PERFORMANCE BASED BUDGET ALLOCATION MODEL FOR WATER NETWORKS

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ABSTRACT

PERFORMANCE-BASED BUDGET ALLOCATION MODEL FOR WATER NETWORKS

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The assessment of water network is a challenge that concerns municipalities worldwide. Most of the water distribution systems around the world are deteriorating and, thus, their rehabilitation become urgent while it costs billions of dollars. According to the Canadian Infrastructure Report Card (CIRC, 2016), the Canadian water distribution systems are graded as "good: adequate for now" with 35% graded from "fair" to "very poor" and the estimated replacement cost is almost CAD 60 billion. The American Society of Civil Engineers Report Card has evaluated the condition of drinking water networks in the United States as "poor" with a grade "D", stating that the United States water networks need USD 126 billion in order to reach a grade "B" by 2020 (ASCE, 2013). Thus, it is obvious that the necessity of providing continuous potable water under tight budgets plunks extra pressure on municipalities and triggers the need for a proper performance assessment.

Accordingly, this research aims at developing a Water Networks Performance-Based Budget Allocation (WNPBA) model, composed of two sub-models: (1) Water Networks Performance Assessment (WNPA) model to precisely assess the performance of the water network components and (2) Budget Allocation (BA) model to optimally allocate budget according to the performance assessment. The WNPA model encompasses two key indices: (1) Pipes Performance Index (PPI) and (2) Accessories Performance Index (API). These indices reflect the status of network components and their deterioration levels and they propose consequent, preventative actions. The WNPA utilize the Fuzzy Analytical Network Process (FANP) to identify and evaluate the weight of functional performance criteria (i.e. physical, operational, quality of service and environmental) of pipes and accessories. It also exploits both the Preference Ranking Organization Method of Enrichment Evaluation (PROMETHEE) and the simple Multi Attribute Utility Theory (MAUT) to compute the functional and global performance indices of the network components. Moreover, the BA model utilize genetic algorithms (GA) and Greedy Heuristics (GH) to optimally allocate the available funds. The required data for this research is collected from experts and two water municipalities (Montreal, QC and Moncton, NB). The developed models are applied to the two water networks.

The results show that most of City of Moncton sub-network 2 components are in a good or medium state, except for pipes 4 & 10 and accessory 7; those are in a poor state, while sub-network 1 is graded excellent for 1 accessory, good for 9 accessories and 7 pipes, medium for 23 accessories and 14 pipes and poor for 2 accessories and 14 pipes. The pipelines in city of Montreal sub-network are graded excellent for 16 pipes, good for 32 pipes and medium for 5 pipes while the accessories are graded excellent for 49 accessories, medium for 8 accessories and poor for 21 accessories. All the sub-networks are generally in a medium state ($4<PI\leq6$). City of Moncton results are verified where the verification factor (VF) is found to be higher than 0.8. Results from the city of Montreal are verified, where almost 90% of the recommended actions from the budget allocation match the actions recommended by the city of Montreal water services. Thus, it can be concluded that WNPBA has proved to be a promising tool with a high capacity in allocating budget to water network components, based on performance indices. Finally, the developed models helps maintain the water supply healthy and work continuously, while maintaining the network in an acceptable condition and protecting it against any unexpected incidents.

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NOMENCLATURE

WNPA: Water Networks Performance Assessment model.

WNPBA: Water Networks Performance based Budget Allocation model.

FANP: Fuzzy Analytical Network Process.

PROMETHEE: Preference Ranking Organization Method for Enrichment Evaluations

MAUT: Multi Attribute Utility Theory.

GA: Genetic Algorithm.

GH: Greedy Heuristics.

NRC: National Research Council.

PI: Performance Index.

FPI: Functional Performance Index.

GPI: Global Performance Index.

PPPI: Pipe Physical Performance Index, **PEPI:** Pipe Environmental Performance Index,

PQPI: Pipe Quality of service Performance Index, **POPI:** Pipe Operational Performance Index.

APPI: Accessories Physical Performance Index, **AEPI:** Accessories Environmental Performance Index, **AQPI:** Accessories Quality of service Performance Index, **AOPI:** Accessories Operational Performance Index.

SPI: Segment Performance Index, **SNPI:** Sub-Network Performance Index, **NPI:** Network Performance Index.

PF: Physical Function.

OF: Operational Function.

QOSF: Quality of Service Function.

EF: Environmental Function.

A: Age.

M: Material.

T: Thickness.

IQ: Installation Quality.

D: Diameter.

BR: Breakage Rate.

RR: Renewal Rate.

LR: Leakage Rate.

C-f: Hazen-Williams Coefficient.

SI: Service Interruptions.

N.H: No. of Households served.

CS: Customer Satisfaction.

WQ: Water Quality.

ST: Soil Type.

GWT: Ground Water Table.

L: Length.

P_{10}: Newly Installed Component.

P_o: Component in critical condition (failing condition).

P.O.S: Probability of Success.

P.O.F: Probability of Failure.

PI_1: Performance Index at year (1).

PI_2: Performance Index at year (2).

PI_3: Performance Index at year (3).

$R.D_1$: Recommended Decision at year (1).

$R.D_2$: Recommended Decision at year (2).

$R.D_3$: Recommended Decision at year (3).

$D.V_1$: Decision Variable at year (1).

$D.V_2$: Decision Variable at year (2).

$D.V_3$: Decision Variable at year (3).

CO_1: Cost at year (1).

CO_2: Cost at year (2).

CO_3: Cost at year (3).

I_1: Improved Performance Index at year (1).

I_2: Improved Performance Index at year (2).

I_3: Improved Performance Index at year (3).

B/C: Benefit / Cost ratio.

VF: Verification Factor.

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CHAPTER I

INTRODUCTION

I.1 OVERVIEW

Water distribution networks are one of the most important infrastructure assets worldwide. According to the Food and Agriculture Organization (FAO, 2013), the total water use in Canada is 1150 gal/inhabitant/day while, in the United States, it is 1146 gal/inhabitant/day. The population nowadays is almost 35 million in Canada and 320 million in the United States, and the population growth, according to the state of the water industry, is 4.6% and 3.9% for Canada and the United States respectively (SOTWI, 2013). Therefore, it is critical for water to be supplied in a safe and clean way, and on a flowing basis. Given that water networks are responsible for transmitting and supplying populations with the main source of life, there is a need to maintain their proper condition through regular inspection and maintenance. As any other infrastructure asset, the water distribution networks are deteriorating in time, due to aging, which is translated into an increasing number of breaks and leaks and low water quality. Thus, a rehabilitation and maintenance plan is required to avoid or reduce the deterioration effects on the system. In order to rehabilitate the deteriorated components within the network, there is a need to have a proper inspection tool to assess the components for rehabilitation.

According to Kleiner and Rajani (2001), there are two methods for component assessment: Direct inspection of the component and assessment prediction models. Comparatively, the direct inspection is very costly and needs a lot of data; the assessment prediction models, however, requires less data and is less costly than the direct inspection method.

When the components are assessed for rehabilitation and assigning proper M&R actions, the main obstacle to implement the actions becomes the tight budget. Most of the water distribution systems need billions of dollars to be rehabilitated. According to the Canadian Infrastructure Report Card (CIRC, 2012), the Canadian water distribution systems were graded as "good: adequate for now" with only 15.4% graded from "fair" to "very poor". The CIRC (2016) has stated that the condition is still "good: adequate for now" but the percentage of pipes graded from fair to very poor is 35. According to the CIRC (2012) and the CIRC (2016), the estimated replacement cost is almost CAD 26 billion and CAD 60 billion respectively. On the other hand, the ASCE (2013) Report Card graded the drinking water networks in the United States as "poor condition" with "D". According to the Environmental Protection Agency's (EPA) fifth report on Drinking Water Infrastructure Needs Survey and Assessment (2013), the water systems in the the United States need around USD 384 billion over the next twenty years. Almost 65% of this amount would be assigned to the distribution part, 19% to the treatment, 10% to the storage, 5% to the source and 1% to other factors. This shows the significance of distribution networks as also the American Water Works Association (AWWA, 2012) has stated that in order to replace pipes in need of replacement, a budget of USD 1 trillion is needed. Based on the ASCE (2013), for the water infrastructure to reach grade "B" by 2020, an estimate of USD 126 billion is required to invest while the funding in 2013 was estimated to be USD 42 billion. Therefore, there was an investment gap of USD 84 billion. All the above-mentioned figures show the significance of conducting a detailed research on the water infrastructure management in order to develop a complete and accurate performance assessment tool.

I.2 RESEARCH OBJECTIVES

The main objective of this research is to optimally distribute the annual budget of any water network over its components according to a performance assessment index of all water network components: Pipes, accessories, segments and sub-networks. This main objective is reached by fulfilling the following sub-objectives:

1) Identify and study the performance indicators of water networks.
2) Develop a performance assessment model of water networks.
3) Build rehabilitation and maintenance plan based on performance indices.
4) Develop a performance-based budget allocation model.

I.3 RESEARCH METHODOLOGY

As mentioned in the research objectives, the aim of this research is to optimally allocate budget to the inspected water network components based on their performance indices. The methodology of this research consists of two main models: Water networks performance assessment model and performance-based budget allocation model. These two models helps the decision makers in the North American water municipalities assess the performance of their water infrastructure systems and optimally distribute budget over these systems. Thus, the methodology is broken into four stages, starting with the literature review, followed by the data collection, then the water networks performance assessment model and finally, the water networks performance-based budget allocation model.

I.3.1. LITERATURE REVIEW

The literature review stage covers the performance indicators definition, the components of the network and the previously developed condition assessment models, budget allocation models and deterioration models of water networks. FANP, PROMETHEE, GA and GH techniques are also explained in the literature review.

I.3.2. DATA COLLECTION

Data is collected through conducting interviews with municipal engineers and managers to identify the indicators that contribute to the performance of the water network components. Also, a questionnaire is prepared to collect the pairwise comparison data of the defined indicators, the attribute values of the indicators, quantitative or qualitative ranges and the thresholds of the different indicators for applying pseudo criteria. Twenty questionnaires are gathered and the data is analyzed. Also, two databases are collected from City of Moncton municipality, New Brunswick and Montreal water services, Quebec. The database for Moncton network covers most of the physical indicators of the water mains except the breakage rate, C-factor and water quality. Other indicators are either assumed or driven from the available indicators. The accessories are assumed to be subjected to the same values as the water mains. On the other hand, Montreal database covers the physical indicators of water mains as well as the breakage rate and the history of rehabilitation actions taken in the past. The remaining data is assumed to be as in City of Moncton (average range) or driven from the available values. The accessories are assumed to be subjected to the same data as the water mains. The environmental data of both networks is obtained from the known location of each network.

I.3.3 WATER NETWORKS PERFORMANCE ASSESSMENT MODEL

The first model in this research is the performance assessment model of water networks and it is implemented in various steps as follows:

1) When the performance indicators from available input sources (i.e. experts and questionnaires) are identified, FANP technique is applied to the water mains and accessories questionnaire results to calculate the relative weight of the importance of the identified indicators with respect to each other and with respect to the function category.
2) PROMETHEE application to get the functional performance indices of each component.
3) MAUT is applied to integrate the functional indices of each component to get one global index for each component utilizing the functions weights from FANP.
4) Weighted probability of failure method.
5) Connectivity ranked matrix.

I.3.4 WATER NETWORKS PERFORMANCE BASED BUDGET ALLOCATION MODEL (WNPBA)

The final output of this research is the performance-based budget allocation model, implemented in the following steps:

1) Develop deterioration curves for all the components utilizing Weibull analysis.
2) Develop performance-based M&R plan, utilizing the defined actions' unit costs and the performance index scale as inputs.

3) Linking the new model to the performance assessment model and using all the performance indices of the different levels of the water network as inputs.
4) Applying the GA and GH means.

I.4 THESIS ORGANIZATION

This thesis consists of six chapters. Chapter I is the introduction. Chapter II presents a detailed literature review on the water networks components, factors and indicators that contribute to the condition of water network components and the condition assessment models previously developed for water systems. It also covers different MCDA techniques such as FANP, PROMETHEE and MAUT. This chapter also illustrates the methods used for the integration of pipes and accessories as well as their segments and the topological clustering. Besides, different rehabilitation, maintenance strategies and budget allocation models of water systems are studied in this chapter. Finally, this chapter illustrates the GA and GH optimization tools. Chapter III shows the methodology of this research, backed by the literature review and followed by the definition of indicators. The methodology is then broken into two models: The performance assessment model and the budget allocation model. The performance assessment model consists of FANP calculations, PROMETHEE calculations and different integration methods to reach the entire network PI. On the other hand, the budget allocation model consists of performance-based rehabilitation and maintenance plan, deterioration curves as inputs and GH model and GA model as outputs. Chapter IV covers the data collection stage. The data is collected from four sources: The literature, interviews with experts, questionnaires and Moncton water municipality and Montreal water services. Thus, the data from twenty questionnaires are analyzed and presented in the data collection chapter. Chapter V – on Model Implementation – illustrates the model implemented on two case studies located in Canada. The first is composed of two sub-networks from City of Moncton, New Brunswick while the second is a sub-network from city of Montreal, Quebec. The implementation starts with FANP calculations over the gathered responses from the questionnaires by developing an integrated Excel-Matlab software. After reaching the relative weights, the fuzzified attribute values are obtained from the fuzzy expert systems on Matlab. Then, PROMETHEE calculations are performed to get the performance indices of components. The integration is done as well to get the segments, sub-networks and entire network performance indices. Finally, the budget is allocated to the components by considering performance-based rehabilitation and maintenance plan, unit costs of the M&R actions and the deterioration of the performance based on Weibull analysis. The last chapter concludes this study by summarizing the research results, limitations and recommendations.

CHAPTER II

LITERATURE REVIEW

II.1 OVERVIEW

This chapter covers the main nine sections as shown in Figure II.1 below. The first section covers the different components of water distribution systems. Section 2 illustrates the different factors that contribute to the deterioration of the water distribution system components and that can be used to assess the condition of these systems. A comprehensive literature review about the different tools of condition assessment of water distribution systems is presented in the third section. In order to have an overview of the most important techniques that can be used in developing performance assessment models, section 4 states some of these techniques such as fuzzy analytical network process (FANP), Preference Ranking Organization Method of Enrichment Evaluation (PROMETHEE) and Multi Attribute Utility Theory (MAUT). Section 5 presents an overview about the models that studied the pipes/accessories integration and the segments integration. It also covered the literature for the topological clustering method. Weibull distribution analysis is illustrated in section 6. An extensive literature review about the different available rehabilitation and maintenance strategies and the cost analysis is covered in the seventh Section. Finally sections 8 and 9 cover the literature review of different budget allocation models and the most important optimization algorithms utilized respectively.

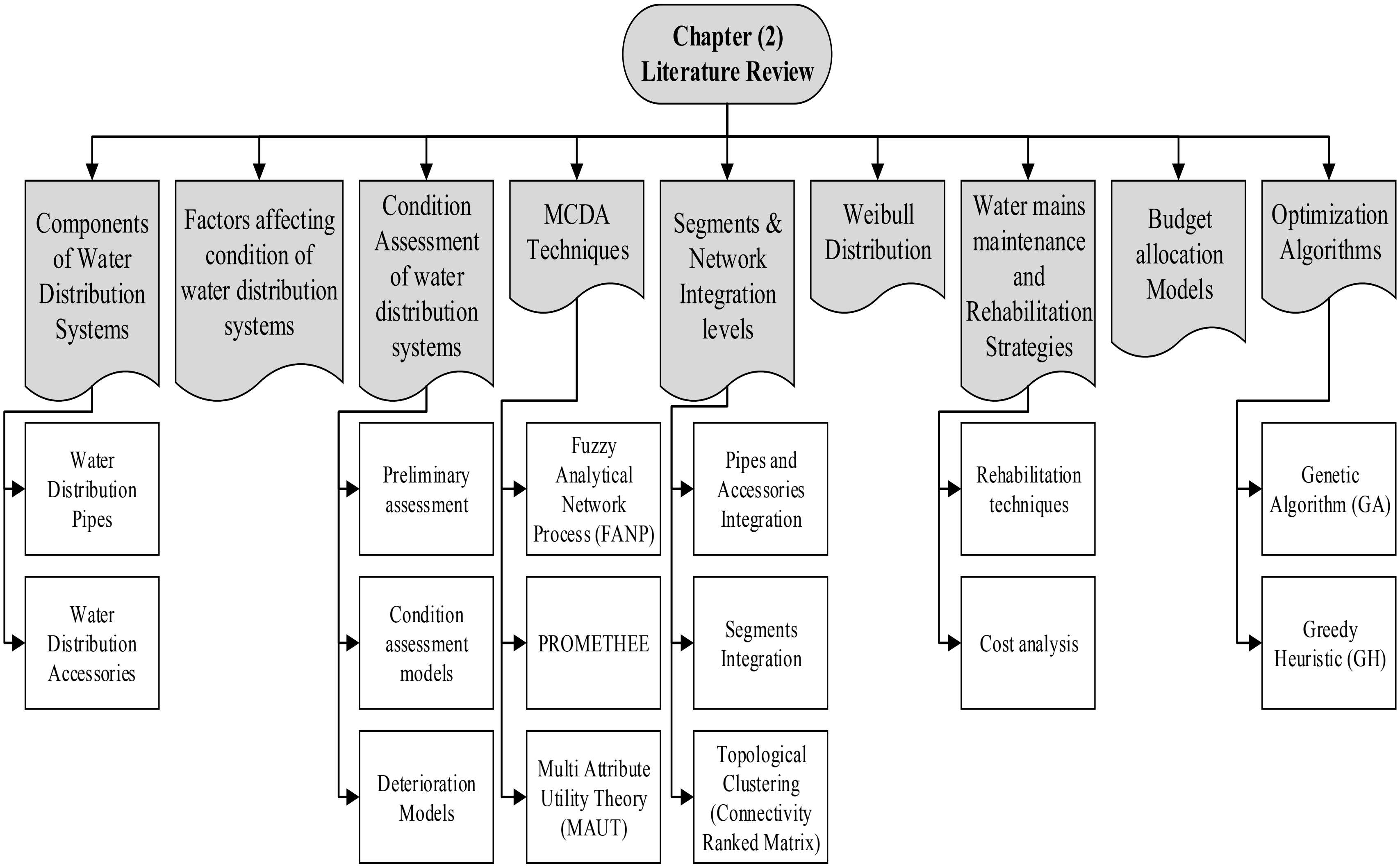


Figure II.1 Literature review structure

II.2 COMPONENTS OF WATER DISTRIBUTION SYSTEM

Based on Amit and Ramachandran (2009), the main purpose of a water distribution network is to provide customers with a reliable supply of high quality water with specific pressure levels under various demand condition. Cullinane (1989) states that water distribution systems consist of several components such as pumps, motors, power transmission, valves, controls, hydrants, pipes and tanks. Therefore, the water networks components can be classified into two parts, which are pipes and accessories.

According to the Australian National Audit Office (Better Practice Guide, 2010), "to determine the effectiveness and efficiency of assets in supporting the delivery of specified service outcomes, an Asset Portfolio should be segmented into largest groups that allow worthwhile analysis." Walski (1993) believes that the segment is a pipe or a group of pipes and that the segment level can be used to obtain a quick assessment of the susceptibility of a system to a single pipe break. June *et al.* (2004) defined the segment as a set of pipes which should be closed during maintenance. Bouchart and Goulter (1991) stated that a new segment "starts whenever the demand along the link or the diameter changes. Salman (2011) stated that the segment is "a single water main pipe or a group of connected pipes (along with all the associated components) which is located between the two nearest intersections at which isolation valves exist and the operation of these valves leads to the isolation of the segment in case of breakage or for regular maintenance of a component in the segment.". Giutolisi and Savic (2010) adopted Walski (1993a) definition for a segment as a portion of a network made of one or more pipes and nodes. El Chanati (2014) defined the segment as group of pipelines and accessories. Therefore, in this thesis, a segment is defined as Salman (2011), while considering the main components are pipes and all other components (valves, Hydrants, Pumps) are called accessories.

According to Izquierdo et al. (2011), “The water networks are almost very large and not usually the result of a unique process of design, but the consequence of years of anarchic response to continually rising demands. Therefore, these large networks are difficult to understand, control and manage. In case of small networks, simple techniques enable to understand and manage the network. As a consequence, there is a need to break each large network into small sub-networks. Sub-Networking can be done either hydraulically or heuristically. Perelman and Ostfeld (2011) proposed a new clustering framework for topological connectivity analysis which break down the network into strongly and weakly connected clusters (sub-networks). The last model is an example of hydraulically sub-networking, while in this research the heuristically sub-networking is applied and the large network is broken down according to the land use.

II.2.1 Water Network Pipelines

Pipes in water distribution network can be divided into two main types; transmission and distribution pipes. Transmission pipes are not included in this research. They mainly transfer the water from the main source to water tanks and they are the most expensive part of any network because of their higher construction cost. While the distribution pipes are the pipes that transfer the water from the tanks to the end users. Rajani and Kleiner (2004) believe that water pipeline materials vary from one city to another and not only within countries. The used pipelines are mainly categorized under three categories based on material, namely; metallic, concrete and poly. The metallic category contains cast and ductile iron. The concrete category includes asbestos and pre-stressed concrete pipes.

Finally, PVC and Glass-Fiber Rein are within the poly category. As shown in Table II-1, the mechanical and thermal properties are different for each pipe material.

It's obvious that Ductile Iron and cast Iron have higher Elastic Modulus and Tensile Strength than other materials. The table also shows that ductile iron and plastic pipes have higher strain at failure (%) than cast iron and asbestos cement pipes. According to the thermal expansion coefficient, plastic pipes is much higher than that of cast iron and ductile iron. The Material is selected based on the mentioned properties besides other construction related factors, environmental related factors and financial factors.

Table II.1 Mechanical and Thermal properties (Rajani and Kleinder, 2004)

Properties	Cast Iron		Ductile Iron	Asbestos Cement	PVC
	Pit	Spun			
Elastic Modulus, GPA	120	137	165	20-25	2.25
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

According to Makar and Kleiner (2000), all pipes deteriorate and fail with time and the failure rate of pipes depends on their material and on their exposure to different environmental and operational conditions. Rajani and Kleiner (2004) stated that the two major categories for deterioration of pipes are; structural and internal. The Effect of structural deterioration of pipes can be summarized in changing in pipe structural resiliency and reduction in the resistance to applied stresses. While, the effect of internal deterioration of pipes can be noticed on the change of hydraulic capacity, water quality and reduction of structural resiliency.

Makar and Kleiner (2000) believe that corrosion is the main reason for the failure of metallic pipes (Cast Iron and ductile Iron). Metallic pipes deteriorate in a faster rate when embedded in aggressive soil. Therefore the deterioration rates of metallic pipes depend on the type of soil they are imbedded in. Makar and Kleiner (2000) also stated that Corroded pre-stressed bars or wires cause the failure of pre-stressed concrete pipes.

Kleiner and Rajani (2001) stated that the failure of Asbestos cement (AC) pipes can be because of aggressive water such as low PH water. AC pipes releases asbestos fibers into the water through the distribution network when it deteriorates; therefore deterioration of (AC) pipes is considered of a great threat to people's health. According to USA Department of Environment (1998), Pipeline epoxy lining helps in preventing this threat. The high resistance to deterioration and corrosion of the Polyvinyl Chloride (PVC) pipes make it the most suitable pipe for corrosive environments. PVC pipes deteriorate if they are exposed to weather, chemical attack, or mechanical degradation from improper installation (Balga, 1973).

II.2.2 Water Distribution Accessories

Water distribution accessories are the water distribution network components other than pipes. El Chanati (2014) and Salman (2011) stated that the major accessories are the valves and the hydrants. Walski (1993) and June et al. (2004) summarized the importance of isolation valves within the water distribution network into four points; closing valves at the two ends isolate a pipe and by isolating the pipe, it can be repaired easily, valves are the key components to water system reliability, the water distribution network would be disabled for every maintenance action if there are no valves and finally, valves control the flow of water.

According to city Engineers Associations of Minnesota (1999), different types of valves are available such as valve housings, gate valves and butterfly valves. Valves have different purposes in water distribution networks such as isolation, air release, drainage, checking and pressure reduction (National Guide of Sustainable Municipal, 2003b). Isolation valves are the most common valves.

El Chanati (2014) stated that isolation valves deteriorate and fail because of different reasons 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 deteriorate and it can also fail due to frost damage. The easily access to the hydrants is the main reason behind being regularly inspection and subjected to maintenance more than valves, as it is not buried as valves.

II.3 FACTORS AFFECTING WATER DISTRIBUTION NETWORK

Various factors affect the deterioration and failure of pipes. Therefore, several studies was conducted on the factors affecting the deterioration of water distribution networks. Karaa and Marks (1990) stated that the performance of water distribution networks can be measured using a number of factors such as the cost of maintaining and operating the system, quality of water supply, serviceability of the system, structural integrity and safety of the system operation and reliability of the water supply. Kleiner and Rajani (2001) classified these factors as operational, environmental and physical characteristics. Rajani and Kleiner (2001) also classified the loads affecting the water distribution networks from the surroundings as external and internal loads such as traffic and frost loads, soil and internal pressure and third party interference. Rajani and Kleiner (2002) classified the factors affecting pipes deterioration into three categories as shown in Figure II.2:

1. Static factors, which do not change with time as pipe material, diameter, installation quality and soil characteristics.

2. Dynamic factors, which that change with time such as age, soil, water temperature, bedding condition, soil moisture and dynamic loading.

3. Operational factors such as internal pressure and replacement rates.

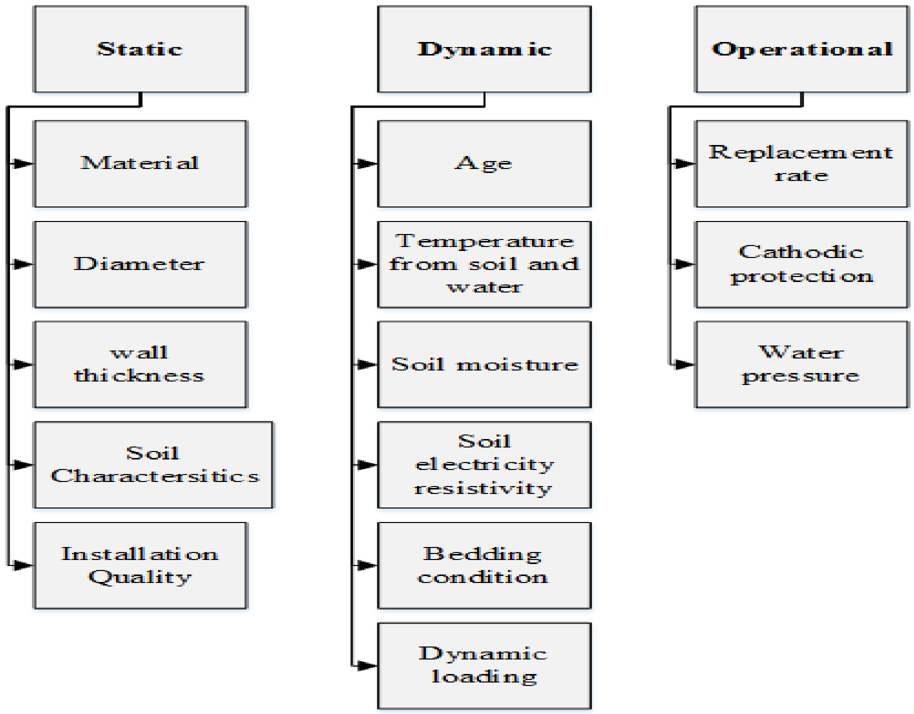


Figure II.2 Factors affecting pipe breakage rate (Rajani and Kleinder, 2002)

National Guide to Sustainable Municipal Infrastructure in their Best Practices (2003b) presented a different classification, includes the following factors (Table II-2):

1. Physical factors, which is mainly about the physical part of the pipeline such as pipe age, material, thickness, diameter and installation process quality.

2. Environmental factors, which covers the environmental aspect surrounding the pipe, include soil type and moisture, ground water presence, pipe location and climate condition.

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.

The last classification by National Guide to Sustainable Municipal Infrastructure in their Best Practices (2003b) was adopted in many researches. Yan and Vairavamoorthy (2003) presented a condition rating model using physical and environmental factors only such as pipe age, diameter and material as physical factors and road loading, soil condition and surroundings as environmental factors. Geem (2003) also developed a condition rating model, using physical and environmental factors. The model included seven physical and environmental factors as pipe age, material, diameter, bedding condition, corrosion, temperature, and trench width. However, the data used was arbitrary generated. Najafi and Kulandaivel (2005) chose physical and environmental factors such as pipe age, size, material, length, depth, slope, and sewer type to be used within their model for the condition prediction of sewer pipes. 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. A variety of physical, operational and environmental factors were also used by El Chanati (2014) in his model for performance assessment of water distribution systems.

There is also another classification presented by the International water association which is named, the IWA system of performance indicators for water supply services (Manual of best practice, 2000). This system classified the indicators into personnel such as no. of employees per connection, physical as the treatment availability and the accessories density, operational as the water losses and mains failure, quality of service indicators as the no. of household covered, the complaints and interruptions, and also water resources related indicators as shown in Table II.3. The last two classifications is adapted through this research in the process of defining the performance indicators of pipes and accessories.

Table II.2 Water system deterioration factors (National guide to sustainable municipal infrastructure best practice, 2003b)

Main Factors	Physical	Environmental	Operational
Sub factors	Pipe material Pipe wall thickness Pipe age Pipe diameter Type of joints Pipe lining and coating Dissimilar metals Pipe installation Pipe manufacture Pipe vintage Thrust restraint	Pipe bedding Trench backfill Soil type Groundwater Climate Pipe location Disturbances Stray electrical currents Seismic activity	Internal water pressure Leakage Water quality Flow velocity Backflow potential O&M practices

Table II.3 IWA system of performance indicators for water supply services (Manual of best practice, 2000)

Main categories	Indicators	Unit
Water resources indicators	Inefficiency of use of water resources	%
	Resources availability ratio	%
Personnel indicators	Employees per connection	(No./1000 connections)
Physical indicators	Treatment availability	%
	Transmission and distribution storage capacity	days
	Valve density & Hydrant density	No./Km
Operational indicators	Inspection and maintenance	%/Year
	Water Mains & service connection rehabilitation	%/Year
	Water losses	m3/connection/year
	Mains failure	No./100 Km/Year
	service connection failure	No./1000 connections/Year
	Hydrants failure	No./1000 hydrants/Year
	Water quality tests performed	%
Quality of service indicators	Households coverage	%
	Quantity of water consumed	L/person/day
	Interruptions per connection	(No./1000 connections)
	Service complaints	No. complaints/connection/Year
	billing complaints	No. complaints/customer/Year
Financial indicators	Average water charges for direct consumption	US$/m3

II.4 Condition Assessment of Water Distribution Systems

The National Guide to Sustainable Infrastructure (2003b) best practice stated two inspection methods which are preliminary assessment and condition rating models. Firstly, the preliminary assessment which mainly depends on the structural condition, hydraulic capacity, leakage and water quality. The best practice presented the needed data to initiate a preliminary assessment and the steps for further detailed investigation based on the results of the initial assessment as shown in Table II.4.

II.4.1 Preliminary Assessment

II.4.1.1 Structural Condition

A various set of indicators can be used to evaluate the structural condition. One of the main indicators is the breakage record. Best practices (2003b) stated that several types of details should be reported such as type, location, date, affected properties affected, etc. The acceptable limit for the breakage rate is different not only from country to country or city to city but from municipality to another, therefore it could be used as an indicator of the structural condition. The location of each break is of an important role in the process of assessment as it clarifies the areas of high breakage rates. The positioning of each break can be done easily by using a combination between geographic Information Systems (GIS) and global positioning system (GPS) to locate each break on its soil which helps linking the high breakage rate areas with the soil type and the surrounding environment (Best practice, 2003b).

II.4.2.2 Hydraulic Capacity

Hydraulic Capacity assessment could take place by studying the low pressure complaints and hydrant flow test results (Al-Barqawi, 2006). The results indicate the state of the system according to the hydraulic capacity either it is changing over time or it is constant. As if the low pressure complaints increased over time, therefore the hydraulic capacity is decreasing which means the system is deteriorating. This could be because of various reasons such as tuberculation in the water mains (Best practice, 2003b).

II.4.1.3 Leakage

Leakage can play an important role in evaluating the condition of the network. The process of evaluating the water leakage was done since a long time using two simple techniques, either by isolating the system into zone and measuring the amount of water entered to maintain the system to a specific working pressure and this technique is named hydrostatic pressure, or by dividing the network into zones too and measuring the total consumption while comparing to the total industrial consumption and consumption/hour. Therefore, any difference is an indication of a leak and this method is called water audit (Best practice, 2003b).

II.4.1.4 Water Quality

Water quality is defined by the best practice (2003b) as the main indicator in the preliminary assessment. The trend of water quality is mainly based on the number of complaints and monitoring data such as chlorine residuals and iron concentration which are the measure of the water quality. As, when the chlorine residuals decrease while the concentration of iron increases, this is a sign of a deteriorated pipe or system and internal corrosion.

Table II.4 Data for preliminary assessment (Adapted from best practice, 2003b)

<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">1) Level of Service
Preliminary investigations indicate an excessive break rate, excessive leakage, inadequate hydraulic capacity and/or impairment of water quality.
2) 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.
3) 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/dem and 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 Condition rating Models

Water Distribution Networks and its components deteriorate over time as any other infrastructure system. Therefore, it faces decreasing hydraulic capacity and level of service over time and consequently increasing rehabilitation and maintenance costs over time. The deterioration of water distribution systems is due to different factors as mentioned before. Recently, the breakage rate of the water mains was found to be increasing. According to Najjaran et al. (2004), more than 700 breaks take place in North America daily. Also 40% of Canada potable water is lost due to leakage in water mains (Al-Aghbar and Moselhi, 2005). Hence, the need for a newly developed condition assessment models with an action plan is increasing. Yan et al. (2003) presented a model that measure the condition of the pipe using fuzzy multi criteria decision making tool (MCDM) and apply it into three levels, from the factors that contributes to the pipe deterioration, to the factors categories which are physical and environmental reaching to the pipe condition (level3) as shown in Figure II3. Geem (2003) developed a Pipe assessment model using back propagation neural network (BPNN). Najafi and kulandaivel (2005) used artificial neural network in their model to assess sewer pipes condition using historical condition assessment data. Al-Barqawi and Zayed (2006) developed a two condition assessment models for water pipelines using AHP and ANP and considering physical, operational and environmental factors through the model. Al-Barqawi and Zayed (2008) used a composite AHP/ANN model to evaluate the sustainability of water pipelines. Salman (2011) presented an intervention model based on the priority index that was developed from the combination between the criticality index and the reliability assessment.

El Chanati (2014) presented a performance assessment model for water distribution systems using Fuzzy Analytical network process to evaluate the components indices and the reliability to get the higher levels (segments, sub-networks) indices, assuming a 50/50 weighting between pipes and accessories and taking into consideration the series and parallel connections within segments.

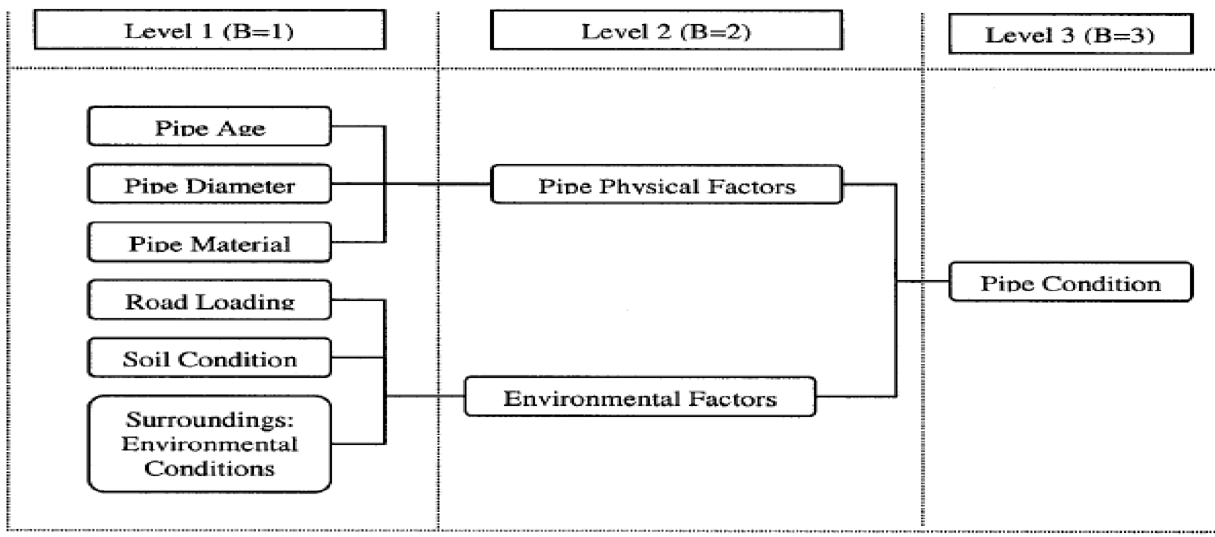


Figure II.3 Levels of pipe condition assessment model (Yan et al., 2003)

Most of the developed models use historical data to assess the current condition of the pipe or the system and the predicted deterioration in the future. Kleinder and Rajani (2001) believe that the condition assessment models can be categorized into two main categories, namely physical and statistical.

Physical Models depend mainly on pipe structural condition and assesses it based on pipe structural properties, internal loads such as operational pressure, external load such as (soil loads, traffic loads and third party interference). According to Kleinder and Rajani (2001) these models can be either deterministic or stochastic. They are mainly used for transmission pipes due to their limitations.

On the other hand, the statistical models depend mainly on sets of historical data to predict future patterns for the breakage. Kleinder and Rajani (2001) classified these models into three classes, namely, deterministic, probabilistic single-variety group-processing and probabilistic multi-variety. This model can be used in the future and it is applicable for water distribution systems. According to Rajani and Kleinder (2001), the statistical model is more expensive as it can be developed to pre-investigate the condition of water systems which enable the municipality for taking a direct action once facing a deteriorated pipe and that aids reaching to better solutions. Therefore, deterioration models plays an important role in asset management because they can predict the future deterioration of an asset or its components (Madanat et al., 1997). The decrease of the condition or performance index over time can be defined as the deterioration. As condition is always a function of time and as mentioned before any component has a decreasing condition over time due to various deterioration factors. The service life of any asset is the period of time from the completion of the asset until the asset or any of its components reaches to the threshold limit or the state that the asset cannot provide acceptable service because of physical deterioration, poor performance, functional obsolescence, or unacceptably high operating costs (Hudson et al. 1997). Service life can be estimated from: (1) empirical experience; (2) a historical database using survivor techniques; (3) established performance models; (4) laboratory testing and (5) accelerated field testing. This section investigates the most important techniques used for modeling and predicting the deterioration. A performance model links a specific performance indicator to a set of causal variables such as age, load, load repetitions, usage history, material properties, environmental factors and M&R history (Hudson et al., 1997).

According to Hudson et al. (1997), a variety of techniques can be used to develop deterioration models, including the following; an expert system incorporating a knowledge base of empirical experience, regression analysis, Markov transition probabilities, Artificial neural network analysis, Bayesian methodology, Econometrics methods. Elhakkem (2005) defined three categories of deterioration evaluating techniques: (1) deterministic, (2) stochastic, and (3) artificial intelligence models.

II.4.3 Sewer and Water Mains Deterioration Models

Chughtai and Zayed (2008) presented a condition assessment model for sewer pipes which uses physical, operational and environmental factors. It utilizes multiple-regression modeling to predict the deterioration. Wang et al., (2009) developed a deterioration model for water mains that uses physical, operational and environmental factors and evaluates the deterioration, using multiple-regression analysis. El Chanati and Zayed (2014) developed a performance assessment model using physical, operational and environmental factors and evaluates the deterioration using reliability based approach.

II.5 MULTI CRITERIA DECISION ANALYSIS TOOLS

A lot of researches have utilized different MCDM tools recently such as, Fuzzy set methods, artificial neural network methods and Multi attribute utility theory (MAUT). This research utilizes Fuzzy Analytical Network Process (FANP), Preference ranking organization method of enrichment evaluation (PROMETHEE) and Multi attribute utility theory (MAUT). Belton and Stewart 2002 stated that there are two philosophies of MCDA and they distinguished those philosophies into either North American school or European school.

The North American school considers that the decision maker has a well information and understanding about the utility scores and the weights of different defined criteria. Multi Attribute Utility Theory (MAUT) developed by Keeny and Raifa (1976), Analytical network process (ANP) developed by Saaty (2001) and Analytical Hierarchy Process (AHP) developed by Saaty (1980) are examples of this school. On the other hand, the European school considers the decision maker doesn't know too much about the preferences. PROMETHEE is one of the well-known techniques within this school. Figure II.4 shows the different categories and different methods of MCDA depending on the aggregation procedure (Petrie et al., 2006).

Figure II.4 Different MCDM (Semaan, 2006)

II.5.1 Fuzzy Analytical Network Process (FANP)

II.5.1.1 Introduction

Multi Criteria Decision Making (MCDM) methods help decision makers and technical experts, to come up with the optimum strategic choice. Saaty (1980) developed a multi-criteria decision support methodology, named analytical hierarchy process (AHP), which belongs to the North American School. Saaty (2001) presented ANP as an extension to overcome AHP limitations with considering interdependencies between the criteria. ANP output is relative importance of different criteria based on different experts' opinions. These opinions are presented in a pair-wise comparison to show the relative effect of one of two elements over the other. Garuti and Sandoval (2005), stated that ANP has the ability to clear all the relationships among variables and as a result decreases the gap between the model and reality. The use of pairwise comparison provides a higher degree of precision that helps in directing attention to a given connection at a time. The real problem of ANP is that it needs a lot of effort to consider all the interdependencies between the criteria while building the hierarchy. Sarkis and Sundarraj (2006), argued that ANP relies only on the experience and knowledge of decision makers included in the process.

Zadeh (1965) developed fuzzy set theory to come over the vagueness and imprecision of humans interaction within the real life system by modeling this uncertainty. There are two kind of sets that any element can belong to, either crisp set or fuzzy set. Within the crisp set, the membership function can be 0 or 1 as the element is either belonging to the set or not. The fuzzy sets provide partial membership ranging from 0 to 1. Using the scale from 1 to 9 within the pairwise comparison in ANP and AHP is simple but it doesn't consider the uncertainty within human judgment.

According to kahraman et al. (2006), ANP needs to simulate the human thinking in order to reach to accurate judgment. Verbal judgments are almost vague and unclear and mostly cannot be described in details. As an example; the decision maker can provide verbal judgments claiming that alternative “X” is strongly or weakly preferred over alternative “Y” but fails to give the exact ratio of the preference. Therefore, Fuzzy AHP (FAHP) and Fuzzy ANP (FANP) were introduced to simulate the uncertainty in the evaluation process as human judgment is mostly uncertain and subjective. FANP is used to overcome the limitations of AHP, ANP and FAHP such as the uncertainties and for considering the interdependencies between the indicators.

II.5.1.2 Fuzzy Linguistic Scales

Etaati (2011) stated that the most used FANP scales are Cheng, Kahraman and Saaty scales. These scales are not the only one used as the researchers who use fuzzy scale can choose the most appropriate one for their research or define their own scale.

Cheng Scale

Cheng (1999) developed his scale based on an integration between linguistic and quantitative variables, using hierarchy method to solve any problem. Cheng’s scale is summarized in Table II.5 (El Chanati, 2014).

Kahraman Scale

An integrated framework between fuzzy-QFD and a fuzzy optimization model to determine the technical requirements for designing a product was introduced by Kahraman (2006). This scale was used in different researches afterwards. The scale is introduced in Table II.5 (El Chanati, 2014).

<u>Saaty Scale</u>

Saaty (1989) presented his own fuzzy scale which was composed of nine points scale. This scale was widely used for AHP and ANP pairwise comparisons by several researchers. The scale is presented in Table II.5 (El Chanati, 2014)

Table II.5 Cheng, Kahraman and Saaty scale (El Chanati, 2014))

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.5.1.3Limited Matrix Calculations

Limited matrix calculations is a continuous process of raising the weighted matrix to large powers until reaching to a duplicated matrix (Adams 2001). Whenever, the diagonal of the weighted matrix is a diagonal of zeros, the limited matrix turns in to a matrix of zeros. Also, if the matrix has columns of zeros (sinks) resulted from no relations between the sub-indicators; it affects the limited matrix as well. Therefore, these sinks are replaced by the same columns from the identity matrix.

II.5.1.4 Fuzzy Preference Programming (FPP)

Fuzzy theory was applied in various researches in different fields because of its simplicity and the improvements of the outputs. Van Laarhoven and Pedrycz (1983) used fuzzy theory to build a fuzzy logarithmic least square methodology to obtain fuzzy weights from triangular fuzzy comparison matrix. An extensive analysis method to provide crisp values for fuzzy matrices was utilized by Chang (1996). Fuzzy least squares priority method

(LSM) was introduced by Xu (2000). Csutora and Buckley (2001) presented Lambda-Max method. Mikhailov (2003; 2004) introduced Fuzzy Preference Programming (FPP).Wang et al (2006) modified fuzzy logarithmic least square method to calculate all local priorities for crisp at one time for ANP.

It is easier to use Matlab® software to apply Fuzzy Preference Programing (FPP) and to get the local weights from the fuzzy matrices (Mikhailov, 2003; 2004). The first Matlab® code to solve the FANP was presented by Zhou, X. (2012). This code was adapted by El Chanati (2014) through his research with a slight modification. The code introduced by El Chanati (2014) is used for this research.

II.5.1.5 Fuzzy Interference System

Ross (2010) stated that the main concept behind fuzzy inference system is producing the system behavior based on past behavior of the system. It was stated also that fuzzy expert system, fuzzy associative memory, fuzzy modelling and fuzzy rule based systems are examples of different fuzzy inference systems. Mamdani et al. (1975) developed the first fuzzy interference system to get control of the combination process between a steam engine and a boiler. There are four steps for any fuzzy interference system which are; fuzzification, Knowledge base, fuzzy inference system and defuzzification.

1-Fuzzification

Alvarez Grima, et al. (2000) defined fuzzification as transformation process. It takes inputs as crisp values and transform it to output of grades utilizing means of membership function and linguistic terms. Membership functions can be in different form according to the problems to be fuzzified, the variables (inputs and outputs) and the experts' experience. These forms can be either linear functions or non-linear (Abouhamad, 2015). Ross (2010) argued that the linear functions are the most used functions in engineering applications for its accuracy and simplicity, Linear functions forms are triangular and trapezoidal, while non-linear forms are various such as S-shaped or bell-Shaped curve. The choice of the most suitable membership function is a very complex process.

2. Knowledge Base

Fuzzy inference engines are mainly based on the knowledge base that should be incorporated in the fuzzy inference system to be able to work. Therefore, the knowledge base can be built using different facilities such as preliminary analysis, literature review, questionnaires and, interviews with industry experts (Abouhamad, 2015). The fuzzy sets and fuzzy rules are the two main elements of the knowledge base as shown in Figure II.5. Fuzzy sets are the membership function as described earlier. Jang et al. (1997) defined the fuzzy rule as "IF premise (antecedent) THEN conclusion (consequent)". Ghasemi and Ataei (2012) stated that experts' judgments, engineering knowledge and experience are utilized to build the fuzzy rules.

3. Fuzzy Inference System (FIS)

Li (2006) stated that If Then rules are used by the fuzzy inference system for the mapping process between the inputs and outputs. According to Ghasemi and Ataei (2012), the different fuzzy inference systems can be compared based on the aggregation of the rules and the defuzzification processes to reach to the best output. The Mamdani fuzzy model, and the Takagi–Sugeno–Kang (TSK) model are examples of FIS.

4. Defuzzification

Defuzzification process is the opposite of fuzzification as it is transforming back fuzzy sets to crisp values. There are various methods for defuzzification such as the Centroid of Area (COA), Bisector of Area (BOA), Mean of Maximum (MOM), Smallest of Maximum (SOM) and Largest of Maximum (LOM). The method most widely used method is the centroid of area (COA) method as it takes all active rules into account during deffuzification process (Abouhamad, 2015).

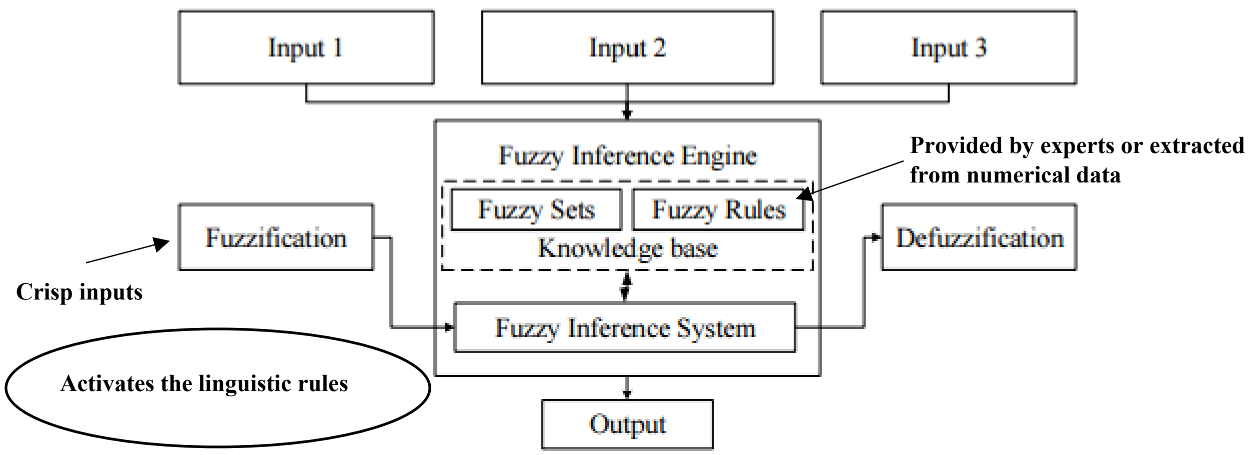


Figure II.5 Fuzzy Inference Engine (Adapted from Abouhamad, 2015)

- **Triangular Fuzzy Number**

One of the well-known forms of linear fuzzy number is triangular fuzzy numbers (TFN) which can presented as $M = (l, m, u)$, where; $l \ll m \ll$u and they refer to the lower, moderate and upper values of the membership function respectively. Triangular membership function is absolutely the most suitable function for this form.

II.5.2 Preference ranking organization method of enrichment evaluation (PROMETHEE)

Brans and Mareschal (1986) developed Preference ranking organization method of enrichment evaluation (PROMETHEE) which is one of the most widely used outranking methods. It has been used in the water management field as: Abu-Taleb and Mareschal (1995), Al-Kloub et al. (1997), Al-Rashdan et al. (1999), Ozelkan and Duckstein (1996) and Raju et al. (2000). It was also used in waste management as Hokannen and salminen (1997). PROMETHEE method is composed of the following steps:

1- **Select Criteria.**

   Criteria herein are all the factors that affect the choice of alternative over the other and those factors supposed to be presented in a hierarchy method from main factors to sub.

2- **Formulate Management alternatives.**

   The alternatives herein are the different solutions that the decision maker chooses between them.

3- **Weighting the criteria.**

   There is no specific method for weighting the criteria. It can be assigned by the decision makers or by some experts. Brans and Mareschal (1986) stated that the sum of the criteria weights should always equal to one. Salminen (1997) developed a weighting method by assigning score from 1 to 7 as 1 is the least important and then by summation and normalization, he was able to get the weights. Roberts and Goodwin (2002) presented three methods of weighting criteria. The first one developed by Von winterfildt and Edwards (1986), which is a direct rating method. It can be implemented using the same method as Salminen (1997) or by using the method developed by

Goodwin and Wright (1998). The second method is point allocation method. Through this method, it is considered that the decision maker has 100 points and they should be distributed over the criteria to get the weights. Baron and Barett (1996) believe that there is no accurate way of measuring weights and that most of the calculated weights depend mainly on the method. They believe that the decision maker is more comfortable to rank the criteria than setting weights. Therefore a lot of method such as rank order centroid (ROC), rank sum (RS) and rank reciprocal weights (RR), which transform the ranking into weights.

Kangas et al. (2001) and Macharis et al. (2004), stated that the weights of the criteria in PROMETHEE could be evaluated using Analytical Hierarchy Process (AHP). Semaan and Zayed (2006) presented the first application of measuring the weights of PROMETHEE using AHP. The weights through this research are evaluated using FANP.

4- **Assessing the performance of alternatives against the criteria.**

Brans and Mareschal (1986) didn't state any specific technique for evaluating the criteria. Therefore, the evaluation could be quantitative for objective criteria and qualitative for subjective criteria. The qualitative evaluation could be performed using fuzzy set theory described earlier in this chapter. Goumas and lygerou (1998) developed a model using PROMETHEE as an outranking method and fuzzy set theory to evaluate the criteria. The flexibility of considering different input and evaluation method for each criteria within PROMETHEE is one of its main advantages and it's probably the main reason behind it being one of the most powerful MCDM.

5- Applying Pseudo Criteria.

One of the advantages of PROMETHEE is that Pseudo concept can be applied within it. The main concept of pseudo is transforming the true criteria into pseudo criteria. According to Roy (1987), the advantages of pseudo concept can be summarized into; considering more precise values, provide a deterministic solutions and considering uncertainty. Pseudo concept is composed of two thresholds; the preference threshold and the indifference threshold and it is also composed of general preference function. It prefers one alternative over the other using those thresholds. The two thresholds could be expressed together in a mathematical function, named the generalized preference function. This function is used to facilitate the process of considering uncertainty within the criteria values, but building this function is a complex process and so far, most of the researchers have a high uncertainty about it. According to Goumas and Lygerou (1998), the generalized preference function could be expressed either in a fuzzy way or in a crisp expression. Brans (1986), presented six types of Crips gpf. as shown in Figure II.6. If those function does not fit the criteria, then the decision maker can define his own gpf. (Gelderman and Rentz, 2000).

[redacted]

Figure II.6 Types of gpf. (Semaan, 2006)

Therefore the preference function is defined as follows:

$$P\left[C_i\left(A_j, A_k\right)\right] = 1\ if\ \ C_i(A_k) - C_i\left(A_j\right) \geq\ P_i(C_i) =\ A_k P A_j \qquad [II.1]$$

$$0\ if\ \ C_i(A_k) - C_i\left(A_j\right) \leq\ q_i(C_i) =\ A_k I A_j \qquad [II.2]$$

$$Otherwise =\ A_k Q A_j \qquad [II.3]$$

Where;

P= Strong Preference, I= Indifference Preference, Q= Weak Preference

6- Applying aggregation.

The aggregation in PROMETHEE is performed as pairwise comparison between the alternatives. As it starts with calculating $P_i\left(A_j, A_k\right)$ for all the criteria and then multi criteria preference index which is the weighted preference of alternative $A_j\ to\ A_k$ considering all criteria is calculated as follows:

$$\pi\left[A_j, A_k\right] = \sum_{i=1}^{n} W_i * P_i(A_j, A_k) \qquad [II.4]$$

From the multi criteria preference index, the measure of strength (the leaving flow) of any alternative over other alternatives and the measure of weakness (the entering flow) for any alternative over other alternatives can be calculated using the following equations:

$$\phi^{+}(A_j) = \sum_{j=1}^{m} \pi[A_j, A_k] \quad \text{[II.5]}$$

$$\phi^{-}(A_j) = \sum_{j=1}^{m} \pi[A_k, A_j] \quad \text{[II.6]}$$

While the net flow is calculated as:

$$\Phi^{net} = \phi^{+}(A_j) - \phi^{-}(A_j) \quad \text{[II.7]}$$

Figure II.7 illustrates the leaving and entering flows.

[redacted]

Figure II. 7 Flow diagram (Semaan, 2006)

7- Ranking of the Alternatives.

Brans and Mareschal (1986) presented two ranking methods; PROMETHEE I and PROMETHEE II. The ranking is done with the leaving flow only Φ^{+} in PROMETHEE I. PROMETHEE II, ranks the alternatives according to the net flow Φ^{net}. Therefore, PROMETHEE I allows two alternatives to have the same rank while PROMETHEE II Provides a unique ranking for each alternative as shown in Figure II.8.

[redacted]

Figure II.8 PROMETHEE ranking (Semaan, 2006)

II.5.3 Multi Attribute Utility Theory (MAUT)

Keeny and Raifa (1976) presented multi attribute utility theory which became one of the most well-known MCDM. It belongs to the North American school. The Decision through this method is taken based on a utility function. This function can be defined based on the desired preferences and the used parameters that the decision maker aims to maximize (Olson, 1996). According to Doumpos and Zopounidis (2002), the concept of MAUT is almost applied within all other MCDA tools.

According to Salman (2011), The steps for utilizing MAUT could be summarized in; determining the alternatives, defining criteria within each alternative, setting a value for each criteria on a unified scale, getting the overall utility score based on the weighted criteria utility and finally using the output utility index in the decision making process. Herein, the challenge is to get all the criteria on a unified scale to be able to compare alternatives on the same scale. Zietsman et al. (2006) reported that calculating the final utility by considering the weighted linear average of criteria is the most straight forward aggregation method.

The MAUT functions could be linear or nonlinear and it may come in the form of additive function or multiplicative function (Keeny and Raifa, 1976).When using additive functions all the utilities should be on the same scale (unit) to have a real value as an output that makes sense. The additive functions' main assumption is that there is mutual independence condition between the criteria as shown in equation [II.8].

If $C_i(A) = C_i(B)$

$C_i(C) = C_i(D)$

And, $C_i(A) = C_i(C)$

$C_i(B) = C_i(D)$

Then U (A) – U (B) = U (C) – U (D)

A is preferred to B

C is preferred to D

Where; A, B, C &D are different alternatives.

Therefore, the additive function can be expressed as follows:

$$U(A) = \sum_{i=1}^{n} W_i * U_i[C_i(A)] \qquad [II.8]$$

Where; n= number of criteria.

W_i= weight of each criteria.

Etezadi-Amoli et al. (1983), stated that the weights can be calculated using different tools as mentioned earlier in PROMETHEE and it can be calculated using probability distribution or simulation. FANP is used in this research for weights calculations. The output of the utility function is an index that facilitate the decision making process and it can be presented in an ordinal scale as well. According to Lam et al. (1997), a lot of researches have shown that additive function provides an output relatively close to the real utility. One of the disadvantages of MAUT is the imprecise parameters due to inaccurate assumptions or vague preference (Lam et al. 1997). Semaan (2006), presented a performance assessment tool for subway stations, using MAUT to transform the functional indices of the stations in to global indices.

II.6 SEGMENTS AND NETWORK INTEGRATION LEVELS

II.6.1 Pipes and Accessories Combination

There is a lack of research in the area of obtaining an integrated assessment for both pipes and accessories to assess the segments properly. Considering the performance of the accessories and its' effect over the network performance is still a vague area that needs to be studied and discovered. El Chanati (2014), developed a performance assessment model for water networks. Through his model, he used the weighted average combination method to combine pipes and accessories performance indices reaching to segments performance indices. Walski (1993) stated that the large mains reliability study should cover the outage in laterals and service lines. Therefore he added the average failure rates of the components together. Salman (2011) adapted the same concept of Walski (1993) with considering the breakage rate to calculate the failure rate and also, adding the weights of importance of each component into the equation. He used hypothetical weights of importance for pipes, hydrants, isolation valves and control valves. Finally, he used the failure rate as an input to the reliability function.

II.6.2 Sub-Networking and Segments Combination

Water distribution networks vary in size from small sub-networks to massive networks that covers a whole city. It is not an easy process to manage, analyze, understand the main structure of the systems and assess the condition in the case of these large networks. Therefore, a network simplification is required in order to facilitate network monitoring, management and understanding the interactions of its components. Wagner et al. (1988) used the algorithms of Rosenthal (1977) and Satyanarayana & Wood (1982) to obtain the Connectivity when a given demand node is connected to a source and the reachability when all demand nodes are connected to a source.

A new methodology for the design of water-distribution systems that use a step-wise combination of network components was developed by Hamberg and Shamir (1988). Yang et al. (1996) proposed a model that uses the minimum cut set method to study the link failures impact on connectivity. Xu et al. (2010) developed a model that partition the network into sub-networks using a facility location model. Finally, there are a lot of methods to divide the water distribution network into smaller sub-networks. However, to decide which method to use, there should be a clear objective to choose the most suitable algorithm.

II.6.3 Topological Clustering (Connectivity Ranked Matrix)

Perelman and Ostfeld (2011) stated that, most of the previous research focused on reliability assessment for combining the components of the network and a limited work was done on topological/connectivity analysis of water distribution (e.g., Jacobs and Goulter (1988); Yang et al. (1996); and Xu et al. (2010)). They presented a new technique for topological/ connectivity analysis. The process of Cluster analysis was defined by

Perelman and Ostfeld (2011) as "partitioning a set of objects into subsets of similar properties." Any water distribution systems is almost broken down to several sub networks which are hydraulically connected or disconnected. They developed a methodology that uses the structure of the network and the connectivity between its components as the main concepts for partitioning the water distribution system into smaller sub-networks. Their model utilized the depth first search (DFS) developed by Tarjan (1972) and breadth first search (BFS) developed by Pohl (1969) to obtain connectivity and clustering. After partitioning the network, the topology chart and the connectivity matrix can be formulated. Kirsteina et al. (2014), also applied topological clustering to investigate the potential use of Norrebro district network.

II.7 WEIBULL DISTRIBUTION ANALYSIS

Jardine and Tsang (2006) stated that Weibull analysis is one of the most widely used methods for deterioration prediction. Waloddi Weibull; the developer of Weibull distribution; believes that the life span of any element can be modeled as illustrated in Equation [II.9]:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \qquad \text{for } t > \gamma \qquad \text{[II.9]}$$

Where β = shape parameter, greater than zero,

γ = location parameter, greater than zero,

η = scale parameter and,

t = time.

And the cumulative Weibull distribution function (cdf) is as shown in Equation [II.10]:

$$F(t) = 1 - e^{-(\frac{t-\gamma}{n})^{\beta}} \qquad [II.10]$$

Therefore, the reliability function is as follows:

$$R(t) = 1 - F(t) = e^{-(\frac{t-\gamma}{n})^{\beta}} \qquad [II.11]$$

The reason behind plotting F (t) and R (t) is to facilitate the estimation of the parameters:

β, γ and η.

The shape β can be in any of the following cases:

- For $0 < \beta < 1$, R (t) decreases sharply and is convex.
- For $\beta = 1$, R (t) decreases less sharply than $0 < \beta < 1$ and is convex.
- For $\beta > 1$, R (t) decreases as time "t" increases. The curve goes through an inflection point, after this point it decreases sharply.

The scale parameter η has the same effect on the cdf and R (t) as the time. The location parameter (γ) locates the distribution along the time. Changing the value of γ has the effect of "sliding" the cdf and R (t) either to the right ($\gamma > 0$), or to the left ($\gamma < 0$). When γ=0, the distribution starts at t=0 or at the origin. Finally, the estimation of the parameters of the Weibull distribution can be found graphically via probability plotting paper, or analytically, either using least squares or maximum likelihood (Semaan, 2011).

II.8 WATER MAINS MAINTENANCE and REHABILITATION STRATEGIES

II.8.1 Rehabilitation techniques

The Selection of the suitable rehabilitation technique for water mains has become a great challenge that faces decision makers. Therefore, a lot of researches have been done in the area of defining the suitable rehabilitation techniques for water mains and the criteria to choose between the defined methods. There are two main rehabilitation techniques for water mains; repair & renovation or replacement. Cleaning, structural linings and non-structural linings are examples of the renovation technique. On the other hand, replacement can be either on-line replacement or off-line. On-line replacement covers slip lining and pipe bursting.

Moselhi and Sigurdaottir (1998) developed a model for selecting the most suitable trenchless pipeline rehabilitation techniques using MAUT. Keliner et al. (1998) developed a model that expect the deterioration of water pipelines and make a decision about the next replacement based on structural and hydraulic deterioration. According to Dandy and Engelhardt (2001), any rehabilitation strategy can be built based on economic, reliability and water quality criteria. Zayed et al. (2011), used AHP and SMART to select the most suitable rehabilitation method for pipes. The NRC (Infraguide: best practices, 2003), presented a model that select the most suitable rehabilitation methods and this model presents various methods for the same condition (criteria) as shown in Figure II.9. Also, NRC (2010) presented “Distribution water mains Renewal Planner (D-WARP)”, which is software that predicts the deterioration and breakage rates. Al-Aghbar (2005), presented a two models for choosing the trenchless technology for rehabilitation of water mains; one is service defects based while the other is structural defects based as shown in Figures II.10 and II.11. Mohamed and Zayed (2008) developed a YES/NO decision support system to determine the most suitable rehabilitation technique based on the breakage rate as illustrated in Figure II.12. As presented through Figure II.13, stochastic life cycle cost analysis was applied to reach to the best rehabilitation scenario using simulation tools (Shahata and Zayed, 2008). Salman (2011) developed a model for selection of rehabilitation techniques based on combination of different factors; cost, impact on environment and experiment new technology. He used SMART as presented in Figure II.14, to combine the effect of the three factors and to reach to a final decision.

II.8.2 Cost Analysis

Cost is considered the most important element in the process of selection of the rehabilitation techniques. There is two main classifications of cost in the literature. The first classification is, primary, secondary, and risk costs (Harbuck, 2000). The primary costs are; Planning, Engineering, Design fees, easement, Construction costs associated with pipe installation and Life cycle costs. The secondary costs are mainly concern about the impact on environment, so it can be the compensation for damage of a property and loss of business and resulting tax revenue. Finally, the risk costs could be unforeseen obstructions, disposal of contaminated soil and impact on geotechnical conditions. Najafi (2004) also, analyzed the cost into; Pre-construction cost, construction costs and post-construction costs. The pre-construction costs cover, planning, permits, legal fees, design fees, preparation of initial drawings and the owner-ship of the land itself. The direct and indirect costs of the project itself are covered under the construction costs. Operation and maintenance costs are examples of post-construction costs.

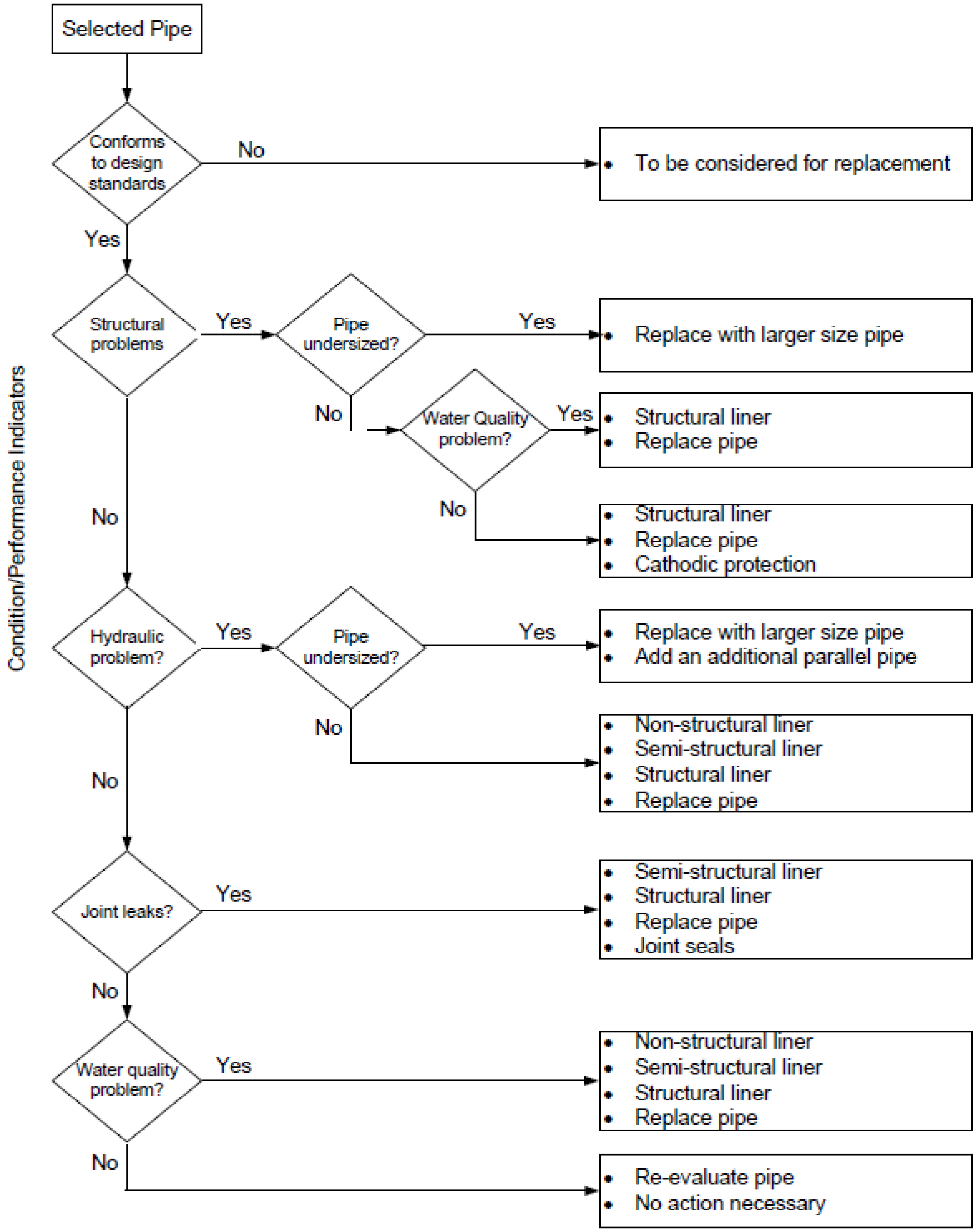


Figure II.9 DSS for selection of rehabilitation methods (Salman, 2011, adopted from NRC infraguide; best practice, 2003)

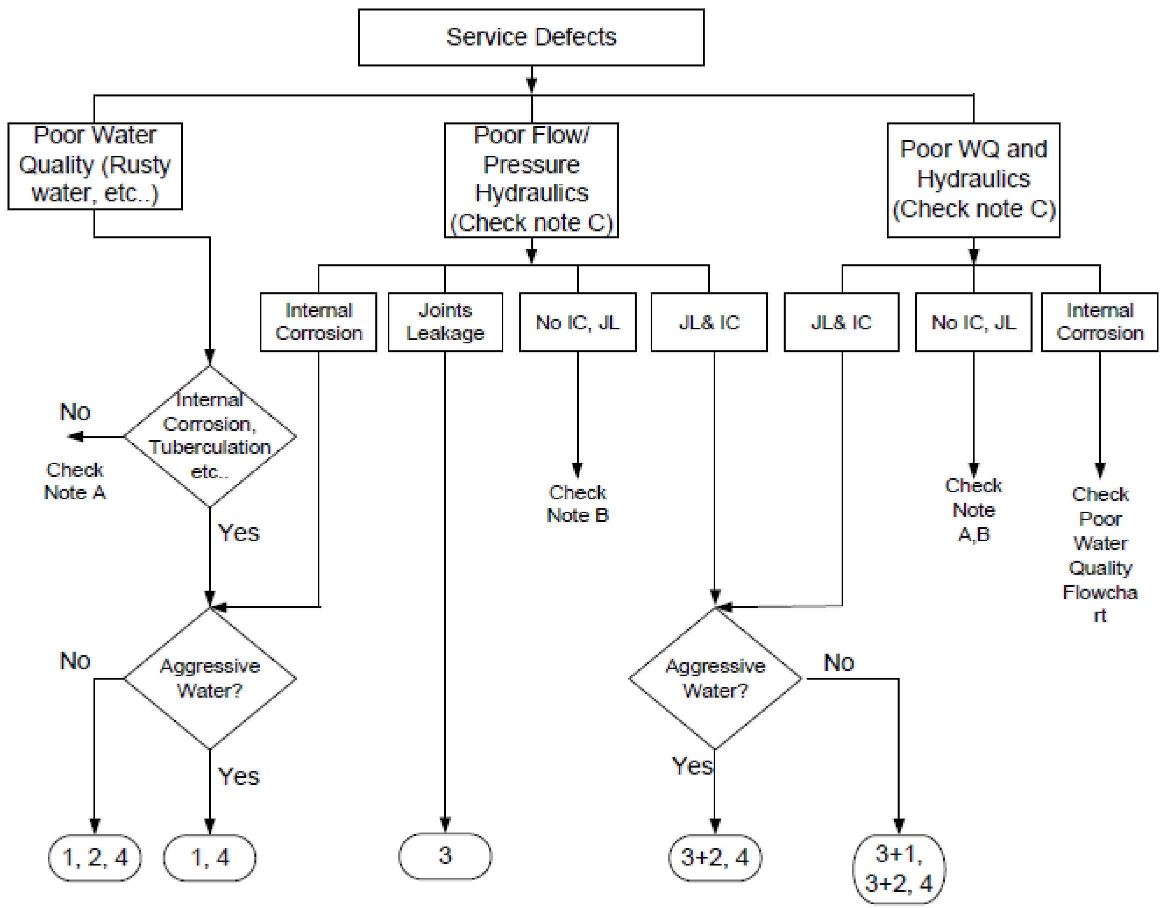


Figure II.10 DSS for selection of rehabilitation methods based on service defects (Al-Aghbar, 2005)

Non-structural Rehabilitation Options:

(1) Epoxy Lining

(2) Cement Lining

(3) Internal Joint Sealing

Semi-structural Rehabilitation Options:

(4) Close Fit Slip lining, Swaged Lining Fold & Formed Lining and Cured In Place Pipes (CIPP)

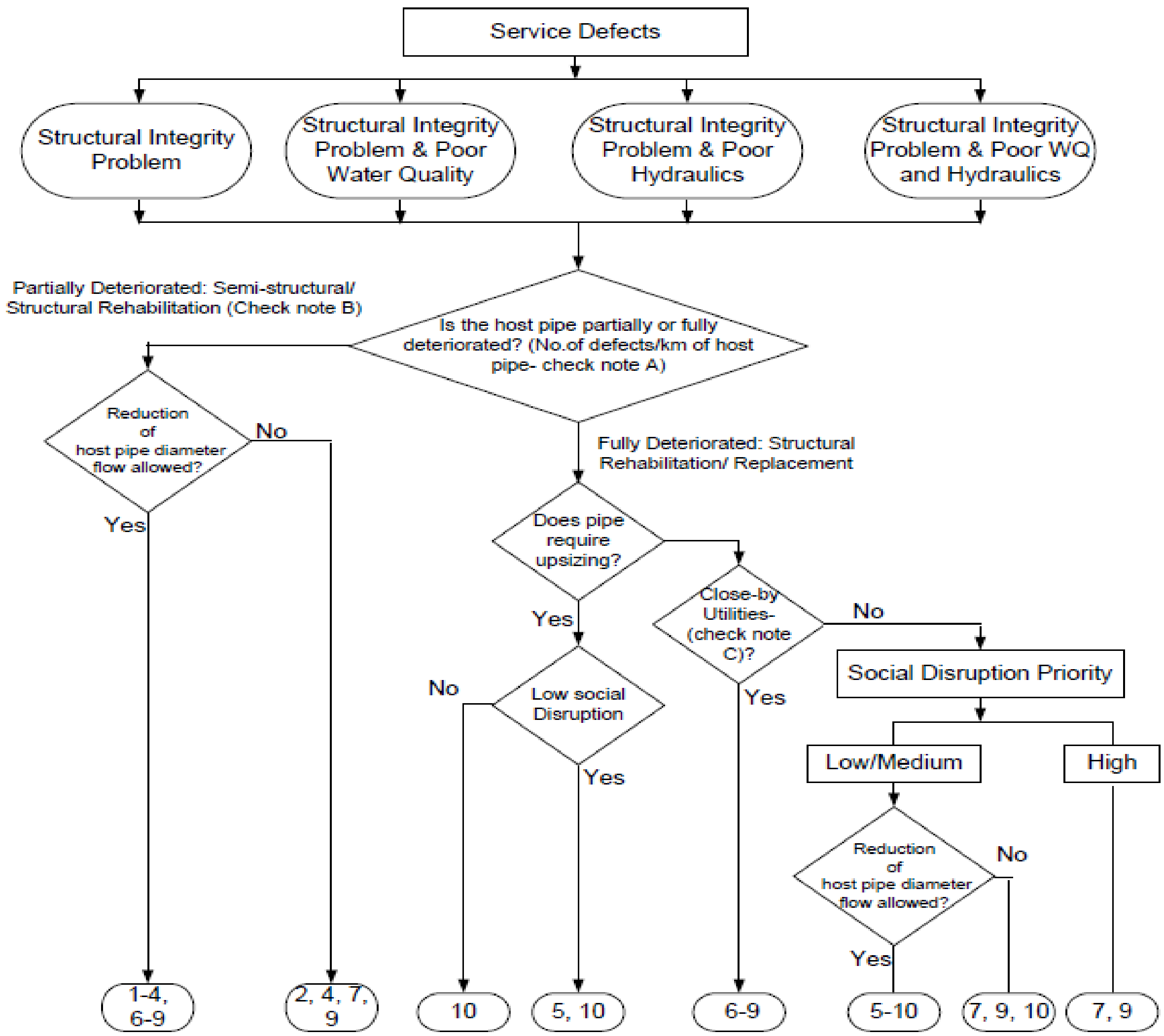


Figure II.11 DSS for selection of rehabilitation methods based on structural defects (Al-Aghabr, 2005)

Semi-structural Rehabilitation Options:

(1) Swaged Lining (Reduced Diameter)
(2) Folded and Formed Lining
(3) Slip lining
(4) Cured In Place Pipes (CIPP)

Structural Rehabilitation Options:

(5) Conventional Open Cut Replacement
(6) Swaged Lining (Reduced Diameter)
(7) Folded and Formed Lining
(8) Slip lining
(9) Cured In Place Pipes (CIPP)
(10) Pipe Bursting.

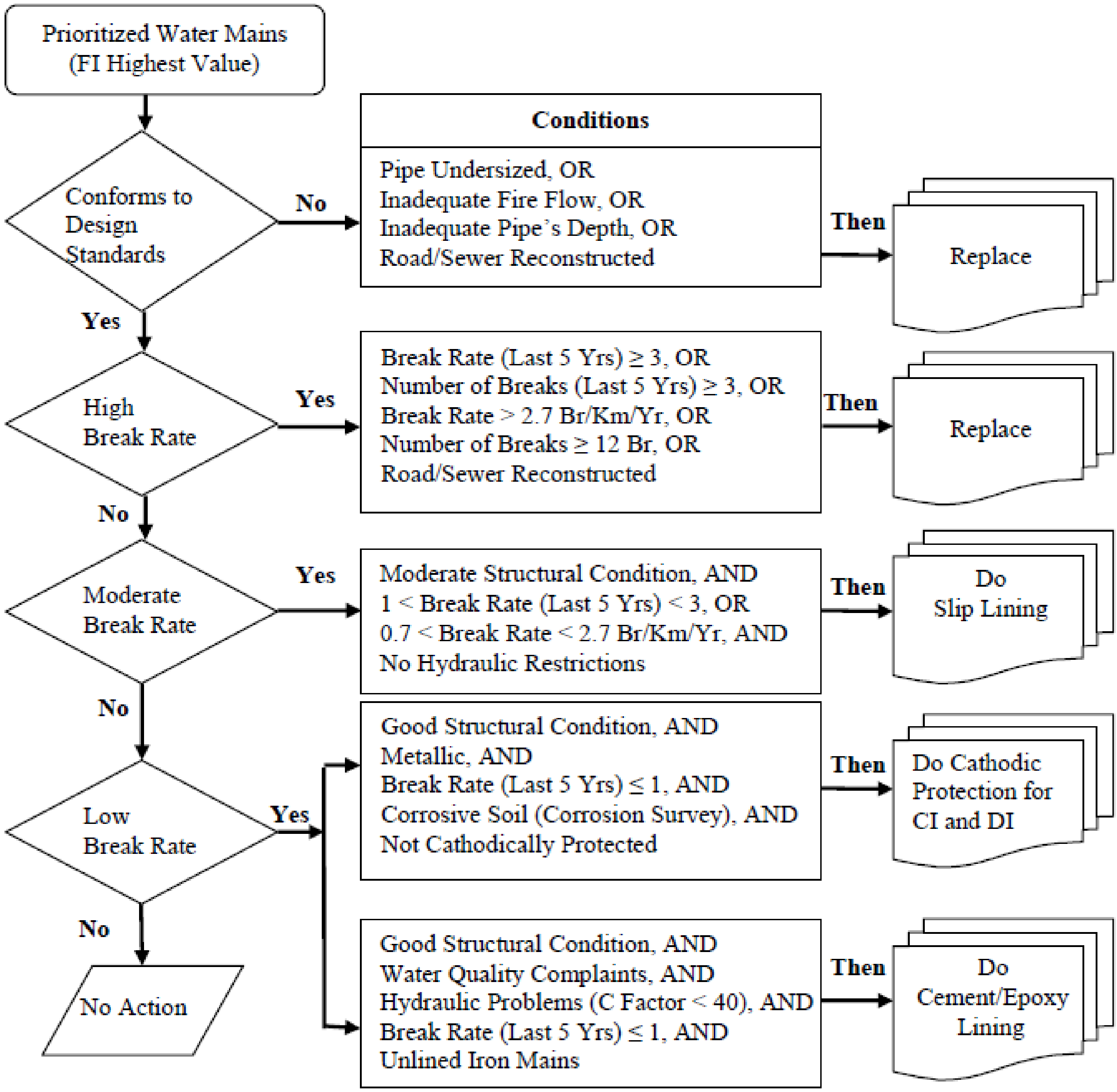


Figure II.12 DSS for selection of rehabilitation methods based on breakage rate (Mohamed and Zayed, 2008)

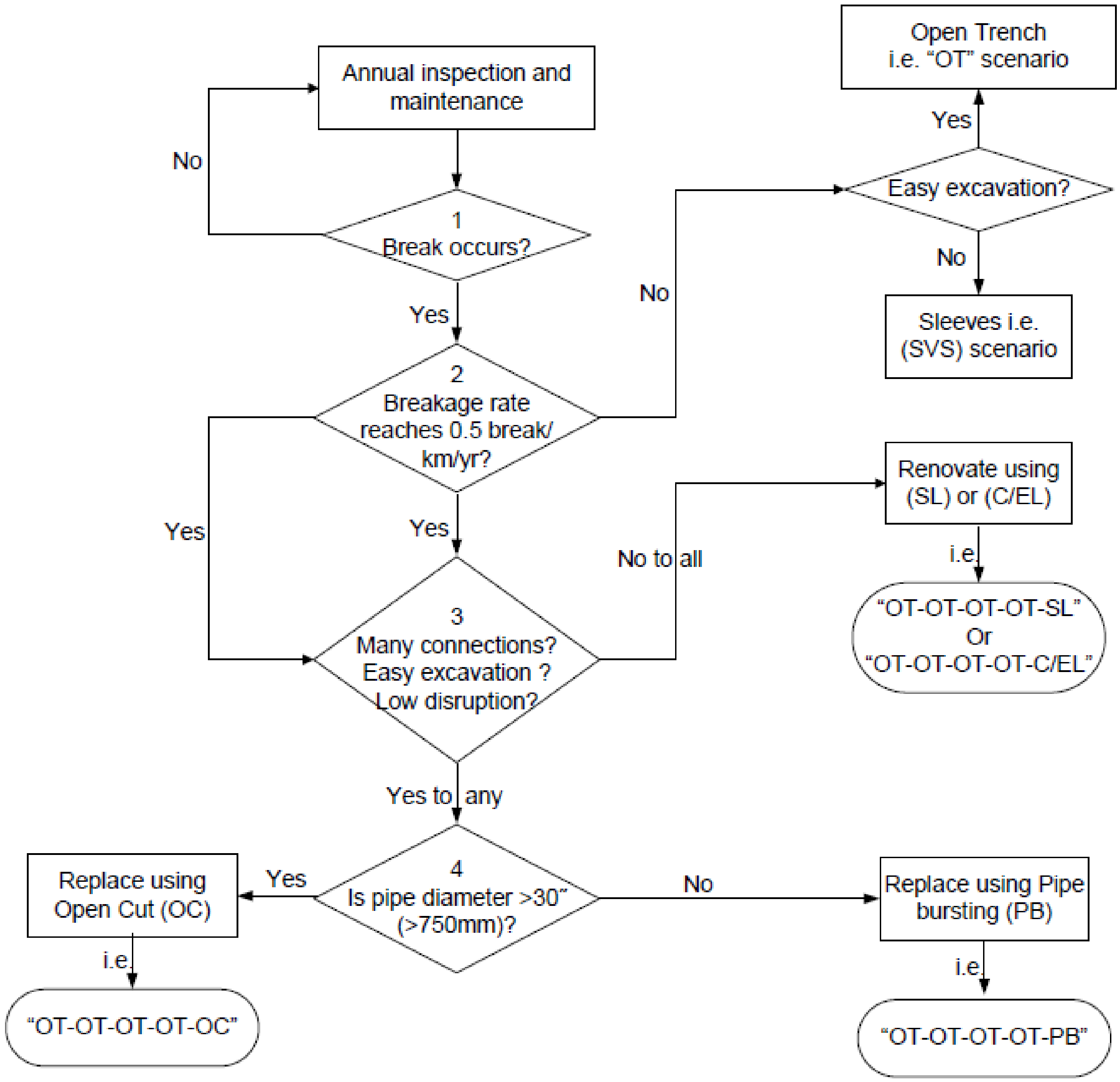


Figure II.13 DSS for selection of rehabilitation methods using simulation (Shahata and Zayed, 2008)

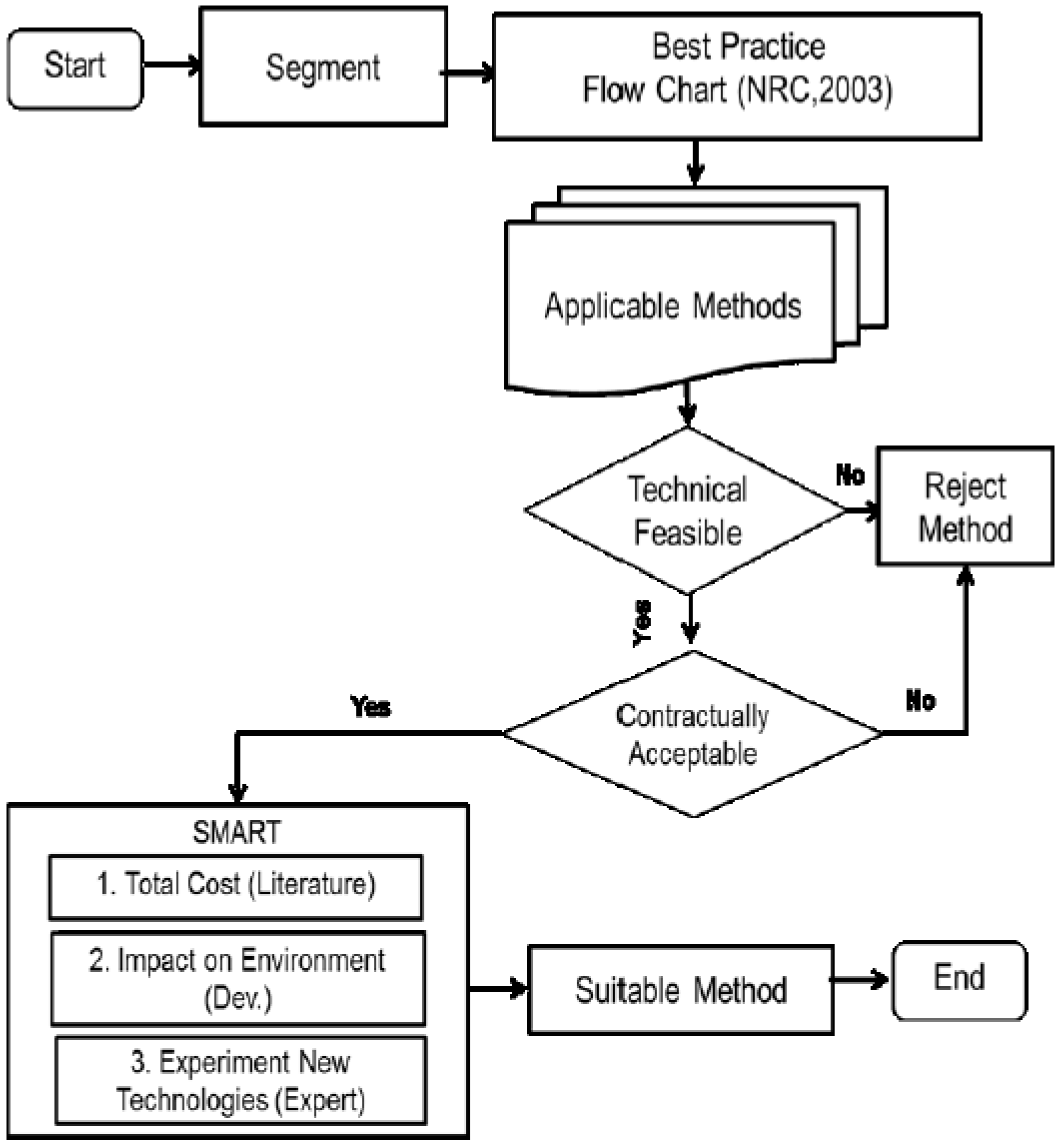


Figure II.14 DSS for selection of rehabilitation methods based on different factors (Salman, 2011)

II.9 BUDGET ALLOCATION MODELS

Brown et al. stated that one of the government authorities is to manage funds allocated under their supervision. Zayed (2004) believes that government agencies are responsible for making intelligent decisions and accordingly funding is allocated to ensure maximum benefits from the limited funds.

The dilemma herein is assessing the improvement or the benefit resulting from expending a specific amount of money. In order to achieve a higher improvement with a limited budget, a sufficient understanding of the inspected structure is needed besides the proper management of the funding. Thus, the complexity of any infrastructure asset is the main reason of facing difficulty in allocating budget to infrastructure accurately. Al-Battaineh (2007) proposed that the nearest solution to the optimum when allocating budget to the entire asset is the combination of elements solutions. A lot of research has been done using several methods to allocate budget for infrastructure, while, the main challenge was to obtain the most optimum solution.

Chen et al. (1996) developed a model for budget allocation using the steepest-ascent. Ariaratnam and Macleod (2002) developed a budget allocation model that uses linear programming to allocate budget for sewer network located in city of Edmonton, Canada. This model is called "Proactive Rehabilitative Infrastructure Sewer Management" (PRISM). Gabriel et al. (2006) presented a budget allocation model for infrastructure focusing on the network-level. They used Pareto with a weighting method to get the optimal points, to minimize the cost and maximize the total value of the projects within the limited fund. Moselhi et al. (2010) presented reliability-based model for allocating budget for water mains. The advantage of this model is considering the network level of service, sub-network reliability and, criticality for the budget allocation calculations. Mohamed and Zayed (2013) utilized an integrated AHP, MAUT and simulation methodology for budget allocation of water mains. The output of this methodology is a fund allocation (priority) index that guide decision makers to allocate budget effectively. An integrated dynamic programming and neural network, budget allocation model for bridges was developed by Razaqpur et al. (1996). Zayed (2004) proposed a budget allocation model for repaint of steel bridges, in Indiana, USA. This model utilized various techniques such as; dynamic programming (DP), Integer programming (IP) and greedy heuristics optimization (GH). Shahata (2013) developed a budget allocation model for infrastructure management using integer programming to solve a multi objective problem by transforming it into single objective by changing some objectives to constraints. The objective of this model was to maximize the risk reduced per dollar spent and the constraints were the budget and performance index. Lee et al. (2004) solved budget allocation problem for roads and streets by prioritizing Maintenance and Rehabilitation (M&R) alternatives based on the effect and the cost. The M&R plan was based on pavement rank, minimum Pavement Condition Index (PCI) and, construction constraints.

II.10 OPTIMIZATION ALGORITHMS

The optimal budget allocation plan for any infrastructure asset can be performed using optimization algorithms. According to Nunoo (2001), there are four optimization algorithms used in infrastructure management; linear, non- linear, integer and dynamic programming. Researchers recently developed a new techniques and algorithms that can be used in infrastructure management as well. Evolutionary programming techniques, such as Genetic Algorithms and Neural Networks techniques are the most popular recently developed techniques. The dilemma herein is to define the decision variables, objective function and the constraints of the problem to be solved, to be able to choose the suitable algorithm. A summary about these techniques is presented in Table II.6.

Optimization is mainly composed of an objective that needs to be maximized or minimized and this objective is subjected to various predefined constraints. Al-Tabtabai et al. (1999) stated that it is a complex process to define and evaluate all possible solutions, while taking constraints into consideration. Chandra (1991) argued that regular optimization algorithms such as linear programming, integer-linear programming and, goal programming is just suitable for small scale problems as these methods tend to simplify the problem to make it mathematically solvable. Once the size of problem is maximized the solution time increases as a result of having more decision variables.

Morcous et al. (2002) believe that evolutionary-based algorithms such as Genetic Algorithms and Neural Networks techniques have the ability to perform large scale problems. They are the most suitable when dealing with large set of variables. The main concept of (EA) is to simulate the metaphor of natural biological evolution and/or social behavior of different species using stochastic approach. Holl and (1975) developed the first evolutionary algorithm, which is Genetic Algorithms (GA). Darwinian concept that states 'survival of the fittest' and the natural process of evolution through reproduction are the main principles behind GA. GA has the ability to self-learn as it solves the problem by saving information from experience, once they are appropriately encoded. Al-Tabtabai et al. (1999) stated that GA can perform multi objective optimization problems with discrete variables and discontinuous functions.

Table II.6 Optimization algorithms types (Adapted from Shahata, 2013)

<table>
<tr><th>Optimization methods</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Linear Programming</td><td>• Objective function and constraints are formulated as linear equations.
• Decision variables are continuous.</td><td rowspan="3">• Cannot handle combinatorial problems.
• Cannot handle a large number of decision variables.</td></tr>
<tr><td>Non-Linear Programming</td><td>• Objective function and constraints are non-linear equations</td></tr>
<tr><td>Integer Programming</td><td>• Objective function and constraints are linear and / or non-linear equations.
• Decision variables are constrained to take integer value (0 or 1). Results in a decision matrix that is composed of a series of 0's and 1's</td></tr>
<tr><td>Dynamic Programming</td><td>• DP is a mathematical technique for making a sequence of interrelated decisions.
• No existing standard mathematical formulation.
• It provides a systematic procedure for determining the optimal combination of decisions.
• It provides a great computational savings over using exhaustive enumeration to find the best combination of decisions, especially for large problems.</td><td>• It requires formulating an appropriate recursive relationship for each individual problem.
• Difficulty in maintaining identity of individual assets segment.</td></tr>
<tr><td>Genetic Algorithm</td><td>• Based on natural selection and natural genetics.
• GA usually starts from a population of randomly generated individuals. In each generation, multiple individuals are selected from the current population (based on their fitness) and modified (recombined and possibly randomly mutated) to form a new population to evolve towards a better solution.
• Capable of solving combinatorial problems.
• Can handle a large number of decision variables,</td><td rowspan="2">• Does not generate a true optimal solution</td></tr>
<tr><td>Heuristic Method</td><td>• Used in place of true integer programming because of the limitation on the size of the problems that can be handled with true integer programming.
• Approximation to true optimization technique.</td></tr>
</table>

II.10.1 GENETIC ALGORITHM

Genetic Algorithms (GA) is one of the most powerful optimization techniques as it can deal with a large set of data and reach to a very close solution to optimum solution. Chan et al. (1994) developed a maintenance planning model for roads using GA. Liu et al. (1997) solved the problem of rehabilitation of bridge deck while minimizing the cost and the deterioration using multi objective GA. Hegazy (1999) presented a GA model for the construction project constraints. He considered the cost as an objective function while the time is a constraint. Hsieh et al. (2004) used GA to build an optimization model for investment considering the investment utility as an objective to be maximized and time-logic and resource as constraints. AL-Battaineh et al. (2005) proposed a budget allocation model using GA. The objective function of this model was to maximize the performance index, while the limited budget was the constraint. Budget allocation for historical buildings in Tainan City was performed by GA model developed by Perng et al. (2007). Farran and Zayed (2012) presented a budget allocation model for public infrastructure based on an integrated Dynamic Markov chain and GA methodology.

II.10.1.1 Genetic Algorithms Operation

This process is similar to the population in humans as a spectrum of genes; coming from chromosomes; represent the solutions. GA works by setting a fitness value for each solution based on how close it is to the optimum. Based on Darwin theory, cross over and mutation should take place between different low fitted solutions to produce a solution with higher fitness value. Cross over is simply transferring the available genes from parents to children through chromosomes, while mutation is producing a new genes that do not exist in the parents and transfer it to children. The GA iteration is represented in Figure II.15.

II.10.1.2 Chromosome Encoding

The encoding is the complex process of generating the required information to build the solution. Thus, the encoding is mainly based on the structure of the problem itself. Finally, the chromosomes encoding can be binary, permutation, value or tree.

II.10.1.3 Fitness evaluation

According to Beasley et al. (1993), the reason for formulating the fitness function through the GA process is to find a proper presenting method for the chromosomes. The fitness function is a processor that takes chromosomes as inputs; to evaluate its' ability to achieve the objectives of the optimization. The outputs of this function is a fitness value for the inputted chromosome. The higher fitness value, the more fit the chromosome is. The optimum solution is not predefined to the optimization problem. Thus, assessing fitness operation is an iterative process, which starts with a specific chromosome and as long as the operation continues, each chromosome fitness value is compared by the last one assessed until reaching to the optimal.

II.10.1.4 Genetic Algorithms Operators

Parents' selection for the next generation through GA is performed by operators' selection within the current population. The selected operator has the ability to find the good spectrum within the population and adapt it using cross over and mutation in order to reach for better results. Chong et al. (2004) stated that "the roulette-wheel selection, tournament scheme, stochastic remainder selection are examples of selection schemes that can be utilized. According to Morcous et al. (2005), the Roulette-wheel is the most widely used selection method, which calculates the probability of selection of any chromosome based on its fitness function. Thus, the probability of selection of specific chromosome as a parent for the next generation is calculated as the fitness function of that chromosome divided by the cumulative fitness of the population used now.

Cross over and mutations are the two main operators for the evolutionary genetic algorithm. The procedure of the crossover operator is composed of three steps. The reproduction step, at which the mating between two randomly selected chromosomes, is happening. The second step is selecting a random a cross site within the length of the chromosome. Finally, the values at the selected site is exchanged between the two chromosomes. There are different forms of crossover such as one point cross over and two point cross over.

On the other hand, Mutation operator is controlling the diversity of the chromosomes' genes as it changes the genes continuously using a specific probability which aids keeping the algorithm working to reach for better solutions and not being trapped within a specific optimal solution. The mutation rates values can be considered as 1/L, while L is the length of the chromosome.

A stopping criterion should be defined to stop the process of the operators. The optimal solution is obtained after various generations. The output report presents the number of generations, maximum improvement to the objective and the computation time used to reach to the optimal solution.

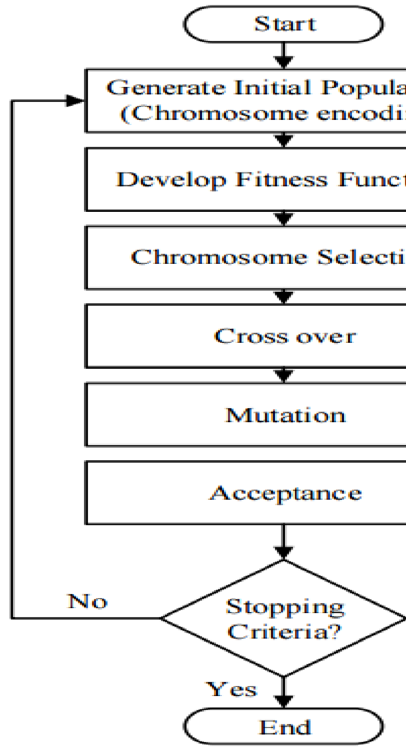


Figure II.15 GA flow chart (Abouhamad, 2015)

II.10.2 Greedy Heuristic

Greedy Heuristic is another powerful optimization tool which can be used for solving budget allocation problems. It was proposed by Chen et al. (1997) to reach to the optimal budget allocation plan. Bayesian concept is the main concept behind greedy heuristic. It uses various pre-defined steps to get the optimal solution or a solution close to the optimum. These steps can be summarized as follows; defining the objective that needs to be maximized or minimized, obtaining the relation between the objective and the inputs (cost, in case of budget allocation model) and finally ranking the elements for budget allocation according to the recently defined relation. The GH main advantages other than different algorithms are its simplicity and the ability to integrate between algorithms nature and human interaction. Otherwise, most of other techniques are black boxed.

Caprara and Fischetti (1997) applied greedy heuristic for building an algorithm for railway crew management, in order to reach to suitable crew restoring. Chen and Lin (2000) presented a budget allocation model using ordinal optimization. They applied simulation for budget allocation model to enhance the output of ordinal optimization. Gotlieb et al. (2003) solved car sequencing problem using, an iterative greedy heuristic model, which proved its efficiency through solving the problem. Zayed (2004) developed a budget allocation model for repainting of steel bridges. He utilized Greedy heuristic and defined it as Morin (1999) and Winston (1994). The definition started by calculating the benefits of repainting of each bridge, then getting the benefit-Cost ratio, and finally ranking the bridges in an ascending order according to B/C ratio. He applied his model on 88 bridges from Indiana department of transportation. The model used also GA and dynamic programming. The GH results were very sufficient and close to the other algorithms, proving that however, GH is a simple technique, it is as powerful as other complicated algorithms.

II.11 LIMITATIONS OF PREVIOUS RESEARCH WORKS

Water distribution systems as any other infrastructure deteriorate with time based on several factors. The deterioration of such important assets is very critical as it has a significant effect on the environment and health of the users. Therefore, the condition and performance assessment of the infrastructure assets is of a great importance to the environment, health and cost management. The previously developed assessment models had various limitations as mentioned earlier in this chapter. Firstly, almost all the previous models did not consider the effect of deterioration of the accessories on the performance of water distribution systems except. Also, most of these models are based on just one factor to assess deterioration which is the breakage rate, neglecting the effect of other factors. Even if the physical and operational factors were considered, the quality of service factors was always ignored. There are many factors that affect the water distribution system and if we are going to consider precautions and preventive actions, then we should consider more factors. There is also a high uncertainty in the outputs of previous models due to many reasons such as lack of historical data and various assumptions. Therefore, using fuzzy logic, Pseudo criteria and integrated methodology between the American and European schools of MCDA, helps in overcoming the limitations of both schools and increases the certainty within the outputs. Although some researchers studied the assessment of the segment and the network levels, there is a real need for an extensive and a more detailed study in this area. Linking between condition/performance indices and the rehabilitation strategies or priority for rehabilitation and the budget allocation issue were not considered in the previous models as well. The research which investigates and assesses in depth the various network levels from pipes and accessories, segments, sub-networks to the entire network level, and also considers linking these levels assessment to budget allocation, rehabilitation and scheduling plans would be of a great importance.

CHAPTER III

RESEARCH METHODOLOGY

III.1 INTRODUCTION

As shown in Figures III.1 and III.2, the research methodology is composed of the following steps: Literature review, model development and model implementation. The literature review is already dealt with in Chapter II. The model development part proposes two models: The water networks performance assessment model and the performance-based budget allocation model. The performance assessment model covers indicators identification, data collection, FANP-based weights for the identified indicators, PROMETHEE and MAUT-based performance index for water distribution networks components, probability-of-failure-based performance assessment of water distribution networks segments and connectivity-based performance assessment of sub-networks. The performance-based budget allocation model covers performance-based rehabilitation and maintenance plans, Weibull-distribution-based deterioration curves and genetic algorithms and greedy heuristics-based budget allocation plans. Finally, the model implementation chapter covers the implementation of the developed model over the case studies from the city of Montreal and city of Moncton.

III.2 LITERATURE REVIEW

The literature review, discussed in Chapter II, covers topics of the components of water distribution systems, models of condition assessment of water distribution systems and the major techniques to develop this model, the available rehabilitation and maintenance strategies and various budget allocation models.

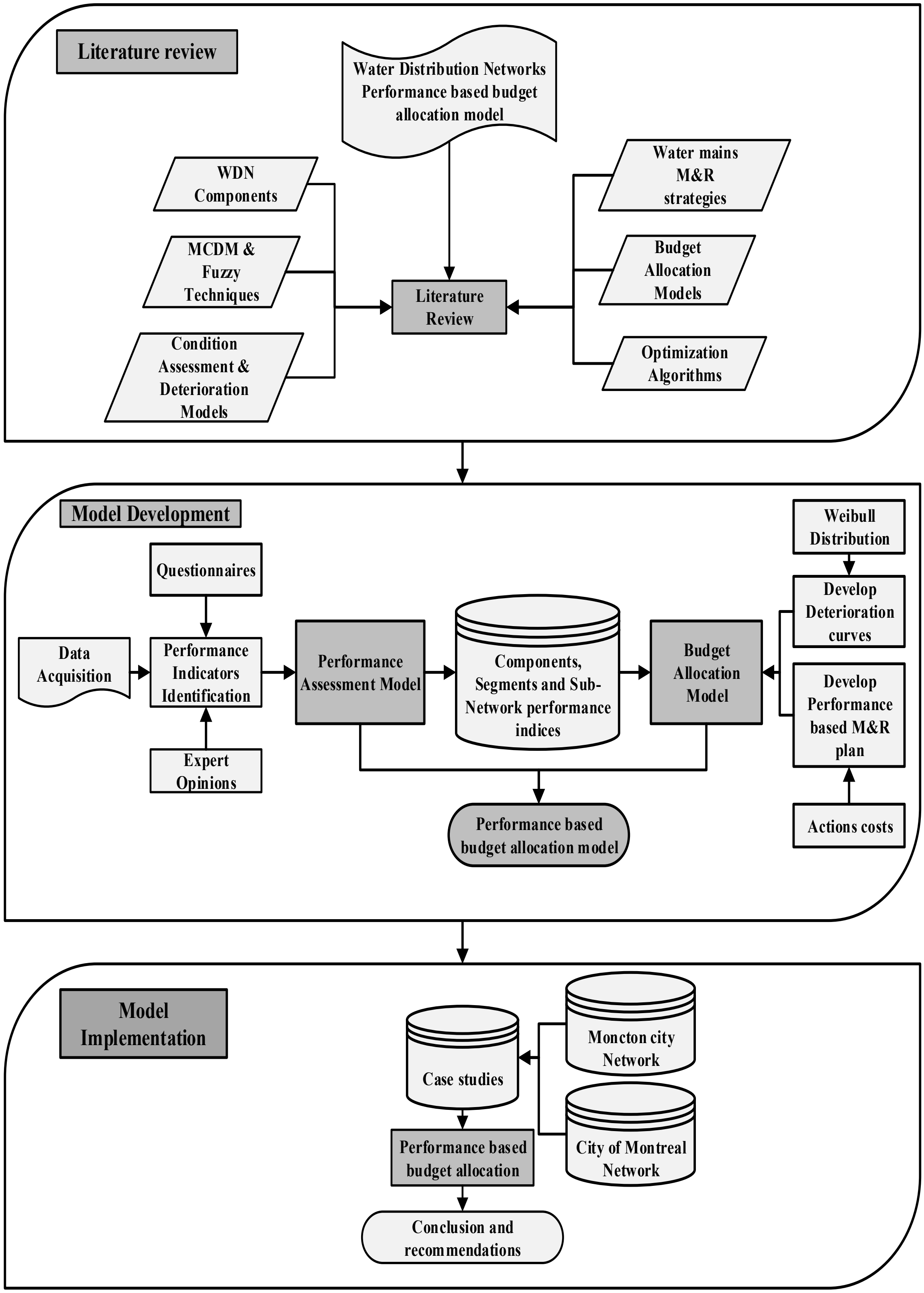
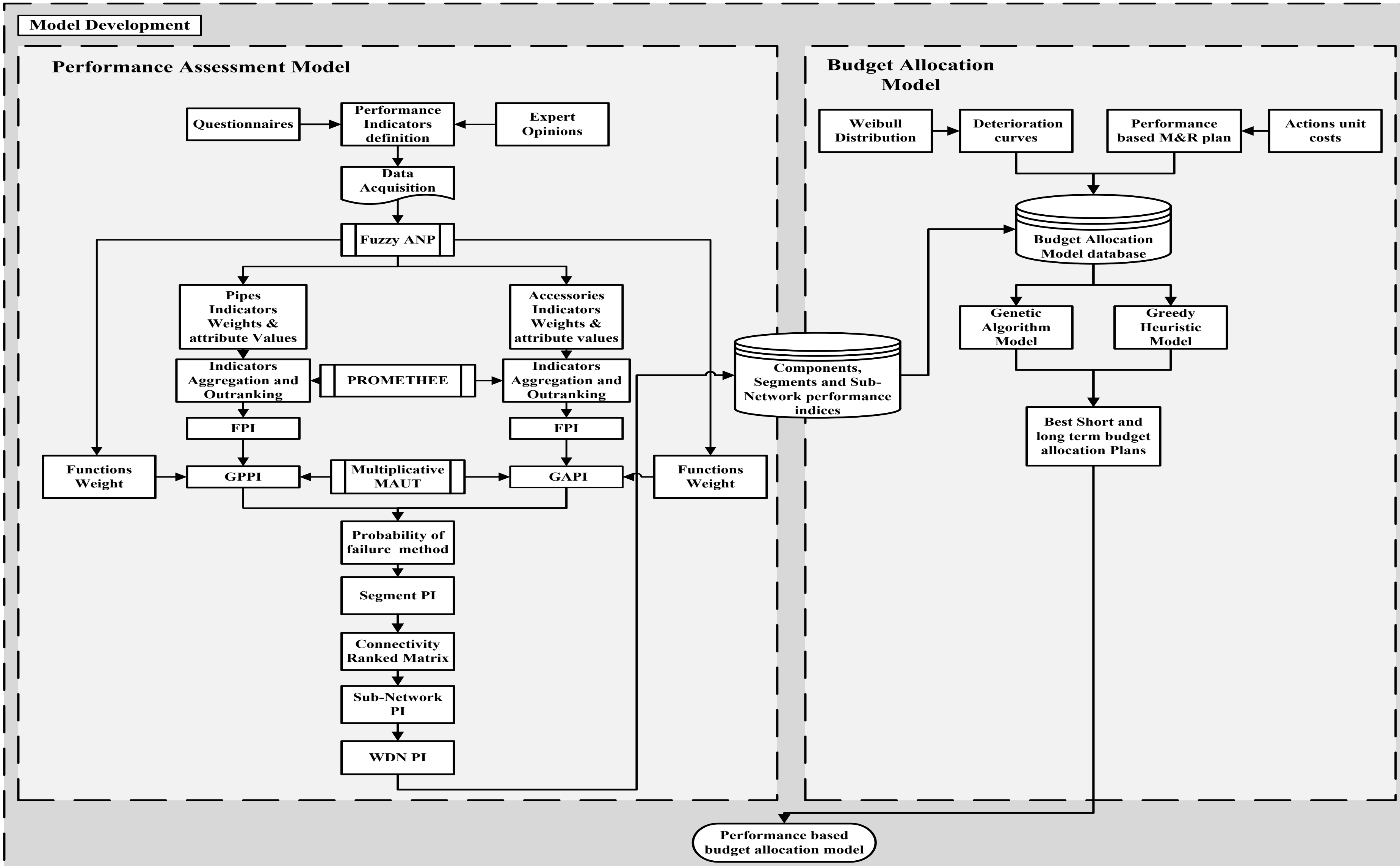


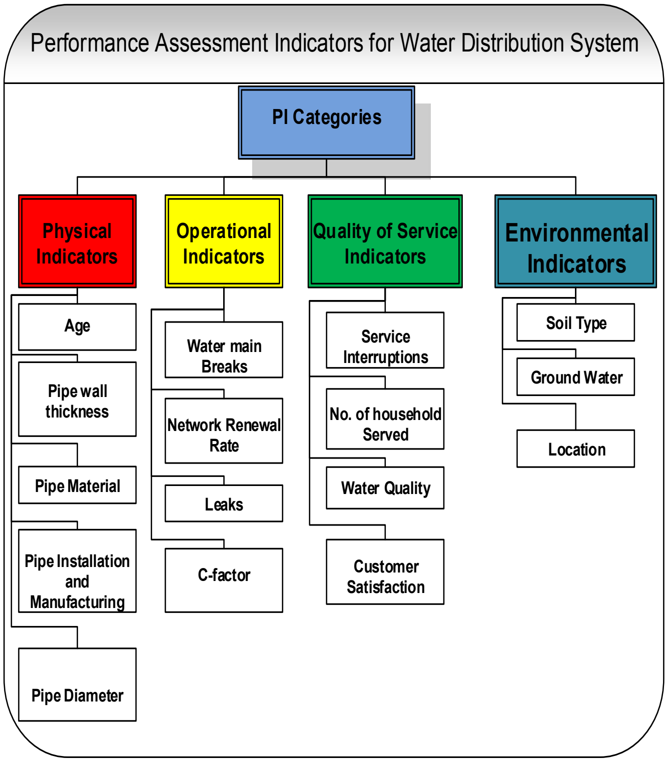
Figure III.1 Research Methodology chart

Figure III.2 Research models description



III.3 FACTORS IDENTIFICATION

Section II illustrates the different factors that contribute to the deterioration of the water distribution systems components, to assess the condition of these systems. The model is developed based on the factors chosen from the National Guide to Sustainable Municipal Infrastructure in their best practices (2003b) and the performance indicators system of the International Water Association (IWA). Expertise opinions are also included in the indicators' identification process through several meetings. Figure III.3 and Figure III.4 summarize the identified indicators that contribute to the performance of the pipes and accessories. These indicators are categorized into four main categories: Physical, operational, quality of service and environmental. The physical category includes the sub-indicators of age, diameter, thickness, material and installation quality. The operational category is composed of the sub-indicators of breakage rate, leakage rate, c-factor and the network renewal rate. The quality of service category includes four sub-indicators: the customer satisfaction, service interruptions, water quality and number of households served. Finally, the environmental category covers the sub-indicators of groundwater, soil type and location. The main differences between the indicators that contribute to the performance of the pipes and accessories are the sub-indicators of the diameter and the pipe thickness. The sub-indicators' descriptions and definitions are presented in Table III.1 and Table III.2 respectively.



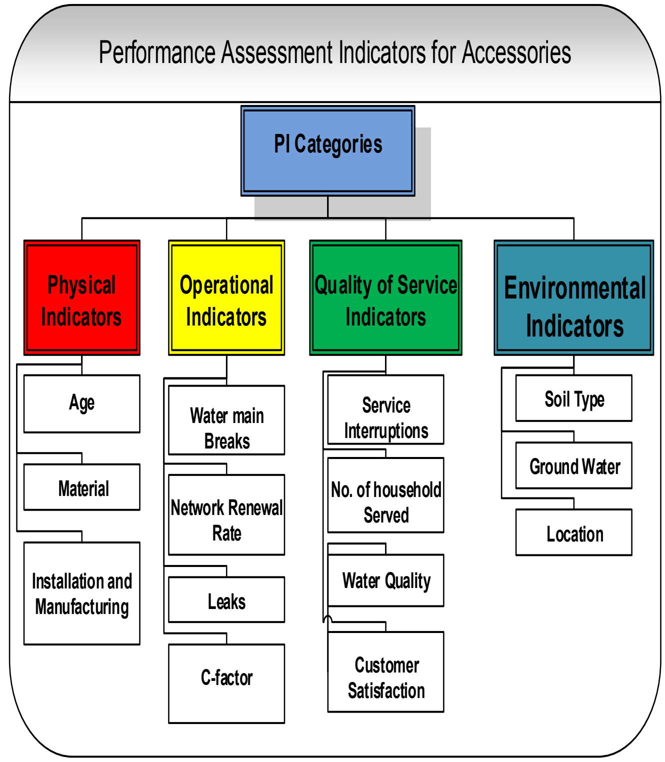


Figure III.3 Performance assessment indicators for water mains

Figure III.4 Performance assessment indicators for accessories

Table III.1 Performance indicators categories and description

Category	Category Identifier	Description
Physical	Ph.	This includes the indicators related to the engineering side of the network and its construction.
Operational	Op.	This includes the indicators of the operational performance of the network
Quality of Service	QS.	This includes the indicators of the quality of drinking water and if it meets specific standards and to what extent does it satisfy customer needs.
Environmental	ENV.	This includes the indicators related to the location of the proposed network and the nature of the site like the soil type and G.W.T.

Table III.2 Performance indicators definitions

Category Identifier	Performance Indicator	Performance measure	Definition
Ph.1	Age	Years	Pipe becomes more deteriorated over time.
Ph.2	Pipe wall thickness (Including Pipe lining and coatings)	The thickness of the water main (mm)	Corrosion penetrates thinner walled pipes quickly. The larger the thickness, the more it resists the penetration of corrosion.
Ph.3	Pipe Material		Each material has different characteristics and different resistance.
Ph.4	Pipe Diameter	The diameter of the pipe (in.)	The smaller diameter the pipe is, the more it is subjected to deterioration. The longer the pipe, the more it is subjected to higher deterioration rates
Ph.5	Pipe installation and manufacturing	Qualitative measure, ex; poor, good, very good	Poor installation practices or defects in pipes during manufacturing can make pipes more vulnerable to failure.
Op.1	Water main breaks	Water main breaks/Km/year	The total number of breaks in mains for the reporting period excluding those that are considered above the ground mains which can be fixed without shutting down the system.
Op.2	Network renewal rate	% of renovation/year	Percentage of the renewed to the total network/ year
Op.3	Leaks	-Leaks per Km. of water main/year -Real water losses per connection per day. -Real water losses per km. per day.	An unplanned event in which water is lost; it happens because of the failure of a pipe, hydrant, valve or joint material and it may cause substantial damage or harm to customers, water quality, flow rate, property or the environment.

Op.4	Internal water pressure	Flow rate. (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.
QS.1	Service interruptions	Water supply interruptions per 100 km. of water main.	-Any event causing a total loss of water supply -Unplanned interruption that is caused by a fault in the water system. -Planned interruption at which the customer receives a notification prior to it. -Leaks are not considered interruptions unless it is needed to shut down all the system for repair.
QS.2	No. of household served.	No. of households per Km.	The total number of households served by this network.
QS.3	Customer satisfaction.	No. of complaints per year.	-No. of complaints received and the response rate to it. -Billing cost compared to no. of complaints.
QS.4	Water Quality	Qualitative measure: poor quality, good, very good	
ENV.1	Soil type	% of Corrosiveness and Presence of hydrocarbons and Solvents	Some soil types are more corrosive than others and some types change in volume when they become subjective to water which will increase the load over the network mains.
ENV.2	Groundwater	The depth of the water (m).	The more the water depth increases the more the probability of corrosion and the soil resistivity increase.
ENV.3	Location	Industrial, Commercial, residential, etc.	The water mains in residential areas are exposed to different conditions than those which are located in industrial areas. For example, water mains under roads are subjected to dynamic load due to the heavy traffic.

III.4 FANP-BASED PERFORMANCE INDEX FOR COMPONENTS

FANP is used here to calculate the weights of importance of the sub-indictors that affect the performance of the pipes and accessories. There are four steps to apply FANP. The first step is to identify the indicators that affect the performance of the water network components. The second is to categorize the sub-indicators into the indicators' categories as shown earlier. The questionnaire-based data collection is the third. Finally, fuzzification scale is applied to accommodate the uncertainties within the data collected.

The output of the previous steps is three matrices, namely, the Lower, the Most Probably and the Upper matrices. Finally, one combined matrix is formed based on the mentioned three matrices. Each element within this matrix represents a fuzzy triangular distribution.

FANP calculations are done here using an Excel-Matlab® interface adapted from El Chanati (2014). Two developed codes are used. The main input for the first code is the three matrices while the output is FAHP relative weights of importance for the sub-indicators. The FAHP weights are used to formulate the unweighted supermatrix. Then, the unweighted supermatrix is normalized to get the weighted supermatrix. Afterward, the weighted supermatrix is used as an input in Matlab® second code, in order to raise it to a large number of powers reaching to the limited matrix. FANP relative weights are introduced in the first column of the limited matrix. The relative weights are defined as the importance of each sub-indicator relative to the other sub-indicator.

III.5 LOCAL FUNCTIONAL AND GLOBAL INDICES (PROMETHEE)

The proposed model utilizes the widely used MCDM technique known as PROMETHEE in the outranking and aggregation. This technique outranks any specific pipe or accessory; however, as the main disadvantage, this outranking is not on an ordinal scale, or a fixed one based on fixed numbers but it is just a rank. Therefore, to overcome this disadvantage, upper and lower datum; representing the extreme cases for any pipe or accessory, either in an excellent or a failing condition; are developed. The datum can be best defined as follows:

$$v_i[c_i(C_0)] = 0 \quad \text{[III.1]}$$

$$v_i[c_i(C_m)] = 10 \quad \text{[III.2]}$$

Where;

C_0=Lower Datum Pipe or Accessory= component (pipe or accessory),

C_m=Upper Datum Pipe or Accessory = Excellent component (pipe or accessory),

Therefore, the outranking for any pipe or accessory can be within the newly defined fictitious extreme cases. These boundaries are not physically real but they just appear in the calculations.

III.5.1 Pseudo-Criteria Evaluation

One of the main advantages of PROMETHEE is its ability to incorporate pseudo criteria within its calculations. It therefore considers the uncertainties and imprecision within the model. PROMETHEE is mainly based on two boundaries defined as indifference threshold and preference threshold for each sub-indicator. Thus, by defining the lower datum= 0 that represents any component in a bad condition and the upper datum = 1 that represents any component in an excellent condition, the two thresholds are transformed into two physical limits as follows:

1) Tolerance threshold: The performance index, for which the component above is considered in a safe or tolerable state. Within this model, the tolerance threshold is considered to be equal to 8 based on the performance index scale.
2) Critical threshold: The performance index, for which the component below is considered in a critical state. Within WNPBA model, the critical threshold is considered to be equal to 3.

In order to represent the thresholds compared to both the lower and upper defined limits, the generalized preference function (GPF) is used. The GPF trade-off points are the tolerance and critical thresholds as presented in Figure III.5.

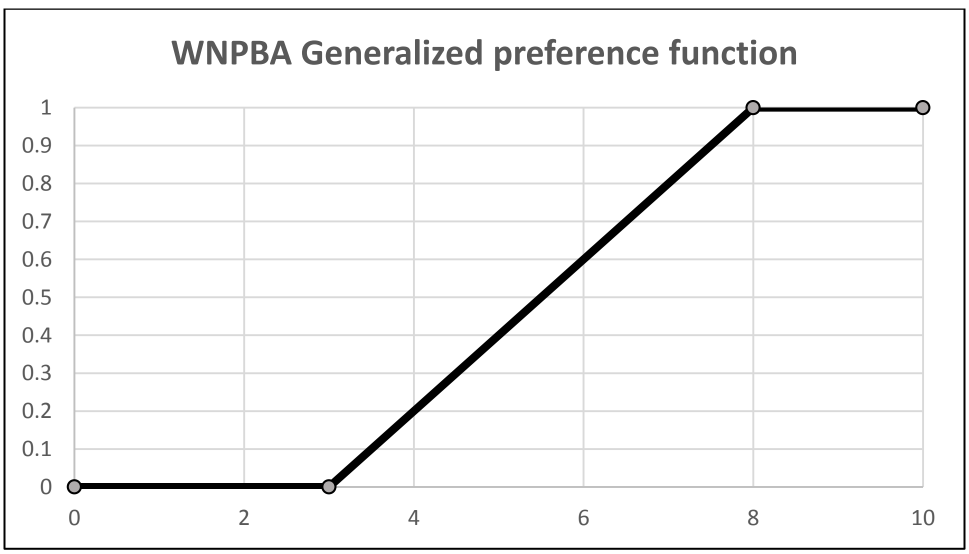


Figure III.5 WNPBA generalized preference function

When the preference = 0, the component performance index equals to or is lower than the critical threshold. While when the preference = 1, the component performance index is greater than the tolerance threshold.

If the performance is higher than the critical threshold and lower than the tolerance threshold, the preference should be calculated using the following equation:

$$\boldsymbol{P_{C_n}} = (\boldsymbol{v_n}[\boldsymbol{c_n}] - \mathbf{CT}) / (\mathbf{TT} - \mathbf{CT}) \qquad [III.3]$$

Where;

$P_{C_n} =$ The preference of the component, $v_n[c_n] =$ the performance index of the component, CT= Critical threshold, TT= Tolerance threshold.

III.5.2 Multi-criteria Aggregation

Multi-criteria aggregation can be done based on equations III.1 and III.2 while the outranking for any specific pipe or accessory is within the newly defined datum as follows:

$$P_i(C_0, C_0) = v_i[c_i(C_0)] - v_i[c_i(C_0)] = 0 \qquad [\text{III}.4]$$

$$P_i(C_0, C_n) = v_i[c_i(C_0)] - v_i[c_i(C_n)] = -ve < 0 \qquad [\text{III}.5]$$

$$P_i(C_0, C_m) = v_i[c_i(C_0)] - v_i[c_i(C_m)] = -10 < 0 \qquad [\text{III}.6]$$

$$P_i(C_n, C_0) = v_i[c_i(C_n)] - v_i[c_i(C_0)] = v_i[c_i(P_n)] \qquad [\text{III}.7]$$

$$P_i(C_n, C_n) = v_i[c_i(C_n)] - v_i[c_i(C_n)] = 0 \qquad [\text{III}.8]$$

$$P_i(C_n, C_m) = v_i[c_i(C_n)] - v_i[c_i(C_m)] = -ve < 0 \qquad [\text{III}.9]$$

$$P_i(C_m, C_0) = v_i[c_i(C_m)] - v_i[c_i(C_0)] = 10 \quad P_i(C_m, C_0) = 1 \qquad [\text{III}.10]$$

$$P_i(C_m, C_n) = v_i[c_i(C_m)] - v_i[c_i(C_n)] = +ve \quad [\text{III}.11]$$

$$P_i(C_m, C_m) = v_i[c_i(C_m)] - v_i[c_i(C_0)] = 0 \quad [\text{III}.12]$$

Where;

$i = 1,$

$C_n = the\ component\ to\ be\ assessed$

C_m & C_0 = the upper and lower limits.

III.5.3 Preference Index

The Multiple Attribute Preference Index of any two components is defined as the weighted average of the preference functions of any component (C_1) to (C_2) as shown in equation [III. 13].

$$\pi[C_1, C_2] = \sum_{i=1}^{n} W_{ci} * P_i(C_1, C_2) \quad [\text{III}.13]$$

Where; 0≤ $\pi[C_1, C_2]$≤1 and i=1 to (n) is the total number of sub-indicators within each indicators category.

Therefore, for each component compared to the defined limits C_m, C_0, the following preference functional indices are generated as follows:

$$\pi[C_0, C_0] = \sum_{i=1}^{n} W_{ci} * P_i(C_0, C_0) \quad [\text{III}.14]$$

$$\pi[C_0, C_n] = \sum_{i=1}^{n} W_{ci} * P_i(C_0, C_n) \quad [\text{III}.15]$$

$$\pi[C_0, C_m] = \sum_{i=1}^{n} W_{ci} * P_i(C_0, C_m) \quad [\text{III}.16]$$

$$\pi[C_n, C_0] = \sum_{i=1}^{n} W_{ci} * P_i(C_n, C_0) \quad [\text{III}.17]$$

$$\pi[C_n, C_n] = \sum_{i=1}^{n} W_{ci} * P_i(C_n, C_n) \quad [\text{III}.18]$$

$$\pi[C_n, C_m] = \sum_{i=1}^{n} W_{ci} * P_i(C_n, C_m) \quad [\text{III}.19]$$

$$\pi[C_m, C_0] = \sum_{i=1}^{n} W_{ci} * P_i(C_m, C_0) = 1 \quad [III.20]$$

$$\pi[C_m, C_n] = \sum_{i=1}^{n} W_{ci} * P_i(C_m, C_n) \quad [III.21]$$

$$\pi[C_m, C_m] = \sum_{i=1}^{n} W_{ci} * P_i(C_m, C_m) \quad [III.22]$$

Where:

$W_{ci} = the\ weight\ of\ the\ defined\ indicators\ within\ specific\ category.$

$i = 1, n = the\ total\ number\ of\ the\ indicators\ within\ one\ indicator\ category$

III.5.4 Pipes and Accessories outranking

The entering flow, leaving flow and net flow are the main evaluation parameters for the outranking. The measure of strength of C_n is calculated as follows:

$$\phi^{+}(C_n) = \pi[C_n, C_0] + \pi[C_n, C_n] + \pi[C_n, C_m] \quad [III.23]$$

$$\phi^{+}(C_n) = \pi[C_n, C_0] \quad [III.24]$$

$$\phi^{+}(C_n) = \sum_{i=1}^{n} W_{ci} * P_i(C_n, C_0) \quad [III.25]$$

The measure of weakness of C_n is calculated as follows:

$$\phi^{-}(C_n) = \pi[C_0, C_n] + \pi[C_n, C_n] + \pi[C_m, C_n] \quad [III.26]$$

$$\phi^{-}(C_n) = \pi[C_m, C_n] \quad [III.27]$$

$$\phi^{-}(C_n) = \sum_{i=1}^{n} W_{ci} * P_i(C_m, C_n) \quad [III.28]$$

The net flow is calculated as follows:

$$\phi^{net}(C_n) = \phi^{+}(C_n) - \phi^{-}(C_n) \quad [III.29]$$

$$\phi^{net}(C_n) = \sum_{i=1}^{n} W_{ci} * P_i(C_n, C_0) - \sum_{i=1}^{n} W_{ci} * P_i(C_m, C_n) \quad [III.30]$$

The net flows for C_0, C_m are:

$$\phi^{net}(C_0) = -1 \quad [III.31]$$

$$\phi^{net}(C_m) = 1 \quad [III.32]$$

Finally, the output of the outranking of any pipe or accessory net flow should be a fixed value between the lower and upper limits [-1, 1].

$$\phi^{net}(C_0) < \phi^{net}(C_n) < \phi^{net}(C_m) \quad [III.33]$$

III.6 COMPONENTS PERFORMANCE INDICES

III.6.1 Pipes and Accessories Functional Performance Index

The net flows are used to compute the functional performance index as it can be transformed from a scale [-1, 1] to a functional index scale within the range [0, 10], using a simple conversion equation in a form of straight line as shown in Figure III.6.

$$Copmonent\ Functional\ Performance\ Index$$
$$(CFPI) = [5 \times \phi^{net}(C_n)] + 5 \quad [III.34]$$

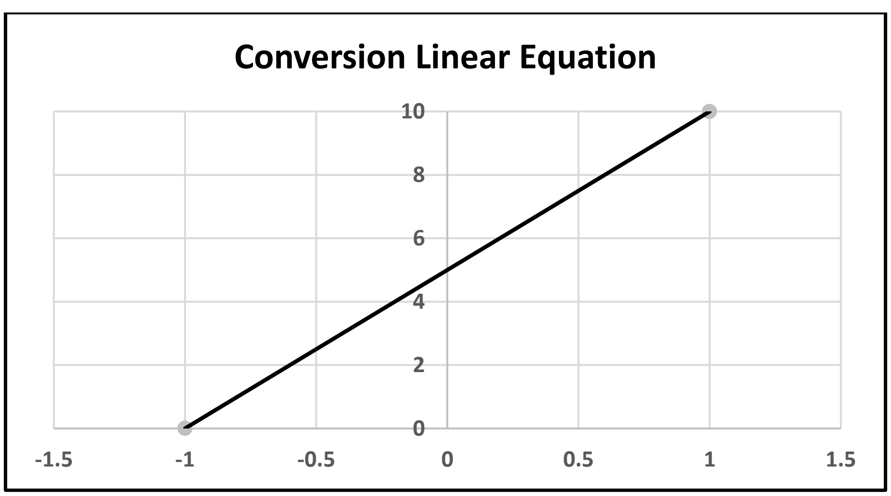


Figure III.6 Conversion straight line for any component FPI

III.6.2 Pipes and Accessories Global Performance Index

The Multi-Attribute Utility Theory is used to transform the functional performance indices into global performance indices. The functional indices can be considered as attributes and by finding the relation between these attributes, a global attribute is generated. The next step is to find the most suitable relation that reflects the real contribution of each functional index on the global index of the component. MAUT has two popular forms, i.e. the additive and the multiplicative. The multiplicative form is utilized in the calculations as it takes the functional relative weights into account. The global condition index can be calculated as follows:

$$GPI = \sum_{i=1}^{i=n} CFPI \times W_{f_i} \qquad [III.35]$$

Where:

$i = Number\ of\ the\ local\ functions\ (indicators\ categories)$

$W_{f_i} = Global\ weight\ of\ each\ function$

Finally, having the functional performance indices (FPI) and the global performance indices (GPI) facilitates the process of budget allocation and thus, can make the worldwide water municipalities develop more rehabilitation and maintenance strategies based on FPI and GPI.

III.7 GLOBAL PERFORMANCE INDICES SCALE

Developed by literature review and supported by water services, WNPBA model presents a global performance indices scale with a numeric description, linguistic description, proposed actions and criteria of each class as shown in Table III.3. For instance, if the component is assessed as Good (B) with a PI within the range from 6 to 8, then the description is that the remaining wall thickness is from 70% to 85% of the original and there are few signs of corrosion; otherwise, the cathodic protection is still good and coatings are intact. Therefore, a reassessment in 8 years and physical inspection in 5 years are proposed. Thus, municipalities can consider both the functional and global analysis of the network components. Furthermore, they can conduct a root-cause analysis to reach the main reasons behind low global index for any component.

Table III.3 Performance index scale with description and proposed actions.

CI (Numeric Scale)	Linguistic & Grading Scale	Criteria Description	Proposed Action
8 < PI ≤ 10	**Excellent (A)**	Newly or recently installed, no signs of corrosion or deterioration, BR ≤0.05, Cathodic protection is very good and coatings are well stabled in place.	Very Long Term: Reassess in 10 years, Annual Review and Physical within 8-10 years.
6 < PI ≤ 8	**Good (B)**	Remaining wall thickness= 70-85% of the original, few signs of corrosion, cathodic protection is good and coatings still stable.	Long Term: Reassess in 8 years, Annual Review and Physical within 5-7 years.
4 < PI ≤ 6	**Medium (C)**	Some damage to coatings and linings, remaining wall thickness =60-70% of the original, average signs of corrosion, cathodic protection is adequate and coatings still intact.	Medium Term: Reassess in 5 years. Annual Review. Schedule for CP and recoating within 2 years.
3 < PI ≤ 4	**Poor (D)**	Significant signs of corrosion with linings or coatings partially damaged, the remaining wall thickness is 40% to 60% and cathodic protection is inadequate.	Short Term: Reassess in 2 years, Semi-Annual Review and schedule for minor rehabilitation, CP and recoating within the next year.
0 ≤ PI ≤ 3	**Critical (E)**	Severe corrosion, coatings almost damaged and the remaining wall thickness is less than 40% of original, BR>3 and cathodic protection is poor.	Schedule for Immediate Physical Intervention (Rehabilitation or replacement).

III.8 NETWORK PERFORMANCE INDEX

In order to calculate the performance index of the water sub-networks and the water networks, its components and how they are linked together have to be studied. As mentioned earlier, each water network consists of connected pipelines and accessories, to formulate segments. At the same time, the segments are connected in series or in parallel, to formulate sub-networks or networks. Therefore, the performance indices of the pipes and accessories provide the performance indices for the segments and consequently obtain the performance indices of the sub-networks and the entire network.

III.8.1 Pipes and Accessories Combination (Probability of Failure Method)

Probability of failure method is developed to integrate the pipes and accessories. It is mainly based on the probability theory as shown in figure III.7. WNPBA uses a double scale between the probability of failure and the global performance indices as shown in Figure III.8, to obtain the probability of failure of pipes and accessories. The component with performance index (10) represents the component with zero probability of failure while the component with performance index (0) represents probability of failure equals to (1). The probabilities of segment failure and segment success and the probability of at least one component failure within the segment are achieved using the probability theory equations as follows:

- $P_{\text{all success}} = \prod_1^n C_n$ [III. 36]

  Where;

- C_n = Probability of success of any component within the segment.
- n = number of components.

- $P_{all\ success}$ = probability of all components succeeding at the same time.
- $P_{ALO} = 1 - P_{all\ success}$ [III.37]

Where;

- $P_{ALLO.}$ = Probability of at least one component failure.

The following step is calculating the contribution of each component within the segment to the probability of at least one component fail using equation [III.38].

- $C_n = \frac{F_n}{P_{ALO}}$ [III.38]

Where;

- F_n = probability of failure of component n
- C_n = Contribution of component n

Finally, by applying the normalization means as shown in equation [III.39], the contribution of each component to the segment failure is achieved. This is considered as an integration ratio between pipes and accessories performance indices reaching to the segment performance index.

- $CF_n = C_n / \sum C_n$ [III.39]

Where CF_n is utilized as a weight to compare and measure the impact of each component on the total failure and criticality of the segment.

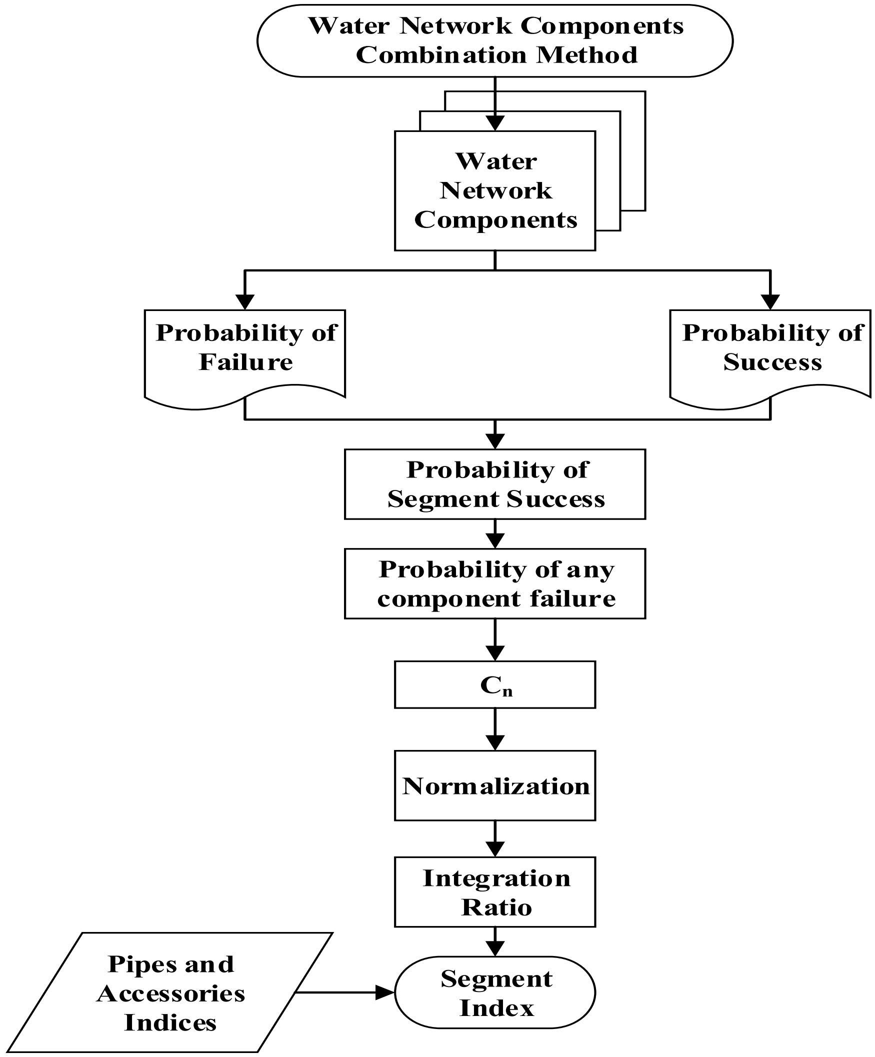


Figure III.7 Probability of failure combination method chart

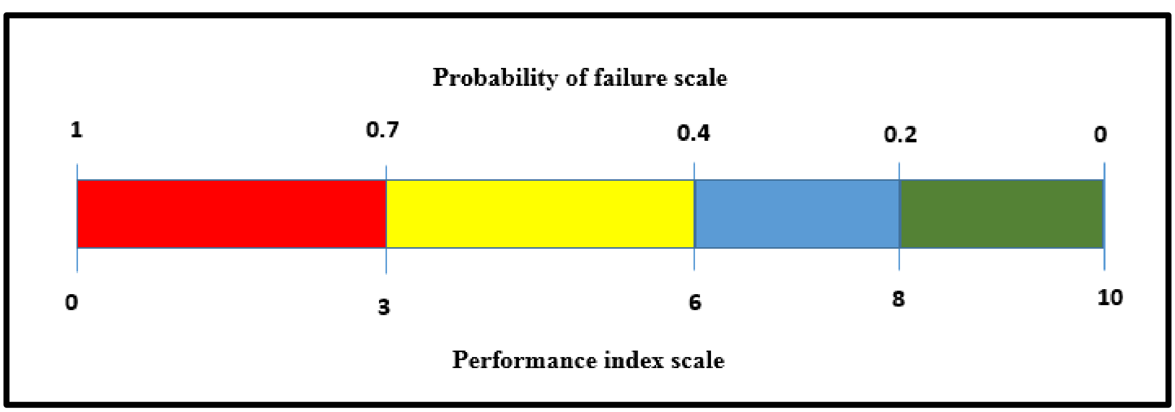


Figure III.8 Double scale between the probability of failure and the PI

III.8.2 Segments Integration

WNPBA adopted the means of topological clustering for the segment integration process, depending on the structure of the network and assuming the hydraulic connectivity. The methodology is similar to Breadth First Search (BFS) starting by partitioning the network into sub-networks based on the land use and the size of each sub-network and also portioning each sub-network in to segments. Partitioning is followed by drawing the topological chart and building the connectivity ranked matrix. Based on the topological chart, the importance of the segment to itself is given a weight of (0.1) in the connectivity matrix followed by (1) for the next level, which represents the segments directly connected to the first segment, (2) for the second level and so on. Finally, by using summation and normalization, the weights of importance of segments within the sub-network and, accordingly, the performance index of the sub-network are obtained.

III.8.3 Sub-Network Integration:

If the entire network has the same land use, then the sub-networks will be integrated using the same methodology as the segments. The sub-networks weights of importance are obtained by drawing a topological chart for the sub-networks and building their connectivity ranked matrix. Those weights of importance of the sub-networks are integrated with the length weight of importance reaching to the final PI of the network. If the land use was not the same, then the land use weight of importance should be integrated.

III.9 REHABILITATION AND MAINTENANCE PLAN

The selection of the rehabilitation actions for the water network components is a complex process. Thus, this research introduced a rehabilitation and maintenance plan for water networks components based on the performance indices of the components as shown in

Figure III.9. This flow chart helps the decision makers to choose the most suitable rehabilitation action for each component based on its PI. There is more than one action to consider for each PI category in this primary selection, which is to be followed by a detailed case by case selection based on the environmental, location and budget constraints. In addition to being environmentally accepted and feasible, all rehabilitation actions should be contractually accepted. The PI index is categorized in five categories. Each category has its own description and recommended action. As an example, the PI is critical when it is below (3) and the description is severe corrosion, coatings are almost damaged, the remaining wall thickness is 30% of the original, and B.R<3 or the cathodic protection is poor. Hence, the recommended action is replacement. Finally, this plan output is allocating the component in a specific category of rehabilitation actions and it should be followed case by case to precisely select process for each component.

III.10 DETERIORATION CURVES

After reaching the performance indices of the network components, the next step is to develop a model that can expect the performance of the component (deterioration model). This model should consider the complexity within the water network hierarchy. The newly developed deterioration model uses Weibull cumulative function to expect the deterioration for each component based on the PI when constructed, the PI after applying the performance model and the expected PI at the end of the service life. Weibull distribution is used here due to its simplicity and because it does not need a lot of data.

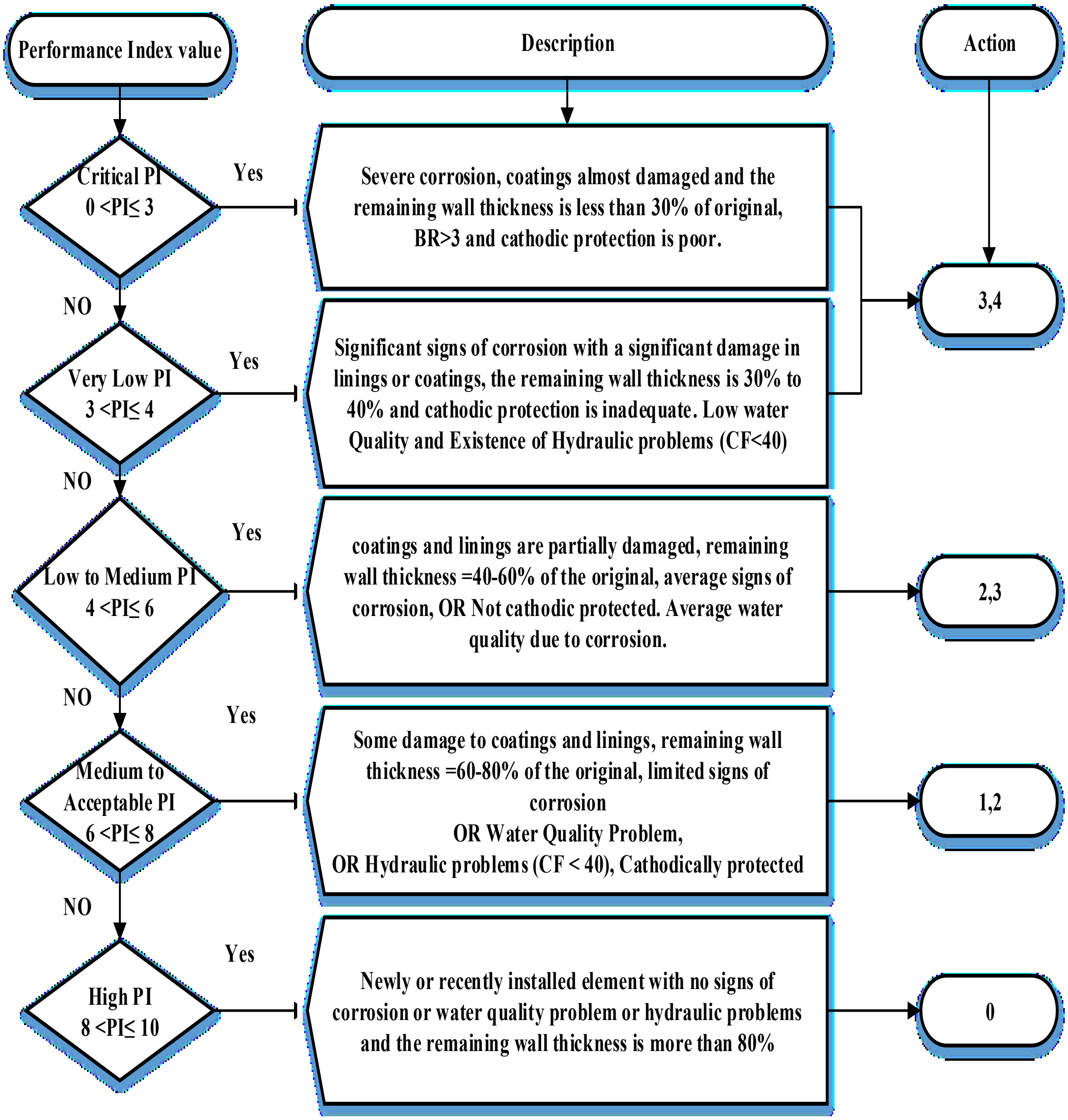


Figure III.9 Rehabilitation and maintenance plan

Where;

(0) No Action.
(1) Epoxy Lining, or Cement Lining, or Internal joint sealing.
(2) Cathodic Protection.
(3) Slip lining, CIPP.
(4) Replacement.

The Weibull probability distribution function is defined from the literature review as follows:

$$f(t) = \frac{\delta}{\tau}(\frac{t-\alpha}{\tau})^{\delta-1} * e^{-(\frac{t-\alpha}{\tau})^{\delta}} \qquad [III.40]$$

Where

α= location parameter

$\tau = Scale\ parameter$

$\delta = Shape\ parameter$

t = time

While the Weibull distribution function is as shown below:

$$F(t) = 1\text{-}\ e^{-(\frac{t-\alpha}{\tau})^{\delta}} \qquad [III.41]$$

Therefore, the Weibull reliability function can be adopted from the cumulative Weibull distributions as shown:

$$R(t) = 1 - F(t) = \ e^{-(\frac{t-\alpha}{\tau})^{\delta}} \qquad [III.42]$$

And the deterioration curve has the same shape as Weibull reliability curve, so it can be presented as:

$$P(t) = \ \alpha * \ e^{-(\frac{t}{\tau})^{\delta}} \qquad [III.43]$$

Where;

P (t) = Performance index at time (t), τ = service life

The deterioration curve for the pipelines and accessories should agree with the following conditions:

1) The newly installed components at t=0 has a PI=10, which can be expressed as 1 on a scale from 0 to 1 :

$$1 = \alpha * e^{-(\frac{0}{\tau})^{\delta}} \qquad [III.44]$$

$$1 = \alpha$$

2) PI=0 at the end of the lifetime span of the component, while PI=3 (critical performance index), which is presented as 0.3 on a scale from 0 to 1 and it represents the end of the useful service life (t):

$0.3 = 1 * e^{-(\frac{100}{\tau})^{\delta}}$, then

ln (0.3) = ln (1) – $(\frac{100}{\tau})^{\delta}$, and finally:

$$\tau = \frac{100}{(-\ln(0.3))^{1/\delta}} \qquad [III.45]$$

3) $\delta = 3$ as it makes the shape of the curve fits more than 1,2,4,5, ….

Hence, by substituting equations [III.44], & [III.45] into equation [III.43] the updated deterioration (performance) curve can be defined as:

$$\mathrm{P(t)} = 1 * \mathrm{e}^{\ln(\mathrm{P_i})(\frac{t}{\tau})^3} \qquad [III.46]$$

After applying the performance assessment model, the performance curve for each component can be predicted. Weibull analysis and the performance indices are used to build the ideal deterioration curves for the components both without and with considering maintenance as shown in Figures III.10 and III.11. Ideal deterioration curves represent the deterioration curves for the ideal components, working for the whole service life.

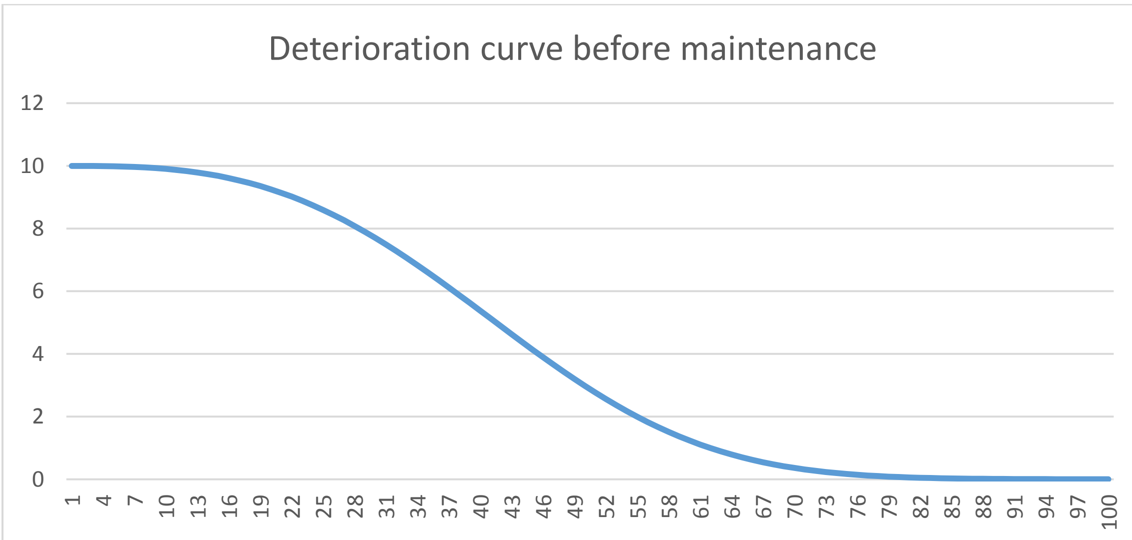


Figure III.10 Ideal deterioration curve before maintenance

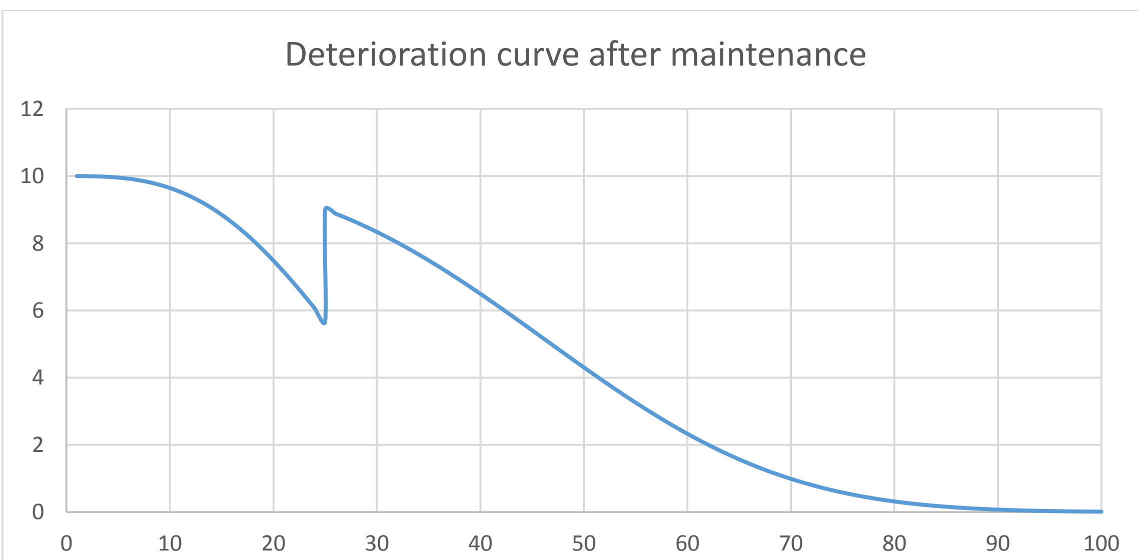


Figure III.11 Ideal deterioration curve after maintenance

III.11 THE BUDGET ALLOCATION MODEL

Water networks are one of the most complicated systems that deteriorate over time. As mentioned in the literature review, huge investments should be made to maximize the performance of these systems. Therefore, a functional tool is required to prioritize the budget allocation process optimally over the network components to reach to the highest PI. Due to the complexity of the water networks, there are limited rehabilitation or maintenance options for each component while there is almost unlimited number of solutions for the whole network.

Through this research, two optimization techniques are applied for reaching the most optimal plan for the budget allocation. These optimization algorithms are the genetic algorithm and the greedy heuristics. Each of the used techniques has its own advantages discussed in the literature review. The two algorithms are applied and the results are compared for a high degree of certainty about the suggested budget allocation plan.

III.11.1 Genetic Algorithm

As concluded from the literature review, the genetic algorithm is one of the most successful techniques in solving budget optimization problems. Thus, GA is used within the methodology of this research to solve the budget allocation model. The budget is allocated based on the performance indices obtained from the performance assessment model. The budget is allocated over the whole network, based on the calculations of each component within the network. The rehabilitation action for each pipe is chosen based on the PI and the calculations of each component are based on the unit cost of each pipe according to its diameter. Besides, the accessories are either be replaced or remained.

The main objective of the model is to increase the performance index of the total network, according to the performance index of the sub-network and the components PI. While the constraint is to keep the cost below the allowable, annual cost, the decision variables are either (1) which represents "doing the recommended action at this point of time" or (0) which represents "do nothing". The model should be applied over a specific time horizon for one year as an example. The model framework is presented earlier in the literature review chapter.

Objective function:

$$Max\ f(x) = \sum_{i=1}^{i=n} W_i * PI_i \qquad [III.47]$$

Subject to the following constraints:

$$\sum_{i=1}^{i=n} \sum_{j=1}^{j=k} C_{ij} \leq C_{max} \qquad [III.48]$$

Where;

$W_i = Weight\ of\ importance\ of\ each\ sub-network\ to\ the\ total\ network$

PI_i = Each sub-network performance index.

$C_i = Cost\ of\ rehabilitation\ strategies\ j\ applied\ to\ sub-network\ i\ components$

$C_{max} = max.\ allowable \frac{budget}{year}, \qquad i = sub-networks = 1,2,3, \dots .n$

The model inputs are:

1) The unit cost of each rehabilitation action for different pipe sizes (cost/m) and accessories replacement costs.
2) Deterioration of the component.
3) Diameter and length of each pipe.
4) Performance indices calculations.

The output of this problem is a budget allocation plan close to the optimal solution, which is here accepted, due to the complexity of the problem, numerous levels within the network and various actions for each component. The utilized actions vary from the simplest and least costly (e.g. Preventive action or cement lining) to the most complicated and costly (e.g. replacement).

The genetic algorithm is composed of several steps as illustrated in the literature review chapter.

- **Population Initialization**

In order to initialize any population, a number of chromosomes per generation are needed. To reach to a higher degree of certainty about the solutions, a higher number of chromosomes should be initialized (Goldberg and Holl, 1988). The sub-networks are here accounted for as chromosomes for the budget optimization.

- **Chromosome Encoding**

During the encoding process, each sub-network within the entire network is represented by a number of genes representing the number of its components to be rehabilitated. Thus, the chromosome encoding can be defined as an array of genes. The M&R actions represent the encoding for the genes. Figure III.12 shows the encoding for the proposed model.

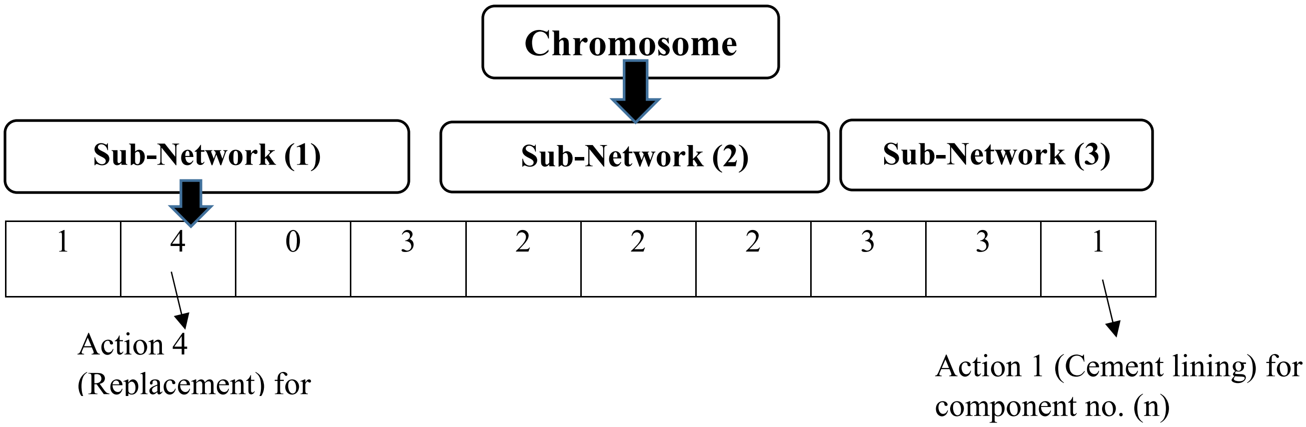


Figure III.12 Chromosome encoding

- **Fitness Calculation**

After initializing the population, a fitness value is calculated for each chromosome based on its characteristics and how much it fits the optimization objectives and constraints. Only chromosomes with higher fitness value, i.e. higher performance index, are considered for the next generation formation while others have the least probability for consideration within the next generation. In this case, the objective function is a maximization problem; therefore, the fitness function is the same as the objective function (maximization of the performance index).

- **Executing Genetic Algorithms**

After running the model, the first generation is mostly “no-action” (0) for all the components to have a realistic view of the elements PI and the system PI. During the second generation, M&R recommended actions start to appear. These actions represent the genes for the new population. The GA keeps working in the same manner until reaching the population size that satisfies the objective function. As a rule of thumb, the distribution is believed to be random.

- **Crossover and Mutation**

Crossover and Mutation are defined as in Chapter II of this research.

- **Stopping Criteria**

The stopping criteria for this model can be one of the following options: Reaching the objective, interrupting the model by the user or reaching the maximum number of defined iterations. The main outputs of this optimization are: (1) Budget distribution, (2) Proposed rehabilitation actions across the components and (3) Water network performance index at the end of the plan, developed based on the rehabilitation actions.

III.11.2 Greedy Heuristics

As mentioned earlier, Greedy Heuristics is another powerful optimization tool to solve budget allocation problems based on the Bayesian concept. The simplicity of GH and its ability to integrate algorithmic nature and human interaction is a major advantage for this tool. Otherwise, most of other techniques are black boxed. Thus, GH is used within the methodology of this research to solve the budget allocation model. The budget in the GA model is allocated based on the performance indices obtained from the performance assessment model. Through the GH, the weights of importance of the components to the segments, the segments to the sub-networks and the sub-networks to the entire network are considered. The rehabilitation actions' selection process is almost the same as the GA while the prioritization is different. The prioritization is mainly based on the weights of importance of each component to the entire network as explained before.

The GH is based on some predefined steps: Defining the objective that needs to be maximized or minimized, getting the relation between the objective and the input (e.g. cost, in the case of budget allocation model) and ranking the elements for budget allocation according to the recently defined relation.

1) Objective function: $Max\, f(x) = \sum_{i=1}^{i=n} W * PI_i$ [III. 49]

2) Benefits calculations for each component = $W_1 * W_2 * W_3$ [III. 50]

Where;

W_1 : $weight\ of\ importance\ of\ the\ component\ within\ the\ segment.$

W_2: $weight\ of\ importance\ of\ the\ segment\ within\ the\ sub-network.$

W_3: $weight\ of\ importance\ of\ the\ sub-network\ within\ the\ total\ network.$

3) Calculating cost for each component.

4) Calculating benefit/cost ratio.

5) Ranking the components for rehabilitation according to B/C ratio in a descending order.

The model inputs, outputs and rehabilitation actions are the same as the genetic algorithm model.

Finally, after applying the GA and GH models, the two budget allocation plans are compared based on the final amount of spent budget, the number of elements rehabilitated, the amount of the remaining elements and the final PI reached. Hence, the best option is selected.

III.12 Methodology summary:

This research is divided into two main models, the performance assessment model and the budget allocation model. The performance assessment model utilizes different tools through the different levels of the water network as shown below in Table III.4. The budget allocation model is linked to the performance model within all the network levels.

Table III.4 Research methodology summary

<table>
<tr><th>Level
Model</th><th>Network Components</th><th>Segment Level</th><th>Sub-network Level</th><th>City Network Level</th></tr>
<tr><td>Performance Assessment Model</td><td>1) Fuzzy ANP (Performance Indicators relative weights calculations)
2) PROMETHEE (FPI calculations)
3) MAUT (Obtaining GPI)</td><td>Probability of failure method based on the components performance indices</td><td colspan="2">Topological clustering (Connectivity ranked matrix) besides the land use weight of importance and the length weight of importance.</td></tr>
<tr><td>Performance-based budget allocation Model</td><td colspan="4">Genetic Algorithm and Greedy Heuristics</td></tr>
</table>

CHAPTER IV

DATA COLLECTION AND ANALYSIS

IV.1 INTRODUCTION

Data is collected for this research from four sources. The first source is the literature review, providing data on the indicators needed to assess the performance of the water distribution systems, to study in detail the different tools that are used and also to gather data about the rehabilitation actions used to rehabilitate the water network components. The second source is the experts' opinions and interviews, and from this source, the indicators to be used in this research are defined and approved. The third source is a questionnaire developed for pipelines and accessories and used to gather the weights of the defined indicators and the attribute values from experts in water networks. The experts fill a pairwise comparison between the defined indicators. The pairwise comparison is used to perform FANP calculations, obtaining the weights of the indicators. The questionnaires are reached by professionals in different fields of expertise within the water industry and in different geographical areas. The number of gathered questionnaires is twenty, with a response rate of 40%. The last type of collected data is the case studies database, collected from City of Moncton and City of Montreal water services.

IV.2 LITERATURE REVIEW

Literature review is the first source for the data in this research. . This source is used to study different kinds of techniques such as MCDA, fuzzy set theory, Weibull distribution, GA and GH. Also, some assessment factors and most of the rehabilitation actions used for water mains are gathered from the literature.

IV.3 EXPERT OPINIONS

Through a lot of interviews with engineers working in water municipalities and people involved in the water field in general, the indicators were defined and given a qualitative and quantitative range. The targeted experts were from various locations, mainly North America. The interviews took place either online or in-person.

IV.4 QUESTIONNAIRES

The developed questionnaire is as shown in Appendix (A) and it consists of four parts as follows:

IV.4.1 General Information part

In this part, the participants are asked about their occupation, years of experience and the geographical area where they acquired most of their experience. This part is very important for the study and analysis of the gathered responses.

IV.4.2 Questionnaire second part (Factors Weights)

The experts are asked in the second part of the questionnaire to fill some tables regarding the weight of importance of the indicators. They are guided to utilize Saaty scale to fill the tables. This scale is composed of a discrete value ranging from 1, which means equally important, to 9, which means absolutely more important. The inverse can be used as well, ranging from 1/9, meaning absolutely less important, reaching to 1, meaning equally important, as shown in Figure IV.1.

These tables are used to conduct a pairwise comparison between all the categories of indicators with respect to the overall performance, between all the sub-indicators with respect to the indicators' categories and finally between the indicators' categories with respect to each other. The pairwise comparison matrices for the water mains is presented in Table IV.1.

IV.4.3 The third Part (Indicators Attribute Values)

The third part mainly covers the attribute values of all the indicators. In this part, a qualitative description is presented for all the factors and the experts are asked to define the attribute values of all the indicators based on the defined qualitative description. The attribute values range from 0 to 10, indicating the lowest effect on performance to the highest effect on performance respectively. The nature of each indicator should be considered while allocating attribute values. For example, if the indicator is the age, the higher the age, the lower the attribute value and the higher the effect on the performance. The pairwise comparisons and the attribute tables for accessories are almost the same as the ones for the water mains when the pipe diameter and the pipe wall thickness are removed. The qualitative and quantitative categories for the attribute value of each indicator is presented to help the decision maker. The attribute values for water mains is shown in Table IV.2

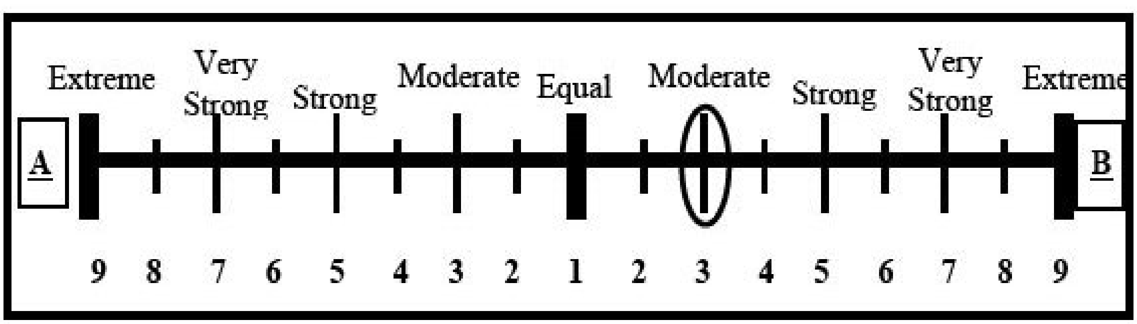


Figure IV.1 Saaty scale

Table IV.1 Pairwise comparison for water mains indicators

Water Network Performance Index										
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	
Physical Indicators										Operational Indicators
										Quality of Service Indicators
										Environmental Indicators
Physical Indicators										
Pipeline Age										Wall Thickness (Metal Loss)
										Pipe Material
										Installation and Manufacturing Quality
										Pipe Diameter
Operational Indicators										
Water main Breaks										Network Renewal Rate
										Leaks
										Internal Water Pressure
Quality of Service Indicators										
Service Interruptions										No. of Household Served
										Customer Satisfaction
										Water Quality
Environmental Indicators										
Soil Type										Ground Water
										Location
PHYSICAL Indicators										
Operational										Quality of Service
										Environmental
OPERATIONAL Indicators										
Quality of Service										Physical
										Environmental
QUALITY OF SERVICE Indicators										
Physical										Operational
										Environmental
ENVIRONMENTAL Indicators										
Physical										Operational
										Quality of Service

Table IV.2 Attribute values weights table from the questionnaire

Main Factor	Sub-factors	Unit of Measure	Qualitative Description	Quantitative Value Range	Effect Value On Performance (0 – 10)
Physical	Age	(Years)	Old	(70) to (100)	( ) to ( )
			Medium	(30) to (70)	( ) to ( )
			Newly Installed	(0) to (30)	( ) to ( )
	Pipe wall thickness	(Millimeters)	Small size	(6) to (8)	( ) to ( )
			Medium size	(8) to (10)	( ) to ( )
			Large size	(10) to (14)	( ) to ( )
	Pipe Material	NA	PVC	NA	( ) to ( )
			Concrete		( ) to ( )
			Asbestos		( ) to ( )
			Cast Iron		( ) to ( )
			Ductile Iron		( ) to ( )
	Pipe Installation, Quality	%	Excellent	(70) to (100)	( ) to ( )
			Moderate	(50) to (70)	( ) to ( )
			Poor	(0) to (50)	( ) to ( )
	Pipe Diameter	mm	Large size	< 300mm	( ) to ( )
			Medium size	300 – 750 mm	( ) to ( )
			Small size	>750 mm	( ) to ( )
Operational	Water main Breaks	Breaks/Km/year	High	>0.5 break/Km/Year	( ) to ( )
			Medium	0.1-0.5	( ) to ( )
			Low	<0.1 break/Km/Year	( ) to ( )
	Network Renewal Rate	% / Year	High	>1.5% / Year	( ) to ( )
			Medium	1-1.5 % / Year	( ) to ( )
			Low	< 1% / Year	( ) to ( )
	Water Losses due to Leakage	% from the flow rate	High	(20) to (60)	( ) to ( )
			Medium	(10) to (20)	( ) to ( )
			Low	(5) to (10)	( ) to ( )
	C-factor	-	High	< 41	( ) to ( )
			Medium	41-101	( ) to ( )
			Low	>101	( ) to ( )
Quality of Service	Service Interruptions	No. of Interruptions/ Km./Year	High	≥ 3	( ) to ( )
			Medium	1-2.99	( ) to ( )
			Low	< 1	( ) to ( )
	No. of Household Served	No. of household served/Km.	High	>30 / 200m	( ) to ( )
			Medium	20-30 / 200m	( ) to ( )
			Low	< 20 / 200m	( ) to ( )
	Customer Satisfaction	No. of Complaints/ Km./Year	High	>2 complaints / 200m	( ) to ( )
			Medium	1-2 / 200m	( ) to ( )
			Low	0 / 200m	( ) to ( )
	Water Quality	%	Excellent	(70) to (100)	( ) to ( )
			Good	(50) to (70)	( ) to ( )
			Poor	(0) to (50)	( ) to ( )

Environmental	Soil Type	% of Corrosiveness and Presence of hydrocarbons and Solvents	Aggressive	( ) to ( )	( ) to ( )
			Moderate	( ) to ( )	( ) to ( )
			Non Aggressive	( ) to ( )	( ) to ( )
	Ground Water Table	(Meters)	Deep	(10) to (30)	( ) to ( )
			Moderate	(6) to (10)	( ) to ( )
			Shallow	(2) to (6)	( ) to ( )
	Location	Surface Type	Rigid	NA	( ) to ( )
			Flexible		( ) to ( )

IV.4.4 Pseudo criteria thresholds definition

This section explains the analysis of the information required to set the critical and tolerance thresholds of each of the sub-indicators. The scale to be used for each sub-indicator is the same as the quantitative range. The critical threshold is the value for which, according to the nature of the sub-indicator, the indicator is considered critical if above or below. The tolerance threshold is the value for which, according to the nature of the sub-indicator, the sub-indicator is considered tolerable or safe if above or below. Unfortunately, the gathered responses from this part are not sufficient to define the thresholds. Therefore, the thresholds are assumed based on the PI scale in this research. Table IV.3 is used to gather the thresholds data in the questionnaire.

IV.4.5 Data Analysis

Data is analyzed to reach to a better understanding of the gathered responses and make a better judgment over its accuracy. Thus, the average of the gathered responses is obtained after calculating the relative weights of the indicators for each individual response. Then, the percent difference of each response from the average is calculated and the responses with a high percent difference are excluded. Almost two responses are taken out. After taking out the bias, the remaining responses are rechecked and the percent of difference is now acceptable.

In order to have further analysis, the occupation of the participants is also categorized into the four following categories: Pipeline inspection experts, pipeline department managers, pipeline engineers and other engineers. The percent of the participants within each category is 36% for other engineers, including planning engineers, followed by 32% for the pipeline engineers, then 20% for the inspection experts and finally 12% for the pipeline department manager as shown in Figure IV.2. Their experience in the field is categorized into five categories, ranging from less than 5 to more than 20 years and increasing by 5 years for each category. As Figure IV.3 illustrates, the participants with experience less than 5 years and more than 20 years represent 24% of all participants each. The highest percent of participants are located in the category from 6 to 10 years of experience with a percentage of 28%. Finally, participants with experience from 11 to 15 years and from 15 to 20 years represent 12% each. Also, Figure IV.4 shows that the location of experience is categorized into four categories: North America, Middle East, Europe and Australia, with a percent of 67%, 13%, 10% and 10% of the participants in each category respectively.

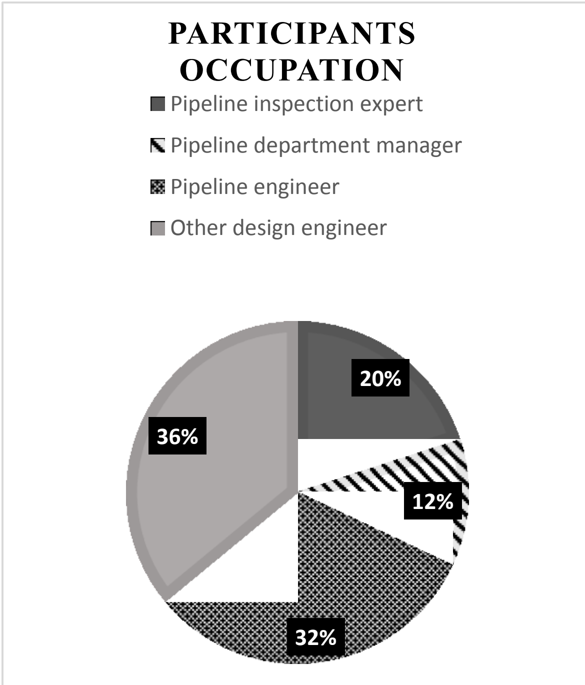
The percentage of difference from the average of the degree of importance of each sub-indicator of the pipelines is calculated and presented in Figure IV.5. It is found that the thickness, material, installation quality, diameter and G.W.T indicators have the least difference from the average throughout all categories. This means that most of the participants agree on the same degree of importance of these factors. It is also shown below that the pipeline department managers and the pipeline engineers almost agree on the degree of importance of all the factors.

Meanwhile, Figure IV.6 shows the percent difference for the sub-factors of accessories. The G.W.T, material and Installation Quality have the lowest percent difference from the average, which means that the participants almost agree on the same degree of importance for these sub-indicators.

The average of the attribute values is also calculated and the outliers have been taken out as well. The average is considered for further research calculations with limited assumptions, to facilitate the calculations. Also, Pseudo thresholds data is gathered but it is not sufficient for the analysis, as most participants preferred not to define the thresholds, believing that this part of data can vary according to the users of the model, not only from one country to another but also for every municipality.

Table IV.3 Critical and tolerance thresholds table from the questionnaire

Criteria	Thresholds according to Quantitative range	
	Critical	Tolerance
Age		
Pipe Wall Thickness		
Pipe Material	NA	NA
Pipe Installing and Manufacturing		
Pipe Diameter		
Water main Breaks		
Network Renewal Rate		
Leaks		
No. of emergency Service Connection Repairs		
Internal Water Pressure		
Service Interruptions		
No. of household Served		
Customer Satisfaction		
Water Quality		
Soil Type		
Ground Water		
Location	NA	NA



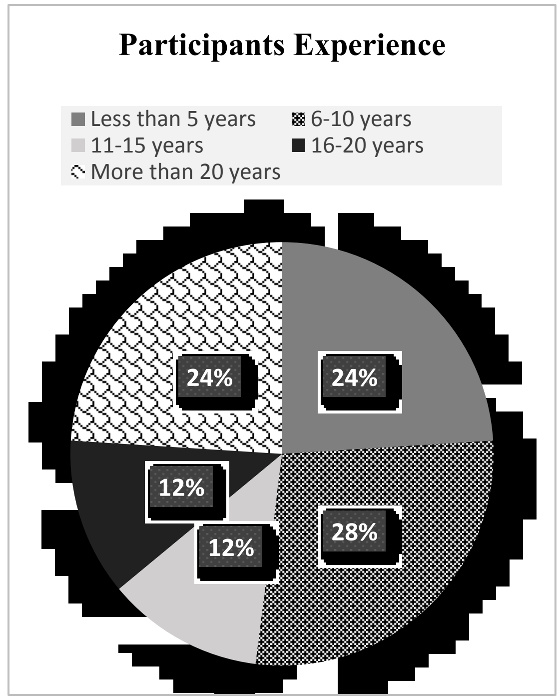


Figure IV.2 Questionnaire participants occupation

Figure IV.3 Questionnaire participants experience

IV.5 CASE STUDY DATA

In order to verify the developed model, two databases are collected from two different cities in Canada. The first database is from the city of Moncton, providing data for 100 water mains located there. It covers the all the physical, operational and environmental indicators. However, it does not cover the quality of service indicators. This database covers only the pipelines and not the accessories. The second database is collected from the city of Montreal water services, providing data for 850 water mains located in the south-west of the city. It also covers most of the indicators except for the quality of service and some of the operational indicators. However, it does not cover the accessories as well. Finally, the model verification is done on two sub-networks from Moncton, with 45 water mains included, and one sub-network from Montreal, with 63 water mains included. The layouts for the case studies are presented in Appendix E.

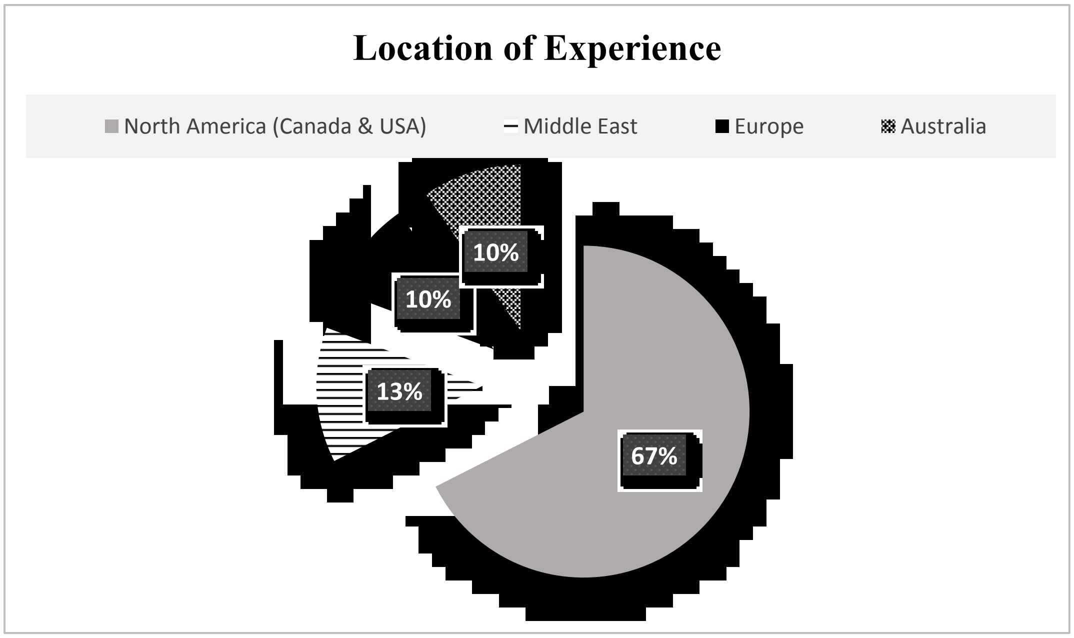


Figure IV.4 Questionnaire participants location of experience

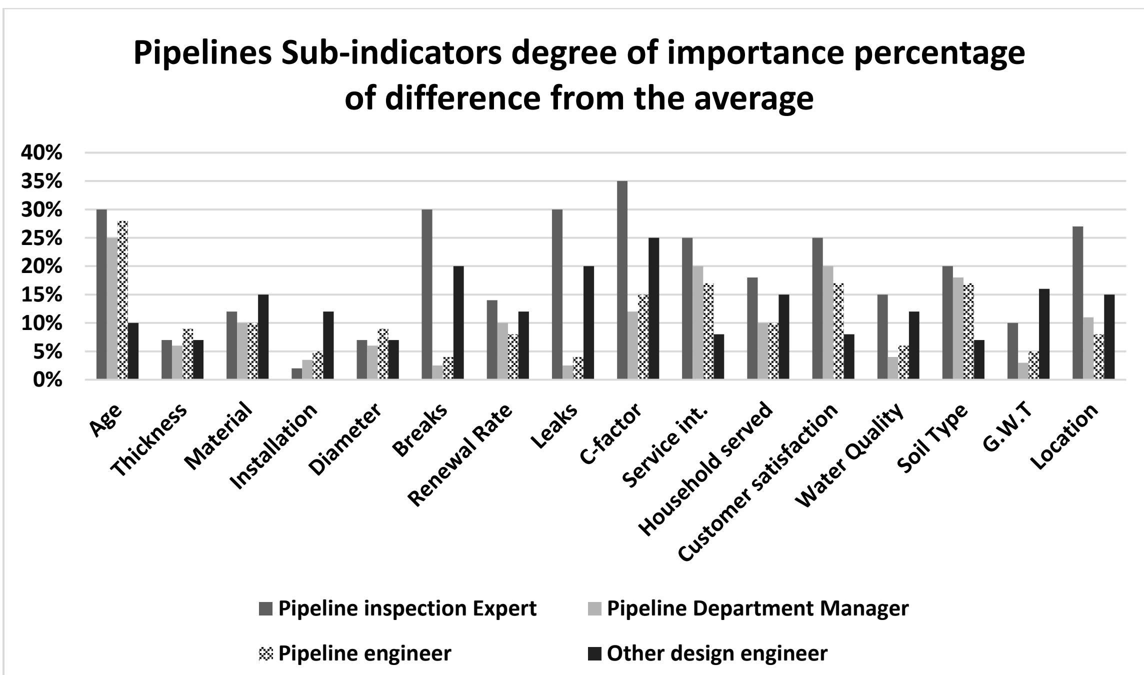


Figure IV.5 Pipelines sub-indicators degree of importance percentage of difference from the average

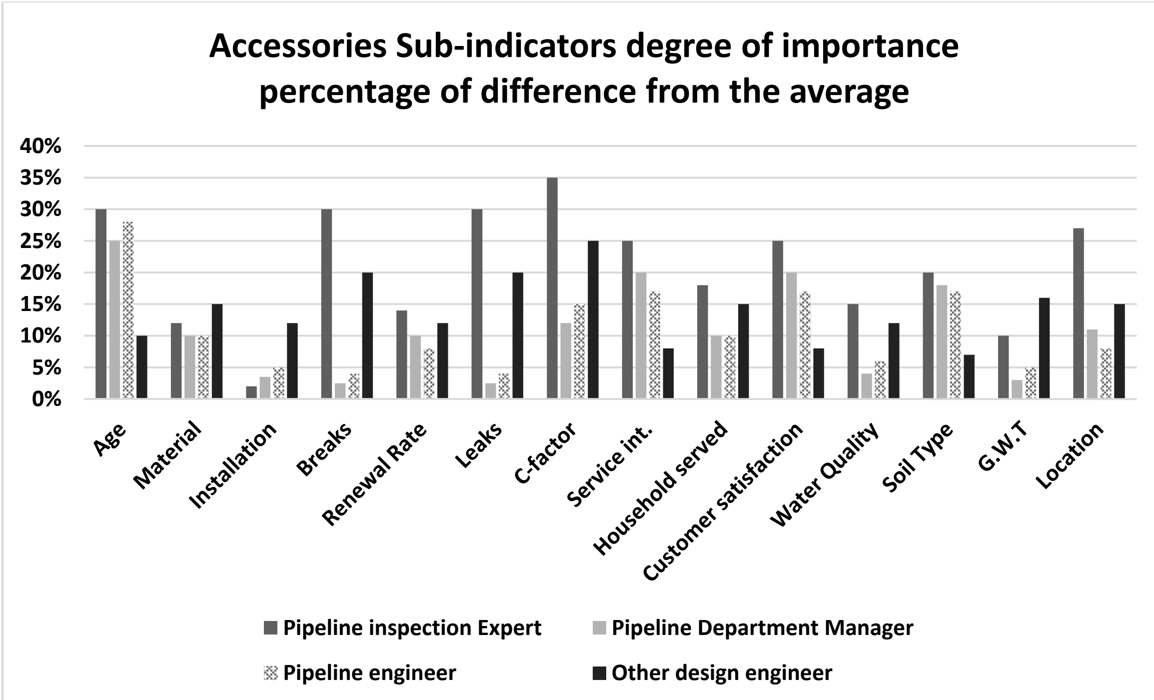


Figure IV.6 Accessories sub-indicators degree of importance percentage of difference from the average

IV.6 SUMMARY

This chapter explained the data collection process, by means of the four data sources. The data collected from the literature review, i.e. the first source, includes the methodology of different techniques, assessment indicators and the widely-used rehabilitation actions. Then, several interviews with experts in the water field from different locations have been conducted to approve the chosen indicators and identify their qualitative and quantitative descriptions. Afterward, the questionnaire is developed to gather the indicators' weights by means of pairwise comparisons and the attribute values for all the indicators. Around 20 questionnaires for pipelines and accessories are collected, with a response rate of 40%.

In the course of calculations, the analysis of the gathered responses has been carried out as shown earlier to indicate the occupation of the participants in the questionnaire. Their experience years are also presented, with the highest contribution from participants with 6 to 10 years of experience, followed by the "more than 20 years" category. The location of the field experience is also presented, with 67% from North America. FANP is applied, resulting in categorical weights and sub-indicators relative weights. The average of the responses is calculated to have the most reliable weights and exclude the unrealistic responses when determined. Also, the percent difference from the average in each category of the responses for each sub-indicator is calculated and it is found that the thickness, material, installation quality, diameter and G.W.T indicators have the least difference from the average in the categories. The pipelines department managers and engineers gave almost the same degree of importance to most of the sub-indicators. Moncton water municipality and Montreal water services are the last sources of data for this research, providing two databases for water network characteristics for the purpose of testing the model.

Chapter V

Model Development and Implementation

V.1 Introduction

The Model is developed using fuzzy ANP means in order to determine the indicators relative weights. Indicators relative weights are considered the main input to PROMETHEE beside the attribute values, reaching to the water network performance index. PROMETHEE is used herein to calculate the water networks components performance indices. These indices are used as inputs to the integration methods. The integration methods are used to calculate the performance index of the water network, starting from the performance indices of the components, passing by the segments, sub-network indices and finally obtaining a water network performance index. In order to come over the complexity of the calculations, an integrated Matlab-Excel® interface is used herein to do all the FANP calculations. The relative weights of the indicators are the main output of this interface. The output from the performance assessment model is used as input to the budget allocation model. The components are prioritized for budget allocation based on their PI. The budget allocation model utilizes Excel automated sheets and Evolver optimization tool to facilitate the allocation and the optimization processes.

The two developed models are applied to a real water networks to prove their functionality. "Moncton Water Municipality" and "Montreal Water Services" provided this research with two databases for part of the water network of each city. Thus, the model is experimented using three sub-networks; two from Moncton and one from Montreal. The databases for these sub-networks cover most of the required indicators for the pipelines. Therefore, the accessories are assumed to have the same indicators values as the pipelines.

V.2 Performance Indicators Definition

The first step of the performance assessment model is defining the performance indicators that will be used. This research is based on (16) indicators, which are categorized into; physical (age, thickness, material, installation, diameter), operational (Breakage rate, renewal rate, leaks, and internal water pressure), quality of service (service interruptions, no. of household served, customer satisfaction, and water quality) and environmental (soil type, ground water table, and location) categories as shown in Table V.1.

Table V.1 Performance Indicators categories

Function	Indicator	Code
PHYSICAL	Age	Ph.1
	Thickness	Ph.2
	Material	Ph.3
	Installation	Ph.4
	Diameter	Ph.5
OPERATIONAL	Water main Breaks	Op.1
	Network Renewal Rate	Op.2
	Leaks	Op.3
	Internal Water Pressure	Op.4
Quality of Service	Service interruptions	QS.1
	No. of household served	QS.2
	Customer satisfaction	QS.3
	Water Quality	QS.4
Environmental	Soil Type	ENV.1
	Ground Water Table	ENV.2
	Location	ENV.3

V.3 Fuzzy Analytical Network Process

The Second step is calculating the relative weights of the defined indicators. Fuzzy Analytical Network Process is used to determine the relative weights. It is composed of a series of calculations which will be illustrated through the following part.

V.3.1 Pairwise Comparison

The experts are asked through the questionnaires about the relative importance between the indicators identified and this is done in three levels as mentioned in the data collection chapter. The pairwise comparison is built using the output of the questionnaires based on "Saaty" scale.

V.3.2 Fuzzified Pairwise Comparison

After creating the pairwise comparison from the questionnaires output, there is a need to fuzzify it. The created pairwise comparison is called the "most probable pairwise comparison or matrix". Therefore, Saaty scale is applied on this matrix to obtain the lower and upper matrices. The fuzzified pairwise comparisons (the three matrices) of questionnaire number 16 are shown in Tables V.2 to V.7 where each cell is composed of three numbers representing the numbers from the lower, most probable and upper matrices. The three matrices are also developed for the accessories part.

Table V.2 Indicators categories pairwise comparison with respect to the overall performance

	Physical	Operational	Quality of Service	Environmental
Physical	(1,1,1)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(4,5,6)
Operational	(6,7,8)	(1,1,1)	(1,1,2)	(8,9,9)
Quality of Service	(6,7,8)	(1/2,1,1)	(1,1,1)	(8,9,9)
Environmental	(1/6,1/5,1/4)	(1/9,1/9,1/8)	(1/9,1/9,1/8)	(1,1,1)

Table V.3 Physical indicators pairwise comparison

	age	material	Thickness	installation	Diameter
age	(1,1,1)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1,1,2)	(1/6,1/5,1/4)
material	(4,5,6)	(1,1,1)	(1/3,1/2,1)	(2,3,4)	(1/3,1/2,1)
Thickness	(2,3,4)	(1,2,3)	(1,1,1)	(4,5,6)	(1,1,2)
installation	(1/2,1,1)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1,1,1)	(1/6,1/5,1/4)
Diameter	(4,5,6)	(1,2,3)	(1/2,1,1)	(4,5,6)	(1,1,1)

Table V.4 Operational indicators pairwise comparison

	Water main Breaks	Network Renewal Rate	Leaks	Internal Water Pressure
Water main Breaks	(1,1,1)	(4,5,6)	(1,1,2)	(4,5,6)
Network Renewal Rate	(1/6,1/5,1/4)	(1,1,1)	(1/6,1/5,1/4)	(1,1,2)
Leaks	(1/2,1,1)	(4,5,6)	(1,1,1)	(4,5,6)
Internal Water Pressure	(1/6,1/5,1/4)	(1/2,1,1)	(1/6,1/5,1/4)	(1,1,1)

Table V.5 Quality of service indicators

	Service Interruptions	No. of Household Served	Customer Satisfaction	Water Quality
Service Interruptions	(1,1,1)	(4,5,6)	(1/6,1/5,1/4)	(1/6,1/5,1/4)
No. of Household Served	(1/6,1/5,1/4)	(1,1,1)	(1/9,1/9,1/8)	(1/9,1/9,1/8)
Customer Satisfaction	(4,5,6)	(8,9,9)	(1,1,1)	(1,1,2)
Water Quality	(4,5,6)	(8,9,9)	(1/2,1,1)	(1,1,1)

Table V.6 Environmental indicators pairwise comparison

	Soil	Ground water	Location
Soil Type	(1,1,1)	(4,5,6)	(1/8,1/7,1/6)
Ground water	(1/6,1/5,1/4)	(1,1,1)	(1/9,1/9,1/8)
Location	(6,7,8)	(8,9,9)	(1,1,1)

Table V.7 Indicators categories pairwise comparison with respect to each other

	Operational	Quality of service	Environmental
Operational	(1,1,1)	1.000	(6,7,8)
Quality of service	1.000	(1,1,1)	(6,7,8)
Environmental	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1,1,1)

	Quality of service	Physical	Environmental
Quality of service	(1,1,1)	(6,7,8)	(6,7,8)
Physical	(1/8,1/7,1/6)	(1,1,1)	(6,7,8)
Environmental	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1,1,1)

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

	Physical	Operational	Quality of service
Physical	(1,1,1)	(1/8,1/7,1/6)	(1/8,1/7,1/6)
Operational	(6,7,8)	(1,1,1)	(1,1,2)
Quality of service	(6,7,8)	(1/2,1,1)	(1,1,1)

V.3.3 Unweighted super matrix

All the previous calculations are done using Excel sheets In order to calculate the unweighted matrix from the three matrices, there is a need to incorporate Matlab® software besides the Excel sheets. Accordingly, by developing a suitable Matlab® code, the three matrices are used as inputs, while the output is an unweighted super matrix which is located automatically in the Excel sheet as presented in Table V.8. For questionnaire number (16), the numbers from the un-weighted super matrix are considered the relative weights using FAHP technique. As an example, the number (0.10) represents the relative weight of importance of the “physical indicators category” has among other functions. Accordingly, the number (0.069) for the age represents relative weight of importance of the age compared to the other physical indicators. We can get the global weights of the indicators categories and the local weights of the sub-indicators directly from the matrix. The summation of the global weights of sub-indicators is supposed to equal to (1) as presented in Table V.9. The columns of zeros (sinks) in the un-weighted matrix are replaced by the same cells or columns from the identity matrix as mentioned through the literature review.

V.3.4 Weighted super matrix

The following step after acquiring the un-weighted super matrix is transforming it in to weighted super matrix by normalizing it. The normalization process is done by getting the summation of each column and then divides each cell within this column over the summation, obtaining a matrix; the summation of each column within it equals 1. The weighted super matrix for questionnaire (16) is presented below in Table V.10.

V.3.5 Limited matrix

As mentioned, the sinks are replaced with columns from the identity matrix and the limited matrix for questionnaire (16) is calculated by raising the weighted super matrix to large powers in a continuous process until one output matrix equals to the last one before it. If the sinks are not replaced, the limited matrix will not be formulated as once we try to raise it to a larger power, it converts to a matrix of zeros. This limited matrix calculation process is done using Matlab® as it is a very complex process and it is multiplied to almost more than 1700 times by itself which made it impossible to be done without having the integrated Excel- Matlab® interface. The FANP relative global weights for the indicators can be obtained from the first column of the limited matrix as shown in Table V.11.

Table V.8 Unweighted super matrix

	WNPA	PF	OF	QOSF	EF	A	M	T	IQ	D	BR	RR	LR	C-f	SI	N.H	CS	WQ	ST	GWT	L
WNPA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PF	0.10	0.00	0.70	0.23	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OF	0.43	0.47	0.00	0.70	0.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
QOSF	0.43	0.47	0.23	0.00	0.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EF	0.04	0.07	0.07	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	0.00	0.07	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M	0.00	0.23	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T	0.00	0.31	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IQ	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WB	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RR	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
L	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C-f	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SI	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
N.H	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
CS	0.00	0.00	0.00	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
WQ	0.00	0.00	0.00	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
ST	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
GWT	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
L	0.00	0.00	0.00	0.00	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Sum	1.00	2.00	1.94	2.00	2.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table V.9 Indicators AHP weights

Global weights	Function Global Weight	Indicators	Local weights	Global weights
PHYSICAL	0.100	Age	0.07	0.007
		Thickness	0.226	0.023
		Material	0.306	0.031
		Installation	0.066	0.007
		Diameter	0.332	0.033
OPERATIONAL	0.431	Water main Breaks	0.393	0.169
		Network Renewal Rate	0.079	0.034
		Leaks	0.393	0.169
		Internal Water Pressure	0.079	0.034
Quality of Service	0.431	Service interruptions	0.118	0.051
		No. of household served	0.039	0.017
		Customer satisfaction	0.422	0.182
		Water Quality	0.422	0.182
Environmental	0.038	Soil Type	0.189	0.007
		Ground Water Table	0.060	0.0023
		Location	0.751	0.03

V.3.6 Indicators relative weights

After obtaining the limited matrix, the indicators global weights are obtained. The summation is checked and it is equal to (1). All the previous steps are done for all the (20) questionnaires and the average of final global weights of all the questionnaires is obtained. The average indicators global weights are shown in Figure V.1. As for the water mains, the indicators with the highest relative weights are breaks and leaks with 16.58% each followed by customer satisfaction and water quality with 13.77% each. They represent around 60% of all indicators importance which reflects their effect on the performance.

Table V.10 Weighted super matrix

	WNPA	PF	OF	QOSF	EF	A	M	T	IQ	D	BR	RR	LR	C-f	SI	N.H	CS	WQ	ST	GWT	L
WNPA	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PF	0.10	0.00	0.36	0.12	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OF	0.43	0.23	0.00	0.35	0.23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
QOSF	0.43	0.23	0.12	0.00	0.23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EF	0.04	0.03	0.03	0.03	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A	0.00	0.03	0.00	0.00	0.00	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	0.00	0.11	0.00	0.00	0.00	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T	0.00	0.15	0.00	0.00	0.00	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
IQ	0.00	0.03	0.00	0.00	0.00	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
D	0.00	0.17	0.00	0.00	0.00	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
WB	0.00	0.00	0.20	0.00	0.00	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
RR	0.00	0.00	0.04	0.00	0.00	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
L	0.00	0.00	0.20	0.00	0.00	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
C-f	0.00	0.00	0.04	0.00	0.00	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
SI	0.00	0.00	0.00	0.06	0.00	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
N.H	0.00	0.00	0.00	0.02	0.00	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
CS	0.00	0.00	0.00	0.21	0.00	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
WQ	0.00	0.00	0.00	0.21	0.00	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
ST	0.00	0.00	0.00	0.00	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
GWT	0.00	0.00	0.00	0.00	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
L	0.00	0.00	0.00	0.00	0.38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.000	1.000	1.000

Table V.11 Limited matrix

	WNPA	PF	OF	QOSF	EF	A	M	T	IQ	D	BR	RR	LR	C-f	SI	N.H	CS	WQ	ST	GWT	L
WNPA	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PF	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OF	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
QOSF	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EF	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A	0.02	0.04	0.02	0.01	0.01	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	0.05	0.13	0.05	0.03	0.02	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T	0.07	0.18	0.07	0.05	0.03	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
IQ	0.02	0.04	0.02	0.01	0.01	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
D	0.08	0.20	0.08	0.05	0.04	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
WB	0.16	0.08	0.24	0.10	0.08	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
RR	0.03	0.02	0.05	0.02	0.02	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
L	0.16	0.08	0.24	0.10	0.08	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
C-f	0.03	0.02	0.05	0.02	0.02	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
SI	0.04	0.02	0.02	0.07	0.02	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
N.H	0.01	0.01	0.01	0.02	0.01	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
CS	0.14	0.07	0.06	0.24	0.07	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
WQ	0.14	0.07	0.06	0.24	0.07	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
ST	0.01	0.01	0.01	0.01	0.10	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
GWT	0.00	0.00	0.00	0.00	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
L	0.04	0.02	0.02	0.02	0.39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

For the accessories part all the previous steps of calculations are done and presented in Appendix (B) obtaining the indicators relative weights as illustrated in Figure V.2. One important observation to be noted is that the weights are almost the same as the relative weights of the pipelines indicators. The breaks, leaks, and Material indicators have the highest contribution to the overall performance. Moreover, the environmental indicators have the least contribution whether for pipelines or accessories. The reason for this is that the environmental part is not considered much effective by the experts as it is almost constant for each sub-network or even for the entire network.

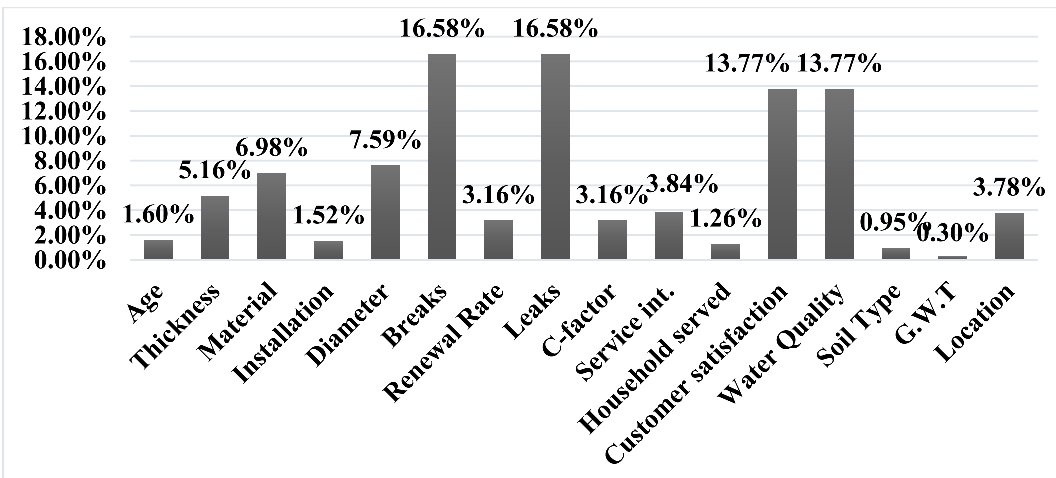


Figure V.1 Pipelines performance indicators relative weights

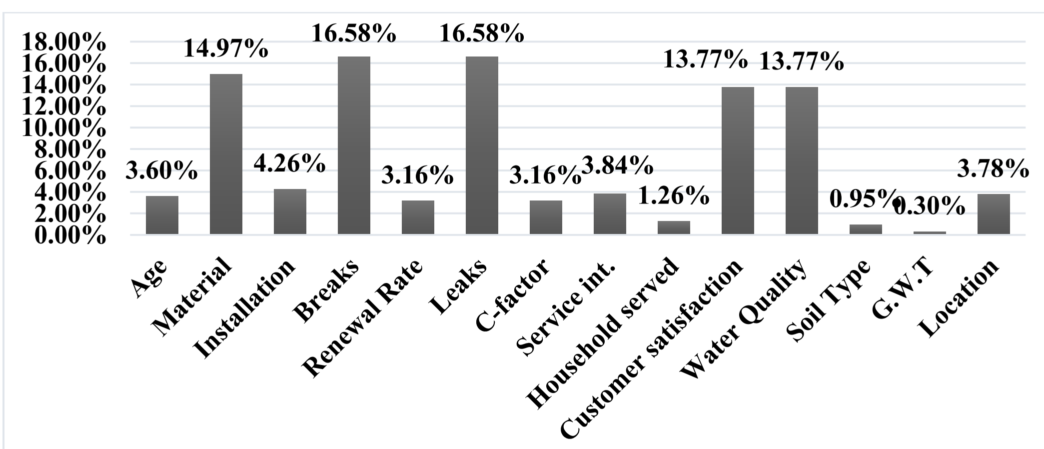


Figure V.2 Accessories performance indicators relative weights

V.4 Assigning Attribute values

The attribute values for the indicators are assigned based on the real data of the indicators from the database of the case study and the average of the gathered responses for the attribute values. A Fuzzy Expert system on Matlab® is used to develop a complete fuzzy system for each indicator to increase the accuracy of the attribute values allocation process. Firstly the membership functions are chosen based on expert opinions and following the simple logic based on the quantitative ranges of the indicators identified from the questionnaires. Therefore, most of the function were chosen within the linear category either triangular or trapezoidal. As an example, the number of breaks from the questionnaires average, is categorized as follows, Low from 0 to 0.2, Medium from 0.1 to 0.5 and High from 0.2 as shown in Figure V.3. This is considered as the input function while the output function; which represents the attribute values; is as illustrated in Figure V.4; Low from 0 to 4, Medium from 3 to 7 and High from 6 to 10. There are a lot of function shapes that can be used like triangular or trapezoidal function. The function is chosen based on data availability and suitability. After building the input and output functions, the rules are defined to link between both functions as shown in Figure V.5. Accordingly, the Fuzzy system is developed and the surface function that link between the input and output function as shown in Figure V.6. It is used mainly to obtain the attribute values (outputs) directly from the number of beaks (inputs). For pipe number 1 from sub-network 1 in City of Moncton, the no. of breaks is 0.2, so the attribute value is calculated based on the rules to be 6. This step is done for all the indicators and for all the case studies. The attribute values allocation process for City of Moncton sub-network 2 is calculated as mentioned earlier and it is shown in Table V.12.

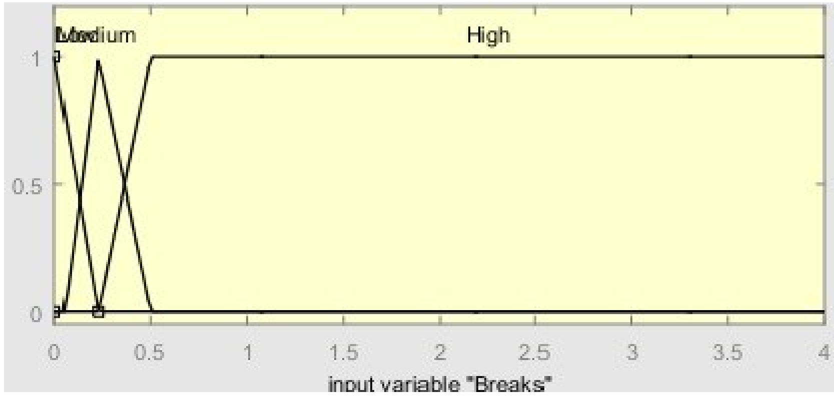


Figure V.3 Breaks input function

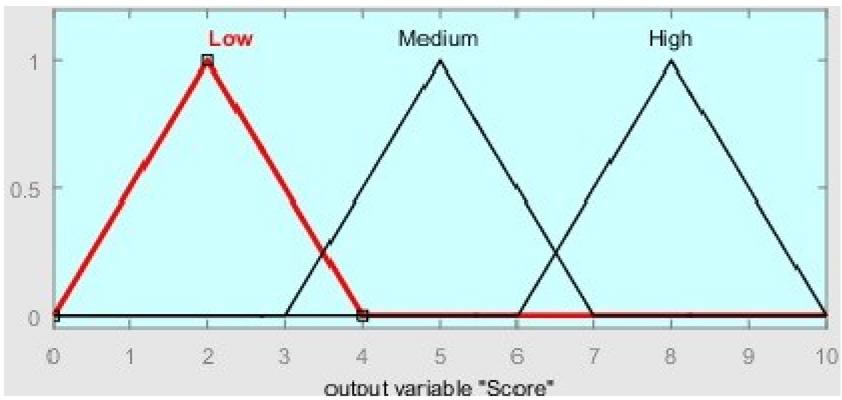


Figure V.4 Fuzzified attribute values output function

Rule 1:
If No. of Breaks (B) is High (HI)
Then the attribute value (R) is Low (L)
Rule 2:
If No. of Breaks (B) is Medium (ME)
Then the attribute value (R) is Medium (M)
Rule 3:
If No. of Breaks (B) is Low (LO)
Then the attribute value (R) is High (H)

Figure V.5 No. of breaks rules for the fuzzy expert system

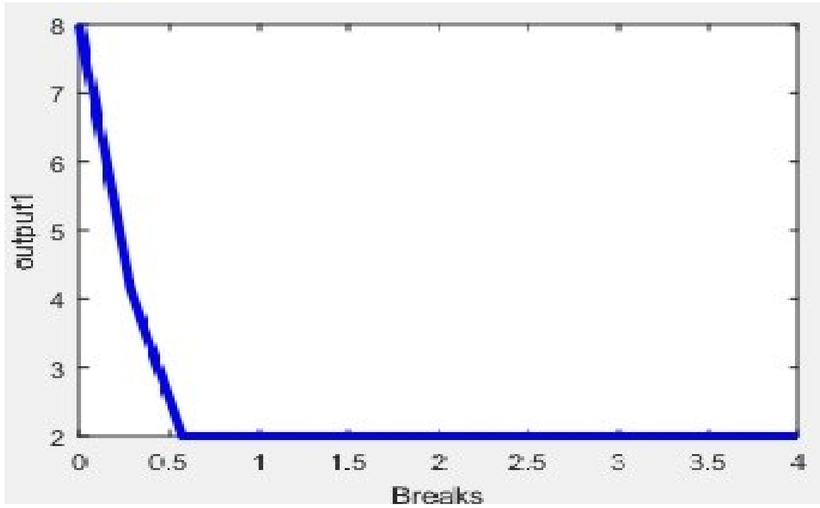


Figure V.6 Surface curve for breaks "fuzzy expert system"

Table V.12 Attribute values of the performance indicators of pipelines from City of Moncton

Sub-network (2)

P#	A	M	D	I.Q	T	G.W.T	S.T	L	C-f	BR	LR	R.R	W.Q	S.I	C.S	N.H
1	2.00	7.00	2.00	9.00	2.00	6.00	5.00	5.00	7.00	6.00	6.00	3.00	2.00	6.00	6.00	6.00
2	2.00	7.00	2.00	9.00	2.00	6.00	5.00	5.00	7.00	6.00	6.00	3.00	2.00	6.00	6.00	6.00
3	1.38	9.00	2.00	7.00	4.00	6.00	5.00	5.00	5.00	6.00	6.00	3.00	9.00	5.00	6.00	6.00
4	2.00	7.00	2.00	9.00	2.00	6.00	5.00	5.00	7.00	3.00	3.00	3.00	2.00	6.00	6.00	6.00
5	1.40	9.00	2.00	7.00	4.00	6.00	5.00	5.00	6.00	3.00	3.00	3.00	9.00	5.00	6.00	6.00
6	1.40	9.00	2.00	7.00	2.00	6.00	5.00	5.00	6.00	2.00	2.00	3.00	9.00	5.00	6.00	6.00
7	2.00	7.00	2.00	9.00	2.00	6.00	5.00	5.00	7.00	6.00	6.00	3.00	2.00	6.00	6.00	6.00
8	2.00	7.00	2.00	9.00	2.00	6.00	5.00	5.00	7.00	6.00	6.00	3.00	2.00	6.00	6.00	6.00
9	1.38	9.00	2.00	7.00	4.00	6.00	5.00	5.00	5.00	4.00	6.00	3.00	9.00	5.00	6.00	6.00
10	1.38	9.00	2.00	7.00	2.00	6.00	5.00	5.00	5.00	1.00	0.00	3.00	9.00	5.00	6.00	6.00
11	1.50	9.00	4.00	9.00	8.00	6.00	5.00	5.00	6.00	6.00	6.00	3.00	9.00	6.00	6.00	6.00
12	1.50	9.00	2.00	9.00	2.00	6.00	5.00	5.00	7.00	6.00	6.00	3.00	9.00	6.00	6.00	6.00

V.5 Functional Performance Index (PROMETHEE)

PROMETHEE is used to reach to the functional performance indices as mentioned before. The main inputs for PROMETHEE are the weights from FANP and the assigned attribute values. As illustrated in the Chapter II, PROMETHEE is done in different steps;

V.5.1 Indicators Aggregation

As mentioned in the research methodology, PROMETHEE is mainly based on the outranking of any component between two limits. Those limits herein are defined as lower limit P_o (0) which means failing component and upper limit P_{10} (10) which means recently installed component in a perfect condition. By comparing the indicators attribute values for pipe number 1 (P_1) in sub-network 2 at City of Moncton with the lower and upper limits, the aggregation is performed as shown in Table V.13. As an example, the attribute value for the age of this pipe is allocated as (2); therefore, the aggregation between this indicator and the lower limit equals to (2), while with the upper limit equals to (8). The aggregation for the remaining components within this sub- network and for other sub-networks is performed and presented in Appendix (C).

V.5.2 Pseudo Criteria Thresholds

It is supposed to define the thresholds based on the collected responses of the questionnaire but as the collected data is not sufficient enough, they are assumed as follows; the Critical threshold equals (3) and the tolerance threshold equals (8) out of 10. This is the same scale as the attribute values and it is adapted for the quantitative range of each indicator based on its nature. Accordingly the gpf. is developed for all the indicators as shown in Figure V.7. This curve is used to calculate pseudo preference indices from the indicators aggregation. By applying pseudo on the attribute values of the age of pipe 1, it is converted from (2) to (0) on pseudo scale. Therefore, the aggregation is transformed from (2) with the lower limit to (0), and from (8) with the upper limit to (1) as shown in Table V.14. The calculations for the other components are done and presented in Appendix (C).

Table V.13 The performance aggregation for P_1, S.N 2 in City of Moncton

Pipe#1	P_o-P_o	P_o-P_1	P_o-P_{10}	P_1-P_o	P_1-P_1	P_1-P_{10}	P_{10}-P_o	P_{10}-P_1	P_{10}-P_{10}
Ph.1	0	0	0	2	0	0	10	8	0
Ph.2	0	0	0	7	0	0	10	3	0
Ph.3	0	0	0	2	0	0	10	8	0
Ph.4	0	0	0	9	0	0	10	1	0
Ph.5	0	0	0	2	0	0	10	8	0
ENV.1	0	0	0	6	0	0	10	4	0
ENV.2	0	0	0	5	0	0	10	5	0
ENV.3	0	0	0	5	0	0	10	5	0
Op.1	0	0	0	7	0	0	10	3	0
Op.2	0	0	0	6	0	0	10	4	0
Op.3	0	0	0	6	0	0	10	4	0
Op.4	0	0	0	3	0	0	10	7	0
QS.1	0	0	0	2	0	0	10	8	0
QS.2	0	0	0	6	0	0	10	4	0
QS.3	0	0	0	6	0	0	10	4	0
QS.4	0	0	0	6	0	0	10	4	0

V.5.3 Indicators Preference Index

The third step of PROMETHEE is calculating the indicators preference index. Indicators preference index can be described as the weighted average of the pseudo preference index and it is calculated using equations [III.13] to [III.22] by multiplying pseudo indices by the indicators global relative weights as shown in Table V.15. The remaining components are presented in Appendix (C).

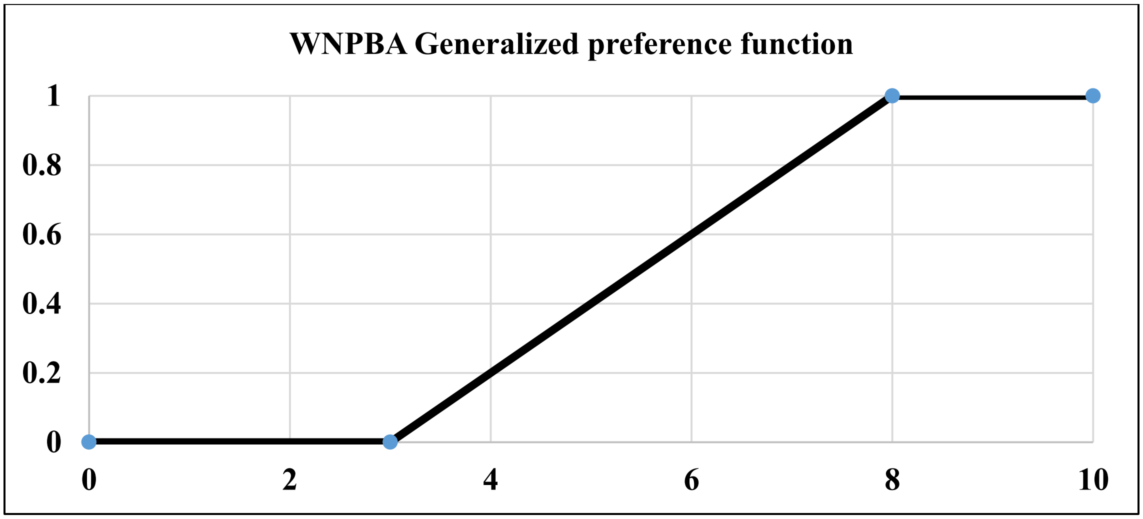


Figure V.7 WNPBA gpf. for all the performance indicators

Table V.14 Pseudo indices calculations for P_1 S.N (2) in City of Moncton

Pipe#1	P_o-P_o	P_o-P_1	P_o-P_{10}	P_1-P_o	P_1-P_1	P_1-P_{10}	P_{10}-P_o	P_{10}-P_1	P_{10}-P_{10}
Ph.1	0	0	0	0	0	0	1	1	0
Ph.2	0	0	0	0.8	0	0	1	0	0
Ph.3	0	0	0	0	0	0	1	1	0
Ph.4	0	0	0	1	0	0	1	0	0
Ph.5	0	0	0	0	0	0	1	1	0
ENV.1	0	0	0	0.6	0	0	1	0.2	0
ENV.2	0	0	0	0.4	0	0	1	0.4	0
ENV.3	0	0	0	0.4	0	0	1	0.4	0
Op.1	0	0	0	0.8	0	0	1	0	0
Op.2	0	0	0	0.6	0	0	1	0.2	0
Op.3	0	0	0	0.6	0	0	1	0.2	0
Op.4	0	0	0	0	0	0	1	0.8	0
QS.1	0	0	0	0	0	0	1	1	0
QS.2	0	0	0	0.6	0	0	1	0.2	0
QS.3	0	0	0	0.6	0	0	1	0.2	0
QS.4	0	0	0	0.6	0	0	1	0.2	0

Table V.15 Indicators preference indices for P_1, S.N (2) in City of Moncton

Pipe#1	P_o-P_o	P_o-P_1	P_o-P_{10}	P_1-P_o	P_1-P_1	P_1-P_{10}	P_{10}-P_o	P_{10}-P_1	P_{10}-P_{10}
Ph.1	0	0	0	0	0	0	0.0158	0.016	0
Ph.2	0	0	0	0.056	0	0	0.0516	0	0
Ph.3	0	0	0	0	0	0	0.0698	0.07591	0
Ph.4	0	0	0	0.015	0	0	0.01518	0	0
Ph.5	0	0	0	0	0	0	0.0759	0.0516	0
ENV.1	0	0	0	0.0018	0	0	0.1659	0.0006	0
ENV.2	0	0	0	0.0038	0	0	0.03159	0.0038	0
ENV.3	0	0	0	0.015	0	0	0.1659	0.01511	0
Op.1	0	0	0	0.025	0	0	0.03159	0	0
Op.2	0	0	0	0.0995	0	0	0.0384	0.0332	0
Op.3	0	0	0	0.0995	0	0	0.0126	0.0332	0
Op.4	0	0	0	0	0	0	0.1377	0.02527	0
QS.1	0	0	0	0	0	0	0.1377	0.1377	0
QS.2	0	0	0	0.023	0	0	0.0095	0.00769	0
QS.3	0	0	0	0.08	0	0	0.003	0.0275	0
QS.4	0	0	0	0.0076	0	0	0.038	0.0025	0

V.5.4 Net flows Calculation

The last step of PROMETHEE is calculating the net flows in order to obtain the functional performance indices. The net flows represent a measure of strength or weakness of the component. It is calculated using equations [III.25], [III.28], & [III.30]. The net flows are calculated by obtaining the difference between the measure of strength and the measure of weakness. Those measures are calculated by summing the results of multiplying the indicators local weights by the pseudo preference indices as shown in Table V.16 for pipe 1 from sub-network (2) in City of Moncton and for the two fictitious components which represent the limits. It is obvious that the net flow for the lower limit is always equal to (-1), while for the upper limit is (1) and the component (P_1) is always between them. This can be used as a check statement because it confirms the main assumptions the technique is based on. The net flows for the remaining components are presented in Appendix (C).

Table V.16 Net flows calculations for P_1, S.N (2) in City of Moncton (with Pseudo)

Pipe#1	P_{1+}	P_{1-}	$P_{1\ net}$	P_{o+}	P_{o-}	$P_{o\ net}$	P_{10+}	P_{10-}	$P_{10\ net}$
Ph.1 Ph.2 Ph.3 Ph.4 Ph.5	0.31	0.63	-0.32	0	1	-1	1	0	1
ENV.1 ENV.2 ENV.3	0.41	0.39	0.02	0	1	-1	1	0	1
Op.1 Op.2 Op.3 Op.4	0.57	0.23	0.34	0	1	-1	1	0	1
QS.1 QS.2 QS.3 QS.4	0.35	0.54	-0.19	0	1	-1	1	0	1

V.5.5 Functional Performance Index

The functional performance index is calculated by using equation [III.34]. It can also be calculated using the straight line conversion curve that convert the net flows from a scale ranging from (-1) to (1) in to a functional performance index on a scale ranging from (0) to (10) as shown in Figure V.8. The functional performance indices for the tested pipe are calculated using the curve and presented in Table V.17. The functional performance index for the upper limit equals to (10). On the other hand, the lower limit performance index equals to (0). While all the components fall in between (0) and (10). The previous steps are applied on sub-network 2 in City of Moncton and City of Montreal sub-network, and it is found that the physical function for the pipelines has almost critical performance indices in Moncton for 67% of the pipes, while in Montreal; the physical indices are good for almost 89% of the pipes. The environmental function for all the sub-network is medium or critical with a PI equals to (5.1) in City of Moncton and (3.8) in city of Montreal. According to the results, the operational function has different ranges; 19 pipes are critical (E-Grade), 2 pipes are Poor (D-Grade), 1 pipe is medium (C-Grade) and 41 pipes are Excellent (A-Grade) in the city of Montreal, while 7 are good, 1 is medium and 4 are critical in City of Moncton sub network (2). Finally the quality of service function is always not lower than medium performance for all the pipes of the two sub-networks. On the other hand, the accessories physical function is mostly good. The operational indices are either in the poor or critical range or in the range of excellent or good and this difference is mainly because of the difference in the breakage rate. The environmental and quality of service function have the same PIs as the pipelines. The analyzed results are presented in Table V.18 & Table V.19 for City of Moncton sub-network 2 and in Table V.20 & Table V.21 for City of Montreal sub-network. The performance indices without considering Pseudo criteria are presented in Appendix (C).

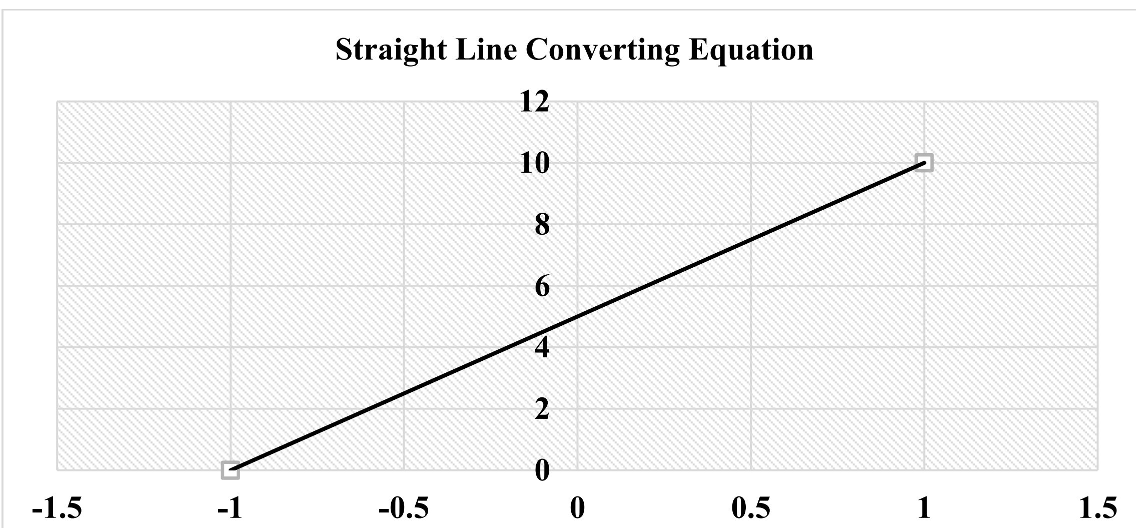


Figure V.8 Straight line converting equation from PROMETHEE output to FPI

Table V.17 Functional performance indices calculations for P_1, S.N (2) in Moncton

Function	Indicator#	P_{1+}	P_{1-}	P_{1net}	FPI
Physical	Ph.1	0.31	0.63	-0.32	3.4
	Ph.2				
	Ph.3				
	Ph.4				
	Ph.5				
Environmental	ENV.1	0.41	0.39	0.02	5.1
	ENV.2				
	ENV.3				
Operational	Op.1	0.57	0.23	0.34	6.7
	Op.2				
	Op.3				
	Op.4				
Quality of service	QS.1	0.35	0.54	-0.19	4.05
	QS.2				
	QS.3				
	QS.4				

Table V.18 Pipelines FPI for S.N (2)

Pipe #	PPPI	PEPI	POPI	PQPI
1	3.4	5.1	6.7	4.0
2	3.4	5.1	6.7	4.0
3	4.3	5.1	6.4	8.0
4	3.4	5.1	1.6	4.0
5	4.3	5.1	1.5	8.0
6	3.7	5.1	0.6	8.0
7	3.4	5.1	6.7	4.0
8	3.4	5.1	6.7	4.0
9	4.3	5.1	4.7	8.0
10	3.7	5.1	0.5	8.0
11	7.0	5.1	6.5	8.3
12	3.7	5.1	6.7	8.3

Table V.19 Accessories FPI for S.N (2)

Acc. #	PPPI	PEPI	POPI	PQPI
1	7.8	5.1	6.7	4.0
2	7.8	5.1	6.7	8.3
3	7.8	5.1	6.4	8.3
4	8.2	5.1	6.7	4.0
5	7.8	5.1	1.5	8.3
6	8.2	5.1	1.5	8.3
7	8.2	5.1	0.8	4.0
8	7.8	5.1	6.7	4.0
9	7.8	5.1	6.4	8.3
10	8.2	5.1	3.0	8.0
11	8.2	5.1	0.6	8.0
12	8.4	5.1	6.7	4.0
13	8.4	5.1	6.7	4.0

Table V.20 Pipelines functional performance indices for Montreal sub-network

Pipe #	PPI	EPI	OPI	QPI
1	7.498	3.761	0.640	4.450
2	8.114	3.761	9.360	9.845
3	7.285	3.761	9.040	9.845
4	7.285	3.761	0.640	4.450
5	9.305	3.761	9.200	9.845
6	7.498	3.761	9.040	9.845
7	7.577	3.761	9.680	9.845
8	7.976	3.761	9.040	9.845
9	7.498	3.761	0.800	4.450
10	7.498	3.761	9.200	9.845
11	7.976	3.761	9.200	9.845
12	7.577	3.761	9.680	9.845
13	7.976	3.761	9.040	9.845
14	7.975	3.761	9.680	9.845
15	7.301	3.761	9.520	9.845
16	7.976	3.761	9.040	9.845
17	7.976	3.761	0.640	4.450
18	7.976	3.761	0.640	4.450
19	7.976	3.761	9.040	9.845
20	7.976	3.761	9.040	9.845
21	7.285	3.761	2.480	5.529
22	7.976	3.761	0.640	4.450
23	5.717	3.761	9.040	9.845
24	7.779	3.761	9.520	9.845
25	7.285	3.761	9.040	9.845
26	7.498	3.761	2.320	5.529
27	7.046	3.761	0.800	4.450
28	7.285	3.761	9.040	9.845
29	7.498	3.761	0.800	4.450
30	7.498	3.761	4.000	6.608
31	7.025	3.761	0.960	4.450
32	7.025	3.761	9.360	9.845
33	7.577	3.761	9.680	9.845
34	5.717	3.761	0.640	4.450
35	7.285	3.761	0.800	4.450
36	8.188	3.761	9.680	9.845
37	7.285	3.761	9.040	9.845
38	7.046	3.761	9.200	9.845

Pipe #	PPI	EPI	OPI	QPI
39	8.055	3.761	9.680	9.845
40	7.498	3.761	2.320	5.529
41	7.498	3.761	6.320	7.687
42	7.976	3.761	0.640	4.450
43	7.285	3.761	9.200	9.845
44	7.976	3.761	9.040	9.845
45	7.976	3.761	9.040	9.845
46	7.577	3.761	9.680	9.845
47	7.498	3.761	9.040	9.845
48	7.498	3.761	9.040	9.845
49	7.498	3.761	9.200	9.845
50	7.498	3.761	9.200	9.845
51	7.498	3.761	9.200	9.845
52	7.636	3.761	9.360	9.845
53	7.285	3.761	0.480	4.450
54	7.285	3.761	9.040	9.845
55	7.285	3.761	9.040	9.845
56	7.285	3.761	2.160	5.529
57	7.498	3.761	9.200	9.845
58	7.498	3.761	9.040	9.845
59	7.285	3.761	3.840	6.608
60	8.188	3.761	9.680	9.845
61	7.976	3.761	8.880	9.845
62	7.046	3.761	9.040	9.845
63	7.498	3.761	0.640	4.450

Table V.21 Accessories functional performance indices for Montreal sub-network

Accessory #	PPI	EPI	OPI	QPI
1	6.515	3.761	0.640	4.450
2	6.515	3.761	0.640	4.450
3	6.515	3.761	9.360	9.845
4	6.515	3.761	0.800	4.450
5	6.515	3.761	0.800	4.450
6	6.515	3.761	9.200	9.845
7	6.515	3.761	9.040	9.845
8	6.515	3.761	0.640	4.450
9	6.515	3.761	0.640	4.450
10	6.515	3.761	0.640	4.450
11	6.515	3.761	0.640	4.450
12	6.515	3.761	0.640	4.450
13	6.515	3.761	0.640	4.450
14	6.515	3.761	0.640	4.450
15	6.515	3.761	0.640	4.450
16	6.515	3.761	2.480	5.529
17	6.515	3.761	9.040	9.845
18	6.515	3.761	0.800	4.450
19	6.515	3.761	9.200	9.845
20	6.180	3.761	9.520	9.845
21	6.515	3.761	0.640	4.450
22	6.515	3.761	9.040	9.845
23	6.515	3.761	0.800	4.450
24	6.515	3.761	0.800	4.450
25	6.515	3.761	9.040	9.845
26	6.515	3.761	0.640	4.450
27	6.515	3.761	0.640	4.450
28	6.515	3.761	9.040	9.845
29	6.515	3.761	9.040	9.845
30	6.515	3.761	9.040	9.845
31	6.515	3.761	9.040	9.845
32	6.515	3.761	9.200	9.845
33	6.594	3.761	9.680	9.845
34	6.515	3.761	9.040	9.845
35	6.515	3.761	9.200	9.845
36	6.515	3.761	2.320	5.529
37	6.515	3.761	9.040	9.845
38	6.515	3.761	9.200	9.845
39	6.594	3.761	9.680	9.845

Accessory #	PPI	EPI	OPI	QPI
40	5.904	3.761	0.960	4.450
41	5.904	3.761	0.960	4.450
42	5.904	3.761	9.360	9.845
43	6.515	3.761	9.040	9.845
44	6.594	3.761	9.680	9.845
45	6.594	3.761	9.680	9.845
46	6.594	3.761	9.680	9.845
47	7.205	3.761	9.680	9.845
48	7.205	3.761	9.680	9.845
49	6.515	3.761	9.040	9.845
50	6.515	3.761	9.040	9.845
51	6.456	3.761	9.680	9.845
52	6.515	3.761	9.200	9.845
53	6.515	3.761	9.200	9.845
54	6.515	3.761	9.200	9.845
55	6.515	3.761	9.200	9.845
56	6.515	3.761	9.200	9.845
57	6.515	3.761	9.040	9.845
58	6.515	3.761	9.040	9.845
59	6.515	3.761	2.320	5.529
60	6.515	3.761	2.320	5.529
61	6.515	3.761	5.840	7.687
62	6.515	3.761	9.360	9.845
63	6.515	3.761	3.840	6.608
64	6.515	3.761	3.840	6.608
65	7.205	3.761	9.680	9.845
66	7.205	3.761	9.680	9.845
67	6.515	3.761	8.880	9.845
68	6.515	3.761	8.880	9.845
69	6.515	3.761	9.040	9.845
70	6.515	3.761	0.640	4.450
71	6.515	3.761	0.480	4.450
72	6.515	3.761	9.040	9.845
73	6.515	3.761	9.040	9.845
74	6.515	3.761	2.160	5.529
75	6.515	3.761	9.200	9.845
76	6.515	3.761	9.040	9.845
77	6.515	3.761	9.040	9.845
78	7.205	3.761	9.680	9.845

V.6 Global Performance Index (Multi Attribute Utility Theory)

The global performance index for each component is calculated by utilizing means of multi attribute utility theory (MAUT). The functional global weights and performance indices are considered the main inputs to the multiplicative function described in equation [III.35]. The outputs of this equation are the global performance indices. Table V.22 shows the calculations of the GPI for the tested pipe. The global performance indices for the components of the studied sub-networks and the linguistic description are obtained. It is found that most of City of Moncton sub-network 2 components are in Good or Medium state except; pipes (4 & 10) and accessory (7) which are in Poor state as shown in Tables V.23, & V.24. On the other hand, the pipelines in city of Montreal sub-network are graded as excellent for (16) pipes, good for (32) pipes and medium for (5) pipes, while the accessories are graded as Excellent for (49) accessories, Medium for (8) accessories and poor for (21) accessories as shown in Tables V.25 & V.26. The environmental function index does not have this much effect over the GPI because of its small weight of importance and because of the fact that it is constant for each sub-network. The functional and global indices are shown in Figures V.9, V.10, V.11 and V.12 for the components of the two sub-networks.

Table V.22 Global performance index calculations for P_1, S.N (2) in City of Moncton

Function	Indicator#	FPI	Function Weights	GPI
Physical	Ph.1	3.4	0.228	4.997
	Ph.2			
	Ph.3			
	Ph.4			
	Ph.5			
Environmental	ENV.1	5.1	0.050	
	ENV.2			
	ENV.3			
Operational	Op.1	6.7	0.395	
	Op.2			
	Op.3			
	Op.4			
Quality of service	QS.1	4.05	0.326	
	QS.2			
	QS.3			
	QS.4			

Table V.23 Pipelines GPI and grading description for S.N (2) in City of Moncton

Pipe #	GPI (with Pseudo)	Linguistic and grading description
1	5.00	Medium (C)
2	5.00	Medium (C)
3	6.38	Good (B)
4	3.01	Poor (D)
5	4.45	Medium (C)
6	4.00	Medium (C)
7	5.00	Medium (C)
8	5.00	Medium (C)
9	5.72	Medium (C)
10	3.90	Poor (D)
11	7.12	Good (B)
12	6.44	Good (B)

Table V.24 Accessories GPI and grading description for S.N (2) in City of Moncton

Accessory #	GPI (with Pseudo)	Linguistic and grading description
1	6.0	Good (B)
2	7.4	Good (B)
3	7.2	Good (B)
4	6.1	Good (B)
5	5.3	Medium (C)
6	5.4	Medium (C)
7	3.8	Poor (D)
8	6.0	Medium (C)
9	7.2	Good (B)
10	5.9	Medium (C)
11	5.0	Medium (C)
12	6.1	Good (B)
13	6.1	Good (B)

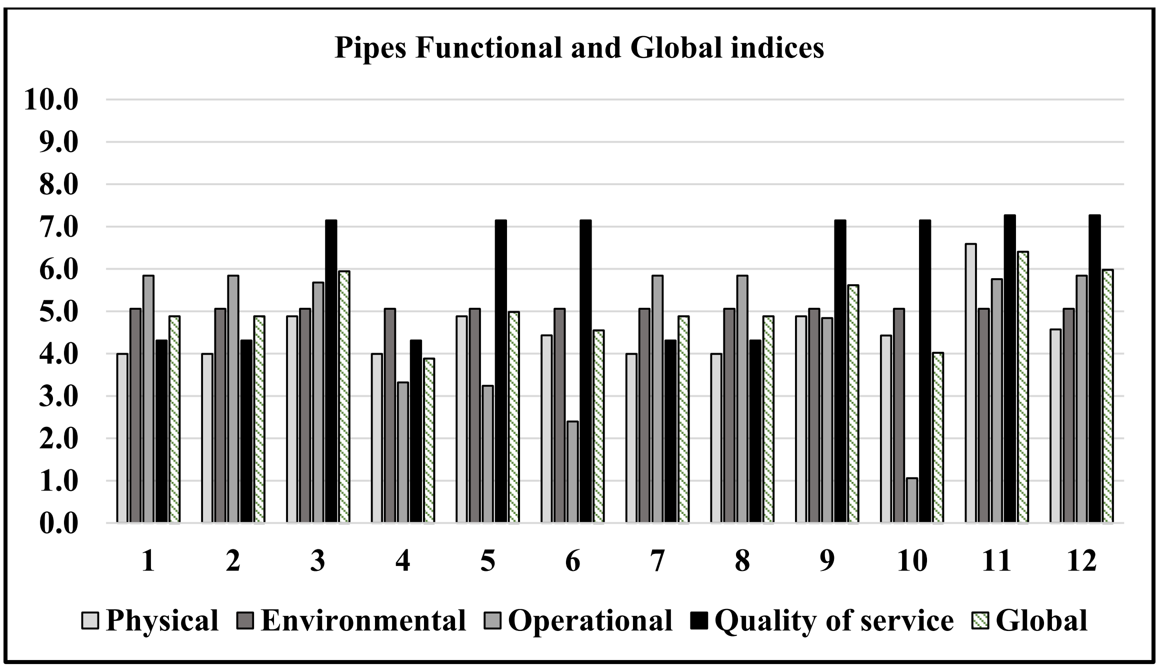


Figure V.9 Pipes functional and global indices, sub-network (2), City of Moncton

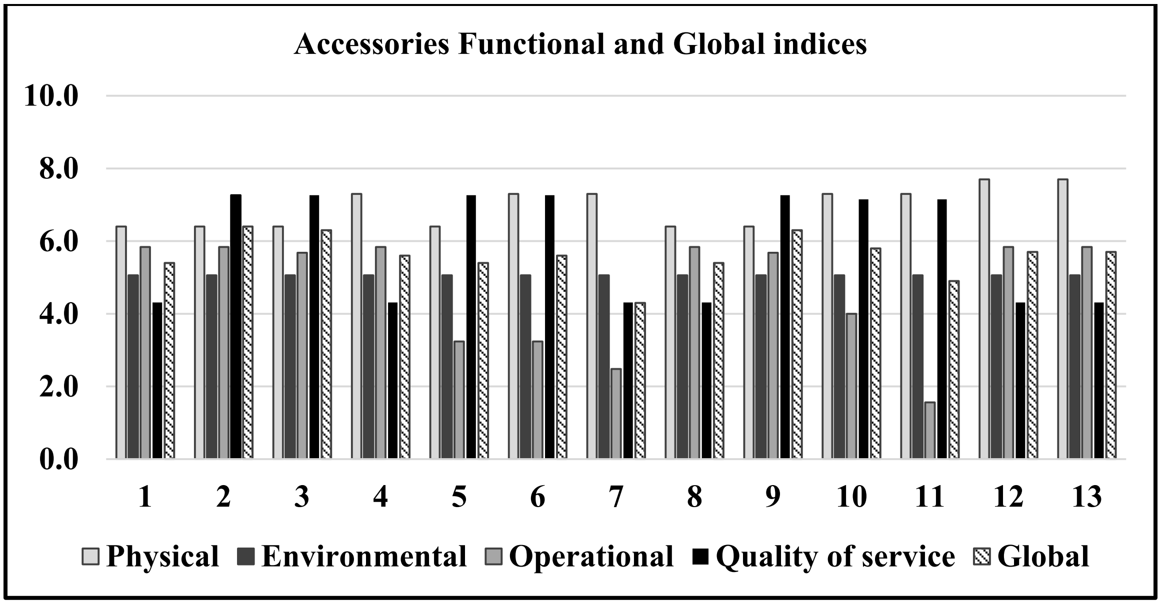


Figure V.10 Accessories functional and global indices, sub-network (2), City of Moncton

V.7 Network Performance Indices

Water network performance index is calculated by obtaining the performance indices of its components. Then, integrating each segment components together is performed in order to obtain the segment PI. After that, the segments are integrated together to calculate the sub-network PI. Finally by utilizing the sub-network PIs, the entire network PI is calculated.

V.7.1 Segments Performance Indices

As mentioned in Chapter III, the double scale is used to convert the PI of each component to a probability of success and therefore a probability of failure. By using the probability theory means; the probability of success of each segment is calculated by multiplying the probability of success of its components. Accordingly, the probability of failure is calculated as well. The segment probability of failure equals to the probability of at least one component fail within the segment as it will interrupt the service within it. By dividing the probability of failure of each component over the probability of failure of the segment, the weighted failure for each component is calculated. This step shows the probability that any component within a segment could be the reason for its failure. Finally; by summing the weighted failure of all the components within a segment and normalizing them over the summation, the weights of importance of each component within the segments can be calculated beside the segment performance index. As an example, segment (1) within the sub-network (2) of City of Moncton, the components PIs are converted to P.O.S equals to 0.5 and 0.6, 0.74 for the pipe and the two accessories respectively. Therefore, the P.O.F of the three components is 0.5, 0.4, & 0.26 for the pipe and the two accessories respectively. The P.O.S of the segment equals to (0.5*0.6*0.74=0.222) and the probability of segment failure equals to (1-0.222=0.778). Then the weighted average is calculated as 0.64, 0.514 and 0.32 for the three components respectively. By applying summation and normalization, weights of importance are calculated as 0.434, 0.35, 0.217 for the pipe and the two accessories respectively. By multiplying the weights of importance and the GPI for each component and summing the results, the SPI is calculated as 5.88. The calculated weights of importance demonstrate the usage of this technique as it provides the pipe which has the lowest PI within the segment components (PI= 5.00) with the highest weight of importance (0.434). Moreover, the second accessory which has the highest PI (7.40), has the lowest weight of importance (0.217). These values make sense because whenever the component has a low PI, it will be more influential to the failure of the segment and vice versa. The calculations for the studied sub-network are presented in Tables V.27, & V.28. The weights of importance of the pipes and accessories within each segment are presented in Table V.27 and Figure V.13. The calculations for the remaining case studies are presented in Appendix (C).

Table V.25 Pipelines GPI and grading description for Montreal sub-network

Pipe #	GPI	Description
1	3.61	Medium (C)
2	8.95	Excellent (A)
3	8.64	Good (B)
4	3.56	Excellent (A)
5	9.16	Excellent (A)
6	8.69	Good (B)
7	8.96	Excellent (A)
8	8.79	Good (B)
9	3.67	Medium (C)
10	8.75	Good (B)
11	8.86	Good (B)
12	8.96	Excellent (A)
13	8.79	Good (B)
14	9.05	Excellent (A)
15	8.83	Good (B)
16	8.79	Good (B)
17	3.72	Medium (C)
18	3.72	Medium (C)
19	8.79	Good (B)
20	8.79	Good (B)
21	4.64	Medium (C)
22	3.72	Medium (C)
23	8.28	Good (B)
24	8.94	Excellent (A)
25	8.64	Good (B)
26	4.62	Medium (C)
27	3.57	Medium (C)
28	8.64	Good (B)
29	3.67	Excellent (A)
30	5.64	Medium (C)
31	3.63	Excellent (A)
32	8.70	Good (B)
33	8.96	Excellent (A)
34	3.20	Medium (C)
35	3.62	Medium (C)
36	9.10	Excellent (A)

Pipe #	GPI	Description
37	8.64	Good (B)
38	8.65	Good (B)
39	9.07	Excellent (A)
40	4.62	Medium (C)
41	6.91	Good (B)
42	3.72	Excellent (A)
43	8.70	Good (B)
44	8.79	Good (B)
45	8.79	Good (B)
46	8.96	Excellent (A)
47	8.69	Good (B)
48	8.69	Good (B)
49	8.75	Good (B)
50	8.75	Good (B)
51	8.75	Good (B)
52	8.84	Good (B)
53	3.50	Medium (C)
54	8.64	Good (B)
55	8.64	Good (B)
56	4.51	Medium (C)
57	8.75	Good (B)
58	8.69	Good (B)
59	5.53	Medium (C)
60	9.10	Excellent (A)
61	8.73	Good (B)
62	8.58	Good (B)
63	3.61	Excellent (A)

Table V.26 Accessories GPI and grading description for Montreal sub-network

Accessory #	GPI	Description
1	3.38	Poor (D)
2	3.38	Poor (D)
3	8.59	Excellent (A)
4	3.45	Poor (D)
5	3.45	Poor (D)
6	8.52	Excellent (A)
7	8.46	Excellent (A)
8	3.38	Poor (D)
9	3.38	Poor (D)
10	3.38	Poor (D)
11	3.38	Poor (D)
12	3.38	Poor (D)
13	3.38	Poor (D)
14	3.38	Poor (D)
15	3.38	Poor (D)
16	4.46	Medium (C)
17	8.46	Excellent (A)
18	3.45	Poor (D)
19	8.52	Excellent (A)
20	8.57	Excellent (A)
21	3.38	Poor (D)
22	8.46	Excellent (A)
23	3.45	Excellent (A)
24	3.45	Poor (D)
25	8.46	Excellent (A)
26	3.38	Poor (D)
27	3.38	Poor (D)
28	8.46	Excellent (A)
29	8.46	Excellent (A)
30	8.46	Excellent (A)
31	8.46	Excellent (A)
32	8.52	Excellent (A)
33	8.73	Excellent (A)
34	8.46	Excellent (A)
35	8.52	Excellent (A)
36	4.40	Medium (C)
37	8.46	Excellent (A)
38	8.52	Excellent (A)
39	8.73	Excellent (A)

Accessory #	GPI	Description
40	3.37	Poor (D)
41	3.37	Poor (D)
42	8.45	Excellent (A)
43	8.46	Excellent (A)
44	8.73	Excellent (A)
45	8.73	Excellent (A)
46	8.73	Excellent (A)
47	8.87	Excellent (A)
48	8.87	Excellent (A)
49	8.46	Excellent (A)
50	8.46	Excellent (A)
51	8.70	Excellent (A)
52	8.52	Excellent (A)
53	8.52	Excellent (A)
54	8.52	Excellent (A)
55	8.52	Excellent (A)
56	8.52	Excellent (A)
57	8.46	Excellent (A)
58	8.46	Excellent (A)
59	4.40	Medium (C)
60	4.40	Medium (C)
61	6.49	Medium (C)
62	8.59	Excellent (A)
63	5.35	Medium (C)
64	5.35	Medium (C)
65	8.87	Excellent (A)
66	8.87	Excellent (A)
67	8.40	Excellent (A)
68	8.40	Excellent (A)
69	8.46	Excellent (A)
70	3.38	Poor (D)
71	3.32	Poor (D)
72	8.46	Excellent (A)
73	8.46	Excellent (A)
74	4.33	Medium (C)
75	8.52	Excellent (A)
76	8.46	Excellent (A)
77	8.46	Excellent (A)
78	8.87	Excellent (A)

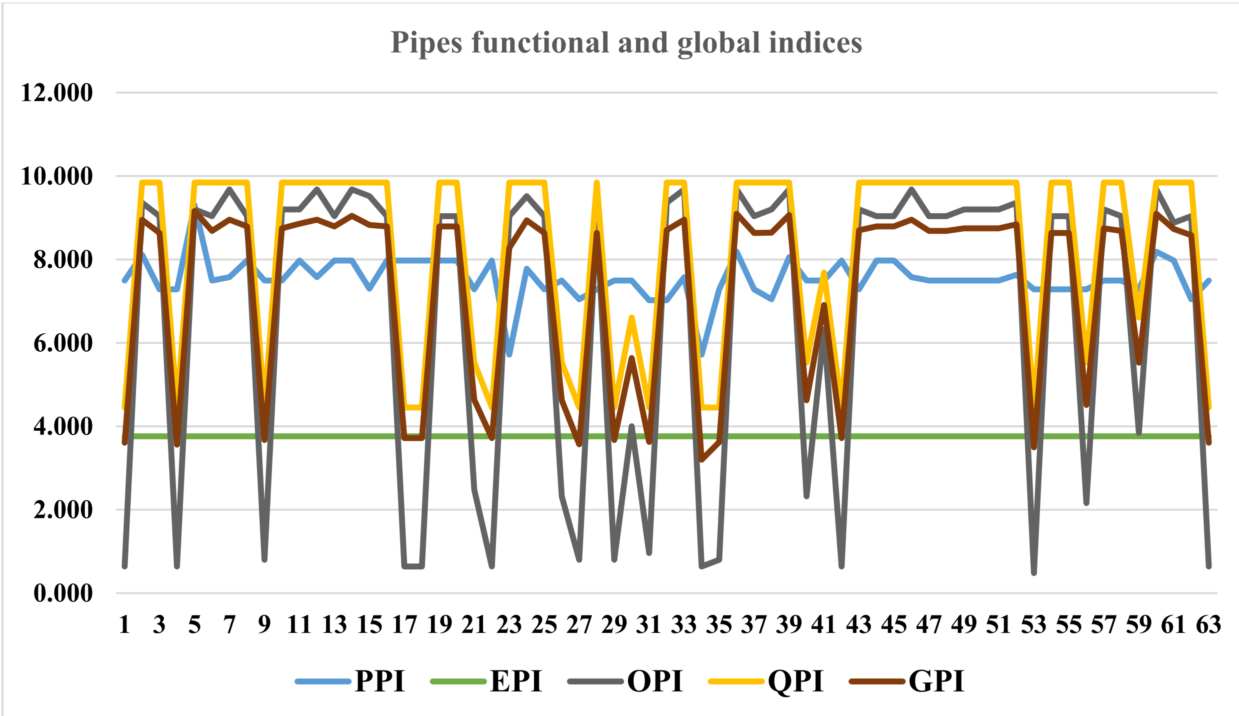


Figure V.11 Pipes functional and global indices, sub-network (2), City of Montreal

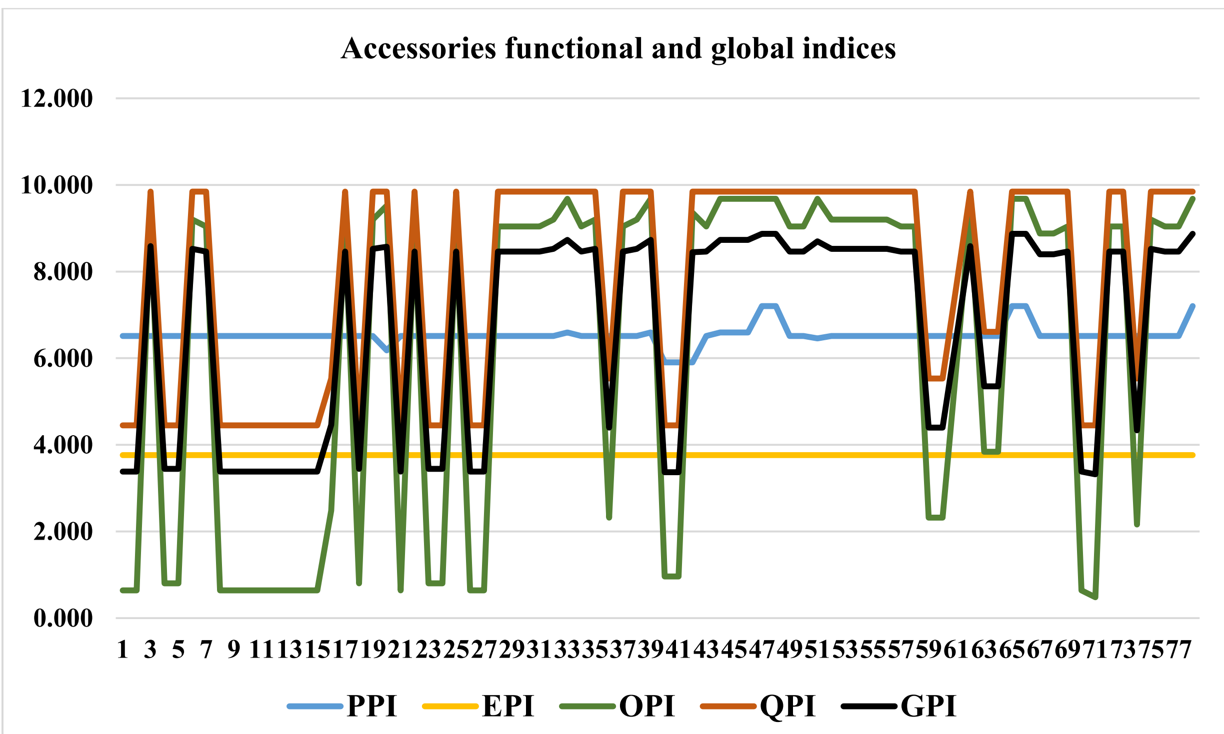


Figure V.12 Accessories functional and global indices, S.N 2, City of Montreal

Table V.27 Pipes/Accessories weights of importance calculations for sub-netowrk (2), City of Moncton

Segment #	No. pipes	No. accessories	P.O.S pipes	P.O.S Accessories	P.O.S segment	P.O.F one component	P.O.F pipes	P.O.F Accessories	Weighted Pipes failure	Weighted Accessories failure	Sum	Weights of importance	
1	1.00	2.00	0.50	0.60	0.22	0.78	0.51	0.45	0.66	0.58	1.70	0.39	0.34
				0.74				0.36		0.46			0.27
2	1.00	1.00	0.50	0.72	0.36	0.64	0.51	0.36	0.80	0.57	1.37	0.59	0.41
3	1.00	1.00	0.64	0.61	0.39	0.61	0.41	0.43	0.66	0.71	1.37	0.48	0.52
4	1.00	1.00	0.30	0.53	0.16	0.84	0.61	0.46	0.73	0.55	1.27	0.57	0.43
5	1.00	1.00	0.45	0.54	0.24	0.76	0.50	0.44	0.66	0.58	1.24	0.53	0.47
6	1.00	1.00	0.40	0.38	0.15	0.85	0.55	0.57	0.64	0.67	1.31	0.49	0.51
7	1.00	1.00	0.50	0.60	0.30	0.70	0.51	0.50	0.73	0.72	1.45	0.50	0.50
8	1.00	1.00	0.50	0.72	0.36	0.64	0.51	0.36	0.80	0.57	1.37	0.59	0.41
9	1.00	1.00	0.57	0.59	0.34	0.66	0.44	0.41	0.66	0.62	1.29	0.51	0.49
10	1.00	1.00	0.39	0.50	0.20	0.81	0.60	0.51	0.74	0.63	1.38	0.54	0.46
11	1.00	1.00	0.71	0.61	0.43	0.57	0.36	0.42	0.64	0.75	1.39	0.46	0.54
12	1.00	1.00	0.64	0.61	0.39	0.61	0.40	0.42	0.66	0.70	1.36	0.49	0.51

Table V.28 Segments performance indices calculations for S.N (2), City of Moncton

Weight of importance		GPPI (WNPA Model)	GAPI (WNPA Model)	Segment PI
0.39	0.34	5.00	6.00	5.99
	0.27		7.40	
0.59	0.41	5.00	7.20	5.91
0.48	0.52	6.38	6.10	6.24
0.57	0.43	3.01	5.30	3.99
0.53	0.47	4.45	5.40	4.89
0.49	0.51	3.97	3.80	3.88
0.50	0.50	5.00	6.00	5.50
0.59	0.41	5.00	7.20	5.91
0.51	0.49	5.72	5.90	5.81
0.54	0.46	3.90	5.00	4.41
0.46	0.54	7.12	6.10	6.57
0.49	0.51	6.44	6.10	6.27

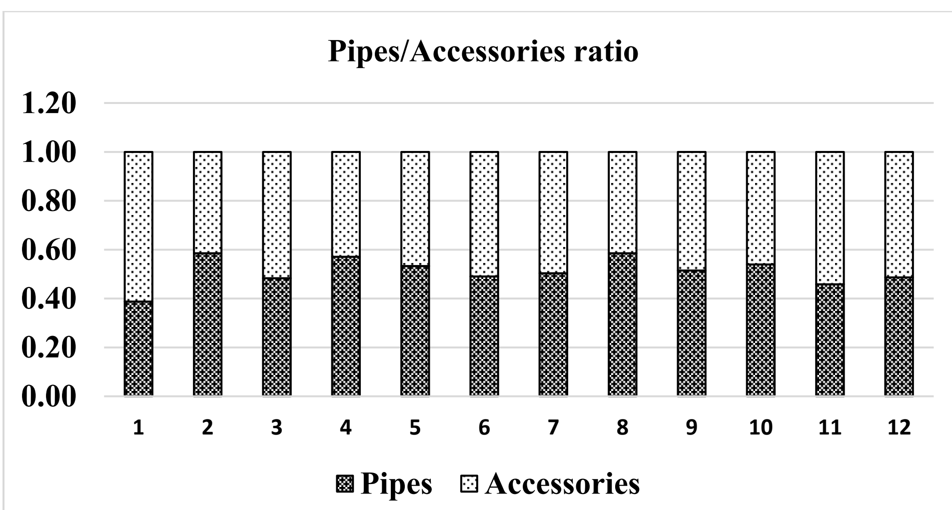


Figure V.13 Pipes/Accessories weights of importance

V.7.2 Sub-Networks Performance Indices

After calculating the segments PI, the methodology adapted from the Topological clustering means is used to integrate the segments' performance indices to obtain the sub-network PI. Firstly the topological chart is drawn as shown in Figures V.14 & V.15 for City of Moncton sub network 2 and Montreal sub-network respectively. Then the connectivity ranked matrix is formulated based on the rules mentioned in the methodology as illustrated in Table V.29. Finally, by applying summation and normalization, the weight of importance of each segment within the sub-network is calculated and by multiplying those weights by the segments indices, the sub-network PI is calculated. As an example, segment (11) which is the feeding segment to the entire sub-network and it is considered connected to all segments with different degrees of connectivity. Segment (11) is assumed to be firstly dependent on itself so a value of (0.1) is assigned for it in the connectivity matrix (0.1 is utilized rather than 0 in the original technique as an assumption through this research to avoid having 0 weight of importance). It is also connected directly to segments 10, 9 & 12; therefore a value 1 is assigned to the three segments in the matrix. Then segment 9 is connected directly to segments 8 and 5. Thus, the assigned value to those segments is 2 as they represent the second level of connectivity for segment 11 and so on. The matrix formulation continues through different levels of connections. After completing the matrix, the summation and normalization are applied. The weight of importance of segment 11 represents almost 50%, which makes sense as this is the feeding segment for the entire sub-network and its failure causes service interruption to the sub-network. The analyzed sub-network PI is calculated as (6.09) as shown in Table V.30. The same calculations are done for Montreal Case study and the results are as shown in Table V.31.

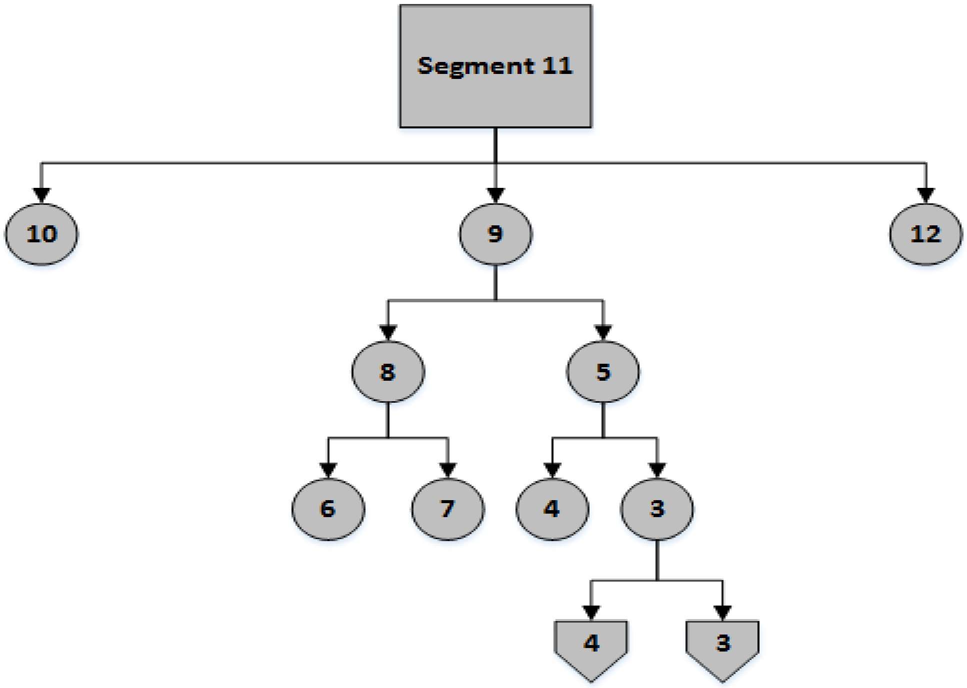


Figure V.14 Topological chart for sub-network (2), City of Moncton

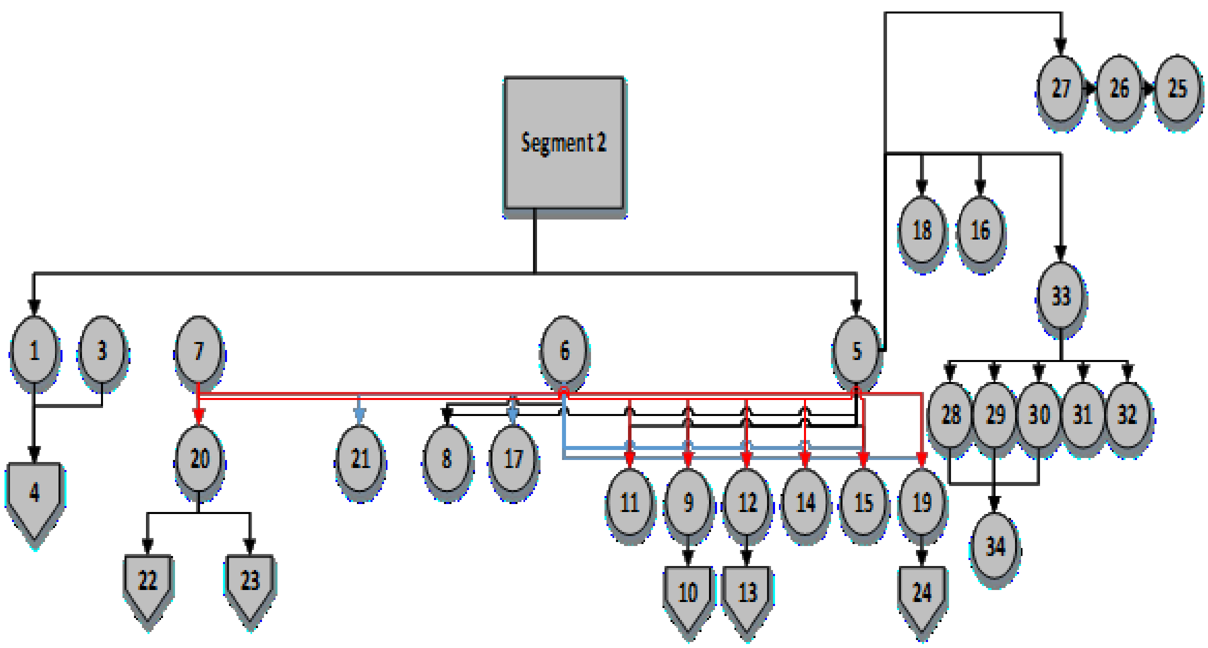


Figure V.15 Topological chart for Montreal sub-network

Table V.29 Connectivity ranked matrix for segments of S.N 2 in City of Moncton

Connectivity Ranked Matrix														
	11.00	10.00	9.00	12.00	8	5.00	7.00	6.00	4.00	3.00	2.00	1.00	Sum	
11	0.10	1.00	1.00	1.00	2.00	2.00	3.00	3.00	3.00	3.00	4.00	4	27.10	0.499
10	0.10	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.004
9	0.00	0.00	0.10	0.00	1.00	1.00	2.00	2.00	2.00	2.00	3.00	3.00	16.10	0.297
12	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.002
8	0.00	0.00	0.00	0.00	0.10	0.00	1.00	1.00	0.00	0.00	0.00	0.00	2.10	0.039
5	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	1.00	1.00	2.00	2.00	6.10	0.112
7	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.10	0.002
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.10	0.002
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.10	0.002
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	1.00	1.00	2.10	0.039
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.10	0.002
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.002
												Sum	54.30	

Table V.30 sub-network (2), City of Moncton, performance index calculations

Segment #	Segment PI	Segment weight	Weighted Segment PI
1	**5.99**	0.002	0.01
2	**5.91**	0.002	0.01
3	**6.24**	0.039	0.24
4	**3.99**	0.002	0.01
5	**4.89**	0.112	0.55
6	**3.88**	0.002	0.01
7	**5.50**	0.002	0.01
8	**5.91**	0.039	0.23
9	**5.81**	0.297	1.72
10	**4.41**	0.004	0.02
11	**6.57**	0.499	3.28
12	**6.27**	0.002	0.01
Sub-Network PI		**6.09**	

Table V.31 Montreal sub-network performance index calculations

S#	Weight of importance		GPPI	GAPI	S.PI	Segment weight
1	0.33	0.34	3.61	3.38	3.46	0.005
	0.00	0.34	0.00	3.38		
2	0.04	0.06	8.95	8.59	4.61	0.386
	0.05	0.27	8.75	3.45		
	0.26	0.27	3.67	3.45		
	0.00	0.06	0.00	8.52		
3	0.47	0.53	8.64	8.46	8.54	0.005
	0.00	0.00	0.00	0.00		
	0.00	0.00	0.00	0.00		
4	0.25	0.25	3.56	3.38	3.43	0.005
	0.00	0.25	0.00	3.38		
	0.00	0.25	0.00	3.38		
	0.00	0.00	0.00	0.00		
5	0.12	0.12	3.72	3.38	3.56	0.188
	0.12	0.12	3.72	3.38		
	0.13	0.12	3.20	3.38		
	0.02	0.12	8.78	3.38		
	0.00	0.12	0.00	3.38		
6	0.17	0.18	4.64	4.46	4.95	0.174
	0.06	0.05	8.28	8.46		
	0.21	0.21	3.62	3.45		
	0.07	0.05	7.82	8.52		
7	0.03	0.04	8.83	8.57	4.24	0.097
	0.17	0.17	3.57	3.38		
	0.04	0.04	8.64	8.46		
	0.17	0.17	3.67	3.45		
	0.00	0.17	0.00	3.45		
8	0.05	0.07	8.80	8.46	4.12	0.005
	0.28	0.30	3.72	3.38		
	0.00	0.30	0.00	3.38		
9	0.12	0.16	8.80	8.46	8.58	0.005
	0.12	0.16	8.80	8.46		
	0.12	0.16	8.80	8.46		
	0.00	0.16	0.00	8.46		

S#	Weight of importance		GPPI	GAPI	S.PI	Segment weight
13	0.59	0.41	8.19	8.73	8.41	0.006
14	0.28	0.30	3.63	3.37	4.10	0.005
	0.06	0.30	8.70	3.37		
	0.00	0.07	0.00	8.45		
15	0.14	0.16	8.69	8.46	7.29	0.005
	0.11	0.13	8.96	8.73		
	0.46	0.00	5.64	0.00		
16	0.29	0.35	8.96	8.73	8.80	0.005
	0.00	0.35	0.00	8.73		
17	0.44	0.28	8.22	8.87	8.58	0.005
	0.00	0.28	0.00	8.87		
18	0.44	0.56	8.80	8.46	8.61	0.005
19	0.37	0.27	7.92	8.46	8.07	0.005
	0.37	0.00	7.92	0.00		
20	0.60	0.40	8.08	8.70	8.33	0.020
21	0.59	0.41	7.87	8.52	8.14	0.005
22	0.42	0.29	7.87	8.52	8.25	0.005
	0.00	0.29	0.00	8.52		
23	0.42	0.29	7.87	8.52	8.25	0.005
	0.00	0.29	0.00	8.52		
24	0.29	0.21	7.81	8.46	8.08	0.005
	0.29	0.21	7.81	8.46		
25	0.30	0.35	5.16	4.40	4.63	0.005
	0.00	0.35	0.00	4.40		
26	0.50	0.50	6.55	6.49	6.52	0.005
27	0.59	0.41	7.97	8.59	8.22	0.015
28	0.32	0.34	5.71	5.35	5.46	0.005
	0.00	0.34	0.00	5.35		
29	0.44	0.28	8.22	8.87	8.58	0.005
	0.00	0.28	0.00	8.87		
30	0.40	0.30	7.86	8.40	8.18	0.005
	0.00	0.30	0.00	8.40		
31	0.60	0.40	7.71	8.46	8.01	0.005
32	0.42	0.58	5.20	3.38	4.15	0.005

10	0.23	0.30	8.86	8.52	8.75	0.005		33	0.18	0.22	4.38	3.32	5.16	0.034
	0.21	0.26	8.96	8.73					0.07	0.05	7.76	8.46		
11	0.27	0.39	8.94	8.46	8.65	0.005			0.07	0.05	7.76	8.46		
	0.34	0.00	8.64	0.00					0.16	0.19	5.04	4.34		
12	0.04	0.07	9.16	8.52	6.26	0.010		34	0.24	0.17	7.87	8.52	8.17	0.000
	0.26	0.27	4.62	4.40					0.25	0.17	7.81	8.46		
	0.11	0.07	7.76	8.46					0.00	0.17	0.00	8.46		
	0.11	0.07	7.77	8.52				35	0.46	0.54	9.05	8.87	8.95	0.005
13	0.59	0.41	8.19	8.73	8.41	0.006						**Sub-Network PI**		**4.78**

V.7.3 Network Performance Index

The two sub-networks of City of Moncton are integrated using a combination between three weights of importance for each. Firstly, the weights from the connectivity matrix that is built between the sub-networks as mentioned in the methodology chapter. Secondly, the length weight of importance and finally, the land use weight of importance.

The certainty within the calculated network PI is not high, because of the data that covered only two sub-networks. This research is arguing that if the total data for all the sub-networks within the entire network is available, the model would have provided more accurate results. The integrated weights herein are just the length weight of importance and the land use weight of importance as sub-network (1) is assumed to be residential, while sub-network (2) is industrial. The land use is categorized in to six categories and their weights of importance are calculated as mentioned in chapter II using PROMETHEE and questionnaires. The six categories are; residential (16.75%), industrial (20.10%), institutional (17.87%), agriculture (4.96%), commercial (16.75%) and health care facilities (23.57%). The length weights of importance are calculated as (0.78) and (0.22) for the two sub-networks of Moncton city based on their lengths respectively. Moreover, the land use weights of importance are calculated as (16.75%) for the residential sub-network (sub-network 1) and (20.10%) for the industrial sub-network (sub-network 2). The weights for land use importance of the two sub-networks are transformed to form a total of (100%) then the weights of length and land use importance for each sub-network are integrated together based on the weighted average as shown in Table V.32. To clarify the connectivity ranked matrix between the sub-networks, the two sub-networks are assumed to be replicated five times each and then the connectivity matrix is formulated between these ten fictitious sub-networks to show the application of the same methodology of segments integration over sub-networks as shown in Table V.33.

Table V.32 City of Moncton sub-networks weights of importance calculations

Sub-Network (1)			Sub-Network (2)		
Length	Land use	Weight of importance	Length	Land use	Weight of importance
12493.5 (0.78)	Residential (16.75%)	0.6	3566.5 (0.22)	Industrial (20.10 %)	0.4

Table V.33 Connectivity ranked matrix between fictitious sub-networks

Connectivity Ranked Matrix											
	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00		
1	0.10	1.00	2.00	3.00	3.00	4.00	5.00	6.00	7.00	8.00	39.10	0.273
2	0.00	0.10	1.00	2.00	2.00	3.00	4.00	5.00	6.00	7.00	30.10	0.210
3	0.00	0.00	0.10	1.00	1.00	2.00	3.00	4.00	5.00	6.00	22.10	0.155
4	0.00	0.00	0.00	0.10	0.00	1.00	2.00	3.00	4.00	5.00	15.10	0.106
5	0.00	0.00	0.00	0.00	0.10	1.00	2.00	3.00	4.00	5.00	15.10	0.106
6	0.00	0.00	0.00	0.00	0.00	0.10	1.00	2.00	3.00	4.00	10.10	0.071
7	0.00	0.00	0.00	0.00	0.00	0.00	0.10	1.00	2.00	3.00	6.10	0.043
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	1.00	2.00	3.10	0.022
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	1.00	1.10	0.008
10	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	1.10	0.008
										Sum	143.00	

V.8 Deterioration Curves

Deterioration curves are drawn utilizing Weibull distribution analysis after calculating the current performance indices for all the components. All the components are assumed to start their service life with a performance index equals to 10, reaching the critical threshold at 3 and end its life at 0. Thus, three points for each component are available to draw the performance curve over the time (Deterioration Curve); the assessment point obtained from the performance model, the installation point, and the end of service life point. As an example, pipe 2 in sub-network 2 in City of Moncton, is assessed to have a PI equals to 5 at the age of 42 years and it is assumed to be installed at 10. Therefore, it is expected to reach to the critical threshold at the age of 50 as shown in Figure V.16. Deterioration curves for pipe 1 in sub-network 1 in City of Moncton and pipe 1 in city of Montreal sub-Network are as shown in Figures V.17 and V.18.

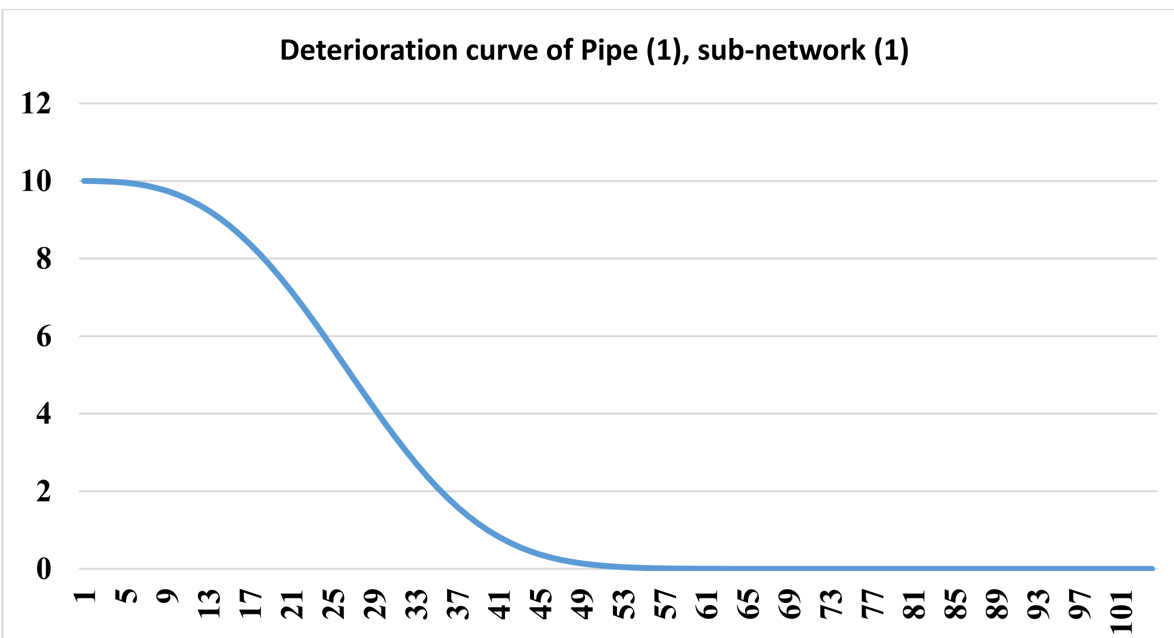


Figure V.16 Deterioration curve of Pipe(1), sub-network (1), City of Moncton

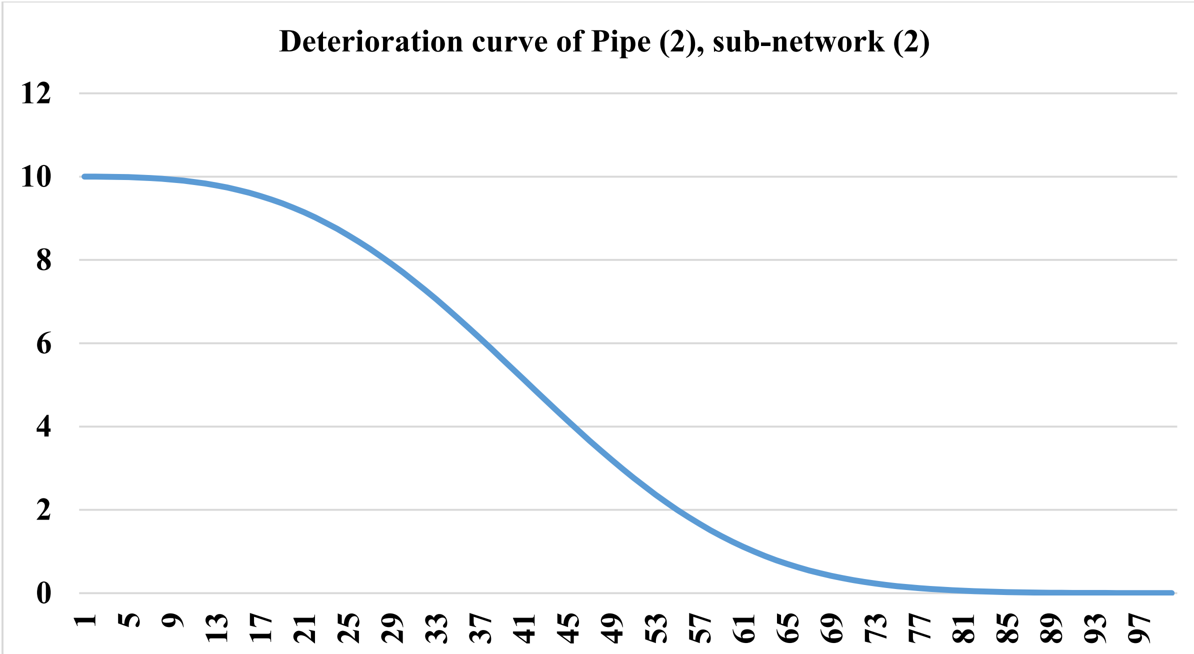


Figure V.17 Deterioration curve of pipe (2), sub-network (2) in City of Moncton

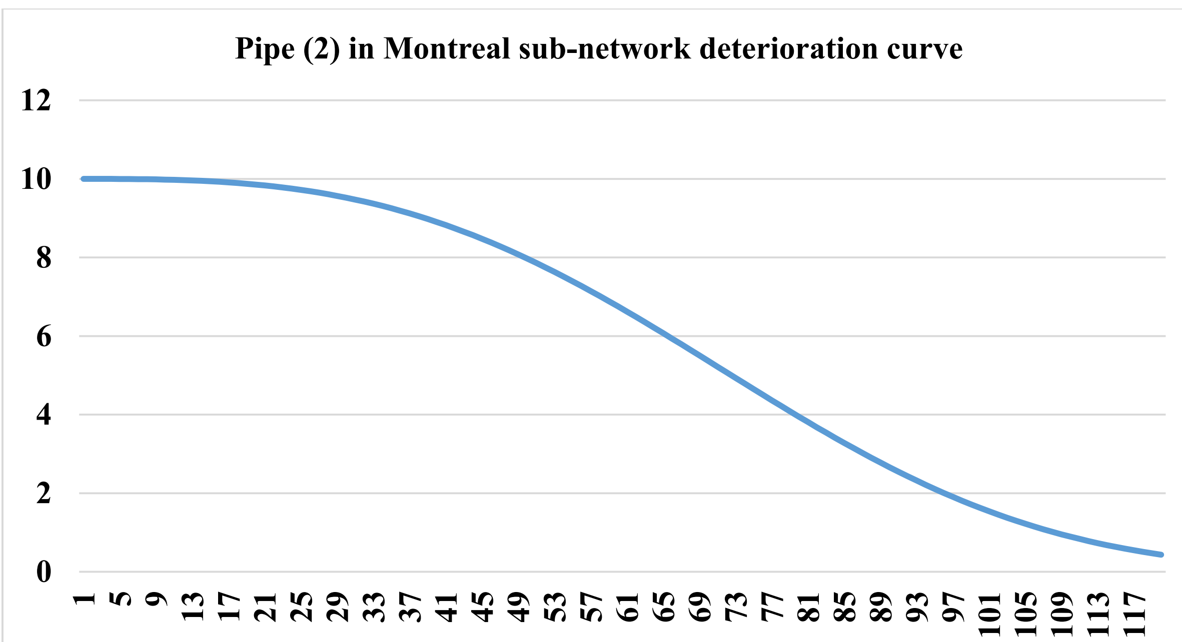


Figure V.18 Deterioration curve of pipe (2) in Montreal sub-network

V.9 Rehabilitation and Budget Allocation Model

All the outputs from the performance assessment model are used as inputs to the budget allocation model. The budget allocation model utilizes Genetic algorithm and Greedy heuristics techniques for optimizing the budget allocation over the network. The Performance is used as the objective. Almost five rehabilitation actions are used from the rehabilitation plan ranging from (0) No action until (5) total replacement. In the GA model, those actions are used as the decision variables. The main constraint is the allowable annual budget. The main inputs for the GA and GH models are the rehabilitation actions, the M&R actions unit costs and the studied network components performance indices. The pipelines diameter and length are also considered as inputs for M&R actions selection process and for cost calculations. Tables V.34 & V.35 present the selection of the defined rehabilitation actions for pipelines and accessories respectively based on the performance indices. It is assumed that all the actions redeem the performance index to (9) except the replacement action which leads to (10). The inflation rate is included within the budget allocation plan to cover the inflation in the costs. The model is also linked to the deterioration model to incorporate the effect of the deterioration. The budget is distributed over the components of each sub-network taking in to consideration the weight of importance of this component to the entire network. The objective function is defined as mentioned in equation [III.47]. The plan is assumed to be a short tem plan (3-Years Plan). The allowable annual budget for City of Moncton network is assumed from the sensitivity analysis to be (1250000) for the first year and (1500000) for the second and third years each, while for city of Montreal sub-network, it is assumed to be (750000) for the first year and (500000) for the second and third years each.

The GA model is defined as presented in Figure V.19, using Evolver optimization software. The model is mainly formulated using an integrated Excel-Evolver tool software. It is obvious that most of the recommended decisions for the pipes in City of Moncton; (9) pipes out of (12); are action (2) which is cathodic protection. Also two pipes need slip lining and only one pipe need cement or epoxy lining as presented in Table V.36 & V.37. On the other hand, around (12) pipes of city of Montreal sub-network need slip lining, (8) need cement or epoxy lining , (6) need cathodic protection and only one requires replacement as presented in Table V.38 & V.39. These recommended actions make sense due to the difference in the age of the water networks in the two cities as City of Montreal water network is much older. The calculations for the other case studies are presented in Appendix (D).

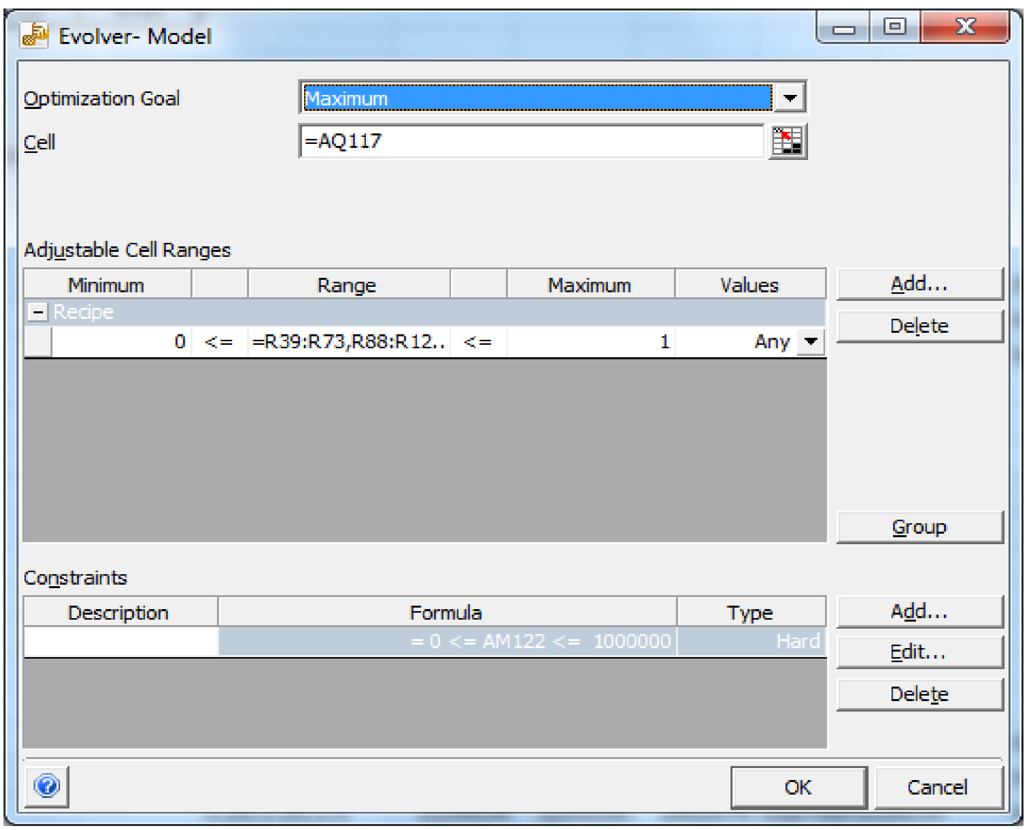


Figure V.19 GA model definition using Evolver optimization tool

Table V.34 Performance based R&M plan for water pipelines

Min (PI)	Max (PI)	Joint	D	Action ID#	Unit Cost ($/m')	Inflation rate (%)
0.00	3	100-4	100	4	454	1.60%
		150-4	150	4	454	
		200-4	200	4	511	
		250-4	250	4	568	
		300-4	300	4	681	
		400-4	400	4	738	
		450-4	450	4	795	
3	4	100-3	100	3	227	
		150-3	150	3	227	
		200-3	200	3	307	
		250-3	250	3	380	
		300-3	300	3	454	
		400-3	400	3	607	
		450-3	450	3	681	
4	6	100-2	100	2	200	
		150-2	150	2	200	
		200-2	200	2	250	
		250-2	250	2	300	
		300-2	300	2	350	
		400-2	400	2	450	
		450-2	450	2	500	
6	8	100-1	100	1	199	
		150-1	150	1	199	
		200-1	200	1	216	
		250-1	250	1	227	
		300-1	300	1	250	
		400-1	400	1	N/A	
		450-1	450	1	N/A	
8	10	100-0	100	0	0	
		150-0	150	0	0	
		200-0	200	0	0	
		250-0	250	0	0	
		300-0	300	0	0	
		400-0	400	0	0	
		450-0	450	0	0	

Table V.35 Performance based R&M plan for water accessories

Min (PI)	Max (PI)	Action ID#	Unit Cost ($/m')	Inflation rate (%)
0.00	4	1	10000	1.60%
4	10	0	0	

Table V.36 GA budget allocation plan for water mains of sub-network (2), City of Moncton

	1	2	3	D	L (m)	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
P.1	42.00	43.00	44.00	150.00	263.73	4.88	4.63	8.93	2	2	0	0	1	0	0.00	53590	0.00	4.88	9.00	8.93
P.2	42.00	43.00	44.00	150.00	263.73	4.88	4.63	8.93	2	2	0	0	1	0	0.00	53590	0.00	4.88	9.00	8.93
P.3	57.00	58.00	59.00	200.00	440.86	5.95	8.95	8.90	2	0	0	1	0	0	110217	0.00	0.00	9.00	8.95	8.90
P.4	44.00	45.00	46.00	150.00	81.38	3.89	3.64	8.94	3	3	0	0	1	0	0.00	18776	0.00	3.89	9.00	8.94
P.5	55.00	56.00	57.00	200.00	71.01	4.98	8.95	8.89	2	0	0	1	0	0	17752	0.00	0.00	9.00	8.95	8.89
P.6	55.00	56.00	57.00	150.00	500.46	4.55	4.35	8.95	2	2	0	0	1	0	0.00	101695	0.00	4.55	9.00	8.95
P.7	42.00	43.00	44.00	150.00	263.73	4.88	4.63	4.38	2	2	2	0	0	1	0.00	0.00	54448	4.88	4.63	9.00
P.8	42.00	43.00	44.00	150.00	263.73	4.88	8.93	8.86	2	0	0	1	0	0	52746	0.00	0.00	9.00	8.93	8.86
P.9	57.00	58.00	59.00	200.00	351.67	5.61	8.95	8.90	2	0	0	1	0	0	87917	0.00	0.00	9.00	8.95	8.90
P.10	57.00	58.00	59.00	150.00	350.26	4.02	3.83	8.95	2	3	0	0	1	0	0.00	80809	0.00	4.02	9.00	8.95
P.11	49.00	50.00	51.00	300.00	477.03	6.41	8.94	8.88	1	0	0	1	0	0	119156	0.00	0.00	9.00	8.94	8.88
P.12	46.00	47.00	48.00	150.00	238.65	5.98	5.78	8.94	2	2	0	0	1	0	0.00	48493	0.00	5.98	9.00	8.94

Table V.37 GA budget allocation plan for Accessories of sub-network (2), City of Moncton

	0	1	2	L (m)	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
Acc.1	42.00	43.00	44.00	1.00	5.44	5.20	4.96	0	0	0	0	0	0	0.00	0.00	0.00	5.44	5.20	4.96
Acc.2	43.00	44.00	45.00	1.00	6.40	6.20	6.00	0	0	0	0	0	0	0.00	0.00	0.00	6.40	6.20	6.00
Acc.3	42.00	43.00	44.00	1.00	6.34	6.13	5.92	0	0	0	1	0	0	0.00	0.00	0.00	6.34	6.13	5.92
Acc.4	57.00	58.00	59.00	1.00	5.63	5.46	5.29	0	0	0	1	0	0	0.00	0.00	0.00	5.63	5.46	5.29
Acc.5	44.00	45.00	46.00	1.00	5.37	5.15	4.92	0	0	0	0	0	0	0.00	0.00	0.00	5.37	5.15	4.92
Acc.6	55.00	56.00	57.00	1.00	5.57	5.39	5.21	0	0	0	1	0	0	0.00	0.00	0.00	5.57	5.39	5.21
Acc.7	55.00	56.00	57.00	1.00	4.30	4.10	3.91	0	0	1	1	0	1	0.00	0.00	10322.56	4.30	4.10	9.90
Acc.8	42.00	43.00	44.00	1.00	5.44	5.20	4.96	0	0	0	0	0	0	0.00	0.00	0.00	5.44	5.20	4.96
Acc.9	42.00	43.00	44.00	1.00	6.34	6.13	5.92	0	0	0	1	0	0	0.00	0.00	0.00	6.34	6.13	5.92
Acc.10	57.00	58.00	59.00	1.00	5.83	5.66	5.49	0	0	0	0	0	0	0.00	0.00	0.00	5.83	5.66	5.49
Acc.11	57.00	58.00	59.00	1.00	4.86	4.68	4.50	0	0	0	0	0	0	0.00	0.00	0.00	4.86	4.68	4.50
Acc.12	49.00	50.00	51.00	1.00	5.72	5.52	5.32	0	0	0	0	0	0	0.00	0.00	0.00	5.72	5.52	5.32
Acc.13	46.00	47.00	48.00	1.00	5.72	5.51	5.30	0	0	0	1	0	0	0.00	0.00	0.00	5.72	5.51	5.30

Table V.38 Sample of GA budget allocation plan for pipelines of Montreal sub-network

	0	1	2	D	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
P.1	125	126	127	200.00	3.61	3.52	8.98	3	3	0	0	1	0	0.00	52571.37	0.00	3.61	9.00	8.98
P.2	49	50	51	300.00	8.95	8.89	8.83	0	0	0	1	0	0	0.00	0.00	0.00	8.95	8.89	8.83
P.3	125	126	127	250.00	8.64	8.61	8.58	0	0	0	1	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.4	5	6	7	250.00	3.56	8.34	7.49	3	0	1	1	0	0	68298.54	0.00	0.00	9.00	8.34	7.49
P.5	82	83	84	150.00	9.16	9.13	9.10	0	0	0	1	0	0	0.00	0.00	0.00	9.16	9.13	9.10
P.6	124	125	126	200.00	8.69	8.66	8.63	0	0	0	1	0	0	0.00	0.00	0.00	8.69	8.66	8.63

Table V.39 Sample of GA budget allocation plan for accessories of Montreal sub-network

	0	1	2	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
Acc. 1	125	126	127	3.38	3.29	3.21	1	1	1	0	0	1	0.00	0.00	10322.56	3.38	3.29	9.90
Acc. 2	125	126	127	3.38	3.29	3.21	1	1	1	0	0	1	0.00	0.00	10322.56	3.38	3.29	9.90
Acc. 3	49	50	51	8.59	8.51	8.42	0	0	0	0	0	0	0.00	0.00	0.00	8.59	8.51	8.42
Acc. 4	102	103	104	3.45	9.90	9.89	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.89
Acc. 5	102	103	104	3.45	9.90	9.89	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.89
Acc. 6	102	103	104	8.52	8.48	8.44	0	0	0	0	0	0	0.00	0.00	0.00	8.52	8.48	8.44

After distributing the budget, the model goes through normal calculations of the new PIs reaching to the entire network level. Finally the new PI is compared to the original PI and replaces it if it is better and so on until finding the most optimum solution that satisfy the objectives and the constraints in the case of GA-Model. The Progress summary for the three years at the end of each year is presented in Figures V.20, V.21 & V.22 for sub-network (2) in City of Moncton .

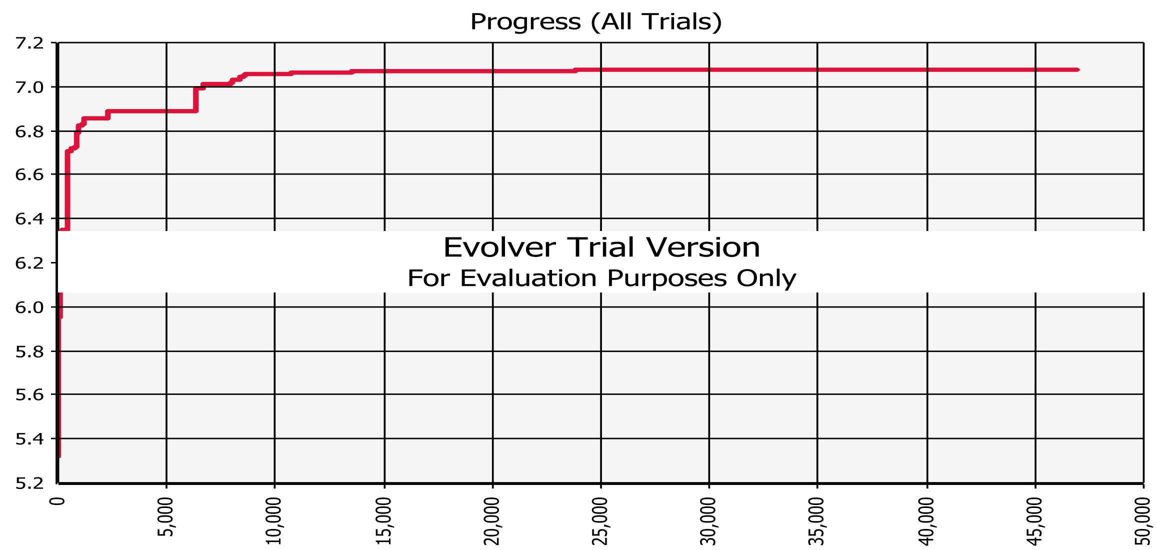


Figure V.20 First year progress summary using Evolver

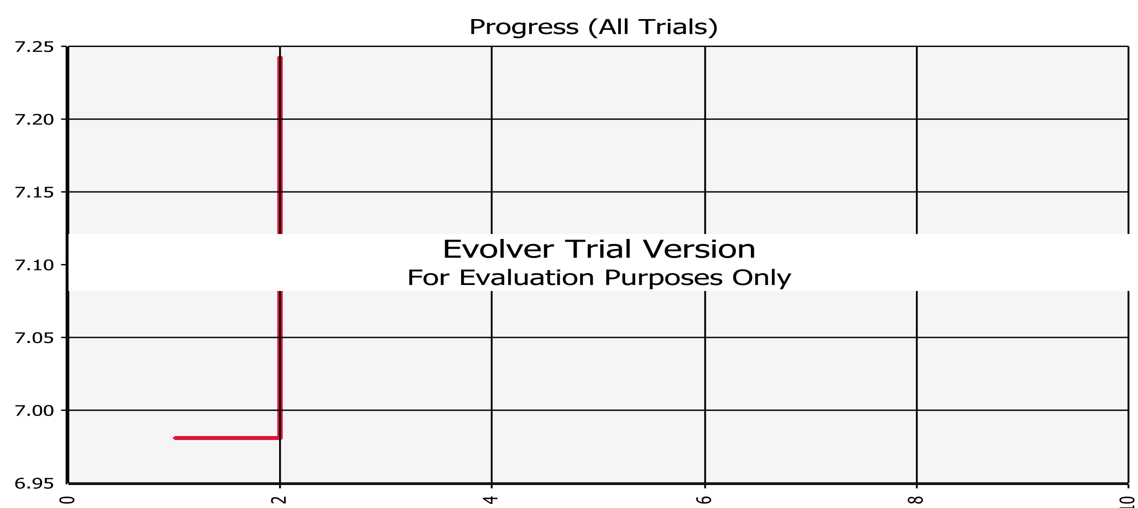


Figure V.21 Second year progress summary using Evolver

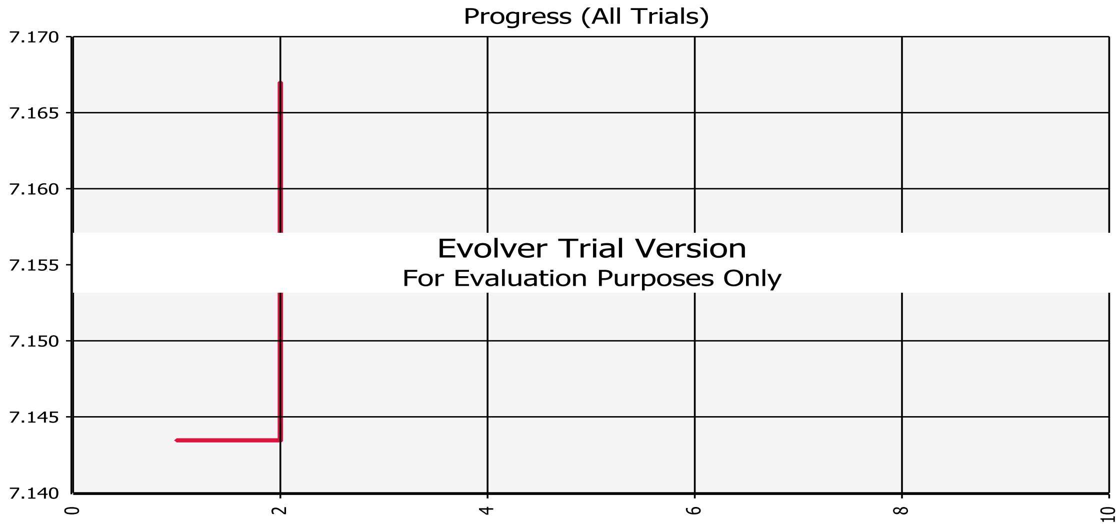


Figure V.22 Third year progress summary using Evolver

On the other hand, the GH model is mainly based on the weights of importance of the components within the entire network, which are obtained using equation [III.50]. Then, the performance indices are incorporated and the recommended decisions are chosen following the steps mentioned in the GA model. The weights of importance are considered as the benefits and by dividing those weights over the cost of the recommended action of each component; Benefit/Cost ratio is obtained. The B/C ratio is sorted in a descending order and the components are rehabilitated based on this order. The objective function and the allowable annual budget are the same as the GA. As an example the weight of importance of pipe 1 within segment 1 of sub network 2 in Moncton equals 0.34, while the weight of importance of segment 1 within sub-network 2 equals 0.002 and finally the weight of importance of sub-network 2 within the entire network equals 0.4. Therefore, by multiplying the three weights, the benefit of the rehabilitation pipe 1 to the entire network is obtained as 0.0003 and the cost of its rehabilitation is 52746. The benefit/ cost ratio is calculated and pipe 1 ranked as the 11^{th} for rehabilitation as shown in Table V.40. The allocation process is presented in Appendix (D) and it is the same as Tables V.38 & V.39, except that it is based on the B/C ratio order. After distributing the budget, the model goes through normal calculations of the new PIs, obtaining the entire network level. Finally the new network PI replaces the original network PI.

Table V.40 GH model calculations and water mains ranking for S.N (2), Moncton

				Benefit	Cost	B/C	Ranking	B/C
Pipe 1	0.34	0.002		0.0003	52746	4.8E-09	**Pipe 5**	1.34E-06
Pipe 2	0.53	0.002		0.0004	52746	7.4E-09	**Pipe 9**	9.37E-07
Pipe 3	0.44	0.039		0.0068	110216	6.2E-08	**Pipe 11**	7.11E-07
Pipe 4	0.58	0.002		0.0004	18480	2.3E-08	**Pipe 8**	1.55E-07
Pipe 5	0.53	0.112		0.0239	17751	1.3E-06	**Pipe 3**	6.18E-08
Pipe 6	0.51	0.002		0.0004	100093	3.8E-09	**Pipe 4**	2.29E-08
Pipe 7	0.50	0.002	0.4	0.0004	52746	6.9E-09	**Pipe 10**	1.56E-08
Pipe 8	0.53	0.039		0.0082	52746	1.5E-07	**Pipe 2**	7.41E-09
Pipe 9	0.69	0.297		0.0824	87917	9.4E-07	**Pipe 7**	6.91E-09
Pipe 10	0.74	0.004		0.0011	70051	1.6E-08	**Pipe 12**	6.78E-09
Pipe 11	0.42	0.499		0.0847	119156	7.1E-07	**Pipe 1**	4.79E-09
Pipe 12	0.44	0.002		0.0003	47729	6.8E-09	**Pipe 6**	3.78E-09

According to the objective of the plan which is maximizing the performance index of the entire network as much as possible, City of Moncton network performance index is (6.09) at the beginning of the plan and became (7.2) at the end of the 3-Years plan, while Montreal sub-network is enhanced from (4.8) to (8.9). The enhancement in City of Moncton sub-network represents almost 20% within the performance, while almost (85%) for city of Montreal sub-network. It is achieved by changing the decision variables within the components reaching to this optimal solution. As an example, pipe (2) in sub-network (2) of City of Moncton is rehabilitated at the end of the second year of the plan and the selected M&R action is action (2), "cathodic protection". Thus its performance is enhanced from (4.6) to (9). Finally, the closeness between the outputs from GA-Model and GH-Model proves a high degree of certainty within the proposed budget allocation plan.

The Performance curve is updated considering the rehabilitation done after allocating the budget as shown in Figures V.23 & V.24 for pipe (1) in sub-network (1) in City of Moncton.

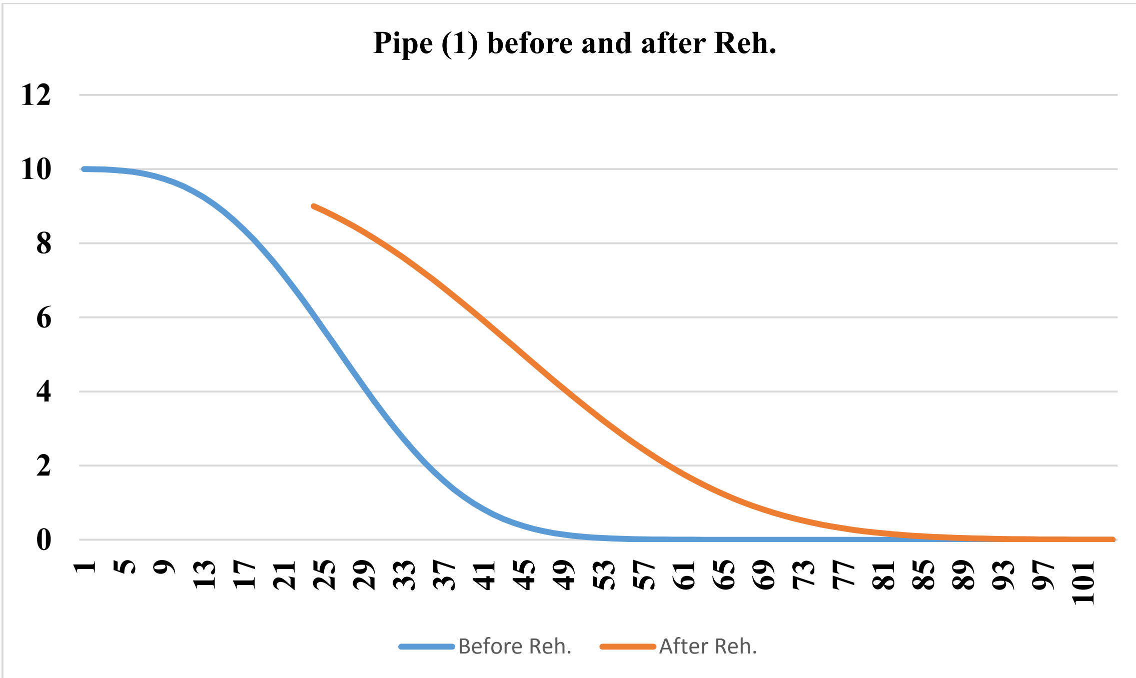


Figure V.23 Deterioration of P_1, S.N (1) in Moncton before and after rehabilitation

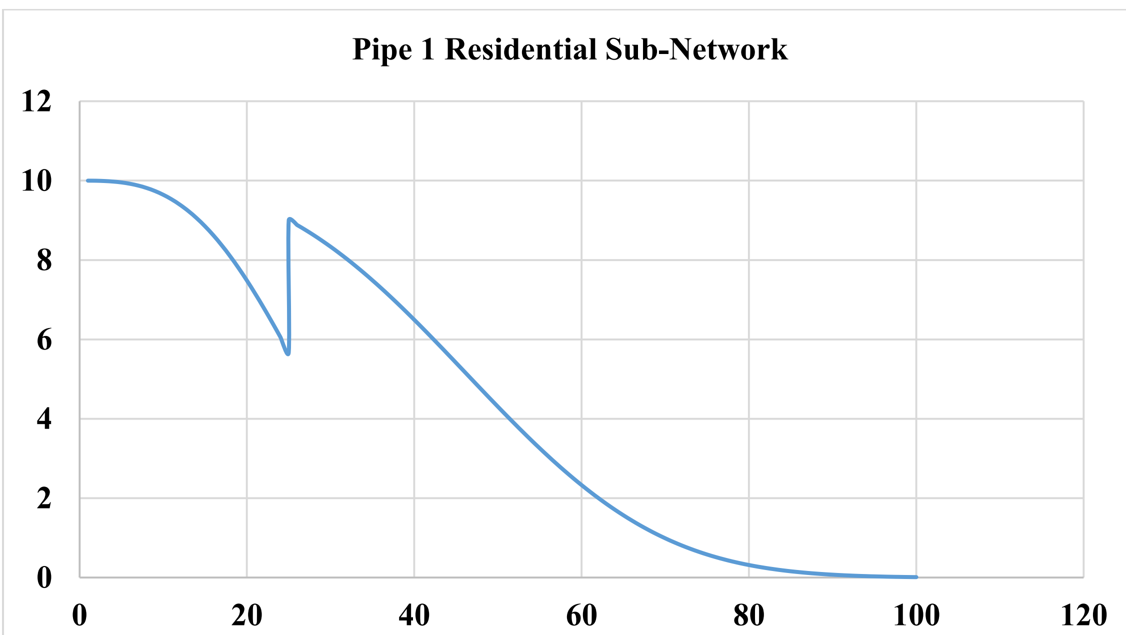


Figure V.24 Deterioration curve of P_1, S.N (1) including M&R

V.10 Sensitivity analysis and simulation

The sensitivity analysis is done to check the degree of certainty within the model output. It is performed on the weights of the indicators within a range of ±25% from the values calculated from the questionnaires. The effect of this change for each indicator on the performance of pipe (1) in sub-network (2) is presented in Figure V.25. It is obvious that Ph.2, Op.2, Op.3 have the greatest effect on the performance index of the pipe. However, all the indicators effect is within ±5% which is acceptable. The sensitivity analysis is repeated for random pipes from the case studies and the values are within the same range. The components which have PIs very close to the limits of the performance categories are called critical components. As an example, any pipe that has a PI of (3.9) any change within this PI changes the PI category, the description and the recommended R&M actions. Therefore, there is a need to study each component based on the GPI and the FPI.

The second kind of sensitivity analysis conducted, is on the annual budget. Allocating the annual budget for the 3-Years plan, is either predefined by the municipality or the water agency responsible for the water network or it shall be assumed by the model user based on the annual allowable budget of the municipality. In order to have a confidence about the assumption, a sensitivity analysis is performed to obtain the best option by allocating budget of (1000000) yearly for City of Moncton and it can be increased by increments of (250000) while the maximum annual budget is (1500000). Accordingly, 27 scenarios are generated which is too much as shown in Table V.41. In order to decrease the number of possible solutions, an assumption; that the budget of the second year cannot be increased before increasing the first one and same for the third year as well; is used. Accordingly, the number of solutions is decreased to (15) solution as illustrated in Table V.42.

Those solutions are performed for the 3 years as shown in Figures V.26 & V.27 and the output is analyzed. It is obvious that for the first year when the budget is increased from 1 M to 1.25 M, the performance is enhanced by almost 5% for sub-network 1 and 17% for sub-network 2 while when the budget is increased for 1.5M the performance increased only by 1-2 %. For the second and third years, it is noticed that increasing the budget to more than 1.25 M/Year, enhances the performance more than keeping it at 1.25 M. Therefore, the optimal solution selected is (1.25, 1.5 and 1.5) Millions. For Montreal, the allocated budget is (500000) annually and it can be increased by increments of (250000) while the maximum annual budget is (750000). Accordingly, (8) scenarios are generated as shown in Table V.43. By using the same assumption mentioned earlier, the number of solutions is decreased to (4) solutions as illustrated in Table V.44. Those solutions are performed for the 3 years as shown in Figure V.28, reaching finally to the best possible solution (0.75, 0.5 and 0.5) Millions. The best scenarios are performed using GA & GH models and the budget distribution over the 3-Years for the two sub-networks of City of Moncton and city of Montreal is as shown in Figures V.29 and V.30 for GA and GH respectively. The distribution is different for the two models but the amount for each sub-network at the end of the plan and the amount required for the remaining part are almost the same. For City of Moncton, the amount of money spent using GA is $ 4222535, and using GH is $ 4233277. Also, the amount required for the remaining part to be rehabilitated is $ 332,282 using the two models. On the other hand, the amount of money spent on Montreal using GA equals ($ 1722108), while using GH equals ($ 1741873). The remaining using GA is $ 481307, while it is $ 388697 using GH. The percentages of rehabilitation done and the remaining parts of the three sub-networks are presented in FigureV.31.

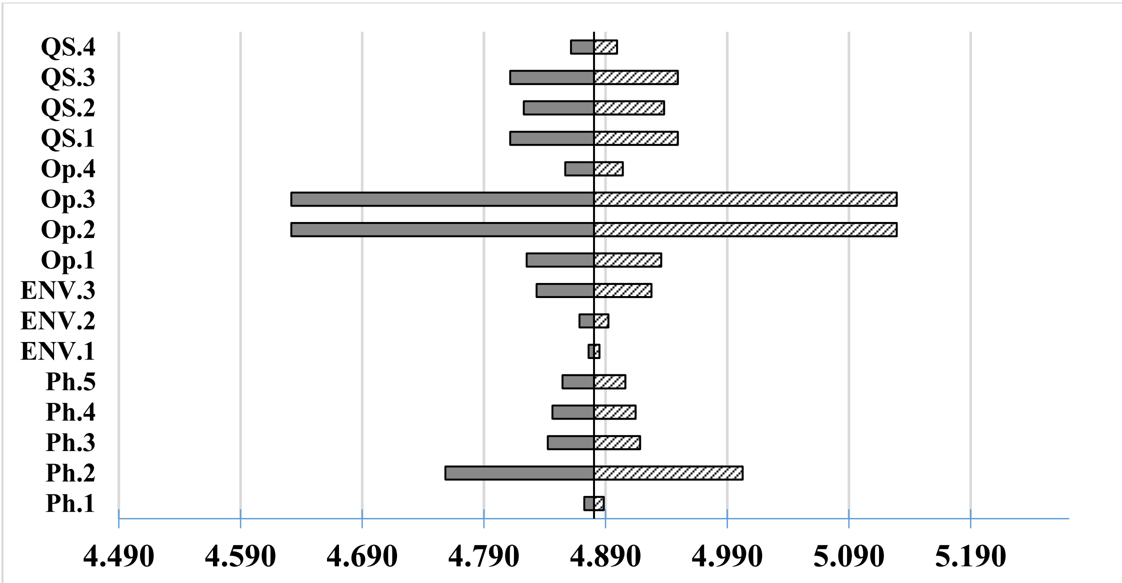


Figure V.25 Sensitivity analysis of the indicators weights

Table V.41 Sensitivity analysis of the annual allocated budget for Moncton (Millions)

(1,1,1)$	(1,1.25,1) $	(1,1.5,1) $	(1,1,1.25) $	(1,1,1.5) $	(1,1.25,1.25) $	(1,1.25,1.5) $	(1,1.5,1.25) $	(1,1.5,1.5) $
(1.25,1,1) $	(1.25,1.25,1) $	(1.25,1.5,1) $	(1.25,1,1.25) $	(1.25,1,1.5) $	(1.25,1.25,1.25) $	(1.25,1.25,1.5) $	(1.25,1.5,1.25)$	(1.25,1.5,1.5) $
(1.5,1,1) $	(1.5,1.25,1) $	(1.5,1.25,1) $	(1.5,1,1.25) $	(1.5,1,1.5) $	(1.5,1.25,1.25) $	(1.5,1.25,1.5) $	(1.5,1.5,1.25) $	(1.5,1.5,1.5) $

Table V.42 Sensitivity analysis of the annual allocated budget (after the assumption)

(1,1,1)$						
(1.25,1,1)$	(1.25,1.25,1)$	(1.25,1.5,1)$	(1.25,1.25,1.25)$	(1.25,1.25,1.5)$	(1.25,1.5,1.25)$	(1.25,1.5,1.5)$
(1.5,1,1)$	(1.5,1.25,1)$	(1.5,1.25,1)$	(1.5,1.25,1.25)$	(1.5,1.25,1.5)$	(1.5,1.5,1.25)$	(1.5,1.5,1.5)$

Table V.43 Sensitivity analysis of the annual allocated budget for Montreal

(0.5,0.5,0.5)$	(0.5,0.75,0.5) $	(0.5,0.5,0.75) $	(0.5,0.75,0.75) $
(0.75,0.5,0.5) $	(0.75,0.75,0.5) $	(0.75,0.5,0.75) $	(0.75,0.75,0.75) $

Table V.44 Sensitivity analysis of the annual allocated budget (after the assumption)

(0.5,0.5,0.5)$		
(0.6,0.5,0.5) $	(0.6,0.6,0.5) $	(0.6,0.6,0.6) $

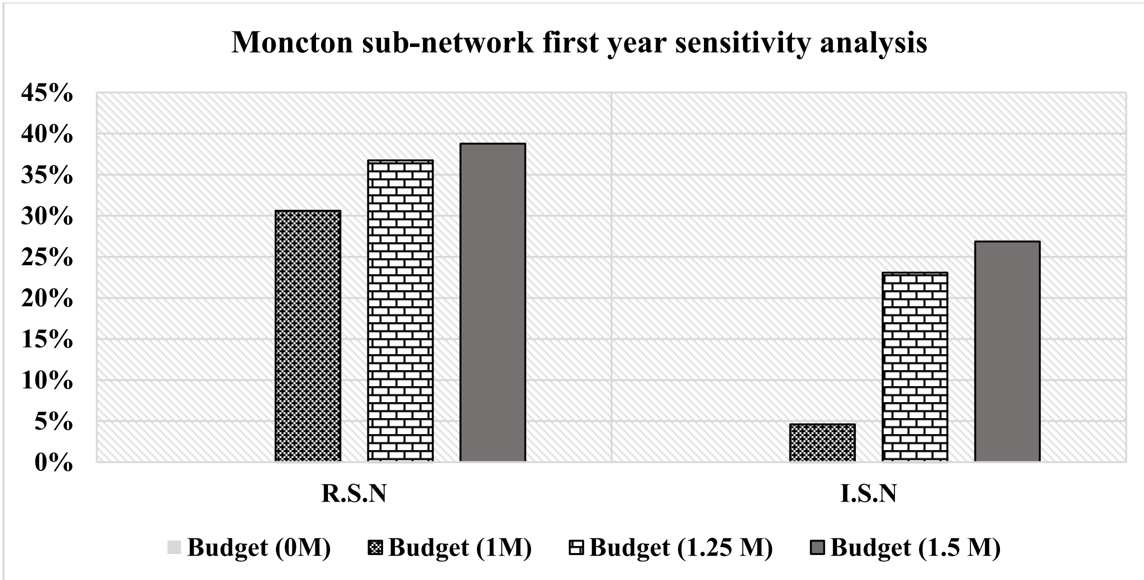


Figure V.26 City of Moncton sub-network first year sensitivity analysis (Budget allocated vs. percentage of performance enhancement)

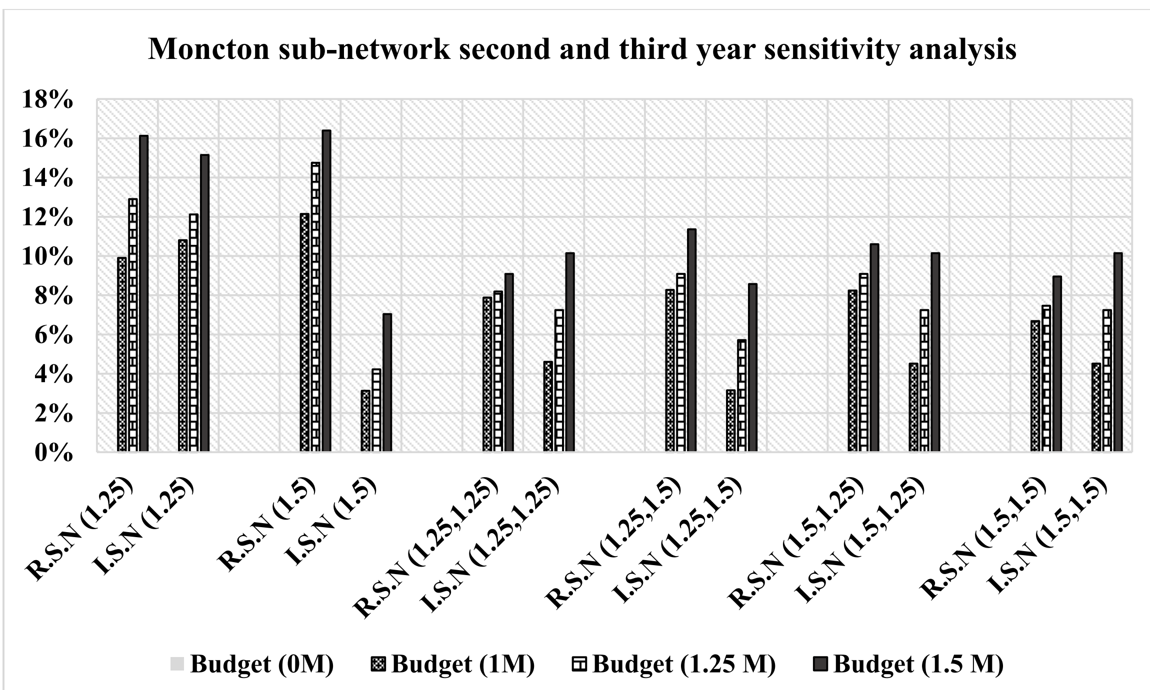


Figure V.27 City of Moncton sub-network, second and third year sensitivity analysis

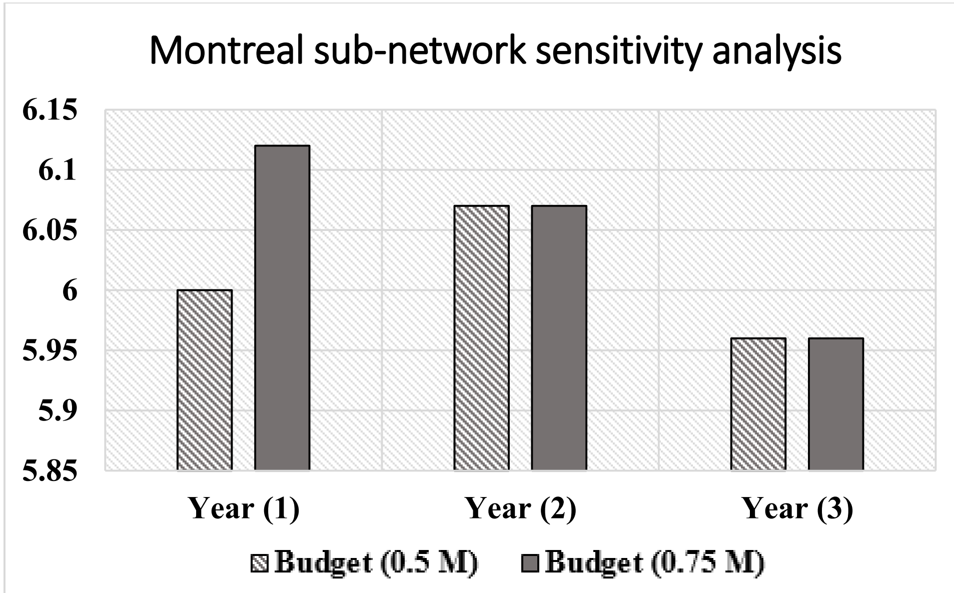


Figure V.28 Montreal sub-network budget allocation sensitivity analysis

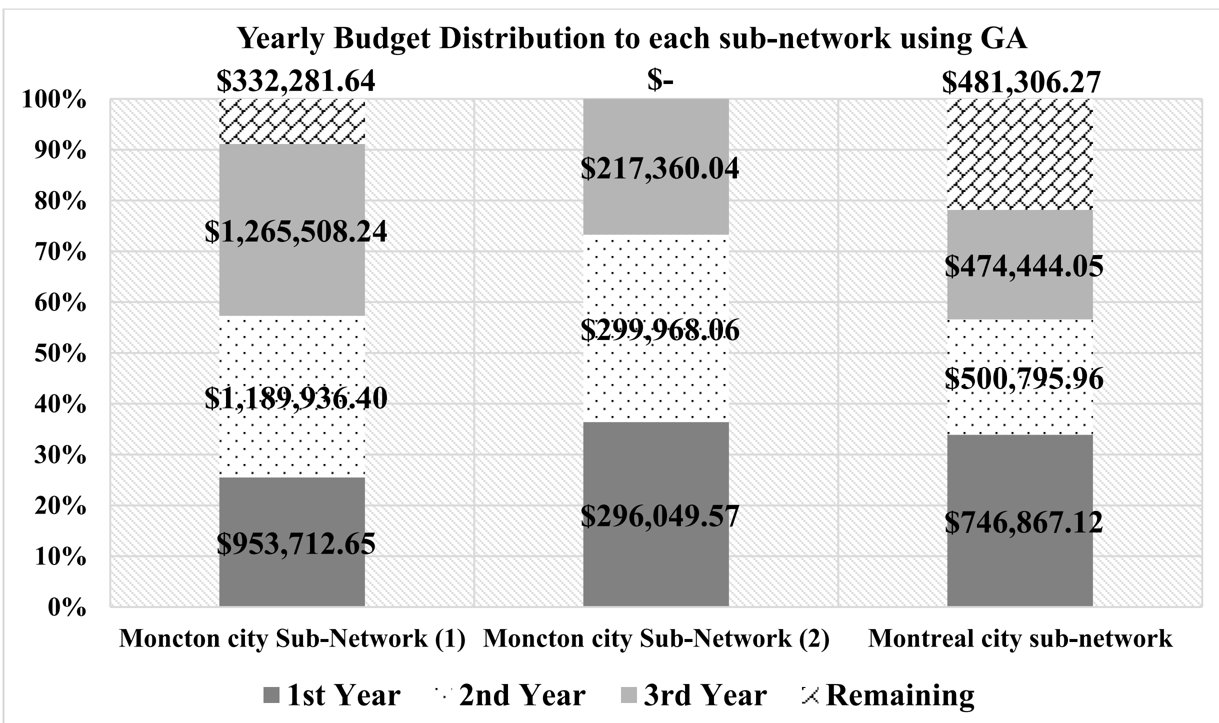


Figure V.29 Budget distribution on the three sub-networks based on the best scenario and using GA

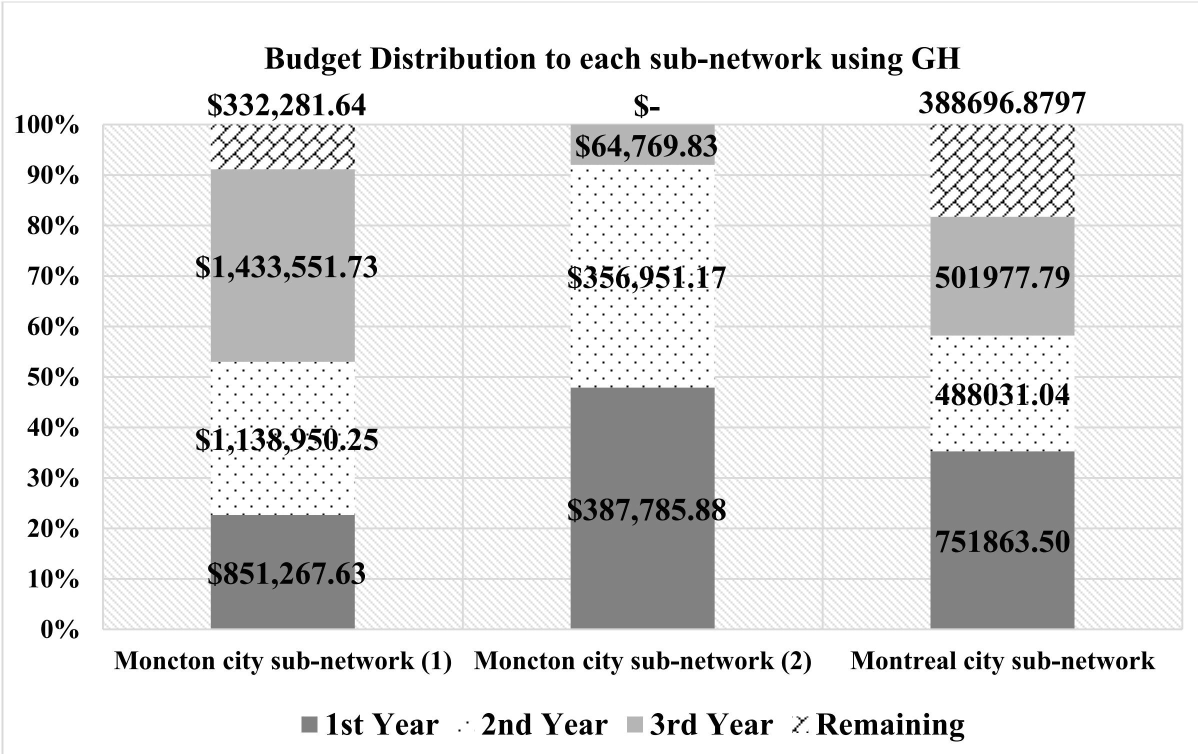


Figure V.30 Budget distribution on the three sub-networks based on the best scenario and using GH

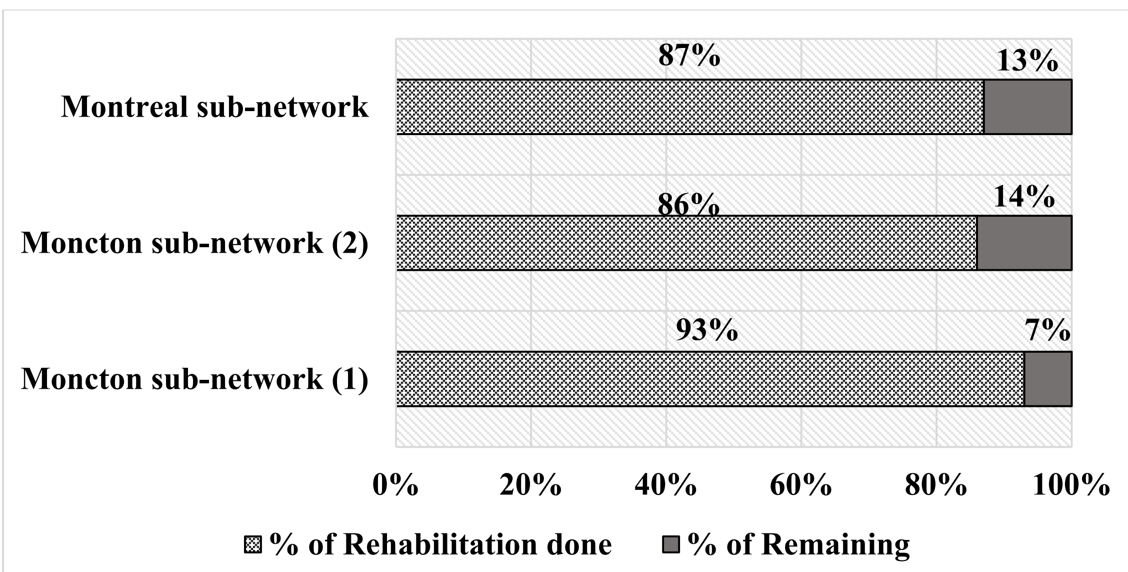


Figure V.31 Percentage of the rehabilitation and the remaining parts of the three sub-networks at the end of the plan

Finally the simulation is conducted for the yearly allocated budget using GA model. It is done using @risk software by assuming ±5% risk within the input unit costs. The risk for the inputs and outputs is defined as triangular distribution. The risk output is defined as the final budget allocated at the end of each year of the plan. This simulation is of a great advantage to municipalities as it helps them covering the risk of any change within the yearly allocated budget by considering the changing in the unit costs. Accordingly, preventing going over the annual maximum allowable budget. As an example, the allocated budget for the first year of City of Moncton network equals 1.25 M and it is conducted from the simulation that it can be increased to 1.33 M or decreased to 1.18 M. The second year budget mean is 1.49 M and the minimum and maximum values are 1.403 M and 1.59 M respectively. Finally, for the third year, the mean is 1.428 M and the minimum and maximum values are 1.39 and 1.6 respectively. Figures V.32, V.33, & V.34 show the simulation of the 3-Years for City of Moncton network respectively.

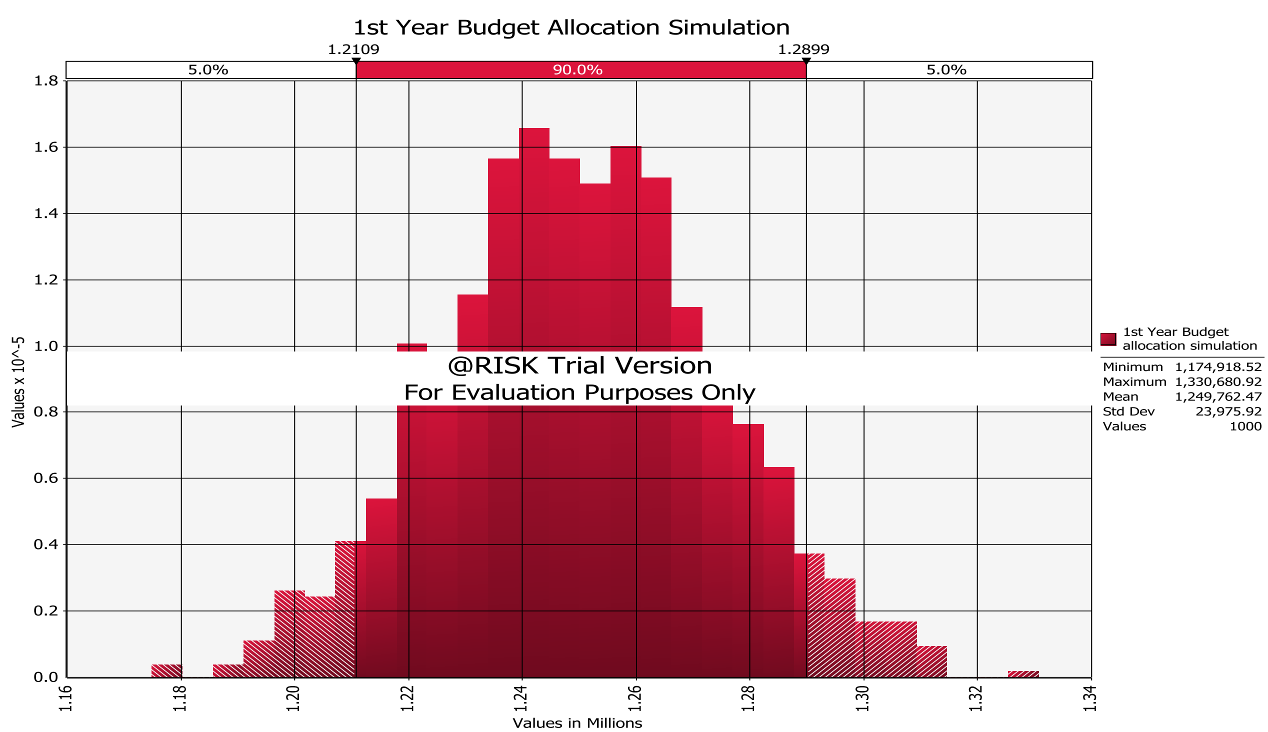


Figure V.32 Simulation of the first year distributed budget

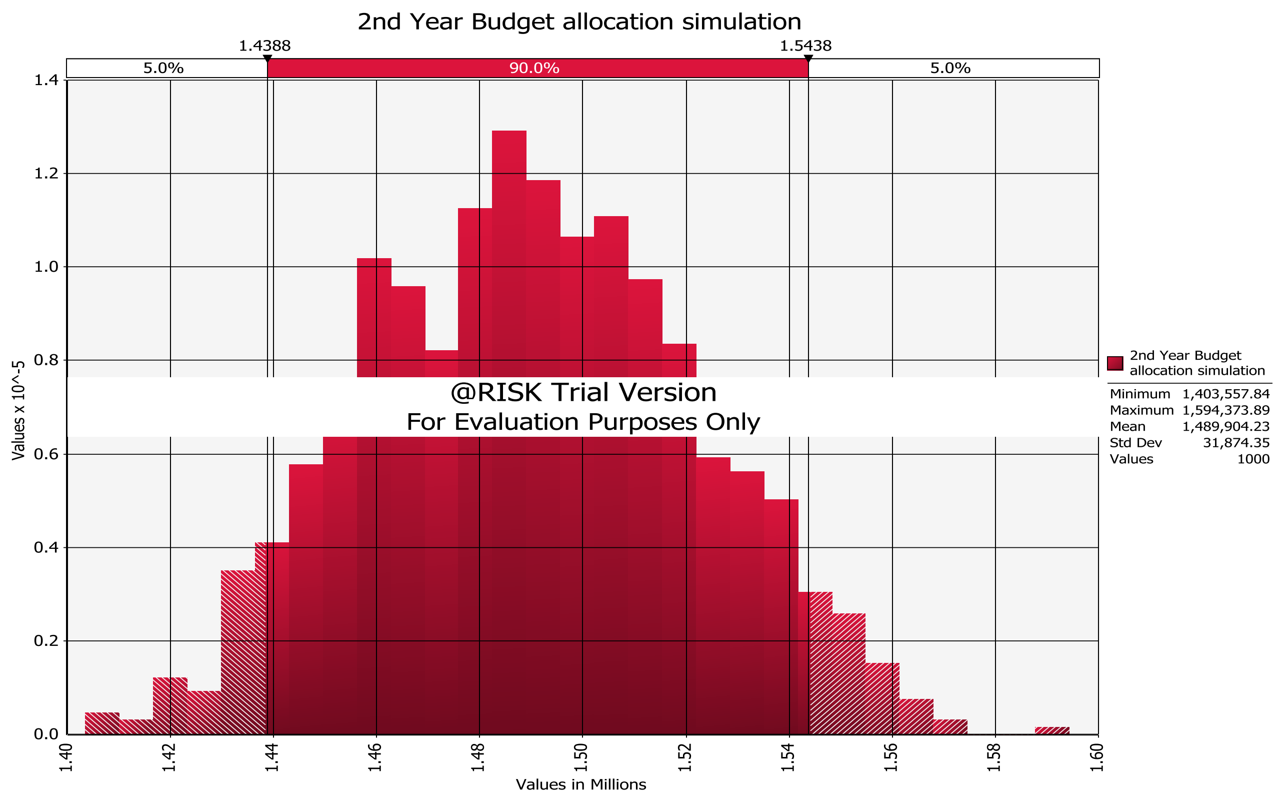


Figure V.33 Simulation of the second year distributed budget

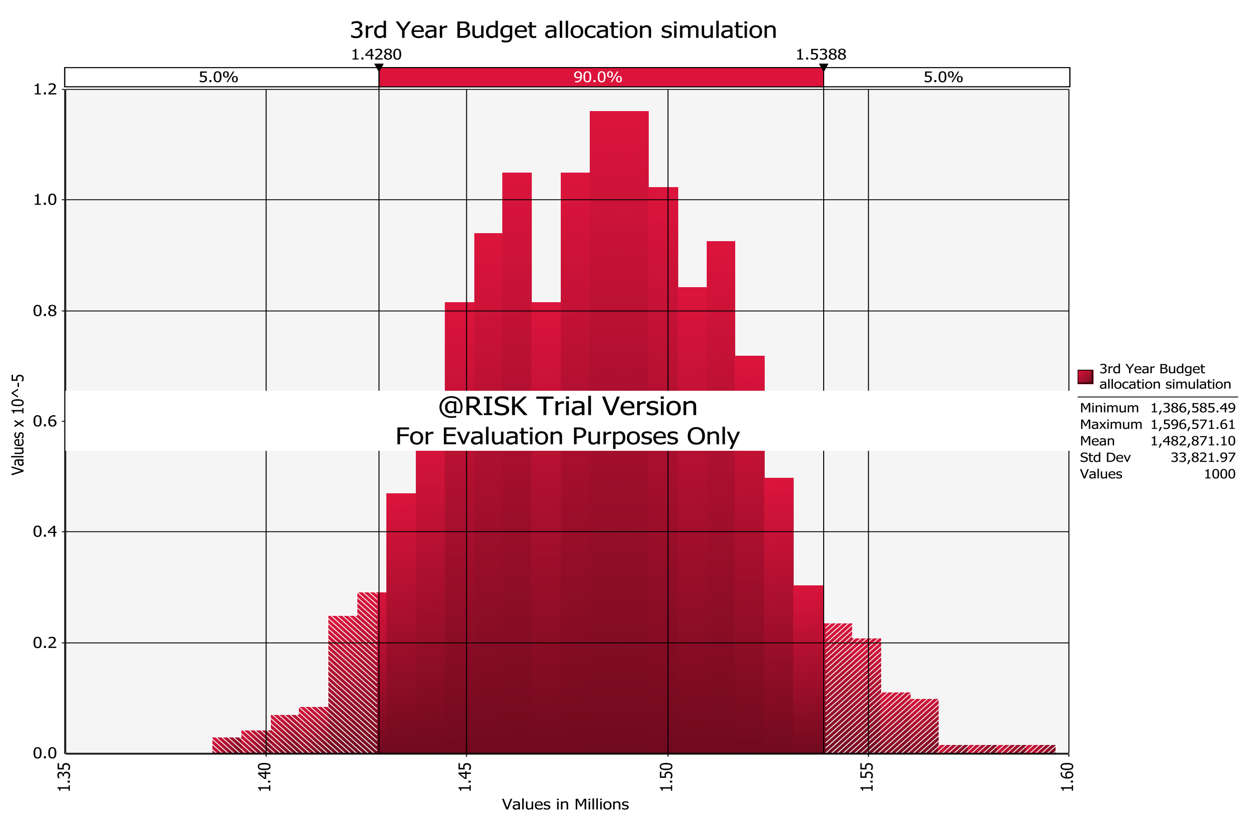


Figure V.34 Simulation of the third year distributed budget

V.11 Developed Model Verification

The Proposed model is verified in two different stages; the first stage is by comparing City of Moncton network results to a previous model developed by El Chanati (2014). This model was applied on the same case study of City of Moncton, and it is based on reliability assessment. The method used for verification is based on the verification factor, which equals to; the proposed model results divided by the old model results. This method is adapted from (Zayed and Halpin, 2004). Tables V.45 & V.46 & V.47 show the results of the verification of the pipes, accessories and segments of sub-network 2 in Moncton respectively. Finally the verification of the two available sub-networks of City of Moncton is presented in Table V.48. The verification factor of pipelines ranges from 0.61 to 1.1. On the other hand, the accessories verification factor is above 0.8 for most of the accessories except accessory number 7 which has a VF equals 0.65. When the components are integrated, the VF results for the segments are around 1 for 8 segments. However, there are some exceptions such as; segments 4 & 10 have a VF equals 0.71, segment 6 has a VF equals 0.65, and segment 5 has a VF equals 0.8. The verification of the two sub-networks is (0.94) and (1.06) respectively. Accordingly, most of the VF ranges are acceptable as they are very close to (1) through all the levels. The difference may be because of the age factor as the two models are applied with a difference of two years. Also, the methods of calculating PI are different. This research is argued to be more accurate by adopting means of PROMETHEE besides FANP. The integration between the components and the segments is different. Through this research a new method based on the probability of failure is experimented and used to integrate the segment components, and topological clustering means are used to integrate the segments to form the sub-network. On the other hand, the previous model used weights of importance assumption (50-50) to integrate the pipes and accessories. It uses also reliability means to integrate the segments and formulate the sub-network PI. This verification is purely subjective for the reasons mentioned above but at least it shows that the proposed model is working and that it has an acceptable degree of certainty and confidence within its results. It also proves that the integration methods within the developed model are accurate. Figure V.35 & V.36 show the two sub-networks of City of Moncton performance indices using reliability model, WNPA model without Pseudo and WNPA model with Pseudo.

The Second part of verification is by comparing the recommended actions from the budget allocation plan of Montreal sub-network to the actions recommended by "AQUAMODEX" (the software utilized by city of Montreal water services department). By comparing both together, it is found that they match in almost 90% of the actions. It is noticed through the comparison that according to AQUAMODEX there is almost three pipes with replacement as the recommended action, while according to WNPBA-Model the same pipes have slip lining as recommended action. After several meetings with municipal engineers and managers, it is found that most of the pipes to be replaced by AQUAMODEX can be lined but due to different factors such as; preventive action, construction site issues and integrated infrastructure management issues; it is recommended to be replaced and this is argued to be the reason for this 10% difference. Thus, the model is proved to have a high degree of certainty within its results based on the verification mentioned earlier, the feedback and comments from the municipal managers and it is recommended to be used as a preventive model.

Table V.45 Verification of Pipelines

Pipe #	WNPBA	Reliability Model	VF
1	5	5.66	0.88
2	5	5.66	0.88
3	6.38	6	1.06
4	3.01	4.93	0.61
5	4.45	6	0.74
6	3.97	6	0.66
7	5	5.66	0.88
8	5	5.66	0.88
9	5.72	6	0.95
10	3.9	6	0.65
11	7.12	6.08	1.17
12	6.44	6.08	1.06

Table V.46 Accessories verification

Accessory #	WNPBA	Reliability Model	VF
1	6	5.89	1.02
2	7.4	6.21	1.19
3	7.2	6.21	1.16
4	6.1	5.49	1.11
5	5.3	6.21	0.85
6	5.4	6.21	0.87
7	3.8	5.89	0.65
8	6	5.89	1.02
9	7.2	6.21	1.16
10	5.9	6.21	0.95
11	5	6.4	0.78
12	6.1	6.4	0.95
13	6.1	5.89	1.04

Table V.47 Segments verification

Segment#	WNPBA	Reliability Model (SPI)	VF
1	5.99	5.81	1.03
2	5.91	5.94	0.99
3	6.24	5.75	1.09
4	3.99	5.57	0.72
5	4.89	6.11	0.8
6	3.88	5.95	0.65
7	5.5	5.78	0.95
8	5.91	5.94	0.99
9	5.81	6.11	0.95
10	4.41	6.2	0.71
11	6.57	6.24	1.05
12	6.27	5.99	1.05

Table V.48 Sub-networks Verification

Sub-Network #	WNPBA	Reliability Model	VF
1	5.00	5.3	**0.94**
2	6.09	5.71	**1.06**

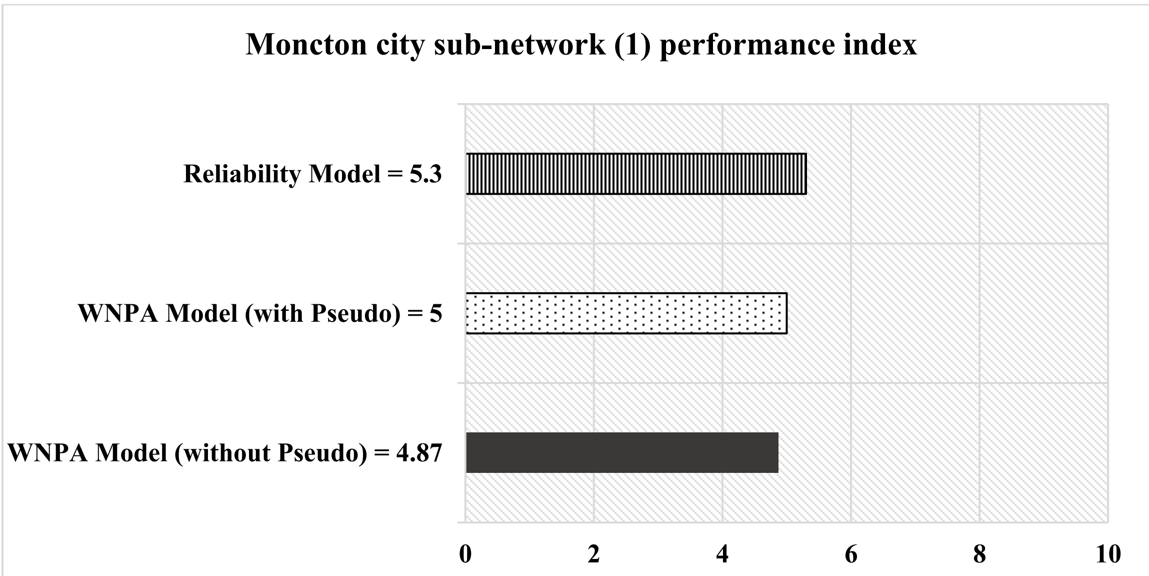


Figure V.35 City of Moncton sub-network (1) performance indices

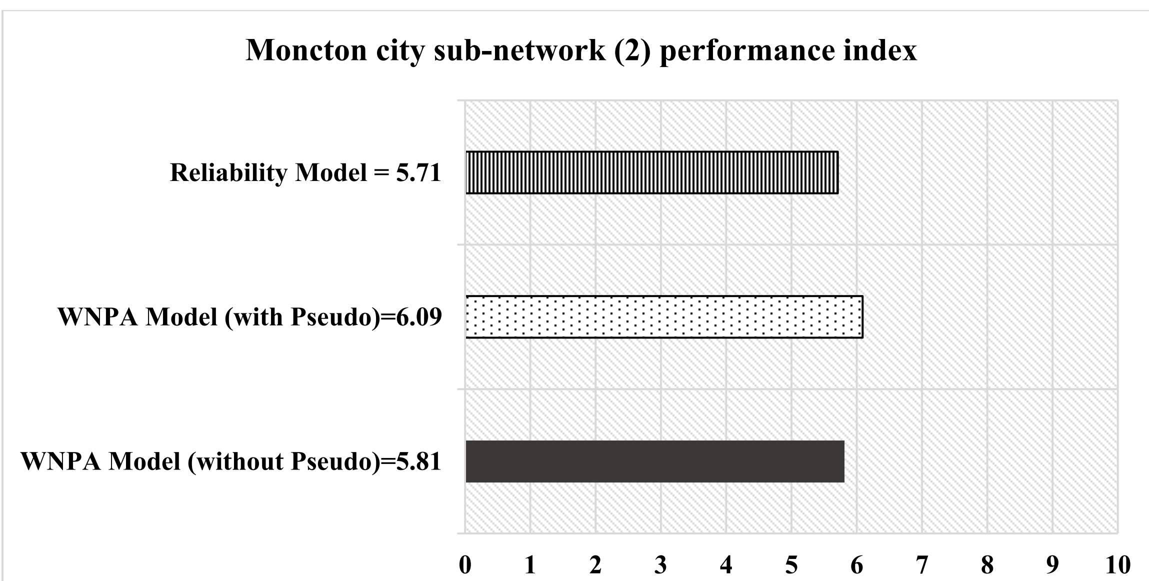


Figure V.36 City of Moncton sub-network (2) performance indices

V.12 Summary

The model is implemented over two case studies, one from City of Moncton which is composed of two sub-networks and the other from city of Montreal which is composed of one sub-network. The model is implemented in steps as following; firstly, the performance indicators to be used are identified, and 20 questionnaires are gathered. The second step is applying FANP on these questionnaires following the technique steps; fuzzified pairwise comparison, unweighted super matrix, weighted super matrix and limited matrix. It is applied using an Excel-Matlab® integrated interface. The outputs of these techniques are the relative weights of the indicators which are used as inputs besides the fuzzified attribute values to PROMETHEE to calculate the performance indices of the components. For the water mains, the indicators with the highest relative weights are the breaks and leaks with 16.58% for each followed by customer satisfaction and water quality with 13.77% for each. They present around 60% of all the indicators, which reflects how much they are effective on the performance. For the accessories, the breaks, leaks, material, customer satisfaction and water quality have the highest contribution of the importance. The fuzzified attribute values are calculated utilizing "FUZZY EXPERT SYSTEM" (fuzzy tool) from Matlab®. The performance indices of the components are integrated together using probability of failure method to get the segments PIs. Then, the segments PIs are integrated using connectivity ranked matrix reaching to the sub-networks indices. The sub-networks indices are integrated together using combination between; the length, land use, and connectivity weights of importance to obtain the entire network PI. The sub-networks indices are (5) and (6.09) for the two sub-networks of City of Moncton respectively, and (4.8) for

Montreal sub-network. The deterioration is analyzed using Weibull distribution analysis and the deterioration curves for the components are drawn.

Three years budget allocation plan is performed and the annual budget is chosen based on the sensitivity analysis, obtaining the best scenario for City of Moncton (1.25, 1.5, 1.5) and for city of Montreal (0.75, 0.5, 0.5) for the three years respectively. The GA and GH models are working properly and the outputs are very similar. The amounts of the money spent and the remaining are almost the same for the two models. The rehabilitation actions defined in the methodology, the unit costs of those actions, the physical properties of each component, and the performance indices of the components are all used as inputs to the budget allocation model. Simulation on the distributed annual budget from the GA-Model is performed utilizing @Risk software and the outputs are shown in triangular distribution. This simulation covers the uncertainty within the allocated budget and helps the municipality to foreseen any unexpected inflation in the budget plan. Also, sensitivity analysis is done on the relative weights of the indicators and the outputs showed that ±25% change in the weights does not lead to more than ±5% change within the performance which also approves the accuracy of the model. Finally, the model is verified for City of Moncton by comparing its results to the results of a previous model which was applied on the same case study, and for city of Montreal by comparing the recommended actions for Montreal sub-network to the recommended actions by the software utilized in city of Montreal water services department (AQUAMODEX). All the verification factors are within an acceptable range and the recommended actions for Montreal case study almost match with those of city of Montreal water services.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

VI.1 CONCLUSIONS

This research was performed to develop a performance assessment model for the water networks components, segments and sub-networks, reaching to the entire network. Then, the budget was allocated to the components of the network based on the performance assessment. This model is discussed to help the water municipalities in the condition and performance assessments and in optimally distributing their limited budget. Thus, the conclusions of this research are presented as follows:

- The four functional weights are equal to 22.8%, 39.5%, 32.6% and 5% for the physical, operational, quality of service and environmental functions respectively.
- The indicators' weights were evaluated using FANP and the indicators with the highest relative weights for the pipelines were breaks, leaks customer satisfaction and water quality, with a percentage of 16.6%, 16.6%, 13.77% and 13.77% respectively. On the other hand, the indicators with the highest weights for the accessories were the same, in addition to material, which had a weight of 15%.
- Based on the model, expert opinions, the conducted interviews and Al Barqawi (2006) linguistic scale, the performance index was categorized into five categories: Critical from 0 to 3, poor from 3 to 4, medium from 4 to 6, good from 6 to 8 and excellent from 8 to 10.
- The failed component has a performance index of 0 while the newly installed component has a PI of 10.

- The model was implemented on three sub-networks, two from City of Moncton and one from city of Montreal, using PROMETHEE to get the performance indices.
- The performance indices of the components of sub-networks of City of Moncton are mostly graded as medium, with a range of PI from 6 to 8.
- The probability of failure method is used for the integration of the indices of the components to reach to the segments PI. It provided the weights of importance of the pipes and the accessories within each segment.
- The topological clustering means, i.e. the connectivity ranked matrix, is used to integrate the segments PI to reach to the sub-network PI.
- The two subnetworks of City of Moncton have PIs equal to 4.9 and 5.81 respectively. The two subnetworks PI using reliability assessment means were equal to 5.66 and 5.71 respectively. Thus, the implemented integration methods are proven to be efficient.
- The sub-networks are integrated using the same methodology as the segments integration besides considering the length and the land use weights of importance.
- A rehabilitation and maintenance plan is developed based on the P scale.
- Weibull distribution is used to predict the performance of the components. It is based on three points: (1) the starting condition at time 0, where PI equals 10; (2) the failing condition at the end of service life, where PI equals 3; and (3) the inspection point performance index.
- Budget is allocated using a GA optimization tool and GH means, based on the performance indices.

- ❖ GA and GH results are very close, also the spent budget as well as the remaining parts to be rehabilitated in the two plans, are almost the same, proving the accuracy of the model and the high degree of certainty in the results.
- ❖ The sensitivity analysis proves that the results of the models are not sensitive to the indicators' relative weights, as any change in the weights of ±25% only causes a ±5% change in the results.
- ❖ Using @risk, the simulation of the yearly allocated budget using GA model is conducted by assuming ±5% risk in the unit cost inputs. The risk for the inputs and outputs is made as a triangular distribution. The risk output is defined as the final budget allocated at the end of each year of the plan. This simulation is of great advantage to municipalities, as it helps them cover the risk of any change in the yearly allocated budget by considering the change in the unit cost and, thus, avoid exceeding the allowable annual budget.
- ❖ The model results' verification is conducted by comparing the model results at hand to a previously developed model, which used FANP and reliability assessment and was applied on the same case study.
- ❖ The verification is done on different levels of the network and the verification factor (VF) is within an acceptable range of 0.7 to almost 1. The VF of the two sub-networks of City of Moncton were equal to 0.87 and 1.02 respectively. This result shows a high degree of certainty within the model output.

VI.2 RESEARCH CONTRIBUTIONS

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

- ❖ Performance indicators hierarchy.
- ❖ Performance assessment model for water distribution systems (WNPA)
- ❖ Performance indices of different levels of the water networks, e.g. components, segments, sub-networks, etc., by using different integration methods.
- ❖ Performance assessment scale for water distribution systems and its components.
- ❖ Budget allocation model based on the performance assessment model. In other words, linking the budget allocation to the performance assessment (WNPBA).
- ❖ Performance prediction of the water networks components, i.e. deterioration curves.

VI.3 RESEARCH LIMITATIONS

The implementation of the proposed model in this research has the following limitations:

- ❖ Lack of historical data, which affected the accuracy of the model.
- ❖ Lack of data for the accessories part, which also led to various assumptions.
- ❖ Lack of proper definition of the pseudo thresholds for each defined factor.
- ❖ FANP weights are based on expert surveys that are numerically and geographically limited and mostly suitable for North America only.
- ❖ Lack of literature review in the area of components and segments integration, which affected the accuracy of the proposed probability of failure and connectivity ranked matrix methods.
- ❖ There is a margin of error within the results as the steps of the model are connected in a cycle, therefore the error can propagate from any step to the following steps.

VI.4 RECOMMENDATIONS AND FUTURE WORK

This model can be enhanced or extended in the future to be more precise and to cover more aspects. The following are some suggested future research enhancements and extensions:

VII.4.1 Research Enhancement

- ❖ Incorporating more historical data into the implemented case studies for a more precise judgment about the model.
- ❖ Defining more indicators that contribute to the performance of the water networks and their components to make the proposed model feasible for different cases.
- ❖ Defining the thresholds for pseudo criteria more accurately by incorporating more expert opinion from the municipal and inspection engineers, as this can help enhance the results of the model.
- ❖ Gathering more questionnaires from different locations.
- ❖ Rehabilitation and maintenance action costs and time analysis should be subjected to a detailed study, to increase the degree of certainty in the budget allocation model.
- ❖ The probability of failure method can be enhanced to more precisely integrate pipes and accessories.
- ❖ Topological clustering for integrating segments needs improvement, by conducting a detailed study on the possible solutions and the connection types between pipelines and accessories and also including the hydraulic connectivity.
- ❖ The deterioration can be predicted using linear equation and then by comparing its results by the results from Weibull analysis, a conclusion about which is more accurate to be used within the model will be obtained.

VII.4.2 Research Extension

- Considering the rehabilitation action time analysis to cover the criticality in the scheduling and its effect on the budget due to cost of the service interruptions.
- Incorporating the hydraulic connectivity in addition to the structural connectivity within the topological clustering, as this makes the segments and the sub-networks integration more realistic.
- Assessing the performance index of each type of the accessories individually such as hydrants, control valves, isolation valves, pumps, etc.
- Developing of a graphical user interface, i.e. an automated tool that can easily draw the network layout considering all the components of the network and the types of connection between them and does all the calculations of the model automatically. This interface should deploy the user inputs for selecting the performance indicators to fill the pairwise comparison. This interface should also be able to record the inputs of relative weights and attribute values to be used for guidance in the future according to the location of the case study.
- The methodology of the performance-based budget allocation can be extended to the assessment of other infrastructures such as sewer and road network elements. Then, these indices can be integrated with the water indices to reach an integrated infrastructure management tool.

REFERENCES

Abouhamad, M. (2014). An Integrated Risk-Based Asset Management Framework for Subway Systems (Doctoral dissertation, Concordia University).

Abu-Taleb, M. F. and Mareschal, B. (1995). "Water resources planning in the Middle East: application of the PROMETHEE V multicriteria method." Eur.J.Oper.Res. 81(3), 500-511.

Adams, W. (2001). Creative Decisions Foundation. Creative decisions, <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.

Al-Battaineh, H. T. (2007). "Infrastructure Intermediate-level Modelling and Optimization of Budget Allocation". PhD Dissertation, Edmonton, Canada: University of Alberta.

Al-Battaineh, H., AbouRizk, S., Siu, K., & Allouche, M. (2005). "The Optimization of Infrastructure Budget Allocation using Genetic Algorithms". 1st CSCE Specialty Conference on Infrastructure Technologies, Management and Policy. Toronto.

Alegre, H., Hirner, W., Baptista, J. M. and Parena, R. (2002). "Highlights of the IWA system of performance indicators for water supply services." Beitrag zum Workshop „Views and Experience Gained Through Implementing IWA Performance Indicators Project ", im Rahmen des 3rd World Water Congress in Melbourne, 2002.

Al-Kloub, B., Al-Shemmeri, T. and Pearman, A. (1997). "The role of weights in multi-criteria decision aid and the ranking of water projects in Jordan." Eur.J.Oper.Res. 99(2), 278-288.

Al-Rashdan, D., Al-Kloub, B., Dean, A. and Al-Shemmeri, T. (1999). "Environmental impact assessment and ranking the environmental projects in Jordan." Eur.J.Oper.Res. 118(1), 30-45.

Al-Tabtabai, H., & Alex, A. P. (1999). “Using genetic algorithms to solve optimization problems in construction”. Engineering Construction and Architectural Management, 6(2), 121-132.

Alvarez Grima, M., Bruines, P. A., & Verhoef, P. N. W. (2000). “Modeling tunnel boring machine performance by neuro-fuzzy methods”. Tunneling and underground space technology, 15(3), 259-269

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

Ariaratnam, S. T. and MacLeod, C. W. (2002). "Financial outlay modeling for a local sewer rehabilitation strategy." J.Constr.Eng.Manage. 128(6), 486-495.

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)

Barron, F. H. and Barrett, B. E. (1996). "Decision quality using ranked attribute weights." Management Science, 42(11), 1515-1523.

Beasley, D., Martin, R., & Bull, D. (1993). “An overview of genetic algorithms: Part 1. Fundamentals”. University computing, 15, 58-58.

Belton, V. and Stewart, T. (2002). Multiple criteria decision analysis: an integrated approach. Springer Science & Business Media.

Bilgiç, T., & Türkşen, I. B. (2000). “Measurement of membership functions: theoretical and empirical work”. Fundamentals of fuzzy sets (pp. 195-227). Springer US.

Brans, J., Vincke, P. and Mareschal, B. (1986). "How to select and how to rank projects: The PROMETHEE method." Eur.J.Oper.Res. 24(2), 228-238.

Buckley, J. J. (1985). "Fuzzy hierarchical analysis." Fuzzy Sets Syst., 17(3), 233-247.

Chang, D. Y. (1996). "Applications of the extent analysis method on fuzzy AHP". 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.

Cheng, C.-H. & Mon, D.L. (1994). "Evaluating weapon system by Analytical Hierarchy Process based on fuzzy scales". Fuzzy Sets and Systems, 63(1), 1-10.

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

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

CSCE. (2016). "Canadian infrastructure report card." Municipal Roads and Water Systems, Volume 1: 2016. 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.

Dandy, G. C. and Engelhardt, M. (2001). "Optimal scheduling of water pipe replacement using genetic algorithms." J.Water Resour.Plann.Manage., 127(4), 214-223.

Dandy, G. C. and Engelhardt, M. O. (2001). "Optimum rehabilitation of water distribution system considering cost and reliability." Proceedings of the World Water and Environmental Resources Congress, Orl ando, Florida.

Di Nardo, A., Di Natale, M., Giudicianni, C., Musmarra, D., Santonastaso, G. F. and Simone, A. (2015). "Water Distribution System Clustering and Partitioning Based on Social Network Algorithms." Procedia Engineering, 119 196-205.

Doumpos, M. and Zopounidis, C. (2002). Multicriteria decision aid classification methods. Springer Science & Business Media.

Dziedzic, R. and Karney, B. W. (2015). "Performance Index for Water Distribution Networks under Multiple Loading Conditions." J.Water Resour.Plann.Manage., 04015040.

Edwards, W. and von Winterfeldt, D. (1986). "Decision analysis and behavioral research."

El Chanati, H. (2014). Performance Assessment of Water Network Infrastructure, M.S. thesis, Concordia University. Montreal, Quebec, Canada.

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).

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.

Etezadi-Amoli, J. and Ciampi, A. (1983). "Simultaneous parameter estimation for the multiplicative multiattribute utility model." Organ.Behav.Hum.Perform. 32(2), 232-248.

Eusuff, M. M. and Lansey, K. E. (2003). "Optimization of water distribution network design using the shuffled frog leaping algorithm." J.Water Resour.Plann.Manage., 129(3), 210-225.

Farran, M. and Zayed, T. (2012). "New life-cycle costing approach for infrastructure rehabilitation." Engineering, Construction and Architectural Management, 19(1), 40-60.

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.

Félio, G. (2012). "Canadian Infrastructure Report Card: Municipal Roads and Water Systems.”.

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)

Fülöp, J. (2005). "Introduction to decision making methods." BDEI-3 Workshop, Washington, Citeseer.”

Garuti, C., & S andoval, 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

Geldermann, J. and Rentz, O. (2000). "Bridging the gap between American and European MADM-approaches." Proc. of the 51st Meeting of the European Working Group "Multicriteria Aid for Decisions", Madrid.

Ghasemi, E., & Ataei, M. (2012). "Application of fuzzy logic for predicting roof fall rate in coal mines". Neural Computing & Applications.http://dx.doi.org/10.1007/s00521-012-0819- 3.

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.

Goodwin, P. W., George. (2004). Decision analysis for management judgement. John Wiley and sons.

Goumas, M. and Lygerou, V. (2000). "An extension of the PROMETHEE method for decision making in fuzzy environment: Ranking of alternative energy exploitation projects." Eur.J.Oper.Res. 123(3), 606-613.

Grablutz, F. and Hanneken, S. (2000). "Economic modeling for prioritizing pipe replacement program." AWWA Infrastructure Conference and Exhibition.

Haralambopoulos, D. and Polatidis, H. (2003). "Renewable energy projects: structuring a multi-criteria group decision-making framework." Renewable Energy, 28(6), 961-973.

Harbuck, R. H. (2000). "Economic evaluation of trenchless technology." AACE International Transactions, RI12A.

Hegazy, T. (1999). "Optimization of construction time-cost trade-off analysis using genetic algorithms". Canadian Journal of Civil Engineering, 26(6), 685-697. Hillier, F. & Lieberman, G. (1972). Introduction to Operation Research. Holden-Day

Ho, W., Xu, X. and Dey, P. K. (2010). "Multi-criteria decision making approaches for supplier evaluation and selection: A literature review." Eur.J.Oper.Res. 202(1), 16-24.

HOKKANEN, J. and SALMINEN, P. (1997). "Locating a waste treatment facility by multicriteria analysis." Journal of Multi-Criteria Decision Analysis, 6(3), 175-184.

Holland, John H. Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence. U Michigan Press, 1975.

Hsieh, T., & Liu, H. (2004). “Genetic Algorithm for Optimization of Infrastructure Investment Under Time-Resource Constraints”. Computer-Aided Civil and Infrastructure Engineering, 19(3), 203-212.

Jacobs, P. and Goulter, I. (1988). "Evaluation of methods for decomposition of water distribution networks for reliability analysis." Civ.Eng.Syst. 5(2), 58-64.

Jang, JSR, Sun, CT and Mizutani, E. (1997), Neuro-fuzzy and soft computing. PTR Prentice Hall.

Jun, H., Loganathan, G., Deb, A., Grayman, W., Snyder, J., Hammell, J. and McCammon, S. (2004). "Isolating subsystems in a water distribution network." Proc., Environmental and Water Resources Institute World Water and Environmental Resources Congress.

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.

Kangas, A., Kangas, J. and Pykäläinen, J. (2001). "Outranking methods as tools in strategic natural resources planning." Silva Fenn, 35(2), 215-227.

Keeney, R. L. and Raiffa, H. (1976). "Decision analysis with multiple conflicting objectives." Wiley& Sons, New York.

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.

Kirstein, J., Albrechtsen, H. and Rygaard, M. (2014). "Simplification of water distribution network simulation by topological clustering–investigation of its potential use in Copenhagen's water supply monitoring and contamination contingency plans." Procedia Engineering, 89 1184-1191.

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.

L Saaty, T. (2008). "The analytic network process." Iranian Journal of Operations Research, 1(1), 1-27.

LAM, P., MOSKOWITZ, H., EPPEL, T. and TANG, J. (1997). "Decomposition, Interdependence and Precision in Multiattribute Utility Measurements." Journal of Multi-Criteria Decision Analysis, 6(1), 25-40.

Lee, K., Corrigan, S. and Park, K. (2004) “Development of an Infrastructure Asset Management System for a Typical Local Government in Rhode Isl and.” Applications of Advanced Technologies in Transportation Engineering, pp. 271-275. doi: 10.1061/40730(144)51

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

Li, Z., & Halang, W. A. (2006). Integration of fuzzy logic and chaos theory.Vol.187. Heidelberg: Springer.

Liong, S. and Atiquzzaman, M. (2004). "Optimal design of water distribution network using shuffled complex evolution." Journal of the Institution of Engineers, Singapore, 44(1), 93-107.

Macharis, C., Springael, J., De Brucker, K. and Verbeke, A. (2004). "PROMETHEE and AHP: The design of operational synergies in multicriteria analysis: Strengthening PROMETHEE with ideas of AHP." Eur.J.Oper.Res. 153(2), 307-317.

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

Mamdani, E. H., & Assilian, S. (1975). “An experiment in linguistic synthesis with a fuzzy logic controller”. International Journal of Man Machine Studies, 7(1), 1-13.

Mays, L. W. (1989). "Reliability analysis of water distribution systems." ASCE.

Mikhailov, L. & Singh, M. (2003). “Fuzzy analytic network process and its application to the development of decision support systems”. Systems, Man and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on, 33(1), 33-41.

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.

Mohamed, E. and Zayed, T. (2012). "Modeling Fund Allocation to Water Main Rehabilitation Projects," Journal of Performance of Constructed Facilities, ASCE, in press.

Mohamed, E. and Zayed, T. (2013). "Budget Allocation and Rehabilitation Plans for Water Systems Using Simulation Approach," Journal of Tunneling and Underground Space Technology, in press.

Morcous, G., & Lounis, Z. (2005). "Maintenance optimization of infrastructure networks using genetic algorithms". Automation in Construction, 14(1), 129-142.

Moselhi, O. and Sigurdardottir, V. (1998). "Rehab select: a decision support system for selecting trenchless pipeline rehabilitation techniques." Proceedings of the North American NO-DIG, 98 5-8.

Moselhi, O., Zayed, T., Khan, Z., & Salman, A. (2010). "Community-Driven and Reliability Based Budget Allocation for Water Networks". In Construction Research Congress 2010. Innovation for Reshaping Construction Practice.

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

Nunoo, C. N. (2001). "Optimization of pavement maintenance and rehabilitation programming using shuffled complex evolution algorithm.".

Özelkan, E. C. and Duckstein, L. (1996). "Analysing water resources alternatives and h andling criteria by multi criterion decision techniques." J.Environ.Manage. 48(1), 69-96.

Perelman, L. and Ostfeld, A. (2008). "Water distribution system aggregation for water quality analysis." J.Water Resour.Plann.Manage., 134(3), 303-309.

Perelman, L. and Ostfeld, A. (2011). "Topological clustering for water distribution systems analysis." Environmental Modelling & Software, 26(7), 969-972.

Perng, Y.-H., Juan, Y.-K., & Hsu, H.-S. (2007). "Genetic algorithm-based decision support for the restoration budget allocation of historical buildings". Building and Environment, 42(2), 770-778.

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.

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-destructive 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.

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

Raju, K. S., Duckstein, L. and Arondel, C. (2000). "Multicriterion analysis for sustainable water resources planning: a case study in Spain." Water Resour.Manage. 14(6), 435-456.

Raouf, A., Duffuaa, S., Ben-Daya, M., Tsang, A. H., Yeung, W., Jardine, A. K. and Leung, B. P. (2006). "Data management for CBM optimization." Journal of Quality in Maintenance Engineering, 12(1), 37-51.

Roberts, R. and Goodwin, P. (2002). "Weight approximations in multi-attribute decision models." Journal of Multi-Criteria Decision Analysis, 11(6), 291-303.

Roder, A. and Tibken, B. (2006). "A fuzzy optimization model for QFD planning process using analytic network approach." Eur.J.Oper.Res. 169(3), 1010-1029.

Ross, T. J. (2010). Fuzzy logic with engineering applications (2nd edition). John Wiley & Sons, Ltd

Roy, B. (1990). "Decision-aid and decision-making." Eur.J.Oper.Res. 45(2-3), 324-331.

Roy, B. (2013). Multicriteria methodology for decision aiding. Springer Science & Business Media.

Roy, B. and Vincke, P. (1987). "Pseudo-orders: definition, properties and numerical representation." Mathematical Social Sciences, 14(3), 263-274.

Saaty, T. L. (1980). "The analytic hierarchy process: planning, priority setting, resources allocation." New York: McGraw.

Saaty, T. L. (1990). "How to make a decision: the analytic hierarchy process." Eur.J.Oper.Res. 48(1), 9-26.

Saaty, T. L. (2001). "Analytic network process." Encyclopedia of Operations Research and Management Science, Springer, 28-35.

Saaty, T. L. (2006). "The analytic network process." Decision making with the analytic network process, Springer, 1-26.

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.

Salminen, P., Hokkanen, J. and Lahdelma, R. (1998). "Comparing multicriteria methods in the context of environmental problems." Eur.J.Oper.Res. 104(3), 485-496.

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.

Satyanarayana, A. and Wood, R. (1982). "Polygon-to-Chain Reductions and Network Reliability, ORC 82-4." Operations Research Center, University of California, Berkeley.

Semaan, N. (2006). Subway Station Diagnosis Index (SSDI): A Condition Assessment Model, M.S. thesis, Concordia University. Montreal, Quebec, Canada.

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

Semaan, N. and Zayed, T. (2009). "Subway station diagnosis index condition assessment model." J Infrastruct Syst, 15(3), 222-231.

Semaan, N. and Zayed, T. (2010). "A stochastic diagnostic model for subway stations." Tunnel.Underground Space Technol., 25(1), 32-41.

Tarjan, R. (1972). "Depth-first search and linear graph algorithms." SIAM Journal on Computing, 1(2), 146-160.

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.

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, Maryl and, 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.

Zayed, T. M. (2004). "Budget allocation for steel bridge paint maintenance." J.Perform.Constr.Facil. 18(1), 36-46.

Zayed, T., Salman, A. and Basha, I. (2011). "The impact on environment of underground infrastructure utility work." Structure and Infrastructure Engineering, 7(3), 199-210.

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.

Zopounidis, C. and Doumpos, M. (2002). "Multicriteria classification and sorting methods: A literature review." Eur.J.Oper.Res. 138(2), 229-246.

APPENDIX (A)

Water Networks Performance Index Questionnaire

Department of Civil, Building and Environmental Engineering

PERFORMANCE ASSESSMENT OF WATER NETWORK

Dear Sir/Madam

We would like to present our appreciation for taking the time to complete this questionnaire that aims to identify the degree of importance for the factors affecting water **networks' Performance**.

This questionnaire is a part of the requirements for an academic research performed under the supervision of Concordia and Qatar Universities represented by Dr. Tarek Zayed, to build a Performance assessment model for water networks. The information in this questionnaire will be used for academic research with complete commitment of confidentiality of your information.

A: GENERAL INFORMATION

1) **How do you describe your occupation?**

- ☐ Pipeline Inspection Expert
- ☐ Pipeline Department Manager
- ☐ Pipeline Engineer
- ☐ Others design engineer

2) **Which best describes your working experience?**

- ☐ Less than 5 years
- ☐ 6 -10 years
- ☐ 11 – 15 years
- ☐ 16 – 20 years
- ☐ More than 20 years
- ☐

3) **Where did you get most of your experience?**

- ☐ Middle East
- ☐ North America
- ☐ Europe
- ☐
- ☐ Australia
- ☐

B: Performance ASSESSMENT MODEL

This part aims to assess the degree of importance of the Indicators affecting the Performance of water pipelines.

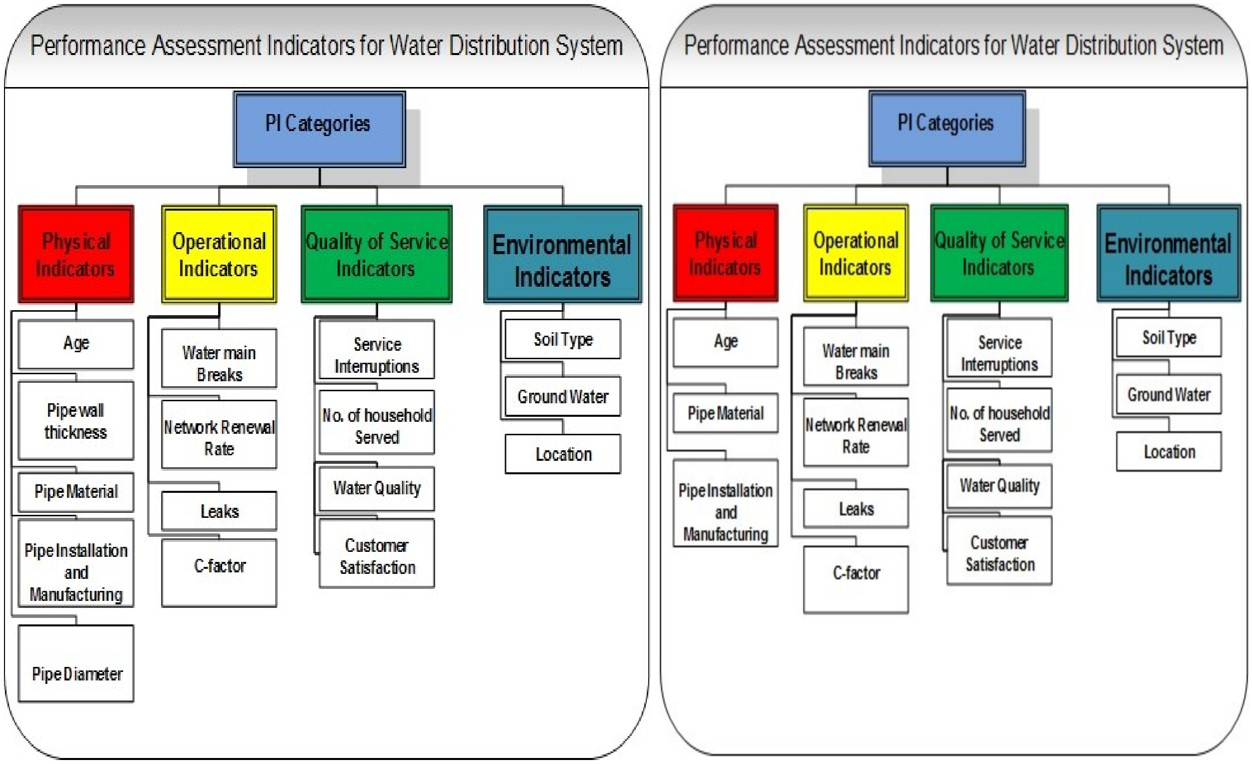


Figure A-1 Indicators for the Performance of Water Pipelines and accessories

PART (B-1): Pairwise comparison between factors:

The Information Gathered from this part of the survey will be used to model the importance of each indicator (Level 1) and sub indicators (Level2) relative to the whole set of indicators and sub indicators respectively. The following questions require a pair-wise comparison between the different indicators (Level 1&2) using the importance scale shown below. The indicators are shown in tables-matrices; using the scale of importance, kindly fill the tables in the following pages by ticking (✓) in the appropriate box from your point of view:

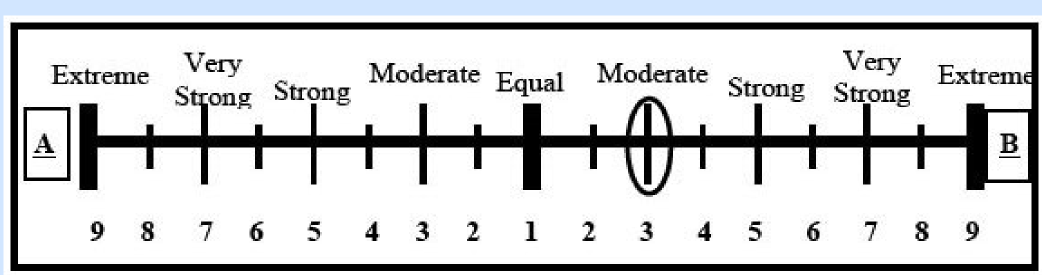


Figure A-2 Degree of Importance scale

Example:

*In the table below, consider comparing **"Pipeline Age"** with **"Pipeline wall thickness"** with respect to **"Physical Factors"**.*

PHYSICAL FACTORS										
Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Pipeline Age										Wall Thickness (Metal Loss)
										Pipe Material
										Installation and Manufacturing Quality

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

*If you consider both "Pipeline Age" and "Pipeline wall thickness" have **"Equal"** importance; then tick (✓) here.*

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

*The same procedure is then followed when comparing **"Age"** with **"Pipe Material"** and **"Installation and Manufacturing Quality"**.*

Water Network pipelines pairwise comparison										
Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	**Criterion (Y)**
Physical Indicators										Operational Indicators
										Quality of Service Indicators
										Environmental Indicators
Physical Indicators										
Pipeline Age										Wall Thickness (Metal Loss)
										Pipe Material
										Installation and Manufacturing Quality
										Pipe Diameter
Operational Indicators										
Water main Breaks										Network Renewal Rate
										Leaks
										No. of Emergency Service Connection Repairs
										Internal Water Pressure
Quality of Service Indicators										
Service Interruptions										No. of Household Served
										Customer Satisfaction
										Water Quality
Environmental Indicators										
Soil Type										Ground Water
										Location
PHYSICAL Indicators										
Operational										Quality of Service
										Environmental
OPERATIONAL Indicators										
Quality of Service										Physical
										Environmental
QUALITY OF SERVICE Indicators										
Physical										Operational
										Environmental
ENVIRONMENTAL Indicators										
Physical										Operational
										Quality of Service

Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Water Network Accessories pairwise comparison										
	← Degree of Importance →									
Physical Indicators										Operational Indicators
										Quality of Service Indicators
										Environmental Indicators
Physical Indicators										
Age										Wall Thickness (Metal Loss)
										Installation and Manufacturing Quality
Operational Indicators										
Breakage rate										Network Renewal Rate
										Leakage rate
										No. of Emergency Service Connection Repairs
										Internal Water Pressure
Quality of Service Indicators										
Service Interruptions										No. of Household Served
										Customer Satisfaction
										Water Quality
Environmental Indicators										
Soil Type										Ground Water
										Location
PHYSICAL Indicators										
Operational										Quality of Service
										Environmental
OPERATIONAL Indicators										
Quality of Service										Physical
										Environmental
QUALITY OF SERVICE Indicators										
Physical										Operational
										Environmental
ENVIRONMENTAL Indicators										
Physical										Operational
										Quality of Service

PART (B-2): DETERMINING THE SCORE OF FACTORS:

In order to determine the performance index, it is required to determine the score of factors. As a result, kindly fill the following tables by identifying for each factor:

* A corresponding quantitative value range for each qualitative parameter

Example:
In the table below, consider evaluating the ***"Pipeline Age"*** *factor.*

Main Factor	Sub-factors	Unit Of Measure	Qualitative Description (Parameters)	Quantitative Value Range (if applicable)	Effect Value Range On Pipeline Condition (0 – 10)
PHYSICAL	Pipeline Age	(Years)	Old	*35 to 50 years*	*0 to 3*
			Medium	*15 to 35 years*	*4 to 7*
			New	*0 to 15 years*	*8 to 10*

The "Quantitative Value Range" can be ***"35 to 50 years", "15 to 35 years",*** *and* ***"0 to 15 years"*** *for the "old", "Medium", and "New" parameters respectively.*

The "Effect Value Range" can be ***"0 to 3", "4 to 7",*** *and* ***"8 to 10 "*** *for the "old", "Medium", and "New" parameters respectively.*

Main Factor	Sub-factors	Unit of Measure	Qualitative Description	Quantitative Value Range	Effect Value On Performance (0 – 10)
Physical	Age	(Years)	Old	( ) to ( )	( ) to ( )
			Medium	( ) to ( )	( ) to ( )
			Newly Installed	( ) to ( )	( ) to ( )
	Pipe wall thickness (Including Coatings and linings)	(Millimeters)	Small size	( ) to ( )	( ) to ( )
			Medium size	( ) to ( )	( ) to ( )
			Large size	( ) to ( )	( ) to ( )
	Pipe Material	NA	PVC	NA	( ) to ( )
			Concrete		( ) to ( )
			Asbestos		( ) to ( )
			Cast Iron		( ) to ( )
			Ductile Iron		( ) to ( )
	Pipe Installation and Manufacturing Quality	%	Excellent	( ) to ( )	( ) to ( )
			Moderate	( ) to ( )	( ) to ( )
			Poor	( ) to ( )	( ) to ( )
	Pipe Diameter	mm	Large size	( ) to ( )	( ) to ( )
			Medium size	( ) to ( )	( ) to ( )
			Small size	( ) to ( )	( ) to ( )
Operational	Water main Breaks	Breaks/Km/year	High	( ) to ( )	( ) to ( )
			Medium	( ) to ( )	( ) to ( )
			Low	( ) to ( )	( ) to ( )
	Network Renewal Rate	Km./Year	High	( ) to ( )	( ) to ( )
			Medium	( ) to ( )	( ) to ( )
			Low	( ) to ( )	( ) to ( )
	Leaks	Leaks/Km/Year	High	( ) to ( )	( ) to ( )
			Medium	( ) to ( )	( ) to ( )
			Low	( ) to ( )	( ) to ( )
	No. of Emergency Service Connection Repairs	No. of Back up Connections/ Km.	High	( ) to ( )	( ) to ( )
			Medium	( ) to ( )	( ) to ( )
			Low	( ) to ( )	( ) to ( )
	Internal Water Pressure	(kPa. or psi)	High	( ) to ( )	( ) to ( )
			Medium	( ) to ( )	( ) to ( )
			Low	( ) to ( )	( ) to ( )
Quality of Service	Service Interruptions	No. of Interruptions/ Km./Year	High	( ) to ( )	( ) to ( )
			Medium	( ) to ( )	( ) to ( )
			Low	( ) to ( )	( ) to ( )
	No. of Household Served	No. of household served/Km.	High	( ) to ( )	( ) to ( )
			Medium	( ) to ( )	( ) to ( )
			Low	( ) to ( )	( ) to ( )
	Customer Satisfaction	No. of Complaints/ Km./Year	High	( ) to ( )	( ) to ( )
			Medium	( ) to ( )	( ) to ( )
			Low	( ) to ( )	( ) to ( )
	Water Quality	%	Excellent	( ) to ( )	( ) to ( )
			Good	( ) to ( )	( ) to ( )
			Poor	( ) to ( )	( ) to ( )

Environmental	Soil Type	% of Corrosiveness and Presence of hydrocarbons and Solvents	Aggressive	( ) to ( )	( ) to ( )
			Moderate	( ) to ( )	( ) to ( )
			Non Aggressive	( ) to ( )	( ) to ( )
	Ground Water Table	(Meters)	Deep	( ) to ( )	( ) to ( )
			Moderate	( ) to ( )	( ) to ( )
			Shallow	( ) to ( )	( ) to ( )
	Location	Surface Type	Asphalt	NA	( ) to ( )
			Seal		( ) to ( )
			Footpath		( ) to ( )
			Unpaved		( ) to ( )

PART (B-4): Criteria Thresholds:

The Information gathered from this part of the survey will help setting critical and tolerance thresholds of each of the sub criteria and category.

So According to the Quantitative value range that you defined for each criteria in the previous table, define critical and tolerance thresholds for each criteria on the same scale of the Qualitative value range.

As the critical value is the value above which the criterion value is considered critical or dangerous and the tolerance value is the value below which the criterion value is considered tolerable or safe.

Criteria	Thresholds according to Quantitative range	
	Critical	Tolerance
Age		
Pipe Wall Thickness		
Pipe Material	NA	NA
Pipe Installing and Manufacturing		
Pipe Diameter		
Water main Breaks		
Network Renewal Rate		
Leaks		
No. of emergency Service Connection Repairs		
Internal Water Pressure		
Service Interruptions		
No. of household Served		
Customer Satisfaction		
Water Quality		
Soil Type		
Ground Water		
Location	NA	NA

Thank You for your Participation

APPENDIX (B)

ACCESSORIES PAIWISE COMPARISON

Table B-1 Indicators categories pairwise comparison with respect to the overall performance

	Physical	Operational	Quality of Service	Environmental
Physical	(1,1,1)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(4,5,6)
Operational	(6,7,8)	(1,1,1)	(1,1,2)	(8,9,9)
Quality of Service	(6,7,8)	(1/2,1,1)	(1,1,1)	(8,9,9)
Environmental	(1/6,1/5,1/4)	(1/9,1/9,1/8)	(1/9,1/9,1/8)	(1,1,1)

Table B-2 Physical indicators pairwise comparison

	age	material	installation
age	(1,1,1)	(1/6,1/5,1/4)	(1,1,2)
material	(4,5,6)	(1,1,1)	(2,3,4)
installation	(1/2,1,1)	(1/4,1/3,1/2)	(1,1,1)

Table B-3 Operational indicators pairwise comparison

	Water main Breaks	Network Renewal Rate	Leaks	C-factor
Water main Breaks	(1,1,1)	(4,5,6)	(1,1,2)	(4,5,6)
Network Renewal Rate	(1/6,1/5,1/4)	(1,1,1)	(1/6,1/5,1/4)	(1,1,2)
Leaks	(1/2,1,1)	(4,5,6)	(1,1,1)	(4,5,6)
Internal Water Pressure	(1/6,1/5,1/4)	(1/2,1,1)	(1/6,1/5,1/4)	(1,1,1)

Table B-4 Quality of service indicators

	Service Interruptions	No. of Household Served	Customer Satisfaction	Water Quality
Service Interruptions	(1,1,1)	(4,5,6)	(1/6,1/5,1/4)	(1/6,1/5,1/4)
No. of Household Served	(1/6,1/5,1/4)	(1,1,1)	(1/9,1/9,1/8)	(1/9,1/9,1/8)
Customer Satisfaction	(4,5,6)	(8,9,9)	(1,1,1)	(1,1,2)
Water Quality	(4,5,6)	(8,9,9)	(1/2,1,1)	(1,1,1)

Table B-5 Environmental indicators pairwise comparison

	Soil	Ground water	Location
Soil Type	(1,1,1)	(4,5,6)	(1/8,1/7,1/6)
Ground water	(1/6,1/5,1/4)	(1,1,1)	(1/9,1/9,1/8)
Location l	(6,7,8)	(8,9,9)	(1,1,1)

Table B-6 Indicators categories pairwise comparison with respect to each other

	Operational	Quality of service	Environmental
Operational	(1,1,1)	1.000	(6,7,8)
Quality of service	1.000	(1,1,1)	(6,7,8)
Environmental	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1,1,1)

	Quality of service	Physical	Environmental
Quality of service	(1,1,1)	(6,7,8)	(6,7,8)
Physical	(1/8,1/7,1/6)	(1,1,1)	(6,7,8)
Environmental	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1,1,1)

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

	Physical	Operational	Quality of service
Physical	(1,1,1)	(1/8,1/7,1/6)	(1/8,1/7,1/6)
Operational	(6,7,8)	(1,1,1)	(1,1,2)
Quality of service	(6,7,8)	(1/2,1,1)	(1,1,1)

APPENDIX (C)

PERFORMANCE INDICES CALCULATIONS TABLES OF THE CASE STUDIES

Functional and global performance indices of pipelines of sub-network (1), City of Moncton (without Pseudo effect):

Pipe #	PPPI	PEPI	POPI	PQPI	GPI
1	7.0	5.1	7.7	3.6	6.1
2	6.1	5.1	7.1	4.5	5.9
3	5.1	5.1	5.4	4.6	5.1
4	5.4	5.1	4.0	7.1	5.4
5	5.4	5.1	2.3	7.1	4.7
6	5.4	5.1	4.0	5.0	4.7
7	4.8	5.1	4.0	7.1	5.3
8	5.5	5.1	5.8	7.3	6.2
9	5.5	5.1	9.1	7.3	7.5
10	5.0	5.1	5.7	7.1	6.0
11	5.0	5.1	2.4	7.1	4.7
12	5.2	5.1	4.2	3.9	4.3
13	4.9	5.1	5.8	7.3	6.0
14	4.9	5.1	1.6	7.3	4.4
15	4.7	5.1	3.2	7.1	4.9
16	4.9	5.1	4.1	7.3	5.4
17	4.9	5.1	5.8	3.9	5.0
18	4.7	5.1	0.7	7.1	4.0
19	4.7	5.1	1.6	7.1	4.3
20	4.9	5.1	2.4	3.9	3.6
21	4.3	5.1	4.2	3.9	4.2
22	4.7	5.1	0.6	7.1	3.9
23	4.7	5.1	1.6	7.1	4.3
24	4.7	5.1	2.4	7.1	4.6
25	4.7	5.1	2.3	7.1	4.6
26	5.0	5.1	5.8	7.1	6.0
27	5.0	5.1	4.0	7.1	5.3
28	5.0	5.1	4.0	7.1	5.3
29	5.0	5.1	4.0	7.1	5.3
30	4.7	5.1	4.0	7.1	5.2
31	4.3	5.1	1.6	3.9	3.1
32	4.7	5.1	0.6	7.1	3.9
33	4.7	5.1	2.3	7.1	4.6
34	4.3	5.1	4.1	3.9	4.1
35	4.9	5.1	4.1	7.3	5.4

Functional and global performance indices of Accessories of sub-network (1), City of Moncton (without Pseudo effect):

Acc. #	APPI	AEPI	AOPI	AQPI	GPI
1	8.2	5.1	7.7	3.6	6.3
2	6.8	5.1	7.1	4.5	6.1
3	6.8	5.1	5.4	4.6	5.4
4	7.4	5.1	4.0	7.1	5.8
5	7.4	5.1	2.3	7.1	5.2
6	7.4	5.1	4.0	5.0	5.1
7	7.4	5.1	4.0	7.1	5.8
8	7.7	5.1	5.8	7.3	6.7
9	7.7	5.1	9.1	7.3	8.0
10	7.4	5.1	5.7	7.1	6.5
11	7.4	5.1	2.4	7.1	5.2
12	7.9	5.1	4.2	3.9	5.0
13	7.7	5.1	5.8	7.3	6.7
14	7.7	5.1	1.6	7.3	5.0
15	7.4	5.1	3.2	7.1	5.5
16	7.7	5.1	4.1	7.3	6.0
17	7.9	5.1	5.8	3.9	5.6
18	7.4	5.1	1.6	7.1	4.9
19	7.4	5.1	1.6	7.1	4.9
20	7.9	5.1	2.4	3.9	4.3
21	7.9	5.1	4.2	3.9	5.0
22	7.4	5.1	0.6	7.1	4.5
23	7.4	5.1	1.6	7.1	4.9
24	7.4	5.1	2.4	7.1	5.2
25	7.4	5.1	2.3	7.1	5.2
26	7.4	5.1	5.8	7.1	6.5
27	7.4	5.1	4.0	7.1	5.8
28	7.4	5.1	4.0	7.1	5.8
29	7.4	5.1	4.0	7.1	5.8
30	7.4	5.1	4.0	7.1	5.8
31	7.9	5.1	1.6	3.9	3.9
32	7.4	5.1	0.6	7.1	4.5
33	7.4	5.1	2.3	7.1	5.2
34	7.7	5.1	4.1	3.9	4.9
35	7.7	5.1	4.1	7.3	6.0

Functional and global performance indices of pipelines of sub-network (1), City of Moncton (with Pseudo effect):

Pipe #	PPPI	PEPI	POPI	PQPI	GPI
1	8.2	5.1	9.3	3.5	7.0
2	6.7	5.1	8.5	4.3	6.6
3	4.7	5.1	6.0	4.5	5.2
4	5.1	5.1	3.0	8.0	5.2
5	5.1	5.1	0.5	8.0	4.2
6	5.1	5.1	3.0	4.2	4.0
7	4.8	5.1	3.0	8.0	5.2
8	5.2	5.1	6.5	8.3	6.7
9	5.2	5.1	9.0	8.3	7.7
10	4.2	5.1	6.4	8.0	6.4
11	4.2	5.1	0.6	8.0	4.1
12	4.3	5.1	3.3	4.0	3.9
13	4.1	5.1	6.5	8.3	6.5
14	4.1	5.1	0.6	8.3	4.1
15	4.0	5.1	1.5	8.0	4.4
16	4.1	5.1	3.2	8.3	5.1
17	4.1	5.1	6.7	4.0	5.1
18	4.0	5.1	0.6	8.0	4.0
19	4.0	5.1	0.6	8.0	4.0
20	4.1	5.1	0.6	4.0	2.8
21	3.8	5.1	3.3	4.0	3.7
22	4.0	5.1	0.5	8.0	4.0
23	4.0	5.1	0.6	8.0	4.0
24	4.0	5.1	0.6	8.0	4.0
25	0.0	5.1	0.5	8.0	4.0
26	4.2	5.1	6.5	8.0	6.4
27	4.2	5.1	3.0	8.0	5.0
28	4.2	5.1	3.0	8.0	5.0
29	4.2	5.1	3.0	8.0	5.0
30	4.0	5.1	3.0	8.0	5.0
31	3.8	5.1	0.6	4.0	2.7
32	4.0	5.1	0.5	8.0	4.0
33	4.0	5.1	0.5	8.0	4.0
34	3.8	5.1	3.2	4.0	3.7
35	4.1	5.1	3.2	8.3	5.1

Functional and global performance indices of Accessories of sub-network (1), City of Moncton (with Pseudo effect):

Acc. #	APPI	AEPI	AOPI	AQPI	GPI
1	8.9	5.1	9.3	3.5	7.1
2	7.1	5.1	8.5	4.3	6.6
3	7.1	5.1	6.0	4.5	5.7
4	8.2	5.1	3.0	8.0	5.9
5	8.2	5.1	0.5	8.0	4.9
6	8.2	5.1	3.0	4.2	4.7
7	8.2	5.1	3.0	8.0	5.9
8	8.4	5.1	6.5	8.3	7.5
9	8.4	5.1	9.0	8.3	8.4
10	8.2	5.1	6.4	8.0	7.3
11	8.2	5.1	0.6	8.0	5.0
12	8.4	5.1	3.3	4.0	4.8
13	8.4	5.1	6.5	8.3	7.5
14	8.4	5.1	0.6	8.3	5.1
15	8.2	5.1	1.5	8.0	5.3
16	8.4	5.1	3.2	8.3	6.1
17	8.4	5.1	6.7	4.0	6.1
18	8.2	5.1	0.6	8.0	5.0
19	8.2	5.1	0.6	8.0	5.0
20	8.4	5.1	0.6	4.0	3.8
21	8.4	5.1	3.3	4.0	4.8
22	8.2	5.1	0.5	8.0	4.9
23	8.2	5.1	0.6	8.0	5.0
24	8.2	5.1	0.6	8.0	5.0
25	8.2	5.1	0.5	8.0	4.9
26	8.2	5.1	6.5	8.0	7.3
27	8.2	5.1	3.0	8.0	5.9
28	8.2	5.1	3.0	8.0	5.9
29	8.2	5.1	3.0	8.0	5.9
30	8.2	5.1	3.0	8.0	5.9
31	8.4	5.1	0.6	4.0	3.8
32	8.2	5.1	0.5	8.0	4.9
33	8.2	5.1	0.5	8.0	4.9
34	8.4	5.1	3.2	4.0	4.7
35	8.4	5.1	3.2	8.3	6.1

Functional and global performance indices of pipelines of sub-network (2), City of Moncton (without Pseudo effect):

Pipe #	PPI	EPI	OPI	QPI	GPI
1	4.71	5.06	5.76	4.31	4.88
2	4.71	5.06	5.76	4.31	4.88
3	4.96	5.06	5.52	7.15	5.95
4	4.71	5.06	3.24	4.31	3.89
5	4.96	5.06	3.00	7.15	4.98
6	4.51	5.06	2.40	7.15	4.55
7	4.71	5.06	5.76	4.31	4.88
8	4.71	5.06	5.76	4.31	4.88
9	4.96	5.06	5.76	7.15	5.61
10	4.51	5.06	0.72	7.15	4.02
11	6.07	5.06	5.76	7.27	6.41
12	4.96	5.06	5.52	7.15	5.98

Functional and global performance indices of Accessories of sub-network (2), City of Moncton (without Pseudo effect):

Accessory #	PPI	EPI	OPI	QPI	GPI
1	7.36	5.06	4.08	4.31	5.44
2	7.36	5.06	3.00	7.27	6.40
3	7.36	5.06	3.24	7.27	6.34
4	7.36	5.06	4.08	4.31	5.63
5	7.36	5.06	3.24	7.27	5.37
6	7.36	5.06	3.24	7.27	5.57
7	7.36	5.06	4.08	4.31	4.30
8	7.36	5.06	4.08	4.31	5.44
9	7.36	5.06	3.00	7.27	6.34
10	9.16	5.06	9.12	7.15	5.83
11	9.00	5.06	8.28	7.15	4.86
12	7.36	5.06	4.08	4.31	5.72
13	7.36	5.06	4.08	4.31	5.72

Functional and global performance indices of Pipelines of Montreal sub-network (without Pseudo effect):

	PPPI	PEPI	POPI	PQPI	GPI
1	6.98	4.82	2.48	4.69	4.35
2	7.65	4.82	9.36	7.92	8.27
3	6.88	4.82	9.20	7.92	8.03
4	6.88	4.82	1.64	4.15	3.81
5	8.51	4.82	9.28	7.92	8.44
6	6.98	4.82	9.20	7.92	8.06
7	6.92	4.82	9.60	7.92	8.20
8	7.45	4.82	9.20	7.92	8.16
9	7.02	4.82	2.56	4.69	4.39
10	7.02	4.82	9.28	7.92	8.10
11	7.52	4.82	9.28	7.92	8.21
12	6.92	4.82	9.60	7.92	8.20
13	7.45	4.82	9.20	7.92	8.16
14	7.43	4.82	9.52	7.92	8.28
15	6.72	4.82	9.44	7.92	8.09
16	7.45	4.82	9.20	7.92	8.16
17	7.45	4.82	1.64	4.15	3.94
18	7.45	4.82	3.32	5.23	4.96
19	7.45	4.82	9.20	7.92	8.16
20	7.45	4.82	9.20	7.92	8.16
21	6.94	4.82	4.24	5.76	5.38
22	7.45	4.82	2.48	4.69	4.45
23	5.87	4.82	9.20	7.92	7.80
24	7.18	4.82	9.44	7.92	8.20
25	6.88	4.82	9.20	7.92	8.03
26	6.98	4.82	4.16	5.76	5.36
27	6.93	4.82	2.56	4.69	4.37
28	6.88	4.82	9.20	7.92	8.03
29	6.98	4.82	1.72	4.15	3.87
30	6.98	4.82	5.00	6.30	5.87
31	6.58	4.82	1.80	4.15	3.81
32	6.58	4.82	9.36	7.92	8.03
33	6.92	4.82	9.60	7.92	8.20
34	5.87	4.82	2.48	4.69	4.09
35	6.94	4.82	3.40	5.23	4.88
36	7.53	4.82	9.52	7.92	8.31
37	6.88	4.82	9.20	7.92	8.03
38	6.93	4.82	9.28	7.92	8.08

	PPPI	PEPI	POPI	PQPI	GPI
39	7.39	4.82	9.52	7.92	8.28
40	6.98	4.82	4.16	5.76	5.36
41	7.02	4.82	6.16	6.84	6.51
42	7.45	4.82	2.48	4.69	4.45
43	6.94	4.82	9.28	7.92	8.08
44	7.45	4.82	9.20	7.92	8.16
45	7.45	4.82	9.20	7.92	8.16
46	6.85	4.82	9.52	7.92	8.15
47	6.98	4.82	9.20	7.92	8.06
48	6.98	4.82	9.20	7.92	8.06
49	7.02	4.82	9.28	7.92	8.10
50	7.02	4.82	9.28	7.92	8.10
51	7.02	4.82	9.28	7.92	8.10
52	7.19	4.82	9.36	7.92	8.17
53	6.88	4.82	1.56	4.15	3.78
54	6.88	4.82	9.20	7.92	8.03
55	6.88	4.82	9.20	8.77	8.31
56	6.88	4.82	4.08	5.76	5.31
57	7.02	4.82	9.28	7.92	8.10
58	6.98	4.82	9.20	7.92	8.06
59	6.88	4.82	4.92	6.30	5.81
60	7.53	4.82	9.52	7.92	8.31
61	7.45	4.82	9.12	7.92	8.13
62	7.19	4.82	9.20	7.92	8.10
63	6.98	4.82	1.64	4.15	3.84

Functional and global performance indices of Accessories of Montreal sub-network (without Pseudo effect):

	APPI	AEPI	AOPI	AQPI	GPI
1	6.14	4.82	2.48	4.69	4.15
2	6.14	4.82	2.48	4.69	4.15
3	6.35	4.82	9.36	7.92	7.98
4	6.21	4.82	2.56	4.69	4.20
5	6.21	4.82	2.56	4.69	4.20
6	6.21	4.82	9.28	7.92	7.91
7	6.14	4.82	9.20	7.92	7.86
8	6.14	4.82	1.64	4.15	3.65
9	6.14	4.82	1.64	4.15	3.65
10	6.14	4.82	1.64	4.15	3.65
11	6.14	4.82	3.32	5.23	4.66
12	6.14	4.82	2.48	4.69	4.15
13	6.14	4.82	2.48	4.69	4.15
14	6.14	4.82	2.48	4.69	4.15
15	6.14	4.82	2.48	4.69	4.15
16	6.21	4.82	4.24	5.76	5.22
17	6.14	4.82	9.20	7.92	7.86
18	6.21	4.82	3.40	5.23	4.71
19	6.21	4.82	9.28	7.92	7.91
20	5.88	4.82	9.44	7.92	7.90
21	6.14	4.82	1.64	4.15	3.65
22	6.14	4.82	9.20	7.92	7.86
23	6.14	4.82	1.72	4.15	3.68
24	6.14	4.82	1.72	4.15	3.68
25	6.14	4.82	9.20	7.92	7.86
26	6.14	4.82	1.64	4.15	3.65
27	6.14	4.82	1.64	4.15	3.65
28	6.14	4.82	9.20	7.92	7.86
29	6.14	4.82	9.20	7.92	7.86
30	6.14	4.82	9.20	7.92	7.86
31	6.14	4.82	9.20	7.92	7.86
32	6.21	4.82	9.28	7.92	7.91
33	6.08	4.82	9.60	7.92	8.01
34	6.14	4.82	9.20	7.92	7.86
35	6.21	4.82	9.28	7.92	7.91
36	6.14	4.82	4.16	5.76	5.17
37	6.14	4.82	9.20	7.92	7.86
38	6.21	4.82	9.28	7.92	7.91
39	6.08	4.82	9.52	7.92	7.98
40	5.74	4.82	1.80	4.15	3.62
41	5.74	4.82	1.80	4.15	3.62
42	5.74	4.82	9.36	7.92	7.84
43	6.14	4.82	9.20	7.92	7.86
44	6.08	4.82	9.60	7.92	8.01
45	6.08	4.82	9.60	7.92	8.01
46	6.08	4.82	9.60	7.92	8.01
47	6.69	4.82	9.52	7.92	8.12
48	6.69	4.82	9.52	7.92	8.12
49	6.14	4.82	9.20	7.92	7.86
50	6.14	4.82	9.20	7.92	7.86
51	6.01	4.82	9.52	7.92	7.96
52	6.21	4.82	9.28	7.92	7.91
53	6.21	4.82	9.28	7.92	7.91
54	6.21	4.82	9.28	7.92	7.91
55	6.21	4.82	9.28	7.92	7.91
56	6.21	4.82	9.28	7.92	7.91
57	6.14	4.82	9.20	7.92	7.86
58	6.14	4.82	9.20	7.92	7.86
59	6.14	4.82	4.16	5.76	5.17
60	6.14	4.82	4.16	5.76	5.17
61	6.21	4.82	5.92	6.84	6.23
62	6.35	4.82	9.36	7.92	7.98
63	6.14	4.82	4.92	6.30	5.65
64	6.14	4.82	4.92	6.30	5.65
65	6.69	4.82	9.52	7.92	8.12
66	6.69	4.82	9.52	7.92	8.12
67	6.14	4.82	9.12	7.92	7.83
68	6.14	4.82	9.12	7.92	7.83
69	6.14	4.82	9.20	7.92	7.86
70	6.14	4.82	1.64	4.15	3.65
71	6.14	4.82	1.56	4.15	3.61
72	6.14	4.82	9.20	7.92	7.86
73	6.14	4.82	9.20	7.92	7.86
74	6.14	4.82	4.08	5.76	5.14
75	6.21	4.82	9.28	7.92	7.91
76	6.14	4.82	9.20	7.92	7.86
77	6.14	4.82	9.20	7.92	7.86
78	6.69	4.82	9.52	7.92	8.12

APPENDIX (D)

BUDGET ALLOCATION TABLES OF THE CASE STUDIES

GA budget allocation plan for pipelines of sub-network (1) in City of Moncton:

	1	2	3	D	L (m)	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
P.1	24.00	25.00	26.00	450.00	1303.06	6.06	5.68	8.88	1.00	2.00	0.00	0.00	1.00	0.00	0.00	661956.7	0.00	6.06	9.00	8.88
P.2	102.00	103.00	104.00	450.00	660.97	5.93	8.97	8.94	2.00	0.00	0.00	1.00	0.00	0.00	330487.25	0.00	0.00	9.00	8.97	8.94
P.3	98.00	99.00	100.00	300.00	122.08	5.07	8.97	8.94	2.00	0.00	0.00	1.00	0.00	0.00	42728.70	0.00	0.00	9.00	8.97	8.94
P.4	58.00	59.00	60.00	300.00	721.70	5.40	5.23	8.95	2.00	2.00	0.00	0.00	1.00	0.00	0.00	256637.5	0.00	5.40	9.00	8.95
P.5	59.00	60.00	61.00	300.00	173.58	4.74	4.56	8.95	2.00	2.00	0.00	0.00	1.00	0.00	0.00	61725.76	0.00	4.74	9.00	8.95
P.6	65.00	66.00	67.00	300.00	124.91	4.69	8.96	8.91	2.00	0.00	0.00	1.00	0.00	0.00	43720.08	0.00	0.00	9.00	8.96	8.91
P.7	58.00	59.00	60.00	61.00	62.00	5.26	8.95	8.90	2.00	0.00	0.00	1.00	0.00	0.00	225832.0	0.00	0.00	9.00	8.95	8.90
P.8	49.00	50.00	51.00	52.00	53.00	6.17	5.98	5.80	1.00	2.00	2.00	0.00	0.00	1.00	0.00	0.00	172345.0	6.17	5.98	9.00
P.9	49.00	50.00	51.00	52.00	53.00	7.49	7.36	7.22	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	7.49	7.36	7.22
P.10	57.00	58.00	59.00	60.00	61.00	5.96	5.80	5.64	2.00	2.00	2.00	0.00	0.00	1.00	0.00	0.00	113771.2	5.96	5.80	9.00
P.11	55.00	56.00	57.00	58.00	59.00	4.67	4.48	8.95	2.00	2.00	0.00	0.00	1.00	0.00	0.00	18035.32	0.00	4.67	9.00	8.95
P.12	43.00	44.00	45.00	46.00	47.00	4.35	4.10	3.85	2.00	2.00	3.00	0.00	0.00	1.00	0.00	0.00	55127.07	4.35	4.10	9.00
P.13	46.00	47.00	48.00	49.00	50.00	6.03	5.83	5.63	1.00	2.00	2.00	0.00	0.00	1.00	0.00	0.00	49268.82	6.03	5.83	9.00
P.14	49.00	50.00	51.00	52.00	53.00	4.35	4.13	3.92	2.00	2.00	3.00	0.00	0.00	1.00	0.00	0.00	36456.32	4.35	4.13	9.00
P.15	55.00	56.00	57.00	58.00	59.00	4.95	4.76	8.95	2.00	2.00	0.00	0.00	1.00	0.00	0.00	36954.01	0.00	4.95	9.00	8.95
P.16	47.00	48.00	49.00	50.00	51.00	5.37	5.15	8.94	2.00	2.00	0.00	0.00	1.00	0.00	0.00	50051.05	0.00	5.37	9.00	8.94

P.17	42.00	43.00	44.00	45.00	46.00	4.96	4.71	8.93	2.00	2.00	0.00	0.00	1.00	0.00	0.00	53589.83	0.00	4.96	9.00	8.93
P.18	50.00	51.00	52.00	53.00	54.00	3.95	8.94	8.88	3.00	0.00	0.00	1.00	0.00	0.00	43346.58	0.00	0.00	9.00	8.94	8.88
P.19	55.00	56.00	57.00	58.00	59.00	4.29	8.95	8.89	2.00	0.00	0.00	1.00	0.00	0.00	69924.48	0.00	0.00	9.00	8.95	8.89
P.20	44.00	45.00	46.00	47.00	48.00	3.60	8.93	8.87	3.00	0.00	0.00	1.00	0.00	0.00	18479.76	0.00	0.00	9.00	8.93	8.87
P.21	43.00	44.00	45.00	46.00	47.00	4.16	8.93	8.86	2.00	0.00	0.00	1.00	0.00	0.00	37942.86	0.00	0.00	9.00	8.93	8.86
P.22	57.00	58.00	59.00	60.00	61.00	3.92	3.73	3.54	3.00	3.00	3.00	0.00	0.00	1.00	0.00	0.00	82101.80	3.92	3.73	9.00
P.23	55.00	56.00	57.00	58.00	59.00	4.29	4.09	3.89	2.00	2.00	3.00	0.00	0.00	1.00	0.00	0.00	117311.3	4.29	4.09	9.00
P.24	55.00	56.00	57.00	58.00	59.00	4.62	4.42	4.23	2.00	2.00	2.00	0.00	0.00	1.00	0.00	0.00	100673.0	4.62	4.42	9.00
P.25	57.00	58.00	59.00	60.00	61.00	4.59	4.40	4.21	2.00	2.00	2.00	0.00	0.00	1.00	0.00	0.00	72311.74	4.59	4.40	9.00
P.26	54.00	55.00	56.00	57.00	58.00	6.00	5.82	5.65	2.00	2.00	2.00	0.00	0.00	1.00	0.00	0.00	85028.37	6.00	5.82	9.00
P.27	57.00	58.00	59.00	60.00	61.00	5.30	5.12	4.95	2.00	2.00	2.00	0.00	0.00	1.00	0.00	0.00	90752.49	5.30	5.12	9.00
P.28	57.00	58.00	59.00	60.00	61.00	5.30	5.12	4.95	2.00	2.00	2.00	0.00	0.00	1.00	0.00	0.00	37811.56	5.30	5.12	9.00
P.29	58.00	59.00	60.00	61.00	62.00	5.30	5.13	4.95	2.00	2.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	5.30	5.13	4.95
P.30	58.00	59.00	60.00	61.00	62.00	5.25	5.07	4.90	2.00	2.00	2.00	0.00	0.00	1.00	0.00	0.00	149027.4	5.25	5.07	9.00
P.31	44.00	45.00	46.00	47.00	48.00	3.13	2.89	2.65	3.00	4.00	4.00	0.00	0.00	1.00	0.00	0.00	76460.09	3.13	2.89	9.90
P.32	58.00	59.00	60.00	61.00	62.00	3.92	3.73	3.55	3.00	3.00	3.00	0.00	0.00	1.00	0.00	0.00	82146.19	3.92	3.73	9.00
P.33	58.00	59.00	60.00	61.00	62.00	4.59	4.40	4.22	2.00	2.00	2.00	0.00	0.00	1.00	0.00	0.00	53367.84	4.59	4.40	9.00
P.34	44.00	45.00	46.00	47.00	48.00	4.12	8.93	8.87	2.00	0.00	0.00	1.00	0.00	0.00	28805.88	0.00	0.00	9.00	8.93	8.87
P.35	46.00	47.00	48.00	49.00	50.00	5.37	5.15	4.93	2.00	2.00	2.00	0.00	0.00	1.00	0.00	0.00	49268.82	5.37	5.15	9.00

GA budget allocation plan for Accessories of sub-network (1) in City of Moncton:

	1	2	3	L (m)	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
ACC.1	24.00	25.00	26.00	1.00	6.34	5.98	5.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.34	5.98	5.61
ACC.2	102.00	103.00	104.00	1.00	6.09	6.00	5.91	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	6.09	6.00	5.91
Acc. 3	98.00	99.00	100.00	1.00	5.45	5.35	5.24	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	5.45	5.35	5.24
Acc. 4	58.00	59.00	60.00	1.00	5.85	5.69	5.52	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	5.85	5.69	5.52
Acc. 5	59.00	60.00	61.00	1.00	5.19	5.01	4.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.19	5.01	4.84
Acc. 6	65.00	66.00	67.00	1.00	5.13	4.97	4.82	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	5.13	4.97	4.82
Acc. 7	58.00	59.00	60.00	1.00	5.85	5.69	5.52	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	5.85	5.69	5.52
Acc. 8	49.00	50.00	51.00	1.00	6.67	6.50	6.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.67	6.50	6.33
Acc. 9	49.00	50.00	51.00	1.00	7.99	7.88	7.77	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	7.99	7.88	7.77
Acc. 10	57.00	58.00	59.00	1.00	6.51	6.36	6.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.51	6.36	6.22
Acc. 11	55.00	56.00	57.00	1.00	5.22	5.03	4.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.22	5.03	4.85
Acc. 12	43.00	44.00	45.00	1.00	4.97	4.73	4.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.97	4.73	4.49
Acc. 13	46.00	47.00	48.00	1.00	6.67	6.49	6.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.67	6.49	6.31
Acc. 14	49.00	50.00	51.00	1.00	5.01	4.80	4.59	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	5.01	4.80	4.59
Acc. 15	55.00	56.00	57.00	1.00	5.55	5.37	5.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.55	5.37	5.19
Acc. 16	47.00	48.00	49.00	1.00	6.00	5.81	5.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.00	5.81	5.61
Acc. 17	42.00	43.00	44.00	1.00	5.63	5.40	5.17	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	5.63	5.40	5.17
Acc. 18	50.00	51.00	52.00	1.00	4.89	4.68	4.47	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	4.89	4.68	4.47

Acc. 19	55.00	56.00	57.00	1.00	4.89	4.70	4.51	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	4.89	4.70	4.51
Acc. 20	44.00	45.00	46.00	1.00	4.28	4.03	3.79	0.00	0.00	1.00	1.00	0.00	1.00	0.00	0.00	10322.56	4.28	4.03	9.90
Acc. 21	43.00	44.00	45.00	1.00	4.97	4.73	4.49	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	4.97	4.73	4.49
Acc. 22	57.00	58.00	59.00	1.00	4.52	4.33	4.15	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	4.52	4.33	4.15
Acc. 23	55.00	56.00	57.00	1.00	4.89	4.70	4.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.89	4.70	4.51
Acc. 24	55.00	56.00	57.00	1.00	5.22	5.03	4.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.22	5.03	4.85
Acc. 25	57.00	58.00	59.00	1.00	5.19	5.01	4.83	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	5.19	5.01	4.83
Acc. 26	54.00	55.00	56.00	1.00	6.54	6.39	6.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.54	6.39	6.23
Acc. 27	57.00	58.00	59.00	1.00	5.85	5.68	5.52	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	5.85	5.68	5.52
Acc. 28	57.00	58.00	59.00	1.00	5.85	5.68	5.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.85	5.68	5.52
Acc. 29	58.00	59.00	60.00	1.00	5.85	5.69	5.52	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	5.85	5.69	5.52
Acc. 30	58.00	59.00	60.00	1.00	5.85	5.69	5.52	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	5.85	5.69	5.52
Acc. 31	44.00	45.00	46.00	1.00	3.94	9.89	9.89	1.00	0.00	0.00	1.00	0.00	0.00	10000.00	0.00	0.00	9.90	9.89	9.89
Acc. 32	58.00	59.00	60.00	1.00	4.52	4.34	4.15	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	4.52	4.34	4.15
Acc. 33	58.00	59.00	60.00	1.00	5.19	5.01	4.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.19	5.01	4.83
Acc. 34	44.00	45.00	46.00	1.00	4.90	4.67	4.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.90	4.67	4.43
Acc. 35	46.00	47.00	48.00	1.00	6.00	5.80	5.60	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	6.00	5.80	5.60

GH budget allocation plan for Pipelines of sub-network (1) in City of Moncton:

	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	B	C	B/C	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
P.1	6.06	5.68	8.88	1.00	2.00	0.00	0.06	661956.77	0.00	0.00	1.00	0.00	0.00	661956.77	0.00	6.06	9.00	8.88
P.2	5.93	8.97	8.94	2.00	0.00	0.00	0.06	330487.25	0.00	1.00	0.00	0.00	330487.25	0.00	0.00	9.00	8.97	8.94
P.3	5.07	8.97	8.94	2.00	0.00	0.00	0.07	42728.70	0.00	1.00	0.00	0.00	42728.70	0.00	0.00	9.00	8.97	8.94
P.4	5.40	5.23	8.95	2.00	2.00	0.00	0.00	252595.98	0.00	0.00	1.00	0.00	0.00	256637.52	0.00	5.40	9.00	8.95
P.5	4.74	8.95	8.90	2.00	0.00	0.00	0.00	60753.70	0.00	1.00	0.00	0.00	60753.70	0.00	0.00	9.00	8.95	8.90
P.6	4.69	8.96	8.91	2.00	0.00	0.00	0.06	43720.08	0.00	1.00	0.00	0.00	43720.08	0.00	0.00	9.00	8.96	8.91
P.7	5.26	8.95	8.90	2.00	0.00	0.00	0.06	225832.04	0.00	1.00	0.00	0.00	225832.04	0.00	0.00	9.00	8.95	8.90
P.8	6.17	5.98	5.80	1.00	2.00	2.00	0.00	119155.96	0.00	0.00	0.00	1.00	0.00	0.00	172345.07	6.17	5.98	9.00
P.9	7.49	7.36	7.22	1.00	1.00	1.00	0.00	110447.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.49	7.36	7.22
P.10	5.96	5.80	5.64	2.00	2.00	2.00	0.00	110216.08	0.00	0.00	0.00	1.00	0.00	0.00	113771.20	5.96	5.80	9.00
P.11	4.67	4.48	8.95	2.00	2.00	0.00	0.00	17751.30	0.00	0.00	1.00	0.00	0.00	18035.32	0.00	4.67	9.00	8.95
P.12	4.35	4.10	8.93	2.00	2.00	0.00	0.00	43551.60	0.00	0.00	1.00	0.00	0.00	44248.43	0.00	4.35	9.00	8.93
P.13	6.03	5.83	5.63	1.00	2.00	2.00	0.00	47417.91	0.00	0.00	0.00	1.00	0.00	0.00	49268.82	6.03	5.83	9.00
P.14	4.35	4.13	8.94	2.00	2.00	0.00	0.00	31105.40	0.00	0.00	1.00	0.00	0.00	31603.09	0.00	4.35	9.00	8.94
P.15	4.95	8.95	8.89	2.00	0.00	0.00	0.00	36372.06	0.00	1.00	0.00	0.00	36372.06	0.00	0.00	9.00	8.95	8.89
P.16	5.37	5.15	8.94	2.00	2.00	0.00	0.00	49262.84	0.00	0.00	1.00	0.00	0.00	50051.05	0.00	5.37	9.00	8.94
P.17	4.96	4.71	8.93	2.00	2.00	0.00	0.00	52745.90	0.00	0.00	1.00	0.00	0.00	53589.83	0.00	4.96	9.00	8.93
P.18	3.95	8.94	8.88	3.00	0.00	0.00	0.00	43346.58	0.00	1.00	0.00	0.00	43346.58	0.00	0.00	9.00	8.94	8.88
P.19	4.29	4.09	8.95	2.00	2.00	0.00	0.00	69924.48	0.00	0.00	1.00	0.00	0.00	71043.27	0.00	4.29	9.00	8.95
P.20	3.60	8.93	8.87	3.00	0.00	0.00	0.00	18479.76	0.00	1.00	0.00	0.00	18479.76	0.00	0.00	9.00	8.93	8.87
P.21	4.16	8.93	8.86	2.00	0.00	0.00	0.00	37942.86	0.00	1.00	0.00	0.00	37942.86	0.00	0.00	9.00	8.93	8.86

P.22	3.92	3.73	3.54	3.00	3.00	3.00	0.00	79536.27	0.00	0.00	0.00	1.00	0.00	0.00	82101.80	3.92	3.73	9.00
P.23	4.29	4.09	3.89	2.00	2.00	3.00	0.00	100092.80	0.00	0.00	0.00	1.00	0.00	0.00	117311.32	4.29	4.09	9.00
P.24	4.62	4.42	4.23	2.00	2.00	2.00	0.00	97527.20	0.00	0.00	0.00	1.00	0.00	0.00	100673.04	4.62	4.42	9.00
P.25	4.59	4.40	4.21	2.00	2.00	2.00	0.00	70052.14	0.00	0.00	0.00	1.00	0.00	0.00	72311.74	4.59	4.40	9.00
P.26	6.00	5.82	5.65	2.00	2.00	2.00	0.00	82371.40	0.00	0.00	0.00	1.00	0.00	0.00	85028.37	6.00	5.82	9.00
P.27	5.30	5.12	4.95	2.00	2.00	2.00	0.00	87916.65	0.00	0.00	0.00	1.00	0.00	0.00	90752.49	5.30	5.12	9.00
P.28	5.30	5.12	4.95	2.00	2.00	2.00	0.00	36630.03	0.00	0.00	0.00	1.00	0.00	0.00	37811.56	5.30	5.12	9.00
P.29	5.30	5.13	4.95	2.00	2.00	2.00	0.00	211451.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.30	5.13	4.95
P.30	5.25	5.07	4.90	2.00	2.00	2.00	0.00	144370.60	0.00	0.00	0.00	1.00	0.00	0.00	149027.42	5.25	5.07	9.00
P.31	3.13	2.89	9.89	3.00	4.00	0.00	0.00	37035.43	0.00	0.00	1.00	0.00	0.00	75255.99	0.00	3.13	9.90	9.89
P.32	3.92	3.73	3.55	3.00	3.00	3.00	0.00	79579.28	0.00	0.00	0.00	1.00	0.00	0.00	82146.19	3.92	3.73	9.00
P.33	4.59	4.40	4.22	2.00	2.00	2.00	0.00	51700.20	0.00	0.00	0.00	1.00	0.00	0.00	53367.84	4.59	4.40	9.00
P.34	4.12	3.88	8.94	2.00	3.00	0.00	0.00	28805.88	0.00	0.00	1.00	0.00	0.00	33229.55	0.00	4.12	9.00	8.94
P.35	5.37	5.15	4.93	2.00	2.00	2.00	0.00	47729.26	0.00	0.00	0.00	1.00	0.00	0.00	49268.82	5.37	5.15	9.00

GH budget allocation plan for Pipelines of sub-network (2) in City of Moncton:

	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	B	C	B/C	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
P.1	4.88	4.63	4.38	2.00	2.00	2.00	0.00	52745.90	0.00	0.00	0.00	1.00	0.00	0.00	54447.27	4.88	4.63	9.00
P.2	4.88	4.63	8.93	2.00	2.00	0.00	0.00	52745.90	0.00	0.00	1.00	0.00	0.00	53589.83	0.00	4.88	9.00	8.93
P.3	5.95	8.95	8.90	2.00	0.00	0.00	0.01	110216.08	0.00	1.00	0.00	0.00	110216.08	0.00	0.00	9.00	8.95	8.90
P.4	3.89	8.93	8.87	3.00	0.00	0.00	0.00	18479.76	0.00	1.00	0.00	0.00	18479.76	0.00	0.00	9.00	8.93	8.87
P.5	4.98	8.95	8.89	2.00	0.00	0.00	0.02	17751.30	0.00	1.00	0.00	0.00	17751.30	0.00	0.00	9.00	8.95	8.89
P.6	4.55	4.35	4.16	2.00	2.00	2.00	0.00	100092.80	0.00	0.00	0.00	1.00	0.00	0.00	103321.39	4.55	4.35	9.00
P.7	4.88	4.63	4.38	2.00	2.00	2.00	0.00	52745.90	0.00	0.00	0.00	1.00	0.00	0.00	54447.27	4.88	4.63	9.00
P.8	4.88	8.93	8.86	2.00	0.00	0.00	0.01	52745.90	0.00	1.00	0.00	0.00	52745.90	0.00	0.00	9.00	8.93	8.86
P.9	5.61	8.95	8.90	2.00	0.00	0.00	0.06	87916.65	0.00	1.00	0.00	0.00	87916.65	0.00	0.00	9.00	8.95	8.90
P.10	4.02	3.83	8.95	2.00	3.00	0.00	0.00	70051.20	0.00	0.00	1.00	0.00	0.00	80808.85	0.00	4.02	9.00	8.95
P.11	6.41	8.94	8.88	1.00	0.00	0.00	0.09	119155.96	0.00	1.00	0.00	0.00	119155.96	0.00	0.00	9.00	8.94	8.88
P.12	5.98	5.78	8.94	2.00	2.00	0.00	0.00	47729.26	0.00	0.00	1.00	0.00	0.00	48492.93	0.00	5.98	9.00	8.94

The budget allocation for the accessories part using GH-Model (after considering the benefit / cost ratio calculations) is the same as allocation the budget using GA-Model

GA budget allocation plan for Pipelines of Montreal sub-network:

	0	1	2	D	L (m)	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
P.1	125	126	127	200.00	168.55	3.61	3.52	8.98	3	3	0	0	1	0	0.00	52571.37	0.00	3.61	9.00	8.98
P.2	49	50	51	300.00	207.20	8.95	8.89	8.83	0	0	0	1	0	0	0.00	0.00	0.00	8.95	8.89	8.83
P.3	125	126	127	250.00	250.99	8.64	8.61	8.58	0	0	0	1	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.4	5	6	7	250.00	179.73	3.56	8.34	7.49	3	0	1	1	0	0	68298.54	0.00	0.00	9.00	8.34	7.49
P.5	82	83	84	150.00	298.48	9.16	9.13	9.10	0	0	0	1	0	0	0.00	0.00	0.00	9.16	9.13	9.10
P.6	124	125	126	200.00	149.41	8.69	8.66	8.63	0	0	0	1	0	0	0.00	0.00	0.00	8.69	8.66	8.63
P.7	5	6	7	200.00	148.90	8.96	8.27	7.39	0	0	1	0	0	0	0.00	0.00	0.00	8.96	8.27	7.39
P.8	126	127	128	300.00	155.44	8.79	8.77	8.74	0	0	0	1	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.9	102	103	104	200.00	172.63	3.67	8.97	8.94	3	0	0	1	0	0	52997.87	0.00	0.00	9.00	8.97	8.94
P.10	102	103	104	200.00	137.81	8.75	8.71	8.68	0	0	0	1	0	0	0.00	0.00	0.00	8.75	8.71	8.68
P.11	83	84	85	300.00	108.01	8.86	8.82	8.78	0	0	0	1	0	0	0.00	0.00	0.00	8.86	8.82	8.78
P.12	14	15	16	200.00	118.62	8.96	8.73	8.48	0	0	0	1	0	0	0.00	0.00	0.00	8.96	8.73	8.48
P.13	122	123	124	300.00	158.20	8.79	8.77	8.74	0	0	0	1	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.14	5	6	7	250.00	219.43	9.05	8.41	7.60	0	0	1	1	0	0	0.00	0.00	0.00	9.05	8.41	7.60
P.15	34	35	36	200.00	138.37	8.83	8.73	8.63	0	0	0	0	0	0	0.00	0.00	0.00	8.83	8.73	8.63
P.16	124	125	126	300.00	148.53	8.79	8.77	8.74	0	0	0	1	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.17	124	125	126	300.00	77.76	3.72	3.63	3.54	3	3	3	0	0	0	0.00	0.00	0.00	3.72	3.63	3.54
P.18	127	128	129	300.00	215.65	3.72	8.98	8.95	3	0	0	1	0	0	97906.01	0.00	0.00	9.00	8.98	8.95
P.19	122	123	124	300.00	159.68	8.79	8.77	8.74	0	0	0	0	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.20	122	123	124	300.00	175.67	8.79	8.77	8.74	0	0	0	0	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.21	88	89	90	250.00	277.12	4.64	8.97	8.93	2	0	0	1	0	0	83135.92	0.00	0.00	9.00	8.97	8.93
P.22	127	128	129	300.00	141.77	3.72	8.98	8.95	3	0	0	1	0	0	64362.08	0.00	0.00	9.00	8.98	8.95
P.23	127	128	129	300.00	72.27	8.28	8.24	8.20	0	0	0	1	0	0	0.00	0.00	0.00	8.28	8.24	8.20
P.24	36	37	38	300.00	211.67	8.94	8.85	8.76	0	0	0	0	0	0	0.00	0.00	0.00	8.94	8.85	8.76

P.25	123	124	125	250.00	169.61	8.64	8.61	8.57	0	0	0	1	0	0	0.00	0.00	0.00	8.64	8.61	8.57
P.26	123	124	125	200.00	247.07	4.62	4.54	4.45	2	2	2	0	0	1	0.00	0.00	63759.5	4.62	4.54	9.00
P.27	82	83	84	150.00	170.17	3.57	3.43	3.30	3	3	3	0	0	1	0.00	0.00	39875.1	3.57	3.43	9.00
P.28	127	128	129	250.00	170.59	8.64	8.61	8.58	0	0	0	1	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.29	5	6	7	200.00	188.69	3.67	8.34	7.49	3	0	1	1	0	1	57928.40	0.00	42072.1	9.00	8.34	9.00
P.30	124	125	126	200.00	325.37	5.64	5.56	5.48	2	2	2	0	0	0	0.00	0.00	0.00	5.64	5.56	5.48
P.31	45	46	47	200.00	294.85	3.63	3.38	3.15	3	3	3	0	0	0	0.00	0.00	0.00	3.63	3.38	3.15
P.32	45	46	47	200.00	168.27	8.70	8.62	8.54	0	0	0	1	0	0	0.00	0.00	0.00	8.70	8.62	8.54
P.33	7	8	9	200.00	167.77	8.96	8.48	7.91	0	0	1	0	0	0	0.00	0.00	0.00	8.96	8.48	7.91
P.34	127	128	129	300.00	168.15	3.20	8.98	8.95	3	0	0	1	0	0	76338.11	0.00	0.00	9.00	8.98	8.95
P.35	88	89	90	250.00	199.74	3.62	8.97	8.93	3	0	0	1	0	0	75900.19	0.00	0.00	9.00	8.97	8.93
P.36	5	6	7	200.00	161.99	9.10	8.49	7.71	0	0	1	1	0	0	0.00	0.00	0.00	9.10	8.49	7.71
P.37	127	128	129	250.00	272.50	8.64	8.61	8.58	0	0	0	0	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.38	82	83	84	150.00	167.83	8.65	8.60	8.55	0	0	0	1	0	0	0.00	0.00	0.00	8.65	8.60	8.55
P.39	16	17	18	300.00	204.95	9.07	8.89	8.70	0	0	0	1	0	0	0.00	0.00	0.00	9.07	8.89	8.70
P.40	125	126	127	200.00	260.40	4.62	4.54	4.45	2	2	2	0	0	0	0.00	0.00	0.00	4.62	4.54	4.45
P.41	102	103	104	200.00	426.04	6.91	6.83	6.76	1	1	1	0	0	1	0.00	0.00	94992.6	6.91	6.83	9.00
P.42	5	6	7	300.00	391.41	3.72	1.81	9.84	3	4	0	0	1	0	0.00	270812.2	0.00	3.72	9.90	9.84
P.43	88	89	90	250.00	384.95	8.70	8.66	8.62	0	0	0	1	0	0	0.00	0.00	0.00	8.70	8.66	8.62
P.44	126	127	128	300.00	166.96	8.79	8.77	8.74	0	0	0	0	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.45	126	127	128	300.00	220.76	8.79	8.77	8.74	0	0	0	1	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.46	22	23	24	200.00	58.00	8.96	8.82	8.67	0	0	0	1	0	0	0.00	0.00	0.00	8.96	8.82	8.67
P.47	126	127	128	200.00	119.23	8.69	8.66	8.63	0	0	0	1	0	0	0.00	0.00	0.00	8.69	8.66	8.63
P.48	126	127	128	200.00	258.62	8.69	8.66	8.63	0	0	0	1	0	0	0.00	0.00	0.00	8.69	8.66	8.63
P.49	102	103	104	200.00	165.58	8.75	8.71	8.68	0	0	0	0	0	0	0.00	0.00	0.00	8.75	8.71	8.68
P.50	102	103	104	200.00	198.38	8.75	8.71	8.68	0	0	0	0	0	0	0.00	0.00	0.00	8.75	8.71	8.68
P.51	102	103	104	200.00	185.35	8.75	8.71	8.68	0	0	0	1	0	0	0.00	0.00	0.00	8.75	8.71	8.68

P.52	55	56	57	200.00	190.70	8.84	8.78	8.72	0	0	0	1	0	0	0.00	0.00	0.00	8.84	8.78	8.72
P.53	146	147	148	250.00	102.45	3.50	3.42	8.98	3	3	0	0	1	0	0.00	39553.93	0.00	3.50	9.00	8.98
P.54	140	141	142	250.00	120.46	8.64	8.61	8.58	0	0	0	1	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.55	140	141	142	250.00	22.57	8.64	8.61	8.58	0	0	0	1	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.56	146	147	148	250.00	285.62	4.51	4.44	8.98	2	2	0	0	1	0	0.00	87058.49	0.00	4.51	9.00	8.98
P.57	102	103	104	200.00	159.15	8.75	8.71	8.68	0	0	0	1	0	0	0.00	0.00	0.00	8.75	8.71	8.68
P.58	119	120	121	200.00	95.73	8.69	8.65	8.62	0	0	0	1	0	0	0.00	0.00	0.00	8.69	8.65	8.62
P.59	146	147	148	250.00	288.92	5.53	5.46	5.39	2	2	2	0	0	1	0.00	0.00	89471.8	5.53	5.46	9.00
P.60	5	6	7	200.00	245.79	9.10	8.49	7.71	0	0	1	1	0	1	0.00	0.00	54802.4	9.10	8.49	9.00
P.61	146	147	148	300.00	71.63	8.73	8.71	8.68	0	0	0	1	0	0	0.00	0.00	0.00	8.73	8.71	8.68
P.62	144	145	146	100.00	219.87	8.58	8.55	8.53	0	0	0	1	0	0	0.00	0.00	0.00	8.58	8.55	8.53
P.63	125	126	127	200.00	282.33	3.61	3.52	3.43	3	3	3	0	0	1	0.00	0.00	89470.7	3.61	3.52	9.00

GA budget allocation plan for Accessories of Montreal sub-network:

	0	1	2	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
Acc. 1	125	126	127	3.38	3.29	9.90	1	1	0	0	1	0	0.00	10160.00	0.00	3.38	9.90	9.90
Acc. 2	125	126	127	3.38	3.29	9.90	1	1	0	0	1	0	0.00	10160.00	0.00	3.38	9.90	9.90
Acc. 3	49	50	51	8.59	8.51	8.42	0	0	0	0	0	0	0.00	0.00	0.00	8.59	8.51	8.42
Acc. 4	102	103	104	3.45	9.90	9.89	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.89
Acc. 5	102	103	104	3.45	9.90	9.89	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.89
Acc. 6	102	103	104	8.52	8.48	8.44	0	0	0	1	0	0	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 7	125	126	127	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 8	5	6	7	3.38	9.83	9.73	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.83	9.73
Acc. 9	5	6	7	3.38	1.54	9.84	1	1	0	0	1	0	0.00	10160.00	0.00	3.38	9.90	9.84
Acc. 10	5	6	7	3.38	9.83	9.73	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.83	9.73
Acc. 11	127	128	129	3.38	9.90	9.90	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.90
Acc. 12	127	128	129	3.38	9.90	9.90	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.90
Acc. 13	127	128	129	3.38	9.90	9.90	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.90
Acc. 14	5	6	7	3.38	9.83	9.73	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.83	9.73
Acc. 15	5	6	7	3.38	9.83	9.73	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.83	9.73
Acc. 16	88	89	90	4.46	4.34	4.22	0	0	0	1	0	0	0.00	0.00	0.00	4.46	4.34	4.22
Acc. 17	127	128	129	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 18	88	89	90	3.45	9.90	9.89	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.89
Acc. 19	88	89	90	8.52	8.48	8.43	0	0	0	1	0	0	0.00	0.00	0.00	8.52	8.48	8.43
Acc. 20	34	35	36	8.57	8.45	8.33	0	0	0	1	0	0	0.00	0.00	0.00	8.57	8.45	8.33
Acc. 21	82	83	84	3.38	9.90	9.89	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.89
Acc. 22	127	128	129	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 23	5	6	7	3.45	9.83	9.73	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.83	9.73
Acc. 24	5	6	7	3.45	9.83	9.73	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.83	9.73
Acc. 25	124	125	126	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39

Acc. 26	124	125	126	3.38	3.29	9.90	1	1	0	0	1	0	0.00	10160.00	0.00	3.38	9.90	9.90
Acc. 27	124	125	126	3.38	9.90	9.90	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.90
Acc. 28	122	123	124	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 29	122	123	124	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 30	122	123	124	8.46	8.43	8.39	0	0	0	0	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 31	122	123	124	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 32	83	84	85	8.52	8.47	8.42	0	0	0	1	0	0	0.00	0.00	0.00	8.52	8.47	8.42
Acc. 33	14	15	16	8.73	8.46	8.17	0	0	0	1	0	0	0.00	0.00	0.00	8.73	8.46	8.17
Acc. 34	123	124	125	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 35	82	83	84	8.52	8.47	8.42	0	0	0	0	0	0	0.00	0.00	0.00	8.52	8.47	8.42
Acc. 36	123	124	125	4.40	4.31	4.22	0	0	0	1	0	0	0.00	0.00	0.00	4.40	4.31	4.22
Acc. 37	127	128	129	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 38	82	83	84	8.52	8.47	8.42	0	0	0	0	0	0	0.00	0.00	0.00	8.52	8.47	8.42
Acc. 39	16	17	18	8.73	8.50	8.24	0	0	0	1	0	0	0.00	0.00	0.00	8.73	8.50	8.24
Acc. 40	45	46	47	3.37	9.89	9.89	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.89	9.89
Acc. 41	45	46	47	3.37	3.13	9.89	1	1	0	0	1	0	0.00	10160.00	0.00	3.37	9.90	9.89
Acc. 42	45	46	47	8.45	8.35	8.25	0	0	0	1	0	0	0.00	0.00	0.00	8.45	8.35	8.25
Acc. 43	124	125	126	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 44	7	8	9	8.73	8.17	7.50	0	0	0	1	0	0	0.00	0.00	0.00	8.73	8.17	7.50
Acc. 45	5	6	7	8.73	7.91	6.89	0	0	0	1	0	0	0.00	0.00	0.00	8.73	7.91	6.89
Acc. 46	5	6	7	8.73	7.91	6.89	0	0	0	1	0	0	0.00	0.00	0.00	8.73	7.91	6.89
Acc. 47	5	6	7	8.87	8.13	7.20	0	0	0	0	0	0	0.00	0.00	0.00	8.87	8.13	7.20
Acc. 48	5	6	7	8.87	8.13	7.20	0	0	0	1	0	0	0.00	0.00	0.00	8.87	8.13	7.20
Acc. 49	126	127	128	8.46	8.43	8.39	0	0	0	0	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 50	126	127	128	8.46	8.43	8.39	0	0	0	0	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 51	22	23	24	8.70	8.53	8.35	0	0	0	1	0	0	0.00	0.00	0.00	8.70	8.53	8.35
Acc. 52	102	103	104	8.52	8.48	8.44	0	0	0	1	0	0	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 53	102	103	104	8.52	8.48	8.44	0	0	0	0	0	0	0.00	0.00	0.00	8.52	8.48	8.44

Acc. 54	102	103	104	8.52	8.48	8.44	0	0	0	1	0	0	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 55	102	103	104	8.52	8.48	8.44	0	0	0	1	0	0	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 56	102	103	104	8.52	8.48	8.44	0	0	0	1	0	0	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 57	126	127	128	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 58	126	127	128	8.46	8.43	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 59	125	126	127	4.40	4.31	4.23	0	0	0	1	0	0	0.00	0.00	0.00	4.40	4.31	4.23
Acc. 60	125	126	127	4.40	4.31	4.23	0	0	0	1	0	0	0.00	0.00	0.00	4.40	4.31	4.23
Acc. 61	102	103	104	6.49	6.41	6.33	0	0	0	1	0	0	0.00	0.00	0.00	6.49	6.41	6.33
Acc. 62	55	56	57	8.59	8.51	8.44	0	0	0	1	0	0	0.00	0.00	0.00	8.59	8.51	8.44
Acc. 63	146	147	148	5.35	5.28	5.21	0	0	0	1	0	0	0.00	0.00	0.00	5.35	5.28	5.21
Acc. 64	146	147	148	5.35	5.28	5.21	0	0	0	1	0	0	0.00	0.00	0.00	5.35	5.28	5.21
Acc. 65	5	6	7	8.87	8.13	7.20	0	0	0	1	0	0	0.00	0.00	0.00	8.87	8.13	7.20
Acc. 66	5	6	7	8.87	8.13	7.20	0	0	0	1	0	0	0.00	0.00	0.00	8.87	8.13	7.20
Acc. 67	146	147	148	8.40	8.37	8.34	0	0	0	1	0	0	0.00	0.00	0.00	8.40	8.37	8.34
Acc. 68	146	147	148	8.40	8.37	8.34	0	0	0	1	0	0	0.00	0.00	0.00	8.40	8.37	8.34
Acc. 69	144	145	146	8.46	8.43	8.40	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.40
Acc. 70	125	126	127	3.38	9.90	9.90	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.90
Acc. 71	146	147	148	3.32	9.90	9.90	1	0	0	1	0	0	10000.00	0.00	0.00	9.90	9.90	9.90
Acc. 72	140	141	142	8.46	8.43	8.40	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.40
Acc. 73	140	141	142	8.46	8.43	8.40	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.43	8.40
Acc. 74	146	147	148	4.33	4.26	4.19	0	0	0	0	0	0	0.00	0.00	0.00	4.33	4.26	4.19
Acc. 75	102	103	104	8.52	8.48	8.44	0	0	0	1	0	0	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 76	119	120	121	8.46	8.42	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.42	8.39
Acc. 77	119	120	121	8.46	8.42	8.39	0	0	0	1	0	0	0.00	0.00	0.00	8.46	8.42	8.39
Acc. 78	5	6	7	8.87	8.13	7.20	0	0	0	1	0	0	0.00	0.00	0.00	8.87	8.13	7.20

GH budget allocation plan for Pipelines of Montreal sub-network:

	0	1	2	D	L (m)	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
P.1	125	126	127	200.00	168.55	3.61	3.52	8.98	3	3	0	0	1	0	0.00	52495.77	0.00	3.61	9.00	8.98
P.2	49	50	51	300.00	207.20	8.95	8.89	8.83	0	0	0	0	0	0	0.00	0.00	0.00	8.95	8.89	8.83
P.3	125	126	127	250.00	250.99	8.64	8.61	8.58	0	0	0	0	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.4	5	6	7	250.00	179.73	3.56	1.68	9.84	3	4	0	0	1	0	0.00	103667.17	0.00	3.56	9.90	9.84
P.5	82	83	84	150.00	298.48	9.16	9.13	9.10	0	0	0	0	0	0	0.00	0.00	0.00	9.16	9.13	9.10
P.6	124	125	126	200.00	149.41	8.69	8.66	8.63	0	0	0	0	0	0	0.00	0.00	0.00	8.69	8.66	8.63
P.7	5	6	7	200.00	148.90	8.96	8.27	7.39	0	0	1	0	0	0	0.00	0.00	0.00	8.96	8.27	7.39
P.8	126	127	128	300.00	155.44	8.79	8.77	8.74	0	0	0	0	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.9	102	103	104	200.00	172.63	3.67	8.97	8.94	3	0	0	1	0	0	52921.66	0.00	0.00	9.00	8.97	8.94
P.10	102	103	104	200.00	137.81	8.75	8.71	8.68	0	0	0	0	0	0	0.00	0.00	0.00	8.75	8.71	8.68
P.11	83	84	85	300.00	108.01	8.86	8.82	8.78	0	0	0	0	0	0	0.00	0.00	0.00	8.86	8.82	8.78
P.12	14	15	16	200.00	118.62	8.96	8.73	8.48	0	0	0	0	0	0	0.00	0.00	0.00	8.96	8.73	8.48
P.13	122	123	124	300.00	158.20	8.79	8.77	8.74	0	0	0	0	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.14	5	6	7	250.00	219.43	9.05	8.41	7.60	0	0	1	0	0	0	0.00	0.00	0.00	9.05	8.41	7.60
P.15	34	35	36	200.00	138.37	8.83	8.73	8.63	0	0	0	0	0	0	0.00	0.00	0.00	8.83	8.73	8.63
P.16	124	125	126	300.00	148.53	8.79	8.77	8.74	0	0	0	0	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.17	124	125	126	300.00	77.76	3.72	3.63	3.54	3	3	3	0	0	1	0.00	0.00	36454.90	3.72	3.63	9.00
P.18	127	128	129	300.00	215.65	3.72	8.98	8.95	3	0	0	1	0	0	97940.69	0.00	0.00	9.00	8.98	8.95
P.19	122	123	124	300.00	159.68	8.79	8.77	8.74	0	0	0	0	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.20	122	123	124	300.00	175.67	8.79	8.77	8.74	0	0	0	0	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.21	88	89	90	250.00	277.12	4.64	8.97	8.93	2	0	0	1	0	0	83135.92	0.00	0.00	9.00	8.97	8.93
P.22	127	128	129	300.00	141.77	3.72	8.98	8.95	3	0	0	1	0	0	64384.88	0.00	0.00	9.00	8.98	8.95

P.23	127	128	129	300.00	72.27	8.28	8.24	8.20	0	0	0	0	0	0	0.00	0.00	0.00	8.28	8.24	8.20
P.24	36	37	38	300.00	211.67	8.94	8.85	8.76	0	0	0	0	0	0	0.00	0.00	0.00	8.94	8.85	8.76
P.25	123	124	125	250.00	169.61	8.64	8.61	8.57	0	0	0	0	0	0	0.00	0.00	0.00	8.64	8.61	8.57
P.26	123	124	125	200.00	247.07	4.62	4.54	4.45	2	2	2	0	0	1	0.00	0.00	63759.46	4.62	4.54	9.00
P.27	82	83	84	150.00	170.17	3.57	8.96	8.93	3	0	0	1	0	0	38642.71	0.00	0.00	9.00	8.96	8.93
P.28	127	128	129	250.00	170.59	8.64	8.61	8.58	0	0	0	0	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.29	5	6	7	200.00	188.69	3.67	8.34	7.49	3	0	1	1	0	1	57845.10	0.00	42018.82	9.00	8.34	9.00
P.30	124	125	126	200.00	325.37	5.64	5.56	5.48	2	2	2	0	0	0	0.00	0.00	0.00	5.64	5.56	5.48
P.31	45	46	47	200.00	294.85	3.63	3.38	3.15	3	3	3	0	0	0	0.00	0.00	0.00	3.63	3.38	3.15
P.32	45	46	47	200.00	168.27	8.70	8.62	8.54	0	0	0	0	0	0	0.00	0.00	0.00	8.70	8.62	8.54
P.33	7	8	9	200.00	167.77	8.96	8.48	7.91	0	0	1	0	0	0	0.00	0.00	0.00	8.96	8.48	7.91
P.34	127	128	129	300.00	168.15	3.20	8.98	8.95	3	0	0	1	0	0	76365.15	0.00	0.00	9.00	8.98	8.95
P.35	88	89	90	250.00	199.74	3.62	8.97	8.93	3	0	0	1	0	0	75972.03	0.00	0.00	9.00	8.97	8.93
P.36	5	6	7	200.00	161.99	9.10	8.49	7.71	0	0	1	0	0	1	0.00	0.00	36072.65	9.10	8.49	9.00
P.37	127	128	129	250.00	272.50	8.64	8.61	8.58	0	0	0	0	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.38	82	83	84	150.00	167.83	8.65	8.60	8.55	0	0	0	0	0	0	0.00	0.00	0.00	8.65	8.60	8.55
P.39	16	17	18	300.00	204.95	9.07	8.89	8.70	0	0	0	0	0	0	0.00	0.00	0.00	9.07	8.89	8.70
P.40	125	126	127	200.00	260.40	4.62	4.54	4.45	2	2	2	0	0	1	0.00	0.00	67199.75	4.62	4.54	9.00
P.41	102	103	104	200.00	426.04	6.91	6.83	6.76	1	1	1	0	0	1	0.00	0.00	94872.22	6.91	6.83	9.00
P.42	5	6	7	300.00	391.41	3.72	1.81	9.84	3	4	0	0	1	0	0.00	270908.10	0.00	3.72	9.90	9.84
P.43	88	89	90	250.00	384.95	8.70	8.66	8.62	0	0	0	0	0	0	0.00	0.00	0.00	8.70	8.66	8.62
P.44	126	127	128	300.00	166.96	8.79	8.77	8.74	0	0	0	0	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.45	126	127	128	300.00	220.76	8.79	8.77	8.74	0	0	0	0	0	0	0.00	0.00	0.00	8.79	8.77	8.74
P.46	22	23	24	200.00	58.00	8.96	8.82	8.67	0	0	0	0	0	0	0.00	0.00	0.00	8.96	8.82	8.67

P.47	126	127	128	200.00	119.23	8.69	8.66	8.63	0	0	0	0	0	0	0.00	0.00	0.00	8.69	8.66	8.63
P.48	126	127	128	200.00	258.62	8.69	8.66	8.63	0	0	0	0	0	0	0.00	0.00	0.00	8.69	8.66	8.63
P.49	102	103	104	200.00	165.58	8.75	8.71	8.68	0	0	0	0	0	0	0.00	0.00	0.00	8.75	8.71	8.68
P.50	102	103	104	200.00	198.38	8.75	8.71	8.68	0	0	0	0	0	0	0.00	0.00	0.00	8.75	8.71	8.68
P.51	102	103	104	200.00	185.35	8.75	8.71	8.68	0	0	0	0	0	0	0.00	0.00	0.00	8.75	8.71	8.68
P.52	55	56	57	200.00	190.70	8.84	8.78	8.72	0	0	0	0	0	0	0.00	0.00	0.00	8.84	8.78	8.72
P.53	146	147	148	250.00	102.45	3.50	8.98	8.96	3	0	0	1	0	0	38967.88	0.00	0.00	9.00	8.98	8.96
P.54	140	141	142	250.00	120.46	8.64	8.61	8.58	0	0	0	0	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.55	140	141	142	250.00	22.57	8.64	8.61	8.58	0	0	0	0	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.56	146	147	148	250.00	285.62	4.51	8.98	8.96	2	0	0	1	0	0	85687.49	0.00	0.00	9.00	8.98	8.96
P.57	102	103	104	200.00	159.15	8.75	8.71	8.68	0	0	0	0	0	0	0.00	0.00	0.00	8.75	8.71	8.68
P.58	119	120	121	200.00	95.73	8.69	8.65	8.62	0	0	0	0	0	0	0.00	0.00	0.00	8.69	8.65	8.62
P.59	146	147	148	250.00	288.92	5.53	5.46	5.39	2	2	2	0	0	0	0.00	0.00	0.00	5.53	5.46	5.39
P.60	5	6	7	200.00	245.79	9.10	8.49	7.71	0	0	1	1	0	0	0.00	0.00	0.00	9.10	8.49	7.71
P.61	146	147	148	300.00	71.63	8.73	8.71	8.68	0	0	0	0	0	0	0.00	0.00	0.00	8.73	8.71	8.68
P.62	144	145	146	100.00	219.87	8.58	8.55	8.53	0	0	0	0	0	0	0.00	0.00	0.00	8.58	8.55	8.53
P.63	125	126	127	200.00	282.33	3.61	3.52	3.43	3	3	3	0	0	1	0.00	0.00	89342.08	3.61	3.52	9.00

GH budget allocation plan for Accessories of Montreal sub-network:

	0	1	2	PI_1	PI_2	PI_3	$R.D_1$	$R.D_2$	$R.D_3$	$D.V_1$	$D.V_2$	$D.V_3$	CO_1	CO_2	CO_3	I_1	I_2	I_3
Acc. 1	125	126	127	3.38	3.29	3.21	1.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10322.56	3.38	3.29	9.90
Acc. 2	125	126	127	3.38	3.29	3.21	1.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10322.56	3.38	3.29	9.90
Acc. 3	49	50	51	8.59	8.51	8.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.59	8.51	8.42
Acc. 4	102	103	104	3.45	9.90	9.89	1.00	0.00	0.00	1.00	0.00	0.00	10000.00	0.00	0.00	9.90	9.90	9.89
Acc. 5	102	103	104	3.45	9.90	9.89	1.00	0.00	0.00	1.00	0.00	0.00	10000.00	0.00	0.00	9.90	9.90	9.89
Acc. 6	102	103	104	8.52	8.48	8.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 7	125	126	127	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 8	5	6	7	3.38	9.83	9.73	1.00	0.00	0.00	1.00	1.00	0.00	10000.00	0.00	0.00	9.90	9.83	9.73
Acc. 9	5	6	7	3.38	1.54	9.84	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10160.00	0.00	3.38	9.90	9.84
Acc. 10	5	6	7	3.38	1.54	9.84	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10160.00	0.00	3.38	9.90	9.84
Acc. 11	127	128	129	3.38	9.90	9.90	1.00	0.00	0.00	1.00	0.00	0.00	10000.00	0.00	0.00	9.90	9.90	9.90
Acc. 12	127	128	129	3.38	9.90	9.90	1.00	0.00	0.00	1.00	0.00	0.00	10000.00	0.00	0.00	9.90	9.90	9.90
Acc. 13	127	128	129	3.38	9.90	9.90	1.00	0.00	0.00	1.00	0.00	0.00	10000.00	0.00	0.00	9.90	9.90	9.90
Acc. 14	5	6	7	3.38	9.83	9.73	1.00	0.00	0.00	1.00	0.00	0.00	10000.00	0.00	0.00	9.90	9.83	9.73
Acc. 15	5	6	7	3.38	1.54	9.84	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10160.00	0.00	3.38	9.90	9.84
Acc. 16	88	89	90	4.46	4.34	4.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.46	4.34	4.22
Acc. 17	127	128	129	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 18	88	89	90	3.45	9.90	9.89	1.00	0.00	0.00	1.00	0.00	0.00	10000.00	0.00	0.00	9.90	9.90	9.89
Acc. 19	88	89	90	8.52	8.48	8.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.52	8.48	8.43
Acc. 20	34	35	36	8.57	8.45	8.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.57	8.45	8.33
Acc. 21	82	83	84	3.38	3.25	3.12	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	3.38	3.25	3.12
Acc. 22	127	128	129	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 23	5	6	7	3.45	1.59	9.84	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10160.00	0.00	3.45	9.90	9.84
Acc. 24	5	6	7	3.45	1.59	9.84	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10160.00	0.00	3.45	9.90	9.84

Acc. 25	124	125	126	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 26	124	125	126	3.38	3.29	3.21	1.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10322.56	3.38	3.29	9.90
Acc. 27	124	125	126	3.38	3.29	3.21	1.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10322.56	3.38	3.29	9.90
Acc. 28	122	123	124	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 29	122	123	124	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 30	122	123	124	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 31	122	123	124	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 32	83	84	85	8.52	8.47	8.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.52	8.47	8.42
Acc. 33	14	15	16	8.73	8.46	8.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.73	8.46	8.17
Acc. 34	123	124	125	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 35	82	83	84	8.52	8.47	8.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.52	8.47	8.42
Acc. 36	123	124	125	4.40	4.31	4.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.40	4.31	4.22
Acc. 37	127	128	129	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 38	82	83	84	8.52	8.47	8.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.52	8.47	8.42
Acc. 39	16	17	18	8.73	8.50	8.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.73	8.50	8.24
Acc. 40	45	46	47	3.37	3.13	2.90	1.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10322.56	3.37	3.13	9.90
Acc. 41	45	46	47	3.37	3.13	2.90	1.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10322.56	3.37	3.13	9.90
Acc. 42	45	46	47	8.45	8.35	8.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.45	8.35	8.25
Acc. 43	124	125	126	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 44	7	8	9	8.73	8.17	7.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.73	8.17	7.50
Acc. 45	5	6	7	8.73	7.91	6.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.73	7.91	6.89
Acc. 46	5	6	7	8.73	7.91	6.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.73	7.91	6.89
Acc. 47	5	6	7	8.87	8.13	7.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.87	8.13	7.20
Acc. 48	5	6	7	8.87	8.13	7.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.87	8.13	7.20
Acc. 49	126	127	128	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 50	126	127	128	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 51	22	23	24	8.70	8.53	8.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.70	8.53	8.35

Acc. 52	102	103	104	8.52	8.48	8.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 53	102	103	104	8.52	8.48	8.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 54	102	103	104	8.52	8.48	8.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 55	102	103	104	8.52	8.48	8.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 56	102	103	104	8.52	8.48	8.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 57	126	127	128	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 58	126	127	128	8.46	8.43	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.39
Acc. 59	125	126	127	4.40	4.31	4.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.40	4.31	4.23
Acc. 60	125	126	127	4.40	4.31	4.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.40	4.31	4.23
Acc. 61	102	103	104	6.49	6.41	6.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.49	6.41	6.33
Acc. 62	55	56	57	8.59	8.51	8.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.59	8.51	8.44
Acc. 63	146	147	148	5.35	5.28	5.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.35	5.28	5.21
Acc. 64	146	147	148	5.35	5.28	5.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.35	5.28	5.21
Acc. 65	5	6	7	8.87	8.13	7.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.87	8.13	7.20
Acc. 66	5	6	7	8.87	8.13	7.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.87	8.13	7.20
Acc. 67	146	147	148	8.40	8.37	8.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.40	8.37	8.34
Acc. 68	146	147	148	8.40	8.37	8.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.40	8.37	8.34
Acc. 69	144	145	146	8.46	8.43	8.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.40
Acc. 70	125	126	127	3.38	3.29	3.21	1.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10322.56	3.38	3.29	9.90
Acc. 71	146	147	148	3.32	3.24	9.90	1.00	1.00	0.00	0.00	1.00	0.00	0.00	10160.00	0.00	3.32	9.90	9.90
Acc. 72	140	141	142	8.46	8.43	8.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.40
Acc. 73	140	141	142	8.46	8.43	8.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.43	8.40
Acc. 74	146	147	148	4.33	4.26	4.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.33	4.26	4.19
Acc. 75	102	103	104	8.52	8.48	8.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.52	8.48	8.44
Acc. 76	119	120	121	8.46	8.42	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.42	8.39
Acc. 77	119	120	121	8.46	8.42	8.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	8.42	8.39
Acc. 78	5	6	7	8.87	8.13	7.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.87	8.13	7.20

APPENDIX (E)

CASE STUDIES DATABASE and LAYOUT

The databases for the selected sub-networks only, are presented through this appendix because of the limited space but it should be mentioned that the database from City of Moncton composed of (547) pipes and the database of city of Montreal composed of (857) pipes.

City of Moncton sub-networks layout:

Figure E-1 Moncton city sub-network location

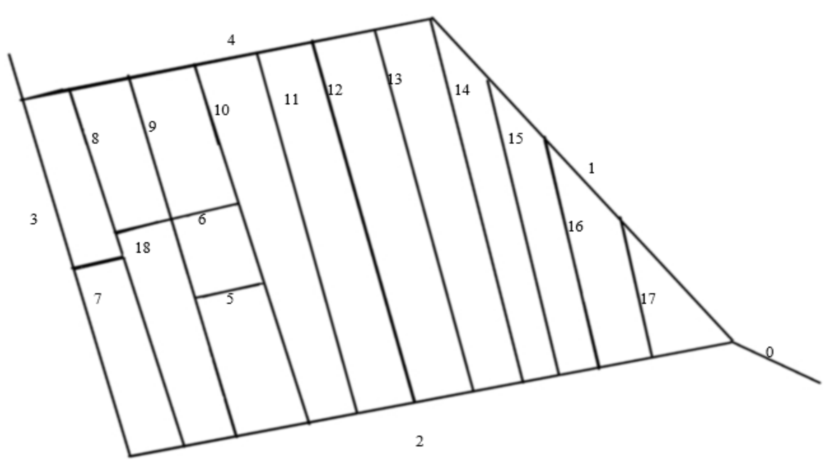


Figure E-2 Sub-network (1) layout

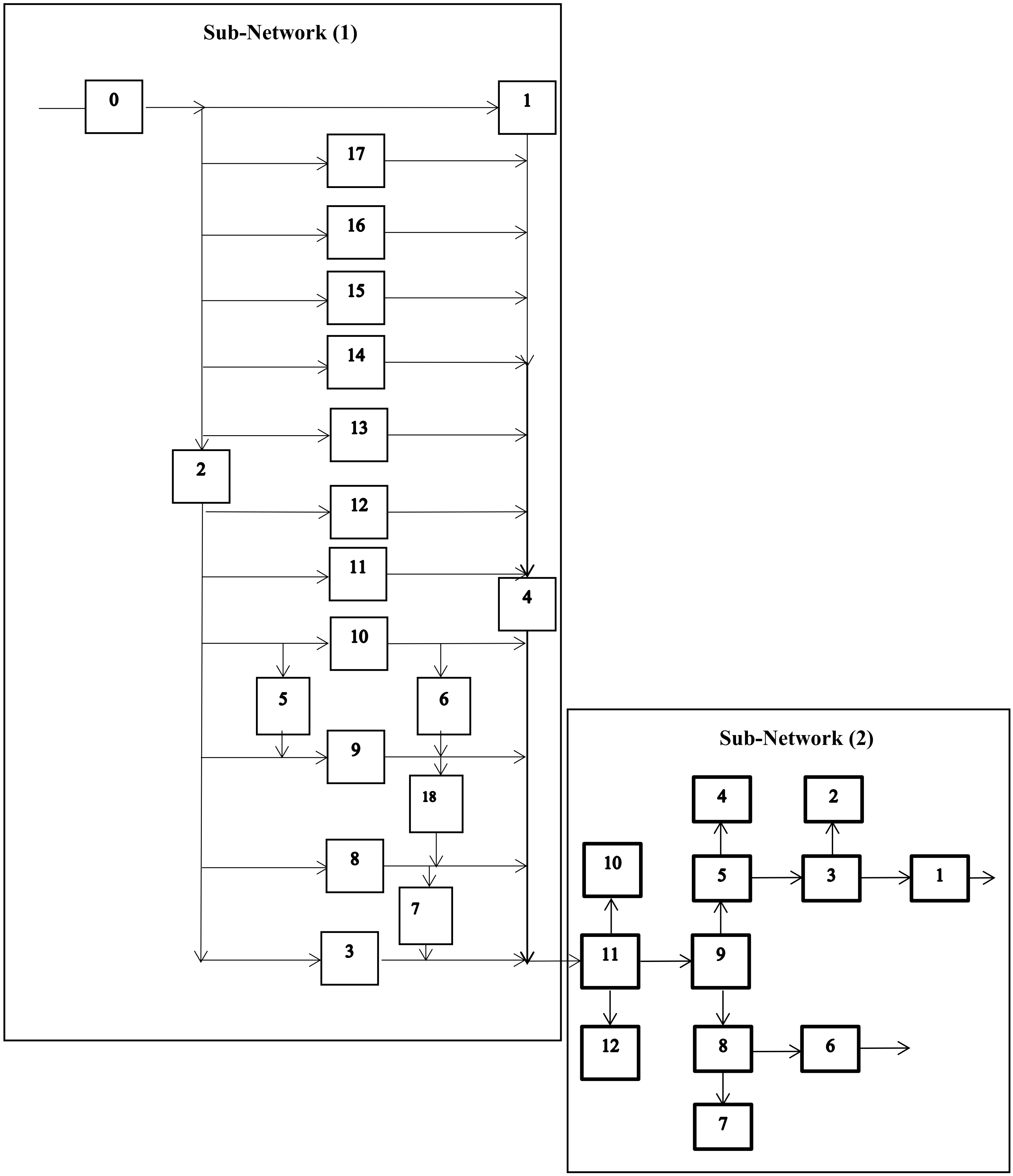


Figure E-3 Moncton city sub-networks segmentation

City of Montreal sub-network layout:

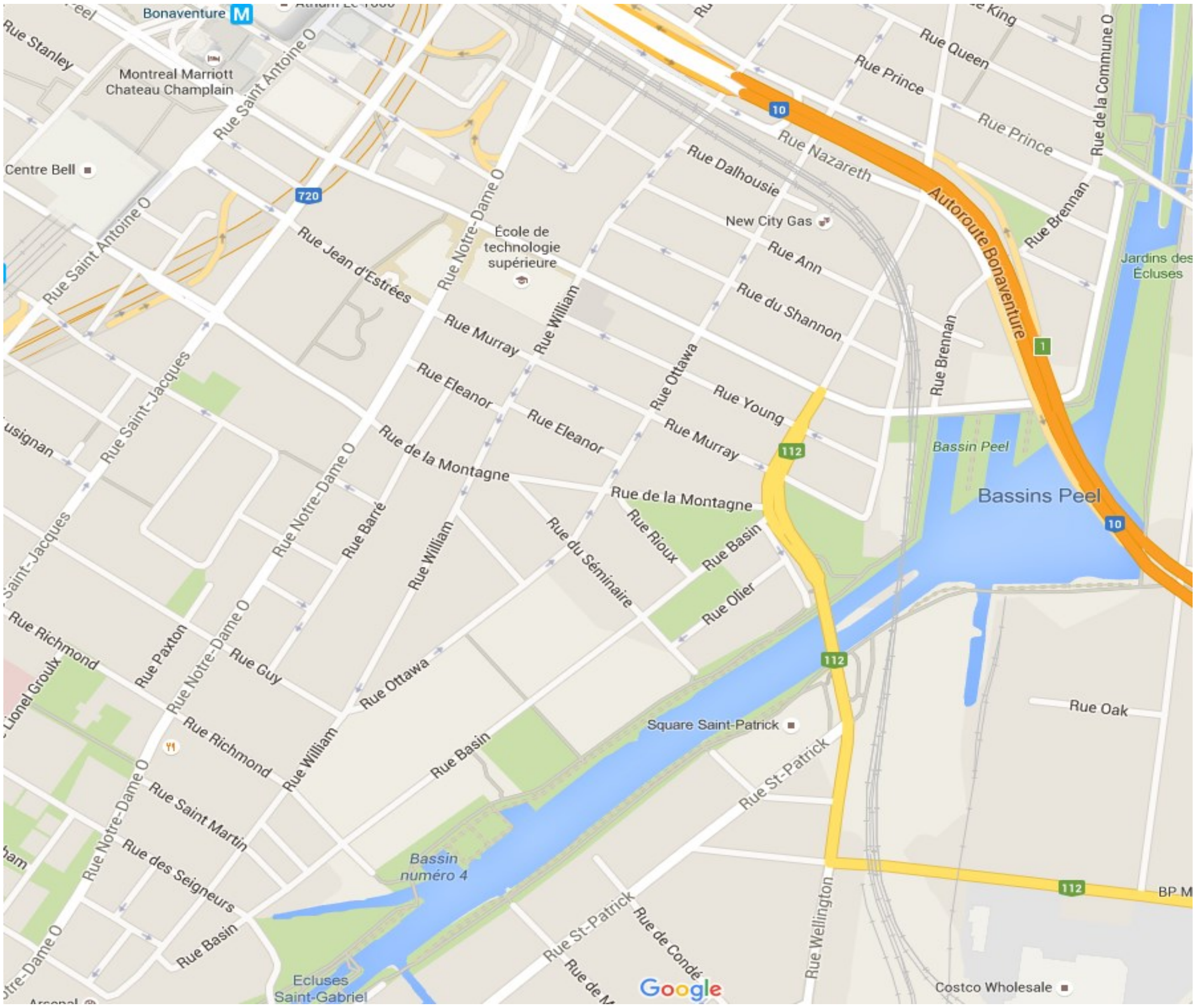


Figure E-4 City of Montreal sub-network location

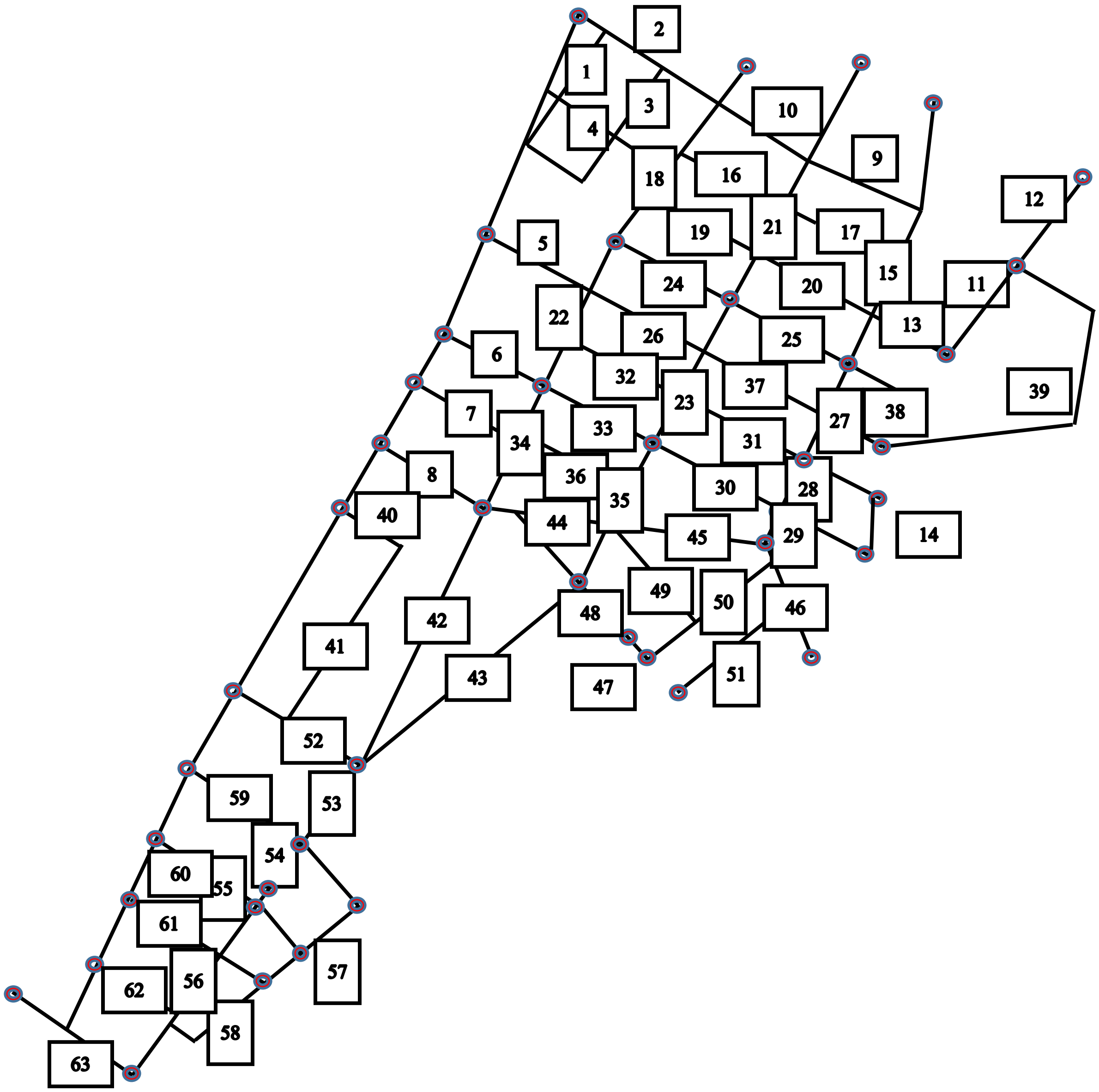


Figure E-5 City of Montreal sub-network layout

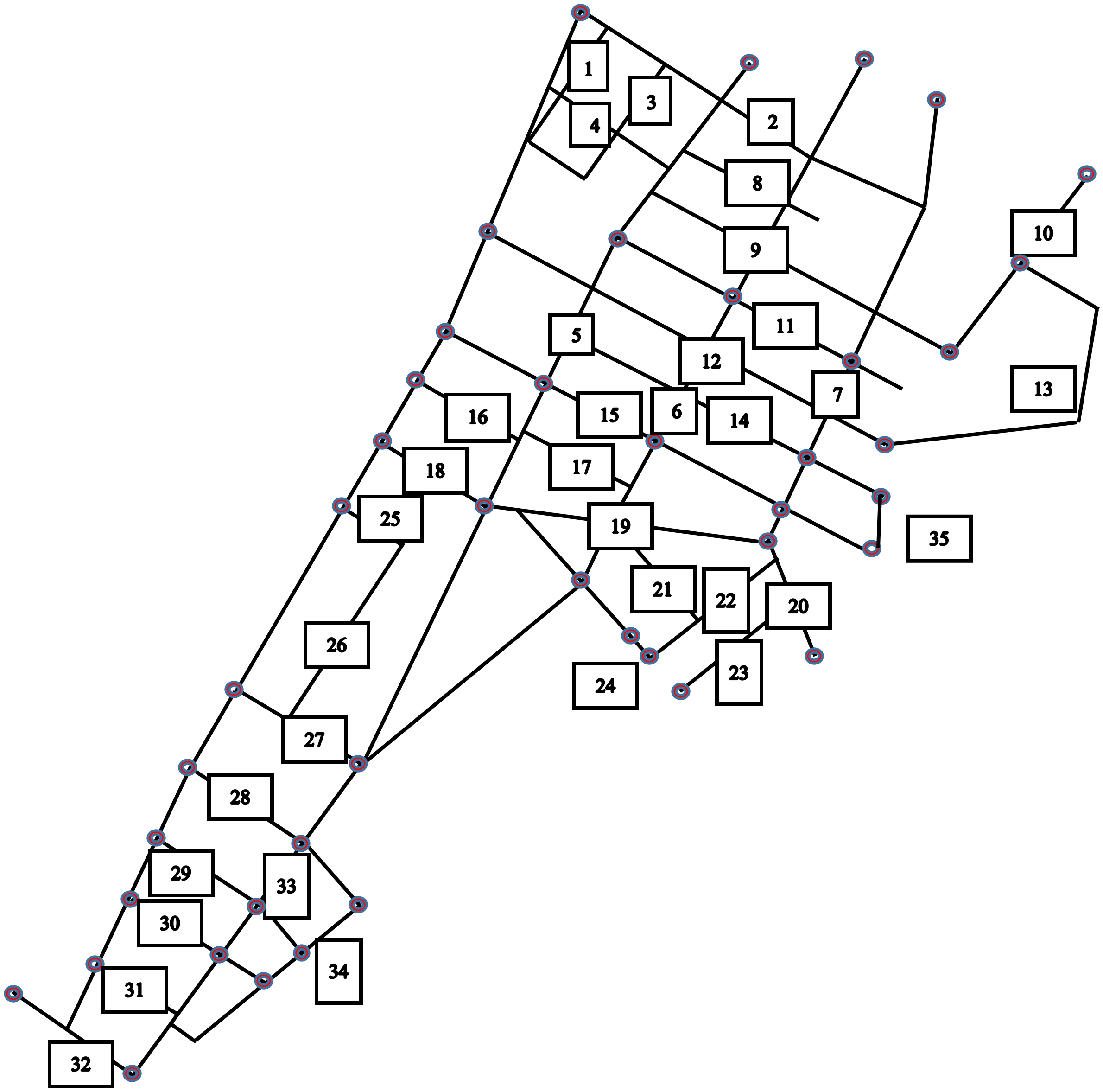


Figure E-6 City of Montreal sub-network segmentation

City of Moncton, sub-network (1) database:

pipe#	RANK	WATERAGE #	STREET	***DESCRIPTION***	***FROM***	***TO***	***Material***	**A**	***YEAR INSTALLED***	***D***	***L***	***COUNT***	**Breaks/km/yr**	**C - Factor**
364	261	1232	MOUNTAIN ROAD	from Cedar St. to Waverly Ave.			CAST IRON	57	1957	12	722	5	0.3	72
368	118	1233	MOUNTAIN ROAD	from Killam Dr. to Cedar St.	Killam	Cedar	CAST IRON	58	1956	12	174	2	0.6	71
278	254	886	KILLAM DRIVE	from Keillor St. west			CAST IRON	64	1950	12	125	1	0.4	65
277	263	883	KILLAM DRIVE	from Waverly Ave. to Ayer Ave.			CAST IRON	57	1957	12	645	4	0.3	72
30	277	83	AYER AVENUE	from Killam Dr. to Danforth	Killam	Danforth	CAST IRON	48	1966	12	477	2	0.2	81
32	396	82	AYER AVENUE	from Danforth to Crandall			CAST IRON	48	1966	12	442	0	0.0	81
120	308	410	CRANDALL STREET	Watson Ave. to Purdy Ave.			CAST IRON	56	1958	8	441	2	0.2	73
121	139	409	CRANDALL STREET	from Watson St. to Whitney	Watson	Whitney	CAST IRON	54	1960	8	71	1	0.7	75
18	467	51	ARGYLE STREET	from Snow Ave. to McKenzie Ave.	Snow	McKenzie	D.I	42	1972	8	174	1	0.3	87
300	366	985	LORNE STREET	McKenzie to Whitney			CAST IRON	45	1969	6	239	1	0.2	84
125	189	1914	DANFORTH STREET	from Ayer Ave to Whitney Ave	Ayer	Whitney	CAST IRON	48	1966	6	156	3	1.0	81
532	245	1843	WHITNEY AVENUE	from Crandall St to Hastings St			CAST IRON	54	1960	6	182	2	0.5	75
533	364	1839	WHITNEY AVENUE	from Cole Ave. northerly			CAST IRON	46	1968	6	246	2	0.4	83
534	516	1838	WHITNEY AVENUE	from Argyle St to Smith St			D.I	41	1973	6	264	1	0.2	88
457	85	1569	SNOW AVENUE	Crandall St.southerly	Crandall	Lorne	CAST IRON	49	1965	6	191	5	1.3	80

338	203	1142	MCKENZIE AVENUE	Lorne to Crandall			CAST IRON	54	1960	6	350	6	0.9	75
339	433	1140	MCKENZIE AVENUE	Melville southerly			D.I	43	1971	6	81	1	0.6	86
340	491	1139	MCKENZIE AVENUE	Melville to Argyle			D.I	42	1972	6	190	1	0.3	87
443	26	1520	SECOND AVENUE	from Crandall St.to Lorne St.	Crandall	Lorne	CAST IRON	56	1958	6	350	15	2.1	73
444	200	1519	SECOND AVENUE	from Killam Dr.to Lorne St.			CAST IRON	54	1960	6	500	9	0.9	75
174	208	605	FIRST AVENUE	from Lorne St. to Killam Dr.			CAST IRON	54	1960	6	488	8	0.8	75
175	219	606	FIRST AVENUE	from Crandall St.to Lorne St.			CAST IRON	56	1958	6	350	5	0.7	73
396	369	1375	PURDY	from Melville to Lorne			CAST IRON	53	1961	8	329	1	0.2	76
397	291	1378	PURDY AVENUE	from Crandall St.to Lorne St.			CAST IRON	56	1958	8	352	3	0.4	73
398	297	1376	PURDY AVENUE	from Killam Dr.to Melville St.			CAST IRON	56	1958	8	147	1	0.3	73
509	300	1738	WAVERLY AVENUE	Mtn.Rd. to Killam			CAST IRON	57	1957	8	846	5	0.3	72
25	331	72	ATKINSON AVENUE	from Mtn. Rd. to Killam Dr.			CAST IRON	57	1957	6	722	6	0.4	72
434	422	1495	SALTER	Argyle southerly			D.I	43	1971	6	163	3	0.9	86
435	74	1496	SALTER AVENUE	from Mtn.Rd.to Argyle St.	Mountain	Argyle	CAST IRON	57	1957	6	350	10	1.4	72
377	213	1289	OAKL and AVENUE	from Mtn.Rd. to Argyle St.			CAST IRON	57	1957	6	259	4	0.8	72
378	486	1288	OAKL and AVENUE	Melville to Argyle			D.I	43	1971	6	144	1	0.3	86
300	366	985	LORNE STREET	McKenzie to Whitney			CAST IRON	45	1969	6	239	1	0.2	84

City of Moncton, sub-network (2) database:

pipe#	RANK	WATERAGE #	STREET	***DESCRIPTION***	***FROM***	***TO***	***PIPE_TYPE***	**A**	***YEAR INSTALLED***	***S***	***L***	***COUNT***	**Breaks/km/yr**	**C - Factor**
534	516	1838	WHITNEY AVENUE	from Argyle St to Smith St			DUCTILE IRON	42	1973	6	264	1	0.2	88
534	516	1838	WHITNEY AVENUE	from Argyle St to Smith St			DUCTILE IRON	42	1973	6	264	1	0.2	88
120	308	410	CRANDALL STREET	Watson Ave. to Purdy Ave.			CAST IRON	57	1958	8	441	2	0.2	73
339	433	1140	MCKENZIE AVENUE	Melville southerly			DUCTILE IRON	44	1971	6	81	1	0.6	86
121	139	409	CRANDALL STREET	from Watson St. to Whitney	Watson	Whitney	CAST IRON	55	1960	8	71	1	0.7	75
444	200	1519	SECOND AVENUE	from Killam Dr.to Lorne St.			CAST IRON	55	1960	6	500	9	0.9	75
534	516	1838	WHITNEY AVENUE	from Argyle St to Smith St			DUCTILE IRON	42	1973	6	264	1	0.2	88
534	516	1838	WHITNEY AVENUE	from Argyle St to Smith St			DUCTILE IRON	42	1973	6	264	1	0.2	88
397	291	1378	PURDY AVENUE	from CRANDALL St.to Lorne St.			CAST IRON	57	1958	8	352	3	0.4	73
443	26	1520	SECOND AVENUE	from CRANDALL St.to Lorne St.	CRANDALL	Lorne	CAST IRON	57	1958	6	350	15	2.1	73
30	277	83	AYER AVENUE	from Killam Dr. to Danforth	Killam	Danforth	CAST IRON	49	1966	12	477	2	0.2	81
300	366	985	LORNE STREET	McKenzie to Whitney			CAST IRON	46	1969	6	239	1	0.2	84

City of Montreal sub-network database:

Montreal case study database contains various performance indicators real values as shown below and it also covered the rehabilitation history in the last 10 years, the coordinates of each pipe and the “AQUAMODEX” data including the final cost of the implemented action and the PI but the last parts are not presented herein due to limited space.

ID	NOM_ VOIE	NOM_ VOIE_DE	NOM_ VOIE_A	DATE INSTALL	A	M	D	L	TYPE_INTERVENTION_AQUAMODEX	DATE_INTERVENTION_AQUAMODEX	JURIDICTION	PROPRIETAIRE	STATUS	POSSIBILITE ENTREE_ PLOMB_REF	HIERARCHISATION
43016	Saint-Maurice	Nazareth	Notre-Dame	1891	125	Fonte grise	200	168.5455094			Loc Ctre-ville	Sud-Ouest	Existant		A
43017	Nazareth	William	Notre-Dame	1967	49	Fonte grise	300	207.1996916			Loc Ctre-ville	Sud-Ouest	Existant		B
43018	Saint-Paul	Nazareth	Notre-Dame	1891	125	Fonte grise	250	250.9930425			Loc Ctre-ville	Sud-Ouest	Existant		A
43019	Inspecteur	William	Notre-Dame	1892	124	Fonte grise	250	179.7330106	Remplacement	01-Jan-11	Loc Ctre-ville	Sud-Ouest	Existant		A
43020	Peel	William	Notre-Dame	1934	82	Fonte grise	150	298.4781463			Loc Ctre-ville	Sud-Ouest	Existant		A
43021	Murray	William	Notre-Dame	1892	124	Fonte grise	200	149.4114001			Loc Ctre-ville	Sud-Ouest	Existant		C
43022	Eleanor	William	Notre-Dame	2011	5	Fonte ductile	200	148.9018036			Loc Ctre-ville	Sud-Ouest	Existant		C
43023	Montagne	William	Notre-Dame	1890	126	Fonte grise	300	155.4430726	Remplacement	01-Jan-50	Loc Ctre-ville	Sud-Ouest	Existant	Oui	C
43024	Nazareth	Wellington	Ottawa	1914	102	Fonte grise	200	172.6314917			Loc Ctre-ville	Sud-Ouest	Existant		B
43025	Nazareth	William	Ottawa	1914	102	Fonte grise	200	137.8120617			Loc Ctre-ville	Sud-Ouest	Existant		B
43026	Brennan	#880 Brennan	Commune	1933	83	Fonte grise	300	108.0094748			Loc Ctre-ville	Sud-Ouest	Existant		A
43027	Brennan	#880 Brennan	Commune	2002	14	Fonte ductile	200	118.619656			Loc Ctre-ville	Ville-Marie	Existant		A
43028	Ann	#75 Ann	Wellington	1894	122	Fonte grise	300	158.200469			Loc Ctre-ville	Sud-Ouest	Existant		A
43029	Smith	#1095 Smith	#1095 Smith	2011	5	Fonte grise	250	219.4297686			Loc Ctre-ville	Sud-Ouest	Existant	Oui	A
43030	Wellington	#800 Wellington	Shannon	1982	34	Fonte ductile	200	138.3689031			Loc Ctre-ville	Sud-Ouest	Existant		B
43031	Dalhousie	#172 Dalhousie	William	1892	124	Fonte grise	300	148.5337818			Loc Ctre-ville	Sud-Ouest	Existant		A
43032	Dalhousie	#172 Dalhousie	William	1892	124	Fonte grise	300	77.76046002			Loc Ctre-ville	Sud-Ouest	Existant		C
43033	William	#809 William	Shannon	1889	127	Fonte grise	300	215.652009			Loc Ctre-ville	Sud-Ouest	Existant		A
43034	Ann	Ottawa	William	1894	122	Fonte grise	300	159.6779757			Loc Ctre-ville	Sud-Ouest	Existant		C
43035	Ann	Wellington	Ottawa	1894	122	Fonte grise	300	175.6713635			Loc Ctre-ville	Sud-Ouest	Existant		C

43036	Ottawa	#800 Ottawa	Shannon	1928	88	Fonte grise	250	277.1197389			Loc Ctre-ville	Sud-Ouest	Existant		C
43037	William	Shannon	Murray	1889	127	Fonte grise	300	141.7666909			Loc Ctre-ville	Sud-Ouest	Existant		A
43038	Ottawa	Shannon	Murray	1889	127	Fonte grise	300	72.26794317			Loc Ctre-ville	Sud-Ouest	Existant		A
43039	Shannon	Ottawa	William	1980	36	Fonte ductile	300	211.6675723			Loc Ctre-ville	Sud-Ouest	Existant	Oui	A
43040	Shannon	Smith	Ottawa	1893	123	Fonte grise	250	169.6126084			Loc Ctre-ville	Sud-Ouest	Existant		C
43041	Peel	Ottawa	William	1893	123	Fonte grise	200	247.0683953			Loc Ctre-ville	Sud-Ouest	Existant	Oui	C
43042	Wellington	Shannon	Young	1934	82	Fonte grise	150	170.171921			Loc Ctre-ville	Sud-Ouest	Existant		A
43043	Wellington	Murray	Murray	1889	127	Fonte grise	250	170.5864395			Loc Ctre-ville	Sud-Ouest	Existant		A
43044	Wellington	Murray	Murray	1916	100	Fonte grise	200	188.6918484	Remplacement	01-Jan-11	Loc Ctre-ville	Sud-Ouest	Existant	Oui	B
43045	Murray	Smith	Ottawa	1892	124	Fonte grise	200	325.3733159			Loc Ctre-ville	Sud-Ouest	Existant	Oui	C
43046	Young	Smith	Ottawa	1971	45	Fonte ductile	200	294.8470762	Réhabilitation	01-Jan-11	Loc Ctre-ville	Sud-Ouest	Existant	Oui	C
43047	Young	Ottawa	William	1971	45	Fonte ductile	200	168.2747219			Loc Ctre-ville	Sud-Ouest	Existant	Oui	A
43048	Murray	Ottawa	William	2009	7	Fonte ductile	200	167.7747408			Loc Ctre-ville	Sud-Ouest	Existant	Oui	C
43049	William	Murray	Montagne	1889	127	Fonte grise	300	168.1456125			Loc Ctre-ville	Sud-Ouest	Existant	Oui	A
43050	Ottawa	Murray	Séminaire	1928	88	Fonte grise	250	199.7373322			Loc Ctre-ville	Sud-Ouest	Existant	Oui	C
43051	Eleanor	Ottawa	William	2011	5	Fonte grise	200	161.9896666			Loc Ctre-ville	Sud-Ouest	Existant	Oui	C
43052	Peel	Smith	Ottawa	1889	127	Fonte grise	250	272.5041359			Loc Ctre-ville	Sud-Ouest	Existant		A
43053	Peel	Smith	Ottawa	1934	82	Fonte grise	150	167.8266859			Loc Ctre-ville	Sud-Ouest	Existant	Oui	A
43054	Commune	#987 Commune	Peel	2000	16	Fonte ductile	300	204.9538196			Loc Ctre-ville	Sud-Ouest	Existant		A
43055	Aqueduc	Barré	Notre-Dame	1891	125	Fonte grise	200	260.3995712			Loc Ctre-ville	Sud-Ouest	Existant	Oui	C
43056	Barré	Guy	Aqueduc	1914	102	Fonte grise	200	426.0380245			Loc Ctre-ville	Sud-Ouest	Existant	Oui	C
43057	William	Montagne	Guy	1889	127	Fonte grise	300	391.405899	Remplacement	01-Jan-11	Loc Ctre-ville	Sud-Ouest	Existant		B
43058	Ottawa	Séminaire	Guy	1928	88	Fonte grise	250	384.9450516			Loc Ctre-ville	Sud-Ouest	Existant		C

43059	Montagne	Ottawa	William	1890	126	Fonte grise	300	166.9613248			Loc Ctre-ville	Sud-Ouest	Existant	Oui	A
43060	Montagne	Wellington	Ottawa	1890	126	Fonte grise	300	220.7596549			Loc Ctre-ville	Sud-Ouest	Existant	Oui	C
43061	Square-Gallery	#108 Square-Gallery	Montagne	1994	22	Fonte ductile	200	58.00170876			Loc Ctre-ville	Sud-Ouest	Existant		C
43062	Séminaire	#151 Séminaire	Basin	1890	126	Fonte grise	200	119.2319976			Loc Ctre-ville	Sud-Ouest	Existant		A
43063	Séminaire	Basin	Montagne	1890	126	Fonte grise	200	258.6169641			Loc Ctre-ville	Sud-Ouest	Existant	Oui	A
43064	Rioux	Basin	Montagne	1914	102	Fonte grise	200	165.5782006			Loc Ctre-ville	Sud-Ouest	Existant		C
43065	Basin	Square-Gallery	Séminaire	1914	102	Fonte grise	200	198.3762138			Loc Ctre-ville	Sud-Ouest	Existant		C
43066	Olier	Square-Gallery	Séminaire	1/1/1914		Fonte grise	200	185.3487601			Loc Ctre-ville	Sud-Ouest	Existant		C
43067	Guy	William	Notre-Dame	1/1/1961		Fonte grise	200	190.7035918			Loc Ctre-ville	Sud-Ouest	Existant		A
43068	William	Guy	Saint-Martin	1/1/1870		Fonte grise	250	102.4500811			Locale	Sud-Ouest	Existant	Oui	C
43069	William	Guy	Saint-Martin	1/1/1876		Fonte grise	250	120.457145			Locale	Sud-Ouest	Existant		C
43070	William	Guy	Saint-Martin	1/1/1876		Fonte grise	250	22.57305746			Loc Ctre-ville	Sud-Ouest	Existant		C
43071	William	Saint-Martin	Canning	1/1/1870		Fonte grise	250	285.6249764			Locale	Sud-Ouest	Existant	Oui	C
43072	Basin	Richmond	#1910 Basin	1/1/1914		Fonte grise	200	159.1511785			Locale	Sud-Ouest	Existant	Oui	C
43073	Basin	Richmond	#1910 Basin	1/1/1897		Fonte grise	200	95.72600454			Locale	Sud-Ouest	Existant		A
43074	Richmond	Basin	Notre-Dame	1/1/1870		Fonte grise	250	288.9199147			Locale	Sud-Ouest	Existant		C
43075	Saint-Martin	Basin	Notre-Dame	12/31/2011		Fonte grise	200	245.7864965			Locale	Sud-Ouest	Existant		C
43076	Seigneurs	Basin	Notre-Dame	1/1/1870		Fonte grise	300	71.62668332			Locale	Sud-Ouest	Existant		A
43077	Chatham	Notre-Dame	William	1/1/1872		Fonte grise	100	219.8662582	Remplacement	01-Jan-50	Locale	Sud-Ouest	Existant		C
43078	Canning	Workman	William	1/1/1891		Fonte grise	200	282.3288364	Réhabilitation	01-Jan-11	Locale	Sud-Ouest	Existant		C