PERFORMANCE ASSESSMENT OF WATER NETWORK INFRASTRUCTURE

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ABSTRACT

PERFORMANCE ASSESSMENT OF WATER NETWORK INFRASTRUCTURE

Hisham El Chanati

In the fifth report of the drinking water infrastructure (2013), the US Environment Protection Agency (EPA) had stated that a total of 384.2$ billion is needed in water infrastructure investments in United States over the next 20 years. About 247.5$ billion, which is 64.4% of this investment, is required for the transmission and distribution segments of the water infrastructure. Thus, it is essential that the water infrastructure functions properly to ensure the continuous supply of healthy water with the required pressure. The deterioration of water distribution networks leads to impaired water quality, increased leakage and breakage rate, and reduced hydraulic capacity. The development of inspection, maintenance, and rehabilitation plans is crucial to reduce the failure risk of deteriorated infrastructures. The performance indices of water distribution networks and their components help municipalities plan inspection and avoid crises due to pipe failures and breaks.

The main purpose of this research is to assess the performance index of water distribution networks by integrating the performance indices of its components (pipelines and accessories). The water distribution network is divided into three hierarchal levels: components, segments, and distribution network or sub-network. To assess the performance indices of water distribution network components, the critical factors affecting them were identified and studied. Three main groups of factors were identified,

namely, physical, environmental and operational. Each of the three main groups is in turn sub-divided into a list of sub-factors. The Fuzzy Analytical Network Process (FANP) method was used to obtain the relative weights of the identified factors and sub-factors. These weights were used along with the effect values gathered from the experts to assess the performance index of the various components in the network. The performance indices of the segments were then assessed based on the components that make the segment. The performance indices of various segments were aggregated to obtain the sub-network or network performance using reliability analysis. Network performance could be utilized to prioritize the rehabilitation of components and segments and to construct comprehensive intervention plans for the entire network or sub-network. An Excel-Matlab® interface was developed to implement the developed models that perform the above mentioned procedure.

The resulting performance index, which represents the condition of the water distribution network, helps municipalities to minimize the number of scheduled maintenance activities and to predict the performance of the distribution network. This reduces health hazards and maintains the water supply safe, sustainable, and cost-effective.

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CHAPTER I

INTRODUCTION

I.1. OVERVIEW

A water distribution system is considered to be the most expensive component in a water supply system (Giustolisi et al. 2006). The National Guide to Sustainable Municipal Infrastructure best practice (2003) stressed on the importance of a planned inspection program for water distribution systems to minimize health and safety concerns and to ensure that municipalities provide an adequate supply of water in a safe, cost-effective, reliable, and sustainable manner. The deterioration of water distribution network leads to a compromised water quality, increased breakage and leakage rates, and reduced hydraulic capacity. The development of inspection, maintenance, and rehabilitation plans is crucial to reduce the failure and breakage risks associated with deteriorated infrastructures. There exist two methods for pipeline assessment: The first method is a physical-based approach (i.e., Direct inspection), which studies the physical mechanisms underlying pipe failures. However, such method requires data, which is costly or impossible to obtain (Kleiner and Rajani 2001). Consequently, physical models are only justified for major transmission water pipelines because of their potential failure cost. The second method is a statistical prediction one, which can be used for the majority of water pipelines because its input data is less costly and easy to obtain.

The 2013 ASCE report card had rated the US drinking water infrastructure with a score of (D+), which is translated into “Poor”. According to AWWA, replacing all pipes would cost more than $1 trillion. In addition, EPA's fifth report on Drinking Water Infrastructure Needs Survey and Assessment (2013) reported that a total of 384.2$ billion is needed in water infrastructure investments in United States over the next 20 years. An investment portion of 64.4%, which is about 247.5$ billion, is assigned for transmission and distribution segments of the water infrastructure. The majority of this amount is used for replacing or refurbishing aging or deteriorating pipelines. Figure I.1 shows the huge share that water distribution occupies in the entire water infrastructure system. On the other hand, the Canadian water infrastructure is rated as "Good" according to the CSCE infrastructure report (2012). Despite the good ranking, some concerns are still present especially with the presence of few pipe deterioration and breakage.

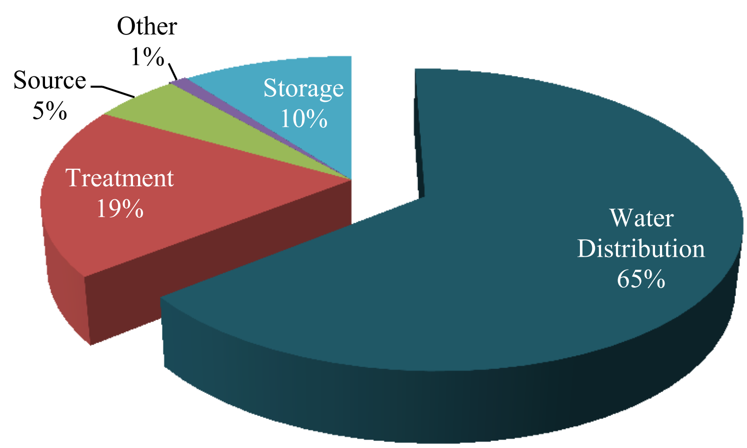


Figure I.1 Water Infrastructure Required Investment (EPA 2013)

I.2. RESEARCH OBJECTIVES

The objective of this research is to assess the performance index of water network infrastructure using the performance indices of its components. It can be achieved by completing the following tasks:

1) Identify and study the critical factors affecting the water distribution components.
2) Assess the performance index of water distribution components.
3) Develop an integrated performance index of the water distribution network.

I.3. RESEARCH METHODOLOGY

The main purpose of this work is to assess the performance index of water distribution networks using the performance indices of its components. The resulting index will help municipalities and maintenance companies develop a maintenance and rehabilitation plan for the entire network, its sub-networks, and even its components.

I.3.1. Literature Review

A comprehensive literature review was conducted in the areas related to water distribution networks. It included water distribution network components and their failure types as well as factors affecting water distribution network components. The literature review also covered existing condition rating and deterioration models. Finally, Fuzzy Analytical Network Process (FANP) and reliability based models were also reviewed.

I.3.2. Data Collection

A questionnaire was prepared and sent to engineers and experts in water distribution networks in Qatar and in the Gulf region. A total of 77 questionnaires (i.e., 40 for network pipeline and 37 network accessories) were collected and analyzed. The questionnaires were divided into two parts. The first part consists of a pairwise comparison between the sub-factors, while the second part was about the determination of the effect value for each predetermined characteristic of sub-factors.

Then, a data set was collected from Moncton, New Brunswick, municipality in Canada. The data included the following pipe characteristics: pipe age, material, size, breakage rate, C-factor, water quality, and type of surface. This data set was used to test the model on a small water distribution network in the same city.

I.3.3 Performance Index for Water Distribution Network Components

The model was developed using the following steps:

1) Identification and analysis of the main factors and sub-factors affecting the water distribution network and its components.
2) Development of a FANP-based performance index for water network pipeline accessories.
3) Use of a reliability based method to combine the pre-identified performance indices of the pipeline and accessories to obtain the performance index of water distribution network.

I.4 THESIS ORGANIZATION

The following Chapter, Chapter II, summarizes a detailed literature review which covered the water distribution network components and their failure type. The Literature review also shed the light on the factors affecting the performance of water distribution network components. The current evaluation practices and condition rating models were also studied. The Fuzzy Analytical Network Process and reliability based models were reviewed too. Chapter III describes the research methodology followed to perform this work. It includes the literature review, factor identification, data collection, the procedure to obtain the performance index using the fuzzy analytical network process (FANP) for water distribution network components, and the reliability based models used to develop the performance index for the entire network or part of it. Chapter IV presents the data collection step in this research and the analysis done on the collected data. Chapter V describes the detailed procedure to obtain the performance index for water distribution network components (pipeline and accessories). The Fuzzy Analytical Network Process (FANP) method was used to calculate the weights of the selected sub-factors. An Excel-Matlab® interface was created to automate the calculation. Chapter VI presents a case study where the Fuzzy Analytical Network Process (FANP) model was used to calculate the performance indices for water distribution network components. Then, using reliability based models; the calculated indices were used to determine the performance index for a preselected network. Finally, Chapter VII presents the research conclusions, limitations, and recommendations.

CHAPTER II

LITERATURE REVIEW

II.1. OVERVIEW

This chapter consists of six sections as shown in Figure II.1. Section II.2 provides the definition of water distribution networks. It also discusses the major components, their characteristics, and their behavior at failure. In the next section, section II.3, the main-factors and sub-factors affecting water distribution network components will be discussed. All of the sub-factors were grouped under three main factors, namely, Physical, Environmental, and Operational. A description of the sub-factors is also provided.

Section II.4 discusses the condition rating and performance index models that are currently used to predict the condition and performance of water distribution networks and their components. Sections II.5 and II.6 describes the fuzzy analytical network process (FANP) and the reliability based approaches, respectively. The two approaches were used to determine the performance indices of water distribution networks and their components.

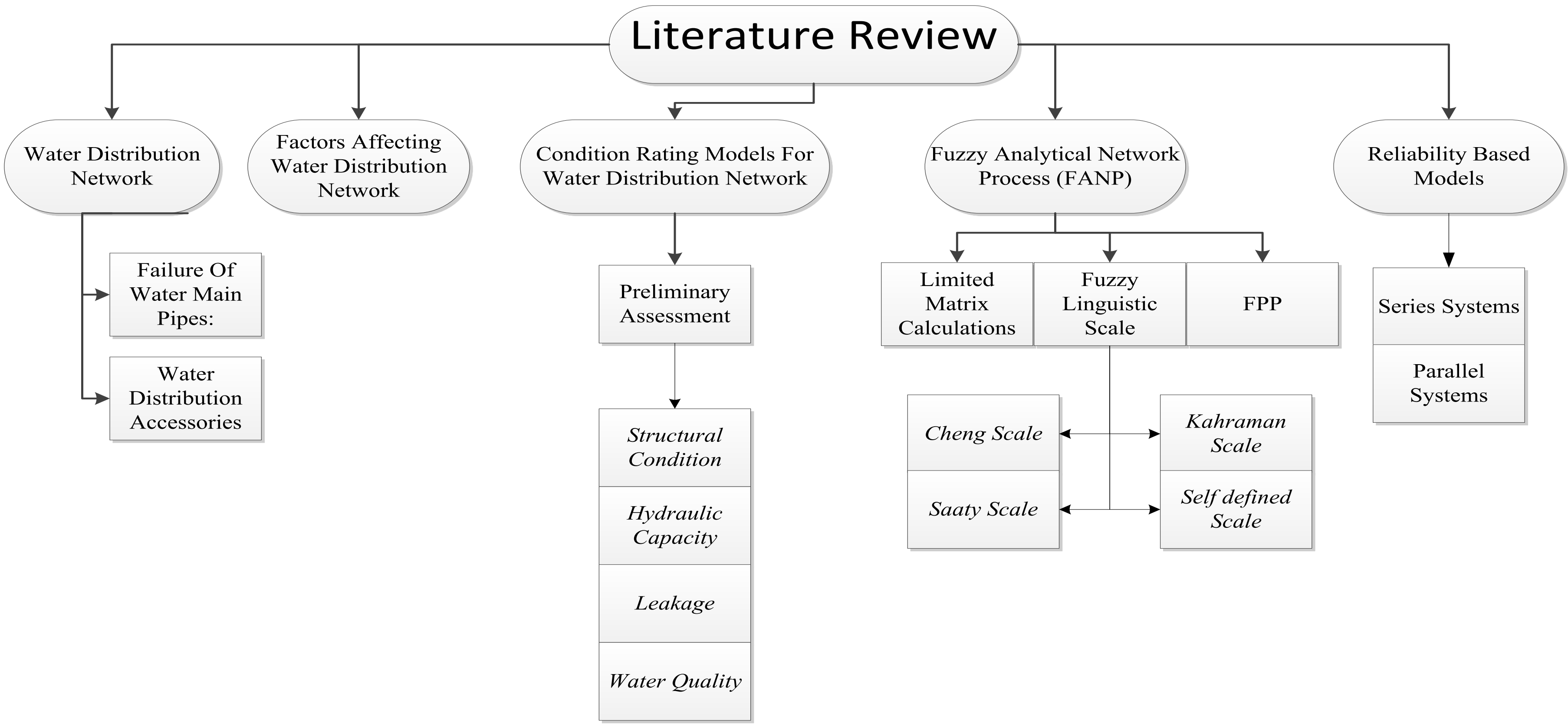


Figure II.1 Literature Review Diagram

II.2 WATER DISTRIBUTION NETWORK

Amit and Ramachandran (2009) stated that the main purpose of water distribution network is to provide customers with a reliable supply of good quality water with specific pressure levels under various demand condition. For this purpose, water distribution networks are made of several components such as pipes, reservoirs, pumps, valves, and other hydraulic components. According to Cullinane (1989), water distribution systems are made of several components such as pipes, valves, hydrants, motors, pumps, power transmission and tanks. The Australian National Audit Office (2010) stated that in order to determine the effectiveness and efficiency of assets in supporting the delivery of specific service outcomes, an asset portfolio should be segmented into the largest grouping that allow worthwhile analysis. Salman (2011) stated that a pipeline is divided into several segments, which are located between two or more isolation valves. The purpose of the isolation valves is to isolate a segment from the entire network during maintenance. Jun and Loganathan (2007) proposed a method for identifying the segments that are formed after the installation and closure of isolation valves in a water distribution network (Walski 1993a,b; Walski 2002). Giutolisi and Savic (2010) adopted Walsks's (1993a) definition for segments as a portion of a network made of one or more pipes and nodes. Figure II.2 shows two possible water distribution network layouts. All network components other than pipelines will be named here in this work as accessories. Thus, the water distribution network is considered herein to be made of pipelines and accessories.

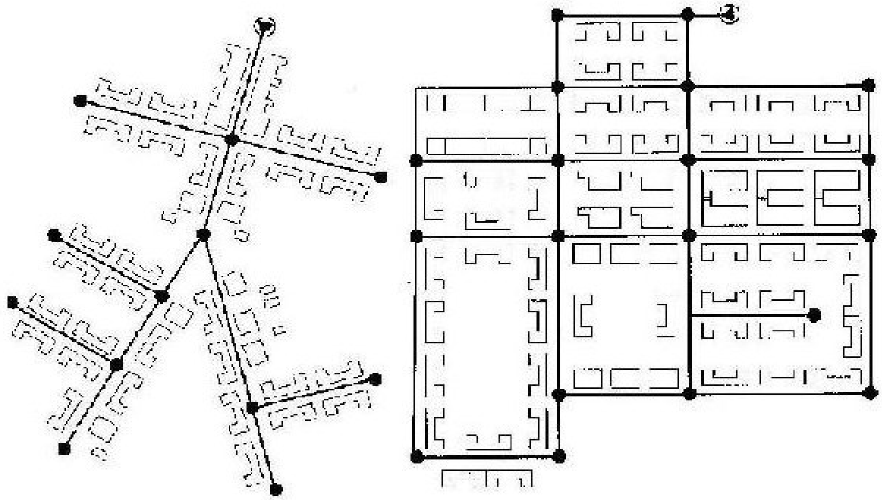


Figure II.2 Water Distribution Network Possible Layouts (Lennetech Water Treatment Solutions, 2014)

II.2.1 Water Distribution Network Pipes

According to Rajani and Kleiner (2004), water pipeline materials vary from one city to another. Three major categories of pipeline material are commonly used, namely, metallic, concrete, and poly. Cast and ductile iron fall under the metallic category. Asbestos and pre-stressed concrete pipes fall under the concrete category. Finally, the poly category includes PVC and Glass-Fiber Rein.

The mechanical and thermal characteristics vary between categories. Table II-1 summarizes the mechanical and thermal properties of pipe materials (Rajani and Kleiner 2004). Ductile iron and plastic pipes have higher strain at failure (%) than cast iron and asbestos cement pipes. On the other hand, the thermal expansion coefficient of plastic pipes is more than six times higher than that of cast iron and ductile iron. This means that the expansion of plastic pipes under heat is more than six time higher than that of cast and ductile iron. These properties must be taken into consideration during the pipeline selection. It is important to select the most suitable and economical pipe material. The selection process is also driven by several other factors, namely, price, size, fitting, availability, installation cost, location, ease of taping and repair, and environmental conditions such as soil type and water quality.

Table II-1 Mechanical and Thermal Properties of Pipe Material (Rajani and Kleiner 2004)

Properties	Cast Iron		Ductile Iron	Asbestos	PVC
	Pit	Spun			
Elastic Modulus, GPa	120	137	165	20-25	2.25
Ultimate Tensile Strength, MPA	173	250	290	25	48
Strain to Failure, %	0.5	0.5	7	1	10
Poisson's Ratio	0.3	0.3	0.28	0.3	0.42
Thermal Coefficient	12	12	11	8.5	79

Makar and Kleiner (2000) stated that pipes deteriorate and fail with time. They also reported that the failure rate of pipes depends on their material and on their exposure to different environmental and operational conditions. The deterioration of pipes can be classified into two categories, namely, structural and internal. The structural deterioration of pipes affects their structural resiliency and their ability to resist applied stresses. On the other hand, the internal deterioration of pipes affects their hydraulic capacity and water quality and reduces their structural resiliency (Rajani and Kleiner 2004)

Corrosion is considered as the main reason for the failure of metallic pipes (Makar and Kleiner 2000). The corrosion and deterioration rates of metallic pipes depend on the type of soil they are imbedded in. Metallic pipes deteriorate and fail faster when embedded in aggressive soil. Al Barqawi (2006) reported that polyethylene sheets are used to wrap pipes to isolate them from the surrounding soil. This helps reduce the deterioration rate of metallic pipes (Saint-Gobain 2002).

The main reason of failure for pre-stressed concrete pipes (CPP/PCCP) is also corrosion. Pre-stressed concrete pipes with corroded/broken pre-stressed bars or wires fail because they are no longer able to resist the water pressure (Makar and Kleiner 2000). Rajani and Kleiner (2004) reported that CPP/PCCP is weakened when embedded in low PH soil. This is due to the fact that low PH soil can lower the PH value of the concrete matrix to a level that allows the corrosion of the pre-stressed bars or wires.

Kleiner and Rajani (2001) reported that aggressive water such as low PH water can trigger the deterioration of Asbestos Cement (AC) pipes. This represents a threat to people's health because deteriorated AC pipes releases asbestos fibers into the water that is carried through the distribution network. Pipeline epoxy lining helps in preventing this type of damage (USA Departement of Environment 1998)

Polyvinyl Chloride (PVC/uPVC) pipes are most suitable for very corrosive environments because they have high resistance to deterioration and corrosion unless they are exposed to weather, chemical attack, or mechanical degradation from improper installation (Balga 1973). For PVC pipes, the resistance to chemical attack decreases with the increase in the concentration of a specific chemical. For example, the failure of PVC/uPVC pipes due to expansion and rupture will occur when exposed to organic chemicals like solvents and gasoline. Joint imperfection, material degradation, and improper pipe installation also deteriorate PVC pipes. Organic chemicals can also pass through the walls of the pipe (Blaga 1981; Blaga 1982; Best Practice 2003)

II.2.2 Water Distribution Accessories

Water distribution accessories are the water distribution network components other than pipes. The two major accessories are the valves and hydrants. Different types of valves are available such as valve housings, gate valves, and butterfly valves (City Engineers Associations of Minnesota 1999). According to National Guide of Sustainable Municipal (2003_b), valves have different purposes in water distribution networks. They are used for isolation, air release, drainage, and checking and pressure reduction. The most common ones are the isolation valves. Two different types of isolation valves exist. The first one is buried gate valve, which is used for isolation of small water pipes and services. The second one is butterfly valve, which is used for large diameter mains. Isolation valves deteriorate and fail in different ways such as stripped; broken or bent stems; leaking O-rings or packing; corrosion of the valve body and connecting bolts; and wear on the valve disk and seat. Hydrants are also subjected to deterioration, frost damage and failure. However, their inspection and maintenance is done more often than that of buried valves.

The literature review shows that water distribution network components have different failure forms and that several factors influence their deterioration. Thus, studying and understanding these factors will help the municipalities reduce the impact of deterioration and failure of these components. Based on their exposure to specific factors, these components deteriorate and fail causing severe damage to their surroundings and health in general.

II.3 FACTORS AFFECTING WATER DISTRIBUTION NETWORK

Several researches studied the factors affecting the deterioration of water distribution index. Kleiner and Rajani (2001) stated that these factors include operational, environmental, and physical characteristics. Kleiner and Rajani (2001) also stated that the time dependent factors, the climate condition, and the soil type are the reasons behind the deterioration rate variation of buried pipelines. On the other hand, water distribution networks are subjected to different load types from its surroundings. These loads can be classified as external and internal such as traffic and frost loads, soil and internal pressure, and third party interference (Rajani and Kleiner 2001). Three classifications (Table II-2) had been created for water pipelines deterioration factors (Rajani and Kleiner 2002):

1. Static factors, which do not change with time, include pipe material and diameter, installation quality, and soil characteristics.
2. Dynamic factors, which that change with time like age, include soil and water temperature, bedding condition, soil moisture, properties and electrical resistivity, and dynamic loading.
3. Operational factors such as cathodic protection, internal pressure, and replacement rates.

Table II-2 Factors affecting pipe breakage rate (Rajani and Kleiner 2002)

Static	Dynamic	Operational
Material Diameter Wall Thickness Soil Characteristics Installation Quality	Age Temperatures (from soil and water) Soil Moisture Soil Electrical Resistivity Bedding Condition Dynamic Loading	Replacement Rates Cathodic Production Water Pressure

A different classification was proposed by the National Guide to Sustainable Municipal Infrastructure in their Best Practices (2003_b). The classification includes the following factors (Table II-3):

1. Physical factors, which consider the physical attribute of the pipeline such as pipe age, material, thickness, diameter, coating, types of joints and manufacture processes.

2. Environmental factors, which consider the environmental aspect surrounding the pipe, include soil type and moisture, ground water presence, pipe location, climate, stray electrical currents, seismic activities.
3. Operational factors, which consider the operational attribute in the pipe such as internal pressure, water quality, flow velocity, back flow, and operational and maintenance practices.

Many researchers adopted the late classification in their condition rating models. Yan and Vairavamoorthy (2003) developed their condition rating model using physical and environmental factors only. They considered pipe age, diameter and material as physical factors, and road loading, soil condition and surroundings as environmental factors. Only one type of soil was considered in their model. The authors recommended using other factors in future models. Another condition rating model was developed by Geem (2003). It included seven physical and environmental factors, namely, pipe age, material and diameter, bedding condition, corrosion, temperature, and trench width. However, the data used was arbitrary generated. Najafi and Kulandaivel (2005) developed a model for the condition prediction of sewer pipes. Seven physical and environmental factors were also used for the model development, namely, pipe age, size, material, length, depth, slope, and sewer type. Al Barqawi (2006) used in his model the soil type, road surface, pipe depth, diameter, material, age, number of breaks, and C-factor to assess the condition of pipeline.

Table II-3 Water System Deterioration Factors (Al Barqawi 2006; NRCC and FCM 2003)

Main Factors	Sub-Factors	Explanation
Physical	Pipe material	Pipes made from different materials fail in different ways.
	Pipe wall thickness	Corrosion will penetrate thinner walled pipe more quickly.
	Pipe age	Effects of pipe degradation become more apparent over time.
	Pipe vintage	Pipes made at a particular time and place may be more vulnerable to failure.
	Pipe diameter	Small diameter pipes are more susceptible to beam failure.
	Type of joints	Some types of joints have experienced premature failure (e.g., leadite joints).
	Thrust restraint	Inadequate restraint can increase longitudinal stresses.
	Pipe lining and coating	Lined and coated pipes are less susceptible to corrosion.
	Dissimilar metals	Dissimilar metals are susceptible to galvanic corrosion.
	Pipe installation	Poor installation practices can damage pipes, making them vulnerable to failure.
	Pipe manufacture	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure. This problem is most common in older pit cast pipes.
Environmental	Pipe bedding	Improper bedding may result in premature pipe failure.
	Trench backfill	Some backfill materials are corrosive or frost susceptible.
	Soil type	Some soils are corrosive; some soils experience significant volume changes in response to moisture changes, resulting in changes to pipe loading. Presence of hydrocarbons and solvents in soil may result in some pipe deterioration.
	Groundwater	Some groundwater is aggressive toward certain pipe materials.
	Climate	Climate influences frost penetration and soil moisture. Permafrost must be considered in the north.
	Pipe location	Migration of road salt into soil can increase the rate of corrosion.
	Disturbances	Underground disturbances in the immediate vicinity of an existing pipe can lead to actual damage or changes in the support and loading structure on the pipe.
	Stray electrical currents	Stray currents cause electrolytic corrosion.
	Seismic activity	Seismic activity can increase stresses on pipe and cause pressure surges.
Operational	Internal water pressure, transient pressure	Changes to internal water pressure will change stresses acting on the pipe.
	Leakage	Leakage erodes pipe bedding and increases soil moisture in the pipe zone.
	Water quality	Some water is aggressive, promoting corrosion
	Flow velocity	Rate of internal corrosion is greater in unlined dead-ended mains.
	Backflow potential	Cross connections with systems that do not contain potable water can contaminate water distribution system.
	O&M practices	Poor practices can compromise structural integrity and water quality.

II.4 PRELIMINARY ASSESSMENT AND CONDITION RATING MODELS FOR WATER DISTRIBUTION NETWORK

II.4.1 Preliminary Assessment

The National Guide to Sustainable Infrastructure (2003_b) identified as best practices two inspection phases, namely, preliminary assessment and comprehensive investigation based on the results of the first phase. The preliminary assessment involves evaluating the structural condition, hydraulic capacity, leakage, and water quality. The most effective way to perform the initial assessment is through the analysis of the gathered data. For each problem to be inspected, specific data should be gathered and analyzed. Table II-4 shows the required data needed to perform the initial assessment. It also shows when a detailed investigation is required based on the results of the preliminary assessment.

II.4.2.1 Structural Condition

The main indicator in the structural condition is the break record. Every municipality should have a break record of its water distribution network pipes. According to best practices (2003_b), several types of observations and details should be reported such as type, location, date, affected properties affected, etc. Each municipality has its own acceptable limit of breakage rate, which could be an indicator of the state of the structural condition. However, the most important information obtained from the collected data is the trend and pattern. Another way of viewing the breaks is through location. Identifying the exact location of each break will help in locating the areas of high breakage rate (i.e., with high numbers of breaks). These locations can be investigated to check the reason behind the high number of breaks, whether from it is from the soil type or from the compatibility between pipe material and the surrounding environment or any other reason. It is important to mention that recent accurate positioning technologies such as GPS and Geographic Information Systems (GIS) will facilitate this process.

Table II-4 Investigation of Water Distribution Systems

<table>
<tr><th>Problem</th><th>Preliminary Assessment</th><th>Reasons for More Detailed Investigation</th><th>Detailed Investigation</th></tr>
<tr><td>Structural Condition</td><td>• Spatial and temporal analysis of water main breaks
• Compilation of soil map
• Routine inspection of valves and hydrants
• Routine inspection of insulation and heat tracing in northern areas</td><td rowspan="4">Level of Service
• Preliminary investigations indicate an excessive break rate, excessive leakage, inadequate hydraulic capacity and/or impairment of water quality

Cost Effectiveness
• To facilitate capital planning and asset management programs
• Pilot testing of new technologies to facilitate long-range planning support
• Opportunistic work, such as when a water main is temporarily out of service

Risk Management
• Risk analysis identifies critical water mains that have a high potential for significant property damage, environmental impact or loss of service.
• Due diligence (e.g. failure analysis of a failed critical water main)</td><td>• Detailed analysis of break patterns rates and trends
• Statistical and physical models
• Pipe sampling
• Soil corrosivity measurements
• Pit depth measurements
• Non-destructive testing
• Failure analysis
• Visual inspection
• Thermal analysis (far north)</td></tr>
<tr><td>Hydraulic Capacity</td><td>• Low-Pressure complaints
• Hydrant flow tests
• Rusty/colored water occurrences
• Visual inspection of pipe interior
• Monitoring of pressure and pumping costs</td><td>• Hazen-Williams C factor tests (pipe roughness)
• Computer modeling</td></tr>
<tr><td>Leakage</td><td>• Water use audit
• Per capita water demand
• Routine leak detection survey</td><td>• Leak detection survey
• Detailed limited area leakage/damage assessment</td></tr>
<tr><td>Water Quality</td><td>• Water quality complaints
• Routine sampling data
• Results of flushing program</td><td>• Detailed water quality investigation
• Computer modeling</td></tr>
</table>

II.4.2.2 Hydraulic Capacity

A record of the details and locations of low pressure complaints must be kept by the municipalities as an initial assessment of the hydraulic capacity. A large number of these complaints suggest a deteriorating condition of the hydraulic capacity. Mapping these complaints and performing a spatial analysis will help figuring out the possible causes of these complaints. Some of these causes must be taken into consideration in the analysis. However, other causes such as low-pressure complaints related to construction and maintenance activities must be ignored. Hydrant-flow and visual or camera inspection tests can be performed to assess the hydraulic capacity. They can give an indication about the degree of tuberculation in water mains (Best Practices2003$_b$).

II.4.2.3 Leakage

According to Best Practices (2003$_b$), the leak detection can be a significant indicator to determine the deterioration of water distribution systems. Several techniques are currently used for identifying leaks in water distribution networks. The basic concept of these techniques is to divide the network into manageable zones and to calculate the ingoing and outgoing flows in each zone. The most common methodologies used to detect water distribution system leaks are hydrostatic leakage test and water audit (Al Barqawi 2006).

II.4.2.4 Water Quality:

Similar to the hydrostatic capacity, the preliminary assessment of water quality is done using the complaint records and the regular water quality monitoring data. Complaints due to construction and maintenance activities should be excluded from the analysis process. However, they should be tracked and monitored to check their status after the end of the construction / maintenance activities. A continuous check of the water quality in the distribution system will report any changes in the quality of the transmitted water, which give an indication about the condition of the distribution system. For example, low chlorine residuals in some parts of the system may indicate that the water mains in these places are deteriorating. Likewise, the concentration of iron in the water may demonstrate the degree of internal corrosion in the mains (Best Practices 2003_b)

II.4.2 Condition Rating Models

Several condition and deterioration models were developed to predict the current condition and the deterioration rate of water pipelines, respectively. Yan and Vairavamoorthy (2003) assessed the condition of water mains using fuzzy multi-criteria decision-making (MCDM) techniques. Geem (2003) developed a decision support system for pipeline condition assessment using Artificial Neural Networks (ANN). Najafi and Kulandaivel (2005) also used ANN to develop a model that predicts the condition of sewer pipelines based on historical condition assessment data. Al-Barqawi and Zayed (2006a; 2006b) developed AHP and ANN-based models to predict and assess the condition of water pipelines using physical, operational, and environmental deterioration factors. Al-Barqawi and Zayed (2008) also evaluated the sustainability of water pipelines using an integrated AHP/ANN approach. Salman (2011) developed a model for the reliability based management of water distribution networks using an intervention priority index (PI) that considers the combination of reliability assessment and criticality index for water networks.

Water distribution systems deteriorate and fail over time. However, the failure rate of a water main depends on its material and its exposure to environmental and operational factors (Makar and Kleiner 2000). Ozger (2003) related the failure of water distribution systems to performance/mechanical factors, namely, static (i.e., Material, diameter, wall thickness, soil, etc.), Dynamic (i.e., Age, temperature, soil moisture, resistivity, and loading), and operational (i.e., Replacement rates, cathodic protection, and water pressure). The factors causing the deterioration of water pipelines are categorized into physical, environmental, and operational as discussed in section "II.3". Previously developed models have used the factors similar to those shown in Table II-3. The deterioration models are developed using recorded historical data. They predict the current condition and the deterioration behavior of the pipe. According to Kleiner and Rajani (2001), the developed deterioration models can be grouped into two categories, namely, physical and statistical.

The physical models were developed to improve the understanding of the structural performance of water mains. They were also used to predict the failure of the pipeline by analyzing its subjected loads and its ability to resist them. The structural performance is affected by the external and internal loads due to soil pressure, loads due to traffic and frost, operational pressure, and third party interference. the first physical models were deterministic, while the latest ones are more likely to have a probabilistic approach. Thus, it is safe to classify the physical models into two categories, namely, deterministic and probabilistic. Due to their limitations, physical models are only justified for large water mains (Rajani and Kleiner 2001).

On the other hand, the statistical models consider the historical break record of water main in order to identify breakage patterns, which are assumed to still apply in the future. They were classified into three categories, namely, deterministic, probabilistic single-variety, group-processing and probabilistic multi-variety. In the deterministic models, equations of two or three parameters are being used to model breakage pattern. For the best utilisation of these models, the group of water mains being assessed must be subjected to the same factors influencing their breakage pattern. On the other hand, the probabilistic multi-variety models require less restriction in the homogeneity of the influencing factors since they can consider many covariate influencing factors. However, significant technical expertise and sufficient data are required to handle the multiple varieties. Finally, the probabilistic single-variable group-processing models use probabilistic processes on gathered data to obtain probabilities for the pipe life expectancy and breakage, which can be used for long-term and short term rehabilitation, maintenance and replacement plans.

II.5 FUZZY ANALYTICAL NETWORK PROCESS (FANP)

II.5.1 Introduction

Multi Criteria Decision Making (MCDM) methods help decision makers, technical experts, and stakeholders apply value judgments to come up with the optimum strategic choice. Saaty (2005) developed AHP as a multi-criteria decision support methodology, which derives relative scales of absolute numbers known as ‘priorities’ from judgments expressed numerically on an absolute fundamental scale. Later, Saaty (2008) developed ANP as an extension to AHP problems with dependencies and feedback among the criteria. ANP works on deriving, from a group of judgments, relative priority scales of absolute numbers. These judgments illustrate the relative influence of one of two elements over the other in a pairwise comparison manner, with respect to an underlying control criterion. Garuti and Sandoval (2005) reported that ANP provides a way to clear all the relationships among variables; which significantly decreases the gap between the model and reality. The use of the pairwise comparison to formulate the relations among variables helps in directing attention to a given connection at a time, allowing a more precise and inclusive analysis. The simplification level needed to build hierarchy models requires an unusual effort to identify and handle the multiple interconnections between components that the real problem has. In addition, ANP relies on the accumulated experience and knowledge of decision makers, instead of merely supplying them with data that may provide little decision support (Sarkis and Sundarraj 2006).

The fuzzy set theory, which was first introduced by (Zadeh 1965), models the uncertainty caused by the vagueness and imprecision of the human cognitive processes in real life systems. A crisp set is a set where an element either belongs to or not to a set. In other words, its membership function is either 0 or 1. On the other hand, fuzzy sets allow partial membership, which allows an element to belong to a set with any membership value ranging from 0 to 1.

Despite the various advantages of the AHP/ANP framework, the ANP-based decision model is ineffective when dealing with the inherent fuzziness or uncertainty in judgment during the pairwise comparison process. The use of the discrete scale of 1 to 9 to represent the verbal judgment in pairwise comparisons has the advantage of being simple and straight forward. However, it does not account for the uncertainty and imprecision associated with the mapping of a person's perception or judgment to a crisp number. In order to capture the expert's knowledge, the ANP-based decision model still needs to reflect the human thinking style (Kahraman et al. 2006). In real-life situations, the decision makers or experts could be uncertain about their own level of preference due to incomplete information, insufficient knowledge, complexity, lack of appropriate measurement scale, or uncertainty within the decision environment. They also tend to specify preferences in the form of often vague and uncertain natural language (Promentilla et al. 2008).

Fuzzy logic is a natural way to incorporate the uncertainty or the vagueness of human judgment. When comparing two elements, the uncertain numerical ratio is expressed in a fuzzy manner rather than an exact one. Fuzzy AHP (FAHP) and Fuzzy ANP (FANP) were introduced to capture the 'fuzziness' or the vagueness and uncertainty in the evaluation of alternatives. Human judgment is characterized by uncertainty and subjectivity, which makes acquiring exact judgments in pairwise comparisons sometimes unrealistic and infeasible. It is easy to provide verbal judgments when giving subjective assessment. An expert may confidently claim that alternative "A" is strongly preferred over alternative "B" with respect to a control criterion but may fail to provide the exact ratio of how strong the preference is. Many of the pipeline characteristics and condition criteria are often available in a linguistic manner rather than a numerical state, which calls for using a fuzzy approach. Thus, the use of FANP is justified to overcome the limitations of the previously mentioned AHP, ANP, and FAHP in overcoming the uncertainties and accounting for the interdependencies between the factors. According to Etaati (2011), several research fields of research have used FANP, namely, strategic and safety management, selection of suppliers, transportation-mode, containers, and decision support systems, etc..

II.5.2 Fuzzy Linguistic Scale

Herrera et al. (2008) stated that many aspects of real world activities are best described in qualitative way rather than quantitative. In these cases, the used linguistic assessments and variables are subjected to uncertainties. In the FANP, these linguistic judgements take place in the pairwise comparison. Etaati (2011) mentioned three of the most used FANP scales, namely, Cheng, Kahraman, and Saaty scales. It is important to note that these scales are not the only used. The researcher who uses fuzzy linguistic scale needs to choose the most appropriate one for his research.

Table II-5 Cheng, Kahraman and Saaty Scale (Etaati et al. 2011)

Scale	Fuzzy Linguistic Scale
Cheng	{(0,0,0.25); (0,0.25,0.5) ; (0.25,0. 5,0.75) ; (0.5,0.75,1); (0.75,1,1);}
Kahraman	{(1,1,1); (0.5,1,1.5) ; (1,1. 5,2) ; (1.5,2,1.5); (2,2.5,3); (2.5,3,3.5)}
Saaty	{(1,1,1); (2,3,4) ; (4,5,6) ; (6,7,8); (8,9,10)}

II.5.2.1 Cheng Scale

In any evaluation process, attributes can be described by linguistic and quantitative variables. Thus, Cheng (1999) used a hierarchy diagram to structure complicated problems with fuzzy theory to deal with linguistic and qualitative requirements. He used fuzzy language to construct the look-up table for values and to derive its corresponding value to the mean of fuzzy numbers. Cheng's scale is summarized in Table II-5 (Etaati et al. 2011).

II.5.2.2 Kahraman Scale

Kahraman (2006) proposed an integrated framework based on fuzzy-QFD and a fuzzy optimization model to determine the technical requirements for designing a product. Several researchers adopted his scale in their work. Kahraman's scale is shown in Table II-5 (Etaati et al. 2011)

II.5.2.3 Saaty Scale

In 1989, Saaty proposed a nine point fundamental scale which was generally used in AHP and ANP pair wise comparisons. Several researchers adopted Saaty's linguistic scale as reliable source. Table II-5 illustrates Saaty's scale. (Etaati et al. 2011).

II.5.2.4 Self defined Scale

As stated by Etaati (2011), several researchers developed their own linguistic scale. These developed scales are based on their type of research and can be used for similar field researches. Table II-6 shows some of the self-defined scales along with the researchers who developed them.

Table II-6 Self Defined Scales (Etaati et al. 2011)

Researchers	Self-Defined Scales
Chen & I, 2010	{(1,1,3); (1,3,5) ; (3,5,7) ; (5,7,9); (7,9,9)}
Lin, Lee & Wu, 2009	{(1,1,1);(1,2,3);(2,3,4);(3,4,5);(4,5,6);(5,6,7);(6,7,8);(7,8,9);(9,9,9)}
Ayub, Md, & Md, 2009	{(1,1,1);(1,1,3);(1,2,3);(1,3,5);(2,4,6);(3,5,7);(4,6,8);(5,7,9);(6,8,10);(7,9,11)}
Zhou & Xu, 2008	{(1,1,1);(1,2,3);(2,3,4);(3,4,5);(4,5,6);(5,6,7);(6,7,8);(7,8,9);(8,9,10)}
Qu & et al., 2009	(0.5,1,1.5);(1.5,2,2.5);(2.5,3,3.5);(3.5,4,4.5);(4.5,5,5.5);(5.5,6,6.5);(6.5,7,7. 5);(7.5,8,8.5);(8.5,9,9.5)}

II.5.3 Limited Matrix Calculations

Limited matrix is the last step in the FANP calculation from which the weights of the factors are obtained. The basic concept behind the limited matrix calculation is raising the weighted matrix to large powers until the new resulted matrix is the same as the one before it. This power is determined from the weighted matrix degree (Adams 2001). Due to matrix properties, and the type of problem being solved this limited matrix might converge to a matrix of zeroes. If the weighted supermatrix with diagonals of zero is raised to large powers, the entire matrix will converge to be a matrix of zeroes, yielding no weights. An integrated Excel-Matlab® standalone interface was created to do the FANP calculations for the purpose of this research. The calculation steps of FANP limited matrix is the same as those of ANP. However the unweight matrix, the weighted matrix and limited matrix eventually, are computed differently. The super decision programme developed by Creative Decision Foundation is used herein for the AHP and

ANP calculations by just entering the pairwise comparison results. However, the programme does not do FANP calculations. Creative Decision Foundation (2012) developed a brief description of the algorithms used in its software for ANP calculation. According to their description, the calculation methods are grouped into Out of date, Current, and Vargas. More information about SuperDecision® software can be found in the brief description of Creative Decision Foundation (2012). For a sufficiently connected network, the calculations are relatively easy and can be done with no problem. However, the calculations are more difficult in the case of insufficiently connected networks. The insufficiently connected networks are the networks that have sinks, which are the columns of zeroes in the matrix resulting from no relations between the corresponding sub-factors (Table II-7). As mentioned previously, these sinks make the matrix yield to a matrix of zeroes when raised to high powers. In order to overcome this issue, the same columns from the identity matrix will be used to replace the sinks (Table II-8).

Table II-7 Supermatrix with Sinks

	WMF	PF	EF	OF	A	M	S	IQ	L	GW	ST	C-FACTOR	BR	WQ
WMF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PF	0.143	0	0.5	0.833	0	0	0	0	0	0	0	0	0	0
EF	0.714	0.167	0	0.167	0	0	0	0	0	0	0	0	0	0
OF	0.143	0.833	0.5	0	0	0	0	0	0	0	0	0	0	0
A	0	0.405	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0.060	0	0	0	0	0	0	0	0	0	0	0	0
S	0	0.405	0	0	0	0	0	0	0	0	0	0	0	0
IQ	0	0.130	0	0	0	0	0	0	0	0	0	0	0	0
L	0	0	0.143	0	0	0	0	0	0	0	0	0	0	0
GW	0	0	0.714	0	0	0	0	0	0	0	0	0	0	0
ST	0	0	0.143	0	0	0	0	0	0	0	0	0	0	0
C-FACTOR	0	0	0	0.333	0	0	0	0	0	0	0	0	0	0
BR	0	0	0	0.333	0	0	0	0	0	0	0	0	0	0
WQ	0	0	0	0.333	0	0	0	0	0	0	0	0	0	0

Table II-8 Sink Replacement with Identity Columns

	WMF	PF	EF	OF	A	M	S	IQ	L	GW	ST	C-FACTOR	BR	WQ
WMF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PF	0.143	0	0.5	0.833	0	0	0	0	0	0	0	0	0	0
EF	0.714	0.167	0	0.167	0	0	0	0	0	0	0	0	0	0
OF	0.143	0.833	0.5	0	0	0	0	0	0	0	0	0	0	0
A	0	0.405	0	0	1	0	0	0	0	0	0	0	0	0
M	0	0.060	0	0	0	1	0	0	0	0	0	0	0	0
S	0	0.405	0	0	0	0	1	0	0	0	0	0	0	0
IQ	0	0.130	0	0	0	0	0	1	0	0	0	0	0	0
L	0	0	0.143	0	0	0	0	0	1	0	0	0	0	0
GW	0	0	0.714	0	0	0	0	0	0	1	0	0	0	0
ST	0	0	0.143	0	0	0	0	0	0	0	1	0	0	0
C-FACTOR	0	0	0	0.333	0	0	0	0	0	0	0	1	0	0
BR	0	0	0	0.333	0	0	0	0	0	0	0	0	1	0
WQ	0	0	0	0.333	0	0	0	0	0	0	0	0	0	1

II.6.4 Fuzzy Preference Programming (FPP)

Dealing with the fuzzy comparison matrices that result from the application of the fuzzification scale was the point of interest for many researchers. According to Zhou (2012), Van Laarhoven and Pedrycz (1983) proposed a fuzzy logarithmic least squares method to obtain fuzzy weights from triangular fuzzy comparison matrix. Buckley (1985) used geometric mean method to calculate fuzzy weights. Chang (1996) suggested an extent analysis method, which derives crisp weights for fuzzy comparison matrices. Fuzzy least squares priority method (LSM) was proposed by Xu (2000). Csutora and Buckley (2001) came up with Lambda-Max method, which is the direct fuzzification of the kmax method. Fuzzy Preference Programming was created by Mikhailov (2003; 2004) to derive crisp weights from fuzzy comparison matrices. Srdjevic (2005) proposed a multicriteria approach for combining prioritization methods within the AHP, including additive normalization, eigenvector, weighted least-squares, logarithmic least-squares, logarithmic goal programming, and fuzzy preference programing. A modified fuzzy logarithmic least square method was proposed by Wang et al (2006). Yu & Cheng (2007) created a multiple objective programming approach to calculate all local priorities for crisp at one time for ANP. Huo et al. (2011) suggested new parametric prioritization methods (PPMs) for the determination of priority vectors in AHP. According to Kiris (2013), Fuzzy Preference Programing (FPP) derives consistency values and calculates local weights from the fuzzy pairwise comparison matrix easily using Matlab® software. Zhou, X. (2012) proposed a code to solve the fuzzy analytical network process (FANP) using Matlab®. The proposed code was adopted and modified to fit the work in this research.

II.7 RELIABILITY BASED MODELS

The Reliability based models are widely used for the purpose of infrastructure network assessment, such as the assessment of subway, bridge, and road networks. Govil (1983) defined the reliability of an item as its probability to perform its intended function within a specific time, under certain operating condition. In other words, it is the probability of fulfilling its purpose without failing. The main role of the water distribution network is to deliver water from one point to another. Since the purpose of the water distribution network is to deliver good quality water within specific pressure levels to the end users, the reliability of this distribution network can be divided into hydraulic and mechanical reliability. Cullinane (1989) defined the hydraulic reliability as the ability of the system to deliver specific quantity of water to the appropriate place at the required time under the desired pressure. Cullinane (1989) defined the mechanical reliability as the ability of the distribution system components to provide continuous and long term operation without the need of frequent repairs or replacements. Thus, finding the reliability of water distribution networks will be based on its component reliabilities. As previously defined, the water distribution network is made of pipelines and accessories. The reliability of each one of these components is determined by the probability of performing its intended function without failure starting from the installation time (time zero) until a specific time. According to Cullinane (1989), the reliability of a component can be mathematically represented using equation (1):

$$\boldsymbol{R(t) = \int_{t}^{\infty} f(t)dt} \quad (1)$$

Where f(t) is the probability density function of the installation time to the failure time of the component. This probability density function is either assumed or obtained using historical data and for the repaired components, time of repair is considered as time zero.

The failure of systems was the point of interest for many researchers. Several researchers assumed pipe failure as breakage rate or number of breaks that occurs in a specific time range. For example, Salman (2011) mentioned that if one failure occurred in a period of ten years, the failure rate is 1f/10y which is equivalent to (0.1 f/y). Monte-Carlo method is used for predicting the probability of failure. It can simulate the behavior of structures in term of failure and predict its rate. In this case, the probability of failure is computed using the following equation:

$$P_f = \frac{n_f}{n} \quad (2)$$

Where (n) is the number of simulations and (n_f) is the number of failures. However, Estes and Frangopol (2005) stated that this method requires a large number of simulations in order to obtain valid results.

Since the reliability is used to assess complex network systems, several techniques were used for that purpose, namely, fault-tree analysis, Cut-Set, Cut/tie Set (Path-set), Spanning-tree analysis, polygon-to-chain reduction, method of bonus and connection matrix technique (Quimpo 1996). It is essential to choose the most suitable method for network systems.

II.7.1 Series Systems

The failure of a component in a series system will lead to the failure of the entire system (Terruggia 2010). A series system is weaker than its weaker link. In series systems, each component is considered as a cut. Figure II.3 properly visualizes the series system.

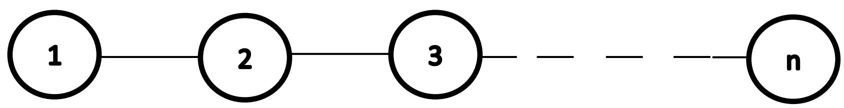


Figure II.3 Series Systems

A series system fails when one of its components fails. Thus, for series systems the performance index is defined using the following equation:

$$\boldsymbol{PI = PI1.PI2\ \ldots\ldots PIn = \prod_1^n (PIn)} \quad (3)$$

The probability of failure of a series system is given by the following equation:

$$\boldsymbol{Pf = 1 - [(PI1).(PI2)\ \ldots\ldots (PIn)] = 1 - \prod_1^n (PIn)} \quad (4)$$

This can also be re-written using the following equation:

$$\boldsymbol{Pf = 1 - [(1 - Pf1).(1 - Pf2)\ \ldots\ldots (1 - Pfn)] = 1 - \prod_1^n (1 - Pfn)} \quad (5)$$

Thus, the reliability of a system with connections in series is given by the following equation:

$$\boldsymbol{R = 1 - Pf = \prod_1^n (PIn)} \quad (6)$$

II.7.2 Parallel Systems

In parallel systems, only one functioning component will make the system function. This means, a parallel system functions if at least one of its components is still functioning. In parallel systems, all the components are considered as paths. Figure II.4 visualizes the parallel system, which functions under the condition that at least one of its components is functioning (Terruggia 2010). Thus the PI for this index is given by the following equation:

$$\boldsymbol{PI = \{1-(1-PI1)\}.\{1-(1-PI2\}\ldots\ldots\{1-(1-PIn)\} = 1-\prod_1^n(1-PIn)} \quad \textbf{(7)}$$

The probability of failure of this system is given by the following equation:

$$\boldsymbol{Pf = 1-[\{1-(1-PI1)\}.\{1-(1-PI2\}\ldots\ldots\{1-(1-PIn)\}] = \prod_1^n(1-PIn)} \quad \textbf{(8)}$$

The reliability of this system is given by the following equation:

$$\boldsymbol{R = 1-Pf = 1-\prod_1^n(1-PIn)} \quad \textbf{(9)}$$

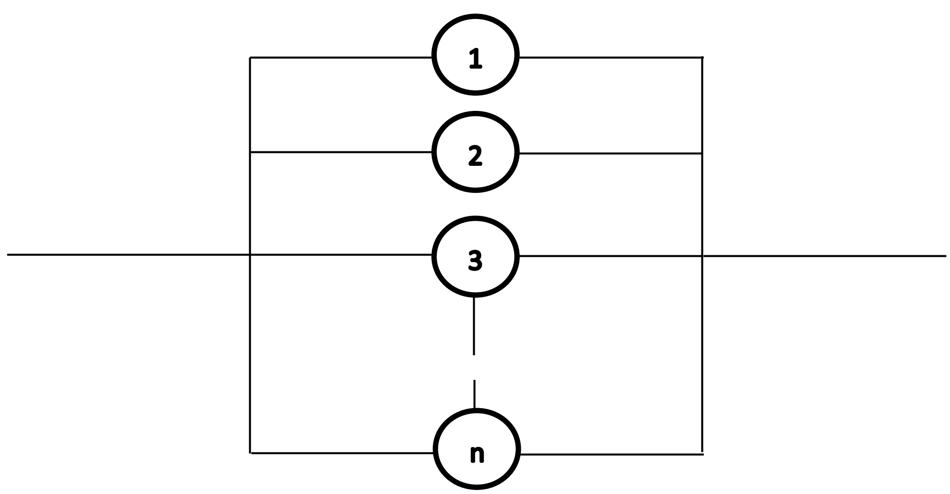


Figure II.4 Parallel Systems

II.8 SUMMARY AND LIMITATIONS

The literature review covered the water distribution networks and their components. The deterioration of these components and the factors affecting their deterioration were pointed out. The FANP method and its calculation approaches were also illustrated along with reliability based models, and its series, parallel system or combination of both.

The deterioration of water distribution networks causes reduced water quality, high leakage rate, and frequent breaks (Best Practices National Guide to Sustainable Municipal 2003b). In order to reduce the costly health, environmental, and structural impacts that result from the failure of water distribution networks or their components, it is essential to have condition assessment models. None of the previously mentioned models have considered the interdependent relationships amongst the factors that affect network elements' conditions. This is an important aspect to take into consideration since the factors do not work independently rather dependently. In addition, the inherited uncertainties present in some of the models were taken into account while developing previous models that were available in the literature. Another limitation of the previously developed models that most of them assess the condition of pipelines only, none of the mentioned models consider the accessories (hydrant, valves and etc.) condition, keeping in mind their important role in the distribution network.

Water distribution networks are made of different components and not only pipes. Very limited condition rating models have assessed the entire network, and when they did, they considered breakage rate as a representation of network failure. Several factors, beside breakage rate, contribute to network failure because considering only breakage rate neglects the effect of other factors. On the other hand, having properly analyzed physical deterioration models depends mainly on the quality of available data. Data are either unavailable or costly to obtain which make them only justifiable for large water mains. The statistical deterioration models are economically justifiable for small distribution network where data on breakage rate is already available. However, more validation and improvement is required for these deterioration models.

CHAPTER III

RESEARCH METHODOLOGY

III.1 INRODUCTION

The research methodology, which is shown in Figure III.1, includes the following steps: literature review, factors identification, data collection, FANP-based performance index for water distribution pipelines and accessories, reliability based assessment for water distribution segments, sub-network and network, and conclusion and recommendation.

III.2 LITERATURE REVIEW

The literature review is discussed thoroughly in Chapter II. A summary of what is discussed is presented herein. Section II.2 discussed water distribution networks and their components which are grouped into pipelines and accessories (i.e., valves, hydrants, and any component other than pipeline). The definitions of a segment along with the failure of water distribution networks were also discussed. Section II.3 illustrated the factors affecting the condition of water distribution networks and their components. Table II-3 summarized the factors identified from literature, which were grouped into physical, environmental, and operational factors.

Section II.4 presented the preliminary assessment step and several studies that were carried out to assess the condition of water pipelines and develop deterioration models for water distribution networks and pipelines. The section also presented the limitations of these models. Sections II.5 and II.6 presented an overview of FANP and Reliability based models, respectively.

III.3 FACTORS IDENTIFICATION

Section II.3 presented an extensive overview of all the factors affecting the water distribution network. The factors used in the model development were chosen based on the classification that was developed by the National Guide to Sustainable Municipal Infrastructure in their Best Practices (2003_b). In this work, the performance index of the distribution network is assessed based on the performance index of the pipeline and its accessories. Thus, the factors that affect the water distribution network pipes and accessories were identified. Several meetings with experts were conducted to identify these factors. Figure III.2 and Figure III.3 summarize the identified factors for each network component, respectively. The factors were classified into three main categories, namely, physical, environmental, and operational. The selected factors were distributed each under its corresponding category. The physical factors category includes the sub-factors of age, size, material, and installation quality. The environmental factors category includes the sub-factors of Ground water, soil type, and location. Finally, the operational factors category includes the sub-factors of the breakage rate, c-factor, and water quality. Figures III.2 and III.3 show that the only difference between the sub-factors of the pipelines and accessories is the “size” sub-factor under the physical category. The descriptions of the selected sub-factors are summarized in Table III-1.

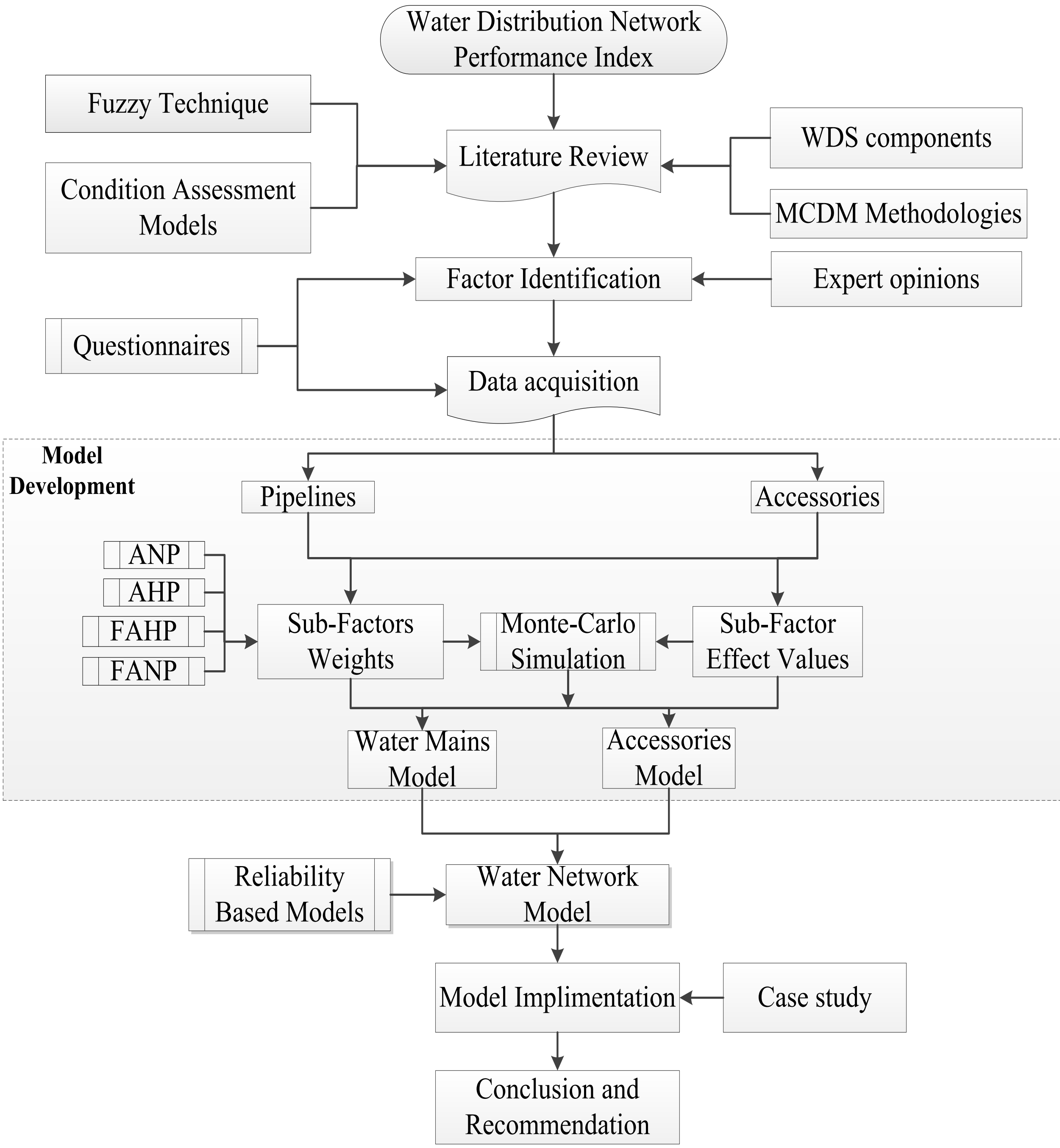


Figure III.1 Research Flow Chart

Table III-1 Descriptions of the selected factors

MAIN FACTORS	SUB FACTOR	DESCRIPTION
Physical	Material	Components made from different materials fail in different ways.
	Age	It means how long the component had been operating. Effects of component degradation become more apparent over time.
	Size (only pipelines)	The smaller diameter the pipe is, the more it is subjected to deterioration. The larger the thickness, the more it resists the penetration of corrosion. The longer the pipe, the more it's subjected to higher deterioration rates
	Installation Quality	Whether the installation was done carefully as per specification and standards or not. Poor installation quality leads to high breakage rate. Improper pipe bedding may result in pipe failure.
Environmental	Ground Water	The amount of water in soil affects the soil resistivity, which inversely relates to the corrosion rate. The ground water may affect in corroding the component directly when salts and some corrosive substances exist in the ground water.
	Soil Type	Some soils are corrosive; some soils experience significant volume changes in response to moisture changes, resulting in changes to pipe loading. Presence of hydrocarbons and solvents in soil may result in some component deterioration.
	Location	Components under roads in the cities are subjected to dynamic load and road salts from the heavy traffic. Components in residential areas are exposed to different conditions than those which are located in industrial areas.
Operational	C-Factor	The pressure resulted from transients in the water distribution systems may cause pump and device failure, system fatigue or component ruptures. High velocity water corrodes the internal walls of the pipe and will cause many disturbances especially when moving between pipes with different diameters. These disturbances will break the pipe and corrode it.
	Breakage rate	Leaked water will increase the moisture content in the surrounding soil and the probability of external corrosion. Also it will erode and move the bedding soil and cause a change in the stress distribution and eventually leads to pipe break. Breakage rate is number of breaks per km per year. High breakage rate indicates how poor is the component and an action must be taken.
	Water Quality	How impurities and added chemicals affect the internal surface of the component.

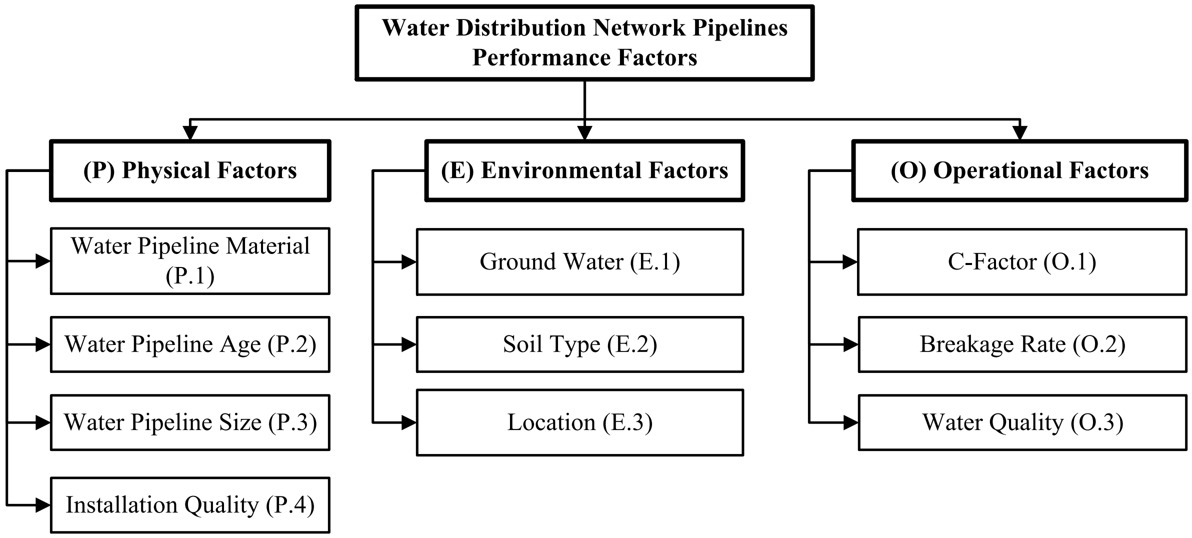


Figure III.2 Identified factors for pipelines

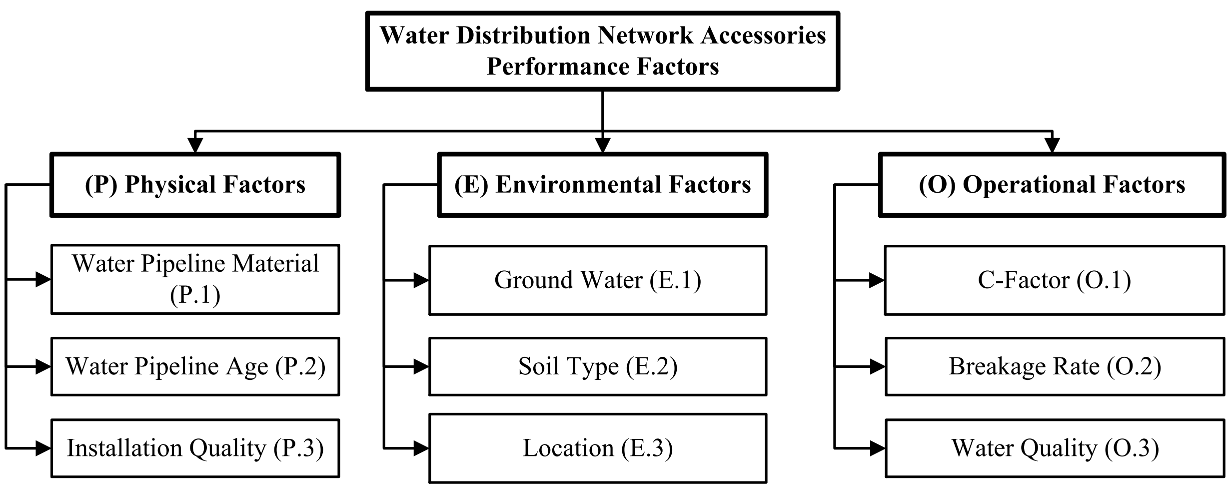


Figure III.3 Identified factors for accessories

III.4 FANP-BASED PERFORMANCE INDEX FOR COMPONENTS

The performance index of water distribution network pipelines and accessories are calculated using fuzzy analytical network (FANP) method as in incorporates uncertainties and interdependencies among the defined factors. The process starts by identifying the factors affecting the performance index of water distribution network components and categorizing them as shown in Figures III.2 and III.3. Then, a fuzzification scale is applied on the gathered responses to accommodate the uncertainties present at this level. This process yields three matrices, namely, Lower, Most Probably and Upper. These three matrices can be combined into one big matrix, where each element represents the three heads of a fuzzy triangle (Figure III-4). The fuzzification scale used herein is similar to Saaty's fuzzification scale, where the difference between most probable (which is the actual response gathered) with the upper and lower matrices respectively is equal to one. This is applied to all the pairwise comparisons gathered from the questionnaires.

An Excel-Matlab® interface was developed and used for the purpose of FANP calculations. It uses the three matrices as inputs to yield sub-factors FAHP relative weights. These weights compose the unweight super-matrix, which is created using Excel® and then normalized and raised to a large number of powers to obtain the limited matrix. The first column of the limited matrix represents the FANP relative weights. These relative weights represent the importance of each sub-factor relative to the other sub-factors. The developed interface is also able to determine the Analytical Hierarchy Process (AHP), the Analytical Network Process (ANP), and the Fuzzy Analytical Hierarchy process (FAHP). The AHP weights can be obtained in Excel® and used to build the unweighted super-matrix, which will then be normalized and raised to large number of powers to obtain the limited matrix and ANP relative weights. In order to make sure that the interface is working properly, the ANP results were compared with the ANP calculations from the SuperDecision® software. The weights obtained from the 4 methods are then compared with each other to check the differences. After that, Monte-Carlo simulation was used to overcome accumulated uncertainties and deviation from the weights. Finally, the performance index is acquired for each component using equation (10) with the FANP weights and effect values. The condition scale developed by Al Barqawi (2006) was used to compute the condition of the components. This scale identifies the condition of the assessed pipeline or accessory using the following equation:

$$\mathbf{PI = \sum_{k=1}^{n} W_i \ x \ EV_i} \qquad (10)$$

Where, PI = performance index for the water distribution component; EV_i = effect value for factor i reflecting the factor score; and W_i= final weight for sub-factor i; k = number of component segments, and i = sub-factor under consideration.

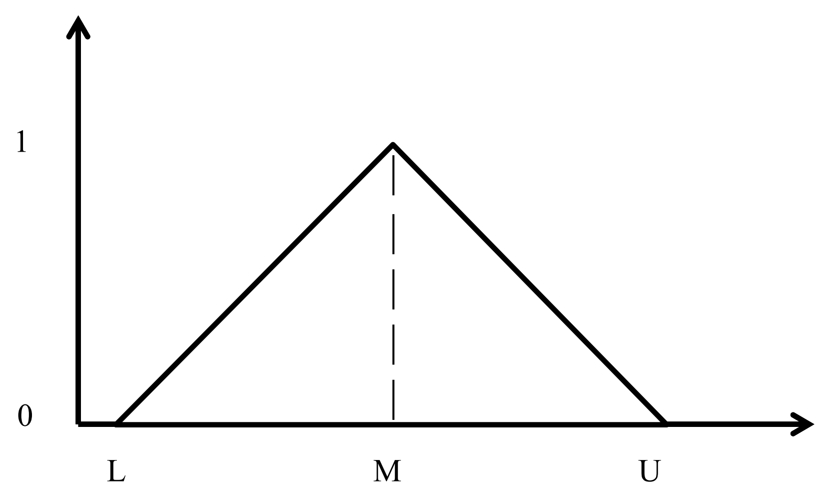


Figure III.4 Fuzzy Triangular Number

III.5 CONDITION RATING SCALE

The condition scale developed by Al Barqawi (2006), which is adopted herein (Table III-2), identifies at which state the assessed pipeline or accessory is at. The condition scale ranges from “10” to “0” reflecting the condition of “Excellent to “Critical”, respectively. This scale will help municipalities identifying the required action based on the condition.

Table III-2 Al Barqawi (2006) Condition Rating Scale

Scale	Linguistic Interpretation	Criteria
9-10	Excellent	New or Recently Installed
8-9	Very Good	No signs of corrosion or deterioration. Pipe wall thickness is even. BR ≤ 0.05
6-8	Good	Coatings, lining still ib tact. Remaining wall thickness more than 90% of original
4-6	Moderate	Some damage ti coating and/or linings noted. Remaining wall thickness 75% or more of original.
3-4	Poor	No lining or coating. Significant signs of internal or external corrosion. Remaining wall thickness 50% to 75% of original
<3	Critical	Severe internal or external corrosion. Remaining wall thickness less than 50% of original. BR>3

III.6 NETWORK PERFORMANCE INDEX

In order to obtain its performance index, a better understanding of the water distribution network composition is required. Figure III.4 illustrates the composition of water distribution networks. The components of water distribution networks, which consist of pipelines and accessories, make the segments. On the other hand, the segments connect with each other either in series or parallel to make the sub-networks or networks. Thus, a segment performance index is obtained from those of its components. Likewise, the network performance index is obtained from those of its segments.

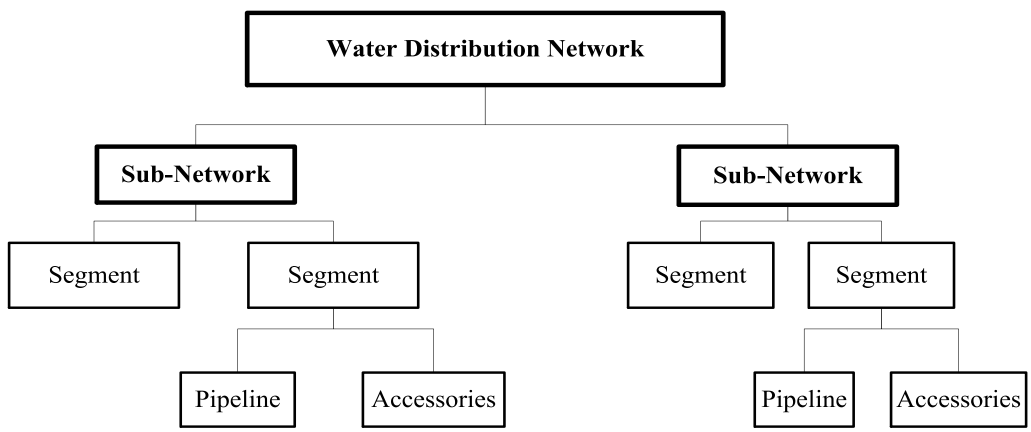


Figure III.5 Water Distribution Network Composition

III.6.1 Segment Performance Index

The segments are made of pipelines and accessories. The performance index of a segment is computed using the following equation:

$$\mathbf{PI_{segment}} = \frac{\boldsymbol{\rho}\,[(\mathbf{W})(\mathbf{PI})]}{\sum \mathbf{N}} \tag{11}$$

Where, W_p ≔ weight of pipelines and accessory, $(PI)_p$ = performance index of pipe and accessories, and $\rho =$ performance index threshold factor.

The performance index threshold factor is used when the segment performance index is in bad condition. It has two values, either "1" or "0". The value (ρ) is taken equal to "1" when the performance indices of the segment pipelines and accessories, are above the values of (0.3) and (0.4), respectively. Otherwise, the value of (ρ) is taken equal to "0"

III.6.2 Network Performance Index

Reliability based models are used to assess the performance index of the entire network or a sub-network. The part of the network to assess its performance index must be identified first. Then, the segments of the identified network must be identified. Finally, the water pipelines and accessories in the identified segments must be located and their performance indices computed using the FANP model. The performance indices of the segments are then obtained using equation 11. As defined in the literature, the failure of a series system occurs when one of its components fails. On the other hand, the failure of a parallel system occurs when all of its components fail. The failure of water distribution network system is considered when service disruptions are affecting certain clients (Tung 1985). This applies for both sub-networks and entire networks. The water flow helps in the determination of the segments that are in series and those that are in parallel. If one segment stopped working due to a failure, and another segment connected to it stopped working as a result, then the connection type is in series, otherwise it is in parallel. The proposed model takes into account the water flow direction. If the water flow is stopped in one segment due to the failure of another segment, then the two segments are connected in series. Similarly, if the water did not stop flowing in a segment despite the failure of another segment, then the two segments are in parallel. The diameter of water pipelines can be an indicator for the water flow direction. Larger pipeline diameters feed smaller diameter which are usually located in residential area. How the segments are connected and whether a failure in one of them will cause disruption to certain clients, determine which equation to use (i.e., Equations 3 and 7).

To facilitate the use of the performance index of the components, a Matlab® program was written to generate all possible combinations with their used sub-factors and corresponding effect values. The generated data base can be used to determine the performance index of a water distribution network component given its characteristics. It also helps to improve the given pipeline by identifying which sub-factor contributes more to its low performance index. The weights of the sub-factors and their corresponding effect values can be updated by entering the new values in their corresponding table.

CHAPTER IV

DATA COLLECTION

IV.1 INTRODUCTION

The performance index models for water distribution network pipelines and accessories require data from experts in the same field. Two questionnaires, one for pipelines and the other for accessories, were developed to serve this purpose. The questionnaires were developed in an open-ended structure for the respondents to verify also the selected factors.

The data collection was done in two steps. The first stage was the identification of the factors affecting the water distribution network pipeline and accessories. This step is discussed in section III.3. Then, the experts were asked to perform pairwise comparisons among the selected factors. The responses of the pairwise comparisons were used to build the FANP performance index models. A total of 40 questionnaires were collected for water distribution network pipelines and 37 for the accessories representing response rates of 80% and 74%, respectively. The questionnaires targeted a wide spectrum of water network operators and professionals from different sectors, specifically, material specification engineers, water project design engineers, maintenance engineers, water system analysis engineers, water planning engineers, as well as water project consultants in the state of Qatar. The structured questionnaires gathered the following data types:

IV.2 FACTORS WEIGHTS

The objective of the first part is to perform an importance pairwise comparison between the selected factors. It was conducted on three levels: 1) between the main factors with respect to the overall condition; 2) between the sub-factors with respect to the main factors; and 3) between the main-factors with respect to each other. Tables IV-2 and IV-3 illustrate the three levels of pairwise comparisons.

Saaty's fundamental scale (1980) was used for the pairwise comparison. Assigning a degree of importance value of "1" implies that the two factors under consideration have "equal" importance with respect to the specified goal while an assigned value of "9" indicates that the factor has an absolute importance over the compared factor. Table IV-1 summarizes Saaty's scale.

IV.3 FACTORS EFFECT VALUES

In the second part of the questionnaire, the experts were asked to give a range of effect values for each of the descriptions that were previously assigned to each sub-factor. These descriptions will be used to describe the condition of the assessed component. Tables IV-4 and IV-5 show the sub-factors along with their description for water mains and accessories. The effect values ranges between the values of "0" and "10", where "0" and "10" indicates the lowest and highest effects, respectively. For example, if the component's age is 10, the effect value that corresponds to age 10 is considered. This applies for all the sub-factors.

Table IV-1 Saaty's Scale

Degree of Importance	1	2	3	4	5	6	7	8	9
Interpretation	Equal Importance	Weak Importance	Moderate importance	Moderate plus	Strong Importance	Strong Plus	Very Strong Importance	Very Strong Importance	Extreme Importance

Table IV-2 Water Distribution Network Accessories Pairwise Comparison

Criterion (X)	← Degree of Importance →									Criterion (Y)
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	
WATER NETWORK ACCESSORIES CONDITION										
Physical Factors										Environmental Factors
										Operational Factors
PHYSICAL FACTORS										
Water Network Accessories Age										Water network accessories Material
										Water network accessories Installation Quality
ENVIROMENTAL FACTORS										
Location										Ground Water
										Soil Type
OPERATIONAL FACTORS										
C-Factor										Breakage Rate
										Water Quality
PHYSICAL FACTORS										
Environmental Factors										Operational Factors
ENVIRONMENTAL FACTORS										
Physical Factors										Operational Factors
OPERATIONAL FACTORS										
Physical Factors										Environmental Factors

Table IV-3 Water Distribution Network Pipeline Pairwise Comparison

	← Degree of Importance →									
Criterion (X)	(9) Absolut e	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
WATER MAINS CONDITION										
Physical Factors										Environmental Factors
										Operational Factors
PHYSICAL FACTORS										
Water Mains Age										Water Mains Material
										Water Mains Size
										Water Mains Installation Quality
ENVIROMENTAL FACTORS										
Location										Ground Water
										Soil Type
OPERATIONAL FACTORS										
C-Factor										Breakage Rate
										Water Quality
PHYSICAL FACTORS										
Environmental Factors										Operational Factors
ENVIRONMENTAL FACTORS										
Physical Factors										Operational Factors
OPERATIONAL FACTORS										
Physical Factors										Environmental Factors

Table IV-4 Sub-Factor Description for Pipelines

Main Factor (A)	Sub-factors (B)	Unit Of Measure (C)	Qualitative Description (Parameters) (D)
PHYSICAL	Water Mains Age	(Years)	>50
			30-50
			15-30
			5-15
			<5
	Water Mains Size (Diameter)	mm	Small Size <200mm
			Medium Size (200-350)
			Large Size>350
	Material	-	PVC
			Concrete
			Asbestos
			Ductile Iron
			Cast Iron
	Water Mains Installation Quality	(%)	Good
			Fair
			Poor
ENVIRONMENTAL	Ground Water Depth	(m)	Shallow depth
			Moderate depth
			Deep depth
	Soil Type	(% of Corrosiveness and Presence of hydrocarbons and Solvents)	Aggressive
			Moderate
			Non-Aggressive
	Location	Surface Type	Asphalt
			Seal
			Foot Path
			Unpaved
OPERATIONAL	C-Factor	-	High> 101
			Medium(41 - 101)
			Low< 41
	Breakage Rate	Breaks/km/year	High (>1)
			Medium
			Low(<0.1)
	Water Quality	(% of Impurity and added chemicals)	High
			Medium
			Low

Table IV-5 Sub-Factor Description for Water Distribution Network Accessories

Main Factor (A)	Sub-factors (B)	Unit Of Measure (C)	Qualitative Description (Parameters) (D)
PHYSICAL	Water Mains Age	(Years)	>50
			30-50
			15-30
			5-15
			<5
	Material	-	Good
			Fair
			Poor
	Water Mains Installation Quality	(%)	Good
			Fair
			Poor
ENVIRONMENTAL	Ground Water Depth	(m)	Shallow depth
			Moderate depth
			Deep depth
	Soil Type	(% of Corrosiveness and Presence of hydrocarbons and Solvents)	Aggressive
			Moderate
			Non-Aggressive
	Location	Surface Type	Asphalt
			Seal
			Foot Path
			Unpaved
OPERATIONAL	C-Factor	-	High> 101
			Medium(41 - 101)
			Low< 41
	Breakage Rate	Breaks/km/year	High
			Medium
			Low
	Water Quality	(% of Impurity and added chemicals)	High
			Medium
			Low

IV.4 DATA ANALYSIS

The gathered responses were analyzed in order to check for unrealistic responses. The percent difference between the relative weights obtained from each of the gathered response and the average weight is calculated. At this step of analysis, one of the questionnaires was taken out due to the high percent difference. Then the percent difference was checked again using the remaining responses, and they were in the acceptable range. For further analysis of the gathered responses, 3 groups were created based on the respondents' positions. The first group had those who work in planning and design and includes 12 respondents. The second group included the operation and maintenance experts and included 9 questionnaires, while the rest was in the third group which included engineers and consultants who are in direct contact with the pipeline construction. For the accessories the same three groups were created, however, they included 12, 9, and 15 responses respectively.

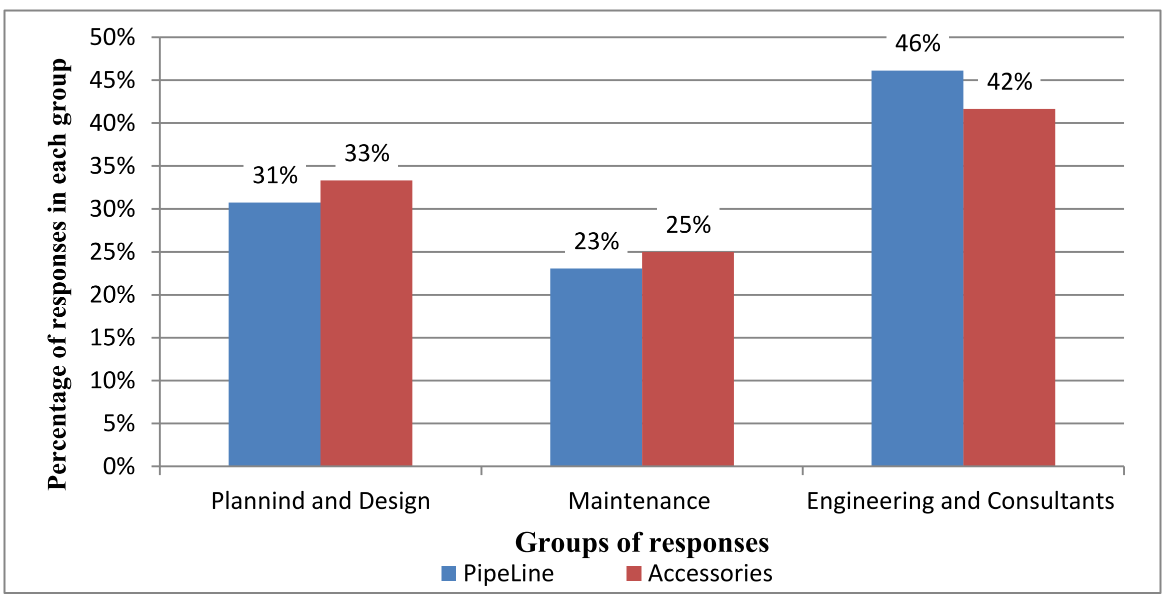


Figure IV.1 Percentage of responses in each of the three groups

Then, the average weights of the three groups were calculated and their percent difference with the total average weights is obtained. Figure IV.2 shows the percent difference between the three groups and the total average weight for all of the sub-factors for the water pipelines. It can be seen from the figure that the sub-factors “installation quality”, “size”, “material” and “water Quality” have low percent difference for the three groups. This means that the three groups agree on the relative weight of these sub-factors. On the other hand, Figure IV.3 shows the percent difference between the three groups and the total average weight for the sub-factors of accessories. As shown in the figure, the sub-factors that have the lowest percent difference are size, soil type, ground water, and C-factor. This also means that the respondents from the three groups agree on the relative weights of these sub-factors.

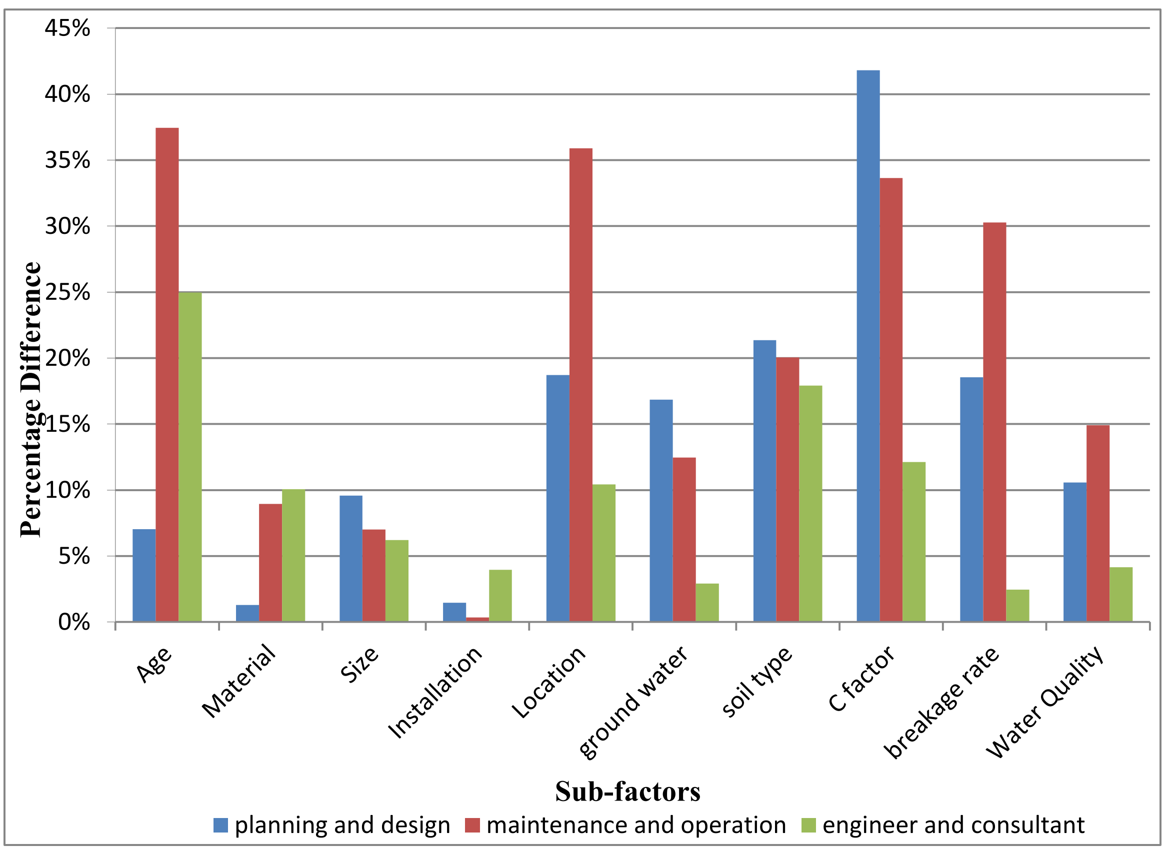


Figure IV.2 Percent Difference between three groups and total average weights for water pipelines

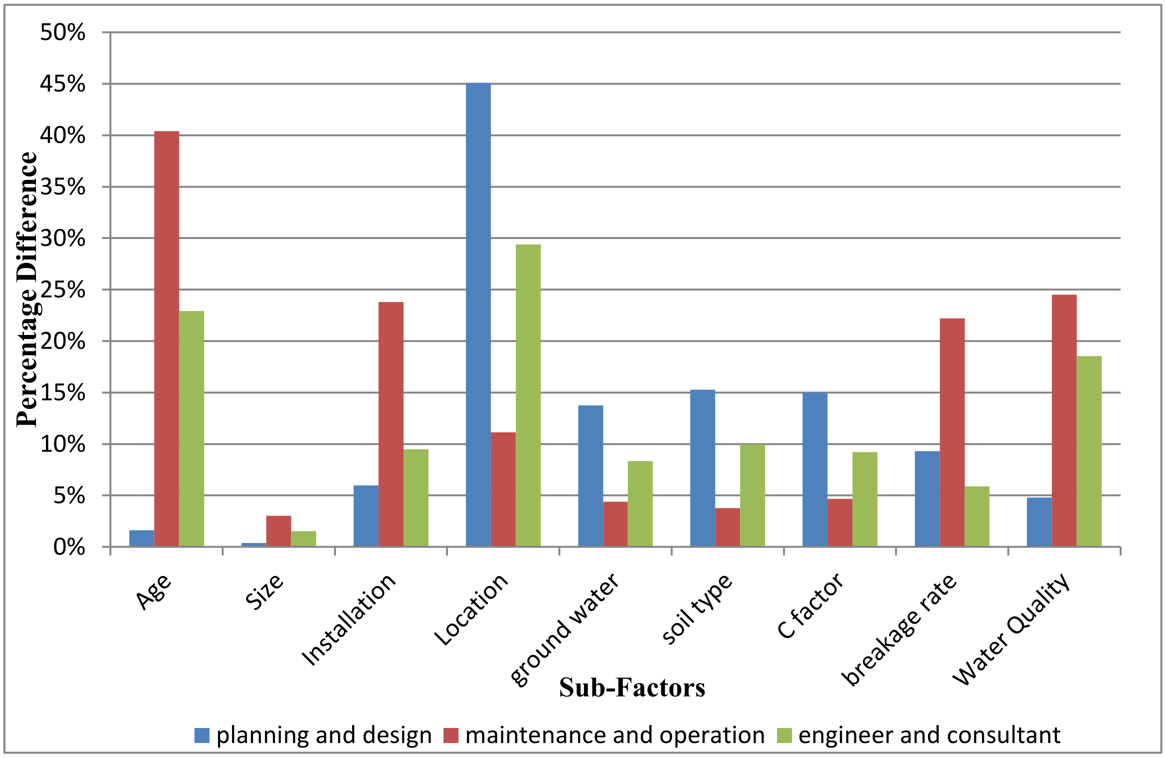


Figure IV.3 Percent Difference between three groups and total average weights for water accessories

In order to understand the behavior of the respondents, three ranges of sub-factors weights were identified, namely, 0 to 10%, 10% to 20%, and more than 20%. The weights obtained from each questionnaire for each sub-factor are checked with the identified categories. Figure IV.4 shows the percentage of responses in each category for each sub-factor in water mains. For example, for the age sub-factor, 71% of the gathered responses gave the age a relative weight between 0 and 10%, 18% a relative weight between 10% and 20 %, and 12% a relative weight of more than 20%. It is very clear from the figure that the high percentage of responses gave all sub-factors a relative weight between 0 to 10%. This indicates that the respondents were conservative in their opinions.

Likewise, the same three categories were identified for accessories questionnaires and the same comparison was done. Figure IV.5 shows the percentage of responses in each category for each accessories sub-factor. For all the identified sub-factors affecting the accessories, most of the responses were between 0 and 10% except for material and installation quality. A 44% of the responses gave the material a relative weight of more than 20%, 33% a relative weight between 0 and 10%, and 22% a relative weight between 10% and 20%. On the other hand, 36% of responses gave the installation quality a relative weight of more than 20%, 33% a relative weight between 0 and 10%, and 31% a relative weight between 10% and 20%. This indicates that the experts were conservative in their opinions except for Material and Installation quality.

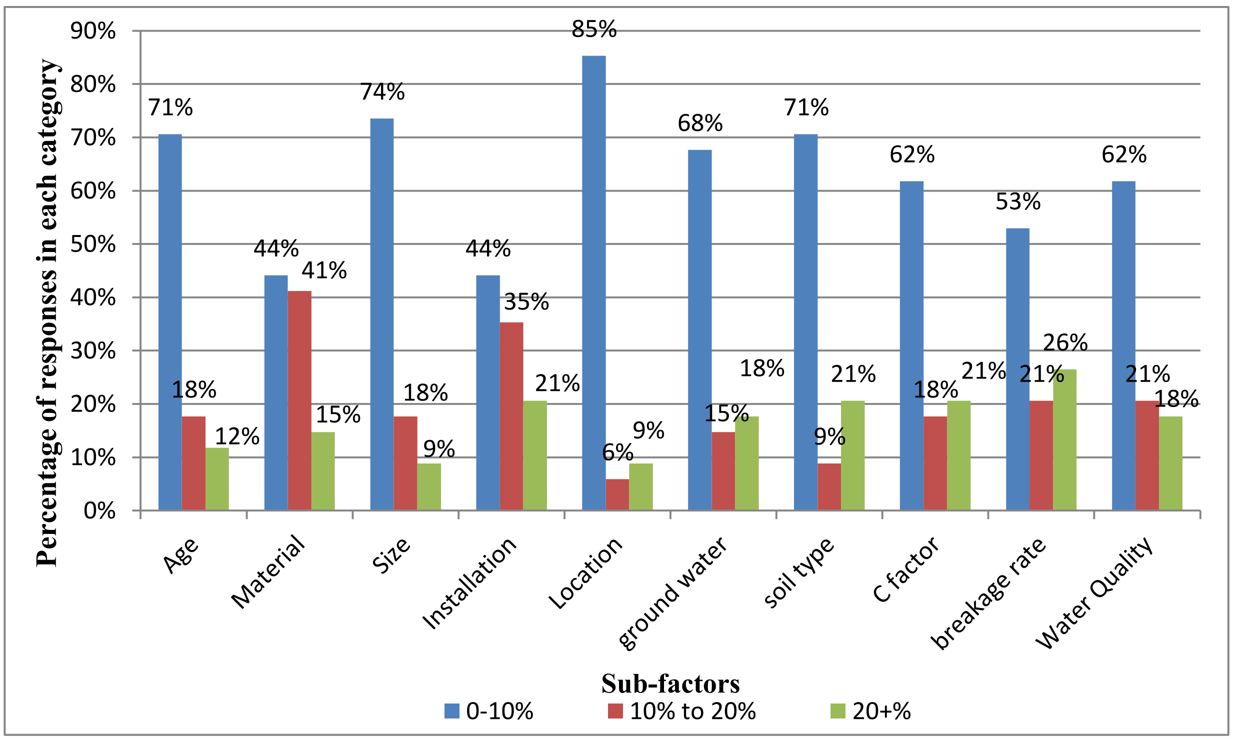


Figure IV.4 Percentage of responses for each sub-factor for pipe

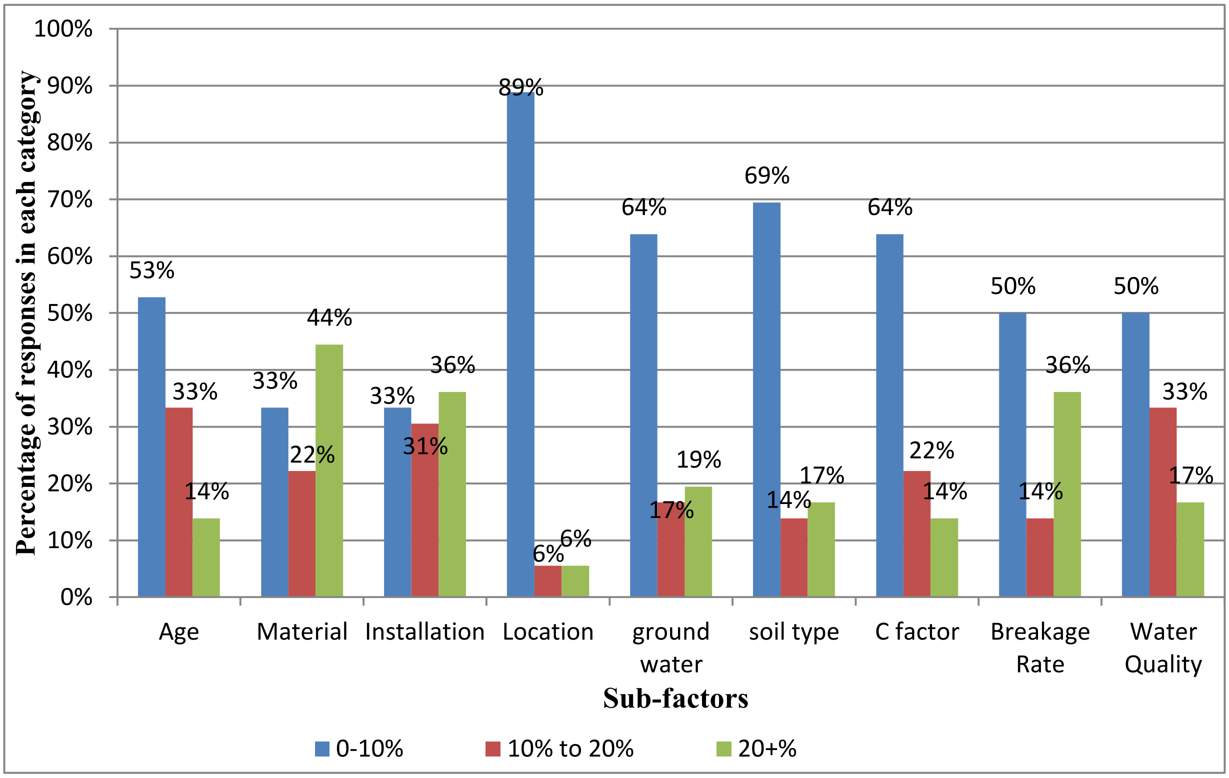


Figure IV.5 Percentage of responses for each sub-factor for accessories

IV.5 SECOND SET OF QUESTIONNAIRES

The same questionnaire sent to Qatari experts was developed online and sent to the experts in water pipelines. The responses were mainly gathered from Canada and the US. Few responses were also gathered from UK, Australia and India. This was done for the purpose of comparing the gathered responses with those obtained from Qatar. The weights obtained from this set of questionnaires and the comparison of responses will be discussed in section V.7.

In order to analyze the gathered responses, three ranges of sub-factor weights were identified, namely, 0 to 10%, 10% to 20%, and more than 20%. The sub-factor weight from each response is compared to the three ranges. Figure IV.6 shows the percentage of responses in each range. Almost for all the sub-factors, most of the responses are located in the first range (0% to 10%). For the "breakage rate" sub-factor, most of the responses gave weights in the range of (10% to 20%). The Installation Quality sub-factor has an equal number of responses for less than 10% and more than 20%. This is similar for the Location sub-factor; however the equal number of response is between the ranges "less than 10%" and between "10% and 20%." None of the experts gave the "soil type" a relative weight more than 20%, since 89% of the responses gave it relative weight less than 10% and 11% of them think the relative weight is between 10% and 20%.

Figure IV.7 represents the same analysis for accessories questionnaires. For the sub-factors "water quality", "C-factor", "soil type" and "Installation Quality" most of the respondents weighted them in the range between 0-10%. For the sub-factors, "location", "material" and "Breakage rate" equal number of respondents gave a relative weight between less than 10% and between 10% and 20%. However, for the age sub-factor, most of the respondents gave a relative weight of more than 20%. For both pipeline and accessories, there is general agreement among the respondents about the relative weight of the soil type to be less than 10%.

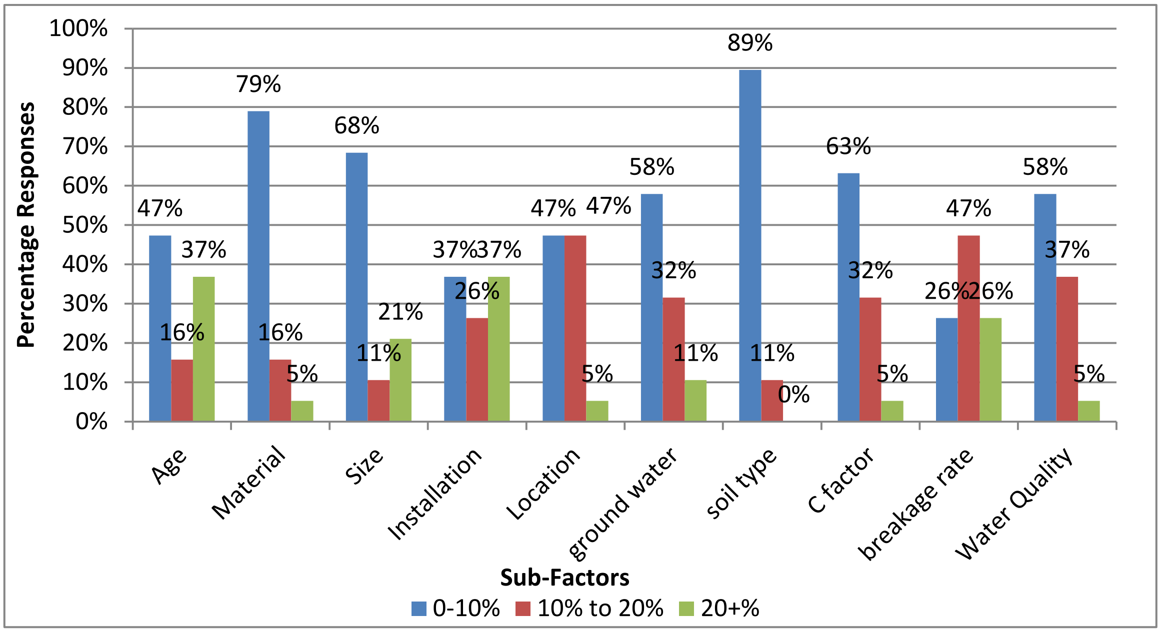


Figure IV.6 Percentage of responses from 2nd set for each sub-factor for Pipelines

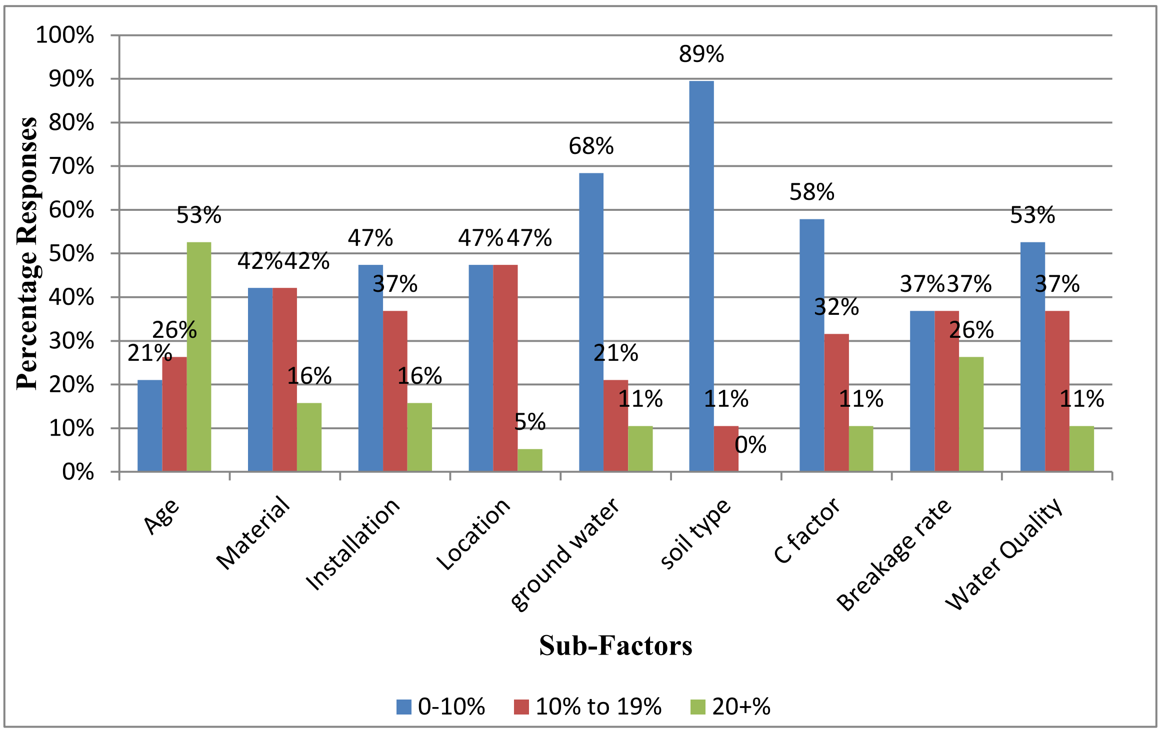


Figure IV.7 Percentage of responses from 2nd set for each sub-factor for Accessories

IV.6 CASE STUDY DATA

A set of data was collected from Moncton, New Brunswick, municipality. The data included the following pipe characteristics: pipe age, material, size, breakage rate, C-factor, water quality and type of surface. The data only had information about the pipelines and it does not include information about the accessories. A sub-network from Moncton city was then selected and its pipelines were identified and imposed on it. This selected network will be used for the purpose of testing the model.

IV.7 SUMMARY

The chapter discussed the data collection stage of this research. First, the questionnaires were sent to the Qatari experts in the field of water distribution networks. For each gathered response, the final weights of the sub-factors affecting the water distribution network were calculated. Then the final average weight from all the responses of each sub-factor was calculated. The percent differences between the weights of each questionnaire and the average weights were calculated. The questionnaire with high percent difference was then taken out from consideration. Three groups, namely, planning and design, maintenance and operation, and engineering and consultant, were then created for the remaining questionnaires. The average weights from each group were then compared with the total average weight for all the questionnaires. The sub-factors that the three groups agreed on their relative weights were highlighted. Then, the respondents' behavior was studied by studying their relative weight. The study showed that the respondents were more conservative in their pairwise comparison between sub-factors. A second online set of questionnaires were sent to experts in water distribution networks, mainly from Canada and US, to compare with those obtained from Qatari experts. Finally, a pipeline data set from Moncton, NB was obtained for the testing of the model.

CHAPTER V

PERFORMANCE INDEX MODEL DEVELOPMENT

V.1 INTRODUCTION

Fuzzy Analytical Network Process (FANP) was used herein to develop performance index models for water distribution network pipeline and accessories. The obtained performance indices are used as inputs in the reliability based model for obtaining the performance index of the entire network or part of it. The Fuzzy Analytical Network Process (FANP) was selected for its ability to consider the interdependences among the selected factors and to deal with the inherited uncertainties in the ANP and AHP processes. Equation (10) is used to obtain the performance index. An integrated Matlab-Excel® interface was developed to perform all of the required calculations. The final output of this interface is the relative weights of the sub-factors affecting the water distribution network components. These weights will be used in equation (10) along with the effect values gathered from the questionnaires to calculate the performance index of the assessed component.

V.2 PAIRWISE COMPARISON

The pairwise comparison results were obtained from the gathered questionnaires. The experts provided their opinion regarding the relative importance between the two sub-factors being compared. The comparison was done in three levels. The pairwise comparison used Saaty's scale (Table IV-1). After gathering the responses, they were analyzed and checked and the outliers were taken out. This made the actual number of questionnaires considered for pipelines and accessories equal to 39 and 35, respectively.

V.3 PAIRWISE COMPARISON FUZZIFIED MATRICES

A pairwise comparison matrix is built using the pairwise responses gathered using questionnaires. The matrix created directly from the questionnaires is called most probable matrix. By applying fuzzification scale on this matrix, the "lower matrix" and "upper matrix" matrices are created. The lower, most probable, and upper matrices can be visualised as the lower, most probable, and upper values or triangular fuzzy. To simplify the calculations, these matrices were developed using Excel. The matrices were automatically generated using the pairwise comparison results as input in the prepared excel sheet. The Analytical Hierarchy Process (AHP) weights are also obtained from the prepared excel sheet.

Tables V-2 to V-8 show the pairwise comparisons of the respondent (39) for the main factors and sub-factors of water distribution pipes. The same matrices for accessories were also created. Appendix A shows the pairwise comparison matrices for the accessories. Each cell in the Tables 17 to 23 has three values that reflect the Lower, Most Probable, and Upper values obtained from the fuzzification.

Table V-1 Fuzzification Scale

Fuzzy Linguistic Scale
{(1/9,1/9,1/8),(1/9,1/8,1/7),(1/8,1/7,1/6),(1/7,1/6,1/5),(1/6,1/5,1/4),(1/5,1/4,1/3),(1/4,1/3,1/2), (1/3,1/2,1),(1/2,1,1), (1,1,2),(1,2,3),(2,3,4),(3,4,5),(4,5,6),(5,6,7),(6,7,8),(7,8,9),(8,9,9)}

Table V-2 Main Factors Pairwise Comparison with Respect to Main Goal for Pipelines (Lower, Most Probable, Upper) (Questionnaire 39)

	Physical	Environmental	Operational
Physical	(1,1,1)	(6,7,8)	(1/4,1/3,1/2)
Environmental	(1/8,1/7,1/6)	(1,1,1)	(1/9,1/9,1/8)
Operational	(2,3,4)	(8,9,9)	(1,1,1)

Table V-3 Physical Sub-Factors Pairwise Comparison for Pipeline (Lower, Most Probable, Upper) (Questionnaire 39)

	Age	Material	Size	Installation
Age	(1,1,1)	(1/9,1/9,1/8)	(6,7,8)	(1/8,1/7,1/6)
Material	(8,9,9)	(1,1,1)	(8,9,9)	(1,1,2)
Size	(1/8,1/7,1/6)	(1/9,1/9,1/8)	(1,1,1)	(1/9,1/9,1/8)
Installation	(6,7,8)	(1/2,1,1)	(8,9,9)	(1,1,1)

Table V-4 Environmental Sub-Factors Pairwise Comparison for Pipeline (Lower, Most Probable, Upper) (Questionnaire 39)

	Location	Ground water	Soil Type
Location	(1,1,1)	(1/9,1/9,1/8)	(4,5,6)
Ground water	(8,9,9)	(1,1,1)	(1,1,2)
Soil Type	(1/6,1/5,1/4)	(1/2,1,1)	(1,1,1)

Table V-5 Environmental Sub-Factors Pairwise Comparison for Pipeline (Lower, Most Probable, Upper) (Questionnaire 39)

	C factor	Leakage Rate	Water Quality
C factor	(1,1,1)	(4,5,6)	(2,3,4)
Leakage Rate	(1/6,1/5,1/4)	(1,1,1)	(1/3,1/2,1)
Water Quality	(1/4,1/3,1/2)	(1,2,3)	(1,1,1)

Table V-6 Pairwise Comparison between Environmental and Operational for Pipeline (Lower, Most Probable, Upper) (Questionnaire 39)

	Environmental Factor	Operational Factors
Environmental Factor	(1,1,1)	(1/6,1/5,1/4)
Operational Factors	(4,5,6)	(1,1,1)

Table V-7 Pairwise Comparison between Physical and Operational for Pipeline (Lower, Most Probable, Upper) (Questionnaire 39)

	Physical Factor	Operational Factors
Physical Factor	(1,1,1)	(4,5,6)
Operational Factors	(1/6,1/5,1/4)	(1,1,1)

Table V-8 Pairwise Comparison between Physical and Environmental for Pipeline (Lower, Most Probable, Upper) (Questionnaire 39)

	Physical Factors	Environmental Factors
Physical Factors	(1,1,1)	(2,3,4)
Environmental Factors	(1/4,1/3,1/2)	(1,1,1)

V.4 UNWEIGHTED SUPER MATRIX

The lower, most probable and upper matrices were calculated for all the pairwise comparison. These matrices were used as input in Matlab® to calculate the fuzzified relative weights. The Matlab® code was adjusted to fit the research objectives. The Matlab® outcome at this step is pasted in a specific place in the same input excel file. The Global Weights for the sub-factors can be obtained by multiplying the “Global Weights” of the main factors with “Local Weights” of sub-factors, and their total summation must equal to “1”. Table V-9 the fuzzified relative weights for pipelines which is also the weights obtained using FAHP method. For the accessories fuzzified relative weights the table can be found in Appendix A. The calculated fuzzified relative weights are used to build the unweighted super matrix shown in Table V-10. As an example, the number (0.351) represents the relative weight that the “physical factors” has compared to “operational factors” and “Environmental factors”. Also, the number (0.436) next to the material represents relative weight that the sub-factor “material” has among the physical sub-factors. On the other hand, (0.153) represent the relative weight of the sub-factor “material” among all the identified sub-factors. As described in the methodology, for the purpose of limited matrix calculations, the sinks (columns of zeroes) were replaced by the same columns from the identity matrix.

V.5 WEIGHTED SUPER MATRIX

After building the unweighted super matrix for both pipelines and accessories, the weighted super matrix can be calculated simply by normalizing each column in the unweighted matrix. The normalization is done by dividing each cell over the summation of the column it is in. Considering column 2 as an example, the vertical summation equal to “2” as can be calculated from table V-10, then each cell in column 2 is normalized by divided it over the summation “2”. This process was performed in the Excel file. Table V-11 show a weighted matrix for pipelines obtained from respondent number 39. The accessories weighted matrix is shown in Appendix A.

Table V-9 Fuzzified Relative Weights for Pipelines (Questionnaire 39)

Main Factors	Global Weights	Sub-Factors	Local Weights	Global Weights
Physical	0.351	**Age**	0.081	**0.028**
		Material	0.436	**0.153**
		Size	0.048	**0.017**
		Installation Quality	0.434	**0.152**
Environmental	0.065	**Location**	0.059	**0.004**
		ground water	0.517	**0.034**
		soil type	0.424	**0.028**
Operational	0.584	**C factor**	0.648	**0.379**
		breakage rate	0.127	**0.074**
		Water Quality	0.225	**0.132**
			Total	**1.000**

Table V-10 Unweighted Super Matrix for Pipeline (Questionnaire 39)

	WMF	PF	EF	OF	A	M	S	IQ	L	GW	ST	C-FACTOR	BR	WQ
WMF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PF	0.351	0	0.833	0.75	0	0	0	0	0	0	0	0	0	0
EF	0.065	0.167	0	0.25	0	0	0	0	0	0	0	0	0	0
OF	0.584	0.833	0.167	0	0	0	0	0	0	0	0	0	0	0
Age	0	0.081	0	0	1	0	0	0	0	0	0	0	0	0
Material	0	0.436	0	0	0	1	0	0	0	0	0	0	0	0
Size	0	0.048	0	0	0	0	1	0	0	0	0	0	0	0
IQ	0	0.434	0	0	0	0	0	1	0	0	0	0	0	0
Location	0	0	0.059	0	0	0	0	0	1	0	0	0	0	0
GW	0	0	0.517	0	0	0	0	0	0	1	0	0	0	0
Soil Type	0	0	0.424	0	0	0	0	0	0	0	1	0	0	0
C-FACTOR	0	0	0	0.648	0	0	0	0	0	0	0	1	0	0
BR	0	0	0	0.127	0	0	0	0	0	0	0	0	1	0
WQ	0	0	0	0.225	0	0	0	0	0	0	0	0	0	1

Table V-11 Weighted Super Matrix for Pipeline (Questionnaire 39)

	WMF	PF	EF	OF	A	M	S	IQ	L	GW	ST	C-FACTOR	BR	WQ
WMF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PF	0.351	0	0.417	0.375	0	0	0	0	0	0	0	0	0	0
EF	0.065	0.083	0	0.125	0	0	0	0	0	0	0	0	0	0
OF	0.584	0.417	0.083	0	0	0	0	0	0	0	0	0	0	0
Age	0	0.040	0	0	1	0	0	0	0	0	0	0	0	0
Material	0	0.218	0	0	0	1	0	0	0	0	0	0	0	0
Size	0	0.024	0	0	0	0	1	0	0	0	0	0	0	0
IQ	0	0.217	0	0	0	0	0	1	0	0	0	0	0	0
Location	0	0	0.029	0	0	0	0	0	1	0	0	0	0	0
GW	0	0	0.258	0	0	0	0	0	0	1	0	0	0	0
Soil Type	0	0	0.212	0	0	0	0	0	0	0	1	0	0	0
C-FACTOR	0	0	0	0.324	0	0	0	0	0	0	0	1	0	0
BR	0	0	0	0.063	0	0	0	0	0	0	0	0	1	0
WQ	0	0	0	0.113	0	0	0	0	0	0	0	0	0	1

V.6 LIMITED MATRIX

The limited matrix can be obtained by raising the weighted matrix to large powers based on its degree. The weighted matrices were raised to powers until the resulting matrix becomes equal to the raised matrix (Adams 2001). As discussed in the literature, if the weighted super matrix with diagonals of zero is raised to large powers, the limited matrix converges to a matrix of zeroes, yielding no weights. Thus, the importance of making the diagonal equal to 1 instead of zero is evident. This allows the continuity of the multiplications without converging to zero until the targeted results are reached. The diagonal must change only from zero to one for the sinks, which are the columns with only zeroes in their cells. The columns that will replace "sinks" are from the identity matrix and they are called Identity columns. These zero columns or sinks are due to the absence of a relationship between the sub-factors themselves. If a relationship exists between the sub-factors, the columns will have a value from the pairwise comparison. There are different ways of calculating the limit matrix. The Identity At Sinks method is one of the best methods dealing with the identity columns (Adams 2001). The multiplication was done using Matlab® due to the large degree of the weighted matrix. It was multiplied by itself approximately 1075 times. Table V-12 shows a sample of the limit matrix. The first column in the limited matrix reflects the relative weights between the sub-factors. For example, the number (0.033) for age sub-factors represents its relative weight among the identified sub-factors. It is important to note that the relative weights of the main factors (Physical, Environmental and Operational factors) are equal to 0 as the Identity at sinks method yields the relative weights of the sub-factors immediately.

Table V-12 Pipeline Limited Matrix

	WMF	PF	EF	OF	A	M	S	IQ	L	GW	ST	C-FACTOR	BR	WQ
WMF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Age	0.033	0.052	0.023	0.022	1	0	0	0	0	0	0	0	0	0
Material	0.176	0.279	0.126	0.120	0	1	0	0	0	0	0	0	0	0
Size	0.020	0.031	0.014	0.013	0	0	1	0	0	0	0	0	0	0
IQ	0.176	0.278	0.126	0.120	0	0	0	1	0	0	0	0	0	0
Location	0.007	0.005	0.032	0.006	0	0	0	0	1	0	0	0	0	0
GW	0.065	0.045	0.282	0.052	0	0	0	0	0	1	0	0	0	0
Soil Type	0.053	0.037	0.231	0.043	0	0	0	0	0	0	1	0	0	0
C-FACTOR	0.305	0.177	0.108	0.404	0	0	0	0	0	0	0	1	0	0
LR/BR	0.060	0.035	0.021	0.079	0	0	0	0	0	0	0	0	1	0
WQ	0.106	0.062	0.037	0.140	0	0	0	0	0	0	0	0	0	1

V.7 SUB-FACTORS WEIGHTS

The final global weights for the sub-factors using the FANP method can be obtained directly from the first column of the limit matrix first column. The Identity at Sinks method will give the final global weights for the sub-factor directly. Adding the weights obtained from the limit matrix yields a value of one which validates the final weights. This above process was done for all the gathered questionnaires (i.e., 39 for pipelines and 36 for accessories). Then, the calculated weights were averaged to obtain the final weights of the sub-factors. Figure V.1 show the obtained sub-factor final FANP weights for water pipelines.

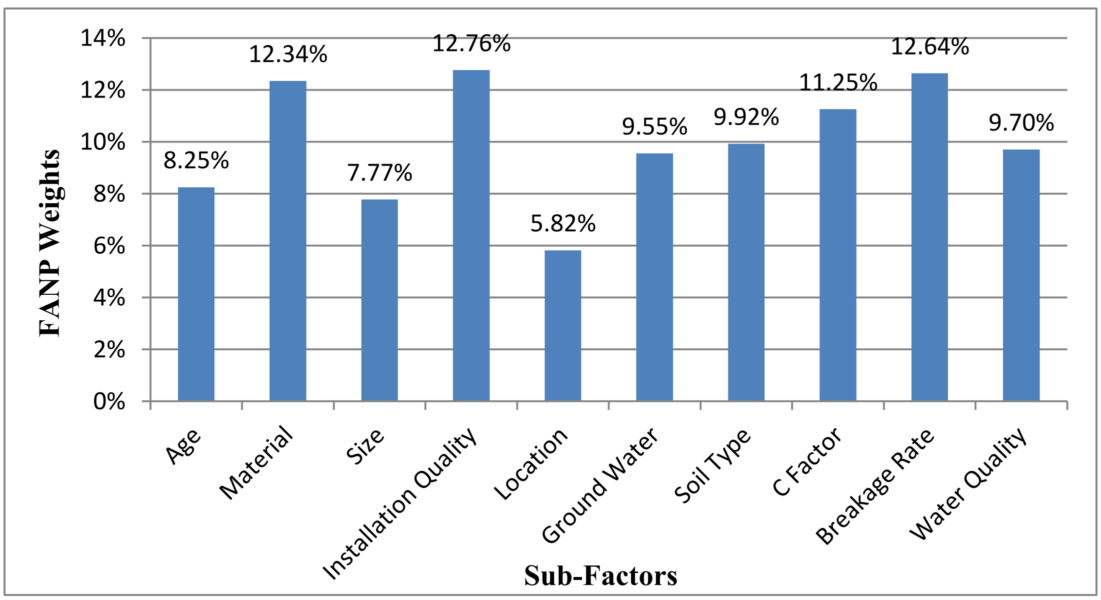


Figure V.1 Water Pipeline Sub-Factor FANP Weights

For the water pipelines, and according to the gathered responses from the experts, the Installation Quality, Breakage Rate, and Material have the highest weights (12.76%, 12.64%, and 12.34% respectively). They also contribute with about 38% of all of the sub-factors. This means that these three factors contribute more to the performance of the pipeline. One possible reason for the low weight of the "Age" sub-factor is that the experts are located is a developing area where the effect of "Age" sub-factor is not important yet. To check that, questionnaires were sent to experts in Canada, USA, UK and some other European countries, for the purpose of checking the weights obtained from Qatari expert responses. From the 2nd set of questionnaires, the Installation Quality has still the highest weights. However, the sub-factor "Age" replaces "Material" as the 2nd highest weight, while breakage rate was is the third highest weight. Figure V.2 shows the comparison between the two gathered groups of responses.

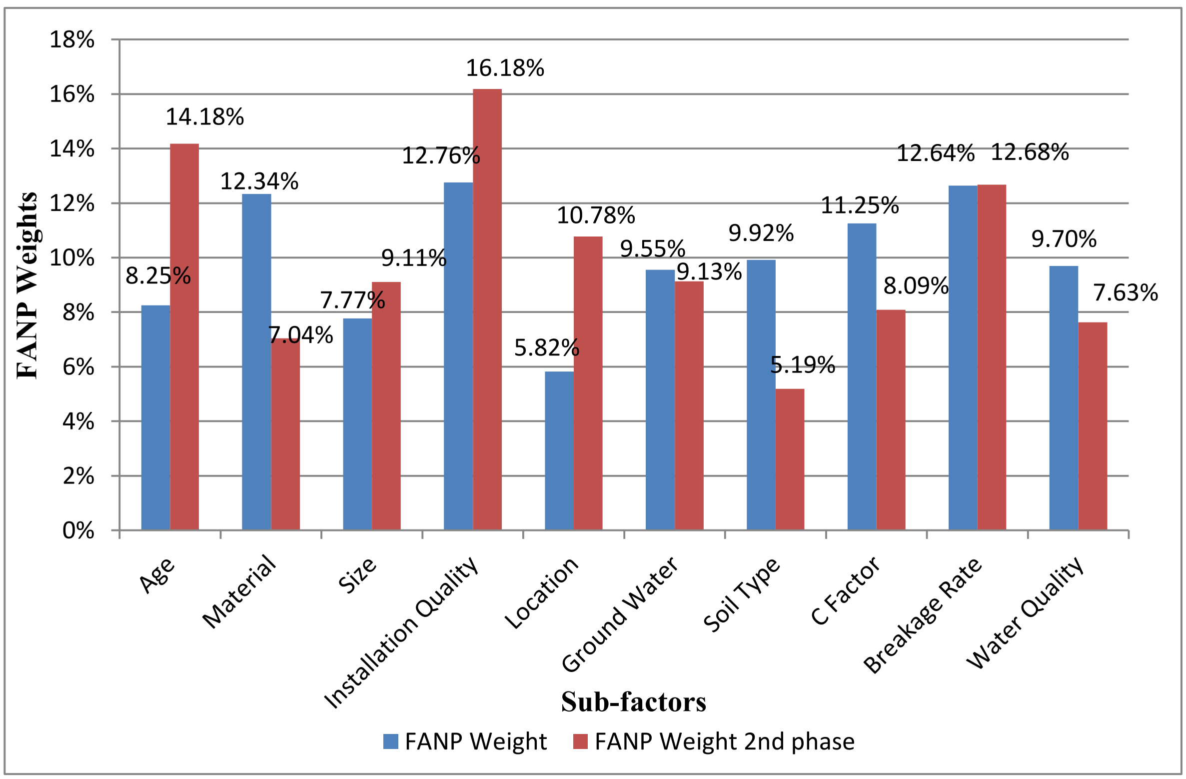


Figure V.2 Pipeline FANP Weights comparison

For the water distribution accessories, the sub-factors “Size”, “Installation Quality” and Breakage Rate have the highest weights. These Sub-factors contributes with approximately 44% of the total weights (i.e., 15.8 %, 14.6%, and 14% respectively). Figure V.3 shows the weight distribution. The Age sub-factor has a high weight but not as high as the first three because the maintenance of accessories is done more frequently except for buried valves. A second set of questionnaires for pipelines was conducted targeting Canada, USA, UK and some other European countries. Figure V.4 shows a comparison between the weights obtained from the second set of questionnaires and those from Qatar. A major change in the relative weights of the sub-factor “Age” can be noted. The experts from Qatar gave the sub-factor “Age” a relative weight of 9.82% while those from Canada and US gave it 21.56% which is considered as a major change. Qatari experts gave the material sub-factor a weight of 15.48% while the weight of the same sub-factor gathered from Canada and US was 11.45%. The same change for the weight of “soil type” can be noted. On the other hand, a value of 10.86% was obtained for the weight of “location” sub-factor from the responses gathered from Canada and the US compared to a value of 4.93% obtained from Qatar questionnaires. For the other sub-factors, no major changes were noted.

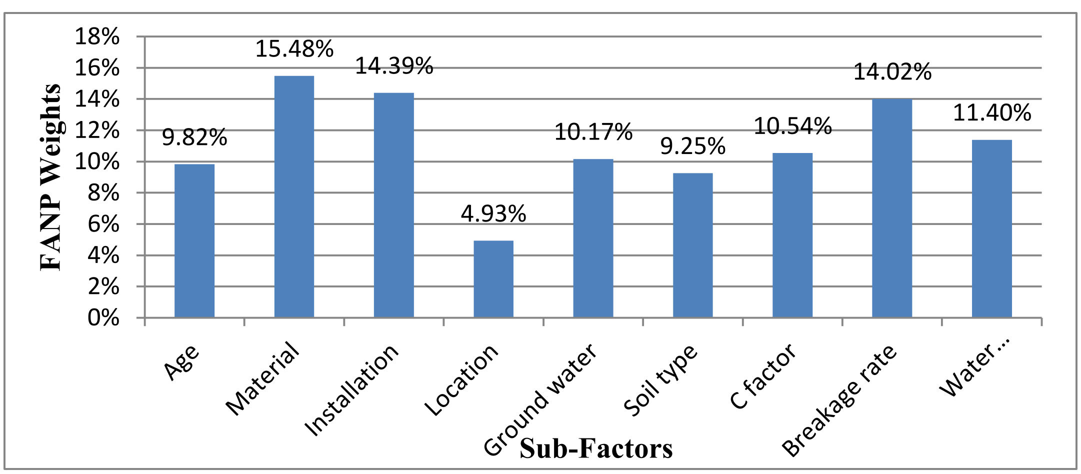


Figure V.3 Accessories Sub-Factor FANP Weights

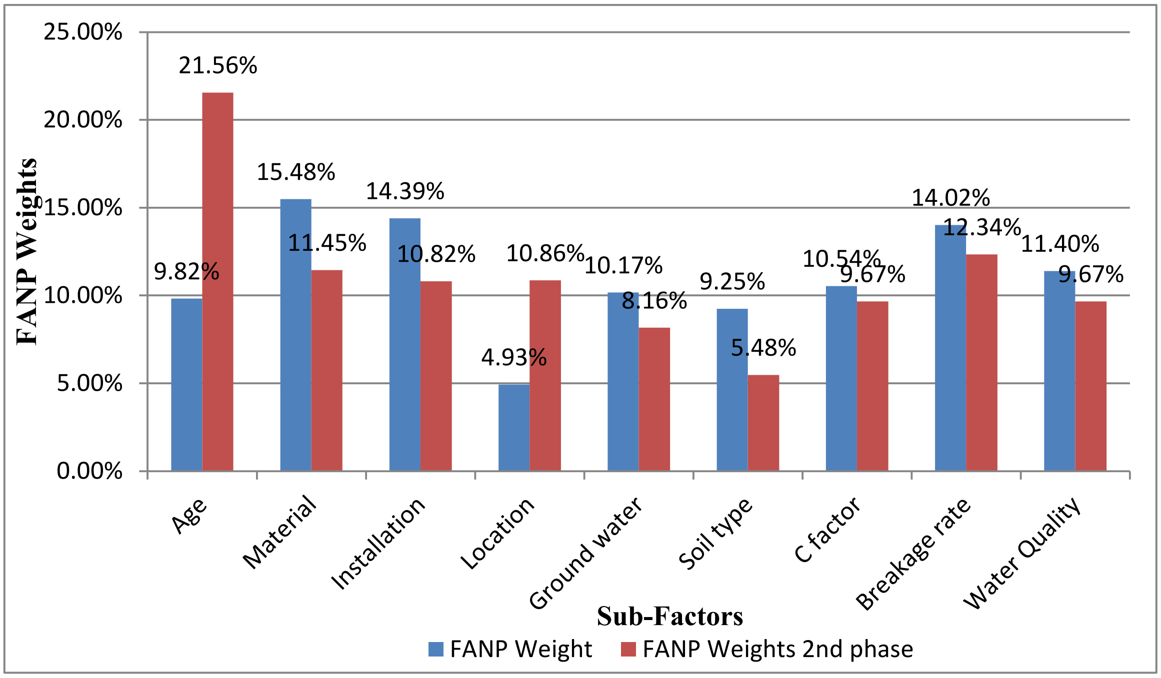


Figure V.4 Comparison for Accessories FANP Weights obtained

V.8 Other Techniques

Since the developed interface is able to perform the calculation of the relative weights of the methods: Analytical Hierarchy Process (AHP), Fuzzy Analytical Hierarchy Process (FAHP), Analytical Network Process (ANP), and Fuzzy Analytical Network Process (FANP), it is important to check the difference between the relative weights obtained from them. A small case study was used to compare between the weights that were obtained using the four methods (Figure V.5). It showed that the condition index obtained using FANP is different but close to the one obtained using AHP, FAHP, and ANP. Despite the close results for this case, FANP provided more credible results than the other methods as it took into account the interdependency among the criteria and the uncertainties of the pair-wise comparison linguistic scale and the human judgment. Table V-13 shows performance indices obtained from the four methods.

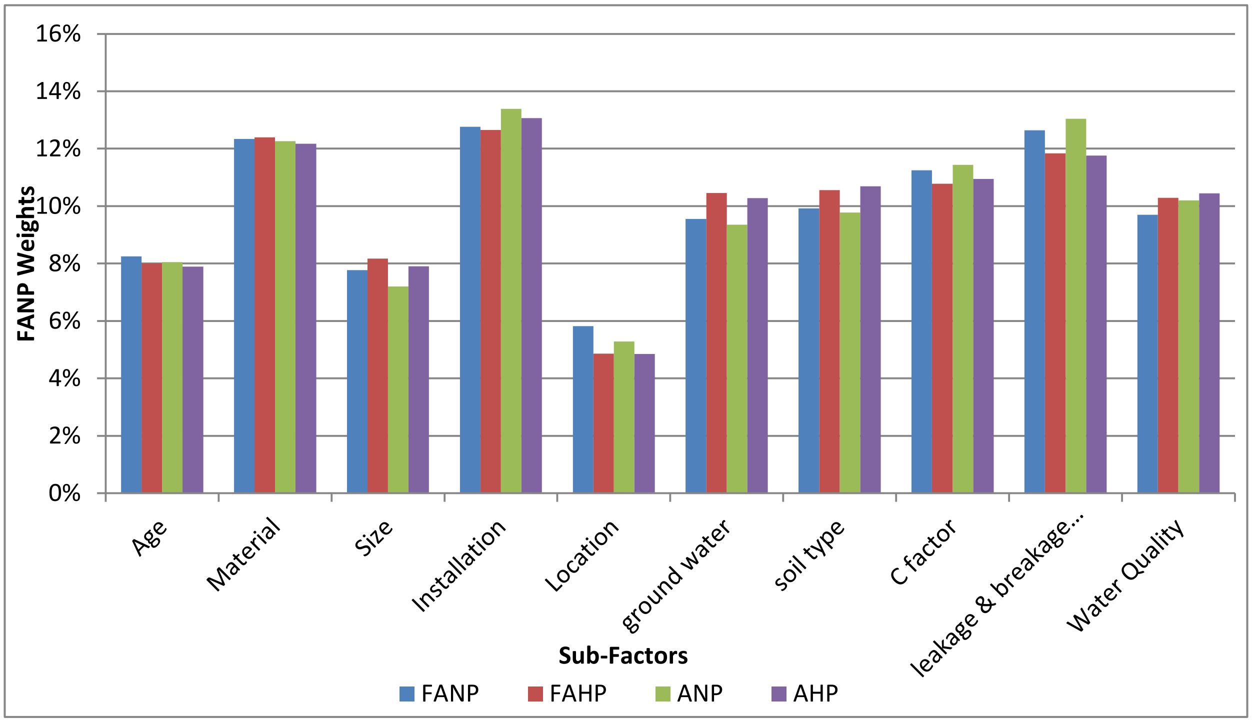


Figure V.5 Relative weights obtained from the four methods

Table V-13 4 Methods Performacne Indices

AHP	ANP	FAHP	FANP
5.748	5.701	5.724	5.660
5.748	5.701	5.724	5.660
6.077	6.044	6.048	5.997
4.955	4.941	4.933	4.934
6.077	6.044	6.048	5.997
6.077	6.044	6.048	5.997
5.748	5.701	5.724	5.660
5.748	5.701	5.724	5.660
6.077	6.044	6.048	5.997
6.077	6.044	6.048	5.997
6.155	6.125	6.128	6.080
6.155	6.125	6.128	6.080
5.748	5.701	5.724	5.660
7.135	7.218	7.113	7.135

V.9 EFFECT VALUE

The effect values describe actual component condition. For example if the component is recently installed (i.e, age <5 years), the description of the age sub-factor is selected. This will apply on all the sub-factors. The effect value of each description given to the sub-factors was provided through the gathered questionnaires. The effect values are then averaged to obtain an effect value for each description. Table V-14 and Table V-15 show the average effect values for pipelines and accessories, respectively.

V.10 PERFORMANCE INDEX

After obtaining the sub-factors weights and effect values the performance index can be calculated using equation (10). Comparing the actual situation of the pipeline or accessories to be assessed with the corresponding description of the effect value and sub-factor will satisfy the inputs of the equation. The performance index is a reflection of the condition of the pipeline or accessories. The calculated performance indices will be used as inputs for the reliability based models to calculate the performance index of the network. Section VI.2 and VI.3 will illustrate more about the performance index calculations in a case study.

V.11 MONT-CARLO SIMULATION

FANP method was used in this research to overcome the uncertainties in the actual responses gathered from experts before obtaining the weights. The performance index obtained at this step, after obtaining the FANP weights, has accumulated uncertainties in the model due to differences in weight assessment. In order to overcome these accumulated uncertainties, Monte-Carlo simulation was used. The final global weights obtained from FANP using all gathered questionnaires were used as input in the

Oracle Crystal Ball® software to fit a probability distribution for each sub-factor weight affecting water distribution network components. The same applies to the effect value obtained from the questionnaires. All the effect values were used as input for Oracle Crystal Ball® software for the purpose of fitting the probability. After having all the fitted curves for the weights and effect values, Oracle Crystal Ball® software was used to run the simulation and randomly generate 1000 data points based on the fitted curves. The result of the simulation for the weights and effect values was an average weight and effect value for each sub-factor in a probability distribution form. In order to find the performance index of a pipe and an accessory, Oracle Crystal Ball® was used to multiply the weight of each sub-factor with the corresponding effect value criteria which yielded a probabilistic performance index of the network component. This ensured that the uncertainties were taken into account while obtaining component's performance index. The probabilistic performance index provided a degree of confidence to the obtained performance index. All statistical analysis data that will serve the purpose of analyzing the attained probability distribution such as Mode, median, Std. deviation, skewness, variance and coefficient of variance can be obtained from the output of the simulation. In order to facilitate the process of obtaining the probabilistic performance indices, all the possible combinations that would occur from multiplying each sub-factor weight by the corresponding effect value (once at a time) were obtained and inserted in an excel data sheet. Appendix C shows a sample of the created data base.

Table V-14 Pipeline Effect Values

Main Factor (A)	Sub-factors (B)	Unit Of Measure (C)	Qualitative Description (Parameters) (D)	Effect Value (EV)
PHYSICAL	Water Mains Age	(Years)	>50	1
			30-50	2
			15-30	5
			5-15	7
			<5	10
	Water Mains Size (Diameter)	mm	Small Size <200mm	4
			Medium Size (200-350)	6
			Large Size>350	10
	Material	-	PVC	8
			Concrete	7
			Asbestos	6
			Ductile Iron	7
			Cast Iron	10
	Water Mains Installation Quality	(%)	Good	10
			Fair	6
			Poor	2
ENVIRONMENTAL	Ground Water Depth	(m)	Shallow depth	2
			Moderate depth	5
			Deep depth	10
	Soil Type	(% of Corrosiveness and Presence of hydrocarbons and Solvents)	Aggressive	2
			Moderate	5
			Non-Aggressive	10
	Location	Surface Type	Asphalt	6
			Seal	6
			Foot Path	6
			Unpaved	5
OPERATIONAL	Pressure/Flow velocity and C factor	-	High> 101	10
			Medium(41 - 101)	6
			Low< 41	3
	Leakage/Breakage Rate	Breaks/km/year	High	1
			Medium	5
			Low	10
	Water Quality	(% of Impurity and added chemicals)	High	2
			Medium	5
			Low	10

Table V-15 Accessories Effect Values

Main Factor (A)	Sub-factors (B)	Unit Of Measure (C)	Qualitative Description (Parameters) (D)	Effect Value (EV)
PHYSICAL	Water Mains Age	(Years)	>50	0
			30-50	2
			15-30	4
			5-15	7
			<5	10
	Material	-	Good	10
			Fair	5
			Poor	2
	Water Mains Installation Quality	(%)	Good	10
			Fair	6
			Poor	2
ENVIRONMENTAL	Ground Water Depth	(m)	Shallow depth	2
			Moderate depth	5
			Deep depth	10
	Soil Type	(% of Corrosiveness and Presence of hydrocarbons and Solvents)	Aggressive	2
			Moderate	5
			Non-Aggressive	10
	Location	Surface Type	Asphalt	6
			Seal	6
			Foot Path	6
			Unpaved	5
OPERATIONAL	Pressure/Flow velocity and C factor	-	High> 101	10
			Medium(41 - 101)	6
			Low< 41	3
	Leakage/Breakage Rate	Breaks/km/year	High	1
			Medium	5
			Low	10
	Water Quality	(% of Impurity and added chemicals)	High	2
			Medium	5
			Low	10

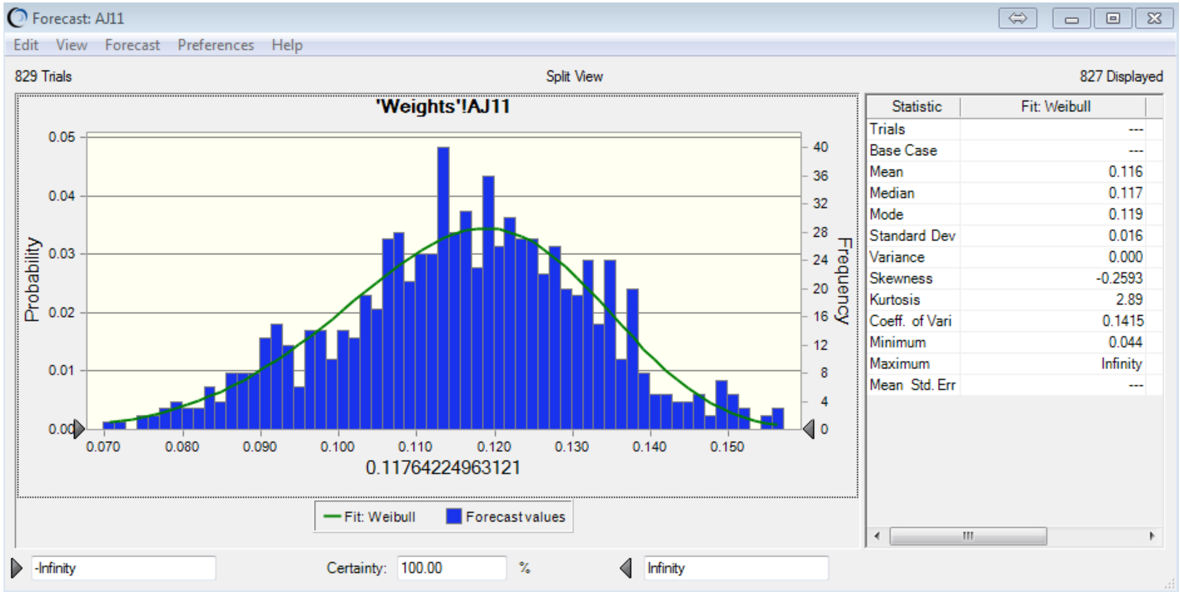


Figure V.6 Probability Distribution of Installation Quality

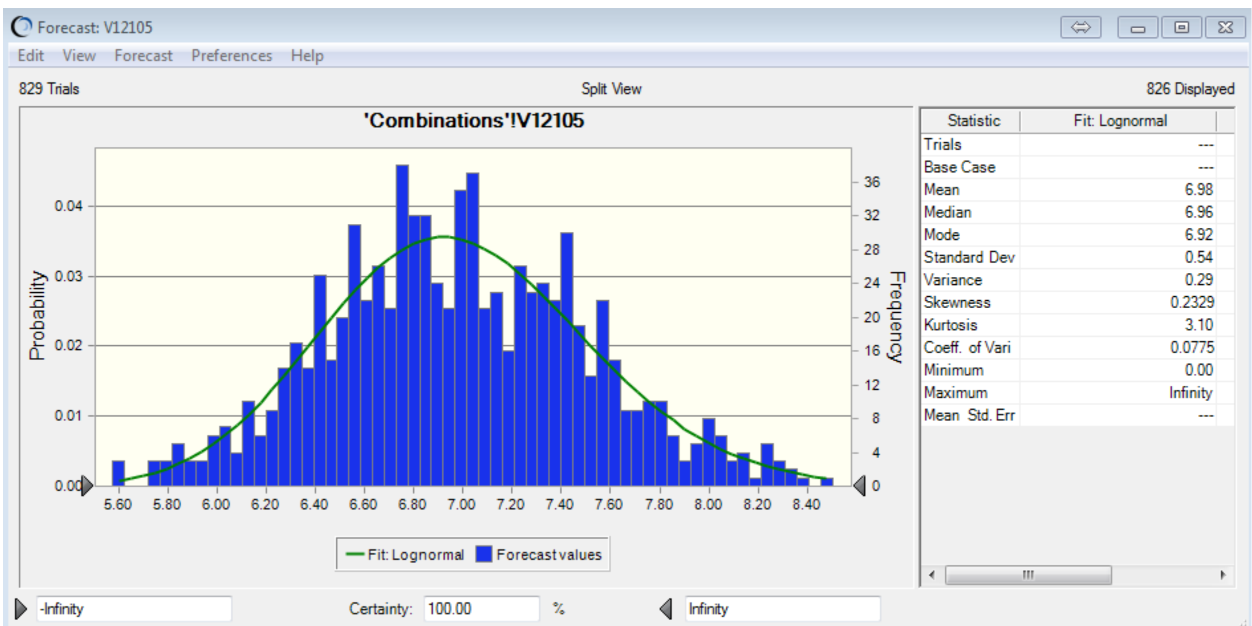


Figure V.7 Probabilistic Performacne Index

V.12 SUMMARY

The Fuzzy Analytical Network Process was used to obtain the performance indices for water distribution network components (pipeline and accessories). The factors affecting these components were identified then pairwise comparisons between the factors were obtained using collected questionnaires. An excel sheet was developed to fuzzify the pairwise comparison results. An Excel-Matlab® interface was created to perform all the FANP calculations. According to the calculated weights for the pipelines, the sub-factors "Installation Quality", "Breakage Rate" and "Material" have the highest weights representing about 38% of the total weights (i.e., 12.76%, 12.64%, and 12.34%, respectively). On the other hand, the weights obtained for "Material", "Installation Quality" and "Breakage Rate" of accessories represent 44.4% of the total weights (i.e., 15.8%, 14.6%, and 14%, respectively). The developed interface was tested and validated using SuperDecision® software. The final output of the interface is the factor weights of Effect values needed to compute the performance index using equation (10). This performance index is used as an input for reliability based models to obtain the Performance Index of segment, sub-network and networks.

CHAPTER VI

MODEL IMPLEMENTATION

VI.1 INTRODUCTION

The model is tested herein using a case study. The data for a water distribution network pipeline was gathered from Moncton, New Brunswick, municipality in Canada. The water distribution accessories were assumed to be exposed to the same factors. This case will cover all the connections for the water distribution segments, sub-networks and networks. The case is implemented in stages. As shown in Figure III.5, starting from the bottom, the first stage is the performance index of water distribution network components (pipeline and accessories). Then the Performance Index for segments, sub-networks, and networks are calculated. The output of this case will be a value representing the performance index of the assessed water distribution network.

VI.2 PERFORMANCE INDEX FOR WATER DISTRIBUTION PIPELINE.

Equation (10) will be used to determine the performance index of water distribution pipelines. The weights of the factors affecting the pipelines were obtained using FANP while the effect values given to the factors were provided by experts through questionnaires. The case study contains 500 pipelines. The information needed to obtain the performance index and the condition assessments were available except “Installation Quality”, “Ground Water Depth” and “Soil Type”. The missing information was assumed as “Good” for Installation Quality, and “Moderate” for both Ground Water Depth and Soil Type. Table VI-1 shows a sample of 22 pipes from this case study. The table shows the effect values and final performance indices for the first 22 pipes in the case study.

VI.3 PERFORMANCE INDEX FOR WATER DISTRIBUTION ACCESSORIES.

Since there was no data available in the case study, the water distribution accessories were assumed to be exposed to the same condition as the pipelines. To assess the performance index for the accessories, the weights of the accessories sub-factors and effect values were assumed the same as those used for pipelines. Table VI-2 shows the effect values and performance indices of the accessories.

Table VI-1 Pipeline Case Study Sample

pipe #	Age	Material	Size	Installation Quality	Locatio n	GW	Soil Type	C factor	BR	Water Quality	PI
1.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	3.00	1.00	10.00	5.66
2.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	3.00	1.00	10.00	5.66
3.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.00
4.00	2.00	7.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	2.00	4.93
5.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.00
6.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.00
7.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	3.00	1.00	10.00	5.66
8.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	3.00	1.00	10.00	5.66
9.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.00
10.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.00
11.00	2.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.08
12.00	2.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.08
13.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	3.00	1.00	10.00	5.66
14.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.00
15.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.00
16.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	10.0 0	10.00	7.14
17.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.00
18.00	2.00	7.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	2.00	4.93
19.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	5.00	10.00	6.50
20.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.00
21.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.00
22.00	1.00	10.00	4.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.00

Table VI-2 Accessories Case Study Sample

pipe #	Age	Material	Installation Quality	Location	GW	Soil Type	C factor	BR	Water Quality	PI
1.00	0.00	10.00	10.00	6.00	5.00	5.00	3.00	1.00	10.00	5.89
2.00	0.00	10.00	10.00	6.00	5.00	5.00	3.00	1.00	10.00	5.89
3.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.21
4.00	2.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	2.00	5.49
5.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.21
6.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.21
7.00	0.00	10.00	10.00	6.00	5.00	5.00	3.00	1.00	10.00	5.89
8.00	0.00	10.00	10.00	6.00	5.00	5.00	3.00	1.00	10.00	5.89
9.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.21
10.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.21
11.00	2.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.40
12.00	2.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.40
13.00	0.00	10.00	10.00	6.00	5.00	5.00	3.00	1.00	10.00	5.89
14.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.21
15.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.21
16.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	10.00	10.00	7.47
17.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.21
18.00	2.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	2.00	5.49
19.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	5.00	10.00	6.77
20.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.21
21.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.21
22.00	0.00	10.00	10.00	6.00	5.00	5.00	6.00	1.00	10.00	6.21

VI.4 PERFORMANCE INDEX FOR WATER DISTRIBUTION SUB-NETWORK

A water distribution network was selected from the city where the data was collected. The performance indices of the pipelines and accessories for the selected area were previously estimated in VI.2 and VI.3. These calculated indices were used to assess performance index of the water distribution network shown in Figure VI.2 and whose layout is illustrated in Figure VI.3. Reliability based models were used for that purpose. A segment failure does not mean a failure of the entire network in all the cases. It is considered case by case. Table VI-4 shows the connection types between the segments. If one segment stopped working due to a failure in another segment connected to it, then the two segments are in series. However, if a segment failure did not cause a stoppage in another segment connected to it, then the two segments are connected in parallel. Thus, the flow direction plays an important role in determining the segment connection type, whether series or parallel. Figure II.3 and Figure II.4 illustrates series and parallel connection types, respectively. Equations 3 and 7 are used for series and parallel connection types, respectively. The flow direction can be determined using the water pipeline diameter. Large diameter pipelines usually go out of the pump station and feed into smaller diameter pipelines (located in main streets), which in turn feed into smaller diameter pipes (used as distribution pipes in the network final destination such as residential areas).

Figure VI.1 Selected Network Location

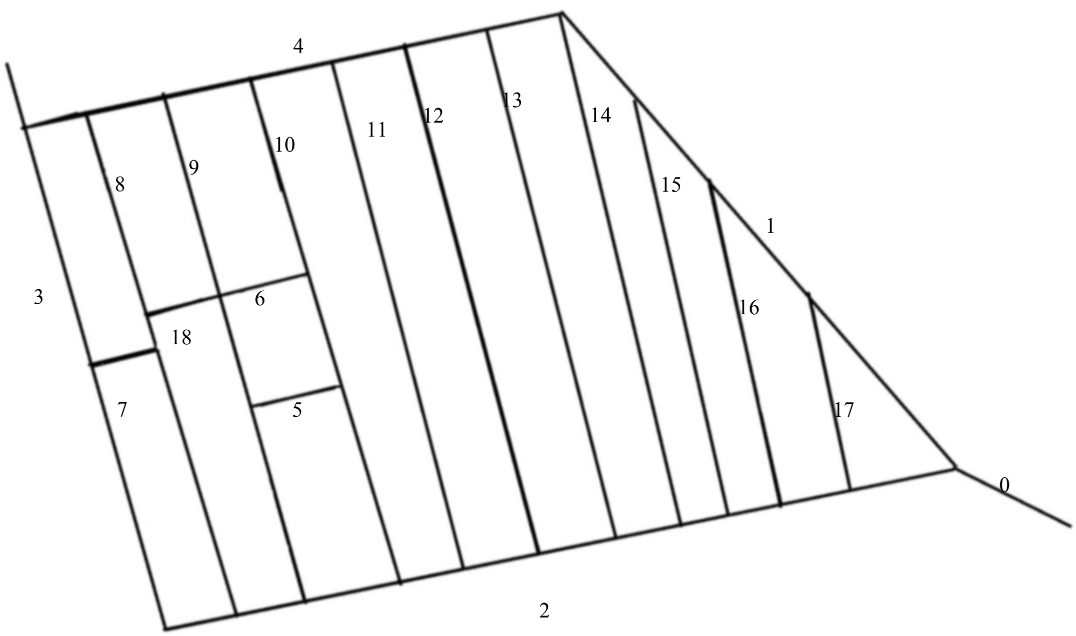


Figure VI.2 Network Layout

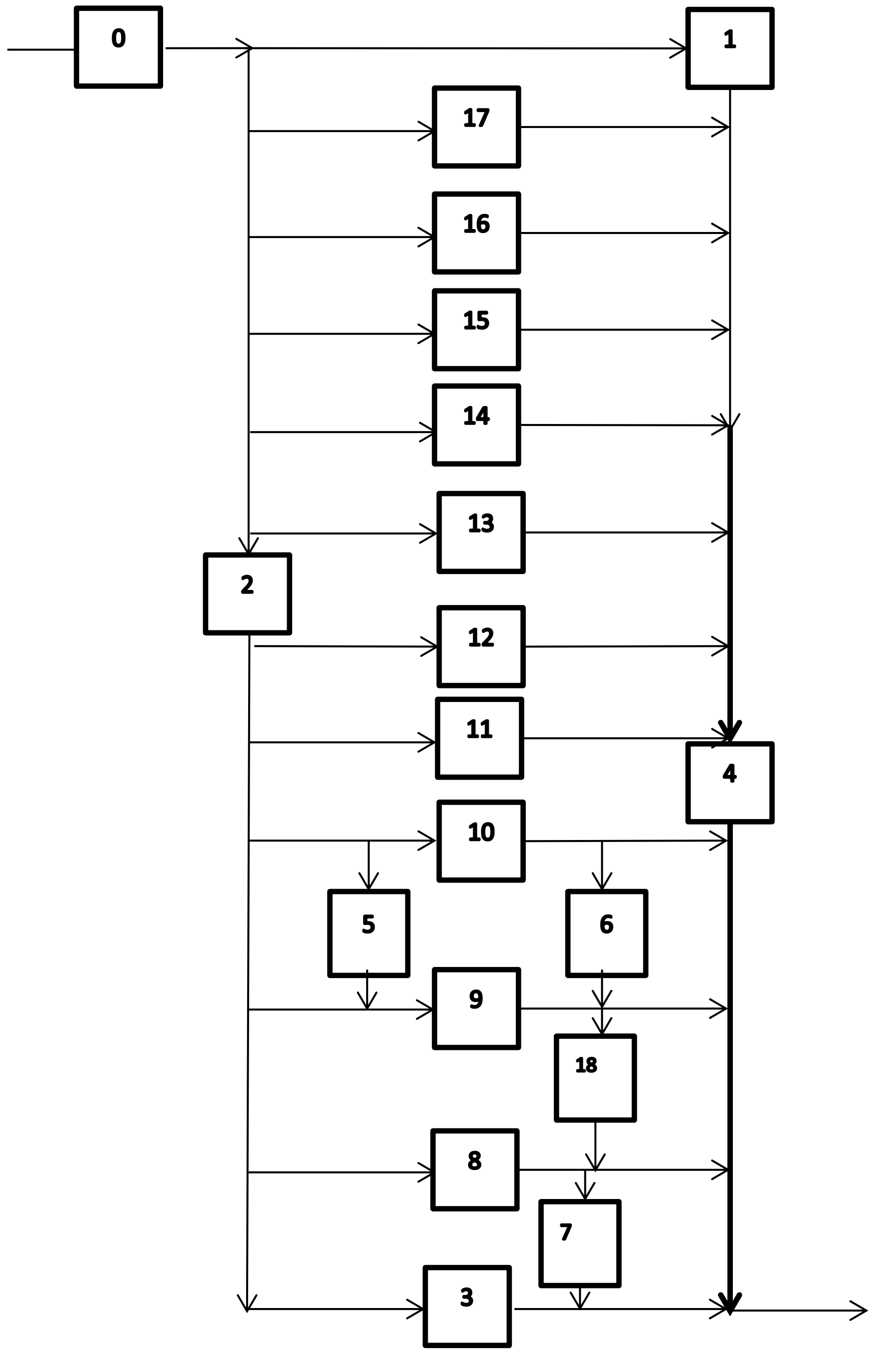


Figure VI.3 Case 1 Network analysis

The performance indices of the segments were obtained using Equation 11. The segment components, diameter, and performance indices are shown in Table VI-3. Based on the connection type shown in Table VI-4, the calculations for performance indices of the sub-networks were done starting from segments 16 and 17. The following observations can be obtained from Figure VI.4:

- The water flow starts from segment 0, and then separates into segments 1 and 2. Segment 1 feeds into segment 4 until reaching the end of network. Segment 2 feeds into the other internal segments. This means that segment 0 is connected in series with segments 1 and 2 and segment 2 is connected in series with the other internal segments (17 to 8 and 3).
- The segments 17 to 8 and 3 are connected in parallel since a failure in one of them does not affect the service in the others.
- The segments 10 and 5 are connected in series, since a failure in 10 will stop the flow in segment 5. The same applies to segments 6 and 10. Segments 5 and 6 are connected in parallel.
- Segments 9 and 18 are connected in parallel because if segment 9 stopped working, segment 6 would still feed segment 18.
- The segments 1 and 4 are connected in parallel, because segment 4 receives the flow from segment 1 and all the other internal segments (17 to 8).
- The performance index of the network, which has a value of 0.566, is presented in Figure VI.3 and analyzed in Figure VI.4. The feeding segment (segment 0) which has performance index of (0.566) is connected in series with the network. This will reduce the performance index of the network from (0.941) to (0.533).

This indicates that maintenance actions must be implemented on the input segment due to its criticality to the considered network.

- It is important to note that when assessing the performance index of the network, segments (17 and 16) were considered as a unit or system connected to segment 15. Similarly, segments (17, 16, and 15) were also considered as one unit connected with segment 14. It is also important to point out that the same result will be obtained if the segments were considered individually not as unit.

Table VI-3 Water Network Components Distribution

Segment #	Number of pipelines	Number of accessories	Diameter "in"	PI for pipelines	PI for Accessories	PI For Segment
1	2	1	12	0.600	0.621	0.610
2	2	1	12	0.600	0.621	0.610
3	2	1	12	0.665	0.766	0.715
4	2	1	8	0.600	0.621	0.610
5	1	2	8	0.493	0.549	0.521
6	1	2	6	0.608	0.640	0.624
7	1	2	6	0.608	0.640	0.624
8	3	2	6	0.584	0.630	0.607
9	1	2	6	0.608	0.640	0.624
10	3	2	6	0.529	0.585	0.557
11	2	2	6	0.600	0.621	0.610
12	2	2	6	0.600	0.621	0.610
13	3	2	8	0.617	0.621	0.619
14	1	2	8	0.600	0.621	0.610
15	1	2	6	0.600	0.621	0.610
16	2	2	6	0.547	0.585	0.566
17	2	2	6	0.537	0.573	0.555
18	1	2	6	0.608	0.640	0.624

Table VI-4 PI Calculations for the sub-networks and entire network

Segments	Connection	PI Equation	PI Value
17 with 16	Parallel	1-[(1-0.566)(1-0.555)]	0.8067
(17,16) with 15	Parallel	1-[(1-0.8067)(1-0.610)]	0.9247
(17 to 15) with 14	Parallel	1-[(1-0.9247)(1-0.610)]	0.9707
(17 to 14) with 13	Parallel	1-[(1-0.9707)(1-0.619)]	0.9888
(17 to 13) with 12	Parallel	1-[(1-0.9888)(1-0.610)]	0.9956
(17 to 12) with 11	Parallel	1-[(1-0.9956)(1-0.610)]	0.9983
5 with 6	Parallel	1-[(1-0.521)(1-0.624)]	0.8200
(5,6) with 10	Series	(0.8200)(0.557)	0.4566
18 with 9	Parallel	1-[(1-0.624)(1-0.624)]	0.8586
(10,5,6)with (18,9)	Parallel	1-[(1-0.4566)(1-0.8586)]	0.9232
(17to11) with ([18,9],[10,5,6])	Parallel	1-[(1-0.9983)(1-0.9232)]	0.99987
7 with 8	Series	(0.624)(0.607)	0.3787
([17to11],[18,9],[10,5,6]) with (7,8)	Parallel	1-[(1-0.9999)(1-0.3787)]	0.99992
([17to11],[18,9],[10,5,6],[7,8]) with 3	Parallel	1-[(1-0.9999)(1-0.715)]	0.99998
([17to11],[18,9],[10,5,6],[7,8],[3]) with 2	Series	(0.9999)(0.610)	0.6104
4 with 1	Parallel	1-[(1-0.610)(1-0.610)]	0.8482
([17to11],[18,9],[10,5,6],[7,8],[3],[2]) with [4,1]	Parallel	1-[(1-0.6104)(1-0.8482)]	0.9408
0 with ([17to11],[18,9],[10,5,6],[7,8],[3],[2], [4,1])	Series	(0.9408) (0.566)	0.5325

VI.5 PERFORMANCE INDEX FOR WATER DISTRIBUTION SUB-NETWORK-CASE 2

The model was implemented on another case study presented in Figure VI.5. 11 segments were identified in the given network. The data for the network components were obtained from the case study presented in sections VI.2 and VI.3. Table VI-5 shows the details of the water distribution components for the purpose of assessing the performance indices of the segments. Table VI-6 shows the connection types between the segments, which are encircled and numbered. Based on the connection type, equations 3 and 7 are used.

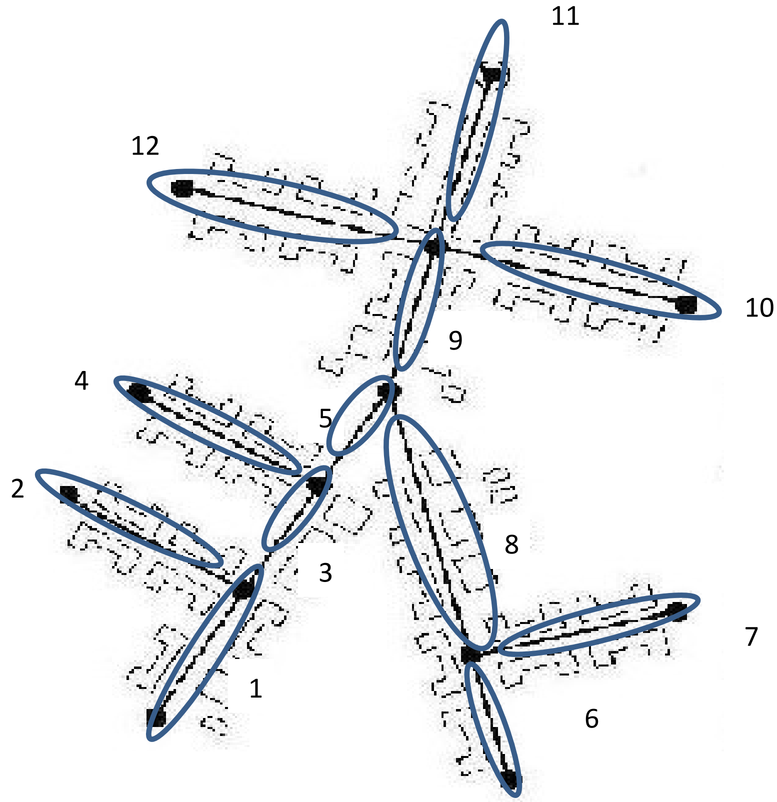


Figure VI.4 Network Sample (Lennetech Water Treatment Solutions, 2014)

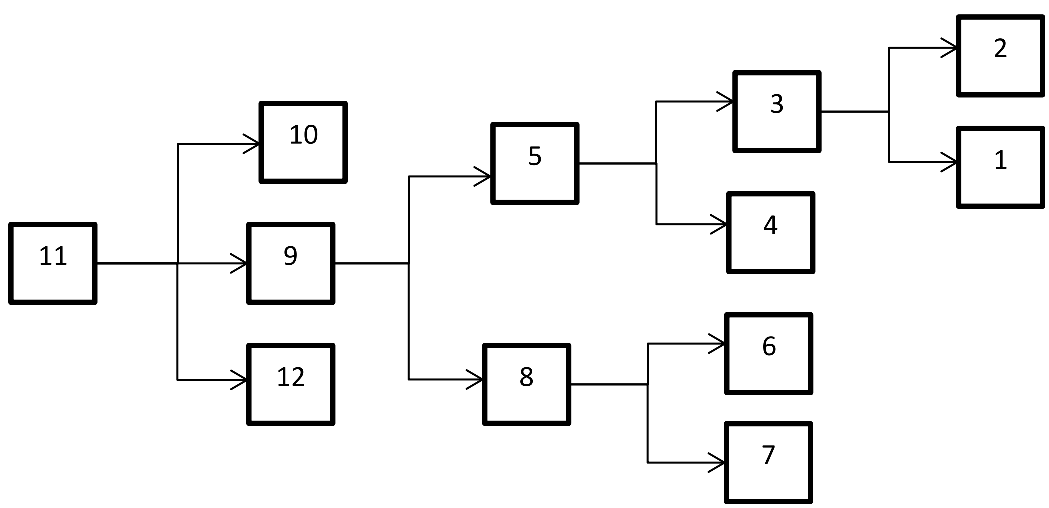


Figure VI.5 Case 2 network analysis

The performance indices of the segments were obtained using equation 11. Table VI-5 shows the calculated performance indices for each of the identified segments. Then, based on the connection type, the calculation for the network performance index was done starting with segments 1 and 2. According to the network analysis presented in Figure VI.6:

- Segments 2 and 1 are connected in series since the failure in one of them, will not cause a failure in the other. However, segment 3 is connected in series with 2 and 1 because if it failed, the flow in segments 2 and 1 will stop. On the other hand, segment 4 is connected is parallel with 3.
- Segments 3, 4 and segments 6, 7 are connected is series with segment 5 and 8, respectively. However, both of them are connected in parallel.
- Segments 5 and 8 are connected in series with segment 9, which is connected in parallel with segments 10 and 12.
- Segment 11 which is the feeding pipe is connected in series with segments 9, 10, and 12.

The network performance index is equal to 0.571 as presented in Figure VI.5 and illustrated and analyzed in Figure VI.6 is 0.571. Table VI-6 presents the calculations of performance indices of the sub-networks starting from segments 1 and 2. This means that the presented network in a functioning condition. However, extensive maintenance work is required.

Table VI-5 Water Network Components Distribution

Segment #	Number of pipelines	Number of accessories	Diameter "in"	PI for pipelines	PI for Accessories	PI For Segment
1	1	2	6	0.566	0.589	0.581
2	1	1	6	0.566	0.621	0.594
3	1	1	8	0.600	0.549	0.575
4	1	1	6	0.493	0.621	0.557
5	1	1	8	0.600	0.621	0.611
6	1	1	6	0.600	0.589	0.595
7	1	1	6	0.566	0.589	0.578
8	1	1	8	0.566	0.621	0.594
9	1	1	8	0.600	0.621	0.611
10	1	1	6	0.600	0.640	0.62
11	1	1	12	0.608	0.640	0.624
12	1	1	6	0.608	0.589	0.599

Table VI-6 PI Calculations for the sub-networks and entire network

Segments	Connection types	PI Equation	PI Value
2 with 1	Parallel	1-[(1-0.581)(1-0.594)]	0.830
7 with 6	Parallel	1-[(1-0.595)(1-0.578)]	0.829
3 with (2,1)	Series	(0.575)(0.830)	0.477
8 with (7,6)	Series	(0.594)(0.829)	0.492
4 with (3,2,1)	Parallel	1-[(1-0.477)(1-0.557)]	0.768
5 with (4,3,2,1)	Series	(0.768)(0.611)	0.469
(5,4,3,2,1) with (8,7,6)	Parallel	1-[(1-0.469)(1-0.492)]	0.730
9 with (8,7,6,5,4,3,2,1)	Series	(0.730)(0.611)	0.446
10 with (9,8,7,6,5,4,3,2,1)	Parallel	1-[(1-0.62)(1-0.446)]	0.789
12 with (10,9,8,7,6,5,4,3,2,1)	Parallel	1-[(1-0.789)(1-0.599)]	0.915
11 with (12,10,9,8,7,6,5,4,3,2,1)	Series	(0.915)(0.624)	0.571

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

VII.1 SUMMARY AND CONCLUSION

The main objectives of this research were to calculate the performance indices for water distribution components (pipeline and accessories) and use these indices to assess the performance index of the entire network or part of it. Al Barqawi (2006) linguistic scale was adopted and used to translate the meaning of the performance index. An Excel-Matlab® Interface was created to perform the calculations of the performance indices of the components. Then the performance index of the segment was assessed using equation 11. Finally, based on the connection type, reliability based models were used to assess the network performance index.

The sub-factors affecting the water distribution network components were identified. They were grouped into three main categories, namely, Physical, Environmental, and Operational. Under each category, sub-factors were also identified. The identified sub-factors were the same for pipelines and accessories except for the sub-factor "size" which is not included in the accessories. Fuzzy Analytical Network Process (FANP) was used to obtain the weights of the identified sub-factors.

Questionnaires were sent to water distribution engineers and experts in the area of Qatar. Several analyses were done on the collected questionnaires to eliminate outliers if present. One of the responses was identified as an outlier and was not considered in this research.

For the FANP models, an Excel-Matlab® interface was created to perform all required calculations. The interface was able to perform the Analytical Hierarchy Process (AHP), Fuzzy Analytical Hierarchy Process (FAHP), Analytical Network Process (ANP), and Fuzzy Analytical Network Process (FANP). A comparison between the four methods was done, to check whether FANP is applicable to the water distribution network case. Then, the interface was validated by comparing the ANP weights obtained from SuperDesicion® software and the interface. The FANP weights were then calculated for both accessories and pipelines.

The sub-factors "Installation Quality", "Breakage Rate" and "Material" had the highest weights representing about 38% of the total weights (i.e., 12.76%, 12.64%, and 12.34, respectively). On the other hand, according to the weights obtained for accessories, "Material", "Installation Quality" and "Breakage Rate" represented 44.4% of the total weights (i.e., 15.8%, 14.6%, and 14%, respectively). The effect values of the descriptions given to the sub-factors were collected through questionnaires. Using the calculated weights and the collected effect values, the performance index of the components were calculated using equation (10).

The performance indices of the segments were calculated by averaging the PIs of its components. Then, reliability based models were used to determine the performance index of the network or sub-network based on the segment connection type whether in series or parallel. Based on the flow direction, if a segment stopped working due to a failure in another segment connected to it, then the two segments are connected in series. On the other hand, two segments are connected in parallel when a failure in one segment will not cause a failure in another segment connected to it. Water pipeline diameter can indicate the flow direction, since large diameter pipelines feed the smaller diameter pipes which are used in the final endpoint of the network such as residential areas.

The model was implemented on a case study of 500 pipelines collected from Moncton NB, Canada. The information of accessories was not available in the gathered data. Thus, accessories were assumed exposed to the same condition as pipelines. The performance indices of accessories were also calculated. A water distribution network from Moncton, NB was selected and the model was implemented on it. After a thorough analysis of the network, the connection types between the segments were identified. The performance index of the network was found equal to 0.533, which means that the network is in a fair to good condition. Therefore, the network requires attention since its components did not have very high performance indices. The maintenance work can be planned based on the assessed performance indices of the components. The developed model was implemented on another case study to acquire more understanding of the model. The types of connections between the segments were identified based on the flow direction. The performance index of the network was found equal to (0.571).

VII.2 RESEARCH CONTRIBUTIONS

The current research achieved the following contributions in the area of condition and performance assessments of water distribution networks and their components:

- Develop performance index models for water distribution pipelines and accessories.
- Use computed indices with reliability based models to calculate the performance index of water distribution network or sub-network. This will help the municipalities build a proper plan for maintenance activities.

- Develop an Excel-Matlab® interface to perform FANP calculations

VII.3 LIMITATIONS

This research calculates the performance index of water distribution network components using FANP method. Then use the computed indices to calculate the performance index of the water distribution network using reliability based models. The limitations in this research are as follows.

- The FANP weights calculated were based on questionnaires gathered from the State of Qatar. This which makes the model most suitable for Qatar. To make the model fit for another country or region, data must be obtained from the experts in that country or region.
- Lack of available data for water distribution network components and mostly accessories and the network as one unit. This will help in building the deterioration models.
- The performance indices of the segments were obtained using the average of the performance indices of its components assuming they have the same weights of the segments which may not be the case in all the situations.
- The selected sub-factors may not apply in all t countries and for all cases. Changing the sub-factors to fit the required needs to be done.

VII.4 RECOMMENDATIONS AND FUTURE WORK

The recommendations and possible future work can be summarized as follows.

- Research Enhancement:
  - Consider more factors affecting water distribution networks and their components in order to generalize the model incorporating all the cases. The developed model is more applicable to State of Qatar as it considers factors affecting water distribution networks in that region and the questionnaires were completed by its experts.
  - Improve the developed interface to be more user-friendly and to allow easy inputting and changing the sub-factors to make it usable world-wide. Also allow the interface to keep records and historical data regarding the relative weights and effect value between different locations and times for future analysis.
  - Develop a condition scale for the performance index for water distribution networks. The scale will help identify the state of the network or sub-network which eventually will help municipalities plan and schedule maintenance activities.
  - In the segment performance index equation, relative weights of pipelines and accessories must be measured. Components' performance indices contribute differently to the segment performance index.

- Research Extensions:
    - Develop performance index models for other types of infrastructure such as sewer infrastructure and combine it with water distribution network models. This will help municipalities to have a general and complete overview of the performance index of the city infrastructure.
    - Assess the criticality of distribution networks for the purpose of budget allocation and scheduling rehabilitation activities. This will help municipalities avoid sudden crises and save money.
    - Apply regular data collection techniques for pipelines, accessories, and networks using recent sensing techniques and technologies that have high accuracy in detecting the small changes in network conditions.
    - Develop a stand-alone graphical user interface that considers all the possible connections of network segments and has the option to identify the network components. The developed interface will be able to draw the network outline and based on the flow direction identify the connection type between the segments.
    - Develop unique performance index models for each type of accessories. Considering them separately will provide more accurate results regarding the accessories performance index.

REFERENCES

A.B. Chance Company. (2012). Vickars. Retrieved from Step7 - Corrosion Guide: <http://www.vickars.com/screwpile_manual/PDF_Files/Step7-Corrosion%20Guide.pdf> (Dec. 15, 2013)

Adams, W. (2001). Creative Decisions Foundation. creativedecisions, <http://www.creativedecisions.net/papers/papers_etc/calc-white-paper.pdf> (May 1, 2013)

Aghber, A. (2005). "Automated selection of trenchless technology for rehabilitation of water mains." M.S. thesis, Concordia University, Montreal, QC, Canada.

Al Barqawi, H. (2006). "Condition Rating Models For Underground Infrastructure: Sustainable Water Mains." M.S. thesis, Concordia University, Montreal, QC, Canada.

Al Barqawi, H., and Zayed, T. (2006). "Assessment Model for Water Main Conditions." *Proc., Pipelines 2006: Service to the Owner*, ASCE, Chicago, Illinois, 1-8.

Al Barqawi, H., and Zayed, T. (2006). "Condition Rating Model for Underground Infrastructure Sustainable Water mains." *J. Performance of Constructed Facilities,* 20(2), 126-135.

Al Barqawi, H., and Zayed, T. (2008). "Infrastructure Management: Integrated AHP/ANN Model to Evaluate Municipal Water Mains' Performance." *J. of Infrastructure Systems*, 14(4), 305-318.

Amit, R., & Ramachandran, P. (2009). "Optimal Design of Water Distribution Networks A Review." *SelectedWorks of R K Amit* <http://works.bepress.com/cgi/viewcontent.cgi?article=1006&context=rkamit.> (Dec. 14, 2013)

ASCE. (2013). "2013 Report card for America's infrastructure." American Society of Civil Engineering, USA.<www.infrastructurereportcard.org>(Dec. 10, 2013)

Australian National Audit Office. (2010). "Better Practice Guide on the Strategic and Operational Management of Assets by Public Sector Entities." Australia.

Balga, A. (1973). "Properties and Behavior of Plastics." National Research Council, Canada. < http://archive.nrc-cnrc.gc.ca/eng/ibp/irc/cbd/building-digest-157.html>(Dec. 18, 2013)

Blaga, A. (1981). "Use of Plastics as Piping Material." National Research Council, Canada. < http://archive.nrc-cnrc.gc.ca/eng/ibp/irc/cbd/building-digest-219.html> (Dec. 18,2013)

Blaga, A. (1982). "Reinforced Thermosetting Plastic Pipe." Canada: National Research, Council.< http://archive.nrc-cnrc.gc.ca/eng/ibp/irc/cbd/building-digest-227.html> (Dec. 18, 2013)

Boulos, P. F., Karney, B. W., Wood, D. J., and Lingireddy, S. (2005). "Hydraulic Transient Guidelines for Protecting Water Distribution Systems." *J. AWWA*, 97(5), 111-124.

Buckley, J.J. (1985). "Fuzzy Hierarchical Analysis." *J. Fuzzy Sets and Systems*, 17 (3), 233-247.

Chang. (1996). "Applications of the extent analysis method on fuzzy AHP". *J. European Journal of Operational Research*, 95(3) , 649-655.

Cheng, & Yang. (1999). "Evaluating attack helicopters by AHP based on linguistic variable weight." *J. European Journal of Operational Research*, 116(2), 423-435.

City Engineers Associations of Minnesota. (1999). "Standard specifications." Minnesota, USA.

CSCE. (2012). “Canadian infrastructure report card.” *Municipal Roads and Water Systems, Volume 1: 2012.* Canadian Society of Civil Engineering, Canada.

Csutora, R., & Buckley, J. (2001). "Fuzzy hierarchical analysis: The Lamda-Max method." *J. Fuzzy Sets and Systems*, 120(2), 181-195.

Cullinane, J. (1989). "Determining availability and reliability for water distribution systems." *Reliability Analysis of Water Distribution Systems*, L. W. Mays, 190-224.

EPA. (2009). "Review draft: control and mitigation of drinking water losses in distribution systems." < http://www.epa.gov/safewater/pws/pdfs/analysis_wa-03_water_loss_doc_final_draft_v62.pdf> (Jan. 5, 2014).

EPA. (2013). "Drinking water infrastructure needs survey and assessment fifth report to congress." < http://water.epa.gov/grants_funding/dwsrf/upload/epa816r13006.pdf> (Jan. 5, 2014).

Estes, A., & Frangopol, D. (2005). "Reliability-Based Condition Assessment." S*tructural Condition Assessment*, J. W. Sons, 25-66.

Etaati, L., Sadi-Nezhad, S., and Moghadam-Abyaneh, P. m. (2011). "Fuzzy Analytical Network Process:An Overview on Methods." *J. American Journal of Scientific Research*, 41, 101-114.

Federation of Canadian Municipalities and National Research Council. (2004). " Monitoring water quality in distribution systems" *National guide to sustainable municipal infrastructure*, Version No. 1.0, Ottawa, Ontario, Canada.

Federation of Canadian Municipalities and National Research Council. (2003). "Deterioration and Inspection of Water Distribution Systems" *National guide to sustainable municipal infrastructure*, Issue No. 1.1, Ottawa, Ontario, Canada.

Free drinking water. (2012). "The Basic Type of Corrosion Explained." <http://www.freedrinkingwater.com/water_quality/chemical/basic-type-of-corrosion-explained.htm> (Dec. 20, 2013)

Garuti, C., & Sandoval, M. (2005). "Comparing AHP and ANP shiftwork models: Hierarchy simplicity v/s network connectivity." *Proc. the 8th International Symposium of the AHP.*

Geem, Z. (2003). "Window-based decision support system for the water pipe condition assessment using artificial neural network." *Proc. World Water & Environmental Resources Congress,* ASCE, New York, 23-26

Giustolisi, O., & Savic, D. (2010). "Identification of segments and optimal isolation valve system design in water distribution networks." *J. Urban Water*, 7(1), 1-15.

Giustolisi, O., Laucelli, D., & Dragan, A. S. (2006). "Development of rehabilitation plans for water mains replacement considering risk and cost-benefit assessment." *J. Civil Engineering and Environmental Systems*, 23(3), 175-190.

Govil, K. (1983). "Reliability Engineering." Tata McGraw-Hill. New Delhi, India.

Herrera, F., Herrera-Viedma, E., & Martínez, L. (2008). "A fuzzy linguistic methodology to deal with unbalanced linguistic term sets." *J. IEEE Transaction on Fuzzy Systems*,16(2), 354-370.

Hu, Y., & Vu, H. (2006). "Field performance of water mains buried in expansive soil." *Proc. 1st International Structural Specialty,* Calgary, Canada, 1-13.

Huo, L.-a., Lan, J., & Wang , Z. (2011). "New parametric prioritization methods for an analytical hierarchy process based on a pairwise comparison matrix." *J. Mathematical and Computer Modelling*, 54(11-12), 2736-2749.

June et al. (2004). Isolating Subsystems in a Water Distribution Network. ASCE- World Water Congress. Salt Lake City, Utah, USA: ACSE.

Kahraman, C., Ertay, T., & Buyukozkan, G. (2006). "A fuzzy optimization model for QFD planning process using analytic network approach." *J. European Journal of Operational Research*, 171(2), 390-411.

Kettler, J., & Goulter, C. (1985). An analysis of pipe breakage in urban water distribution networks. Canadian Journal of Civil Engineering , 286–293.

Kiris, S. (2013). "Multi-Criteria Inventory Classification by Using a Fuzzy Analytic Network Process (ANP) Approach." *J. Informatica*, 24(2), 199-217.

Kleiner, Y., & Rajani, B. (2000). "Considering time-dependent factors in the statistical prediction of water main breaks." *Proc. Infrastructure Conference*, AWWA, 1-12.

Kleiner, Y., & Rajani, B. (2001)$_a$. "Comprehensive review of structural deterioration of water mains: Physical models." *J. Urban Water*, 3(3), 151-164.

Kleiner, Y., & Rajani, B. (2001)$_b$. "Comprehensive review of structural deterioration of water mains: statistical models." *J.Urban Water,* 3(3), 131-150.

Lennetech Water Treatment Solutions. (2014). Lenntech Water Treatment Solution. <http://www.lenntech.com/small-community-water-supplies.htm>(Jan. 15, 2014)

MacLeod, C., Ariaratnam, S., & Chua, K. (2000). "Evaluation of Emergency Repair Attributes for Sewer Infrastructure Management." *Proc. CSCE 2000 conf., Canadian Society of Civil Engineer*, Toronto, Ontario, Canada, 41-59

Makar , J., & Desnoyers, R. (2001). "Three Dimensional Mapping of Corrosion Pits in Cast Iron Pipe Using Remote Field Effect." *Proc. Underground Infrastructure Research: Municipal, Industrial and Environmental Applications*, Kitchener, Ontario, Canada, 1-10.

Makar, J. M., & Kleiner, Y. (2000). "Maintaining water pipeline integrity." *Proc. AWWA Infrastructure Conference and Exhibition*, Baltimore, Maryland, USA.

Mikhailov, L. (2003). "Deriving priorities from fuzzy pairwise comparison judgements." *J. Fuzzy Sets and Systems*, 134(3), 365-385.

Mikhailov, L. (2004). "Group prioritization in the AHP by fuzzy preference programming method." *J. Computers and Operations Research*, 31(2), 293-301.

Najafi, M., & Kulandaivel, G. (2005). "Pipeline Condition Prediction Using Neural Network Models." *Proc. Pipeline Division Specialty Conference 2005*, ASCE, Houston, Texas, United States, 767-781

O'Day, K. (1982). "Organizing and Analyzing Leak and Break Data for Making Main Replacement Decisions." *J. American Water Works Association*, 74(11), 589-594.

Ozger, S. (2003)."A Semi-pressure-driven Approach to Reliability Assessment of Water Distribution Networks." Arizona, USA: Arizona State University.< http://www.public.asu.edu/~lwmays/Ozger_Mays.pdf>(October 20, 2013)

Pelletier, G., Mailhot, A., and Villeneuve, J (2003). "Modeling Water Pipe Breaks-Three Case Studie." *J. Water Resources Planning and Management,* ASCE, 129(2), 123-115.

Promentilla, M. A., Furuichi, T., Ishii, K., and Tanikawa, N. (2008). "A fuzzy analytic network process for multi-criteria evaluation of contaminated site remedial countermeasures." *J. Environmental Management*, 88(3), 479-495.

Qatar Statistics, A. (2012). Qatar infrastructure statistics 2012. Doha: Qatar Statistics Authority.

QCS. (2007). Qatar general organization for standards and metrology. Doha: Qatar Construction Standards.

Quimpo, R. (1996). "Measure of water distribution system reliability." *Proc. ASCE-Risk-Based Decision Making in Water Resources VII*, ASCE, 388-395.

Rajani, B., & Kleiner, Y. (2001). "Comprehensive review of structural deterioration of water mains: Physically based models." *J. Urban Water*, 3(3), 151-164.

Rajani, B., & Kleiner, Y. (2002). "Forecasting variations and trends in water-main breaks." *J. of Infrastructure Systems*, 8(4), 122-131.

Rajani, B., & Kleiner, Y. (2004). "Non-destrctive inspection techniques to determine structural distress indication in water mains." *Proc. Evaluation and Control of Water Loss in Urban Water Networks*, Valencia, Spain, 1-20.

Raychaudhuri, S. (2008). "Introduction to monte carlo simulation." *Proc. Simulation Conference* , IEEE., 91-100

Riverina Environmental Education Centre. Urban salinity in Wagga Wagga.< http://www.reec.nsw.edu.au/geo/salt/text/dryland%20salinity%20in%20wagga.pdf> (dec. 13, 2013)

Ruukki Corporation (2010). "Line pipes water mains joining methods and pipe installation." Ruukki Corporation, Finland.

Saaty. (1980). "The analytic hierarchy process." McGraw-Hill: new McGraw-Hill.

Saaty. (1990). "How to make a decision: The analytic hierarchy process." *J. European Journal of Operational Research*, 48(1), 9-26.

Saaty. (2001). "Decision making with dependence and feedback; The analytic network process" (2nd ed., Vol. 4). Pittsburgh, PA, USA: RWS Publications.

Saaty. (2005). "The Analytic Hierarchy and Analytic Network Processes for the Measurement of Intangible Criteria and for Decision-Making." M*ultiple Criteria Decision Analysis: State of the Art Surveys*, J. Figueira, S. Greco, & M. Ehrogott, 78, 345-405.

Saaty. (2008). "The Analytic Hierarchy and Analytic Network Measurement Processes: Applications to decisions under Risk." *J. European Journal of Pure and Applied Mathematics*, 1(1), 122-196.

Salman, A. (2011). "Reliability-Based Management of Water Distribution Networks." Ph.D. thesis, Concordia University. Montreal, Quebec, Canada.

Sarkis, J., & Sundarraj, R. (2006,). "Evaluation of enterprise information technologies: a decision model for high-level consideration of strategic and operational issues." *J. Systems, Man, and Cybernetics, Part C: Applications and Reviews*, IEEE ,36(2), 260-273.

Semaan, N. (2011). "Structural Performance Model for Subway Network." M.S. thesis, Concordia University. Montreal, Quebec, Canada.

Srdjevic, B. (2005). "Combining different prioritization methods in the-analytic hierarchy process synthesis." *J. Computers & Operations Research*, 32(7), 1897-1919.

Terruggia, R. (2010). "Reliability analysis of probabilistic networks." Ph.D. thesis, University of Turin, Turin, Italy.

Toronto, C. o. (2012). "Watermains and watermain breaks". City of Toronto: <http://www.toronto.ca/water/supply/system/watermains.htm> (June 22, 2012)

Tung. (1985). "Evaluation of water distribtuion ntwork reliability. Hydraulics and hydrology in the small computer age." *Proc. of the Specialty Conference American Society of Civil Engineers Hydraulics Divisio*n, ASCE, Florida.

USA Departement of Environment. (1998). "Deterioration of asbestos cement water mains". Final report to the Department of the Environment: <http://www.fwr.org/pipeline/dwi0131.htm> (Dec. 10, 2012)

Walski. (1993a). "Practical aspects of providing reliability in water distribution systems." *J. Reliability Engineering and System Safety*, 42(1), 13-19.

Walski. (1993b). "Water distribution valve topology." *J. Reliability Engineering and System Safety*, 42(1), 21-27.

Walski. (2002). "Issues in providing reliability in water distribution systems." *Proc. of the ASCE Environmental and Water Resources Institute (EWRI) annual conference* , Roanoke, VA, 19-22.

Wang, Y. (2006). "Deterioration and condition rating analysis of water mains." M.S. thesis, Concordia University. Montreal, Quebec, Canada.

Wang, Y., Elhag, T., & Hua, Z. (2006). "A modified fuzzy logarithmic least squares method for fuzzy analytic hierarchy process." *J. Fuzzy Sets and Systems*, 157 (23), 3055-3071.

Wu, C.R., and Chang, C.W. (2008). "A fuzzy ANP-based approach to evaluate medical organizational performance." *J. Information and Management Sciences,* 19(1), 53-74.

Xu. (2000). "Fuzzy least-squares priority method in the analytic hierarchy process." *J. Fuzzy Sets and Systems*, 112(3), 395-404.

Yan, J., & Vairavamoorthy, K. (2003). "Fuzzy Approach for Pipe Condition Assessment." *Proc. Pipeline Engineering and Construction International Conference,* ASCE, Baltimore, Maryland, United States, 466-476

Yu, J.-R., & Cheng, S.-J. (2007). "An integrated approach for deriving priorities in analytic network process." *J. European Journal of Operational Research*, 180(3), 1427-1432.

Zadeh, L. (1965). "Fuzzy Sets." *J. Information and Control*, 8(3), 338-353.

Zhou, X. (2012). "Fuzzy Analytical Network Process Implementation with Matlab." MATLAB - *A Fundamental Tool for Scientific Computing and Engineering Applications - Volume 3*, V. Katsikis, 133-160.

APPENDIX A

WATER ACCESSORIES TABLES

Table A-1 Main Factors Pairwise Comparison with Respect to Main Goal for Accessories (Lower, Most Probable, Upper) (Questionnaire 31)

	Physical	Environmental	Operational
Physical	(1,1,1)	(6,7,8)	(2,3,4)
Environmental	(1/8,1/7,1/6)	(1,1,1)	(1/3,1/2,1)
Operational	(1/4,1/3,1/2)	(1,2,3)	(1,1,1)

Table A-2 Physical Sub-Factors Pairwise Comparison for Accessories (Lower, Most Probable, Upper) (Questionnaire 31)

	Age	Material	Installation
Age	(1,1,1)	(1/6,1/5,1/4)	(2,3,4)
Material	(4,5,6)	(1,1,1)	(8,9,9)
Installation	(1/4,1/3,1/2)	(1/9,1/9,1/8)	(1,1,1)

Table A-3 Environmental Sub-Factors Pairwise Comparison for Accessories (Lower, Most Probable, Upper) (Questionnaire 31)

	Location	Ground water	Soil
Location	(1,1,1)	(1/4,1/3,1/2)	(1/6,1/5,1/4)
Ground water	(2,3,4)	(1,1,1)	(1/3,1/2,1)
Soil	(4,5,6)	(1,2,3)	(1,1,1)

Table A-4 Environmental Sub-Factors Pairwise Comparison for Accessories (Lower, Most Probable, Upper) (Questionnaire 31)

	C factor	Leakage Rate	Water Quality
C factor	(1,1,1)	(1/6,1/5,1/4)	(6,7,8)
Leakage Rate	(4,5,6)	(1,1,1)	(8,9,9)
Water Quality	(1/8,1/7,1/6)	(1/9,1/9,1/8)	(1,1,1)

Table A-5 Pairwise Comparison between Environmental and Operational for Accessories (Lower, Most Probable, Upper) (Questionnaire 31)

	Environmental Factor	Operational Factors
Environmental Factor	(1,1,1)	(1/8,1/7,1/6)
Operational Factors	(6,7,8)	(1,1,1)

Table A-6 Table 23 Pairwise Comparison between Physical and Operational for Accessories (Lower, Most Probable, Upper) (Questionnaire 31)

	Physical Factors	Operational Factors
Physical Factors	(1,1,1)	(4,5,6)
Operational Factors	(1/6,1/5,1/4)	(1,1,1)

Table A-7 Pairwise Comparison between Physical and Environmental for Accessories (Lower, Most Probable, Upper) (Questionnaire 31)

	Physical Factors	Environmental Factors
Physical Factors	(1,1,1)	(6,7,8)
Environmental Factors	(1/8,1/7,1/6)	(1,1,1)

Table A-8 Fuzzified Relative Weights for Accessories (Questionnaire 31)

Main Factors	Global Weights	Sub-Factors	Local Weights	Global Weights
Physical	0.685	**Age**	0.178	**0.122**
		Size	0.082	**0.506**
		Installation Quality	0.112	**0.056**
Environmental	0.101	**Location**	0.318	**0.011**
		ground water	0.570	**0.032**
		soil type	0.254	**0.057**
Operational	0.215	**C factor**	0.671	**0.055**
		breakage rate	0.075	**0.144**
		Water Quality	0.178	**0.016**
			Total	**1.000**

Table A-9 Unweight Super Matrix for Accessories (Questionnaire 31)

	WMF	PF	EF	OF	A	S	IQ	L	GW	ST	C-FACTOR	LR/BR	WQ
WMF	0	0	0	0	0	0	0	0	0	0	0	0	0
PF	0.685	0	0.833	0.875	0	0	0	0	0	0	0	0	0
EF	0.101	0.125	0	0.125	0	0	0	0	0	0	0	0	0
OF	0.215	0.875	0.167	0	0	0	0	0	0	0	0	0	0
Age	0	0.178	0	0	1	0	0	0	0	0	0	0	0
Size	0	0.739	0	0	0	1	0	0	0	0	0	0	0
IQ	0	0.082	0	0	0	0	1	0	0	0	0	0	0
Location	0	0	0.112	0	0	0	0	1	0	0	0	0	0
GW	0	0	0.318	0	0	0	0	0	1	0	0	0	0
Soil Type	0	0	0.570	0	0	0	0	0	0	1	0	0	0
C-FACTOR	0	0	0	0.254	0	0	0	0	0	0	1	0	0
LR/BR	0	0	0	0.671	0	0	0	0	0	0	0	1	0
WQ	0	0	0	0.075	0	0	0	0	0	0	0	0	1

Table A-10 Weighted Super Matrix for Accessories (Questionnaire 31)

	WMF	PF	EF	OF	A	S	IQ	L	GW	ST	C-FACTOR	LR/BR	WQ
WMF	0	0	0	0	0	0	0	0	0	0	0	0	0
PF	0.685	0	0.417	0.438	0	0	0	0	0	0	0	0	0
EF	0.101	0.062	0	0.063	0	0	0	0	0	0	0	0	0
OF	0.215	0.438	0.083	0	0	0	0	0	0	0	0	0	0
Age	0	0.089	0	0	1	0	0	0	0	0	0	0	0
Size	0	0.370	0	0	0	1	0	0	0	0	0	0	0
IQ	0	0.041	0	0	0	0	1	0	0	0	0	0	0
Location	0	0	0.056	0	0	0	0	1	0	0	0	0	0
GW	0	0	0.159	0	0	0	0	0	1	0	0	0	0
Soil Type	0	0	0.285	0	0	0	0	0	0	1	0	0	0
C-FACTOR	0	0	0	0.127	0	0	0	0	0	0	1	0	0
LR/BR	0	0	0	0.335	0	0	0	0	0	0	0	1	0
WQ	0	0	0	0.037	0	0	0	0	0	0	0	0	1

Table A-11 Accessories Limit Matrix

	WMF	PF	EF	OF	A	S	IQ	L	GW	ST	C-FACTOR	LR/BR	WQ
WMF	0	0	0	0	0	0	0	0	0	0	0	0	0
PF	0	0	0	0	0	0	0	0	0	0	0	0	0
EF	0	0	0	0	0	0	0	0	0	0	0	0	0
OF	0	0	0	0	0	0	0	0	0	0	0	0	0
A	0.097	0.116	0.053	0.054	1	0	0	0	0	0	0	0	0
S	0.400	0.482	0.219	0.224	0	1	0	0	0	0	0	0	0
IQ	0.044	0.054	0.024	0.025	0	0	1	0	0	0	0	0	0
L	0.012	0.007	0.059	0.007	0	0	0	1	0	0	0	0	0
GW	0.034	0.019	0.168	0.019	0	0	0	0	1	0	0	0	0
ST	0.061	0.034	0.302	0.034	0	0	0	0	0	1	0	0	0
C-FACTOR	0.090	0.074	0.044	0.162	0	0	0	0	0	0	1	0	0
LR/BR	0.237	0.194	0.117	0.428	0	0	0	0	0	0	0	1	0
WQ	0.026	0.022	0.013	0.048	0	0	0	0	0	0	0	0	1

APPENDIX B

INTERFACE VALIDATION

An Excel-Matlab® interface was created to perform the calculations of Fuzzy Analytical Network Process (FANP) for the purpose of obtaining sub-factors weights for pipelines and accessories. The step of raising the weighted matrix to large powers is shared between FANP and Analytical Network Process (ANP); however the method of obtaining the weighted matrix is different. The ANP weights obtained from the created interface was compared with the ANP weights obtained from SuperDecision® software. The Identity At Sinks method of calculation must be selected since it is used in this research. Figure (B-1) to Figure (B-4) show the Problem in SuperDecisions® software along with ANP limited matrix which is compared to ANP obtained from the developed interface (Table B-1). By comparing both (Table B-2), it can be seen that both have the same results which makes the developed interface valid.

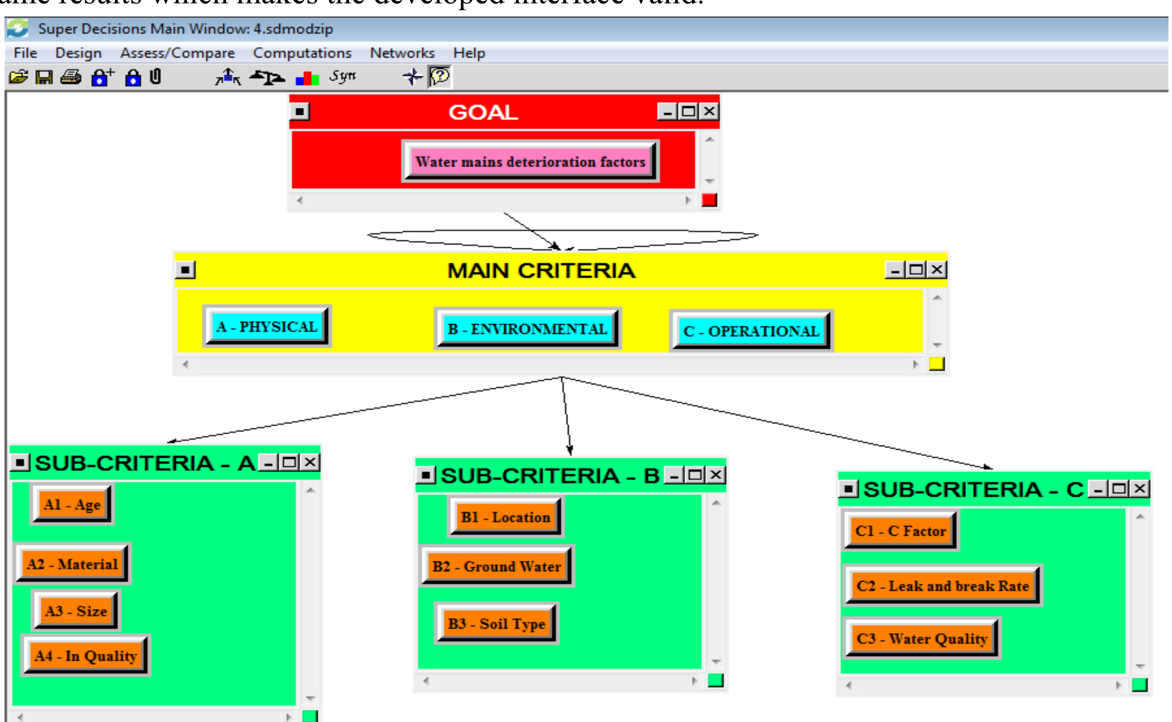


Figure B-1 Setting up the Problem in SuperDesicion®

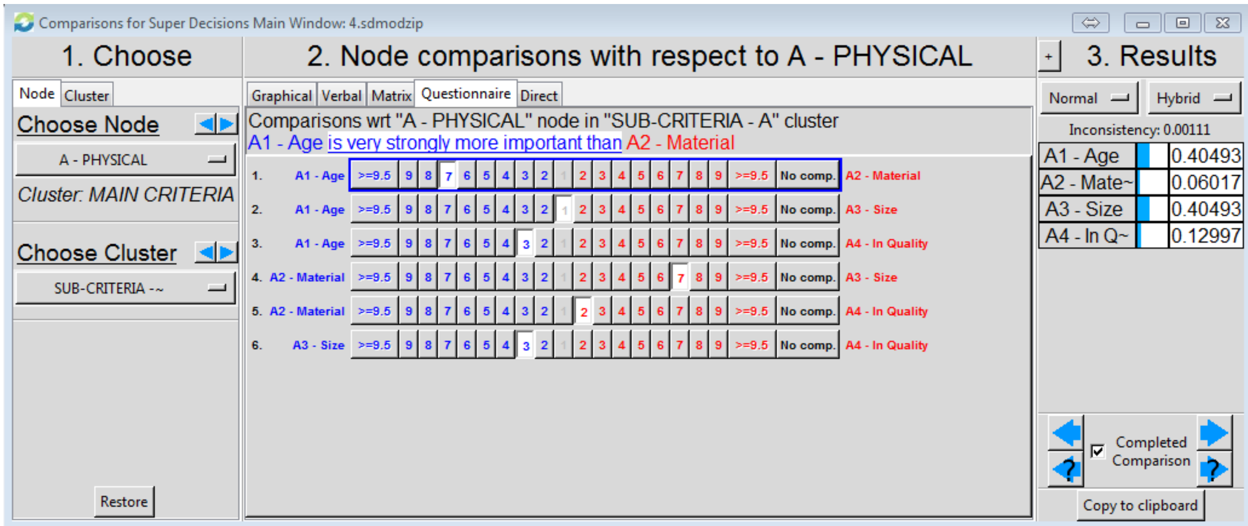


Figure B-2 Filling Pairwise Comparison results

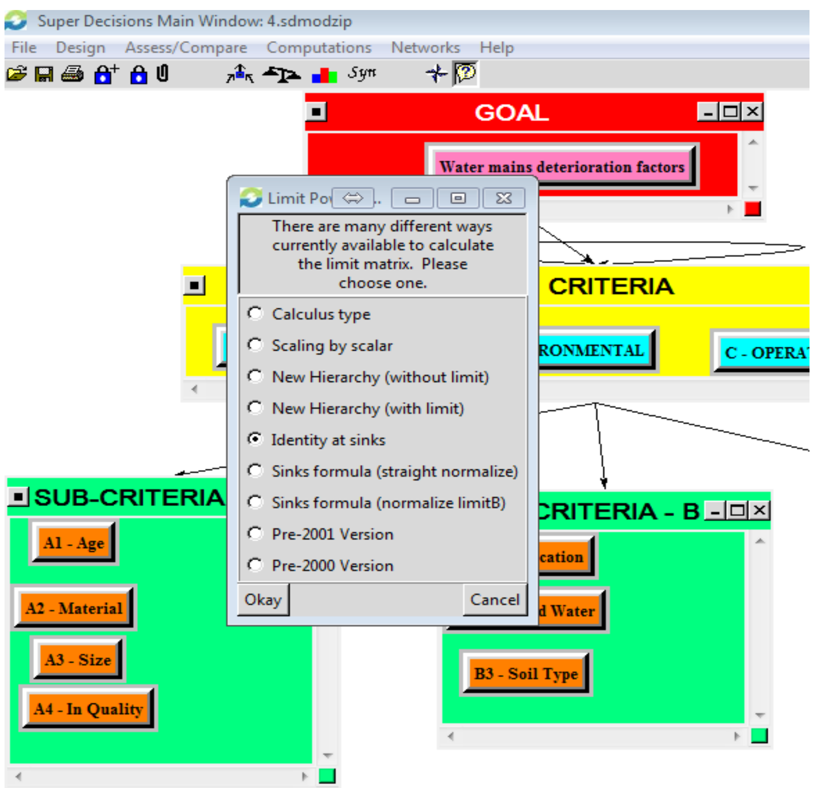
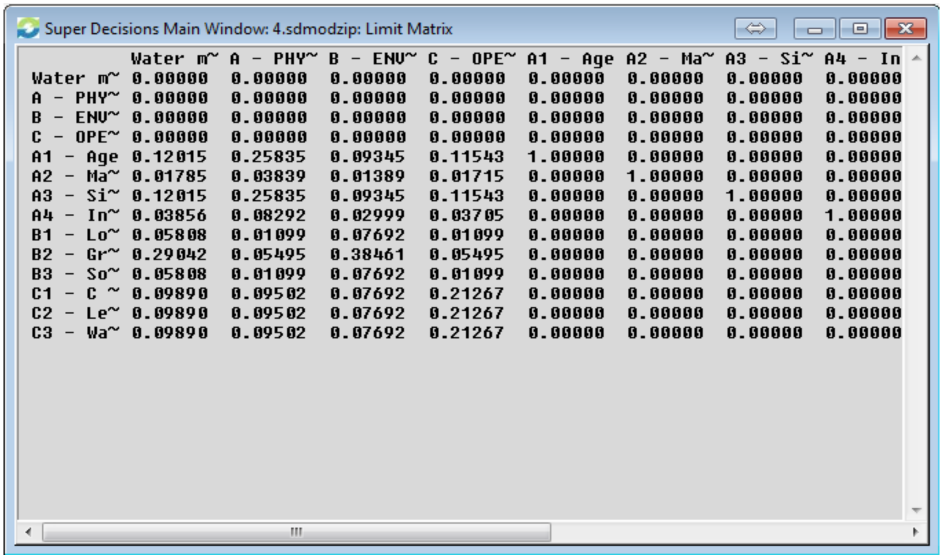


Figure B-3 Choosing Identity at Sinks


Super Decisions Main Window: 4.sdmodzip: Limit Matrix

	Water m~	A - PHY~	B - ENV~	C - OPE~	A1 - Age	A2 - Ma~	A3 - Si~	A4 - In
Water m~	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
A - PHY~	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
B - ENV~	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C - OPE~	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
A1 - Age	0.12015	0.25835	0.09345	0.11543	1.00000	0.00000	0.00000	0.00000
A2 - Ma~	0.01785	0.03839	0.01389	0.01715	0.00000	1.00000	0.00000	0.00000
A3 - Si~	0.12015	0.25835	0.09345	0.11543	0.00000	0.00000	1.00000	0.00000
A4 - In~	0.03856	0.08292	0.02999	0.03705	0.00000	0.00000	0.00000	1.00000
B1 - Lo~	0.05808	0.01099	0.07692	0.01099	0.00000	0.00000	0.00000	0.00000
B2 - Gr~	0.29042	0.05495	0.38461	0.05495	0.00000	0.00000	0.00000	0.00000
B3 - So~	0.05808	0.01099	0.07692	0.01099	0.00000	0.00000	0.00000	0.00000
C1 - C ~	0.09890	0.09502	0.07692	0.21267	0.00000	0.00000	0.00000	0.00000
C2 - Le~	0.09890	0.09502	0.07692	0.21267	0.00000	0.00000	0.00000	0.00000
C3 - Wa~	0.09890	0.09502	0.07692	0.21267	0.00000	0.00000	0.00000	0.00000

Figure B-4 Limited Matrix from SuperDesicion®

Table B-1 ANP Limited Matrix calculated for questionnair 4

	WMF	PF	EF	OF	A	M	S	IQ	L	GW	ST	C-FACTOR	LR/BR	WQ
WMF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A	0.120	0.258	0.093	0.115	1	0	0	0	0	0	0	0	0	0
M	0.018	0.038	0.014	0.017	0	1	0	0	0	0	0	0	0	0
S	0.120	0.258	0.093	0.115	0	0	1	0	0	0	0	0	0	0
IQ	0.039	0.083	0.030	0.037	0	0	0	1	0	0	0	0	0	0
L	0.058	0.011	0.077	0.011	0	0	0	0	1	0	0	0	0	0
GW	0.290	0.055	0.385	0.055	0	0	0	0	0	1	0	0	0	0
ST	0.058	0.011	0.077	0.011	0	0	0	0	0	0	1	0	0	0
C-FACTOR	0.099	0.095	0.077	0.213	0	0	0	0	0	0	0	1	0	0
LR/BR	0.099	0.095	0.077	0.213	0	0	0	0	0	0	0	0	1	0
WQ	0.099	0.095	0.077	0.213	0	0	0	0	0	0	0	0	0	1

Table B-2 Comparison Between sub-factors weights from the interface and SuperDesicion®

Sub-Factor	ANP Interface	ANP SD
Age	0.120	0.120
Material	0.018	0.018
Size	0.120	0.120
Installation Quality	0.039	0.039
Location	0.058	0.058
Ground Water	0.290	0.290
Soil Type	0.058	0.058
C Factor	0.099	0.099
Breakage Rate	0.099	0.099
Water Quality	0.099	0.099

APPENDIX C

DATA BASE

In order to facilitate the use of the identifying the performance index of the components, a Matlab® code was written in order to generate all the possible combinations that could take place using the considered sub-factors and their corresponding effect value. The generated data base can be used for determine the performance index for a given water distribution network component as soon as its characteristics is known. It will also help in improving the component by being able to identify which sub-factor contributes more in its bad index. Later, to modify the data base if there is a change in the weights of the sub-factors or their corresponding effect values, inputting the new weight or effect value is required. A total of 218700 and 43740 combinations were created for pipeline and accessories respectively.

Figure C.1 and Figure C.2 show sample of the created data base for both pipeline and accessories. As can be seen from the figures, the descriptions given to the sub-factors are presented along with their effect value multiplied by their sub-factor weight. At the end, the performance index (PI) for each combination is provided.

Figure C-1 Pipeline Data Base Sample

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	Age		Size		Material		Installation Quality		Ground Water		Soil Type		Location		C-factor		Breakage rate		Water Quality			PI
2	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	High> 101	1.125	High	0.1264	High	0.194		4.8405
3	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	High> 101	1.125	High	0.1264	Medium	0.485		5.1315
4	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	High> 101	1.125	High	0.1264	Low	0.97		5.6165
5	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	High> 101	1.125	Medium	0.632	High	0.194		5.3461
6	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	High> 101	1.125	Medium	0.632	Medium	0.485		5.6371
7	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	High> 101	1.125	Medium	0.632	Low	0.97		6.1221
8	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	High> 101	1.125	Low	1.264	High	0.194		5.9781
9	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	High> 101	1.125	Low	1.264	Medium	0.485		6.2691
10	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	High> 101	1.125	Low	1.264	Low	0.97		6.7541
11	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Medium(4	0.675	High	0.1264	High	0.194		4.3905
12	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Medium(4	0.675	High	0.1264	Medium	0.485		4.6815
13	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Medium(4	0.675	High	0.1264	Low	0.97		5.1665
14	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Medium(4	0.675	Medium	0.632	High	0.194		4.8961
15	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Medium(4	0.675	Medium	0.632	Medium	0.485		5.1871
16	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Medium(4	0.675	Medium	0.632	Low	0.97		5.6721
17	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Medium(4	0.675	Low	1.264	High	0.194		5.5281
18	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Medium(4	0.675	Low	1.264	Medium	0.485		5.8191
19	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Medium(4	0.675	Low	1.264	Low	0.97		6.3041
20	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Low< 41	0.3375	High	0.1264	High	0.194		4.053
21	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Low< 41	0.3375	High	0.1264	Medium	0.485		4.344
22	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Low< 41	0.3375	High	0.1264	Low	0.97		4.829
23	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Low< 41	0.3375	Medium	0.632	High	0.194		4.5586
24	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Low< 41	0.3375	Medium	0.632	Medium	0.485		4.8496
25	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Low< 41	0.3375	Medium	0.632	Low	0.97		5.3346
26	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Low< 41	0.3375	Low	1.264	High	0.194		5.1906
27	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Low< 41	0.3375	Low	1.264	Medium	0.485		5.4816
28	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Asphalt	0.3492	Low< 41	0.3375	Low	1.264	Low	0.97		5.9666
29	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Seal	0.3492	High> 101	1.125	High	0.1264	High	0.194		4.8405
30	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Seal	0.3492	High> 101	1.125	High	0.1264	Medium	0.485		5.1315
31	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Seal	0.3492	High> 101	1.125	High	0.1264	Low	0.97		5.6165
32	>50	0.0825	Small Size	0.3108	PVC	0.9872	Good	1.276	Shallow depth	0.191	Aggressive	0.1984	Seal	0.3492	High> 101	1.125	Medium	0.632	High	0.194		5.3461

Figure C-2 Accessories Data Base Sample

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Age		Material		Installation		Ground Water		Soil Type		Location		C-factor		Breakage Rate		Water Quality			PI
2	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	High> 10	1.05	High	0.14	High	0.228		5.14
3	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	High> 10	1.05	High	0.14	Medium	0.57		5.482
4	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	High> 10	1.05	High	0.14	Low	1.14		6.052
5	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	High> 10	1.05	Medium	0.7	High	0.228		5.7
6	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	High> 10	1.05	Medium	0.7	Medium	0.57		6.042
7	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	High> 10	1.05	Medium	0.7	Low	1.14		6.612
8	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	High> 10	1.05	Low	1.4	High	0.228		6.4
9	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	High> 10	1.05	Low	1.4	Medium	0.57		6.742
10	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	High> 10	1.05	Low	1.4	Low	1.14		7.312
11	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Medium(	0.63	High	0.14	High	0.228		4.72
12	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Medium(	0.63	High	0.14	Medium	0.57		5.062
13	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Medium(	0.63	High	0.14	Low	1.14		5.632
14	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Medium(	0.63	Medium	0.7	High	0.228		5.28
15	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Medium(	0.63	Medium	0.7	Medium	0.57		5.622
16	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Medium(	0.63	Medium	0.7	Low	1.14		6.192
17	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Medium(	0.63	Low	1.4	High	0.228		5.98
18	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Medium(	0.63	Low	1.4	Medium	0.57		6.322
19	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Medium(	0.63	Low	1.4	Low	1.14		6.892
20	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Low< 41	0.315	High	0.14	High	0.228		4.405
21	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Low< 41	0.315	High	0.14	Medium	0.57		4.747
22	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Low< 41	0.315	High	0.14	Low	1.14		5.317
23	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Low< 41	0.315	Medium	0.7	High	0.228		4.965
24	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Low< 41	0.315	Medium	0.7	Medium	0.57		5.307
25	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Low< 41	0.315	Medium	0.7	Low	1.14		5.877
26	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Low< 41	0.315	Low	1.4	High	0.228		5.665
27	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Low< 41	0.315	Low	1.4	Medium	0.57		6.007
28	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Asphalt	0.3	Low< 41	0.315	Low	1.4	Low	1.14		6.577
29	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Seal	0.3	High> 10	1.05	High	0.14	High	0.228		5.14
30	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Seal	0.3	High> 10	1.05	High	0.14	Medium	0.57		5.482
31	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Seal	0.3	High> 10	1.05	High	0.14	Low	1.14		6.052
32	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Seal	0.3	High> 10	1.05	Medium	0.7	High	0.228		5.7
33	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Seal	0.3	High> 10	1.05	Medium	0.7	Medium	0.57		6.042
34	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Seal	0.3	High> 10	1.05	Medium	0.7	Low	1.14		6.612
35	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Seal	0.3	High> 10	1.05	Low	1.4	High	0.228		6.4
36	>50	0	Good	1.58	Good	1.46	Shallow dept	0.2	Aggressive	0.182	Seal	0.3	High> 10	1.05	Low	1.4	Medium	0.57		6.742