon and Shortliffe 2008). All the subsets in the frame of discernment are assigned a value between (0, 1) in which their sum turns to be unity. Therefore, the hypothesis that is not supported by evidence (i.e. an empty set) is given a number of 0. The following formulas explain further the BPA (Bai et al. 2008):

$$\sum_{\Psi\subseteq\Theta} m(\Psi) = 1;\ m(\phi) = 0;\ \ 0 \leq m(\Psi) \leq 1 \qquad for\ all\ \Psi \subseteq \Theta \qquad [2.3]$$

Ψ = any subset of Θ

m (Ψ) = evidence that supports hypothesis Ψ

ϕ = empty set

Once all of the subsets are assigned a certain number from (0, 1) for the evidence of belief, the remaining unassigned total belief, denoted by m(Θ) = 1-∑ m (Ψ), is assigned to the whole frame of discernment Θ. The remaining value is also known as ignorance.

(ii) The Dempster-Shafer Rule of Combination

Aggregating information is a paramount step that aids in simplifying and summarizing the data acquired from one or more sources. The aggregation of the BPA's leads to the measures of belief (Sentz and Ferson 2002). The combination of two BPA's (m1 and m2) is calculated using the following equations (Bai et al. 2008):

$$m_{12}(\Psi) = m_1(\Psi) \oplus m_2(\Psi)$$

$$\sum_{A \cap B = \Psi} \frac{m_1(A) m_2(B)}{1-k} \; ; \; \Psi \neq \phi \; ;$$

$$K = \sum_{A \cap B = \Psi} m_1(A) m_2(B) \qquad [2.4]$$

The basic probability mass between two subsets A and B associated with the conflict is represented by the K-factor (Sentz and Ferson 2002). To avoid calculation complexity when combining several bodies of evidence, the rule of combination is used in a recursive manner.

(iii) The Hierarchical Evidential Reasoning (HER)

The HER method's algorithm is similar to that of the human's logical reasoning in daily life. It abstracts available data and creates simple pieces of the hypothesis that are synthesized to deduce eventually a logical and reasonable conclusion. It comprises of basic elements in which they are combined to form a narrower hypothesis for the attributes. The algorithm of the HER method works through the following set of equations:

Let "H" be the frame of discernment which in this research it is a set of linguistic variables for condition grades (Wang et al. 1995).

$$H = [H_1, H_2, H_3, \dots \dots, H_n, \dots \dots, H_N] \quad [2.5]$$

n = nth variable (Grade)

N = number of variables

To make it simple, consider a hierarchical model that comprises of a two level hierarchy with the 1st level named as attributes and the 2nd level named as elements. Then let Ej represent the elements corresponding to the jth attribute.

$$\mathrm{E}_j = [E_1, E_2, E_3, \dots \dots, E_{ji}, \dots \dots, E_{jL}] \quad [2.6]$$

L = Number of elements

These elements are assigned relative importance weights that can be determined by experts or through measurement techniques. Let "ω" be the relative importance weight corresponding to the ith element with $0 \leq \omega i \leq 1$ and $\sum_{i=1}^{K} \omega_i = 1$

$$\omega = [\omega_1, \omega_2, \omega_3, \dots \dots, \omega_i, \dots \dots, \omega_L] \quad [2.7]$$

The evaluation of a certain element E_{ji} denoted as P (Eji) is written in the following mathematical representation.

$$\mathrm{P}\left(E_{ji}\right) = \left(\frac{\mathrm{H}_n}{\beta_{n,i}}\right) \; ; \; \mathrm{n} = 1 \dots . \mathrm{N}; \; \beta_{n,i} \geq 0 \text{ and } \sum_{n=1}^{N} \beta_{n,i} \leq 1 \quad [2.8]$$

$\beta_{n,i}$ = The degree of confidence to which the evidence supports a certain hypothesis

Consequently, the basic probability assignment "$m(E_{ji})$" of a certain element Eji is calculated using the following formula:

$$m(E_{ji}) = P(E_{ji}) x \, \omega_i \quad [2.9]$$

(iv) Summarized Evidential Reasoning Algorithm

To assign the degrees of belief to different elements and aggregate the outcome, (Yang and Xu 2002)'s paper was consulted, and the following formulas were given.

After the degrees of beliefs ($\beta_{n,i}$) are assigned, the basic probability assignment ($m_{n,i}$) has to be discounted through the following equation:

$$m_{n,i} = \omega_i \beta_{n,i} \quad ; \quad n = 1, \ldots \ldots, N \qquad [2.9]$$

Then, the remaining probability mass ($m_{H,i}$) that is unassigned to any variable in the frame of discernment is calculated through the following equation:

$$m_{H,i} = 1 - \omega_i \sum_{n=1}^{N} \beta_{n,i} \quad ; \quad n = 1, \ldots \ldots, N \qquad [2.10]$$

Moreover, $m_{n,i}$ *and* $m_{H,i}$ can be deduced through combining $m_{n,j}$ *and* $m_{H,j}$ using the following equation:

$$m_{n,(i+1)} = K_{(i+1)}\left(m_{n,i}m_{n,i+1} + m_{n,i}m_{H,i+1} + m_{H,i}m_{n,i+1}\right) ; \ n = 1, \ldots\ldots, N \qquad [2.11]$$

$$m_{H,(i+1)} = K_{(i+1)}m_{H,i}m_{H,i+1} ; \ n = 1, \ldots\ldots, N \qquad [2.12]$$

$$K_{(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{j=1, j \neq t}^{N} m_{t,i}m_{j,i+1}\right]^{-1} ; \ i = 1, \ldots\ldots, L-1 \qquad [2.13]$$

$K_{(i+1)}$ = A normalizing factor in which $\sum_{n=1}^{N} m_{n,i+1} + m_{H,i+1} = 1$

When the aggregation of all elements is complete, the remaining unassigned degrees of belief are redistributed over the frame of discernment using the following formula:

$$\beta n = \frac{m_{n,i(L)}}{1 - \overline{m}_{H,i(L)}} ; n = 1, \ldots., N \qquad [2.14]$$

βn = Aggregated degree of belief

(v) Application of Evidential Reasoning

The evidential reasoning approach was applied to several real life problems especially those that include uncertainty of imperfect knowledge about the case. (Yang and Singh Madan 1994) applied the ER as an MADM tool to deal with uncertainty including qualitative and quantitative attributes of a certain problem. Moreover, the ER approach was applied to assess the safety of a complex engineering system by (Wang et al. 1995) through dividing this system into several hierarchical levels. According to (Yang and Xu 2002), the ER approach was applied to engineer design selection, safety and risk assessment, and supplier assessment type of decision-making problems. Also, (Bai et al. 2008) employed the (HER) to combine various distress indicators to assess the condition of buried pipes. In addition to that, the ER approach is applied by (Sönmez et al. 2002) to deal with the uncertainties due to lack of knowledge, expertise and time pressure problems involved in the contractor prequalification process.

2.5.4 K-Means Clustering Technique

The K-means clustering technique, created in 1956, divides "n" data points into "k" clusters through assuming a vector space formation of the data points (Zhang and Xia 2009). This technique has been used in the analysis of data and in finding patterns as used in data mining. This mathematical tool works by attempting to find the centroids of certain sets or clusters of data points. The Lloyd's algorithm in this clustering technique applies iterations to reach the end result. This algorithm follows the following steps as discussed by (Zhang and Xia 2009):

- Data points are separated into “k” preliminary sets. It can be done randomly or through experience and previous data.
- The centroid of each of the clusters is calculated.
- The data points are re-allocated to various clusters where new partitions are created.
- The centroid of each new cluster is re-calculated.
- The above steps are repeated until the data points remain in their clusters and therefore convergence is achieved.

According to (Zhang and Xia 2009), the Lloyd’s algorithm converges quickly which made it a widespread algorithm.

2.6 Summary and Limitations of Previous work

This chapter discussed the various inspection techniques used in sewer pipeline inspection. It also portrayed the current approaches in sewer pipeline condition assessment through studying and comparing the various types of sewer condition assessment protocols available in the current market. Moreover, it reviewed the previous research that was done on the condition assessment of sewer pipelines. In addition to that, this chapter discussed several MCDM tools including the fuzzy set theory, the analytic network process, the evidential reasoning technique, and k-means clustering technique.

In conclusion, most of the inspection techniques available are accompanied with a considerable amount of uncertainty due to lack of complete information, expertise, and human judgment. Therefore, it is crucial to define a new protocol that would account for the ambiguity and vagueness included in the condition assessment process. Through reviewing the MCDM tools, it has been clear that the fuzzy synthetic evaluation is an important technique that can account for subjectivity in quantifying distress indicators. Also, the Analytic Network Process is a technique used in decision-making that determines the alternatives with the highest priority in a certain problem. Moreover, the evidential reasoning approach is also reviewed in which it is known for its translation of imprecision into useful information through the accumulation of evidence to prove a hypothesis.

After studying the previous condition assessment protocols and previous academic research, some limitations with regards to condition assessment of sewer pipelines were deduced. Most of the currently used protocols assess the pipe's condition in a subjective manner due to poor accuracy in defining the distress indicators. The CCTV internal surveys of sewer pipes are highly dependent on the expertise of the inspector. Therefore, the human judgment in defining the defects is highly associated with uncertainty and incomplete data. Moreover, most of the protocols use the peak or the mean score for assessing the condition. Also, they do not take into consideration the effect of each defect to the whole pipeline's integrity. This leads to a subjective and uncertain assessment that does not take into account the extent of distress indicators and the effect of incomplete information on the pipeline's integrity. Additionally, most of the research and protocols do not take into consideration PACP's limitation of determining the impact of structural defects on the operational integrity of the pipeline. On the other hand, some of the researched work depends heavily on historical data and stochastic models. This approach might be beneficial in predicting the pipes' conditions but is inadequate to determine an accurate assessment of the pipes' conditions.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Overview

The following chapter provides an overview of the research methodology. It includes the flow chart of the research as well as the techniques used and data resources. The first type of data collected in this research is the defect types, natures, and severities. The second type is the relative importance weights of these defects. Moreover, this chapter discusses the utilized condition assessment scale, the model development, and the established condition assessment automated tool. The originality of this work is portrayed in the objective manner of classifying defects and in minimizing uncertainty through aggregation. Due to the criticality of sewer pipelines and due to their vital role in the family of infrastructure, it is crucial to consider comprehensively all the related defects to achieve a credible assessment algorithm. Therefore, this research explores the defects corresponding to sewer pipelines in an objective manner to address the subjectivity and uncertainty available in the current protocols.

In this research, the pipeline segment is divided into three principal components. It comprises of the pipeline (pipe length), the corresponding joints, and the manholes or access holes. Moreover, the defects in each component are classified into three defect categories (structural defects, operational defects, and installation / rehabilitation defects). Each defect category in turn is divided into several defect families in which these families are further split into their corresponding types. Consequently, the relative importance weights of these defects are developed through delivering online and hard copied surveys to experts and knowledgeable people in this topic. Also, to develop a unified condition assessment scale, the K-Means Clustering Technique is utilized. In addition to that, the defect severities are plotted on a Fuzzy diagram platform through which the degrees of belief of each of the defects are reasoned. Finally, the results are aggregated using the Hierarchical Evidential Reasoning Approach. This methodology is also translated into a practical automated tool to be utilized by the end users and facilitate their decision-making process.

3.2 Literature Review

An extensive and comprehensive amount of literature was reviewed throughout the progress of this work. This included, but was not limited to, the current practices in sewer pipeline inspection, current available protocols, and previous research in the field of sewer condition assessment. The literature review also comprised of studying several MCDM techniques along with their advantages, disadvantages, and applicability. This research took the available sewer pipeline condition assessment protocols as a baseline through which this study commenced and progressed further. Figure 3.1 represents a flow chart of the proposed methodology. It includes the conducted literature review, the model development (in details), automated tool, model testing, and case studies. To develop the model, many experts and companies were consulted. Also, data was collected from companies and municipalities in Canada and Qatar. Moreover, to complete the data collection process, surveys were sent out to experts in Canada and Qatar. Additionally, several existing protocols were consulted to check the current methods for quantifying the distress indicators and in assessing the overall pipeline's condition.

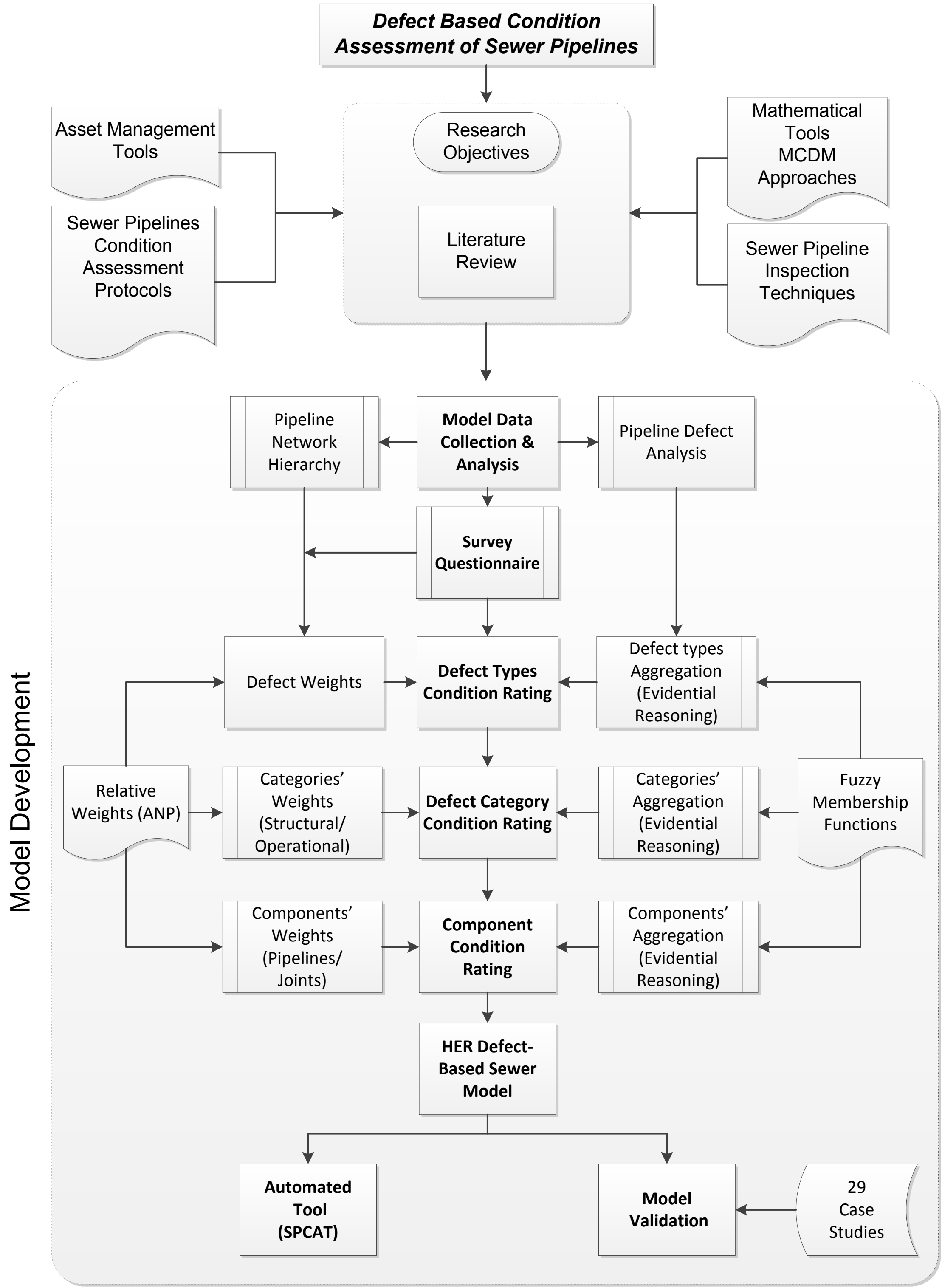


Figure 3. 1 Research Methodology-Flow Chart

3.3 Data Collection

In an attempt to fully comprehend the common used algorithm behind condition assessment of sewer mains, the protocols available in the market were consulted, and their data was analyzed. To develop the proposed model, these data had to be carefully tailored. The data collected is divided into three parts with the first one being the defect types and their descriptions, the second one being the defect severities, and the third one being the defect weights. Also, the condition assessment scales of the current approaches were studied in an attempt to develop a new condition assessment grading scale. Moreover, case studies in the form of inspection surveys from different companies and sources in Qatar and Canada were collected for model testing.

A structured questionnaire was distributed to experts including inspectors, practitioners, engineers, and managers in the field of sewerage in both Qatar and Canada. The questionnaire has been circulated in both, paper and online, to facilitate the survey process. Over 85 surveys were sent out in which 21 complete surveys were received.

3.4 Condition Assessment Scale

After reviewing the literature and current approaches, it has been evident that each protocol uses a grading scale that is different from other scales used by other protocols. Therefore, and in an attempt to create a standard grading scale, a new condition assessment scale was proposed. The suggested scale includes five grades, (Excellent, Good, Fair, Bad, and Critical).This scale comprises of linguistic assessment, a simple and an intermediate scale. It is also linked to a description of each grade as well as to the action required for that specific grade. In practice, this scale is beneficial for engineers, managers, and decision makers to select on maintenance, prioritization, and rehabilitation measures for pipeline segments.

3.5 Model Development

The developed model consists of three sub-models: Analytic Network Process Model, Fuzzy Synthetic Evaluation Model, and Evidential Reasoning Approach. To build the above mentioned model, the pipeline network was divided into sub-components (pipe segment, joints, manholes) in which all their corresponding defects were linked to different defect families (structural, operational, and installation / rehabilitation). Also, K-means clustering technique was utilized to develop a new condition assessment grading scale. The developed model follows the standard Fuzzy Synthetic Evaluation Process that comprises fuzzification, aggregation, and defuzzification. This model involves the assessment of pipelines through studying their components and defects. The assessments of all components and defects are then aggregated in a third sub-model.

3.5.1 The Analytic Network Process

This sub-model was created by first defining the goal (pipe segment) in which its overall condition will be affected by the defects and components' condition. This has been portrayed by a comprehensive defect hierarchy. After that, pairwise comparisons were conducted in three directions in order to apply the interdependency between criteria.

- Between Sub-criteria and each other
- Between Main-criteria and each other
- Between Main-criteria and the goal

The following steps describe the process of ANP utilization to determine the relative importance weights of defect types, their categories, and pipeline components.

1. Questionnaires were distributed online and by hand to obtain expert opinions for comparing criteria and sub-criteria in a pairwise manner using Saaty's Scale as described in Chapter 2.
2. An Excel Sheet was created to input the survey results, calculate the reciprocal values for other criteria, and determine the relative weights of each cluster with respect to its common property.
3. The consistency index and the consistency ratio were calculated using equations [2.1] and [2.2] to prove the consistency of the pairwise comparison of each sub-matrix.
4. Step number 3 is repeated for 41 different sub-matrices to cover all the components, defect categories, defect types, and defect descriptions.
5. The unweighted supermatrix was then developed including the interdependencies of sub-criteria with respect to each other, to the main criteria and each other, and main criteria and goal.
6. The unweighted supermatrix was checked with the unweighted supermatrix generated from the "SuperDecisions" software to check for consistency in the work done.
7. The weighted supermatrix was developed by dividing each value in the unweighted supermatrix by its respective column's total summation and it was also checked with the weighted supermatrix generated from the "SuperDecisions" software to check for consistency in the work done.
8. The limit supermatrix was generated using the "SuperDecisions" software.
9. The relative priorities of all the components, defect categories, defect types, and defect descriptions were generated using the "SuperDecisions" software. It must be

noted that the summation of weights of each sub-criterion with respect to its criteria is equal to unity.

3.5.2 Condition Assessment Grading Scale Development

To develop a unique, reasonable, and standard condition assessment grading scale, seven scales that are currently used were taken as the basis of the new scale. The technique employed in this development was the K-Means Clustering Technique. The data was inserted in terms of minimum and maximum values corresponding to each of the five grades (a common practice). Then K- Means Clustering was performed using MATLAB software in which the data values were assigned to different clusters. The model was created using the following steps:

1. The seven scales corresponding to different protocols were grouped.
2. The ranges of each of the scales were normalized by dividing each number by the maximum deduct value in the scale.
3. All the normalized values were inserted and defined as a data set.
4. The "K" value or number of clusters was chosen to be 5 (representing the five linguistic grades: *Excellent, Good, Fair, Poor, Critical*).
5. The code was run on MATLAB, and the results were transferred to an Excel Sheet.
6. The minimum and maximum normalized value of each cluster was taken as a range for each grade.
7. The values were multiplied by 10 to achieve a (0-10) scale.

3.5.3 Fuzzy Membership Functions

Fuzzy membership functions of distress indicators are employed in this model to encode the defects to condition rating. Since this translation of defects is imprecise by nature and are subject to a vast amount of error due to imperfect knowledge and human subjectivity, fuzzy membership functions were utilized to minimize this uncertainty. This model was created through the following steps:

1. Condition assessment grades were defined as fuzzy sets (subsets of the universe).
2. Defect severities were deduced from literature to be used as defect thresholds (universe in a Fuzzy Membership Function).
3. The defect severities were distributed over the five linguistic graded condition assessment scale established in earlier stages.
4. The thresholds (severities) were fuzzified with respect to their common property.
5. Triangular distributions were used since only the upper and lower boundaries of each subset are known.
6. Fuzzy membership functions were created for all defects.
7. The developed condition assessment scale was also fuzzified into the five linguistic grades (subsets).

3.5.4 Evidential Reasoning Approach

The HER approach was used in this research to account for the uncertainty accompanied with encoding the distress indicators to condition grades. The HER approach was first applied on the defects level using the steps stated below.

1. The criteria (quantified defects) from the CCTV survey were used to enter the previously developed fuzzy membership functions of each defect.
2. The degrees of beliefs ($\beta_{n,i}$) extracted from the fuzzy membership function were assigned to each of the available defects over the five linguistic grades (frame of discernment- Θ).
3. The defects' weights (ω_i), deduced from ANP, were assigned to their corresponding defects as shown in Table 5.16.
4. The degrees of beliefs of each of the defects were discounted by their corresponding weights to get the basic probability assignments using ($m_{n,i}$) equation [3.1].
5. The remaining probability mass ($m_{H,i}$) that is unassigned to any of the condition grades was calculated for each defect using equation [3.2].
6. The normalizing "K" value, representing the conflict between the basic probability masses of the condition grades of the two defects was calculated using equation [3.3].
7. The aggregated degree of belief [$m_{n,(i+1)}$] between any two defects (e.g. Circumferential and Longitudinal) was calculated using equation [3.4]. Also, its remaining unassigned probability [$m_{H,(i+1)}$] was calculated using equation [3.5].
8. After that, the combined degrees of belief for the first two defects obtained in step 7 are combined with the third defect (e.g. Multiple) to achieve the aggregated condition of defects.
9. Steps 7&8 were repeated till all of the defects under one category (e.g. Crack) are aggregated as shown in Table 5.16.
10. After aggregating all of the defects recursively, the remaining unassigned degrees of belief were redistributed over the condition grades using equation [3.6].

11. The same ten steps were applied for each defect group (e.g. Crack, Fracture, Surface Damage…etc.) of each component.
12. The structural defects of each component were first aggregated (using the above ten steps) to determine the structural condition of that component (Pipeline, Joint, or Manhole). The same was done for operational and installation/rehabilitation conditions of each component.
13. The structural, operational, and installation conditions of each component were also combined (using the above ten steps) to determine the component's condition.
14. The final step was to aggregate the pipeline, joint, and manhole's condition altogether (using the above ten steps) to determine the whole segment's condition.

For a more clarified image of the aggregation flow, please consult Table 5.17.

$$m_{n,i} = \omega_i \beta_{n,i} \quad [3.1]$$

$$m_{H,i} = 1 - \omega_i \sum_{n=1}^{N} \beta_{n,i} \quad [3.2]$$

$$K_{(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{j=1, j\neq t}^{N} m_{t,i} m_{j,i+1}\right]^{-1} \quad [3.3]$$

$$m_{n,(i+1)} = K_{(i+1)} \left(m_{n,i} m_{n,i+1} + m_{n,i} m_{H,i+1} + m_{H,i} m_{n,i+1}\right) \quad [3.4]$$

$$m_{H,(i+1)} = K_{(i+1)} m_{H,i} m_{H,i+1} \quad [3.5]$$

$$\beta n = \frac{m_{n,i(L)}}{1 - \overline{m}_{H,i(L)}} \quad [3.6]$$

3.5.5 Defuzzification and Model Test

After obtaining the aggregated degree of belief in terms of percentages to each condition grade, this output has to be defuzzified to suit the usage of decision-makers. Therefore, the results were defuzzified using the weighted average method of the fuzzy set theory. The defuzzification in this model was done on the structural, operational, and installation conditions for each component. Also, the combined degrees of belief of the three components were defuzzified to compute the overall condition using equation 5.1.

Model testing is a major step in proving and obtaining the model's credibility. Therefore, a case study obtained from Qatar involving a whole network of pipelines was applied and the results were compared.

3.6 Integrated Condition Assessment Model

The developed model is built utilizing the common fuzzy synthetic evaluation envelope that includes fuzzification, aggregation, and defuzzification. It also includes other models utilized as complementary models such as the ANP model, and the K-means clustering model. Therefore, in this model, the defect hierarchies were developed in which their relative importance weights to their corresponding attributes and components were obtained using the Analytic Network Process. Furthermore, the K-Means clustering technique was utilized in an attempt to create a unified and standard condition assessment grading scale that current practices lack. Also, defect severities are prolonged into the developed five graded linguistic scale in which membership functions were created to depict the fuzzification of these severities. Moreover, and to fulfill the aggregation task, the hierarchical evidential reasoning was utilized. Outputs from the fuzzy membership model were used as inputs in the developed evidential reasoning model. Finally, all the sub-factors, factors, attributes, and components were integrated to result in the aggregated degree of belief representing the whole pipeline.

Additionally, and since a certain pipeline's condition cannot be described as a percentage of a linguistic grade (0.4 Good, 0.5 Fair, 0.1 Unknown), it has to be transitioned into a crisp value to be utilized by practitioners, engineers, managers, and decision makers. In conclusion, the resulting crisp value was entered into a developed protocol that includes a simple scale, moderate scale, linguistic descriptions, defect examples, and action required for each condition grade to assist decision makers in rehabilitation and maintenance decisions.

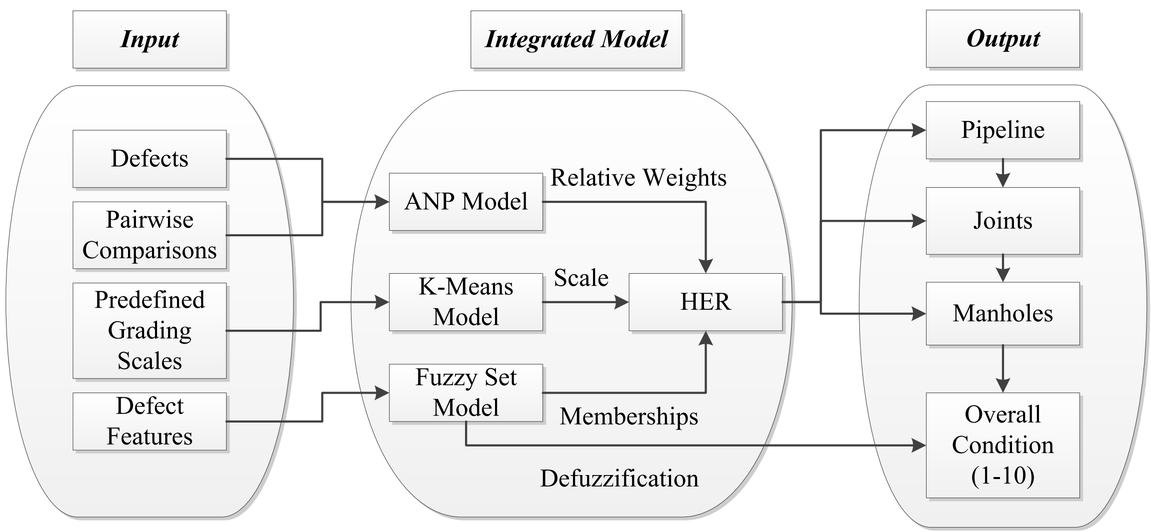


Figure 3. 2 Integrated Model Flowchart

3.7 Sewer Condition Assessment Automated Tool (SPCAT)

The Sewer Pipeline Condition Assessment automated tool consists of three defect families to assess the condition of the sewer components namely, pipelines, joints and manholes through which the overall condition of the pipeline can be deduced. The developed tool is a user-friendly interface that aids the user in obtaining the respective conditions through incorporating the defects obtained from Closed Circuit Television (CCTV) surveys. It was developed through Microsoft Excel, and Visual Basic in which the fuzzy membership functions of each defect, the ANP weights, the developed scale, and the defuzzification approach are all incorporated in this model. It is also linked to the action required tab in which it provides the user with the recommended action corresponding to the selected segment. Moreover, the user can enter the pipeline's details and characteristics in a predefined list through which the results can be saved into a database as a registry for maintenance and future inspection/assessment.

3.8 Summary

This chapter focuses on the research methodology adopted to perform the condition assessment model for sewer pipelines. In brief, the model development passed several stages. Starting with the arrangement of distress indicators that are manifestations of various factors, several defect hierarchies corresponding to different defect categories and pipeline components were created. Following that, K-means clustering technique was utilized to create a unified sewer condition grading scale that ranges between (0-10) with 0 being best and 10 representing a critical situation. Moreover, the analytic network process model was developed to obtain the defects and components weights. The ANP is also used to account for the interdependency between sub-criteria to main criteria, main criteria and each other, and main criteria with respect to the goal. Furthermore, fuzzy synthetic evaluation plays an important role in encoding the distress indicators into condition ratings with the appointment of severities as the universe of discourse thresholds of the available subsets (x-axis in fuzzy membership functions). Consequently, the hierarchical evidential reasoning approach is used through utilizing the defect hierarchies as a guide to the aggregation process in which all defects, defect categories, and components are integrated to result in the overall pipe condition.

CHAPTER FOUR: DATA COLLECTION

4.1 Introduction

To commence the research, several sources of had to be consulted for different types of information. To begin, a list of sewer pipeline condition assessment protocols were consulted in an attempt to comprehend the algorithm behind the pipelines condition assessment. Also, several previous researches were studied in which this model was built upon them. The types of data collected in this research are classified into three types (Defect Types, Components and Defect Weights, and Defect Severities) as shown in the following chart:

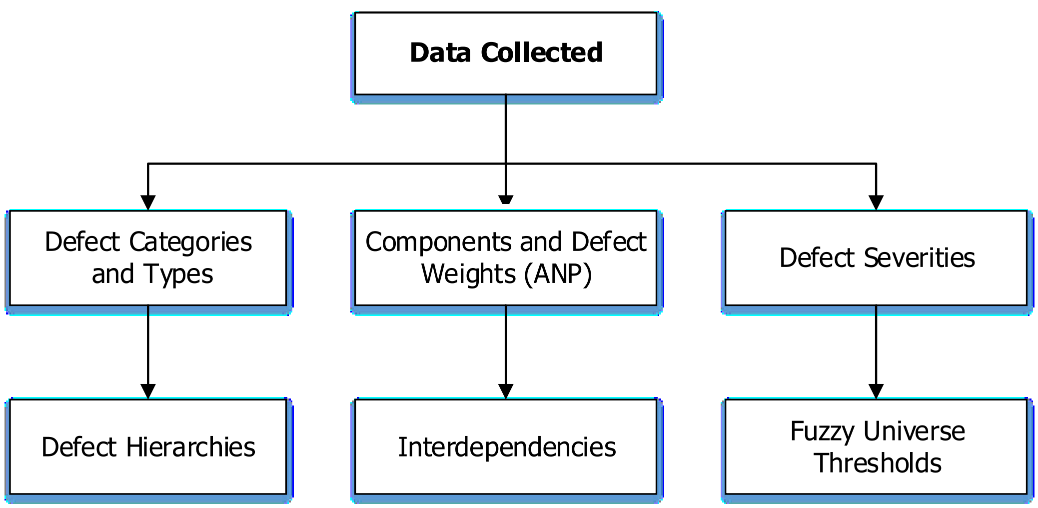


Figure 4. 1 Types of Data Collected

4.2 Defect Categories and Types

This section presents the defect categories, their types, and descriptions related to pipe segments, joints, and manholes based on literature and previous work.

4.2.1 Pipe Segment Defects

The following section contains structural, operational, and installation / rehabilitation defect types adopted from the different available protocols (WRc 2013; Centre for

Expertise and Research on Infrastructures in Urban Areas (CERIU) 2004; Grondin 2012). Since some defects are named differently in different protocols, the defects used in this research will be used as defined in this chapter

(i) Pipe Segment Structural Defects

The structural defects in a pipe segment are used to interpret the pipe's physical condition and their severity. The structural defects are divided into cracks, fractures, holes, surface damages and many more as illustrated in Table 4.1 & 4.2.

Table 4. 1 Pipe Segment Structural Defects

Defect Category	Defect Type	Description
Structural	Crack	A visible crack line in which the pipe wall is not noticeably broken apart
	Fracture	It is the next level of a crack when it becomes noticeably open while the pipe pieces are still in place
	Longitudinal	A defect is considered longitudinal if it breaks in a longitudinal direction on the axis of the pipe.
	Circumferential	A defect is considered circumferential if it breaks in a circles forming a right angle with the sewer axis
	Multiple	A defect is considered multiple if there is a combination of the longitudinal, circumferential, and spiral defects in a relatively small area.
	Spiral	A defect is considered spiral if it changes positions along its run throughout the axis of the sewer pipe. Usually, spiral defects do not cross joints.
	Radiating	A defect is considered radiating if it projects from one point forming a star shape.
	Broken	Parts of the pipe are visibly apart and are not in their primary place, e.g: ½*Pipe thickness or more
	Hole	A defect is classified as "hole" when there is a noticeable hole in the pipe wall
	Sag/Buckling	A bend in the body of the pipe due to pressure

Table 4. 2 Pipe Segment Structural Defects (continued)

Defect Category	Defect Type	Description
Structural	Deformed	A noticeable change in the original cross-section of the pipe. Deformation is measured as a percentage of the actual width (horizontal deformation) or height (vertical deformation) of the pipe
	Collapse	The pipe is said to be collapsed if 50% of more of the cross section is broken in which the pipe completely damaged and cannot be used
	Increased Roughness	Slightly worn surface
	Spalling	Breaking of the surface material into small pieces usually due to expansion of corroded reinforcement or poor material. It is usually a associated with fracture
	Aggregate Visible	When the surface is seriously worn out that aggregates become noticeable
	Aggregate Projecting	When the aggregate is projecting over the pipe's surface
	Aggregate Missing	When small holes occur due to missing aggregates
	Reinforcement Visible	It occur when there is adequate missing aggregate that causes the reinforcement to be visible
	Reinforcement Projecting	When the reinforcement is noticeably projecting over the concrete surface
	Reinforcement Corroded	It is when the damage is due to a visible corrosion and is represented by missing reinforcement parts
	Corrosion	Example is rust if the pipe is metal or chemical attack on concrete such as H_2S (Hydrogen Sulfide).

(ii) Pipe Segment Operational Defects

The operational defects in a pipe segment are used to describe the pipe's ability to comply with its service requirements through indicating the capacity loss or blockage (WRc 2013). The operational defects are divided into roots, leakage, and deposits in which each is divided into its different characteristics to indicate their severity as illustrated in Table 4.2.

Table 4. 2 Pipe Segment Operational Defects

Defect Category	Defect	Description
Operational	***Roots***	When roots from adjacent trees intrude through certain structural defects in the pipe length. Roots enter from structural defects such as fractures, and holes
	Fine Roots	Roots that lead to a reduced flow through blocking the pipe's area
	Single Roots	A single root in which its thickness is more than 10 mm which would damage the pipe.
	Dense Roots	Combined roots that might block the whole pipe's cross section
	Leakage	Leakage is separated into two parts. One is infiltration, which is the intrusion of groundwater through a defect. The other is exfiltration, which is the seeping of sewer flow out of the pipe through a certain defect
	Seeping	A defect is said to be seeping if it is intruding in a slow pattern
	Dripping	A defect is said to be dripping if water is dripping but not continuously
	Running	A defect is said to be running if water is intruding in a continuous manner
	Gushing	A defect is said to be gushing if water is intruding in a pressure-like manner
	Deposits	Deposits are separated into two parts. The first is attached deposits, which is the attachment of materials on pipe surface. The second type is the settled deposits, which is the settling of deposits on the pipe surface that could reduce the flow capacity
	Encrustation	Encrustation is formed by the effect of evaporating infiltrated water throughout defects along the pipe
	Foul	Attached deposits which are remains of foul sewage
	Grease	Attached grease above the flow on the sewer walls
	Soil intrusion	It is the intrusion of surrounding soil into the pipe through certain structural defects
	Protruding Services	Some pipe materials that would be lying in pipe bottom surface causing a reduction in the capacity

(iii) Pipe Segment Installation and Rehabilitation Defects

The following section explains the installation defects that happen during the pipeline's construction. The defects explained in Table 4.3 (defective connection, lining, and repair) are studied to determine their effect on the sewer pipeline.

Table 4. 3 Pipe Segment Installation and Rehabilitation Defects

Defect Category	Defect	Description
Installation & Rehabilitation	Defective Connection	The available connection is intruding into the pipe length blocking the flow, or the connection is damaged or blocked
	Defective Lining	The available lining is defective such as having a missing section or distance with the pipe wall or any other sort of lining failure
	Defective Repair	Any repair that has been applied on the sewer pipe length and has been defective again

4.2.2 Joint Defects

The following section contains structural and operational defect types adopted from the different available protocols (WRc 2013; Centre for Expertise and Research on Infrastructures in Urban Areas (CERIU) 2004; Grondin 2012).

(i) Joint Structural Defects

This section describes the defects that affect the structural integrity of the joints themselves. Defective joints may affect the pipeline's structural and operational integrity due to the intrusion of soil, deposits, and water. Table 4.4 presents the defects associated with the joints (Open Joint, Non-Concentric Joint, and Defective joint).

Table 4. 4 Joint Structural Defects

Defect Category	Defect	Description
Structural	Open Joint	The defect is said to be open joint when two adjacent pipe lengths are longitudinally separated (distant joints)
	Non-Concentric Joint	The defect is said to be off-centered joint when two the joints of two adjacent pipes are not concentric
	Defective Joint	A damage in the joint due to poor handling during or after construction

(ii) Joint Operational Defects

This section describes the defects that affect the structural integrity of the joints themselves. Defective joints may affect the pipeline's structural and operational integrity due to the intrusion of soil, deposits, and water. Table 4.4 presents the defects associated with the joints.

Table 4. 5 Joint Operational Defects

Defect Category	Defect	Description
Operational	Roots	When roots from adjacent trees intrude through certain structural defects in the joint
	Leakage	Leakage is separated into two parts. One is infiltration, which is the intrusion of groundwater through the joint. The other is exfiltration, which is the seeping of sewer flow out of the pipe through the joint
	Deposits	Deposits are separated into two parts. The first is attached deposits, which is the attachment of materials on the joint. The second type is the settled deposits, which is the settling of deposits on the joint that could reduce the flow capacity
	Soil intrusion	It is the intrusion of surrounding soil into the pipe through the joint
	Protruding Services	Some pipe materials that would be lying in the invert level causing a reduction in the capacity

4.2.3 Manholes Defects

This section only contains the defects associated with manholes. For other structural and operational defects, the previously defined descriptions were used as it will be portrayed in throughout the research. The following defect descriptions presented in Table 4.6 were adopted from (WRc 2001; Zhao et al. 2001; WRc 2013).

Table 4. 6 Manhole Defects

Defect Category	Defect	Description
Installation & Rehabilitation	Defective Benching	The benching in the manhole is defective
	Defective Channel	The channel in the manhole is defective
	Defective Ladder	The ladder in the manhole suffers from corrosion, bending, rust, missing anchors, and/or cross-section loss)
	Defective Landing	The landing in the manhole suffers from corrosion, bending, rust, missing anchors, and or cross-section loss)
	Defective Connection	The connection suffers from gaps, infiltration and leakage, and/or fractures
	Frame Damage	Corrosion of manhole frame, rust, loose anchors, deformation.
	Cover Damage	Cover is corroded, cracked, broken.
	Pavement Damage	Pavement is cracked, has large bumps, spalled, or has holes.

4.3 Components and Defects' Weights (ANP)

As mentioned earlier, the analytic network process was used to determine the components and defects' weights. It has also been used in specific to account for the interdependency between sub-criteria, criteria and each other. To do that, questionnaires were distributed both using an online tool and a hard copy format.

4.3.1 Online Website

A website using "Google Sites" was created to accommodate a proper description about the survey. It also included a brief explanation of the research's objectives. Moreover, a detailed explanation of the components and defect types was presented to make the user familiar and to clarify any ambiguities that might result. Consequently, another platform was created using "Survey Expression" survey tool to allow the user to perform pairwise comparisons as requested. Figure 4.2 shows a snapshot of the survey website (https://sites.google.com/site/sewerconditionsurvey/).

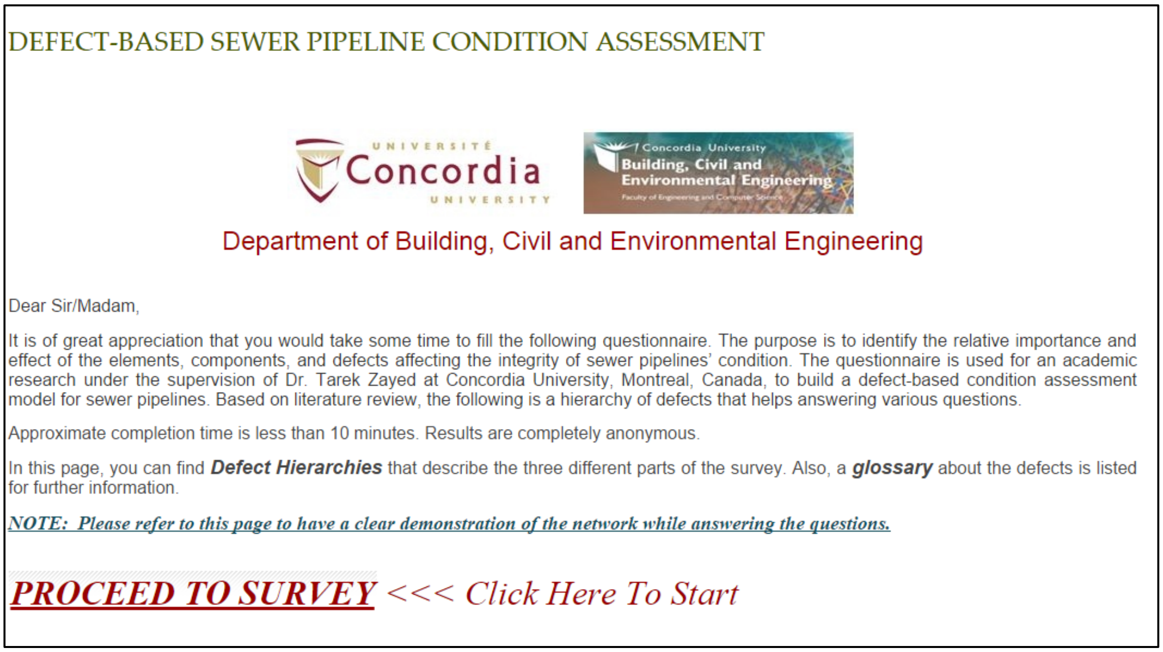
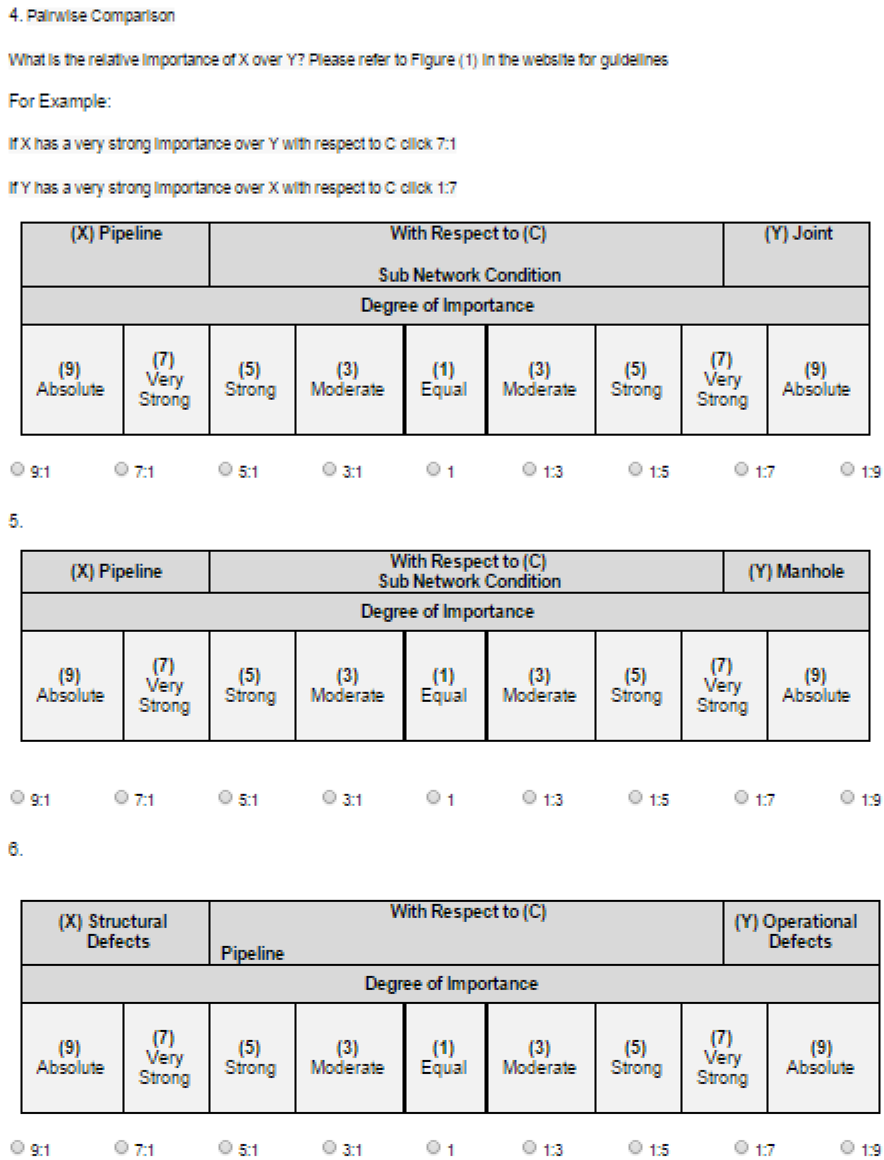


Figure 4. 2 Sewer Pipeline Condition Assessment Website

4.3.2 Online Survey

Both surveys (Online and Hardcopy) consisted of four parts with a total of 62 questions. The general question was in the format of "What is the relative importance of element (X) over an element (Y) with respect to element (C). The first part included a general pairwise comparison of the components and defect categories with respect to the goal to determine their interdependencies. The second part included pairwise comparisons with respect to the pipe segment's condition. The third part compared the joint defects and defect categories. The final part included pairwise comparisons with respect to the manhole's condition. A sample of the online survey questions is provided in Figure 4.3.



4. Pairwise Comparison

What is the relative importance of X over Y? Please refer to Figure (1) in the website for guidelines

For Example:

If X has a very strong importance over Y with respect to C click 7:1

If Y has a very strong importance over X with respect to C click 1:7

(X) Pipeline			With Respect to (C) Sub Network Condition					(Y) Joint
Degree of Importance								
(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute
9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9

5.

(X) Pipeline			With Respect to (C) Sub Network Condition					(Y) Manhole
Degree of Importance								
(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute
9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9

6.

(X) Structural Defects			With Respect to (C) Pipeline					(Y) Operational Defects
Degree of Importance								
(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute
9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9

Figure 4. 3 Sample of Online Survey Questions

4.3.3 Hard Copy Survey

A hardcopy survey with same questions and partitions as of the online survey was also distributed to professionals to facilitate the process. A sample of the survey is provided in Figure 4.4. A full copy of the hardcopy survey can be found in Appendix C.

PART (2): PAIRWISE COMPARISON

In an attempt to determine the degree of importance of factors affecting the sewer pipelines' condition, kindly fill the tables in the next pages by ticking (✓) in the appropriate box from your point of view:

*Example: In the table below, consider comparing "**Pipeline**" (Criterion X) with "**Joints**" (Criterion Y) with respect to the "**Sub Network Condition**".*

Sub Network											
	← Degree of Importance →										
Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)	Remarks
Pipeline										Joint	
										Manhole	

If you consider that "Pipeline" is more important than "Joint" and the degree of this importance is "Strong" then tick (✓) here

If you consider both "Pipeline" and "Joint" have "Equal" importance; then tick (✓) here

If you consider the "Joint" is more important than "Pipeline" and the degree of importance is "Absolute" then tick (✓) here

*The same procedure is then followed when comparing "**Pipeline**" with "**Manhole**".*

1) **Pairwise Comparison Between Elements and Components with respect to Goal:**

With respect to "**Sub Network Condition**" how important is criterion "X" or "Y" when compared to each other?

	← Degree of Importance →										
Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)	Remarks
Sub Network Condition											
Pipeline										Joint	
										Manhole	
Pipeline											
Structural Defects										Operational Defects	
										Installation & Rehab. Defects	
Joints											
Structural Defects										Operational Defects	
Manholes											
Structural Defects										Operational Defects	
										Installation & Rehab. Defects	
Pipeline											
Joint										Manhole	
Joint											
Pipeline										Manhole	
Manhole											
Pipeline										Joint	

Figure 4. 4 Hard Copy Survey

4.3.4 Responses

The survey was sent to more than 85 experts, managers, and engineers in the sewer/drainage engineering and construction area around Canada, and Qatar as properly portrayed in Tables 4.7 & 4.8. Also, the survey involved professionals working in infrastructure research centres such as CERIU, PACP, and others. Moreover, 63.2% of the respondents working in companies that offer sewer condition assessment services were managers whereas 36.8 were engineers as shown in Figure 4.5. Also, Figure 4.6 shows the categories of the respondents and their corresponding percentages. Only 21 questionnaires were received from the distributed samples in which 2 were neglected. The industrial experience of the respondents ranged from 10 to 20 years or more. The below tables and pie charts reflect the respondents' characteristics.

Table 4. 7 Collected Surveys

Surveys	Number
Sent	>85
Received	21
Disregarded	2
Considered	19

Table 4. 8 Survey Respondents

Respondents	Qatar	Canada
Engineers	6	1
Managers	8	4
Total	14	5

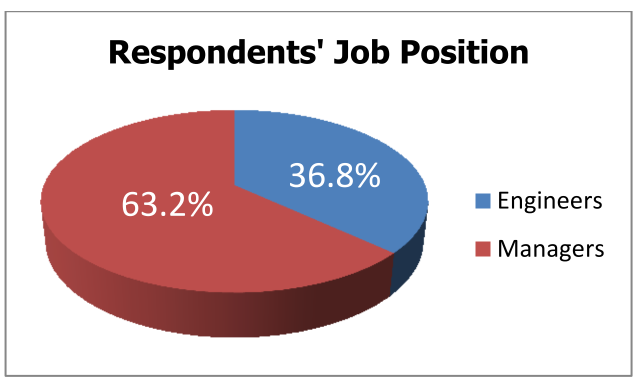


Figure 4. 5 Respondents' Job Position

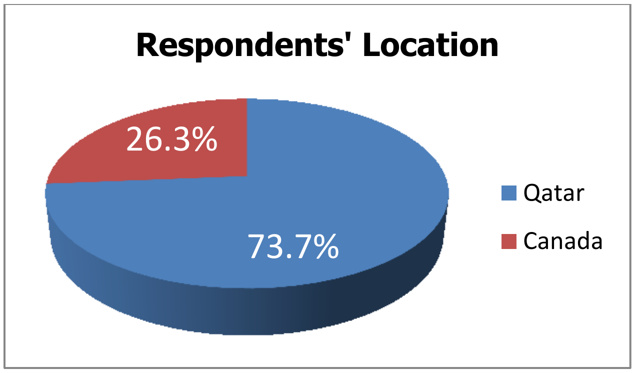


Figure 4. 6 Respondents' Location

4.4 Defect Severities

Defect severities were collected from several sources of information such as (WRc 2001; Grondin 2012; Zhao et al. 2001; Khazraeializadeh 2012; Centre for Expertise and Research on Infrastructures in Urban Areas (CERIU) 2004). The defect severities were collected to represent the universe of discourse in the fuzzy membership functions. The user can enter the fuzzy membership charts with these severities and consequently obtain the degrees of belief. The severities of the defects were also altered and edited to suit the developed condition grading scale as it will be shown in the model development chapter. Therefore, new divisions of defect severities and their classifications are proposed to serve the model objectives and its applicability. These severities also serve as a methodology to quantify the distress indicators through a defect dependent set of criteria as shown in Tables 5.9 to 5.14.

4.5 Sewer CCTV Inspection Reports

Several CCTV inspection reports were collected from companies around Montreal, Canada, and "The Public Works Authority- Ashghal" in Qatar. The CCTV reports were used as case studies in which the developed model was implemented on for verification and testing purposes. A sewer network in Qatar consisting of 21 pipelines, constructed prior to the year of 1966, with a total inspection length of 1325.71 meters was implemented in the case study. Also, a network of 15 pipelines in Montreal with a total inspection length of 1056.4 meters was implemented as well.

4.6 Summary

This chapter presents the data collection methodology implemented during this course of study. First the defect categories and types were investigated and well comprehended. Second, surveys were distributed to professionals to obtain credible pairwise comparisons for obtaining the defects and components weights. Moreover, the defect severities were collected from various sources to be used in the fuzzy set model. Finally, CCTV reports were collected from sewer inspection companies and authorities across Canada and Qatar for model implementation and testing.

CHAPTER FIVE:
MODEL IMPLEMENTATION AND TESTING

5.1 Introduction

This chapter illustrates the application of the above-explained techniques to the developed model through results, case studies, and analysis. First, the constructed defect hierarchy of the pipeline components and their defects is presented. After that, the pipeline's relative importance weights are discussed and analyzed. The relative weights include those of the pipeline's components, defect categories, and defect types. Additionally, the developed condition grading assessment scale is demonstrated. Furthermore, this chapter presents the fuzzy membership functions that correspond to the pipeline's defects. Consequently, the aggregation process is explained through examples along with the defuzzification process. Finally, this chapter is concluded with the implementation of the case studies, as well as the model's verification, and testing.

5.2 Model Hierarchies

To represent the pipeline network and provide a hierarchy to apply the models mentioned beforehand, the model is divided into three main components (Pipeline, Joints, and Manholes) each of which has two or more defect categories as shown in Figure 5.1. The pipeline (also named as pipe segment) serves as the pipe between two consecutive manholes (entry/exit). Each segment consists of one manhole, usually the entry one. Joints serve as the connection points of several pipes. Moreover, the manholes are top access points of the underground facility in which a pipe segment lies in between.

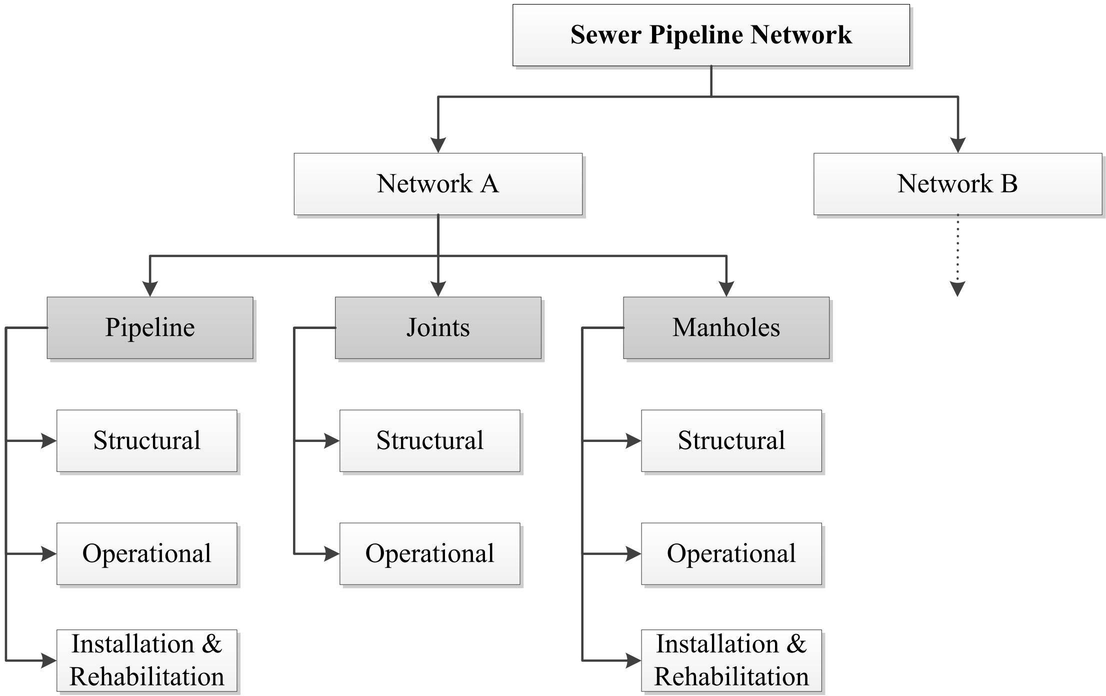


Figure 5. 1 Sewer Pipeline Network Hierarchy

5.2.1 Pipeline Defect Hierarchy

To evaluate the pipe segment, the defects associated with the pipe length were divided into structural, operational, and installation defects as illustrated in Figure 5.2. The structural defects are the defects that affect the physical condition of the pipe length. The service defects are the ones that would affect the pipe's serviceability and capacity. On the other hand, the installation and rehabilitation defects cover the defects that are due to construction or repair. The pipeline defects include cracks, fractures, surface damages, deposits, infiltration, and several more.

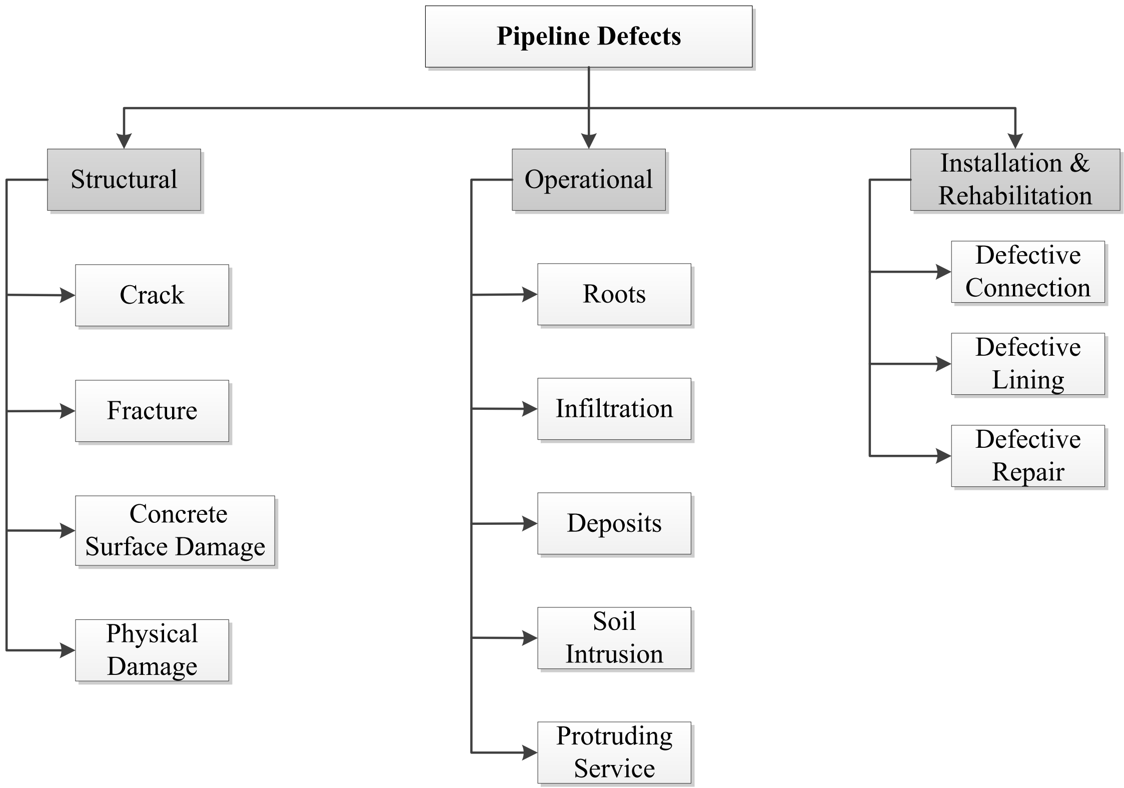


Figure 5. 2 Pipeline Defect Hierarchy

(i) Pipeline's Structural Defects

To further evaluate the structural condition of the pipeline, its structural defects were divided according to their types and severities as shown below. The defects were grouped into four groups including cracks, fractures, concrete surface damage, and physical damage to the pipeline. Each of these groups was further divided into defect types as shown in Figure 5.3. For example, cracks and fractures are divided according to their types and orientation throughout the pipeline whereas the surface damage is split according to its severity.

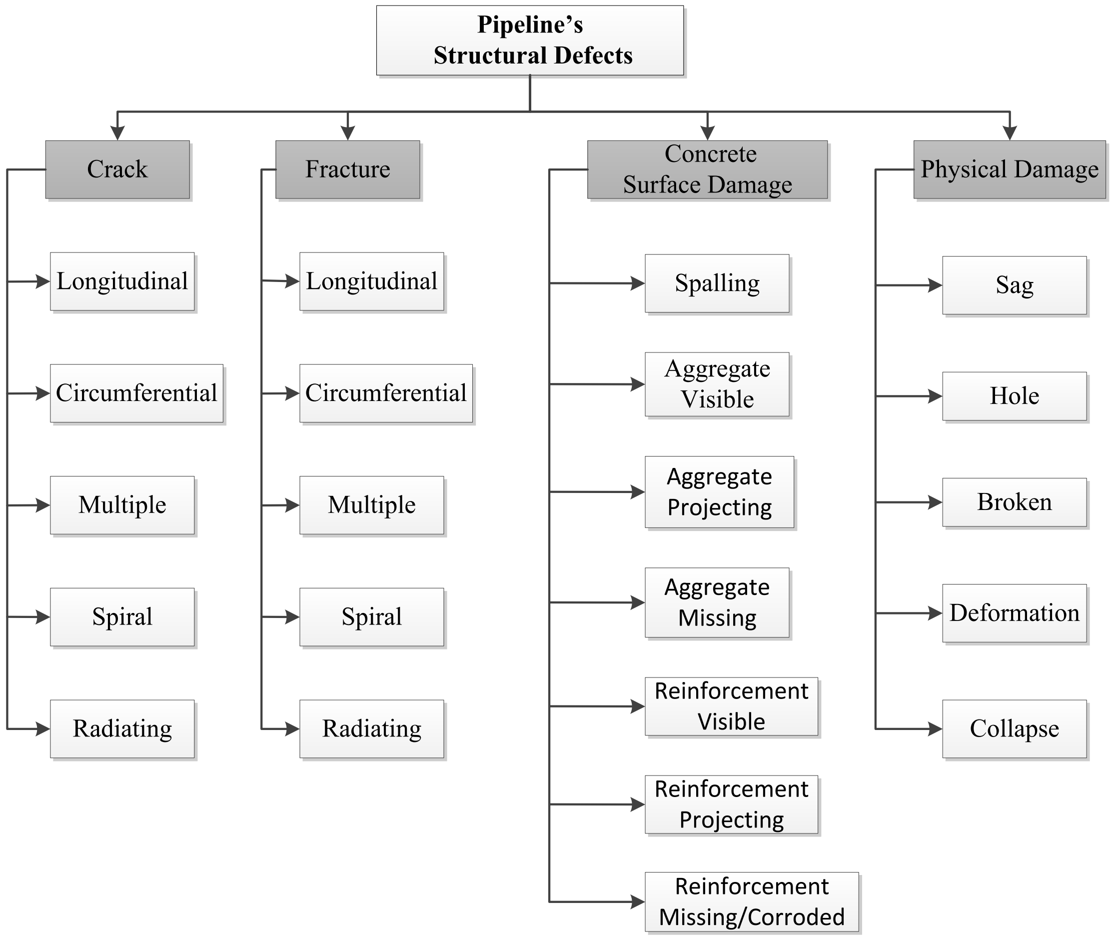


Figure 5. 3 Pipeline's Structural Defects

(ii) Pipeline's Operational Defects

In order to have a comprehensive assessment of the operational condition of the pipeline, the defects relating to its serviceability were divided into roots, infiltration, deposits, soil intrusion and protruding services such as an intruding connection. Furthermore, each of these defects was divided into their corresponding degradations as shown in Figure 5.4.

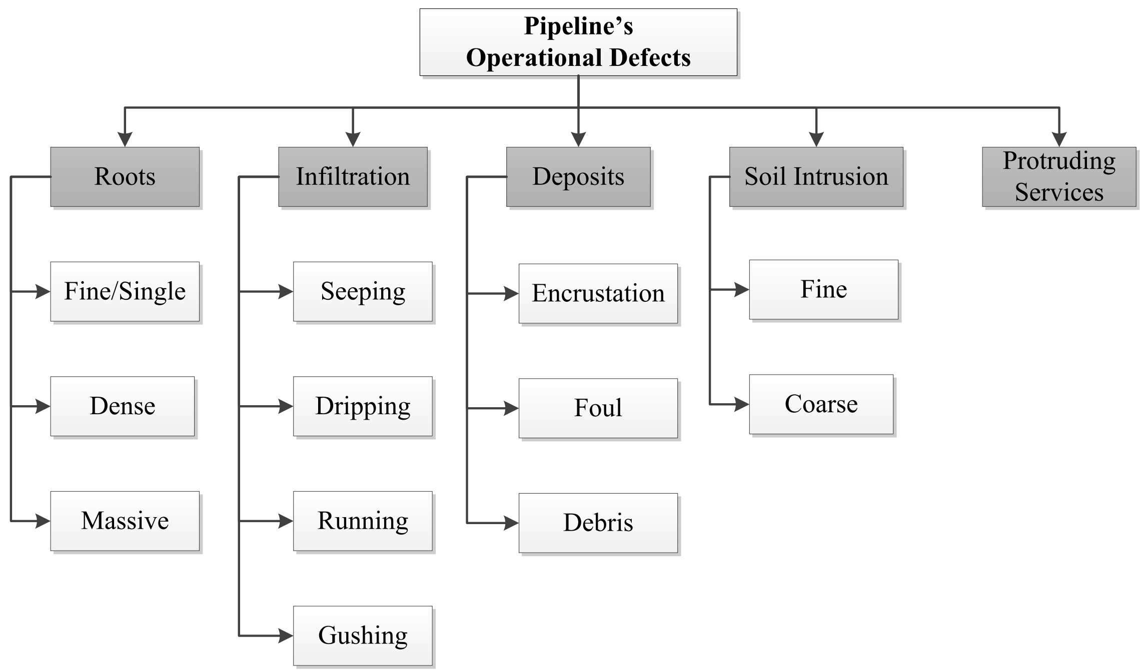


Figure 5. 4 Pipeline's Operational Defects

5.2.2 Joint Defect Hierarchy

The joint plays a significant role throughout the pipe segment as it links it to other pipe segments and connections as well. Therefore, its condition should be well assessed to prevent infiltration and to maintain a firm link between the pipes. The defects in the joint component of the pipeline were also branched into structural and operational defects. The following defects, shown in Figure 5.5, indicate the deficiencies that occur at the joints' areas of the pipeline. The open joint defect signifies any longitudinal opening in the joint that makes the pipe segments distant from each other as shown in Figure 5.6. The non-concentric joint is a defect in which the pipelines' centers are not meeting. Other joint defects are also available throughout the body of research. For the joints operational defects, please consult the pipeline operational defects' hierarchy shown in Figure 5.4.

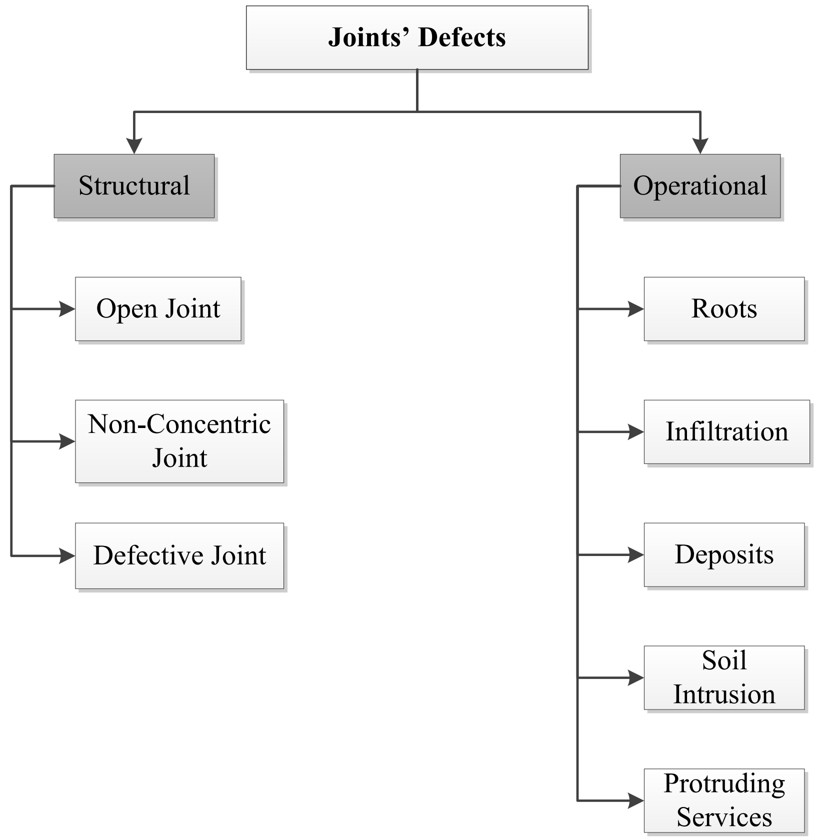


Figure 5. 5 Joint Defect Hierarchy

Figure 5.6 shows an example of an open joint defect in which the "O" Ring is not in place.

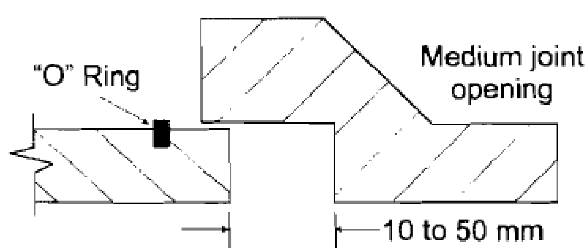


Figure 5. 6 Longitudinal Joint Opening (Zhao et al. 2001)

5.2.3 Manhole Defect Hierarchy

Manholes play a major role in a sewer segment. Manholes serve as access holes for inspection and maintenance requirements. They are also the meeting point of sewer segments. Therefore, it is of vital importance to develop a comprehensive assessment of the manholes condition as it is the entrance to an essential infrastructural facility. The manhole's defects in this research were divided into structural, operational, and installation and rehabilitation defects in which each defect category is subdivided into its defect types as shown in Figure 5.7. It is can be noticed that the manhole defects are similar to those of the pipeline but differ in the defect types and orientations.

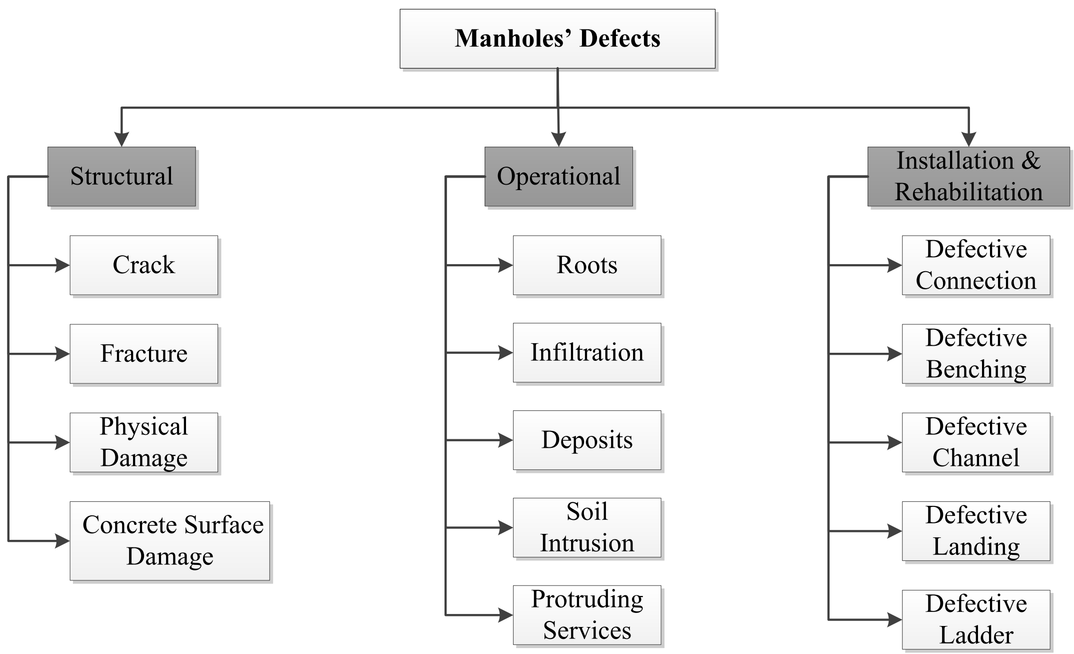


Figure 5. 7 Manholes Defect Hierarchy

(i) Manhole's Structural Defects

The structural defects associated with an access hole contain cracks, fractures, concrete surface damages, and physical damages such as frame and cover damages. These defects are further divided into their corresponding subdivisions. Unlike the pipeline's structural defects, the cracks and fractures in the manhole are described to be in vertical or horizontal position. Moreover, the physical damages include frame, cover, and pavement damages that are exterior to the manhole but have a significant effect to its structural condition. A typical manhole is shown in Figure 5.8 to make it easy to comprehend the associated defects presented in Figure 5.9.

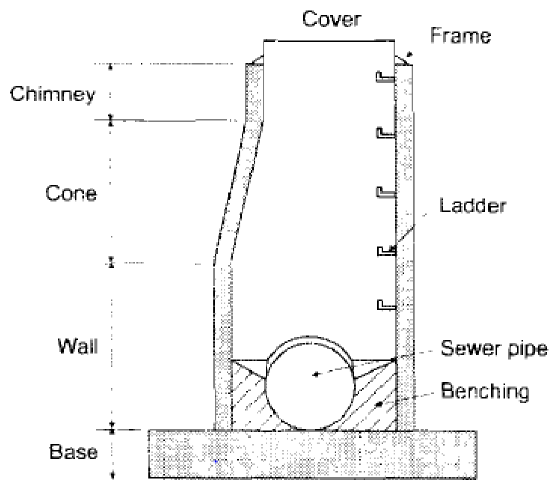


Figure 5. 8 Elevation View of Typical Access Holes (Zhao et al. 2001)

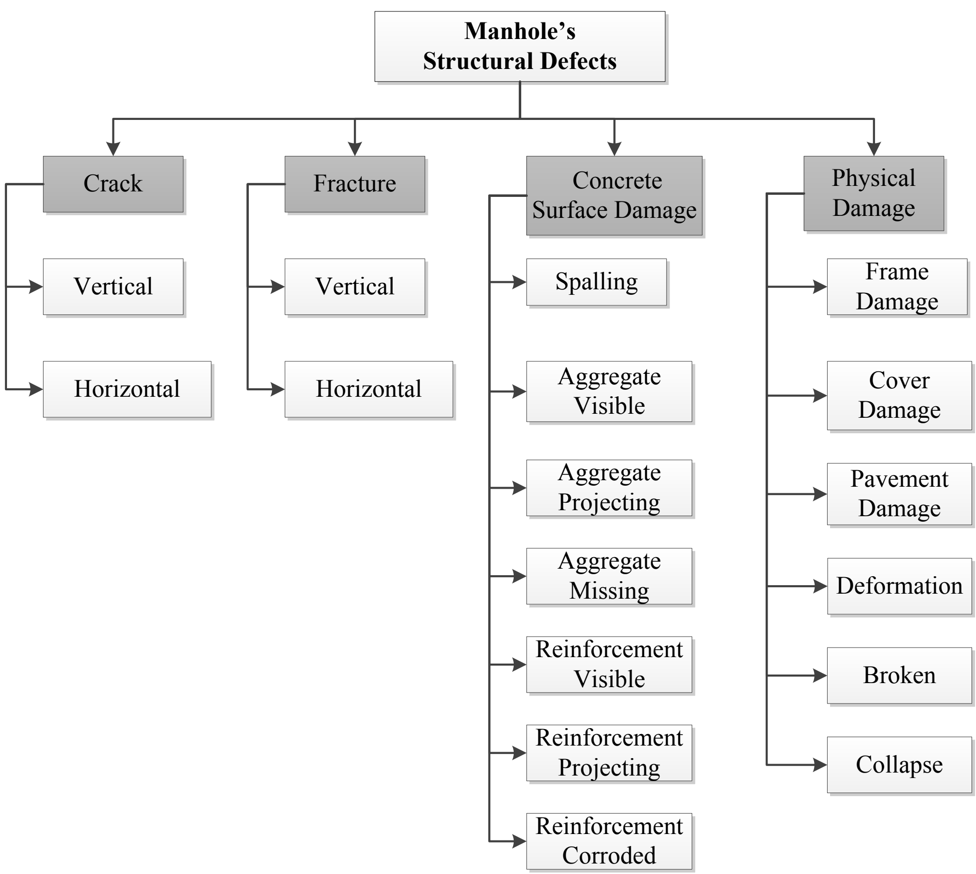


Figure 5. 9 Manhole Structural Defects' Hierarchy

5.3 Pipeline Model's Relative Importance Weights (ANP)

The Analytic Network Process was used to determine the relative importance weights of the components, defect categories, and defect types using the developed hierarchy shown in Figure 5.10. The surveys considered in this analysis are 19. The defect's weights were averaged in which the average weight was used in the aggregation model. Due to the large number of defects, the limit supermatrix was calculated with the aid of "SUPER DECISIONS" software. After that, the final priorities of each component, defect category, and defect type were calculated and presented in this chapter.

5.3.1 Components Relative Importance Weights

Table 5.1 shows that experts in Qatar and Canada have similar beliefs when it comes to which pipeline component affects the whole pipeline. It shows that the pipeline and the joints have equal weights of 38 %, whereas the manhole has a weight of 24%. These results are logical since the joints and the pipe's body would drastically affect the pipe's condition if found defective. The following chart (Figure 5.11) shows the relative weights for each pipe component in regards to two groups of experts. Each component was divided into its corresponding defect categories, types, and descriptions. After that, the three components were linked together to determine their relative weights with respect to the segment's condition. Each of the components was distinguished by a certain color to make it easier to follow.

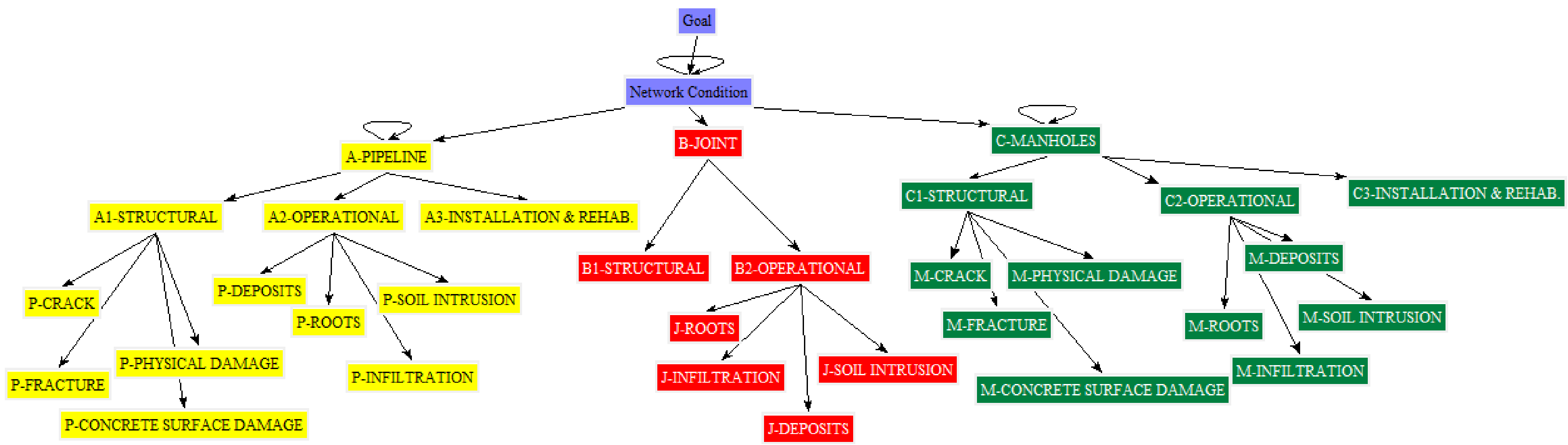


Figure 5. 10 Super Decisions Model

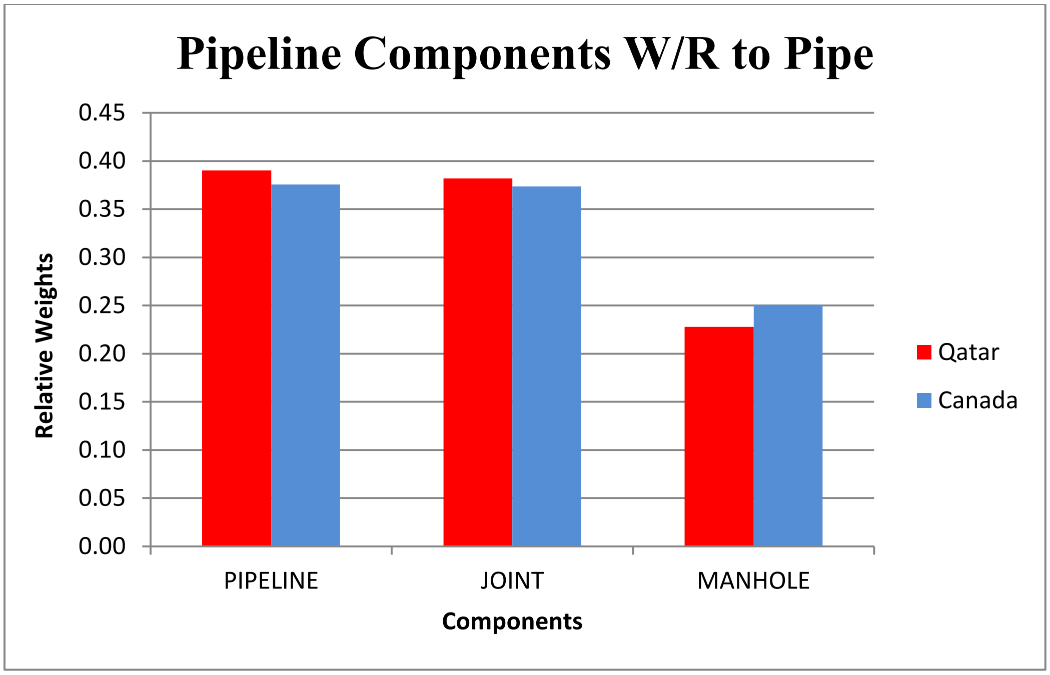


Figure 5. 11 Components Relative Weights Comparison

Table 5. 1 Relative Weights of Segment Components

Segment Components	**Results**				
	Qatar	Canada	Average	% Difference	Standard Deviation
PIPELINE	0.39	0.38	0.38	3.86	0.01
JOINT	0.38	0.37	0.38	2.16	0.00
MANHOLE	0.23	0.25	0.24	9.60	0.01

5.3.2 Pipeline Relative Importance Weights

When it comes to the pipe segment's defect weights, results in Table 5.2 show that the structural defects have a priority (40%) higher than other types of defects. This result is reasonable as the structural defects can lead to operational defects and more. Also, the ANP technique used here accounts for the interdependencies of the structural defects and vice-versa which determines the effect of structural defects on operational defects and vice-versa. Moreover, in the structural defects category the physical damages were given the highest weight with 0.47, and cracks were given the least with 0.06 weight. These results are logical since the cracks and fractures would be in the early stages of any structural defect that would later deteriorate into physical damages and consequently collapse. For the operational defects on the other hand, "protruding services" defect had the highest relative weight of 28%. This result is reasonable since protruding services may reduce the capacity of the pipeline and therefore reduce the pipeline's serviceability in general. It is noticed that experts in Qatar gave the protruding services 44% of importance. However, Canadian experts gave the same defect 11% of importance in which the highest priority was given to infiltration (29%). This is due to the difference in experience and beliefs in regards to which defect affects the pipeline's operational condition more severely. It is important to consider both opinions as it bridges between both experiences and produces better results. The detailed relative importance weights of the whole model are presented in Table 5.2.

Table 5. 2 Relative Weights of Pipeline Defects

Pipeline Defect Categories/Elements	**Respondents**				
Defect Categories	Qatar	Canada	Average	% Difference	Standard Deviation
STRUCTURAL	0.39	0.40	0.40	1.19	0.00
OPERATIONAL	0.26	0.24	0.25	8.03	0.01
INSTALLATION & REHABILITATION	0.35	0.37	0.36	4.19	0.01
Structural Defect Family					
Structural Defects	Qatar	Canada	Average	% Difference	Standard Deviation
CONCRETE SURFACE DAMAGE	0.30	0.29	0.30	3.78	0.01
CRACK	0.05	0.08	0.06	53.21	0.02
FRACTURE	0.15	0.18	0.16	14.48	0.01
PHYSICAL DAMAGE	0.50	0.45	0.47	9.82	0.02

Table 5. 2 Relative Weights of Pipeline Defects (continued)

Pipeline Defect Elements	Respondents				
Structural Defect Types					
Crack Defects	Qatar	Canada	Average	% Difference	Standard Deviation
CIRCUMFERENTIAL	0.08	0.11	0.10	30.74	0.01
LONGITUDINAL	0.08	0.07	0.07	15.92	0.01
MULTIPLE	0.43	0.38	0.41	13.70	0.03
RADIATING	0.28	0.25	0.27	9.05	0.01
SPIRAL	0.13	0.19	0.16	38.87	0.03
Fracture Defects	Qatar	Canada	Average	% Difference	Standard Deviation
CIRCUMFERENTIAL	0.08	0.14	0.11	59.84	0.03
LONGITUDINAL	0.09	0.06	0.08	39.39	0.01
MULTIPLE	0.50	0.27	0.39	58.94	0.11
RADIATING	0.24	0.29	0.26	17.87	0.02
SPIRAL	0.09	0.24	0.16	89.02	0.07
Physical Damage Defects	Qatar	Canada	Average	% Difference	Standard Deviation
HOLE	0.31	0.22	0.27	34.21	0.05
COLLAPSE	0.45	0.42	0.43	6.36	0.01
DEFORMATION	0.12	0.19	0.15	48.23	0.04
BROKEN	0.09	0.11	0.10	23.72	0.01
SAG	0.03	0.05	0.04	46.86	0.01
Concrete Surface Damage Defects	Qatar	Canada	Average	% Difference	Standard Deviation
AGGREGATE MISSING	0.14	0.14	0.14	2.88	0.00
AGGREGATE PROJECTING	0.10	0.15	0.13	35.29	0.02
AGGREGATE VISIBLE	0.05	0.11	0.08	66.60	0.03
REIN. CORRODED	0.27	0.23	0.25	19.45	0.02
REIN. PROJECTING	0.20	0.19	0.19	6.83	0.01
REIN. VISIBLE	0.20	0.16	0.18	19.38	0.02
SPALLING	0.03	0.03	0.03	8.78	0.00

Table 5. 2 Relative Weights of Pipeline Defects (continued)

Pipeline Defect Elements	Respondents				
Operational Defect Family					
Operational Defects	Qatar	Canada	Average	% Difference	Standard Deviation
INFILTRATION	0.19	0.29	0.24	42.50	0.05
PROTRUDING SERVICES	0.44	0.11	0.28	117.08	0.16
ROOTS	0.21	0.17	0.19	18.05	0.02
SOIL INTRUSION	0.11	0.22	0.16	68.39	0.06
DEPOSITS	0.06	0.21	0.14	106.42	0.07
Operational Defect Types					
Infiltration Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DRIPPING	0.16	0.14	0.15	8.27	0.01
GUSHING	0.47	0.51	0.49	7.26	0.02
RUNNING	0.33	0.30	0.31	9.22	0.01
SEEPING	0.05	0.05	0.05	11.61	0.00
Roots Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DENSE	0.33	0.33	0.33	0.10	0.00
FINE/SINGLE	0.08	0.06	0.07	19.90	0.01
MASSIVE	0.59	0.61	0.60	2.17	0.01
Soil Intrusion Defects	Qatar	Canada	Average	% Difference	Standard Deviation
COARSE	0.75	0.77	0.76	2.29	0.01
FINE	0.25	0.23	0.24	7.21	0.01
Deposits Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DEBRIS	0.29	0.21	0.25	31.02	0.04
ENCRUSTATION	0.58	0.63	0.61	7.37	0.02
FOUL	0.13	0.16	0.15	21.71	0.02
Installation and Rehabilitation Defect Family					
Installation and Rehab. Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DEFECTIVE CONNECTION	0.24	0.25	0.25	3.84	0.00
DEFECTIVE LINING	0.47	0.44	0.46	6.42	0.01
DEFECTIVE REPAIR	0.29	0.31	0.30	6.65	0.01

5.3.3 Joints Relative Importance Weights

The results of the joints' weights extraction (shown in Table 5.3) portray that the structural defects corresponding to the joints' condition outweigh the operational defects with a weight of 61% compared to a 39%. The following result is justified by taking into consideration that any defect such as an open joint might lead to infiltration, exfiltration, and intrusion of roots and soil materials. Therefore, the structural condition can be classified as more important than the operational condition to the joints' wellbeing. For the structural defects, the defective joint has the highest priority with a weight of 48%.

Table 5. 3 Relative Weights of Joints' Defects

Joint Defect Categories/Elements	**Respondents**				
Defect Categories	Qatar	Canada	Average	% Difference	Standard Deviation
STRUCTURAL	0.55	0.67	0.61	18.45	0.06
OPERATIONAL	0.45	0.33	0.39	28.87	0.06
Structural Defect Family					
Structural Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DEFECTIVE JOINT	0.52	0.45	0.48	14.62	0.04
NON-CONCENTRIC JOINT	0.15	0.22	0.19	38.16	0.04
OPEN JOINT	0.33	0.33	0.33	0.21	0.00
Operational Defect Family					
Operational Defects	Qatar	Canada	Average	% Difference	Standard Deviation
INFILTRATION	0.19	0.29	0.24	41.83	0.05
PROTRUDING SERVICES	0.46	0.16	0.31	96.90	0.15
ROOTS	0.16	0.16	0.16	1.85	0.00
SOIL INTRUSION	0.11	0.31	0.21	94.87	0.10
DEPOSITS	0.08	0.08	0.08	1.06	0.00
Operational Defect Types					
Infiltration Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DRIPPING	0.15	0.14	0.15	5.53	0.00
GUSHING	0.47	0.51	0.49	6.89	0.02
RUNNING	0.32	0.30	0.31	8.74	0.01
SEEPING	0.05	0.05	0.05	3.14	0.00

Table 5. 3 Relative Weights of Joints' Defects (continued)

Joint Defect Elements	**Respondents**				
Roots Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DENSE	0.34	0.33	0.34	0.86	0.00
FINE/SINGLE	0.07	0.06	0.07	12.25	0.00
Soil Intrusion Defects	Qatar	Canada	Average	% Difference	Standard Deviation
COARSE	0.77	0.83	0.80	7.32	0.03
FINE	0.23	0.17	0.20	29.09	0.03
Deposits Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DEBRIS	0.26	0.28	0.27	6.48	0.01
ENCRUSTATION	0.61	0.60	0.60	2.61	0.01
FOUL	0.13	0.13	0.13	1.38	0.00

5.3.4 Manholes Relative Importance Weights

When considering the manholes' defects, the structural defects, with a weight of 37%, outweigh the rest of the defects. Consequently, the installation defects come in second place (32%) and operational with least effect on the overall manholes' condition with a weight of 30%. This is tied back to the idea of structural defects arising on the pavement level them a higher priority. The detailed weights of manholes' defects are shown in Table 5.4.According to experts in Qatar; the installation defects have a higher priority than the operational defects. On the contrary, the Canadian experts believe otherwise.

Table 5. 4 Relative Weights of Manhole's Defects

Manholes Defect Categories/Elements	**Respondents**				
Defect Categories	Qatar	Canada	Average	% Difference	Standard Deviation
STRUCTURAL	0.37	0.38	0.37	1.94	0.00
OPERATIONAL	0.24	0.37	0.30	44.67	0.07
INSTALLATION & REHABILITATION	0.39	0.25	0.32	44.44	0.07

Table 5. 4 Relative Weights of Manhole's Defects (continued)

Manholes Defect Elements	**Respondents**				
Structural Defect Family					
Structural Defects	Qatar	Canada	Average	% Difference	Standard Deviation
CONCRETE SURFACE DAMAGE	0.31	0.29	0.30	7.86	0.01
CRACK	0.06	0.08	0.07	32.33	0.01
FRACTURE	0.17	0.19	0.18	8.91	0.01
PHYSICAL DAMAGE	0.46	0.45	0.46	3.11	0.01
Structural Defect Types					
Concrete Surface Damage Defects	Qatar	Canada	Average	% Difference	Standard Deviation
AGGREGATE MISSING	0.14	0.11	0.13	23.65	0.02
AGGREGATE PROJECTING	0.10	0.11	0.11	9.45	0.01
AGGREGATE VISIBLE	0.06	0.13	0.10	70.92	0.03
REIN. CORRODED	0.26	0.23	0.25	13.03	0.02
REIN. PROJECTING	0.20	0.19	0.19	7.09	0.01
REIN. VISIBLE	0.20	0.16	0.18	19.65	0.02
SPALLING	0.03	0.06	0.04	77.60	0.02
Crack Defects	Qatar	Canada	Average	% Difference	Standard Deviation
HORIZONTAL	0.32	0.47	0.40	37.68	0.08
VERTICAL	0.68	0.53	0.60	25.08	0.08
Fracture Defects	Qatar	Canada	Average	% Difference	Standard Deviation
HORIZONTAL	0.36	0.46	0.41	23.19	0.05
VERTICAL	0.64	0.54	0.59	16.16	0.05
Physical Damage Defects	Qatar	Canada	Average	% Difference	Standard Deviation
BROKEN	0.20	0.24	0.22	17.95	0.02
COLLAPSE	0.47	0.37	0.42	24.30	0.05
COVER DAMAGE	0.08	0.08	0.08	6.39	0.00
DEFORMATION	0.11	0.16	0.14	31.96	0.02
FRAME DAMAGE	0.09	0.08	0.09	14.66	0.01
PAVEMENT DAMAGE	0.04	0.07	0.06	62.95	0.02

The results also show that the vertical cracks and fractures are always superior to the horizontal ones with percentages of (60% to 40%). Also, it is noticed that the pavement, frame, and cover damages arising from physical defects have similar weights.

Table 5. 4 Relative Weights of Manhole's Defects (continued)

Manholes Defect Elements	Respondents				
Operational Defect Family					
Operational Defects	Qatar	Canada	Average	% Difference	Standard Deviation
INFILTRATION	0.19	0.23	0.21	17.70	0.02
PROTRUDING SERVICES	0.42	0.12	0.27	112.25	0.15
ROOTS	0.17	0.25	0.21	38.32	0.04
SOIL INTRUSION	0.11	0.20	0.16	54.89	0.04
DEPOSITS	0.11	0.20	0.15	62.72	0.05
Operational Defect Types					
Infiltration Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DRIPPING	0.16	0.14	0.15	8.28	0.01
GUSHING	0.47	0.51	0.49	7.26	0.02
RUNNING	0.33	0.30	0.31	9.20	0.01
SEEPING	0.05	0.05	0.05	11.53	0.00
Roots Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DENSE	0.35	0.33	0.34	5.09	0.01
FINE/SINGLE	0.06	0.06	0.06	6.92	0.00
Soil Intrusion Defects	Qatar	Canada	Average	% Difference	Standard Deviation
COARSE	0.76	0.83	0.80	9.34	0.04
FINE	0.24	0.17	0.20	36.49	0.04
Deposits Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DEBRIS	0.27	0.22	0.24	20.19	0.02
ENCRUSTATION	0.61	0.62	0.61	1.24	0.00
FOUL	0.13	0.17	0.15	28.30	0.02
Installation and Rehabilitation Defect Family					
Installation and Rehab. Defects	Qatar	Canada	Average	% Difference	Standard Deviation
DEFECTIVE BENCHING	0.21	0.18	0.20	16.59	0.02
DEFECTIVE CONNECTION	0.28	0.27	0.28	3.98	0.01
DEFECTIVE LADDER	0.12	0.10	0.11	15.23	0.01
DEFECTIVE LANDING	0.09	0.21	0.15	81.78	0.06
DEFECTIVE CHANNEL	0.30	0.24	0.27	21.97	0.03

The installation defect weights show that the defective connection in a manhole is the defect that would have the most effect on the manhole's installation condition. Also, the Canadian experts believe that the defective ladder has a valuable impact on the manhole's condition. However, the experts from Qatar believe that the landing's effect on the manhole's condition is minimal giving it a weight of 9%.

5.4 Condition Assessment Scale

In an attempt to create a novel, unified, and standard condition assessment scale to be employed in a standard condition assessment model, the K-means clustering technique was utilized. The existing limitation in current condition assessment grading scales is that each and every sewer condition assessment protocol utilizes its unique scale in its assessment. This issue created difficulties when converting from one protocol to another since a grade in one protocol would refer to another grade in another protocol, and therefore it would be misleading. To solve this problem, seven existing condition grading scales were collected (for both structural and operational defects) from current protocols and approaches as shown in Table 5.5. Moreover, the values of each grade corresponding to each protocol were normalized to deal with a similar set of numbers ranging from (0-1). After that, the number of clusters (condition grades) was chosen to be five to follow the current market protocols. A code was written in MATLAB to perform the recursive analysis of choosing the centroids (cluster values in this case). To do that, the values were duplicated to have enough data and therefore get better results. Tables 5.5 – 5.6 show the seven grading scales and their values. The scales used to develop the proposed scale were the WRc (structural and operational), PACP, SCREAM, New Zealand (structural and operational), ASCE ((structural and operational), NRC (structural and operational), and one more scale extracted from a published paper.

Table 5. 5 Sewer Condition Grading Scales

Condition Grade	WRc Str.	WRc Op.	PACP	SCREAM Score	New Zealand	New Zealand Op.	ASCE Str.	ASCE Op.	NRC Str.	NRC Op.	(Tagherouit et al. 2011)
1	0-10	0-1	1	1-20	0-2	0-3	1-4	1-2	1-4	1-2	0-5
2	10-39	1-2	2	21-40	2-15	3-7	5-9	3-4	5-9	3-4	5-30
3	40-79	2-5	3	41-60	15-30	7-15	10-14	5-6	10-14	5-6	30-60
4	80-164	5-10	4	61-80	30-50	15-30	15-19	7-8	15-19	7-8	60-95
5	165+	10+	5	81-100	50+	30+	20	9-10	20	9-10	95-100

Table 5. 6 Normalized Sewer Condition Grading Scales

Condition Grade	WRc Str.	WRc Op.	PACP	SCREAM Score	New Zealand Str.	New Zealand Op.	ASCE Str.	ASCE Op.	NRC Str.	NRC Op.	(Tagherouit et al. 2011)
1	0-0.06	0-0.1	0-0.2	0.01-0.2	0-0.04	0-0.1	0.05-0.2	0.1-0.2	0.05-0.2	0.1-0.2	0-0.05
2	0.06-0.24	0.1-0.2	0.2-0.4	0.21-0.4	0.04-0.3	0.1-0.23	0.2-0.45	0.3-0.4	0.2-0.45	0.3-0.4	0.05-0.3
3	0.24-0.48	0.2-0.5	0.4-0.6	0.41-0.6	0.3-0.6	0.23-0.5	0.1-0.7	0.5-0.6	0.1-0.7	0.5-0.6	0.3-0.6
4	0.48-0.99	0.5-1	0.6-0.8	0.61-0.8	0.6-1	0.5-1	0.75-0.95	0.7-0.8	0.75-0.95	0.7-0.8	0.6-0.95
5	1+	1+	0.8-1	0.81-1	1+	1+	1+	0.9-1	1+	0.9-1	0.95-1

Data was inserted in terms of the minimum, maximum of all provided protocol ranges for all condition grades, then the K-mean clustering approach was applied using MATLAB. The values were assigned to different clusters according to Lloyd's algorithm in which the min and max was taken for each cluster as its range. In a final step, the ranges were multiplied by 10 to result in an intermediate scale which can also be linked to the simple (1-5) scale as shown in Table 5.7.

Table 5. 7 Novel Condition Assessment Scale

Clusters	Range(Min-Max)	Scale
1	0-0.1	**0-1**
2	0.1-0.3	**1-3**
3	0.3-0.6	**3-6**
4	0.6-0.8	**6-8**
5	0.8-1.0	**8-10**

5.5 Data Fuzzification

As discussed before, the main limitation in CCTV inspection surveys and consequently in the current protocols remains as the subjective grading of defects. This subjectivity attributes a considerable amount of ambiguity, incomplete information, and uncertainty. To control this lack of data and minimize uncertainty, the fuzzy membership functions were applied and the distress indicators were encoded to degrees of beliefs supporting each of the condition grades. This process is done through employing the defect severities as the universe of discourse (x-axis) in the fuzzy membership functions. To do that, these severities are related into certain subsets belonging to the frame of discernment (Grading Scale) as shown in Tables 5.8 to 5.14.

5.6 Defect Severities

The defect severities in this model were divided according to the defect types and their corresponding components. For example, the pipeline defects are divided into structural, operational, and installation defect types and severities. The same is done for other components such as joints and manholes. The defect severities shown in Tables 5.8 to 5.14 were collected from several sources of information such as (WRc 2001; Grondin 2012; Zhao et al. 2001; Khazraeializadeh 2012; Centre for Expertise and Research on Infrastructures in Urban Areas (CERIU) 2004). Moreover, the defect severities were elongated along the five grading scale developed by this model. This is done since, in the current approaches, most of the severities were over three impact levels (Light, Medium, and Severe). The defects' distribution over the whole scale would minimize the uncertainty and therefore it would fit the whole model in terms of evaluation and aggregation. Therefore, the following distributions of defect severities are proposed in order to be implemented in the developed model and eventually achieve the aim of this research. In this approach the defect severities are either numerical or non-numerical (linguistically assessed) as can be seen below.

5.6.1 Pipeline Defect Severities

The pipeline's defect severities were divided according to the defect hierarchy as discussed earlier. The criteria for the defect severities differ with respect to the types of defects. Some defects such as the fracture has two assessment criteria (width or number per unit length) to make the user comfortable in using whichever criteria available in hand. The installation and rehabilitation defect severities were proposed based on the logic inferred from case studies that were consulted as shown in Table 5.11. For example, in cracks, a single crack per unit length with no leakage results in an acceptable condition (Excellent). Two cracks with no leakage results in a (Good) condition. These severities are all fuzzified to serve the purpose of the research.

Table 5. 8 Pipeline Crack Defect Severities

Defect		Condition State				
		Excellent	*Good*	*Fair*	*Poor*	*Critical*
Crack	Longitudinal	(0-1)Cracks per unit length-No Leakage	(1-2) Cracks per unit length-No Leakage	(2-3) Cracks per unit length-Leakage	> 3 Cracks per unit length Leakage	N/A
	Circumferential	(0-1)Cracks per unit length-No Leakage	(1-2) Cracks per unit length-No Leakage	(2-3) Cracks per unit length-Leakage	> 3 Cracks per unit length Leakage	N/A
	Spiral	(0-1)Cracks per unit length-No Leakage	(1-2) Cracks per unit length-No Leakage	(2-3) Cracks per unit length-Leakage	> 3 Cracks per unit length Leakage	N/A
	Multiple/Radiating	N/A	N/A	N/A	N/A	Always

Table 5. 9 Pipeline Fracture Defect Severities

Defect		Condition State				
		Excellent	*Good*	*Fair*	*Poor*	*Critical*
Fracture	Longitudinal	(0-1) Fracture per unit length/ or single fracture with 5 mm width with visible opening	(1-2) Fractures per unit length/ or 5-10mm wide single fracture	(2-4) Fractures per unit length/ or 10-20mm wide single fracture	(4-5) Fractures per unit length/ or 20-25 mm wide single fracture	(4-5) Fractures per unit length/ or > 25 mm wide single fracture with notransverse displacement
	Circumferential	(0-1) Fracture per unit length/ or single fracture with 5 mm width with visible opening/ incomplete circular round	(1-2) Fractures per unit length/ or 5-10mm wide single fracture	(2-4) Fractures per unit length/ or 10-20mm wide single fracture/ complete circular	(4-5) Fractures per unit length/ or 20-25 mm wide single fracture	(4-5) Fractures per unit length/ or > 25 mm wide

Table 5. 9 Pipeline Fracture Defect Severities (continued)

Defect		Condition State				
		Excellent	*Good*	*Fair*	*Poor*	*Critical*
Fracture	Spiral	(0-1) Fracture per unit length/ or single fracture with 5 mm width with visible opening	(1-2) Fractures per unit length/ or 5-10mm wide single fracture	(2-4) Fractures per unit length/ or 10-20mm wide single fracture	(4-5) Fractures per unit length/ or 20-25 mm wide single fracture	(4-5) Fractures per unit length/ or > 25 mm wide single fracture with no transverse displacement
	Multiple	N/A	N/A	N/A	N/A	Always

Table 5. 10 Pipeline Other Structural Defect Severities

Defect	Condition State				
	Excellent	*Good*	*Fair*	*Poor*	*Critical*
Hole	0	N/A	(1) Clock Position	(2) Clock Positions	>3 Clock Positions or if (Soil visible-Void Visible)
Sag	0	0-50 mm Change of flow level	50-100 mm Change of flow level	>100 mm Change of flow level	N/A
Deformation	0 % Diameter Change	0-5% Diameter Change	5-10% Diameter Change & Leakage	10-25% Diameter Change & Leakage	>25 % Diameter Change
Broken	N/A	N/A	N/A	N/A	Always
Collapse >50% of cross-section is lost	N/A	N/A	N/A	N/A	Always
Surface Damage	0 / Increased Roughness	< 5 mm wall thickness missing Slight Spalling	5-10 mm of wall thickness is missing Aggregate Visible	10-15 mm of wall thickness is missing Aggregate Projecting Reinforcement Visible Reinforcement Projecting	>15 mm of wall thickness is missing Aggregate Missing Reinforcement Missing / Corroded (100% Critical)

Table 5. 11 Pipeline Operational and Installation and Rehabilitation Defect Severities

Defect	Condition State				
	Excellent	***Good***	***Fair***	***Poor***	***Critical***
Roots (each)	0-5% Reduction in Diameter	5-10% Reduction in Diameter	10-25% Reduction in Diameter	25-50% Reduction in Diameter	>50% Reduction in Diameter
Debris (Meter)	0-5% Reduction in Diameter	5-10% Reduction in Diameter	10-25% Reduction in Diameter	25-50% Reduction in Diameter	>50% Reduction in Diameter
Encrustation (meter)	0-5% Reduction in Diameter	5-10% Reduction in Diameter	10-25% Reduction in Diameter	25-50% Reduction in Diameter	>50% Reduction in Diameter
Foul (meter)	0-5% Reduction in Diameter	5-10% Reduction in Diameter	10-25% Reduction in Diameter	25-50% Reduction in Diameter	>50% Reduction in Diameter
Protruding Services (each)	0-5% Reduction in Diameter	5-10% Reduction in Diameter	10-25% Reduction in Diameter	25-50% Reduction in Diameter	>50% Reduction in Diameter
Soil Intrusion (meter)	0-5% Reduction in Diameter	5-10% Reduction in Diameter	10-25% Reduction in Diameter	25-50% Reduction in Diameter	>50% Reduction in Diameter
Infiltration	N.A	Seeping	Dripping	Running	Gushing
Condition State of Pipeline Installation Defects					
Defective Connection	N.A	N.A	0-1/ pipe length	1-3	>3
Defective Lining	N.A	N.A	0-1/ pipe length	1-3	>3
Defective Repair	N.A	N.A	0-1/ pipe length	1-3	>3

5.6.2 Joint Defect Severities

Table 5.12 shows the joint's structural defect severities. For the open joint defect, two pieces of criteria were used as input variables. The first criterion was the longitudinal opening of the joint in mm. The second option measures the opening with respect to the pipe wall thickness. For Operational Defects happening at joint, the pipeline operational defects condition states' thresholds are used.

Table 5. 12 Joint Structural Defect Severities

Defect	Condition State				
	Excellent	*Good*	*Fair*	*Poor*	*Critical*
Non-Concentric Joint	0	(0-1)* Pipe Wall Thickness	(1-1.5) * Pipe Wall Thickness	>1.5 * Pipe Wall Thickness	N.A
Open Joint	0	(0-10 mm) Gasket in Place No Leakage	10-50 mm Leakage Noticeable	>50 mm Leakage Noticeable Soil Visible	N.A
	0	(0-1)* Pipe Wall Thickness	(1-1.5) * Pipe Wall Thickness	>1.5 * Pipe Wall Thickness	N.A

5.6.3 Manhole Defect Severities

Most of the manhole structural defects were given linguistic variables/inputs. The cover and frame damage defects were given scores according to the defect indications as shown in the table below. The following scores (Table 5.13) were improvised and extended throughout the grading scale in this model to the best of knowledge.

Table 5. 13 Manhole Structural and Operational Defect Severities

Defect/Grade	Excellent	Good	Fair	Poor	Critical
Crack (Vertical)	No Crack Score=0	Crack (No Leakage) Score=2	Crack (With Leakage) Score=4	Multiple Cracks (Leakage)	N.A
Crack (Horizontal)	No Crack Score=0	Crack (No Leakage) Score=2	Crack (With Leakage) Score=4	Multiple Cracks (Leakage)	N.A
Fracture Number (Vertical)	No Fracture	1-3	3-4	4-5	5>
Fracture Width (Horizontal)	No Fracture	5-10mm	10-15mm	15-25	25>

Table 5. 13 Manhole Structural and Operational Defect Severities (continued)

Defect/Grade	Excellent	Good	Fair	Poor	Critical
Broken	N/A	N/A	N/A	N/A	Always
Collapse	N/A	N/A	N/A	N/A	Always
Deformation	0 % Diameter Change	0-7% Diameter Change	7-16% Diameter Change & Leakage	16-25% Diameter Change & Leakage	>25 % Diameter Change
Surface Damage	0 / Increased Roughness	< 5 mm wall thickness missing Slight Spalling	5-10 mm of wall thickness is missing Aggregate Visible Reinforcement Visible	10-15 mm of wall thickness is missing Aggregate Projecting Reinforcement Projecting	>15 mm of wall thickness is missing Aggregate Missing Reinforce ment Missing / Corroded (100% Critical)
Frame Damage	0	Slight Corrosion, Rust in anchors Score: 2	Medium Corrosion Score: 4	Heavy Corrosion, Anchors are loose Score:6	Broken Frame Score: 9 100% Critical
Cover Damage	0	Slight Corrosion, Score: 2	Medium Corrosion Score: 4	Heavy Corrosion, Cracked cover Score:8	Broken Cover Score:10 100% Critical
Pavement Damage	0	Slight pavement cracking, Score: 2	Medium pavement cracking Score: 5	Severe pavement cracking, holes Score:9	Broken pavement, huge settlement Score:10 100% Critical
Roots	0	Fine Roots (50% Ex,50% Good)	Bulk Roots (50% Good, 50%Fair)	Massive Roots (50% Fair,50% Poor)	N.A

For other manhole Operational Defects, the pipeline operational defects condition states' thresholds are used since the information about manhole operational defects was scarce. Moreover, Table 5.14 shows the defect severities for installation and rehabilitation defects. Note that, for defective ladder and landing a score was given corresponding to each defect extent (e.g. Medium corrosion, 4).

Table 5. 14 Manhole Installation and Rehabilitation Defect Severities

Defect	Condition State				
	Excellent	***Good***	***Fair***	***Poor***	***Critical***
Defective Ladder	0	Slight Corrosion Slight Bending Score: 2	Medium Corrosion Score: 4	Heavy Corrosion, Deformed bars, Loose Anchors Score:5	Missing Anchors >50% Cross sectional loss 100% Critical
Defective Connection	0	0-10 mm wide gaps	10-15 mm wide gaps	15-25 mm wide gaps Leakage	>25 mm wide gaps (drop pipe is fractured)
Defective Landing	0	Slight Corrosion Slight Bending Score: 2	Medium Corrosion Score: 4	Heavy Corrosion, Deformed bars, Loose Anchors Score:5	Missing Anchors >50% Cross sectional loss 100% Critical

5.7 Fuzzy Membership Functions

After determining the severities and the condition grades, the available severities criteria are fuzzified in order to tackle the available uncertainty and incomplete information associated with human subjectivity. Therefore, a membership function for each defect type was developed based on its corresponding severity criteria in reference to Tables 5.8 to 5.14 in attempt to describe the vagueness of the available information. The condition grades will serve as the subsets in the triangularly fuzzified functions. On the other hand, the defects' severities will serve as the universe of discourse or the criteria that would be transitioning along the fuzzy sets (condition grades). The fuzzy membership functions were divided according to the defect types and their corresponding components. The functions in this model were developed based on 0.5 degrees fuzziness in an attempt to have a summation of the membership functions (of a certain input value) equal to unity and to eliminate the ignorance in the aggregation (HER Model). The triangular fuzzy membership function is used since only the upper and lower bound of the membership is known.

5.7.1 Pipeline Fuzzy Input Variables

The membership functions were developed from the severity tables (5.8 to 5.14) developed earlier. Starting with the pipeline structural defects, (cracks, fractures, holes, deformations, sags, and surface damages) functions were developed in a way where each of the defects' subtypes (longitudinal, circumferential…etc.) membership functions falls into the same function of the parent defect. Note that more than one function was created to some defects such as "fractures" to account for different measuring criteria. In general, the y-axis in the developed functions represents membership function with a value from (0-1) that would be later used as the degrees of belief. The x-axis represents the defect severity inferred from (Tables 5.8-5.14). The severity criteria are used as an input to enter the membership function in order to determine the percentages to which the severity supports the hypothesis which is the condition grades in this case (Good, Fair …etc.). The midpoint of each criteria corresponding to each grade in (Tables 5.8-5.14) is taken as the point that corresponds to a full membership of a certain condition grade. In Figure 5.12 for example, points (0.5, 1.5, 2.5, and 3) correspond to a 100% of their related grades. If the user enters the graph with an input of 2 cracks per unit length, the membership function will be 0.5 Good, 0.5 Fair.

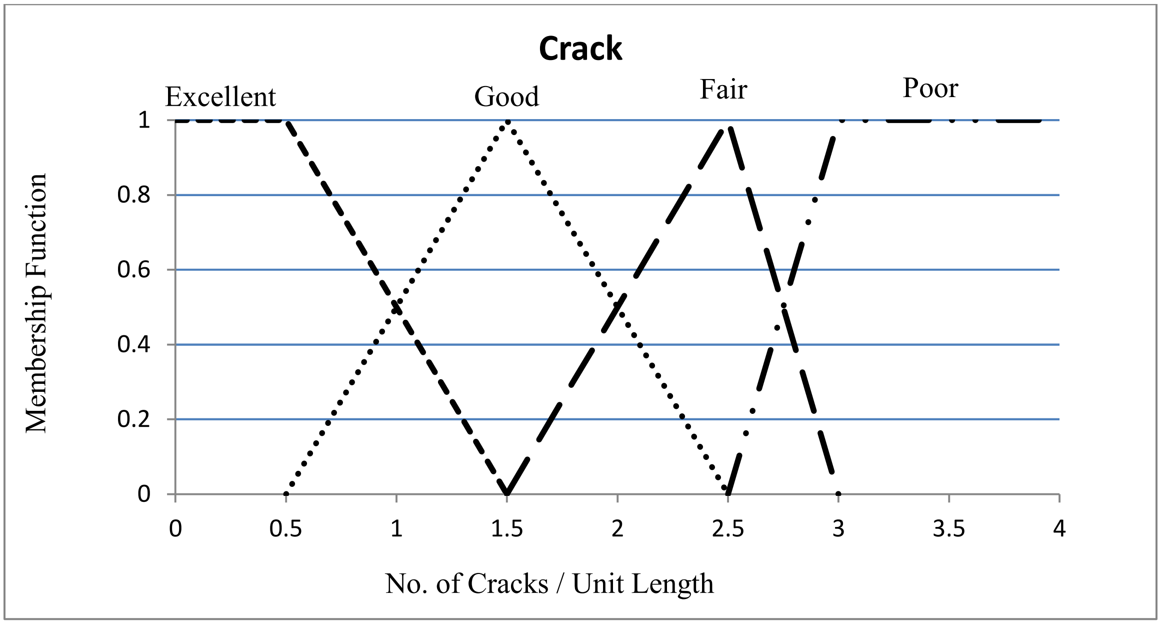


Figure 5. 12 Crack Membership Function

The fracture's membership functions were divided into two parts (a) and (b) to account for two measuring criteria. The fracture's severity is assessed by its number and size. In Figure 5.1, the severity criteria used is the number of fractures per unit length. Five fractures or more give the fracture a 100% critical condition as inferred from Table 5.9 which is based on literature. Also, if a multiple fracture was detected, this model gives it a 100% critical condition to illuminate on the seriousness of the defect. In Figure 5.14, the x-axis is taken to be the fracture's width. Any fissure of width less than 5 mm is negligible since it would be considered as a crack and not fracture. On the other hand, any fracture with a width more than 25 mm is considered as a critical defect.

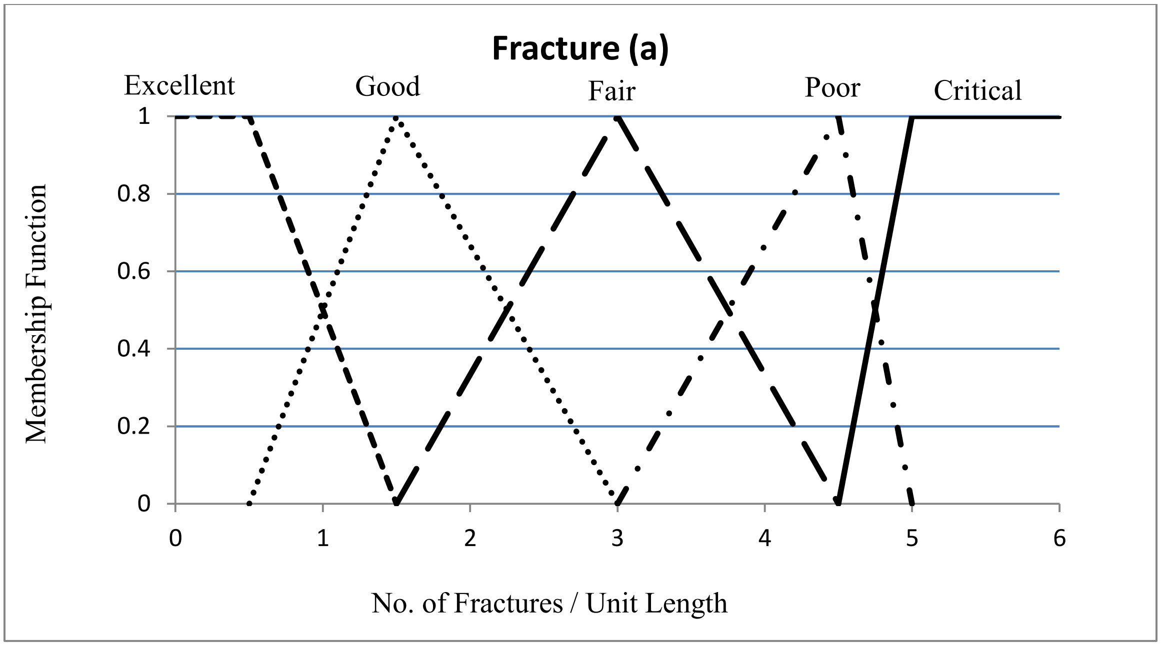


Figure 5. 13 Fracture Membership Function (a)

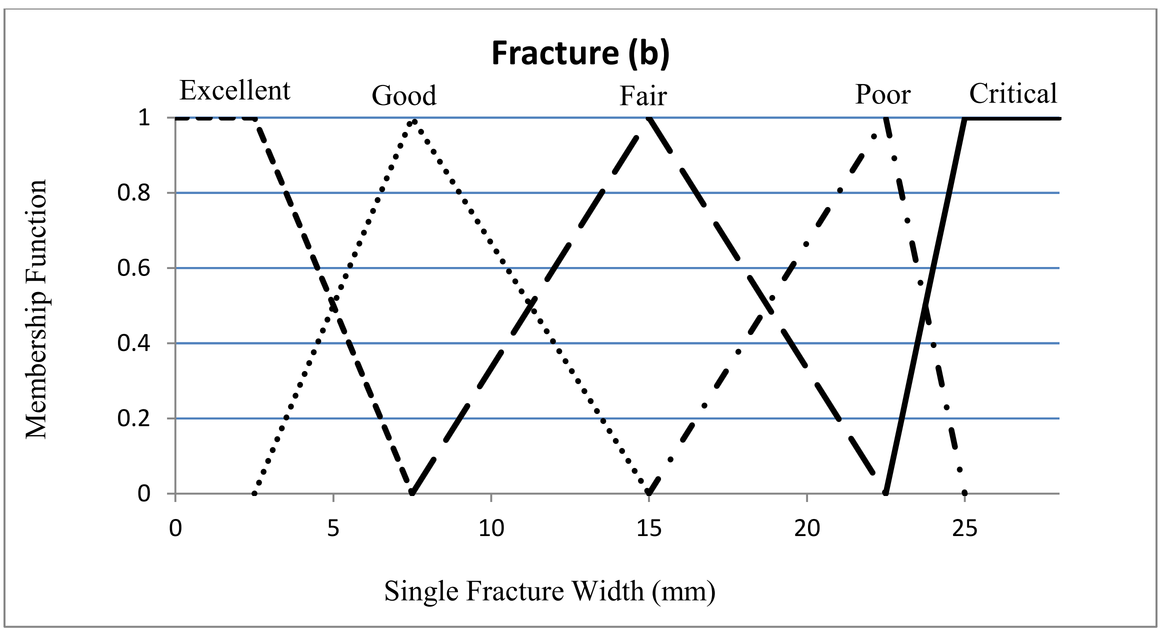


Figure 5. 14 Fracture Membership Function (b)

The “Hole” defect is given only three condition states (Fair, Poor, and Critical) as shown in Figure 5.15. This is because a hole is a severe defect that can never be considered as

Excellent or Good since it may allow for soil intrusion, infiltration and contamination of the surroundings by sewer water.

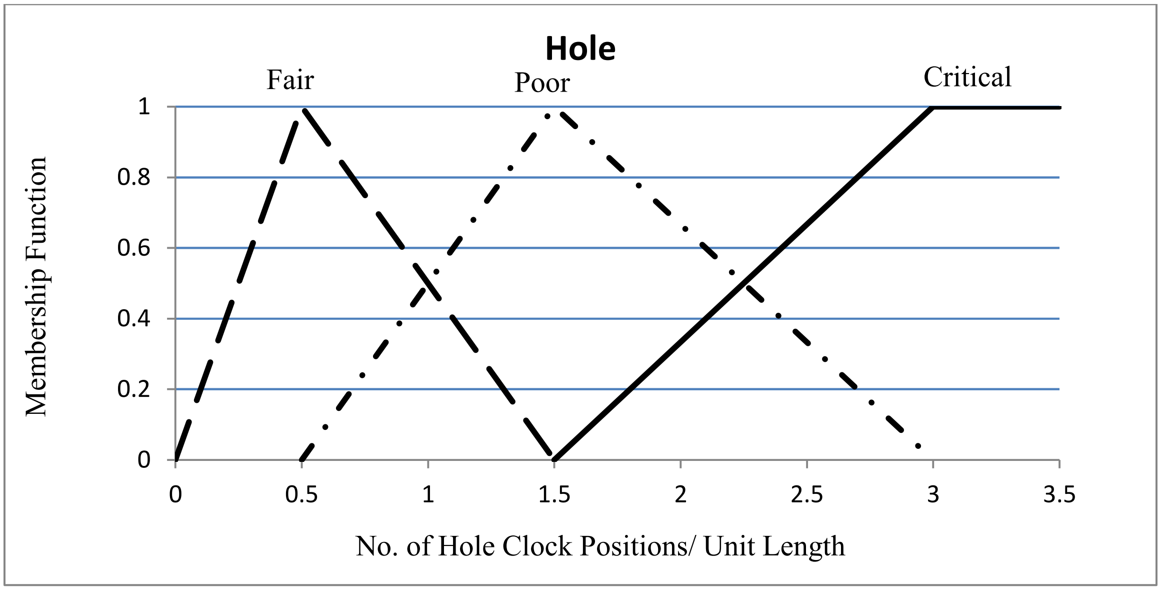


Figure 5. 15 Hole Membership Functions

For the deformation membership function in Figure 5.16, the x-axis is based on the percentage of diameter change in the body of the pipeline. A 30% of diameter change or more is considered critical.

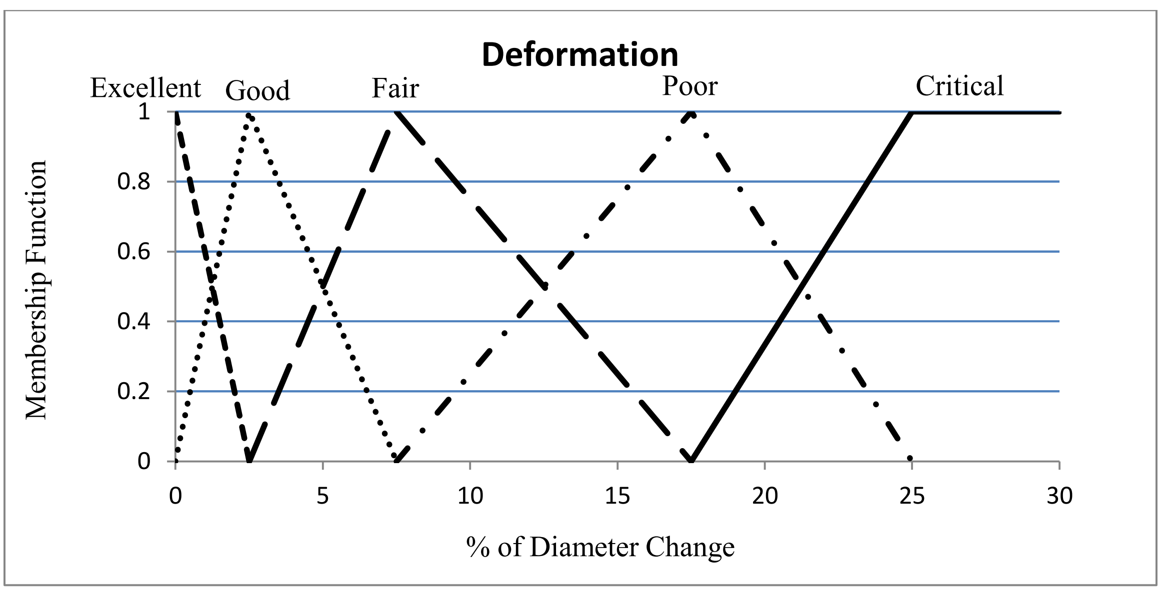


Figure 5. 16 Deformation Membership Function

The sag defect presented in Figure 5.17 is represented by the percentage change of the flow level. However, the maximum condition state corresponding to more than 80% of change is Poor since the Sag does not affect the structural integrity much as proposed in the severity criteria.

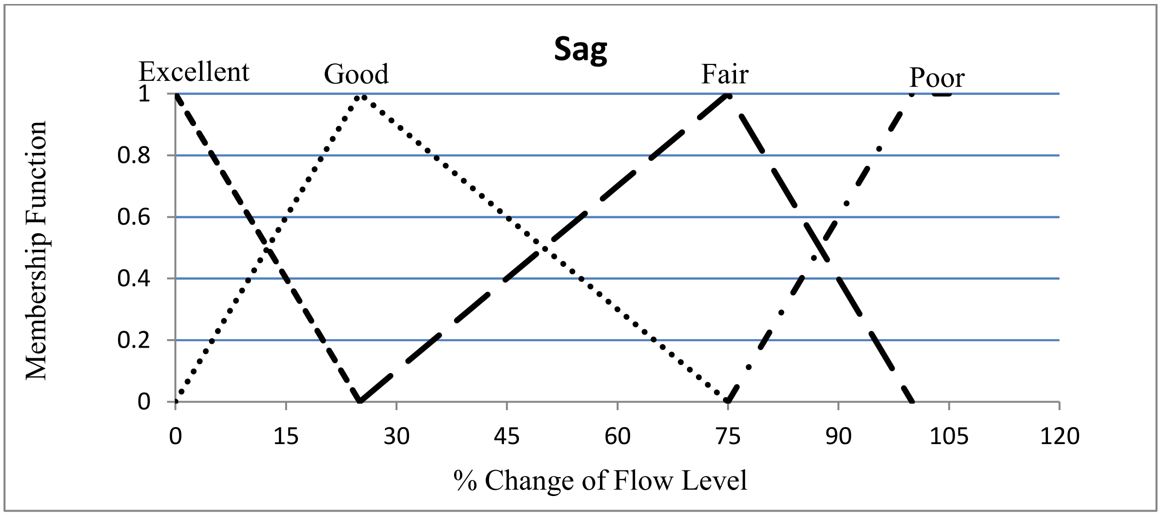


Figure 5. 17 Sag Membership Function

The internal missing wall thickness is used to assess the severity of concrete surface damage.The surface damage in Figure 5.18 is represented by the depth of missing wall thickness. It is also assessed linguistically as shown in Table 5.10.

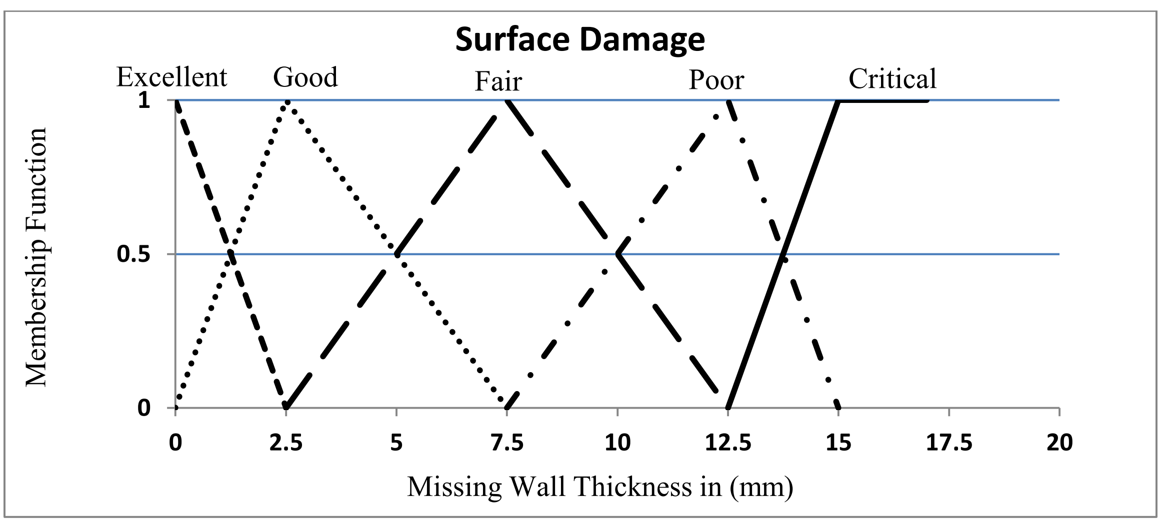


Figure 5. 18 Surface Damage Membership Function

For the pipeline's operational defects, the same procedure was implemented to result in fuzzy membership functions. The membership functions were developed for roots, deposits, soil intrusion, protruding services, and infiltration. For the roots defect for example, the severity is measured by measuring the percentage of diameter reduction due to the availability of this particular defect. All of the other operational defects (Figures 5.20 to 5.22) were treated in a similar manner.

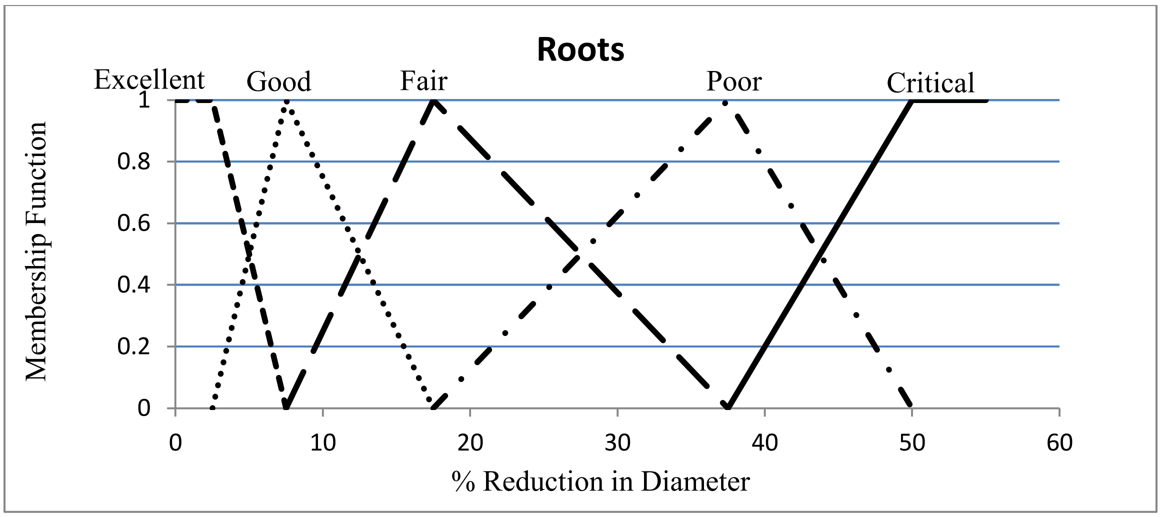


Figure 5. 19 Roots Membership Function

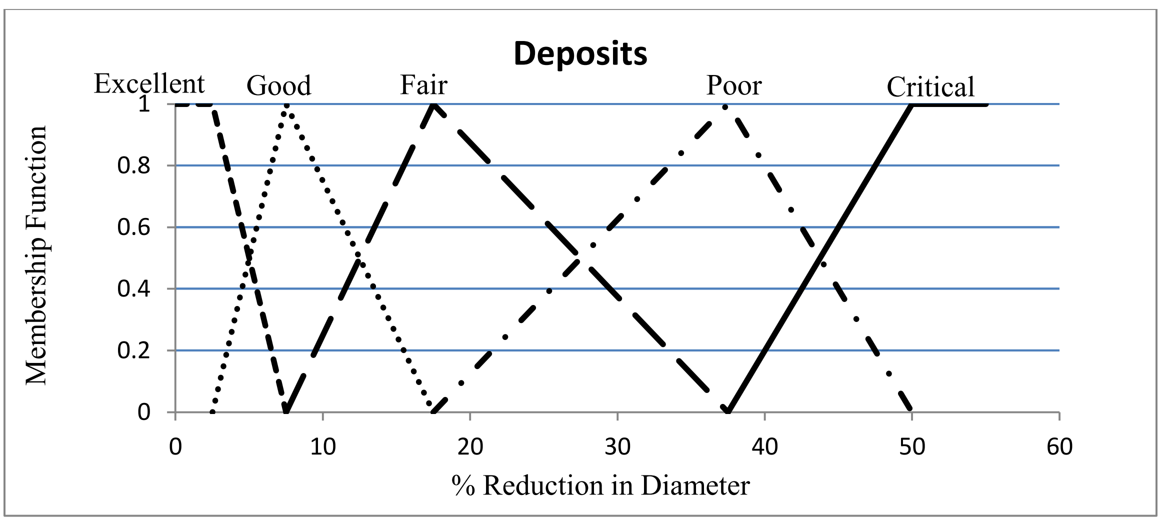


Figure 5. 20 Deposits Membership Function

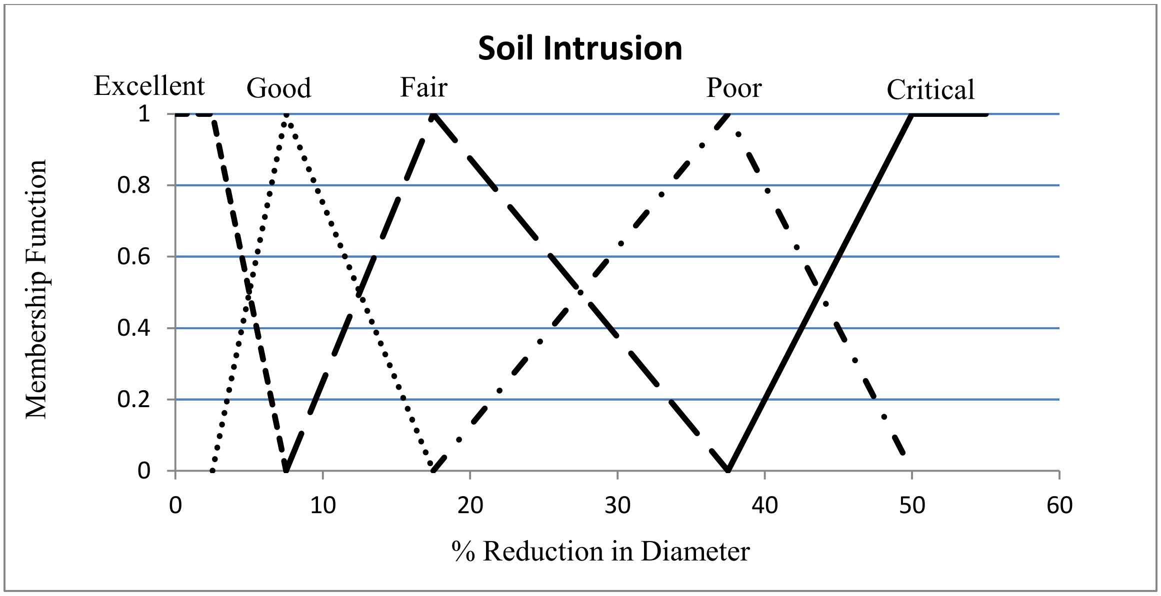


Figure 5. 21 Soil Intrusion Membership Function

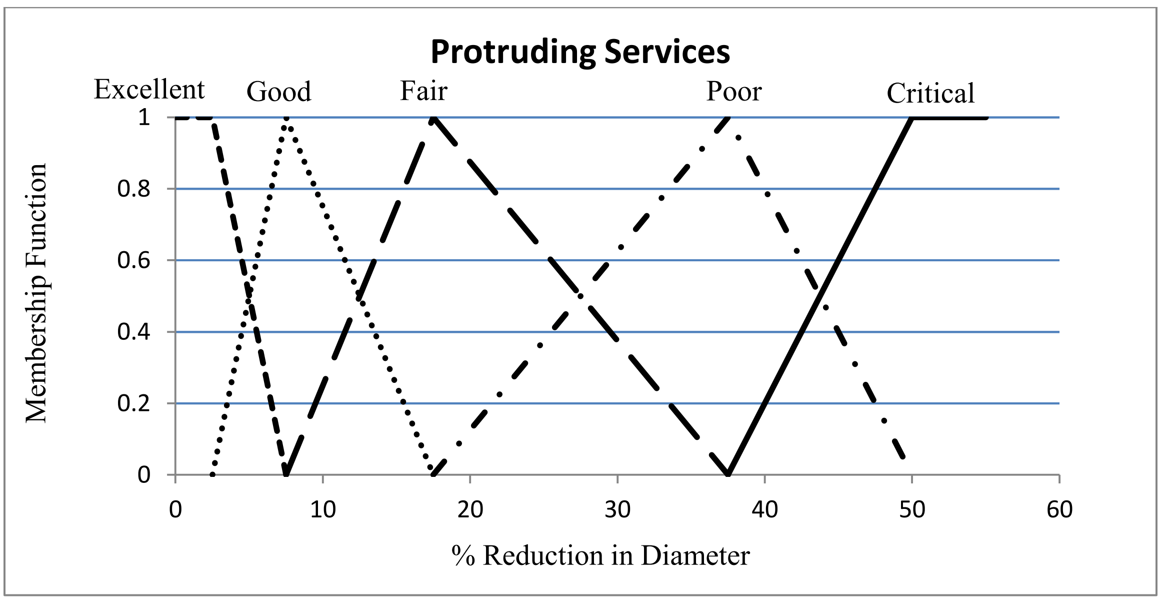


Figure 5. 22 Protruding Services Membership Function

The severities of the pipeline's installation and rehabilitation defects were not available among the literature review. Therefore, real inspection reports were consulted and a severity scheme was deduced to represent the installation and rehabilitation defects. Its validity was tested through the application of several case studies as discussed later. The following (Figure 5.23) is a fuzzy membership function representing the pipeline's installation and rehabilitation defects were the severity of these defects is measured based on the number of defects per pipe length. It is also shown that the minimum condition state with an available installation/rehabilitation defect is Fair since any defect of this kind would affect the flow in the pipeline and therefore could not be considered as Excellent or Good.

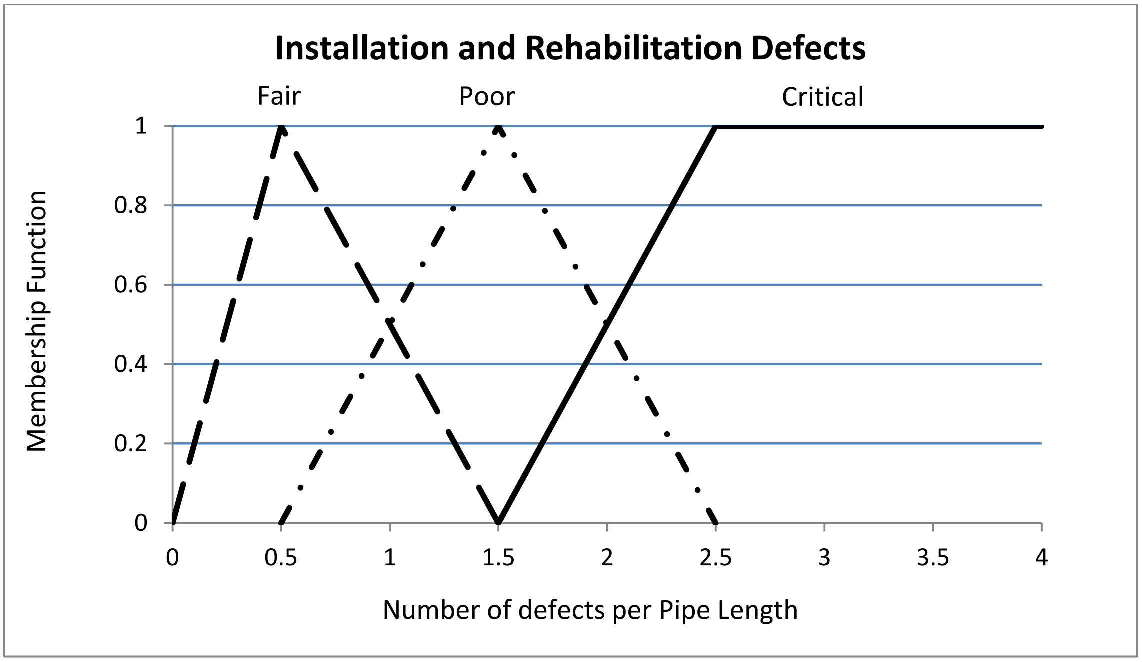


Figure 5. 23 Installation and Rehabilitation Defects Membership Function

5.7.2 Joint Fuzzy Input Variables

The same procedure was applied to obtain the membership functions for the joint defects. The defect severities were also transferred to a fuzzified universe that was used to obtain degrees of belief with values ranging from [0, 1]. The membership functions created included two functions representing open joints and one function for the non-concentric joints. Two membership functions were developed for the open joint defect since the opening can be measured as percentage of pipe thickness as shown in Figure 5.24 in mm as shown in Figure 5.25. The maximum condition state in both of the memberships is

Poor as inferred from literature. For example, in Figures 5.24 and 5.26, an opening or deviation of 1.5*Pipe Wall Thickness is considered as a poor defect. Similarly, an opening greater than 50 mm as shown in Figure 5.6 is considered as Poor.

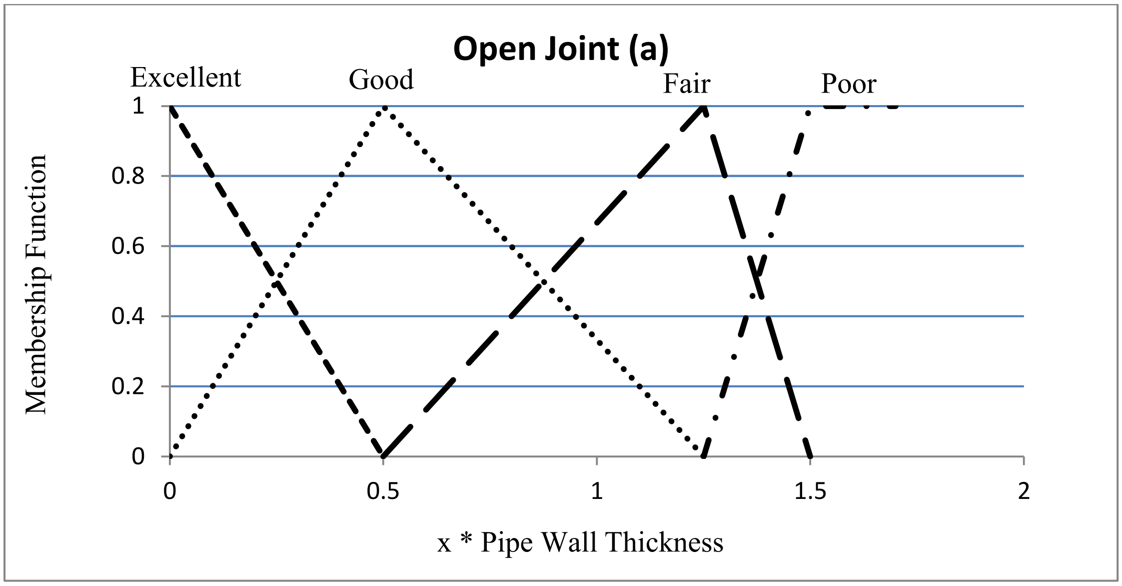


Figure 5. 24 Open Joint Membership Function (1)

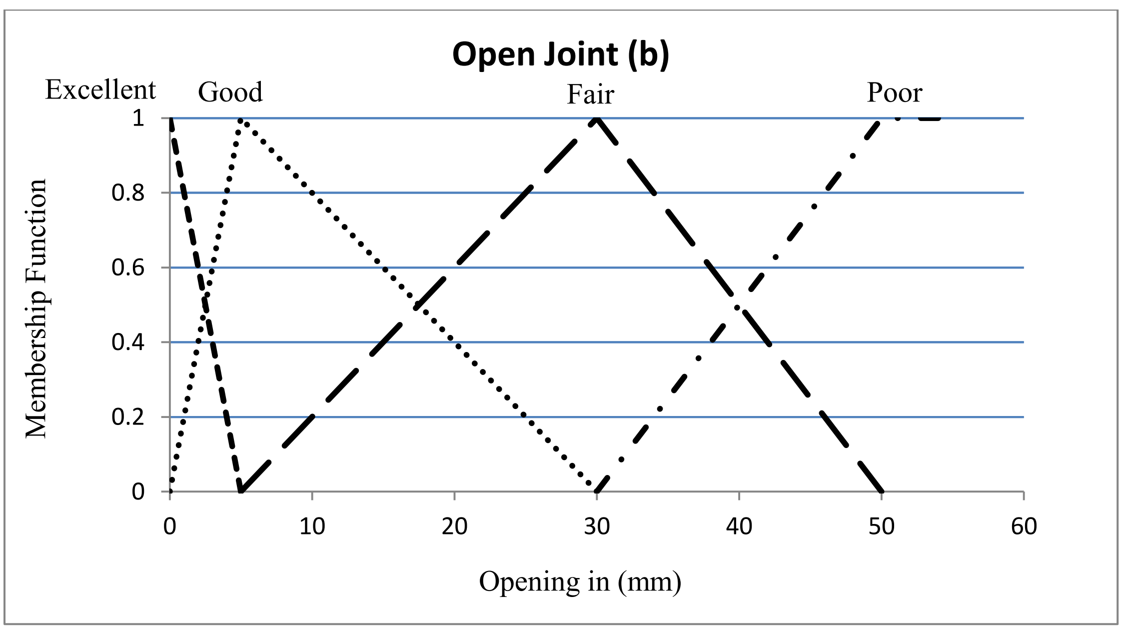


Figure 5. 25 Open Joint Membership Function (2)

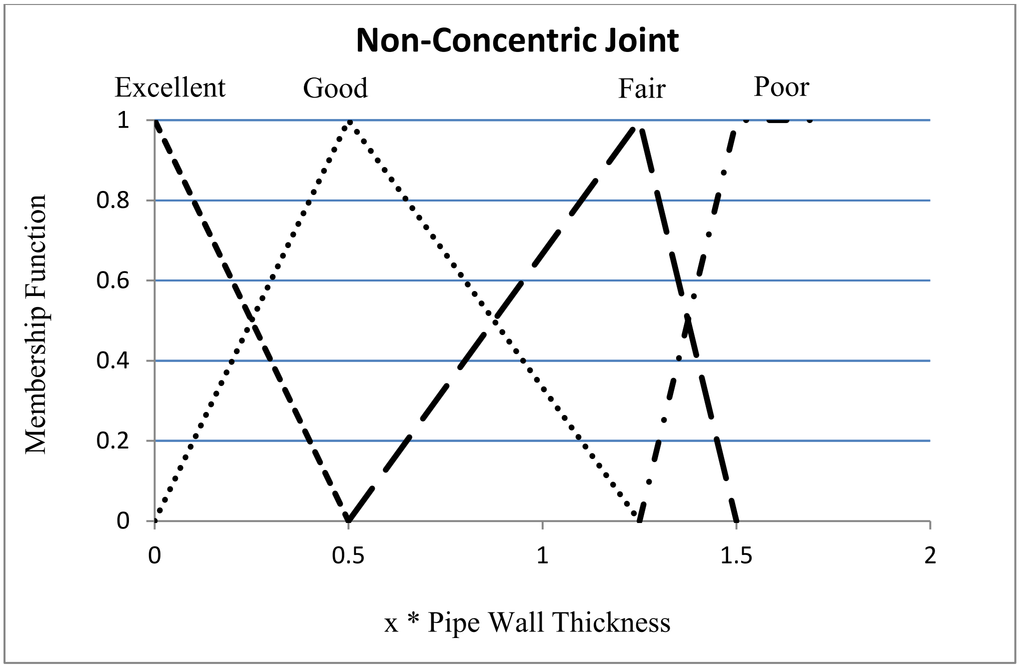


Figure 5. 26 Non Concentric Joint Membership Function

5.7.3 Manhole Fuzzy Input Variables

The manhole or access main in the sewer pipeline is considered as a whole different aspect. However, in this research, the manholes are treated in a simple way in order to determine their condition. To fuzzify the data, structural, operational, and installation / rehabilitation defects were encoded into fuzzified ranges. For the structural defects, (vertical / horizontal cracks and fractures, deformation, surface damage, frame damage, cover damage, and pavement damage) were considered. For the crack defect in Figure 5.27, linguistic terms have been employed to determine a crack score from (1-10) with 10 being worst. The scores presented in Table 5.18 were taken as points corresponding to memberships of 0.5 to account for human subjectivity. Also, the crack in a manhole can be assessed linguistically. For example, a detected crack with leakage would give the user a 0.5% Good and a 0.5% Fair condition.

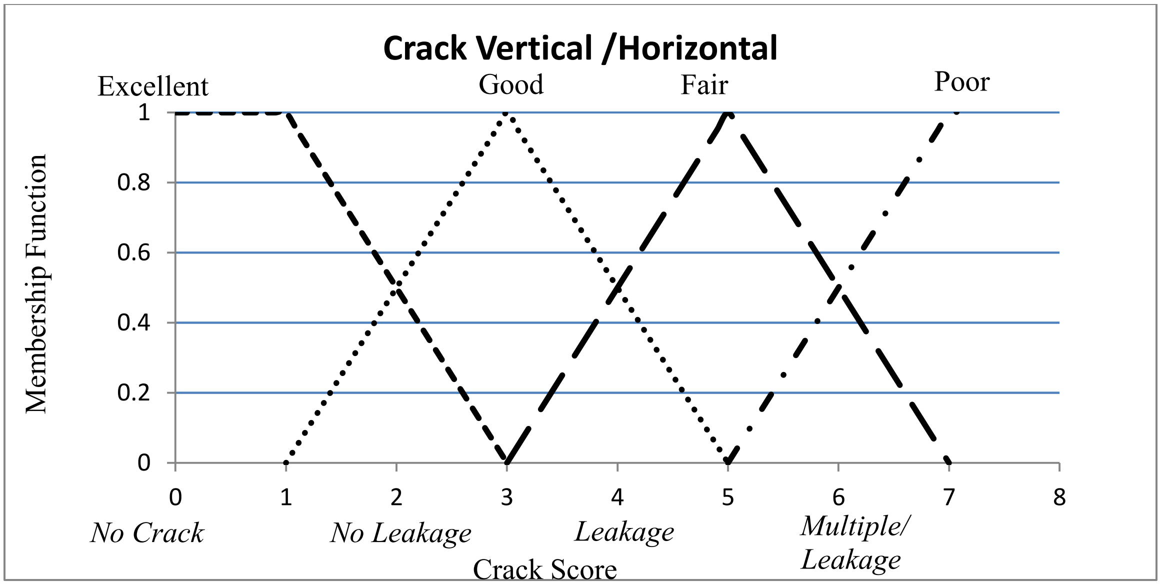


Figure 5. 27 Vertical/Horizontal Crack Membership Function

For the fracture defect, two membership functions were created to cover the two available orientations (vertical/horizontal). In Figure 5.28, the measuring criteria is taken to be the number of fractures per manhole. For example, if there are five fractures in the manhole, the condition is considered critical since these fractures may commence deterioration and allow for surface damage and eventually soil intrusion and infiltration.

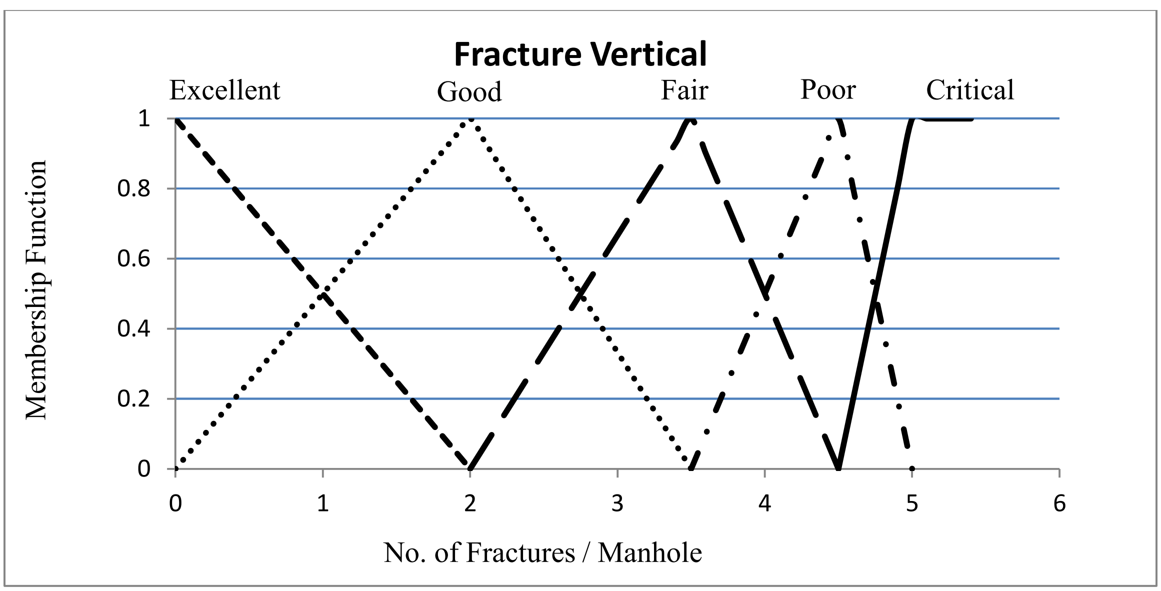


Figure 5. 28 Vertical Fracture Membership Function

The horizontal fracture on the other hand is measured by its width. A fracture with more than 2.5 cm in width is considered to be critical since it will allow for surface damage, soil intrusion, and infiltration if not treated.

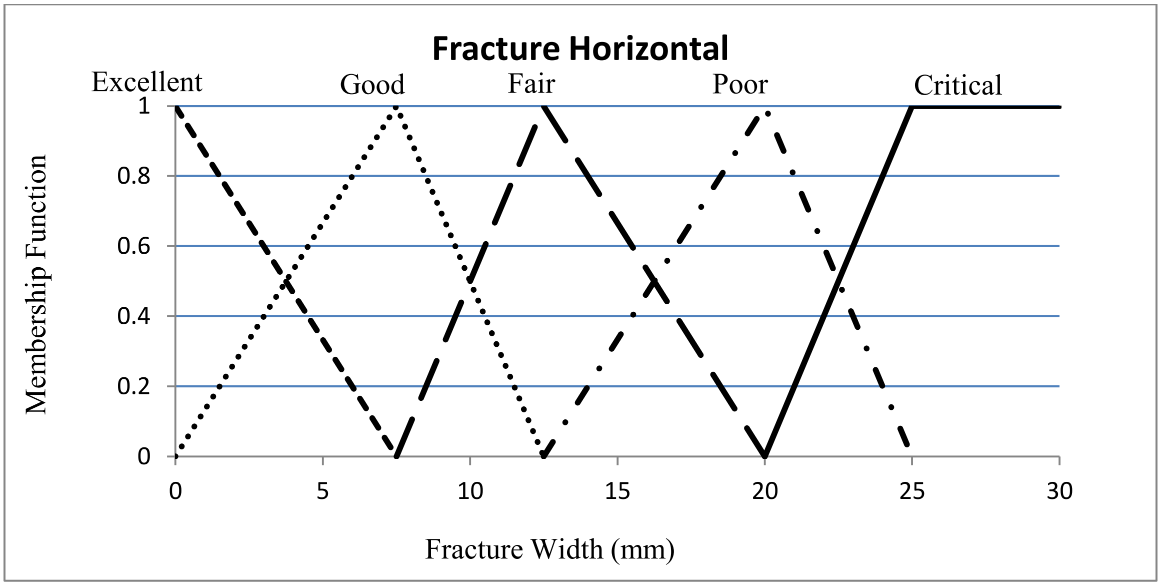


Figure 5. 29 Horizontal Fracture Membership Function

The deformation in manholes as shown in Figure 5.30 is treated in a similar way to that of the pipeline deformation due to lack of information regarding this matter.

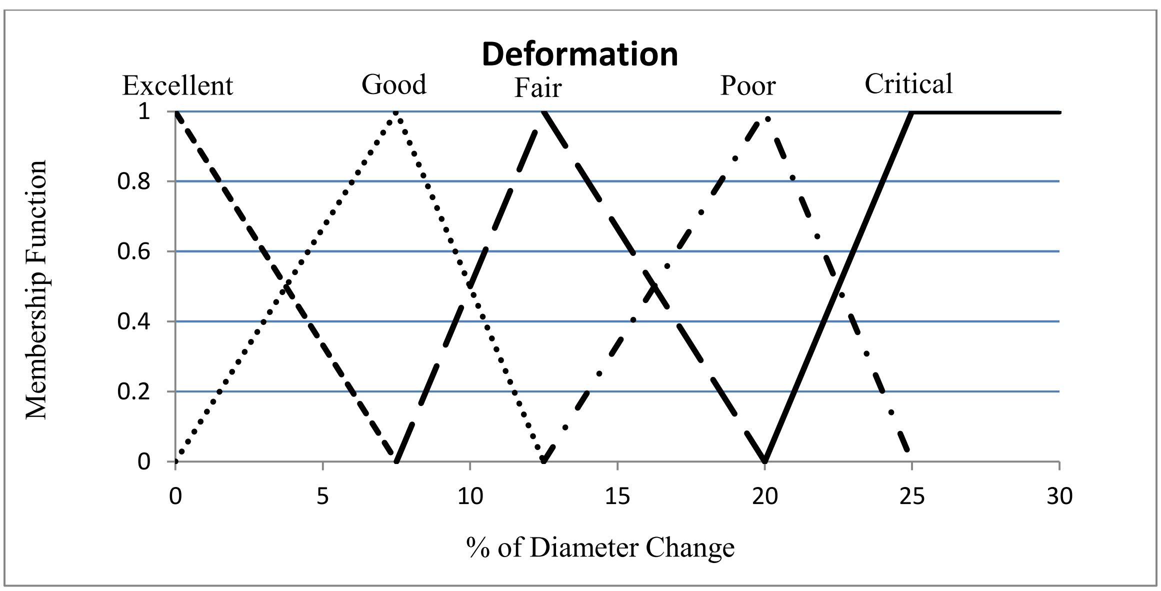


Figure 5. 30 Deformation Membership Function

For the surface damage, the manhole is also treated in a similar way to that of the pipeline deformation as shown in Figure 5.30.

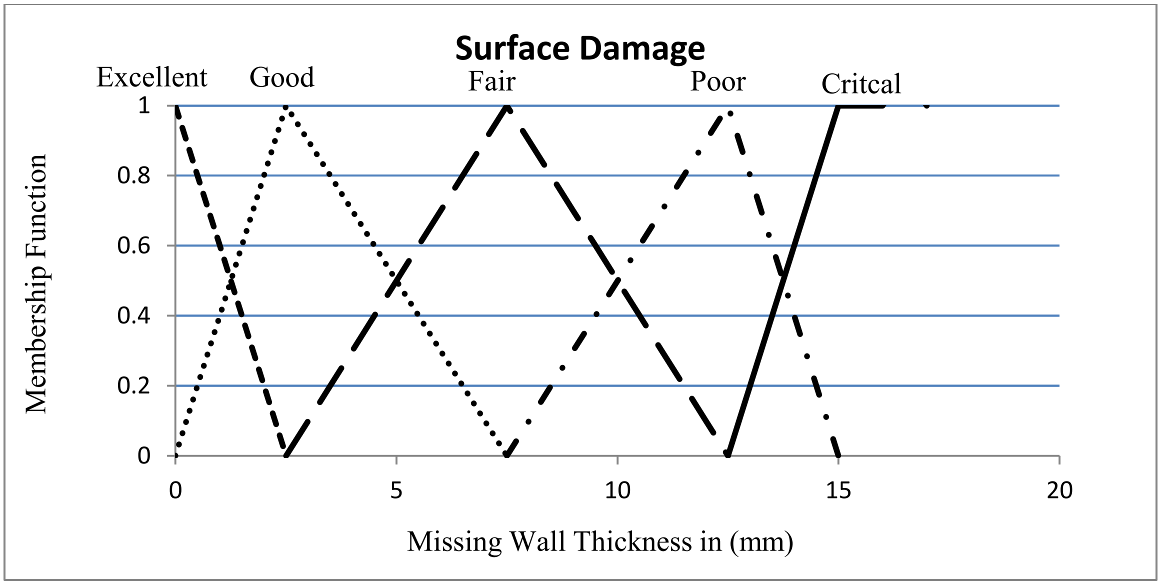


Figure 5. 31 Surface Damage Membership Function

For the frame damage, the defect severities were encoded into scores as inferred from the NRC Guideline (Zhao et al. 2001). The scores corresponding to each state in Table 5.13 were used to develop this function. This is done by taking the midpoint of the score ranges to be equal to 100% of that state. For Example, for the state Good, a score the midpoint of the score range (2-4) is taken which is 3 as shown in Figure 5.32.

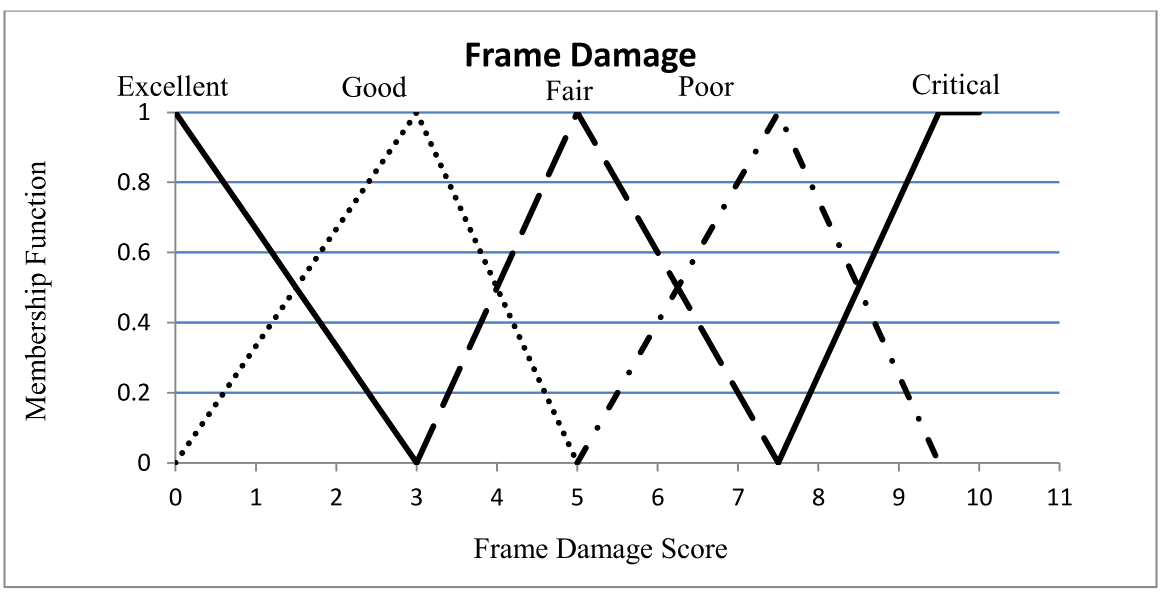


Figure 5. 32 Frame Damage Membership Function

The same procedure that was applied to the Frame Damage defect was applied to quantify the Cover Damage Defect shown in Figure 5.33.

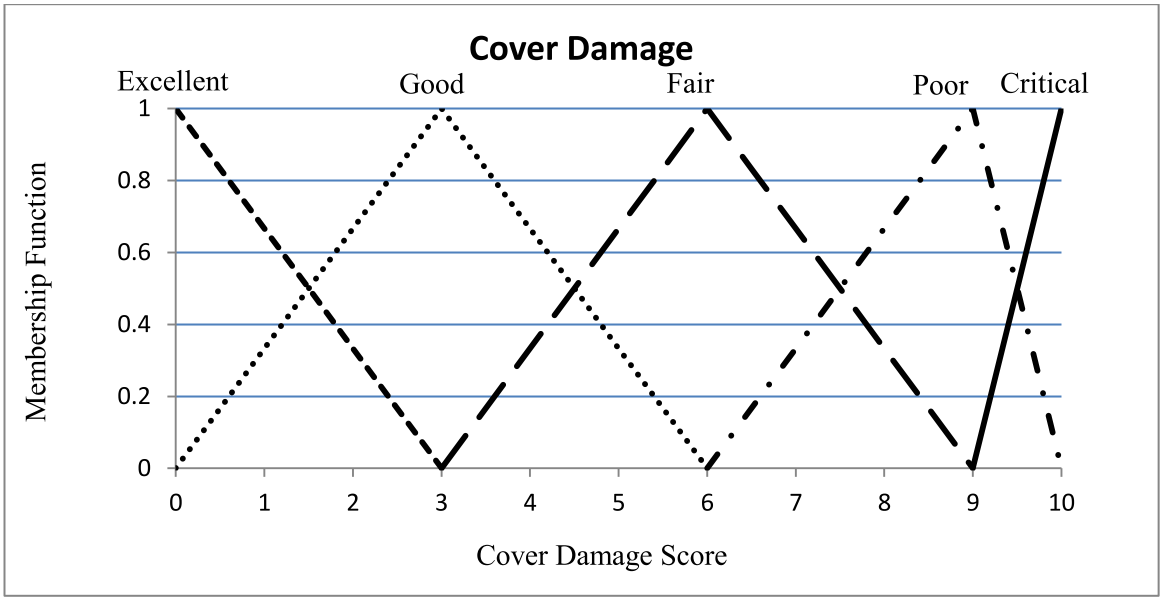


Figure 5. 33 Cover Damage Membership Function

The pavement damage defect was also treated in a similar manner to those of the Frame and Cover Damage with the x-axis being the severity score related to each state inferred from Table 5.13.

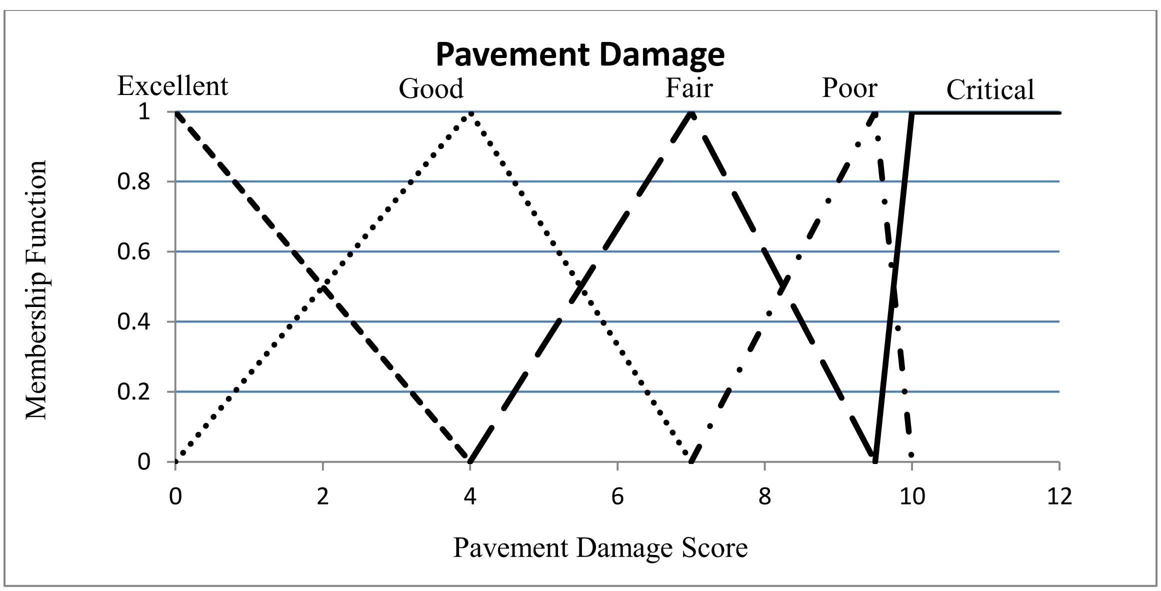


Figure 5. 34 Pavement Damage Membership Function

For the operational defects, the manhole was treated to be a vertical pipeline. Therefore, the operational defects were adopted from the pipeline defect severities as shown in the Table 5.13 and in Figure 5.35.

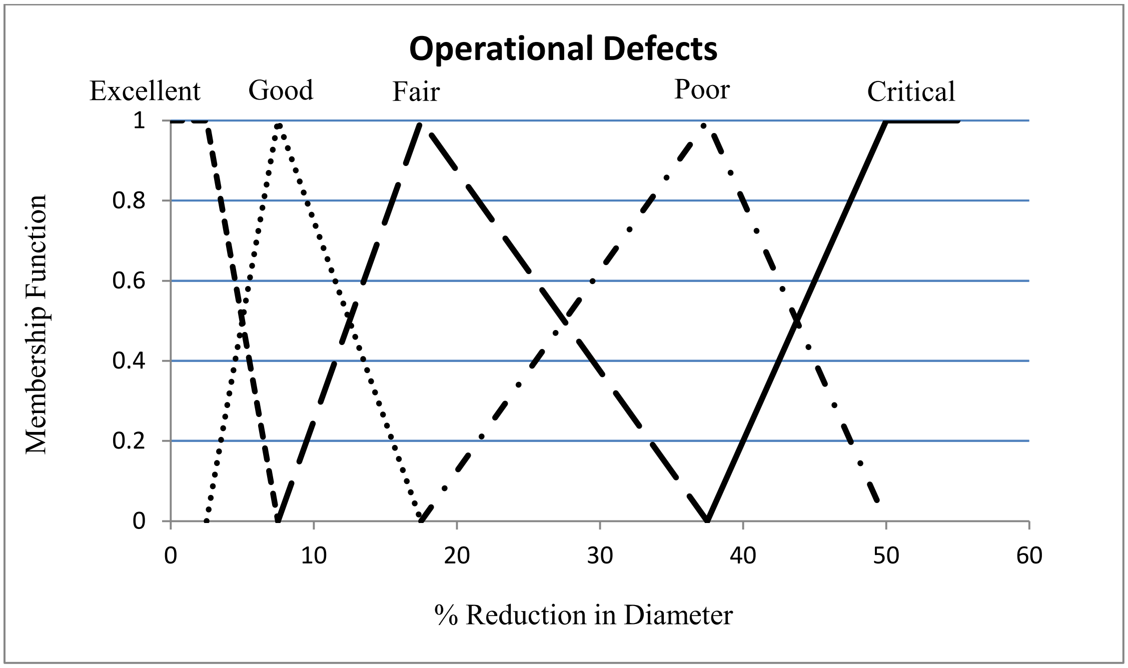


Figure 5. 35 Operational Defects Membership Function

Moreover, for the installation and rehabilitation defects, defective connection, defective ladders, and landing were considered. The measuring criterion for the defective connection was based on the gaps width between the connections. A gap width of 15 mm would result in condition state of 0.6 Fair and 0.4 Good as shown in Figure 5.36.The criteria for the landing and ladder defects used were the defect score as shown in Figure 5.37. The scores were encoded from the defect severities obtained from literature as discussed before. The developed grading scale (1-10) was distributed over the defect severities in order to determine the appropriate score for each observed distress indicator.

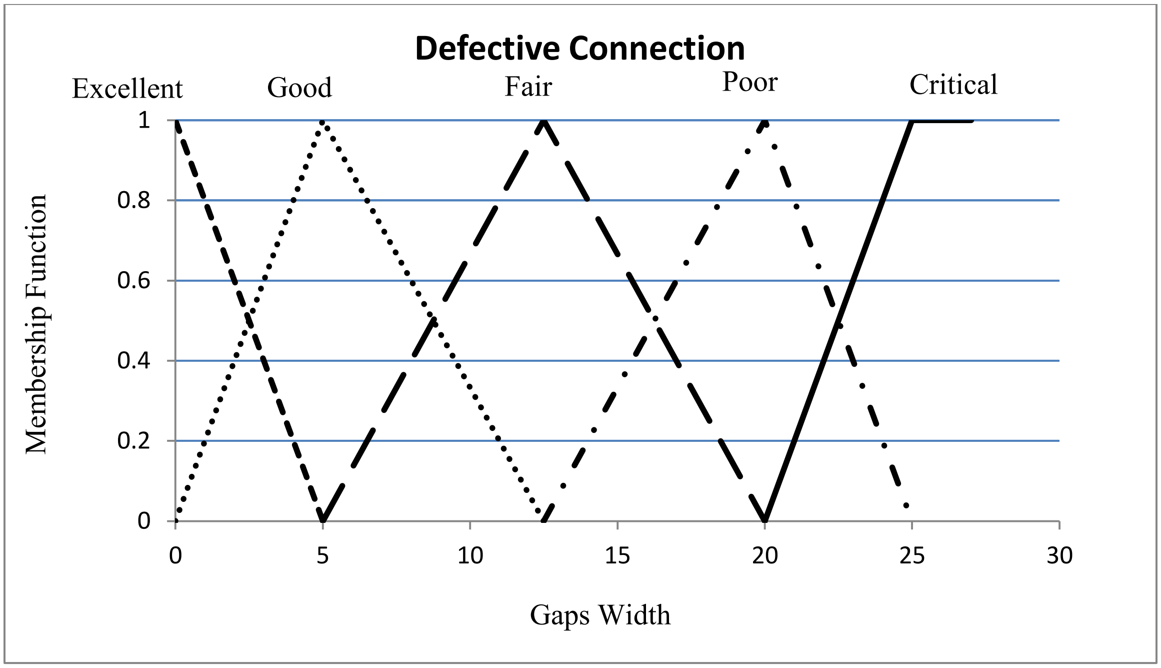


Figure 5. 36 Defective Connection Membership Function

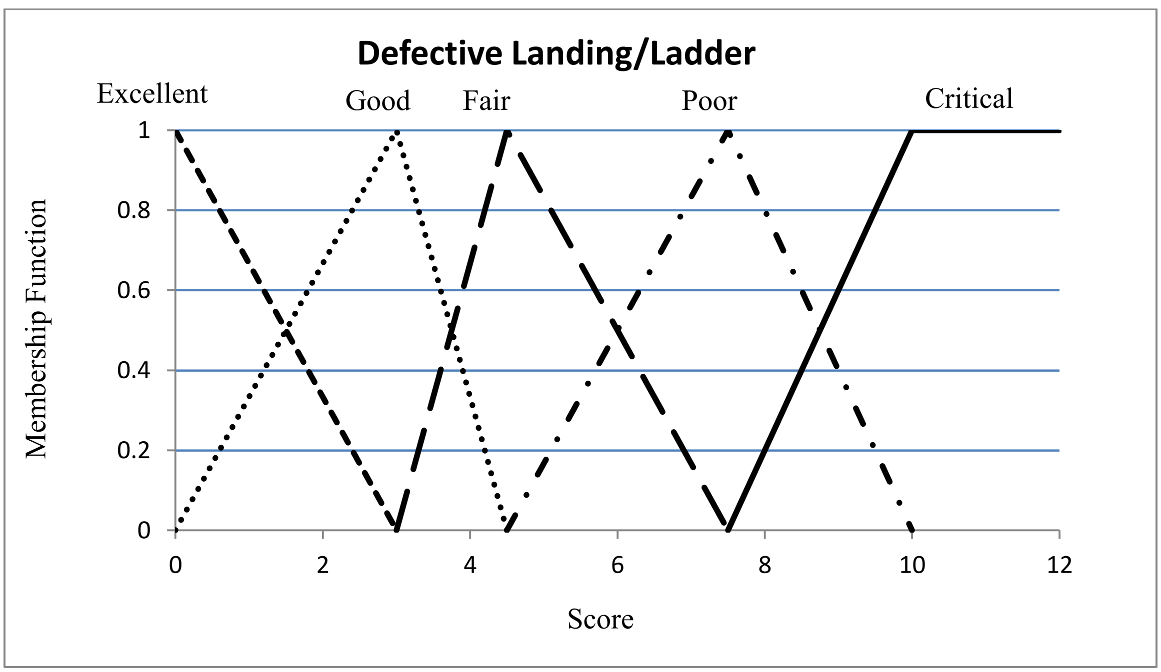


Figure 5. 37 Defective Landing and Ladder Membership Function

5.7.4 Fuzzy Output Variables

In order to represent the overall condition of the pipeline, the condition score is reflected from a fuzzy output variable of the newly created condition grading score. Table 5.15 presents the developed condition grading scale which was used as a fuzzy output variable to determine the overall pipeline condition.

Table 5. 15 Proposed Condition Grading Scale

Linguistic	Numeric
Excellent	**0-1**
Good	**1-3**
Fair	**3-6**
Poor	**6-8**
Critical	**8-10**

Also, Figure 5.38 represents the fuzzy output membership function of the proposed condition grading scale. This function is used to obtain a crisp value through the weighted average defuzzification process.

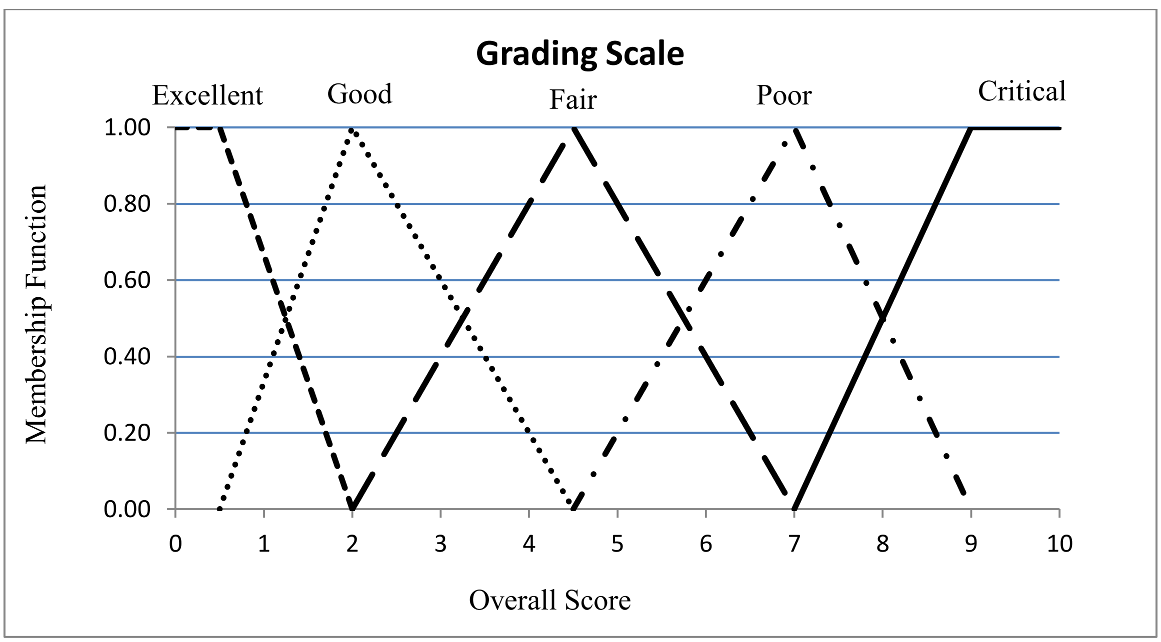


Figure 5. 38 Fuzzy Output Variable – Overall Pipe Condition

5.8 ER Application

As discussed in chapter 3, the Hierarchical Evidential Reasoning Technique was used as a comprehensive aggregation method. The first step in this process is the development of a consistent frame of discernment that will remain the same throughout the whole aggregation process {Excellent, Good, Fair, Poor, and Critical}. In order to result in a clear and accurate condition, the pieces of evidence should be aggregated in a hierarchical recursive manner. As mentioned earlier, the model has been divided into a hierarchy of components followed by defect families and defect types to deduce the overall condition as shown in Figures 5.1 to 5.9. First, the pipeline's structural condition is calculated using the steps stated in Chapter 3. The same steps are applied to compute the pipeline's operational and installation/rehabilitation conditions. After that, the structural, operational, and installation/rehabilitation conditions are aggregated to result in the pipeline's condition. The same is done for the joints and manholes. After calculating the conditions of the pipeline, joint, and manhole, the overall condition is computed by aggregating the three components together using the ER approach explained in chapter 3. As an example to illustrate the aggregation process, the pipeline's crack condition computation is demonstrated in Table 5.16. The following crack defect types (Circumferential, Longitudinal…etc.) were given the degree of beliefs extracted from the developed fuzzy membership functions. Each of these percentages represents the degree to which the hypothesis (condition grade) is supported by the evidences (defects) (Bai et al. 2008).

After assigning the BPA's of each defect type, the weights (λn) are multiplied with the degrees of belief ($\beta_{n,i}$) to obtain the basic probability assignment ($m_{n,i}$) and the remaining probability mass using equations [3.1] and [3.2] as shown in Table 5.16. Moreover, the normalizing "K" value is calculated using equation [3.3]. After that, the combination of defect types was completed using equations [3.4] and [3.5]. This step is done by first combining the circumferential and longitudinal defects. The combined basic probability assignment is then aggregated with the third defect (multiple) where a new K-value is calculated and so on. This is done recursively until all of the defects related to the parent defect are aggregated. Finally, the aggregated degree of belief was calculated using equation [3.6].

In order to obtain an overall condition representing the whole pipe segment, the above mentioned procedure was applied repetitively in the manner presented in Table 5.17.

1. The pipeline's structural defects were aggregated to obtain the pipeline's structural condition $\{E_{11} \oplus E_{12} \oplus E_{13} \oplus E_{14}\}$.
2. The pipeline's operational defects were aggregated to obtain the pipeline's operational condition $\{E_{21} \oplus E_{22} \oplus E_{23} \oplus E_{24}\}$.
3. The pipeline's installation/rehabilitation defects were aggregated to obtain the pipeline's installation/rehabilitation $\{E_{31} \oplus E_{32} \oplus E_{33}\}$.
4. The pipeline's three defect families (structural, operational, and installation/rehabilitation) were aggregated to obtain the pipeline's condition $\{E_1 \oplus E_2 \oplus E_3\}$.
5. The same is done to compute the condition of the joints and manholes.
6. The pipeline, joint, and manhole are aggregated to obtain the segment's overall condition $\{E \oplus S \oplus C\}$.

Table 5. 16 ER Aggregation Process (Crack)

(Crack) Basic Probability Assignment		Excellent	Good	Fair	Poor	Critical	Ignorance	KI (1,2)	1.01
1	CIRCUMFERENTIAL	0.00	0.50	0.50	0.00	0.00	0.00	KI (1,3)	1.07
2	LONGITUDINAL	0.50	0.50	0.00	0.00	0.00	0.00	KI (1,4)	1.03
3	MULTIPLE	0.00	0.00	0.00	1.00	0.00	0.00	KI (1,5)	1.10
4	RADIATING	0.00	0.00	0.00	1.00	0.00	0.00		
5	SPIRAL	0.50	0.50	0.00	0.00	0.00	0.00		
	Weights	λ1	λ2	λ3	λ4	λ5			
		0.1	0.07	0.41	0.27	0.16			
	$m_{n,i}$	Basic Probability Assignment Multiplied by Weight					$m_{H,i}$		
	$m_{1,1}$	0.00	0.05	0.05	0.00	0.00	0.90		
	$m_{1,2}$	0.04	0.04	0.00	0.00	0.00	0.93		
	$m_{1,3}$	0.00	0.00	0.00	0.41	0.00	0.59		
	$m_{1,4}$	0.00	0.00	0.00	0.27	0.00	0.73		
	$m_{1,5}$	0.08	0.08	0.00	0.00	0.00	0.84		
	$m_{n,(i+1)}$	Aggregated Assignments					$m_{H,(i+1)}$		
	$m_{1,2\ (C\&L)}$	0.03	0.08	0.05	0.00	0.00	0.84		
	$m_{1,3\ (C\&L\&M)}$	0.02	0.05	0.03	0.37	0.00	0.53		
	$m_{1,4\ (C\&L\&M\&R)}$	0.01	0.04	0.02	0.53	0.00	0.40		
	$m_{1,5\ (C\&L\&M\&R\&S)}$	0.05	0.07	0.02	0.49	0.00	0.37		
β (P) Crack Condition >>>	β (P) Crack	0.07	0.12	0.03	0.77	0.00	0.00	5.86	

The same procedure is applied to all the defects in the pipe as shown in Table 5.17 in order to aggregate all the pieces of evidences available to obtain an overall hypothesis representing the pipe conditions.

Table 5. 17 Aggregation Workflow &Weights

Component	ω_i	Defect Categories	ω_i	Defects	ω_i	Defect Types	ω_i
PIPELINE (E)	0.38	Structural (E_1)	0.40	Crack (E_{11})	0.06	Circumferential	0.10
						Longitudinal	0.07
						Multiple	0.41
						Radiating	0.27
						Spiral	0.16
						SUM	1.00
				Fracture (E_{12})	0.16	Circumferential	0.11
						Longitudinal	0.08
						Multiple	0.39
						Radiating	0.26
						Spiral	0.16
						SUM	1.00
				Concrete Surface Damage (E_{13})	0.30	Spalling	0.03
						Aggregate Visible	0.08
						Aggregate Projecting	0.13
						Aggregate Missing	0.14
						Rein. Visible	0.18
						Rein. Projecting	0.19
						Rein. Corroded	0.25
				Physical Damage (E14)	0.47	SUM	1.00
						Sag	0.04
						Hole	0.10
						Deformation	0.15
						Broken	0.27
						Collapse	0.43
				SUM	1.00	SUM	1.00
		Operational (E_2)	0.25	Roots (E_{21})	0.19	Fine/single	0.07
						Dense	0.33
						Massive	0.60
						SUM	1.00

Table 5. 17 Aggregation Workflow &Weights (continued)

Component	ω_i	Defect Categories	ω_i	Defects	ω_i	Defect Types	ω_i
PIPELINE (E)	0.38	Operational (E_2)		Deposits (E_{22})	0.14	Debris	0.25
						Encrustation	0.61
						Foul	0.15
						SUM	1.00
				Infiltration (E_{23})	0.24	Seeping	0.05
						Dripping	0.15
						Running	0.31
						Gushing	0.49
						SUM	1.00
				Soil Intrusion (E_{24})	0.16	Coarse	0.76
						Fine	0.24
						SUM	1.00
				Protruding Services (E_{25})	0.28	N.A	
				SUM	1.00		
		Installation & Rehabilitation (E_3)	0.36	Defective Connection (E_{31})	0.25	N.A	
				Defective Lining (E_{32})	0.46		
				Defective Repair (E_{33})	0.30		
		SUM	1.00	SUM	1.00		
JOINT (S)	0.38	Structural (S_1)	0.61	Defective joint (S_{21})	0.48	N.A	
				Non-Concentric Joint (S_{22})	0.19		
				Open Joint	0.33		
				SUM	1.00		
		Operational (S_2)	0.39	Roots (S_{21})	0.16	Fine/single	0.07
						Dense	0.34
						Massive	0.60
						SUM	1.00
				Deposits (S_{22})	0.08	Debris	0.27
						Encrustation	0.60
						Foul	0.13
						SUM	1.00

Table 5. 17 Aggregation Workflow &Weights (continued)

Component	ω_i	Defect Categories	ω_i	Defects	ω_i	Defect Types	ω_i
JOINT (S)	0.38	Operational (S_2)	0.39	Infiltration (S_{23})	0.24	Seeping	0.05
						Dripping	0.15
						Running	0.49
						Gushing	0.31
						SUM	1.00
				Soil Intrusion (S_{24})	0.21	Coarse	0.77
						Fine	0.23
						SUM	1.00
				Protruding Serv. (S_{25})	0.31	N.A	
				SUM	1.00		
MANHOLE (C)	0.24	Structural (C_1)	0.37	Crack (C_{11})	0.07	Horizontal	0.40
						Vertical	0.60
						SUM	1.00
				Fracture (C_{12})	0.18	Horizontal	0.41
						Vertical	0.59
						SUM	1.00
				Concrete Surface Damage (C_{13})	0.30	Spalling	0.04
						Aggregate visible	0.10
						Aggregate missing	0.11
						Aggregate projecting	0.13
						Reinforcement visible	0.18
						Reinforcement projecting	0.19
						Reinforcement corroded	0.25
						SUM	1.00
				Physical damage (C_{14})	0.46	Pavement damage	0.06
						Cover damage	0.08
						Frame damage	0.09
						Deformation	0.14
						Broken	0.22
						Collapse	0.42
				SUM	1.00	SUM	1.00
		Operational (C_2)	0.30	Roots (C_{21})	0.21	Fine/single	0.06
						Dense	0.34
						Massive	0.60
						SUM	1.00

Table 5. 17 Aggregation Workflow &Weights (continued)

Component	ω_i	Defect Categories	ω_i	Defects	ω_i	Defect Types	ω_i
MANHOLE (C)	0.24	Operational (C_2)	0.30	Deposits (C_{22})	0.15	Debris	0.24
						Encrustation	0.61
						Foul	0.15
						SUM	1.00
				Infiltration (C_{23})	0.21	Seeping	0.05
						Dripping	0.15
						Running	0.49
						Gushing	0.31
						SUM	1.00
				Soil Intrusion (C_{24})	0.16	Coarse	0.80
						Fine	0.20
						SUM	1.00
				Protruding Services (C_{25})	0.27	N.A	
				SUM	1.00		
		Installation & Rehabilitation (C_3)	0.39	Defective ladder (C_{31})	0.11	N.A	
				Defective benching (C_{32})	0.20		
				Defective connection (C_{33})	0.28		
				Defective Landing (C_{34})	0.15		
				Defective channel (C_{35})	0.27		
SUM	1	SUM	1	SUM	1.00		

5.9 Defuzzification

The final process in a basic fuzzy synthetic evaluation is the defuzzification. Defuzzification is an important final step to encode the resulting synthesis of evidence into a single crisp value representing the overall condition. Moreover, the resulting number would be used by project managers, engineers, decision makers, and practitioners to decide on maintenance and rehabilitation programs. In this model the weighted – average method is used in order to obtain the crisp value using equation 5.1 adopted from (Ross 2010).

$$Crisp\ Value = \frac{\sum \mu_i z.z}{\sum \mu_i z} \qquad [5.1]$$

μ = degree of membership of each subset

z = centroid of symmetric membership function

For example, if the overall condition was represented by the following degrees of belief Overall Condition = { (E,0.27),(G,0.08),(F,0),(P,0),(C,0.65)}, then the defuzzification process will be calculated using the centroids of the scale fuzzy diagram (Figure 5.37) to give a crisp value of *(6.25/10)* that would be used in the protocol for further decisions.

5.10 Protocol

A protocol was created in order to represent the whole pipeline condition as well as provide some mapping actions relative to each pipe's grade. The following protocol represents the overall scale (0-10) in a (1-5) grading scheme that would enable professionals to describe the whole pipeline as well as compare it with different sewer condition protocols in which the usual grades are from 1-5. It also contains a linguistic description of each scale mapped with its description and examples of defects. Professionals can utilize this protocol in order to perform decision related to inspection, maintenance, and rehabilitation works. The protocol was sent to several experts through which it was revised and tailored according to experts' beliefs and opinions. Therefore, the protocol was verified and it was validated through the testing of the whole model using case studies. The protocol is presented in Table 5.18.

Table 5. 18 Sewer Condition Protocol

Pipe Segment Grade	Overall Scale	Linguistic Scale	Description	Defect Example	Action Plan
1	0-1	Excellent	No or Minor Defects of Low Severity-Acceptable Condition	- No Crack -Increased Roughness	Not Required, Inspect and monitor certain areas/ Intervention not needed
2	1-3	Good	Minor Defects of Low-Medium Severity where defects started to evolve	-Hairline fractures -<5% Deformation -5mm missing wall thickness/Slight Spalling -5% Reduction in area due to operational defects	Remove operational defects and put in place measures to identify defect causes
3	3-6	Fair	Moderate Defects of Medium Severity – Deterioration in progress	-(10-20mm) wide fractures -(10-50) mm Joint Opening with Leakage -(5-10)mm missing wall thickness/Aggregate Visible -(5-10)% Deformation -(10-25)% Reduction in Diameter(operational defects)	-Remove operational defects and put in place measures to identify defect causes -Increase inspection frequency -Consider medium-long term rehabilitation options to repair fractures/leaking joint (e.g. patch repair/resin injection...etc.)
4	6-8	Poor	Severe Defects	-(20-25mm) wide fractures - Major intruding connection affecting structural or operational integrity -Aggregate and/or Reinforcement projecting -Operational defects causing >25% loss of sectional area	Remove operational defects in the immediate term and put in place measures to identify cause/source Evaluate the criticality of the sewer and, subject to the findings, implement remedial measures (replace/rehabilitate) in the immediate-medium terms
5	8-10	Critical	Very Severe Defects /Total loss of structural integrity	->15mm missing wall thickness ->50% Reduction in Diameter due to operational defects -Hole (>3 Clock Positions) -Collapsed Pipe	-Sewer Replacement is needed due to complete disruption of service (failure). - Immediate action to remedy operational deficiencies and investigate the cause to prevent their recurrence)

5.11 Case Study 1 Implementation

5.11.1 Overview

An essential part in the model development is its implementation to real case studies with real data points. This is done to check the feasibility, applicability, and the validity of the model. The first case study was taken from Ville de Laval, Quebec, Canada. It included 15 pipe segments of different characteristics and lengths that sum up to 1056.4 meters of inspection length. The overall condition of each of the pipe segments was calculated and verified with real values.

5.11.2 Implementation and Results

The case studies covered several defects of structural, operational, and installation types and was implemented as shown in Figure

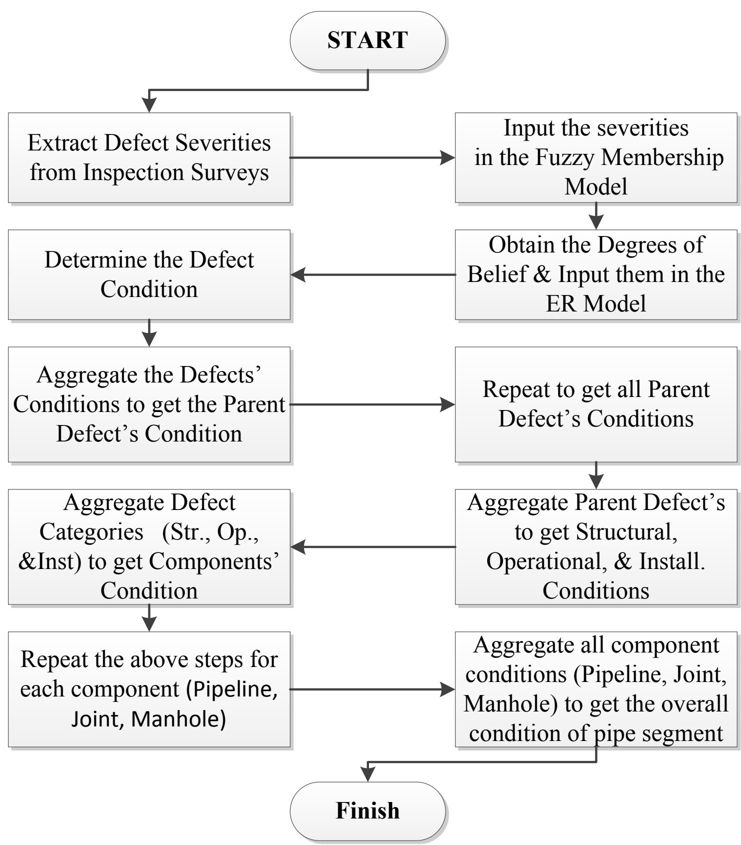


Figure 5. 39 Case Study Workflow

Tables 5.19 & 5.20 represent the condition assessment of two pipeline segments. These tables show the predicted scores in comparison with the real score available in the inspection report. Moreover, the differences between the model predictions and case study values are justified by a logical explanation. For the rest of the pipe segments please refer to Appendix A.

Table 5. 19 Case Study 1 (Segment 1)

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
R-1 Boulevard Saint-Rose Laval Segment 1	Circumferential Crack		0.50	0.50	0.00	0.00	0.00	*8.66* (5)	*2.76* (2)	-	-	-	-	-	-	***Total*** *Overall Condition*
	Crack Longitudinal		0.00	0.00	0.00	1.00	0.00									
	Crack Multiple		0.00	0.00	0.00	1.00	0.00									
	Circumferential Fracture		0.50	0.50	0.00	0.00	0.00									
	Fracture Longitudinal		0.00	0.00	0.33	0.67	0.00									
	Fracture Multiple		0.00	0.00	0.00	0.00	1.00									
	Deformation 25%		0.00	0.00	0.00	0.00	1.00									
	Broken		0.00	0.00	0.00	0.00	1.00									
	Debris 5% Reduction		0.50	0.50	0.00	0.00	0.00									
	Encrustation 1 % Reduction		1.00	0.00	0.00	0.00	0.00									
	Soil Intrusion 10% Coarse		0.00	0.75	0.25	0.00	0.00									
	Protruding Services 16%		0.00	0.15	0.85	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.16	0.05	0.17	0.04	0.58	***6.15*** **(4)**			**-**		**-**			***6.15*** **(5)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(5) Operational=(2)**													

Table 5. 20 Case Study 1 (Segment 2)

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
R-2 Boulevard Saint-Rose Laval Segment 2	Spalling		0.50	0.50	0.00	0.00	0.00	2.15 (2)	2.63 (2)	9.00 (5)	-	-	-	-	-	***Total*** *Overall Condition*
	Crack Longitudinal		0.00	0.00	0.00	1.00	0.00									
	Circumferential Fracture		0.50	0.50	0.00	0.00	0.00									
	Fracture Longitudinal		0.00	0.67	0.33	0.00	0.00									
	Defective Connection >3/Pipe Length		0.00	0.00	0.00	0.00	1.00									
	Protruding Services 16%		0.00	0.15	0.85	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.17	0.43	0.07	0.03	0.30	***3.56*** **(3)**			**-**		**-**			***4.26*** **(3)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(3) Operational=(3)**													

Note: Installation Defects scored a 9/10 which means that there are an adequate number of installation defects that should be considered, inspected, and repaired.

Table 5. 21 Case Study 1 Results

Case Study	Inspection Length (m)	Case Study Results (Scores 1-5)			Model Results (Scores 1-5)								
					Pipeline			Joint		Manhole			Overall Condition
		Str.	Op.	Overall	STr.	Op.	Install. & Rehab.	STr.	Op.	STr.	Op.	Install. & Rehab.	
1	72.60	5	2	N.A	5	2	N.A	N.A	N.A	N.A	N.A	N.A	5
2	71.60	3	3	N.A	2	2	5	N.A	N.A	N.A	N.A	N.A	3
3	102.00	5	4	N.A	4	3	N.A	3	N.A	N.A	N.A	N.A	3
4	25.10	0	3	N.A	0	3	N.A	N.A	N.A	N.A	N.A	N.A	3
5	76.60	3	5	N.A	2	2	N.A	N.A	5	N.A	N.A	N.A	5
6	22.80	2	4	N.A	2	3	N.A	N.A	N.A	N.A	N.A	N.A	3
7	70.10	2	4	N.A	3	2	N.A	N.A	N.A	N.A	N.A	N.A	3
8	96.80	5	2	N.A	3	2	5	N.A	N.A	N.A	N.A	N.A	3
9	60.20	4	2	N.A	4	2	N.A	N.A	N.A	N.A	N.A	N.A	3
10	69.00	2	0	N.A	2	0	N.A	N.A	N.A	N.A	N.A	N.A	2
11	68.40	2	2	N.A	2	2	N.A	N.A	N.A	N.A	N.A	N.A	2
12	94.60	5	3	N.A	4	3	N.A	N.A	N.A	N.A	N.A	N.A	3
13	109.10	5	4	N.A	3	3	N.A	N.A	N.A	N.A	N.A	N.A	3
14	64.60	4	2	N.A	4	2	N.A	N.A	N.A	N.A	N.A	N.A	3
15	53.00	4	3	N.A	4	3	N.A	N.A	N.A	N.A	N.A	N.A	4
Total	1056.50												

Table 5.21 shown above compares the results of the 15 pipe segments that were investigated. It compares the structural and operational defects of the pipeline and joint components between the case study values and model predictions. The case study scores the defects based on NASSCO PACP scoring methodology on a scale from 1-5. It also utilizes the peak score scoring method. Unfortunately, there were no inspection reports that included manhole's investigation to be included in the results discussion. The real structural and operational indices were compared with the predicted structural and operational scores obtained from the developed model. In some cases, the developed model takes into consideration that if one of the defect families (structural, and operational) scores 5/5 (Critical), then the overall condition of the pipeline is taken to be critical. This is since the pipe's structural and operational conditions should not reach the critical stage in order to maintain a good structural integrity and operational performance.

Figures 5.40 and 5.41 are scatter charts that compare the results between the developed model and the case studies. The x-axis in these charts represents the pipe segments whereas the y-axis represents the score. The shapes in the diagram represent the predicted and real values as shown in the legend. Figures 5.42 and 5.43 represent a bar chart that compares some statistics between the developed model and the case studies. The y-axis represents the percentage of a certain score with respect to the total number of scores. For example 35 % of the pipe segments were given a structural condition of 2.

The predicted and real values were identical in segments (1, 4, 9, 10, 11, 14, and 15). In segment number 2, the installation defects scored (5).This indicates that there is a considerable amount of installation defects that need to be inspected and repaired.

In Segments 3, 5, and 6 there is a one grade difference between real and predicted structural and operational conditions. This is because the inspection report considered the CCTV camera being fully submerged in water as a critical defect. The inconsistency in the results here is because this issue was out of the scope of this research.

In segments 8 and 13, there is a two grades difference between the model's value and the case study's value since the latter considered having a visible reinforcement as a critical defect of score 5. However, the model gives this defect a score between (3 and 4). This shows that the current approach used in the inspection report does not represent the pipe's condition in a precise way. It also shows that if the PACP code is used, then a pipe with visible reinforcement and a totally collapsed pipe both receive a score of 5. This will mislead the decision makers in rehabilitation, maintenance, and budget allocation prioritization. However, in the developed model, a pipe with a visible reinforcement receives a score close to 4 which asks for sewer criticality evaluation and rehabilitation measures. This would give a better representation and would allow the decision-makers to perform well tailored decisions to meet their performance expectations.

The mean absolute error and the correlation coefficients were calculated for the structural and operational defects separately.

$$Mean\ Absolute\ Error = \frac{\sum_{i=1}^{n}(Model\ Prediction - Case\ Value)}{Number\ of\ segments} \qquad [5.2]$$

The mean absolute error for structural and operational conditions was calculated by computing the difference between the predicted and real values for each segment. After that, these differences were summed and divided by the number of segments as shown in equation 5.2. Consequently, the MAE values for the structural and operational conditions turned out to be 0.533 and 0.267 respectively. The following errors were justified by the explanations provided above. Mostly, the error is substantial since the difference between results is (one whole number) due to the simple scoring method used. Moreover, the calculated correlation coefficients for the structural and operational defects were 0.846 and 0.934 which indicates that there is a strong linear relationship between the predicted and real values.

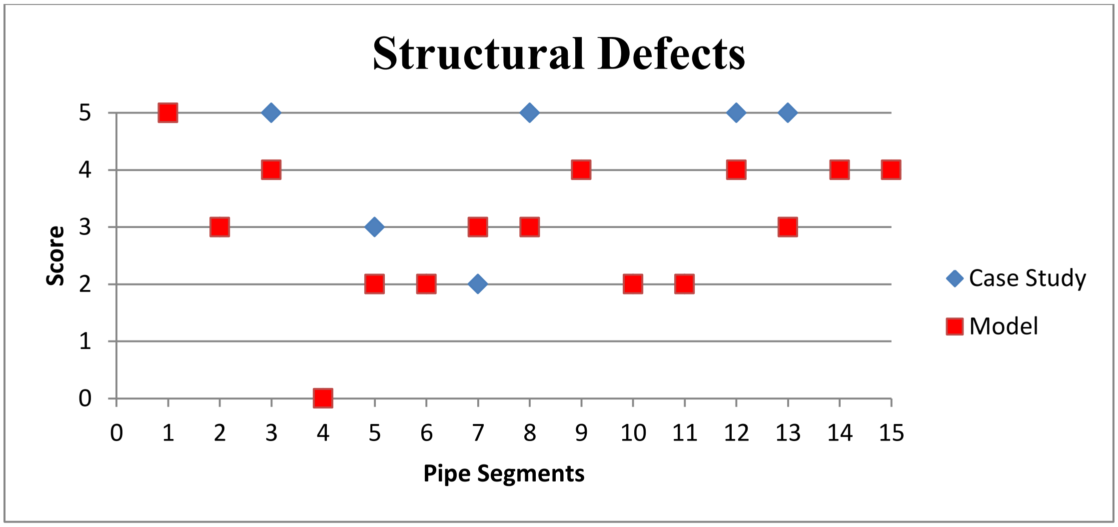


Figure 5. 40 Structural Defects Scatter Diagram (Case Study vs. Model)

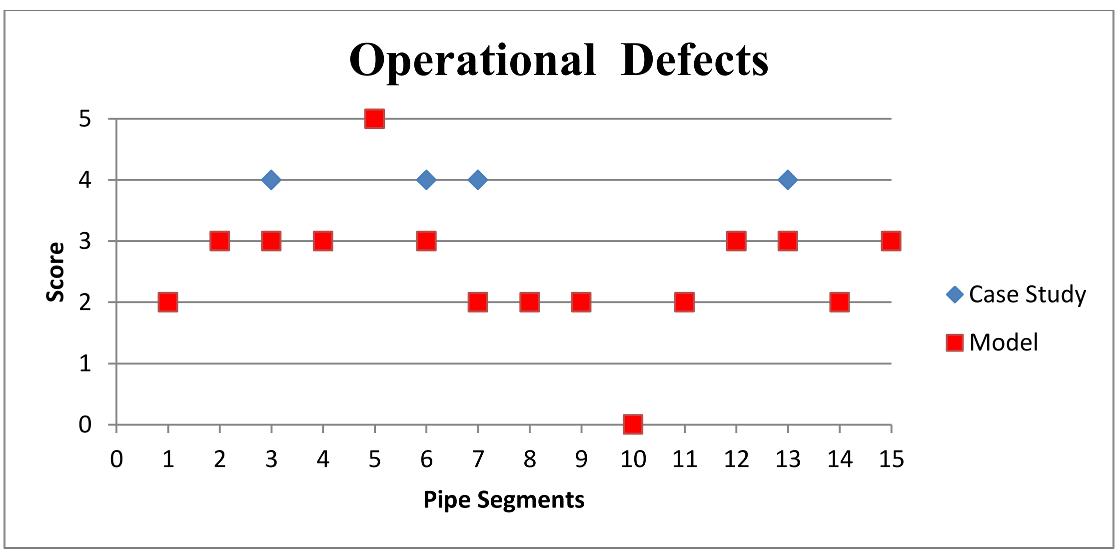


Figure 5. 41 Operational Defects Scatter Diagram (Case Study vs. Model)

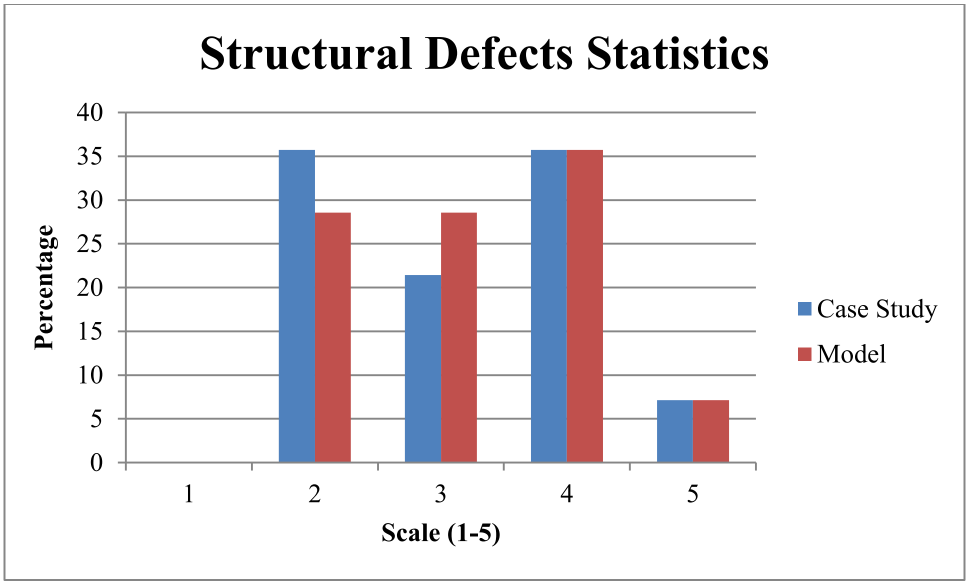


Figure 5. 42 Structural Defects Percentages of Scores (Case Study vs. Model)

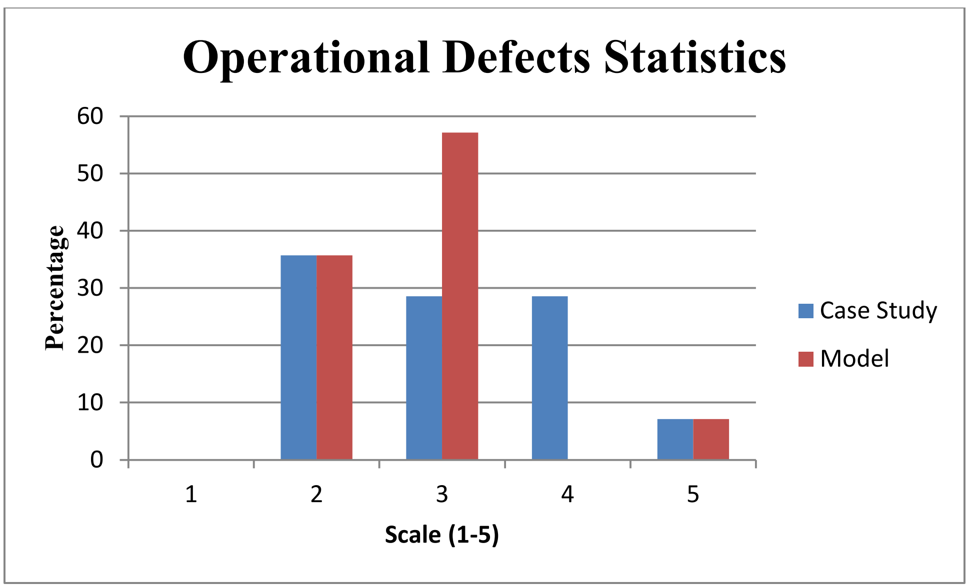


Figure 5. 43 Operational Defects Percentages of Scores (Case Study vs. Model)

5.12 Case Study 2 Implementation

5.12.1 Overview

The second case study was taken from the public works authority (Ashghal) located in Qatar. It included 14 pipe segments of different characteristics with a total inspection length of 909.86 meters. The inspection reports done by Ashghal use the Euro Code (EN13508) for the condition codes and [EUROdss based on (DWA-M 149-3)] for the class model. It was understood from the inspection reports that the scale used was from (0-4) with 0 and 4 being worst and best. Therefore, this scale was encoded to the 5 points scale developed in this model through mapping each number of the report's scale to that of the model's. The investigated pipelines located in Qatar are highlighted in Figure 5.44 from Google Maps. The pipe segments of six major streets were investigated as discussed through the analysis of this case study.

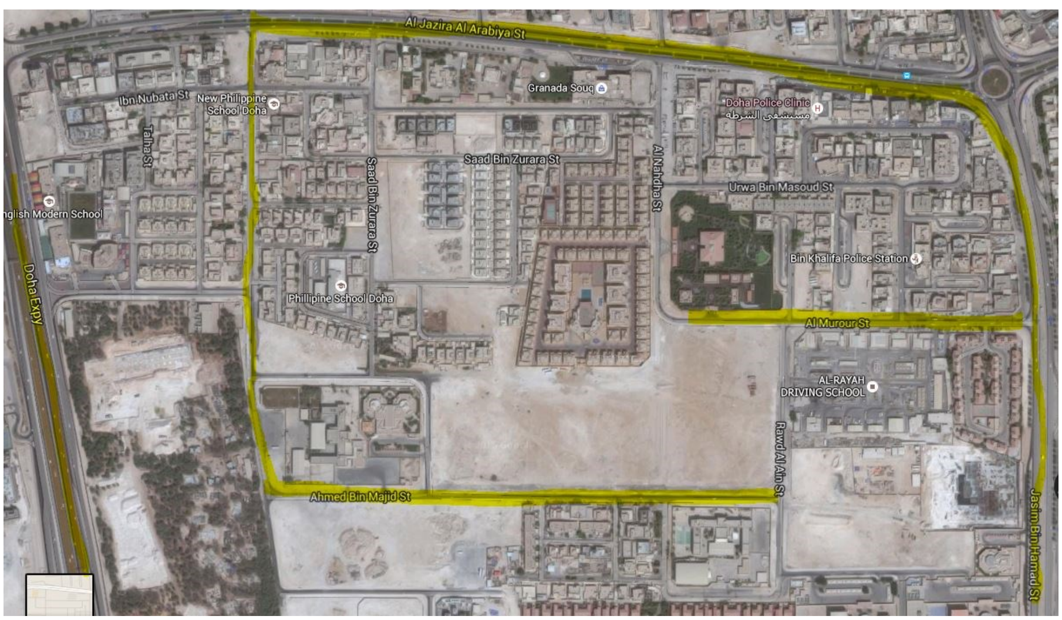


Figure 5. 44 Qatar Pipeline Network (Case Study 2)

Tables 5.22 & 5.23 represent the condition assessment of two pipeline segments. These tables show the predicted scores in comparison with the real score available in the inspection report. Moreover, each difference between the model predictions and case study values is justified by a logical explanation. For the rest of the pipe segments please refer to Appendix B.

Table 5. 22 Case Study 2 (Segment 1)

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			***Total***
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	*Overall Condition*
14_1_B7_10 14_1_B7_9	Spalling		0.50	0.50	0.00	0.00	0.00	*1.50* (2)	*2.72* (2)	-	*2.99* *(3)*	-	-	-	-	
	Deposits (4% Reduction)		0.00	0.70	0.30	0.00	0.00									
	Protruding Services (15%)		0.00	0.25	0.75	0.00	0.00									
	Open Joint 15 mm		0.00	0.60	0.40	0.00	0.00									
	Open Joint (2 & 3 Degrees)		0.40	0.60	0.00	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.20	0.55	0.25	0.00	0.00		***1.88*** **(2)**		***2.99*** ***(3)***			**-**		***2.43*** **(2)**
	Ashghal Results	**(Simple Scale)**	**Overall Condition = (3)**													

Table 5. 23 Case Study 2 (Segment 2)

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			***Total***
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	*Overall Condition*
14_1_B7_11 14_1_B7_10	Deposits (25% Reduction)		0.00	0.00	0.63	0.38	0.00	-	5.42 (3)	-	1.61 (2)	-	-	-	-	
	Protruding Services (25%)		0.00	0.00	0.63	0.38	0.00									
	Open Joint 3 mm		0.40	0.60	0.00	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.20	0.30	0.32	0.18	0.00		***5.42*** **(3)**		**-**			**-**		***3.52*** **(3)**
	Ashghal Results	**(Simple Scale)**	**Overall Condition = (3)**													

Table 5. 24 Case Study 2 Results

Case Study	Inspection Length (m)	Case Study Results (Scores 1-5)			Model Results (Scores 1-5)								
					Pipeline			Joint		Manhole			Overall Condition
		Str.	Op.	Overall	STr.	Op.	Install. & Rehab.	STr.	Op.	STr.	Op.	Install. & Rehab.	
1	55.10	N.A	N.A	3	2	2	N.A	3	N.A	N.A	N.A	N.A	2
2	50.00	N.A	N.A	3	N.A	3	N.A	2	N.A	N.A	N.A	N.A	3
3	71.00	N.A	N.A	3	2	3	N.A	2	N.A	N.A	N.A	N.A	2
4	60.10	N.A	N.A	4	5		N.A	2	N.A	N.A	N.A	N.A	5
5	67.62	N.A	N.A	5	2	5	N.A	2	N.A	N.A	N.A	N.A	5
6	58.29	N.A	N.A	2	2	2	N.A	2	N.A	N.A	N.A	N.A	2
7	81.00	N.A	N.A	3	2	N.A	N.A	3	N.A	N.A	N.A	N.A	3
8	62.50	N.A	N.A	3	2	N.A	N.A	3	N.A	N.A	N.A	N.A	2
9	67.99	N.A	N.A	5	2	3	N.A	3	N.A	N.A	N.A	N.A	3
10	67.92	N.A	N.A	3	N.A	N.A	N.A	3	N.A	N.A	N.A	N.A	3
11	75.10	N.A	N.A	3	2	2	N.A	3	N.A	N.A	N.A	N.A	3
12	60.00	N.A	N.A	5	5	2	N.A	3	N.A	N.A	N.A	N.A	5
13	63.00	N.A	N.A	2	N.A	2	N.A	N.A	N.A	N.A	N.A	N.A	2
14	70.24	N.A	N.A	5	3	2	N.A	N.A	N.A	N.A	N.A	N.A	2
Total	909.86												

5.12.2 Implementation and Results

Table 5.24 compares the results of the 14 pipe segments that were investigated. It compares the pipe's overall condition of each segment between the case study values and model predictions. The case study scores the defects based on a scoring methodology of rehabilitation points on a scale from 0-4 with 4 being worst and 0 being the best. Unfortunately, there were no inspection reports that included manhole's investigation to be included in the results discussion. The overall condition index was compared to the overall score obtained from the developed model for each segment. In some segments, the developed model directly assigns a critical overall condition to the segment if one of the defect families (structural and operational) scores 5/5 (Critical). In some of the investigated segments the overall scores differ by a single grade (example Model=2, Case=3). This is because the scoring methodology used in the case study utilizes the peak score whereas the developed model utilizes the evidential reasoning approach in an attempt to collect all the evidences that lead to a certain hypothesis. This approach gives a precise score rather than the peak score.

Figures 5.45 is a scatter chart that compares the results between the developed model and the case studies. The x-axis in this chart represents the pipe segments whereas the y-axis represents the score. The shapes in the diagram represent the predicted and real values as shown in the legend. Figure 5.46 represents a bar chart that compares the results between the developed model and the case studies. The y-axis represents the percentage of a certain score with respect to the total number of scores.

The predicted and real values were identical in segments (2, 5, 6, 7, 10, 11, 12 and 13). In segment 4, the model gives a critical score of 5 since the structural condition of the pipeline is given to be critical. A critical condition in any component raises a red flag in which the overall condition of the pipeline should be critical. However, the case study gives a score of 4 which assesses the pipe condition as Fair where in fact it should be Critical. In segment 5, the model gives a score of 5(critical) although the structural condition is 2 (good) .This is because 99% of the pipeline's cross section is blocked due to operational defects. This shows that the model takes into consideration the social cost and the consumer's satisfaction through considering the pipeline's performance. In segment 8, the real overall condition value is 3 whereas the model gives an overall score of 2. This is since both pipelines and joints both contribute equally with a weight of 38% to the whole pipeline's condition. This issue flattens the overall score after the components' aggregation. Finally, in segments 9 and 14, the case study gives a critical score of 5 due to 5% soil intrusion. However, the developed model does not consider the soil intrusion as a critical defect giving the pipeline an overall score of 2.

The mean absolute error and the correlation coefficients were calculated for the predicted overall condition scores using equation 5.2 as discussed in case study 1. The mean absolute error turned out to be 0.643. The following errors were justified by the explanations provided above. Mostly, the error is substantial since the difference between results is (one whole number) due to the simple scoring method used. Moreover, the calculated correlation coefficients for the predicted overall condition scores was 0.60 which indicates that there is a linear relationship of medium strength between the predicted and real values due to the above mentioned explanation.

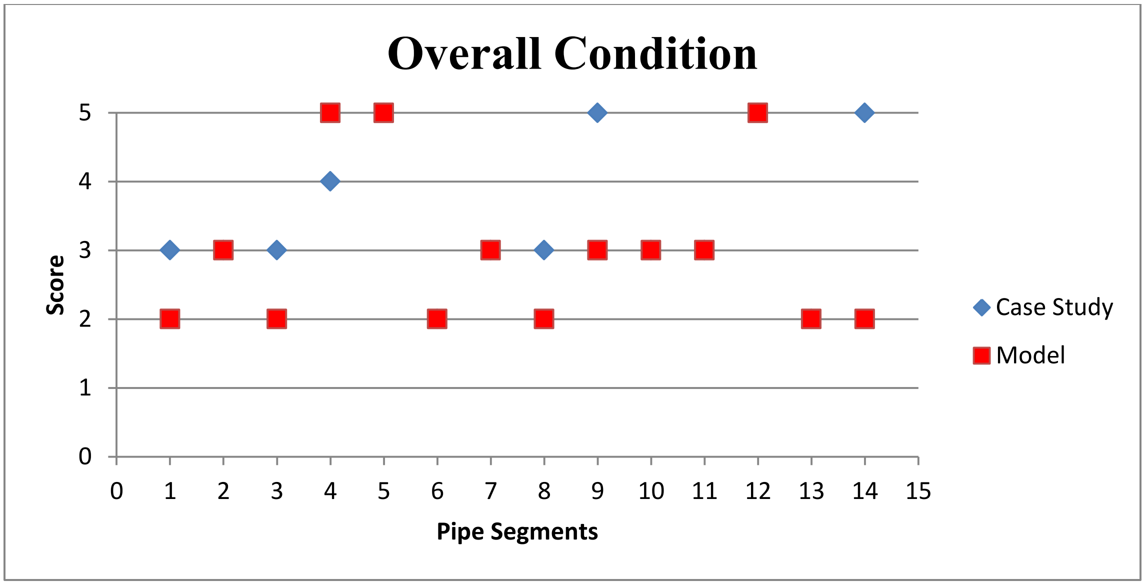


Figure 5. 45 Overall Condition Scores Scatter Diagram (Case Study vs. Model)

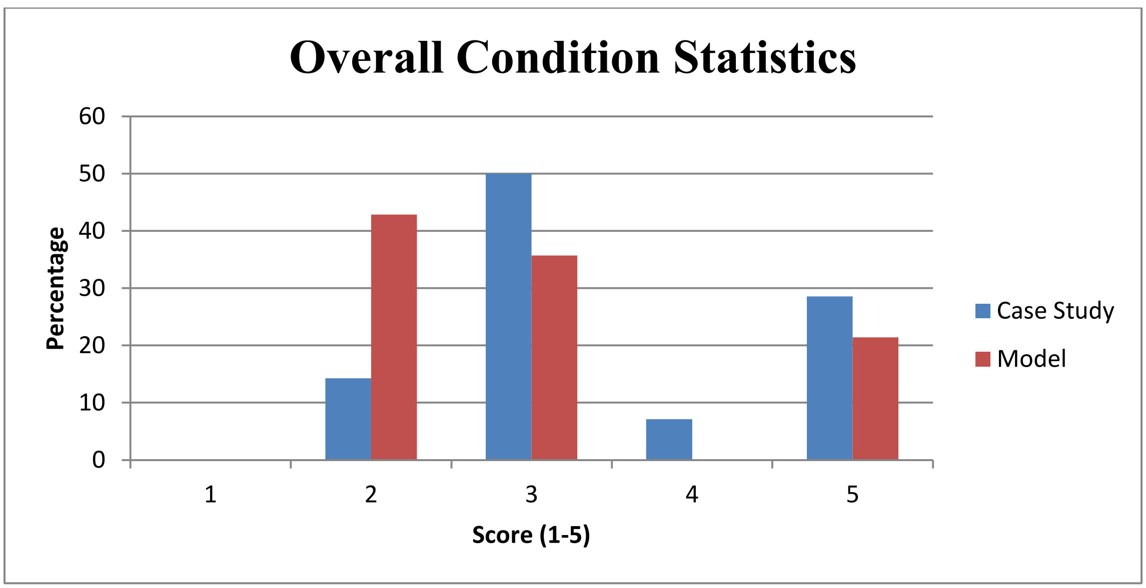


Figure 5. 46 Overall Condition Percentages of Scores (Case Study vs. Model)

5.13 WRc and PACP Vs. Developed Model

The WRc and PACP sewer condition assessment protocols vary from the developed model in several aspects throughout the condition assessment path. Firstly, the existing protocols assign fixed deduct values for the corresponding defects. These deduct values are rarely associated with defect features and are associated with their severity (low, medium, high) mostly. This assignation of deduct values will increase the imprecision throughout the extraction of a defect and encoding it into a conditions score. On the contrary, the developed model inputs the defect features into its fuzzy membership functions to extract basic probability assignments that would portray the degree in which the available evidence (measurable criteria) support the hypothesis (condition grades). This will mitigate the uncertainty and make use of the tolerance associated with imprecision. Secondly, the developed model covers a wide range of defects and combines them in one combined index in which the available protocols treat structural and operational defects separately. Thirdly, the joint is treated as a normal defect in the existing protocols which hinders its effect on the whole pipe length. On the contrary, in the developed model it is treated as a separate component to be able to determine the joints' condition in the pipe segment. Also, the WRc has different grading scales (1-165) for structural and (1-10) for operational defect. However, the developed model has one standard scale that can be used in any municipality or city regardless of the extracted defects. The fifth difference is that most of the available protocols utilize the peak score or weighted average. However, the developed model utilizes the HER aggregation to determine the defects' effect on the whole pipe segment. Finally, the developed model considers the defects' interdependency which is a limitation to existing protocols.

5.14 Sensitivity Analysis

In an attempt to test the robustness of the developed model and its sensitivity to changes in the input values, sensitivity analysis was conducted with respect to the structural, operational, and overall condition of the pipeline. The sensitivity analysis was also conducted to test the relationship between the inputs and structural, operational, and overall output. It also shows the degree to which any change in the inputs (defect features) could affect the potential output.

The methodology adapted in performing the sensitivity analysis commences by maintaining the available defects in an average condition. After that, the input of a particular defect changes from the lowest to the highest available severity. Eventually, the corresponding condition is pointed down in 10% intervals of the input criteria till the sensitivity curve emerges. This methodology was applied on the structural, operational and overall pipeline condition to result in Figures 5.47, 5.48, & 5.49.

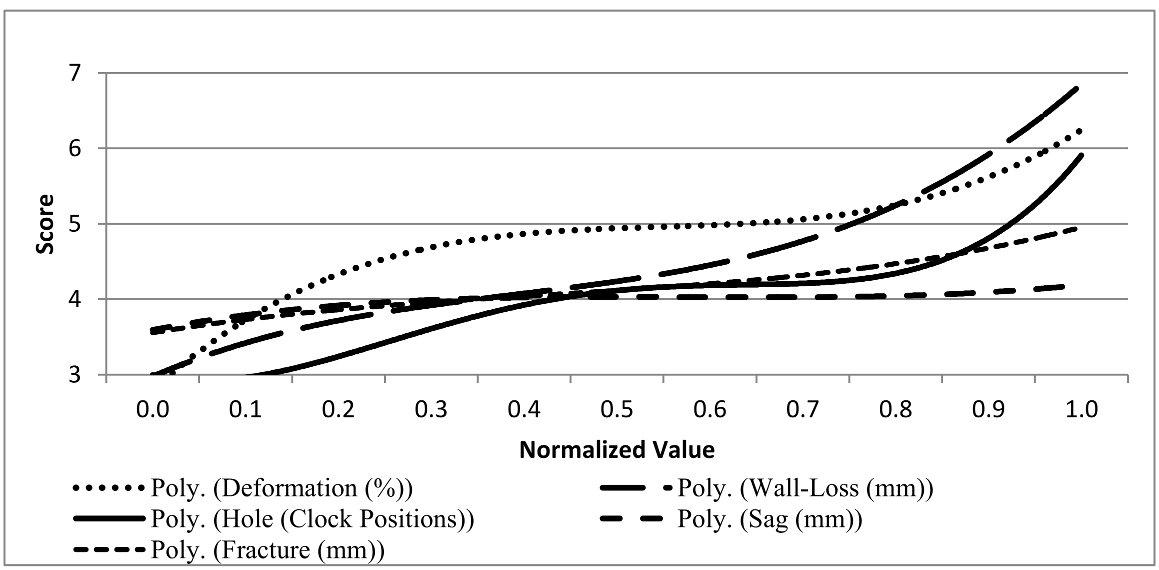


Figure 5. 47 Structural Defects Sensitivity Analysis

The defects swing from score 3 to 7 in different manners according to their effect on the overall structural integrity. Some of them affect the condition drastically over the 10% intervals such as the deformation whereas others might affect the condition slightly as shown in the Sag curve. It is important to note that the defect features where normalized since they have different measuring criteria. The same was done for the operational defects as shown below.

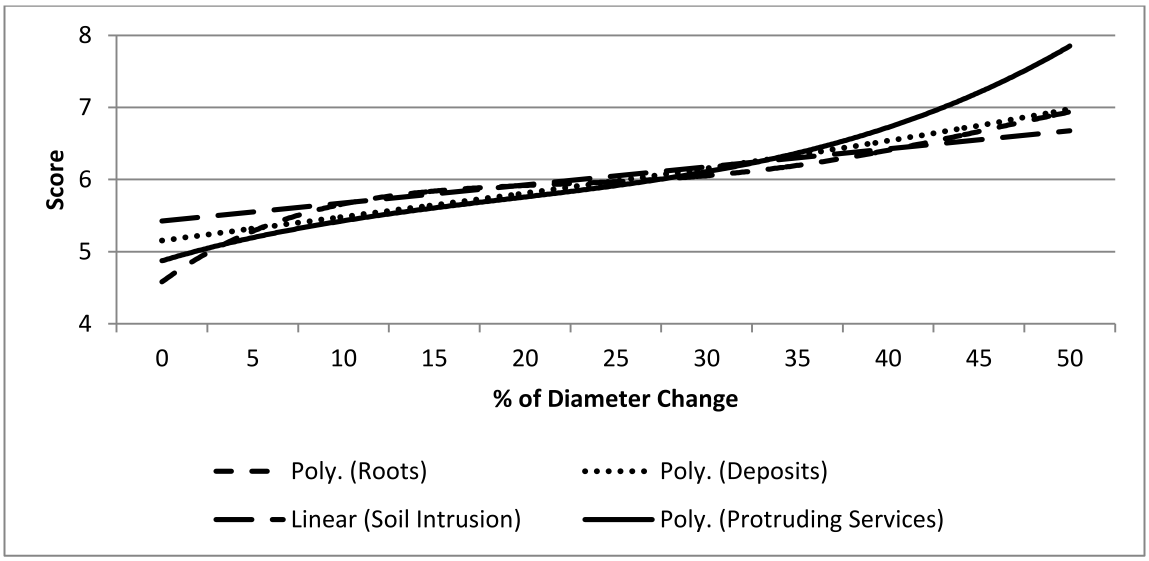


Figure 5. 48 Operational Defects Sensitivity Analysis

It is clear in Figure 5.48 that the protruding services have the most effect on the pipeline's condition. Figure 5.49 shows the sensitivity analysis applied on the overall condition of the pipeline. That is done by first changing one structural defect from lowest to highest while keeping other structural and operational defects in an average condition. Then the same is done for one operational defect while keeping all other defects in overall condition. The third test was by changing two defects (one structural, one operational) while keeping other defects in an average condition. It is referred to the third application as the combined effect.

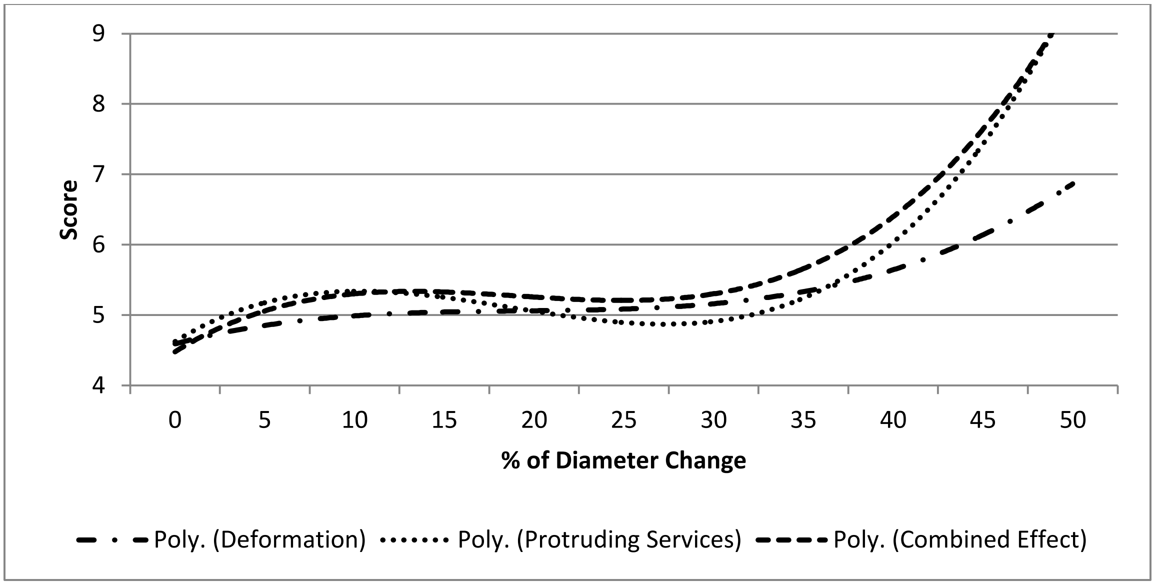


Figure 5. 49 Overall Condition Sensitivity Analysis

It is clear that when the combined effect is used the graph shifts up indicating a higher severity of the pipeline's integrity. This shows that if a combined index is used, it better represents the pipeline's integrity.

CHAPTER SIX:
CONDTION ASSESSMENT AUTOMATED TOOL

6.1 Introduction

After developing the Fuzzy Based Sewer Condition Assessment Model, and incorporating all of the pipeline components and defects, it is essential to put this model into practice. One of the main needed tasks after performing certain work is to present this work and make it comprehensible to the targeted audience. Therefore, this model has been implemented on Excel and Visual Basic incorporating all the inputs and outputs. The whole process has been automated through incorporated formulas and (if/then) functions. The tool includes the fuzzified membership functions that are used to determine the degrees of belief of each component, defect, and defect type. It also includes the relative importance weights of each component, defect, and defect type that were calculated through ANP. Moreover, the whole aggregation process through the ER approach has been done in this framework.

To make this tool practical and effective, a Visual Basic interface was created that will allow users, practitioners, decision-makers, and managers to determine the pipeline's structural, operational, and installation/rehabilitation condition through inputting the available defect severities as indicated in the model. The developed user interface also allows the practitioners to determine the pipeline's overall condition (pipeline, joint, and manholes). It also allows them to save the pipes' characteristics and their respective conditions in a database incorporated in the Excel Sheet.

6.2 Automated Tool Interface

The Sewer Pipeline Condition Assessment Automated Tool (SPCAT) consists of three defect families (structural, operational, installation / rehabilitation) to assess the condition of sewer pipeline components, namely pipelines, joints and manholes through which the overall condition of the pipeline can be reasoned. The developed tool is a user friendly interface that aids the user in obtaining the respective conditions through incorporating the defects obtained from Closed Circuit Television (CCTV) surveys. Below are different snapshots from the proposed developed tool.

1. In the Home Page, select the desired component and proceed to step 2.
2. Insert the defect sub category with maximum severity of each defect type.
3. After inserting all defects press compute
4. Proceed to next page and repeat steps 1&2
5. Repeat the above steps for all of the desired components and their corresponding defect families.
6. Proceed to the “Overall Condition” tab, press “Overall Conditions” button and view the results.
7. A pop-up window will appear asking to save the information to the database.
8. Insert the required information and press save to database.
9. Save the results in the desired location

Figure 6.1 in the next page provides the user with a detailed explanation of the condition assessment flow in the developed user interface.

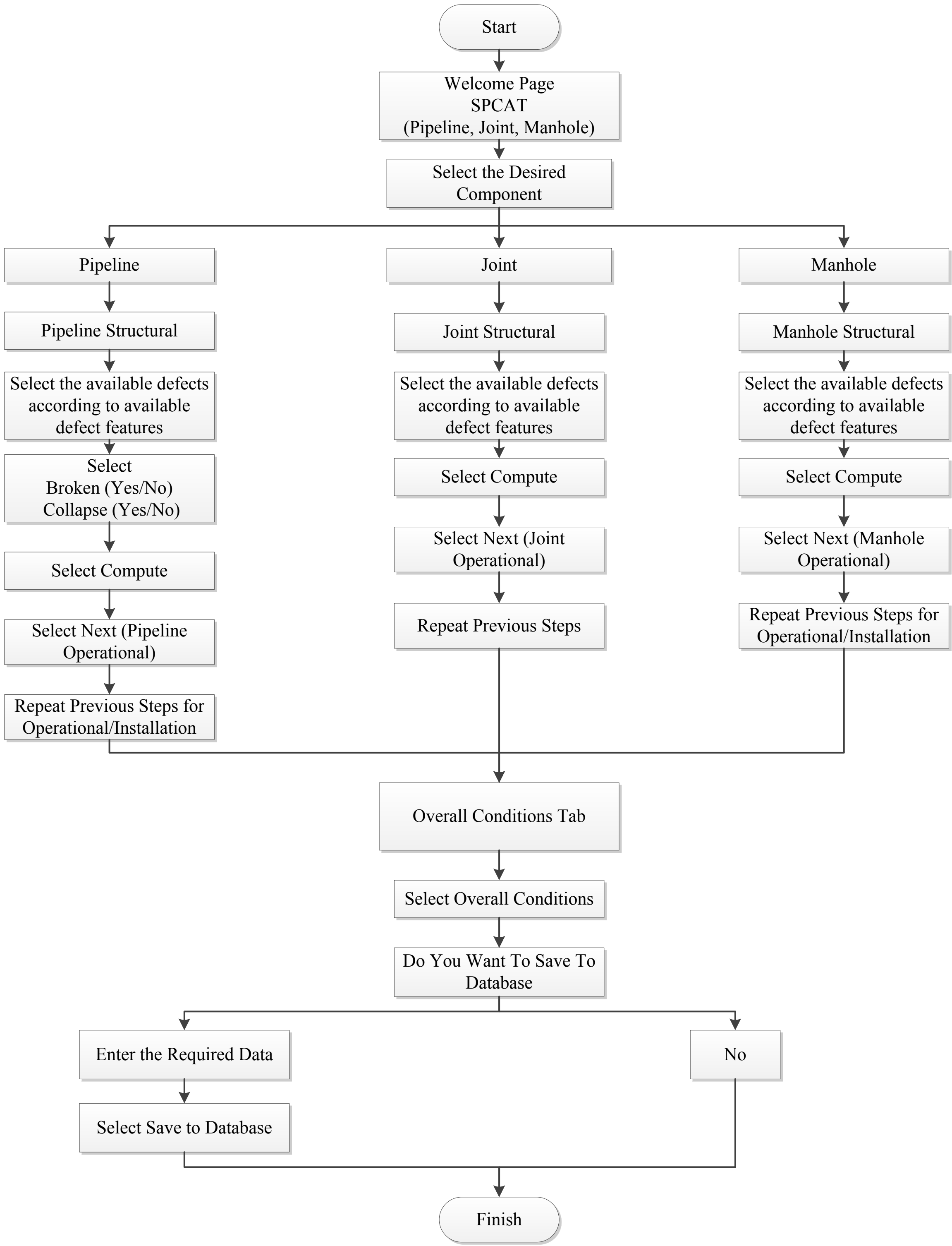


Figure 6. 1 Condition Assessment Automated Tool Flowchart

The following Figures (6.2-6.5) show a sample of the developed automated tool through Visual Basic and Excel Sheets.

The user can find the different components, their types, and the overall condition button in the home page. Pressing any of these buttons will take the user directly to the desired condition assessment page where the inputs are entered.

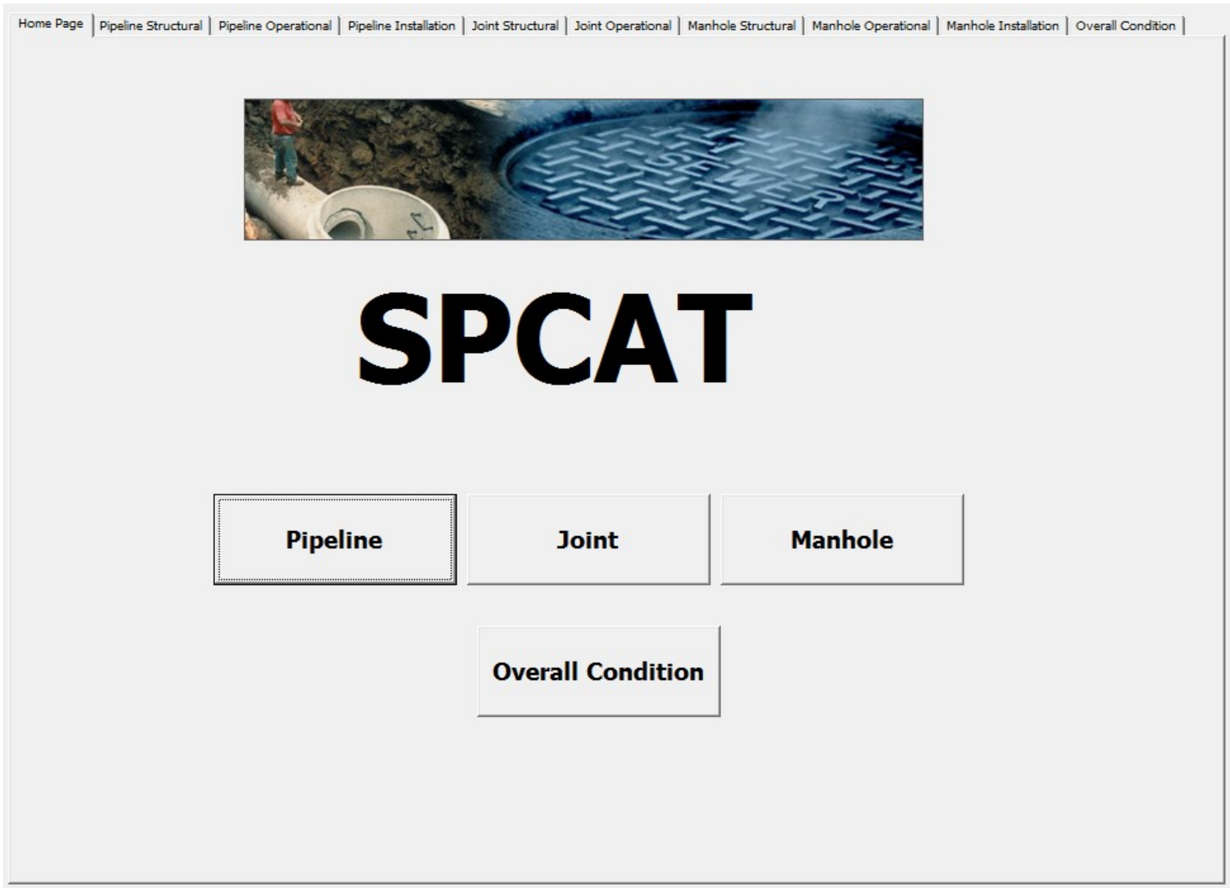


Figure 6. 2 Condition Assessment Automated Tool (Home Page)

In this page, the user can find the different structural defects and their types in which the defect features are selected according from the drop down menus shown. After entering all the desired defects, the user can press *Compute* to calculate the aggregated condition.

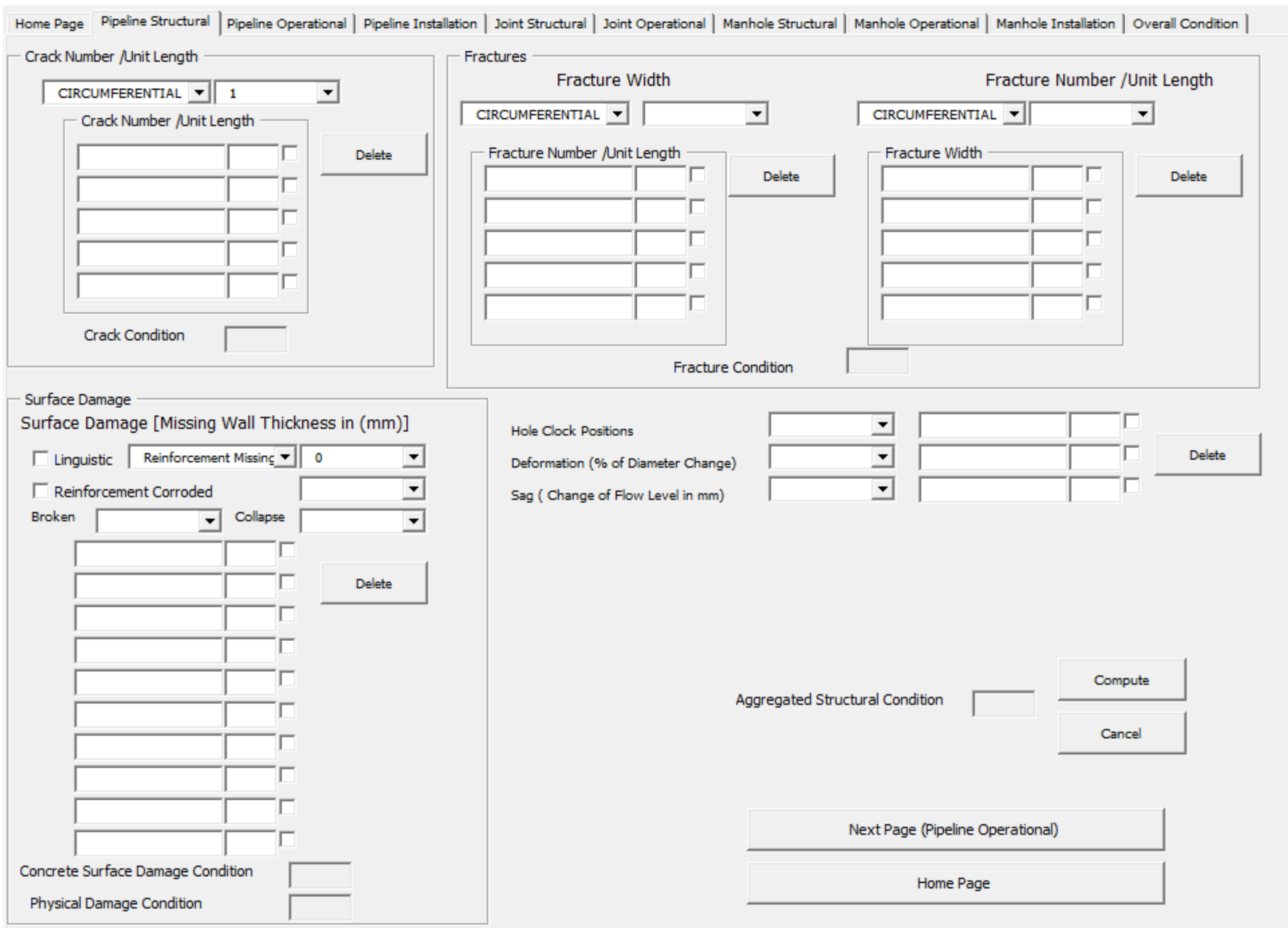


Figure 6. 3 Condition Assessment Automated Tool (Pipeline's Structural Condition)

In this page, the user can find the different operational defects and their types in which they are selected according to the criteria available in hand. After entering all the desired defects, the user can press *Compute* to calculate the aggregated condition.

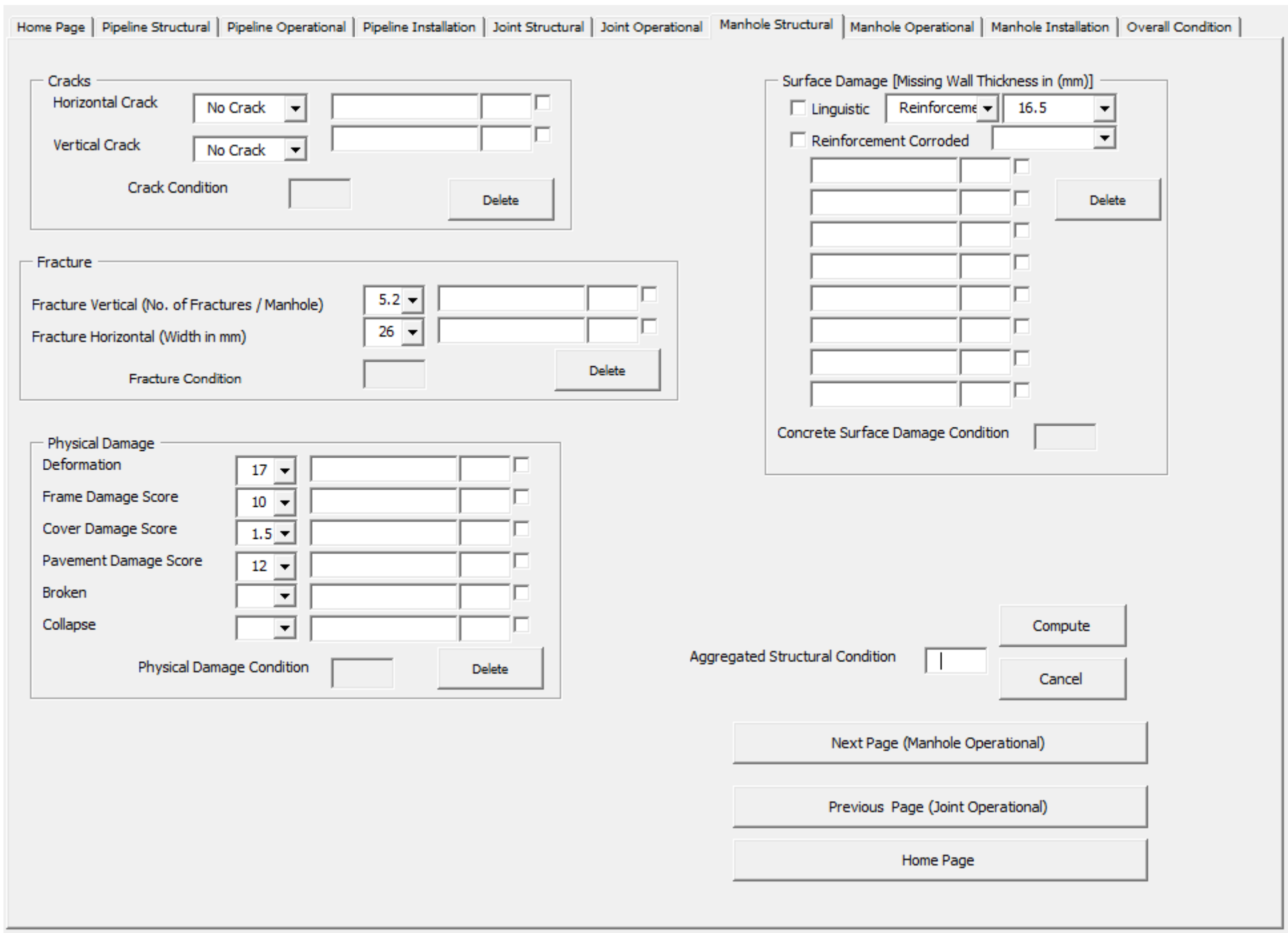


Figure 6. 4 Condition Assessment Automated Tool (Pipeline's Operational Condition)

This is the final page in which all of the components' conditions are aggregated. The overall score is also linked to the developed protocol and the corresponding action plan as shown in Figure 6.5.

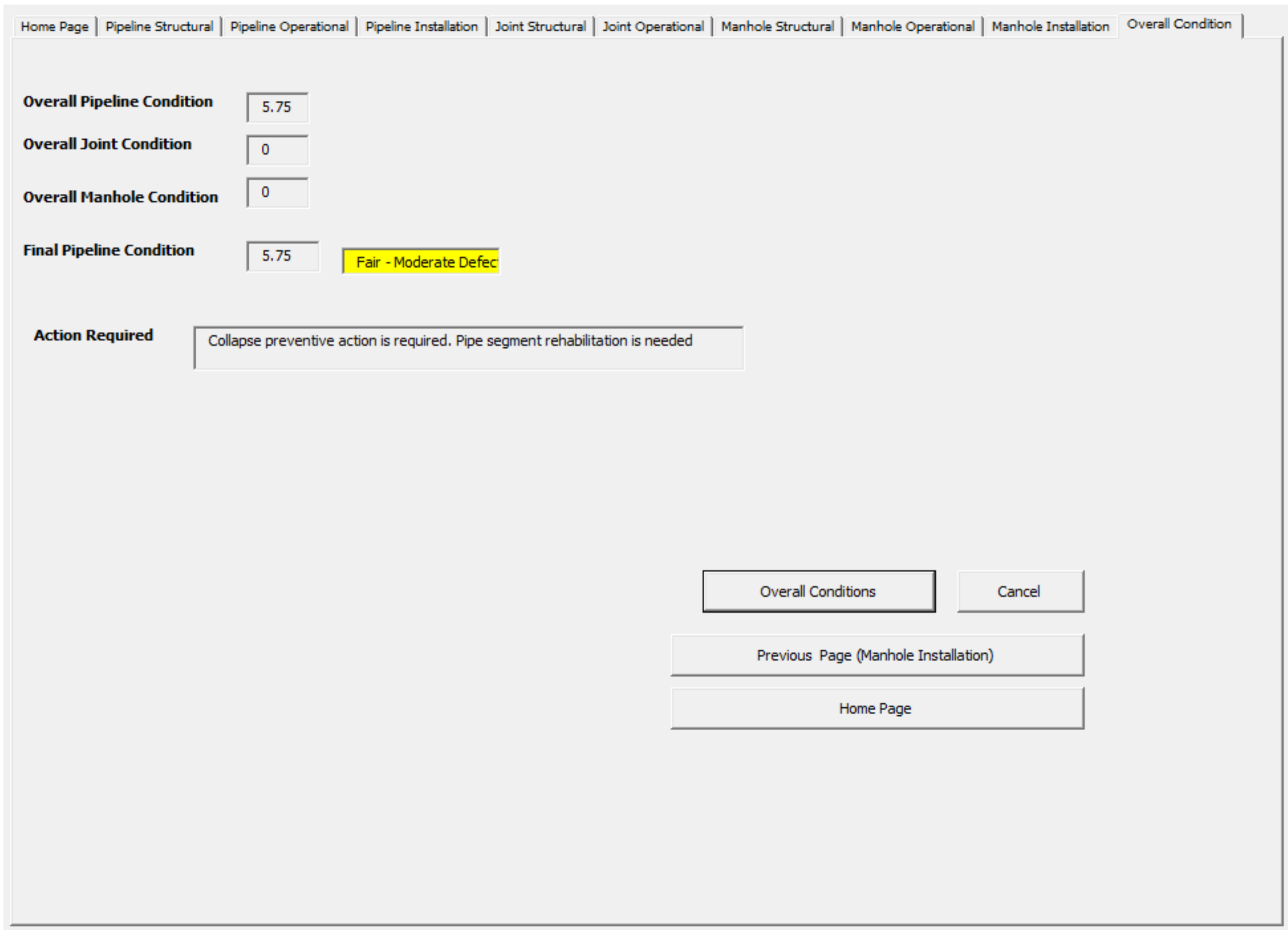


Figure 6. 5 Condition Assessment Automated Tool (Overall Condition)

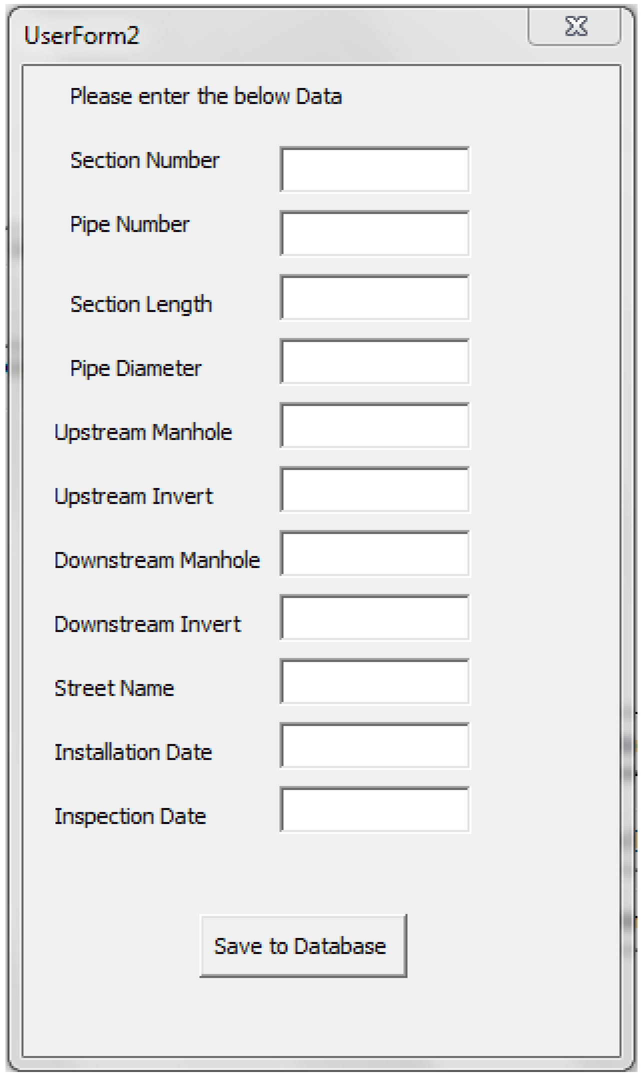


Figure 6. 6 Condition Assessment Automated Tool (Segment Characteristics)

In the figure above, the user can enter the following pipe characteristics and save them in a predefined database along with the computed conditions. In this manner, the user will have a well-established database. This would enable the user to track any assessment conducted on a certain pipe. It also provides the user with a firm data inventory of the city's pipelines and their corresponding conditions.

6.3 Summary

The following chapter presents the sewer condition assessment tool in a user friendly and practical interface. The fuzzy synthetic evaluation is all incorporated in this automated tool through Excel Sheets and Visual Basic. It includes the fuzzy set model, obtained ANP relative importance weights, the evidential reasoning aggregation process, and the defuzzification into an overall crisp valued condition. The inputs in this model are the defect severities through predefined criteria. The outputs are structural, operational, and installation conditions for each component as well as an overall condition representing the whole pipeline. Moreover, the developed protocol and the proposed scale are also incorporated in this model along with color coding for each linguistic condition. To conclude, this automated tool targets all users from practitioners to decision makers whom would like to perform the sewer's condition assessment in a practical and user friendly manner.

CHAPTER SEVEN:
CONCLUSIONS AND RECOMMENDATIONS

7.1 Research Summary

Infrastructure plays an important role in the wellbeing of the economy as it connects the community through roads, bridges, cables, water systems, and sewer systems. Sewer systems in particular are important assets that would carry the human waste into sedimentation tanks and therefore into treatment plants. Moreover, sewer pipelines are suffering from extensive deterioration due to aging, weather changes, improper maintenance, lack of scheduled inspection, and uncertain condition judgements. There are several condition assessment protocols that are being used nowadays. However, most of these protocols have certain limitations and mostly is that they differ from each other in terms of condition scale, severity criteria, and defect weights. Therefore, this research develops a new approach for sewer pipeline condition assessment using fuzzy synthetic evaluation. The end product of this research targets practitioners, inspectors, engineers, managers, and decision-makers to aid them in prioritizing maintenance and rehabilitation work.

In this approach the pipeline is first broken down into a pipe segment, joints, and manholes. After that, each of the above mentioned components are divided into structural, operation, and installation defect categories in which each of these categories are further divided into defects and defect types. Moreover, questionnaires were conducted both online through a customized website and distributed in a hard copy. The survey targeted engineers, managers, inspectors, and practitioners in both Qatar and Canada. Over 85 questionnaires were sent in which only 21 were received and 19 were considered. Consequently, an ANP model was created in both Excel Sheets and SuperDecisions software in order to obtain the final priorities of each of the components, defect categories, defects, and defect types. Furthermore, defect severities criteria of each and every defect type were collected and customized to fit the proposed five grade linguistic scale. Accordingly, fuzzy membership functions were developed for each defect to fuzzify the defect severities (membership functions inputs). This was done in an attempt to reduce the uncertainty involved with human judgment. The outputs of the fuzzy membership functions were used along with the ANP weights as inputs in the developed HER to aggregate the degrees of belief for each and every defect. After that, the obtained aggregated degrees of belief of each defect are aggregated with those of their corresponding defect type in a recursive manner. The same is done until the structural, operational, and installation degrees of belief are obtained and aggregated to give the components' overall condition. The last step involves the components' aggregation to obtain the overall condition of the pipe segment. Finally, the aggregated degrees of belief are defuzzified using the weighted average method to deduce a crisp value with an action plan that can be utilized by decision makers for rehabilitation purposes.

7.2 Research Conclusions

A number of conclusions can be deduced from the development, implementation, and testing of this research:

- The pipeline and joints components both had relative importance weights of 0.38 each, leaving the manhole component with 0.24.

- The structural, operational, and installation and rehabilitation defects' relative weights were (0.4, 0.25, 0.36) for the pipeline, (0.61, 0.39) for the joints since no installation defects were considered, and (0.37, 0.30, 0.39) for the manhole.
- The most significant operational defects in a pipeline were infiltration and protruding services with relative importance weights of 0.24 and 0.28.
- In the manhole, the vertical cracks and fractures were found to be more important than the horizontal ones with relative importance weights of 0.6 and 0.59 with respect to 0.40 and 0.41.
- In case study 1, the mean absolute error for structural and operational defects was 0.533 and 0.267 respectively and the calculated correlation coefficients for the structural and operational defects were 0.846 and 0.934. These results signify a strong relationship between the predicted and real values.
- In case study 2, the mean absolute error was 0.643 when comparing the overall condition with a correlation coefficient of 0.6, signifying a medium strength relationship. The following results are justified in chapter 5.
- The peak score is misleading to decision makers since a collapsed pipe or a pipe with visible reinforcement both score (5-Critical). However, the model accurately describes the condition of the pipe since it gives the collapsed pipe a score of 5 and a pipe with a reinforcement defect a score of 4. This would help decision makers when prioritizing rehabilitation.
- The developed model gives an overall condition score of 5 (critical) if any of the components or defect categories (structural or operational) is of critical condition.

- The main conclusion is that the pipeline should be represented by a precise intermediate score to accurately represent the pipeline's condition and allow for proper budget allocation and rehabilitation prioritization.

7.3 Research Contributions

Several contributions were done through the development of the new sewer pipeline condition assessment model, including but not limited to:

- Developed a pipeline defect hierarchy including components, defect categories, and types that cover the most significant defect factors affecting pipeline's integrity.
- Incorporated the interdependency between structural defects and operational defects through pairwise comparisons.
- Developed a fuzzy synthetic evaluation model including a customized evidential reasoning aggregation working platform to aggregate the defects' degrees of belief.
- Developed a new unified condition assessment scale (K-means clustering technique) along with a sewer pipeline condition protocol mapped with defect descriptions and action plans.
- Developed a sewer pipeline condition assessment automated tool (SPCAT) including structural, operational, and installation defects corresponding to (pipes, joints, and manholes), in order to deduce an index that represents the whole pipe segment.

7.4 Research Limitations

This developed model contains some limitations such as:

- The model is based on a firm defect hierarchy that, if changed, would require the ANP model and ER model to be changed as well.
- The fuzzy membership functions are calculated based on structured inputs (defect severities). In case different criteria are used, the model will not function.
- The model does not take into consideration the hydraulic performance of the pipeline.
- The model does not include the defects that are external to the pipe.
- The developed model does not include external factors such as age, diameter, and weather conditions.

7.5 Future Work Recommendations

The developed model accomplished the research objectives. It included a fuzzy synthetic evaluation with an extensive library of sewer pipeline defects. Another objective was to create a pipeline condition index determining its condition. The model has also been implemented on case studies and the results were validated and justified. However, the model can be incorporated with other secondary models to result in a more extensive and comprehensive assessment of sewer pipeline condition.

7.6.1 Enhancements

- Additional features can be added to the model such as the flow of water, camera submergence, oxygen deficiencies, and porous materials. This would properly reflect the pipeline's scientific numbers and its exact condition.
- Additional pipeline components can be added to the model such as pumps and accessories. Including these components would result in a more comprehensive

condition assessment index that would better represent the pipeline and its compliments.

- External defects can also be incorporated in the model to fulfill the defects surrounding the pipeline. Having external defects integrated with internal defects results in a better representation of the pipeline's condition. This is because external defects encourage internal defects to occur inside the pipeline.
- The questionnaire can be sent to a larger population to obtain more diverse results and better representation of relative importance weights.

7.6.2 Extensions

- Advanced inspection technology such as infrared, SSET, and Sonar, can be incorporated in the developed model to obtain accurate measurements of defects.
- The pipeline's hydraulic performance can be integrated with the developed model to portray a more vivid condition assessment. This can be done by measuring the flow in the pipeline at different stages along its deterioration to check if the flow is up to the demand thresholds.
- Integration of environmental factors with the developed model to provide the user with a complete pipeline evaluation.
- To develop a risk assessment model with the condition index resulting from this model as an input to predict the sewer future deterioration.
- To integrate the developed model with a rehabilitation methodology through mapping each defect to its most suitable rehabilitation method.
- To develop an integrated model including all of the above extensions to have a full life cycle of sewer pipelines' condition.

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Appendix A

Results of Case Study 1

Pipeline	***Defects***	***Severity***					***Pipeline***			***Joints***		***Manholes***			***Total***
		E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	*Overall Condition*
R-1 Boulevard Saint-Rose Laval	Circumferential Crack	0.50	0.50	0.00	0.00	0.00	*8.66* (5)	*2.76* (2)	-	-	-	-	-	-	
	Crack Longitudinal	0.00	0.00	0.00	1.00	0.00									
	Crack Multiple	0.00	0.00	0.00	1.00	0.00									
	Circumferential Fracture	0.50	0.50	0.00	0.00	0.00									
	Fracture Longitudinal	0.00	0.00	0.33	0.67	0.00									
	Fracture Multiple	0.00	0.00	0.00	0.00	1.00									
	Deformation 25%	0.00	0.00	0.00	0.00	1.00									
	Broken	0.00	0.00	0.00	0.00	1.00									
	Debris 5% Reduction	0.50	0.50	0.00	0.00	0.00									
	Encrustation 1 % Reduction	1.00	0.00	0.00	0.00	0.00									
	Soil Intrusion 10% Coarse	0.00	0.75	0.25	0.00	0.00									
	Protruding Services 16%	0.00	0.15	0.85	0.00	0.00									
Total	**Model Results** ***Intermediate*** **(Simple Scale)**	0.16	0.05	0.17	0.04	0.58	***6.15*** **(4)**			**-**		**-**			***6.15*** **(5)**
	CTSPEC Results **(Simple Scale)**	**Structural=(5)** **Operational=(2)**													

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			***Total*** *Overall Condition*
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
R-2 Boulevard Saint-Rose Laval	Spalling		0.50	0.50	0.00	0.00	0.00	2.15 (2)	2.63 (2)	9.00 (5)	-	-	-	-	-	
	Crack Longitudinal		0.00	0.00	0.00	1.00	0.00									
	Circumferential Fracture		0.50	0.50	0.00	0.00	0.00									
	Fracture Longitudinal		0.00	0.67	0.33	0.00	0.00									
	Defective Connection >3/Pipe Length		0.00	0.00	0.00	0.00	1.00									
	Protruding Services 16%		0.00	0.15	0.85	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.17	0.43	0.07	0.03	0.30	***3.56*** **(3)**			**-**		**-**			***4.26*** **(3)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(3) Operational=(3)**													

Note: Installation Defects scored a 9/10 which means that there are an adequate number of installation defects that should be considered, inspected, and repaired.

Pipeline	*Defects*		*Severity*					*Pipeline*			*Joints*		*Manholes*			
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
R-1 Sénécal Laval	Spalling		0.50	0.50	0.00	0.00	0.00	6.92 (4)	5.32 (3)	8 (5)	3.67 (3)	-	-	-	-	***Total*** *Overall Condition*
	Aggregate Visible		0.00	0.50	0.50	0.00	0.00									
	Rein. Corroded		0.00	0.00	0.00	0.00	1.00									
	Encrustation 10 % Reduction		0.00	0.75	0.25	0.00	0.00									
	Infiltration -Running		0.00	0.00	0.00	0.50	0.50									
	Defective Connection 2/Pipe Length		0.00	0.00	0.00	0.50	0.50									
	Non-Concentric Joint-1*Pipe Thickness		0.00	0.33	0.67	0.00	1.00									
Total	**Model Results**	***Intermediate* (Simple Scale)**	0.01	0.27	0.42	0.09	0.22	***5.67* (3)**			***3.67* (3)**		**-**			***5.01* (3)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(5) Operational=(4)**													

Note: The inspection results differ from the model results since the inspector considered the camera being fully submerged as a critical defect and since the PACP code is followed using the peak score.

Pipeline	*Defects*		*Severity*					*Pipeline*			*Joints*		*Manholes*			*Total*
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
R-2 Sénécal Laval	Debris 10% Diameter Reduction		0.00	0.75	0.25	0.00	0.00	-	2.92 (3)	-	-	-	-	-	-	*Overall Condition*
	Gravel Intrusion 15% Diameter Reduction		0.00	0.25	0.75	0.00	0.00									
	Infiltration -Seeping		0.00	0.50	0.50	0.00	0.00									
Total	**Model Results**	***Intermediate* (Simple Scale)**	0.00	0.63	0.37	0.00	0.00	***3* (3)**			**-**		**-**			***3* (3)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(1) Operational=(3)**													

Pipeline	*Defects*		*Severity*					*Pipeline*			*Joints*		*Manholes*			*Total*
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
R-2 Rue De Léry Laval	Aggregate Visible		0.00	0.50	0.50	0.00	0.00	2.69 (2)	2.63 (2)	-	-	10 (5)	-	-	-	***Total*** *Overall Condition*
	Circumferential Fracture		0.50	0.50	0.00	0.00	0.00									
	Encrustation 10 % Reduction		0.00	0.75	0.25	0.00	0.00									
	Fine Roots at Joint (5%)		0.50	0.50	0.00	0.00	0.00									
	Bulk Roots (15%)		0.00	0.25	0.75	0.00	0.00									
	Protruding Services at Joint-Severe		0.00	0.00	0.00	0.00	1.00									
Total	**Model Results**	***Intermediate* (Simple Scale)**	0.04	0.31	0.15	0.00	0.50	***2.65* (2)**			***10* (5)**		**-**			***10* (5)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(3) Operational=(5)**													

Note: The overall condition is said to be 5 since the operational condition is 5 due to a protruding sealing at the joint which is considered a severe defect since it might cause the joint to be loose.

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			***Total*** *Overall Condition*
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
R-1 Rue Poplar Laval	Spalling		0.50	0.50	0.00	0.00	0.00	0.21	0.37	0.28	0.15	0.00	0.21	-	-	
	Debris 20% Diameter Reduction		0.00	0.00	0.88	0.13	0.00									
	Encrustation 10 % Reduction		0.00	0.75	0.25	0.00	0.00									
	Defective Connection 1/Pipe Length		0.00	0.00	0.50	0.50	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.21	0.37	0.28	0.15	0.00	***2.84*** **(3)**			**-**		**-**			***3.24*** **(3)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(2) Operational=(4)**													

Note: The inspection results differ from the model results since the inspector considered the camera being fully submerged as a critical defect and since the PACP code is followed using the peak score.

<table>
<tr><th rowspan="2">Pipeline</th><th rowspan="2" colspan="2">Defects</th><th colspan="5">Severity</th><th colspan="3">Pipeline</th><th colspan="2">Joints</th><th colspan="3">Manholes</th><th rowspan="6">Total
Overall Condition</th></tr>
<tr><th>E</th><th>G</th><th>F</th><th>P</th><th>C</th><th>Str.</th><th>Op.</th><th>Inst.</th><th>Str.</th><th>Op.</th><th>Str.</th><th>Op.</th><th>Inst.</th></tr>
<tr><td rowspan="4">R-1 Boulevard St-Martin Laval</td><td colspan="2">Reinforcement Visible</td><td>0.00</td><td>0.00</td><td>0.50</td><td>0.50</td><td>0.00</td><td rowspan="4">5.75
(3)</td><td rowspan="4">2.39
(2)</td><td rowspan="4">-</td><td rowspan="4">-</td><td rowspan="4">-</td><td rowspan="4">-</td><td rowspan="4">-</td><td rowspan="4">-</td></tr>
<tr><td colspan="2">Aggregate Missing</td><td>0.00</td><td>0.00</td><td>0.50</td><td>0.50</td><td>0.00</td></tr>
<tr><td colspan="2">Encrustation 10 % Reduction</td><td>0.00</td><td>0.75</td><td>0.25</td><td>0.00</td><td>0.00</td></tr>
<tr><td colspan="2">Debris 5% Reduction</td><td>0.50</td><td>0.50</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td rowspan="2">Total</td><td>Model Results</td><td>Intermediate
(Simple Scale)</td><td>0.03</td><td>0.24</td><td>0.41</td><td>0.33</td><td>0.00</td><td colspan="3">4.63
(3)</td><td colspan="2">-</td><td colspan="3">-</td><td>4.63
(3)</td></tr>
<tr><td>CTSPEC Results</td><td>(Simple Scale)</td><td colspan="14">Structural=(2)
Operational=(4)</td></tr>
</table>

Note: The inspection results differ from the model results since the inspector considered the camera being fully submerged as a critical defect and since the PACP code is followed using the peak score.

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			***Total*** *Overall Condition*
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
R-1 Bousquet Laval	Reinforcement Visible		0.00	0.00	0.50	0.50	0.00	4.28 (3)	2.76 (2)	9 (5)	-	-	-	-	-	
	Spalling		0.50	0.50	0.00	0.00	0.00									
	Aggregate Visible		0.00	0.50	0.50	0.00	0.00									
	Protruding Services 10%		0.00	0.75	0.25	0.00	0.00									
	Infiltration -Seeping		0.00	0.50	0.50	0.00	0.00									
	Crack Longitudinal		0.50	0.50	0.00	0.00	0.00									
	Crack Circumferential		0.50	0.50	0.00	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.05	0.28	0.27	0.10	0.31	***4.34*** **(3)**			**-**		**-**			***5.29*** **(3)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(5) Operational=(2)**													

Note: The inspection results differ from the model results since the inspector considered the peak score which is due to the reinforcement visible defect.

Pipeline	Defects		Severity					Pipeline			Joints		Manholes			Total
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
R-1 Rue Lippmann Laval	Debris 5% Reduction		0.50	0.50	0.00	0.00	0.00	6.46 (4)	1.50 (2)	-	-	-	-	-	-	***Total*** *Overall Condition*
	Fracture Multiple		0.00	0.00	0.00	0.00	1.00									
	Fracture Circumferential		0.50	0.50	0.00	0.00	0.00									
	Crack Longitudinal		0.50	0.50	0.00	0.00	0.00									
	Crack Circumferential		0.00	0.50	0.50	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.25	0.31	0.05	0.00	0.38	***4.40*** **(3)**			**-**		**-**			***4.55*** **(3)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(4) Operational=(2)**													

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			***Total***
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
R-2 Rue Lippmann Laval	Fracture Circumferential		0.50	0.50	0.00	0.00	0.00	1.68 (2)	-	-	-	-	-	-	-	*Overall Condition*
	Crack Longitudinal		0.00	0.50	0.50	0.00	0.00									
	Crack Circumferential		0.50	0.50	0.00	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.45	0.50	0.05	0.00	0.00	***1.68*** **(2)**			**-**		**-**			***1.68*** **(2)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(2)** **Operational=(1)**													

Note: The difference in operational score is because the inspection report takes no operational defects as degree 1 (Excellent). However, the model interprets it as 0 since no defects are available.

<table>
<tr><th rowspan="2">Pipeline</th><th rowspan="2" colspan="2">Defects</th><th colspan="5">Severity</th><th colspan="3">Pipeline</th><th colspan="2">Joints</th><th colspan="3">Manholes</th><th rowspan="3">Total

Overall Condition</th></tr>
<tr><th>E</th><th>G</th><th>F</th><th>P</th><th>C</th><th>Str.</th><th>Op.</th><th>Inst.</th><th>Str.</th><th>Op.</th><th>Str.</th><th>Op.</th><th>Inst.</th></tr>
<tr><td rowspan="3">R-1
Boulevard
D’Auteuil
Laval</td><td colspan="2">Encrustation 10 % Reduction</td><td>0.00</td><td>0.75</td><td>0.25</td><td>0.00</td><td>0.00</td><td rowspan="3">1.50
(2)</td><td rowspan="3">2.63
(2)</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="3">-</td></tr>
<tr><td colspan="2">Crack Longitudinal</td><td>0.50</td><td>0.50</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td colspan="2">Crack Circumferential</td><td>0.50</td><td>0.50</td><td>0.00</td><td>0.00</td><td>0.00</td><td></td></tr>
<tr><td rowspan="2">Total</td><td>Model Results</td><td>Intermediate
(Simple Scale)</td><td>0.31</td><td>0.62</td><td>0.08</td><td>0.00</td><td>0.00</td><td colspan="3">1.89
(2)</td><td colspan="2">-</td><td colspan="3">-</td><td>1.89
(2)</td></tr>
<tr><td>CTSPEC Results</td><td>(Simple Scale)</td><td colspan="14">Structural=(2)
Operational=(2)</td></tr>
</table>

<table>
<tr><th rowspan="2">Pipeline</th><th rowspan="2" colspan="2">Defects</th><th colspan="5">Severity</th><th colspan="3">Pipeline</th><th colspan="2">Joints</th><th colspan="3">Manholes</th><th rowspan="2"></th></tr>
<tr><th>E</th><th>G</th><th>F</th><th>P</th><th>C</th><th>Str.</th><th>Op.</th><th>Inst.</th><th>Str.</th><th>Op.</th><th>Str.</th><th>Op.</th><th>Inst.</th></tr>
<tr><td rowspan="4">R-1 Boulevard Des Laurentides Laval</td><td colspan="2">Spalling</td><td>0.50</td><td>0.50</td><td>0.00</td><td>0.00</td><td>0.00</td><td rowspan="4">6.11
(4)</td><td rowspan="4">3.66
(3)</td><td rowspan="4">-</td><td rowspan="4">-</td><td rowspan="4">-</td><td rowspan="4">-</td><td rowspan="4">-</td><td rowspan="4">-</td><td rowspan="4">Total
Overall Condition</td></tr>
<tr><td colspan="2">Reinforcement Visible</td><td>0.00</td><td>0.00</td><td>0.50</td><td>0.50</td><td>0.00</td></tr>
<tr><td colspan="2">Encrustation 10 % Reduction</td><td>0.00</td><td>0.75</td><td>0.25</td><td>0.00</td><td>0.00</td></tr>
<tr><td colspan="2">Protruding Services 20%</td><td>0.00</td><td>0.00</td><td>0.88</td><td>0.13</td><td>0.00</td></tr>
<tr><td rowspan="2">Total</td><td>Model Results</td><td>Intermediate
(Simple Scale)</td><td>0.04</td><td>0.15</td><td>0.27</td><td>0.54</td><td>0.00</td><td colspan="3">5.35
(3)</td><td colspan="2">-</td><td colspan="3">-</td><td>5.35
(3)</td></tr>
<tr><td>CTSPEC Results</td><td>(Simple Scale)</td><td colspan="14">Structural=(5)
Operational=(3)</td></tr>
</table>

Note: The inspection results differ from the model results since the inspector considered the peak score which is due to the reinforcement visible defect.

Pipeline	Defects		Severity E	Severity G	Severity F	Severity P	Severity C	Pipeline Str.	Pipeline Op.	Pipeline Inst.	Joints Str.	Joints Op.	Manholes Str.	Manholes Op.	Manholes Inst.	***Total*** *Overall Condition*
R-1 Rue Salabery Laval	Crack Longitudinal		0.50	0.50	0.00	0.00	0.00	4.57 (3)	5.56 (3)	-	-	-	-	-	-	
	Reinforcement Visible		0.00	0.00	0.50	0.50	0.00									
	Aggregate Visible		0.00	0.50	0.50	0.00	0.00									
	Encrustation 10 % Reduction		0.00	0.75	0.25	0.00	0.00									
	Infiltration –Dripping		0.00	0.00	0.50	0.50	0.00									
	Infiltration -Gushing		0.00	0.00	0.00	0.00	1.00									
Total	**Model Results**	***Intermediate* (Simple Scale)**	0.04	0.26	0.36	0.21	0.13	***4.75* (3)**			**-**		**-**			***4.81* (3)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(5) Operational=(4)**													

Note: The inspection results differ from the model results since the inspector considered the peak score which is the reinforcement visible and the peak score due to gushing infiltration for the operational defects.

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			***Total***
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
R-1 4^{e} Rue Laval	Aggregate Projecting		0.00	0.00	0.50	0.50	0.00	6.83 (4)	2.63 (2)	-	-	2.63 (2)	-	-	-	*Overall Condition*
	Aggregate Missing		0.00	0.00	0.00	0.60	0.40									
	Aggregate Visible		0.00	0.50	0.50	0.00	0.00									
	Encrustation 10 % Reduction		0.00	0.75	0.25	0.00	0.00									
	Fine roots at joint (10%)		0.00	0.75	0.25	0.00	0.00									
	Infiltration (seeping at joint)		0.00	0.00	0.50	0.50	0.00									
Total	**Model Results**	***Intermediate* (Simple Scale)**	0.01	0.52	0.23	0.17	0.06	***5.30* (3)**			***2.63* (2)**		**-**			***3.84* (3)**
	CTSPEC Results	**(Simple Scale)**	**Structural=(4) Operational=(2)**													

<table>
<tr><th rowspan="2">Pipeline</th><th rowspan="2" colspan="2">Defects</th><th colspan="5">Severity</th><th colspan="3">Pipeline</th><th colspan="2">Joints</th><th colspan="3">Manholes</th><th rowspan="7">Total

Overall Condition</th></tr>
<tr><th>E</th><th>G</th><th>F</th><th>P</th><th>C</th><th>Str.</th><th>Op.</th><th>Inst.</th><th>Str.</th><th>Op.</th><th>Str.</th><th>Op.</th><th>Inst.</th></tr>
<tr><td rowspan="5">R-1
Chemin de fer
Laval</td><td colspan="2">Crack Circumferential</td><td>0.50</td><td>0.50</td><td>0.00</td><td>0.00</td><td>0.00</td><td rowspan="5">7.12
(4)</td><td rowspan="5">4.08
(3)</td><td rowspan="5">-</td><td rowspan="5">-</td><td rowspan="5">-</td><td rowspan="5">-</td><td rowspan="5">-</td><td rowspan="5">-</td></tr>
<tr><td colspan="2">Fracture Multiple</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>1.00</td></tr>
<tr><td colspan="2">Debris 5% Reduction</td><td>0.50</td><td>0.50</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td colspan="2">Encrustation 10 % Reduction</td><td>0.00</td><td>0.75</td><td>0.25</td><td>0.00</td><td>0.00</td></tr>
<tr><td colspan="2">Infiltration –Dripping</td><td>0.00</td><td>0.00</td><td>0.50</td><td>0.50</td><td>0.00</td></tr>
<tr><td rowspan="2">Total</td><td>Model Results</td><td>Intermediate
(Simple Scale)</td><td>0.10</td><td>0.22</td><td>0.12</td><td>0.09</td><td>0.47</td><td colspan="3">5.64
(3)</td><td colspan="2">-</td><td colspan="3">-</td><td>6.00
(4)</td></tr>
<tr><td>CTSPEC Results</td><td>(Simple Scale)</td><td colspan="14">Structural=(4)
Operational=(3)</td></tr>
</table>

Appendix B

Results of Case Study 2

Pipeline	***Defects***		***Severity*** E	G	F	P	C	***Pipeline*** Str.	Op.	Inst.	***Joints*** Str.	Op.	***Manholes*** Str.	Op.	Inst.	***Total*** *Overall Condition*
14 1 B7 10 14 1 B7 9	Spalling		0.50	0.50	0.00	0.00	0.00	1.50 (2)	2.72 (2)	-	2.99 (3)	-	-	-	-	
	Deposits (4% Reduction)		0.00	0.00	0.00	0.00	0.00									
	Protruding Services (15%)		0.00	0.25	0.75	0.00	0.00									
	Open Joint 15 mm		0.00	0.60	0.40	0.00	0.00									
	Open Joint (2 & 3 Degrees)		0.40	0.60	0.00	0.00	0.00									
Total	**Model Results**	***Intermediate* (Simple Scale)**	0.20	0.55	0.25	0.00	0.00	***1.88* (2)**			***2.99* (3)**		**-**			***2.43* (2)**
	Inspection Survey	**(Simple Scale)**	**3**													
14 1 B7 11 14 1 B7 10	Deposits (25% Reduction)		0.00	0.00	0.63	0.38	0.00	-	5.42 (3)	-	1.61 (2)	-	-	-	-	***Total*** *Overall Condition*
	Protruding Services (25%)		0.00	0.00	0.63	0.38	0.00									
	Open Joint 3 mm		0.40	0.60	0.00	0.00	0.00									
Total	**Model Results**	***Intermediate* (Simple Scale)**	0.20	0.30	0.32	0.18	0.00	***5.42* (3)**			***1.61* (2)**		**-**			***3.52* (3)**
	Inspection Survey	**(Simple Scale)**	**3**													

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			***Total***
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
14 1 B7 2 14 1 B7 1	Spalling		0.50	0.50	0.00	0.00	0.00	1.50 (2)	3.63 (3)	-	2.47 (2)	-	-	-	-	***Total*** *Overall Condition*
	Protruding Services (14%)		0.00	0.35	0.65	0.00	0.00									
	Open Joint 10 mm		0.00	0.80	0.20	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.14	0.67	0.19	0.00	0.00	***2.21*** **(2)**			***2.47*** **(2)**		**-**			***2.43*** **(2)**
	Inspection Survey	**(Simple Scale)**	**3**													
14 1 B7 3 14 1 B7 2	Spalling		0.50	0.50	0.00	0.00	0.00	10 (5)	-	-	2.00 (2)	-	-	-	-	***Total*** *Overall Condition*
	Soil Intrusion (1% Reduction)		1.00	0.00	0.00	0.00	0.00									
	Broken		0.00	0.00	0.00	0.00	1.00									
	Collapse		0.00	0.00	0.00	0.00	1.00									
	Open Joint 5 mm		0.00	1.00	0.00	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.00	0.50	0.00	0.00	0.50	***10*** **(5)**			***2.00*** **(2)**		**-**			***5.50*** **(5)**
	Inspection Survey	**(Simple Scale)**	**4**													

Note: Since the structural condition is 10 then overall condition is taken as 10 (5 in Simple Scale)

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
14 1 B7 9 14 1 B7 8	Spalling		0.50	0.50	0.00	0.00	0.00	1.50 (2)	1.00 (2)	-	1.30 (2)	-	-	-	-	***Total*** *Overall Condition*
	Deposits (2% Reduction)		1.00	0.00	0.00	0.00	0.00									
	Circumferential Crack		0.50	0.50	0.00	0.00	1.00									
	Open Joint 2 mm		0.60	0.40	0.00	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.72	0.28	0.00	0.00	0.00	***1.30*** **(2)**			***1.30*** **(2)**		**-**			***1.28*** **(2)**
	Inspection Survey	**(Simple Scale)**	**2**													
14 1 B7 4 14 1 B7 3	Spalling		0.50	0.50	0.00	0.00	0.00	1.50 (2)	10.0 0 (5)	-	1.14 (2)	-	-	-	-	***Total*** *Overall Condition*
	Debris (12%)		0.00	0.55	0.45	0.00	0.00									
	Protruding Services (99%)		0.00	0.00	0.00	0.00	1.00									
	Open Joint 1 mm		0.80	0.20	0.00	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.00	0.50	0.00	0.00	0.50	***10*** **(5)**			***1.14*** **(2)**		**-**			***10*** **(5)**
	Inspection Survey	**(Simple Scale)**	**5**													

Note: Since the pipe is 99% blocked by an obstacle the model gives critical condition immediately

Pipeline	***Defects***		***Severity*** E	G	F	P	C	***Pipeline*** Str.	Op.	Inst.	***Joints*** Str.	Op.	***Manholes*** Str.	Op.	Inst.	***Total***
14 1 C10 14 1 C9	Spalling		0.50	0.50	0.00	0.00	0.00	1.50 (2)	-	-	5.13 (3)	-	-	-	-	*Overall Condition*
	Crack Longitudinal		0.50	0.50	0.00	0.00	1.00									
	Open Joint 35mm		0.00	0.00	0.75	0.25	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.25	0.25	0.38	0.12	0.00	***1.50*** **(2)**			***5.13*** **(3)**		**-**			***3.32*** **(3)**
	Inspection Survey	**(Simple Scale)**	**3**													
14 1 C11 14 1 C10	Spalling		0.50	0.50	0.00	0.00	0.00	1.50 (2)	-	-	3 (3)	-	-	-	-	***Total*** *Overall Condition*
	Open Joint 26mm		0.60	0.40	0.00	0.00	0.00									
Total	**Model Results**	***Intermediate*** **(Simple Scale)**	0.24	0.35	0.41	0.00	0.00	***1.50*** **(2)**			***4.10*** **(3)**		**-**			***2.8*** **(2)**
	Inspection Survey	**(Simple Scale)**	**3**													

Note: The difference in this condition rating is due to the 38% contributing of each (Pipelines and Joints), in which the worst defect occurs at the joint

<table>
<tr><th rowspan="2">Pipeline</th><th rowspan="2" colspan="2">Defects</th><th colspan="5">Severity</th><th colspan="3">Pipeline</th><th colspan="2">Joints</th><th colspan="3">Manholes</th><th rowspan="2">Total</th></tr>
<tr><th>E</th><th>G</th><th>F</th><th>P</th><th>C</th><th>Str.</th><th>Op.</th><th>Inst.</th><th>Str.</th><th>Op.</th><th>Str.</th><th>Op.</th><th>Inst.</th></tr>
<tr><td rowspan="3">14 1 C8
14 1 C7</td><td colspan="2">Open Joint 26mm</td><td>0.00</td><td>0.16</td><td>0.84</td><td>0.00</td><td>0.00</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="3">4.75
(3)</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="3">Overall Condition</td></tr>
<tr><td colspan="2">Open Joint 28 mm</td><td>0.00</td><td>0.08</td><td>0.92</td><td>0.00</td><td>1.00</td></tr>
<tr><td colspan="2">Open Joint 32 mm</td><td>0.00</td><td>0.00</td><td>0.90</td><td>0.10</td><td>0.00</td></tr>
<tr><td rowspan="2">Total</td><td>Model Results</td><td>Intermediate (Simple Scale)</td><td>0.00</td><td>0.00</td><td>0.90</td><td>0.10</td><td>0.00</td><td colspan="3">-</td><td colspan="2">4.75
(3)</td><td colspan="3">-</td><td>4.75
(3)</td></tr>
<tr><td>Inspection Survey</td><td>(Simple Scale)</td><td colspan="14">3</td></tr>
<tr><td rowspan="9">14 1 C7
14 1 C6</td><td colspan="2">Deposits (3%)</td><td>0.90</td><td>0.10</td><td>0.00</td><td>0.00</td><td>0.00</td><td rowspan="9">2.75
(2)</td><td rowspan="9">3.71
(3)</td><td rowspan="9">-</td><td rowspan="9">4.00
(3)</td><td rowspan="9">-</td><td rowspan="9">-</td><td rowspan="9">-</td><td rowspan="9">-</td><td rowspan="9">Total
Overall Condition</td></tr>
<tr><td colspan="2">Fracture Longitudinal</td><td>0.50</td><td>0.50</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td colspan="2">Crack Multiple</td><td>0.00</td><td>0.00</td><td>0.00</td><td>1.00</td><td>0.00</td></tr>
<tr><td colspan="2">Circumferential Crack</td><td>0.00</td><td>0.50</td><td>0.50</td><td>0.00</td><td>0.00</td></tr>
<tr><td colspan="2">Coarse Soil Intrusion 20%</td><td>0.00</td><td>0.00</td><td>0.88</td><td>0.12</td><td>0.00</td></tr>
<tr><td colspan="2">Fine Soil Intrusion 5%</td><td>0.50</td><td>0.50</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td colspan="2">Spalling</td><td>0.50</td><td>0.50</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td colspan="2">Protruding Services 22 %</td><td>0.00</td><td>0.00</td><td>0.78</td><td>0.23</td><td>0.00</td></tr>
<tr><td colspan="2">Open Joint 25 mm</td><td>0.00</td><td>0.20</td><td>0.80</td><td>0.00</td><td>0.00</td></tr>
<tr><td rowspan="2">Total</td><td>Model Results</td><td>Intermediate (Simple Scale)</td><td>0.16</td><td>0.25</td><td>0.50</td><td>0.09</td><td>0.00</td><td colspan="3">3.05
(3)</td><td colspan="2">4.00
(3)</td><td colspan="3">-</td><td>3.54
(3)</td></tr>
<tr><td>Inspection Survey</td><td>(Simple Scale)</td><td colspan="14">5</td></tr>
</table>

Note: The condition given in the inspection survey was due to 5% soil intrusion, making the inspector pessimistic

Pipeline	***Defects***		***Severity*** E	G	F	P	C	***Pipeline*** Str.	Op.	Inst.	***Joints*** Str.	Op.	***Manholes*** Str.	Op.	Inst.	***Total*** *Overall Condition*
14 1 C9 14 1 C8	Deposits 3%		0.90	0.10	0.00	0.00	0.00	1.50 (2)	1.10 (2)	-	5.00 (3)	-	-	-	-	
14 1 C9 14 1 C8	Crack Longitudinal		0.50	0.50	0.00	0.00	0.00	1.50 (2)	1.10 (2)	-	5.00 (3)	-	-	-	-	
14 1 C9 14 1 C8	Open Joint 34 mm		0.00	0.00	0.80	0.20	0.00	1.50 (2)	1.10 (2)	-	5.00 (3)	-	-	-	-	
Total	**Model Results**	***Intermediate* (Simple Scale)**	0.33	0.17	0.40	0.10	0.00	***1.34* (2)**			***5.00* (3)**		**-**			***3.17* (3)**
Total	**Inspection Survey**	**(Simple Scale)**	**3**													
14 1 A1 2 1 14 1 A1 2	Coarse (Gravel-10%)		0.00	0.75	0.25	0.00	0.00	10 (5)	2.44 (2)	-	3.00 (3)	-	-	-	-	***Total*** *Overall Condition*
14 1 A1 2 1 14 1 A1 2	Fine Sand 10%		0.00	0.75	0.25	0.00	0.00	10 (5)	2.44 (2)	-	3.00 (3)	-	-	-	-	
14 1 A1 2 1 14 1 A1 2	Visible Aggregate		0.00	0.50	0.50	0.00	0.00	10 (5)	2.44 (2)	-	3.00 (3)	-	-	-	-	
14 1 A1 2 1 14 1 A1 2	Collapse		0.00	0.00	0.00	0.00	1.00	10 (5)	2.44 (2)	-	3.00 (3)	-	-	-	-	
14 1 A1 2 1 14 1 A1 2	Open Joint 15mm		0.00	0.60	0.40	0.00	0.00	10 (5)	2.44 (2)	-	3.00 (3)	-	-	-	-	
Total	**Model Results**	***Intermediate* (Simple Scale)**	0.00	0.30	0.20	0.00	0.50	***10* (5)**			***3.00* (3)**		**-**			***10* (5)**
Total	**Inspection Survey**	**(Simple Scale)**	**5**													

Note: The model gives immediately critical condition if there is collapse (in this case concrete piece was in the pipe)

Pipeline	***Defects***		***Severity***					***Pipeline***			***Joints***		***Manholes***			***Total***
			E	G	F	P	C	Str.	Op.	Inst.	Str.	Op.	Str.	Op.	Inst.	
14 1 A3 14 1 A2	Deposits 5%		0.50	0.50	0.00	0.00	0.00	-	2.09 (2)	-	-	-	-	-	-	*Overall Condition*
	Coarse (Gravel-15%)		0.00	0.25	0.75	0.00	0.00									
Total	**Model Results**	***Intermediate* (Simple Scale)**	0.37	0.45	0.18	0.00	0.00	***2.09* (2)**			**-**		**-**			***2.09* (2)**
	Inspection Survey	**(Simple Scale)**	**2**													
14 1 A1 2 1A 14 1 A1 2 1	Coarse (Gravel-15%)		0.00	0.25	0.75	0.00	0.00	3.25 (3)	2.20 (2)	-	-	-	-	-	-	***Total*** *Overall Condition*
	Fine Sand 10%		0.00	0.75	0.25	0.00	0.00									
	Visible Aggregate		0.00	0.50	0.50	0.00	0.00									
	Deposits 10%		0.00	0.75	0.25	0.00	0.00									
	Protruding Services 3%		0.00	0.60	0.40	0.00	0.00									
Total	**Model Results**	***Intermediate* (Simple Scale)**	0.07	0.55	0.38	0.00	0.00	***2.88* (2)**			**-**		**-**			***2.88* (2)**
	Inspection Survey	**(Simple Scale)**	**5**													

Note: The inspection survey gives a critical condition grade for having fine sands, making the difference between the model and the survey results

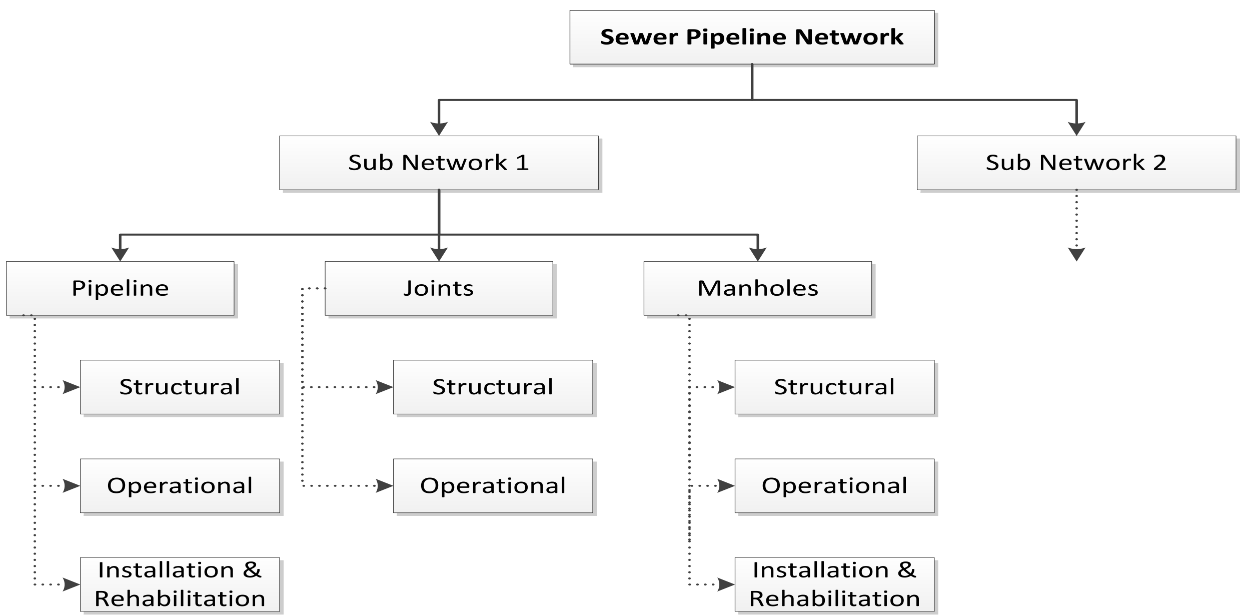
Appendix C

Questionnaire

DEFECT-BASED SEWER PIPELINE CONDITION ASSESSMENT

Dear Sir/Madam

It is of great appreciation that you would take some time to fill the following questionnaire. The purpose is to identify the relative importance and effect of the elements, components, and defects affecting the integrity of sewer pipelines' condition. The questionnaire is used for an academic research under the supervision of Dr. Tarek Zayed at Concordia University, Montreal, Canada, to build a defect-based condition assessment model for sewer pipelines. Based on literature review, the following is a hierarchy of defects that helps answering various questions.



PART (1) : GENERAL INFORMATION

1) **How do you describe your occupation?**
   - ☐ Organization Manager ☐ Project Manager
   - ☐ Construction Manager ☐ Others ____________________

2) **Which best describes your working experience?**
   - ☐ Less than 5 years ☐ 6 -10 years ☐ More than 20 years
   - ☐ 11 – 15 years ☐ 16 – 20 years ☐

3) **How do you describe your organization?**
   - ☐ Public Owner ☐ Consultant ☐ NGOs

☐ International Agency ☐ Implementing Agency ☐ Others ________________

4) **What are the types of implemented projects through your organization?**

☐ Residential Buildings ☐ Infrastructure Projects ☐ Industrial Buildings

☐ Public Buildings ☐ Environ. Projects ☐ Others ________________

PART (2): PAIRWISE COMPARISON

In an attempt to determine the degree of importance of factors affecting the sewer pipelines' condition, kindly fill the tables in the next pages by ticking (✓) in the appropriate box from your point of view:

Example: *In the table below, consider comparing **"Pipeline"** (Criterion X) with **"Joints"** (Criterion Y) with respect to the **"Sub Network Condition".***

Sub Network											
Criterion (X)	← **Degree of Importance** →									**Criterion (Y)**	**Remarks**
	(9) Absolute	**(7)** Very Strong	**(5)** Strong	**(3)** Moderate	**(1)** Equal	**(3)** Moderate	**(5)** Strong	**(7)** Very Strong	**(9)** Absolute		
Pipeline										Joint	
										Manhole	

*If you consider that "Pipeline" is more important than "Joint" and the degree of this importance is **"Strong"** then tick (✓) here*

*If you consider both "Pipeline" and "Joint" have **"Equal"** importance; then tick (✓) here*

*If you consider the "Joint" is more important than "Pipeline" and the degree of importance is **"Absolute"** then tick (✓) here*

*The same procedure is then followed when comparing **"Pipeline"** with **"Manhole"**.*

1) **Pairwise Comparison Between Elements and Components with respect to Goal:**

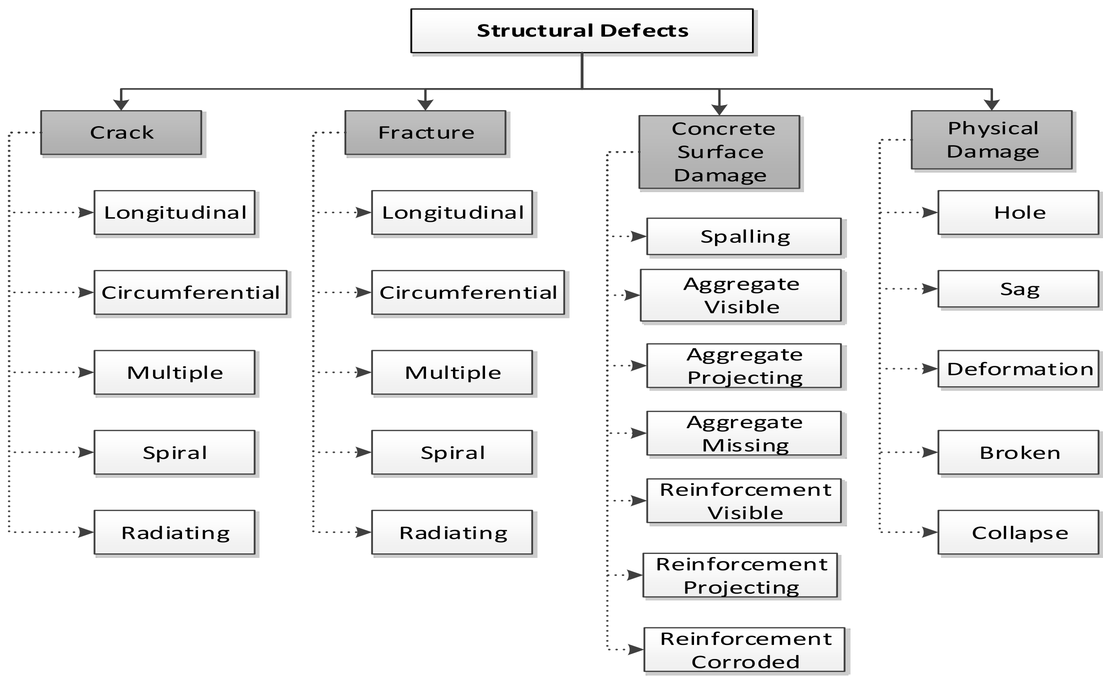
With respect to ***"Sub Network Condition"*** how important is criterion ***"X"*** or ***"Y"*** when compared to each other?

Criterion (X)	← **Degree of Importance** →									**Criterion (Y)**	**Remarks**
	(9) Absolute	**(7)** Very Strong	**(5)** Strong	**(3)** Moderate	**(1)** Equal	**(3)** Moderate	**(5)** Strong	**(7)** Very Strong	**(9)** Absolute		
Sub Network Condition											
Pipeline										Joint	
										Manhole	
Pipeline											
Structural Defects										Operational Defects	
										Installation & Rehab. Defects	
Joints											
Structural Defects										Operational Defects	
Manholes											
Structural Defects										Operational Defects	
										Installation & Rehab. Defects	
Pipeline											

Joint										Manhole	
Joint											
Pipeline										Manhole	
Manhole											
Pipeline										Joint	

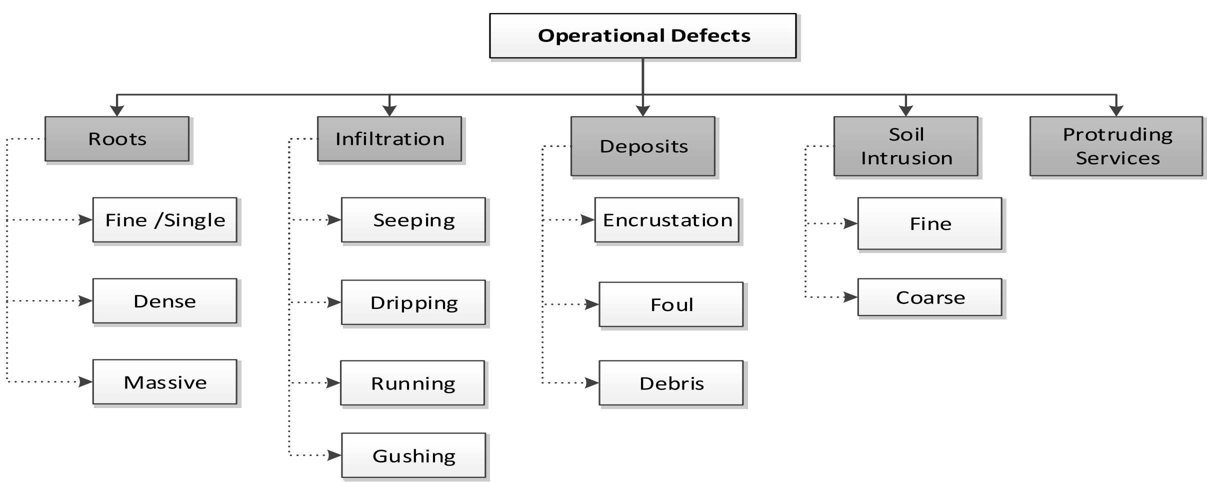
PART (2-B): PAIRWISE COMPARISON

In an attempt to determine the degree of importance of defects affecting the ***PIPELINE***, kindly fill the tables in the next pages by ticking (✓) in the appropriate box from your point of view. The following hierarchy is given to assist you in visualizing the defects.



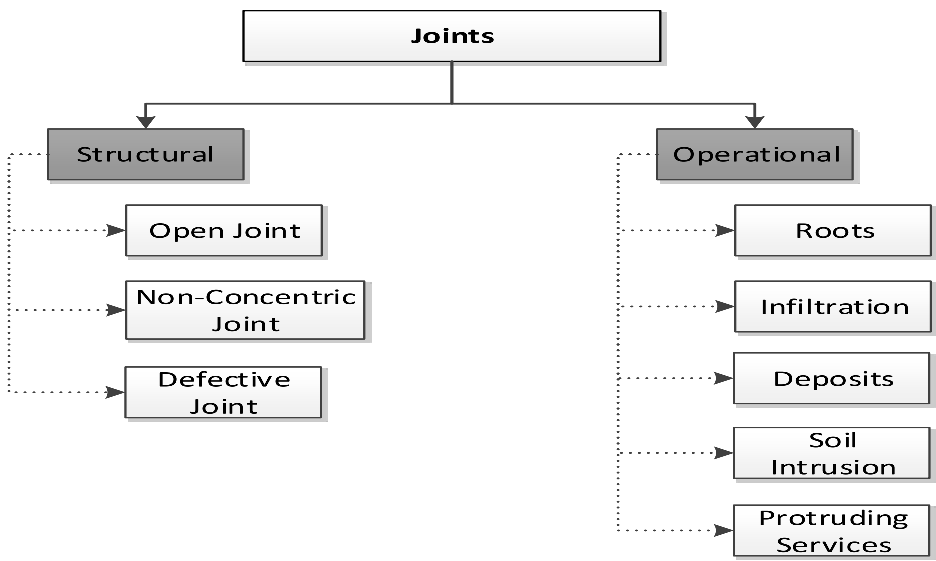
Criterion (X)	← Degree of Importance →									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Operational Defects (Pipeline)											
Structural Defects										Installation & Rehab. Defects	
Structural Defects (Pipeline)											
Operational Defects										Installation & Rehab. Defects	
Installation and Rehabilitation Defects (Pipeline)											
Structural Defects										Operational Defects	
Structural Defects											

Crack										Fracture	
										Concrete Surface Damage	
										Physical Damage	
Crack											
Longitudinal										Circumferential	
										Multiple	
										Spiral	
										Radiating	
Fracture											
Longitudinal										Circumferential	
										Multiple	
										Spiral	
										Radiating	
Concrete Surface Damage											
Spalling										Aggregate Visible	
										Aggregate Projecting	
										Aggregate Missing	
										Reinforcement Visible	
										Reinforcement Projecting	
										Reinforcement Corroded	
Physical Damage											
Hole										Sag	
										Deformation	
										Broken	
										Collapse	

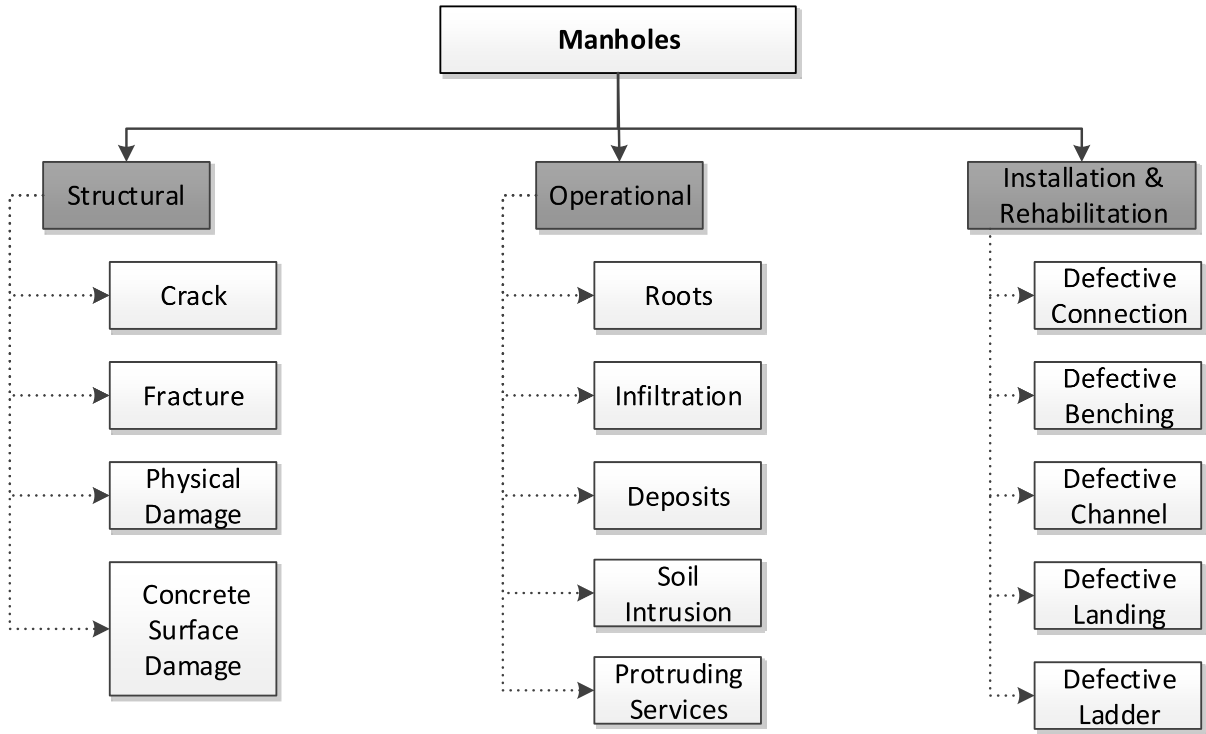


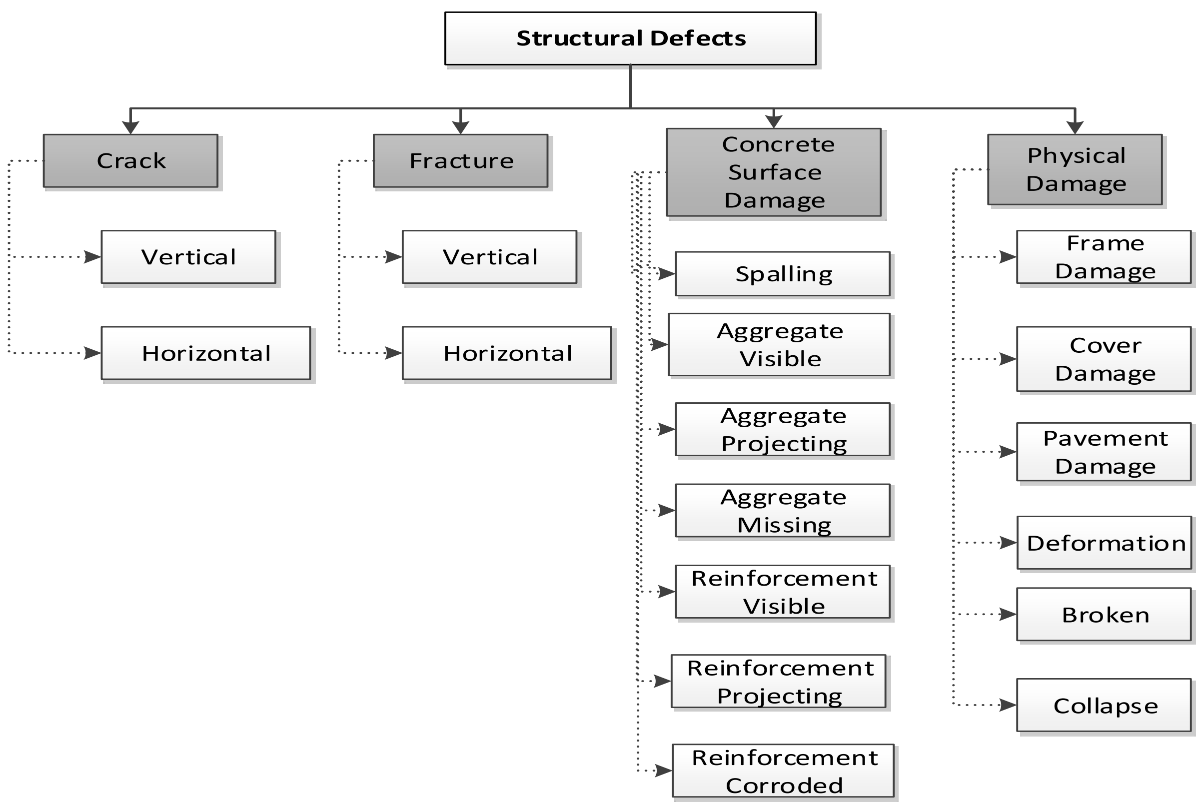
Criterion (X)	**Degree of Importance**									**Criterion (Y)**	**Remarks**
	(9) Absolute	**(7) Very Strong**	**(5) Strong**	**(3) Moderate**	**(1) Equal**	**(3) Moderate**	**(5) Strong**	**(7) Very Strong**	**(9) Absolute**		
Operational Defects											
Roots										Infiltration	

										Deposits	
										Soil Intrusion	
										Protruding Services	
Roots											
Fine/Single										Dense	
										Massive	
Infiltration											
Seeping										Dripping	
										Running	
										Gushing	
Soil Intrusion											
Fine										Coarse	
Deposits											
Encrustation										Foul	
										Debris	
Installation and Rehabilitation Defects											
Defective Connection											Defective Lining
											Defective Repair



Structural Defects											
Criterion (X)	**Degree of Importance**									**Criterion (Y)**	**Remarks**
	(9) Absolute	**(7)** Very Strong	**(5)** Strong	**(3)** Moderate	**(1)** Equal	**(3)** Moderate	**(5)** Strong	**(7)** Very Strong	**(9)** Absolute		
Open Joint										Non-Concentric Joint	
										Defective Joint	


Manholes
Structural
Operational
Installation & Rehabilitation
Crack
Fracture
Physical Damage
Concrete Surface Damage
Roots
Infiltration
Deposits
Soil Intrusion
Protruding Services
Defective Connection
Defective Benching
Defective Channel
Defective Landing
Defective Ladder


Structural Defects
Crack
Fracture
Concrete Surface Damage
Physical Damage
Vertical
Horizontal
Vertical
Horizontal
Spalling
Aggregate Visible
Aggregate Projecting
Aggregate Missing
Reinforcement Visible
Reinforcement Projecting
Reinforcement Corroded
Frame Damage
Cover Damage
Pavement Damage
Deformation
Broken
Collapse

Criterion (X)	Degree of Importance									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Operational Defects (Manhole)											
Structural Defects										Installation & Rehab. Defects	
Structural Defects (Manhole)											
Operational Defects										Installation & Rehab. Defects	
Installation & Rehab. Defects (Manhole)											
Structural Defects										Operational Defects	
Crack											
Vertical										Horizontal	
Fracture											
Vertical										Horizontal	
Physical Damage											
Frame Damage										Cover Damage	
										Pavement Damage	
										Deformation	
										Broken	
										Collapse	
Installation and Rehabilitation											
Defective Benching										Defective Connection	
										Defective Channel	
										Defective Landing	
										Defective Ladder	

Thank You for Filling this Questionnaire.

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