Priority Assessment Model for Water Distribution Networks

Ahmed Moursi

A Thesis

In the Department

Of

Building, Civil, and Environmental Engineering

Presented in Partial Fulfillment of the Requirements

For the Degree of

Master of Applied Science in Building Engineering and Construction Management at

Concordia University

Montreal, Quebec, Canada

July 2016

Concordia University

SCHOOL OF GRADUATE STUDIES

This is to certify that the thesis prepared

By: Ahmed Moursi

Entitled: Priority Assessment Model for Water Distribution Networks

And submitted in partial fulfillment of the requirements for the degree of

MASTER OF APPLIED SCIENCE IN BUILDING AND ENGINEERING
CONSTRUCTION MANAGEMENT

Complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

____ Chair

Dr. L.Amador

____ Supervisor

Dr. T.Zayed

____ External Examiner

Dr. Narayanswamy

____ Examiner

Dr. Z.Chen

____ Examiner

Dr. L .Amador

ABSTRACT

Priority Assessment Model for Water Distribution Networks

Ahmed Moursi

Infrastructure is a critical element in the countries' growth and development. Poor management of these systems would lead to their failure and in turn to disastrous situations. According to the United States Environmental Protection Agency (EPA) fifth report on drinking water infrastructure, the investments in the drinking water utilities need a total amount of $384.2 billion for the next 15 years, i.e. until December 2030. Also, according to the 2013 American's Infrastructure Report Card, the Drinking Water System (DWS) is graded as "D", implying a status between poor and fair, with an increasing failure probability. Similarly, as stated in the last 2016 Canadian Infrastructure Report Card, the water system received a ranking of "Good", representing an 'adequate for now' status. However, about 29 percent of pipelines condition is rated between fair and very poor, signifying that an urgent repair is needed with total replacement cost of $ 60 billion. Meanwhile, due to budget deficits, municipalities find it is a challenge to prioritize which asset to repaire or rehabilitate. Thus, a lot of research is done to predict the probability of failure. Yet, most of this research is limited to the consequence of failure and the criticality of water pipelines.

The main objective of this study is to develop a priority index induced by a combination of the criticality and performance of water distribution network. In this research, criticality factors that affect the water distribution networks are identified. Criticality is divided into three main aspects: (i) Economic, (ii) Environmental/Operational and (iii) Social factors. Each of these key elements is divided into subfactors with different attributes to describe the actual status of the proposed area. Paprika and Swing techniques are used to determine the weights of subfactors. The effect values are obtained from experts from North America, Europe and Qatar through questionnaires and meetings. After all the required data are collected, the data are analyzed and incorporated into the criticality model to determine the criticality index for each pipeline in the desired location. A sensitivity analysis is conducted to define the factors with the highest and the lowest impact on the criticality index. It is determined that the "Road type" sub-factor has the highest influence on the criticality index, based on Qatar's data analysis. Meanwhile, the "Pipeline diameter" sub-factor has the greatest impact on the criticality index, based on North America and Europe data analysis.

The developed criticality index is utilized with the performance index to develop the priority index, which is illustrated on the emerged priority scale and matrix for a better evaluation of the current asset status. It is concluded that "Ville Marrie" sector is found to have the highest priority index in Montreal city, equals to 4.42. While,"Bizard Island" has the lowest priority index value in the city, equals to 3.69. The developed model will guide municipalities and governments to generate a capital plan and allocate the available budget to the most critical parts of their networks. These results are also used as a reference to highlight the key areas in each sector of the designed city that need an urgent repair. This will decrease the risks, defects and health hazards of the water networks while maintaining the safety and durability of the water distribution networks in a cost-effective manner.

ACKNOWLEDGEMENT

Firstly, I would like thank god for giving me health and guidance while pursuing the Master degree.

I wish to express my deepest gratitude and appreciation to my supervisors, Dr. Tarek Zayed for giving me a chance to purist my Master degree in Civil engineering. Also, I would like to thank him for his support and guidance throughout my education at Concordia University.

My deepest expression and love for all my family members. I would like to thank my father and mother for their endless support to me during the preparation of my Master degree.
My warmest love to my daughter, Moushira for her patient and encouragement.

I would like to express my appreciation to all my colleagues for their support and my special thanks to all the researchers and experts who have helped me during my research.

Table of Contents

List of Figures

List of Tables

LIST OF ACRONYMS AND ABBREVIATIONS

AHP	Analytical Hierarchy Process
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
Cri	Criticality Index of Water Pipe
CIRC	Canadian Infrastructure Report Card
DWS	Drinking Water System
EPA	United States Environmental Protection Agency
EV	Effect Value
FANP	Fuzzy Analytical Network Process
L.H.S	Left Hand Side
MCDM	Multi-Criteria Decision Making Method
R.H.S	Right Hand Side
PAPRIKA	Potentially All Pairwise Rankings of All Possible Alternatives
Pi	Priority Index of Water Pipe
Poi	Performance Index of Water Pipe
PVC	Polyvinyl Chloride
SLCC	Stochastic Life-Cost Cycle Model
WDN	Water Distribution Networks
USDOT	United States Department of Transportation

CHAPTER 1

Introduction

1.1 Overview

Infrastructure asset can be defined as a stationery system forming a network and serving communities or societies, where the system as whole is projected to be operated at optimum capacity for its life cycle. To keep working at its optimum capacity, the system needs inspection and monitoring. In some scenarios, the replacement and refurbishment of some of the system components are required to keep the system running during its lifecycle. The combination of management, inspection, financial, engineering and other relevant practices to keep a physical asset working at an approved quality by providing the required level of service with the respect of the cost-effective manner is called asset management (New Zealand Pipe Inspection Manual, 2006).

High-frequency societal functions and public transports are essential in the development of the country. In case of not functioning properly, they cause disastrous situations. However, the value of infrastructure use is not very obvious. For example, over 19 billion tons of freight valued at $13 trillion was moved through the transportation system and its associated networks in the United States during 2002 (USDOT, 2006). Since operating this infrastructure can be vulnerable to natural disasters, accident and international harm, there is a need to know how critically infrastructure and its utility might be affected in case of a disturbance (Murray and Grubesic 2007). Also, some national infrastructures are so essential that their inefficiency has an adverse impact on the national defense or economic security of government (E.O.13010, 1996).

Infrastructure consist of several types – e.g. water, wastewater, gas, solid waste disposal and transportation systems. The primary role of infrastructure is to sustain human activities and support civil societies and governments. In particular, water supply and distribution infrastructure system are considered one of the main components in the massive urban infrastructure (Filion et al. 2004). Water is necessary to sustain life where adequate supply must be available to all types of land use (e.g. residential, industrial, etc.). Extending access to safe drinking water benefit human life development and quality (Organization 2004). To achieve adequate water delivery, a water distribution system is required to provide clean, potable water for domestic use, such as drinking, washing, cleaning and waste disposal, and for emergency cases, such as extinguishing fire (Filion et al. 2004). In the course of time and due to a constant increase of water demands, it is necessary to prioritize and maintain water distribution systems on an acceptable quality by using an accurate forecasting of the pipeline performance and condition (Najafi and Kulandaivel 2005).

1.2 Problem Statement

Currently, Drinking Water System (DWS) infrastructure is graded “D” according to ASCE Report Card. Grade “D” describes the infrastructure status from poor to fair, where the infrastructure elements approach the end of their life service and there is a high risk of system failure (America’s Infrastructure Report Card 2013). As is estimated in the ASCE, about 240,000 water mains break every year in the US. Beside the damages to its system, the broken water mains can damage other parts of infrastructure systems such as roadways, leading to additional repair costs. It is projected that above 1 million miles of water mains need replacement, as estimate by the American Water Works Association (AWWA). The replacements cost will be approximately $2.1 trillion if all the water pipes are modified at the same time (America's Infrastructure Report Card 2013).

In addition to the EPA (United States Environmental Protection Agency), fifth report on the Drinking Water Infrastructure propose that the drinking water utilities need an investment of $384.2 billion in total for the next 15 years, until December 2030 (EPA 2013). These investments cover the repair of pipelines, treatments plants, storage tanks and other key assets to keep the public health in a satisfactory state. Also, the Canadian Infrastructure Report Card estimates a total $ 207 billion is required to replace all potable water assets in Canada. The CIRC ranks the DWS as "Good: Adequate for now". However, about 29 percent of the pipeline's condition is rated between fair to very poor – liable to urgent repair with total replacement cost of $ 60 billion (CIRC. 2016). Figure I.1 shows the physical condition of transmission and distribution pipes.

Due to the last global financial crisis on 2007, and limited fund reserves in governmental municipalities, it is important to prioritize the available budget, assess the infrastructure's life cycle and notify if the system works efficiently. In addition, applying management practices to the entire portfolio of infrastructure assets at all organizational levels leads to minimizing the cost of operation and maintenance while it maintains the system in an efficient process with acceptable risks to the organization (SIMPLE. 2011).

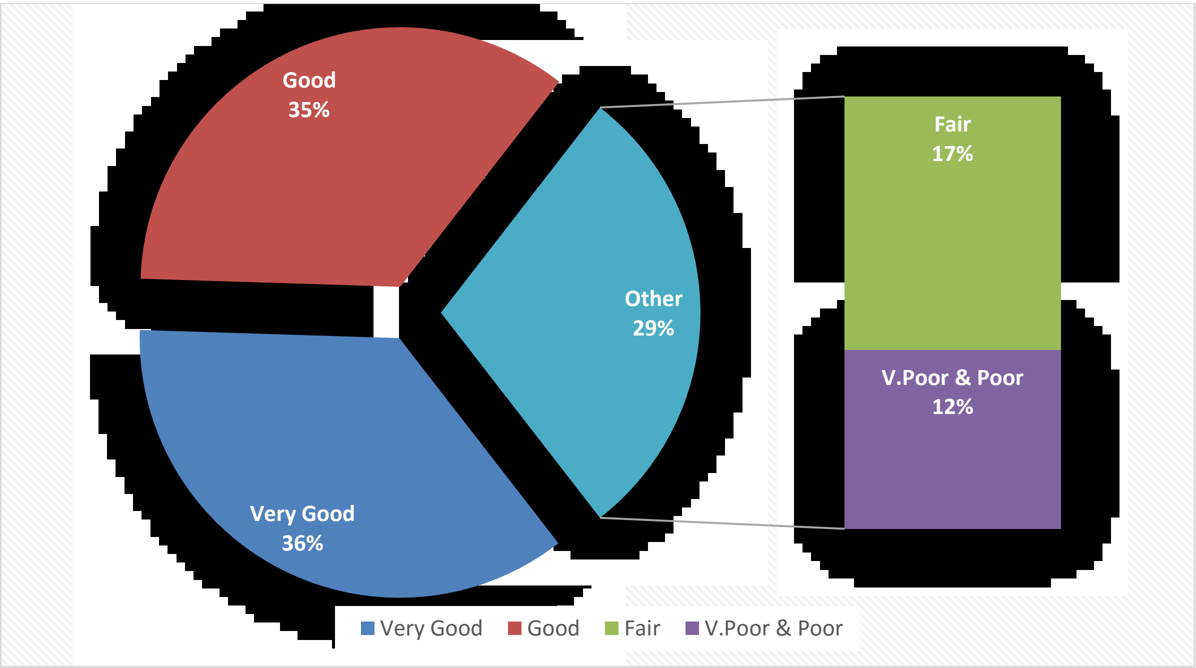


Figure 1-1 the physical condition of transmission and distribution pipes (CIRC 2016)

1.3 Research Objectives

This research mainly aims to develop a priority index of water distribution network based on criticality and performance of its pipeline. It can be achieved by means of the following tasks:

1. Identify and study the criticality factors that affect the water distribution network.
2. Develop a criticality assessment model.
3. Develop priority index and matrix, based on the criticality and performance of a water distribution network.

1.4 Research Methodology

This study aims to develop a priority index for the water distribution, using the criticality and performance indices of water pipelines. These two parameters are explained as follows:

i. Criticality Index, indicating the estimated consequences of failure of water pipelines regarding the economic, environmental/operational and social factors.
ii. Performance Index, indicating the probability of failure for the proposed water pipelines based on their deterioration level.

The priority index is a guide for municipalities to develop a maintenance plan and schedule for the water distribution networks. It also ranks the rehabilitation process of the water pipelines in accordance with their priority index value.

1.4.1 Literature Review

Literature on the water distribution network is reviewed in detailed in the corresponding chapter. It includes the explanation of the water distribution networks, identifying the criticality factors that affect the networks. “PAPRIKA and SWING” methods are applied to develop the criticality index for the proposed water pipelines. The criticality and performance indexes are combined to form the priority index.

1.4.2 Data Collection

A questionnaire was developed under the supervision of Concordia University, to identify the degree of importance for the factors affecting water networks’ reliability and criticality. A total of 30 questionnaires were completed by experts in water distribution networks. Upon collection and analysis, the data were inserted into the criticality assessment model to determine the weights and the effect value of the criticality factors. Other sets of data were collected from the Strategic Management Department of Water Networks in Montreal, Canada. Used in the research case study, these data explain the actual status of water pipelines network in different locations in Montreal.

1.4.3 Priority Index for Water Distribution Networks

The Model was developed in the following procedures:

1) Identification and analysis of criticality main and subfactors that affect the water distribution network.
2) Development of Criticality Index based on applying the Paprika and Swing methods.
3) Combination of Criticality and Performance indices to develop the Priority Index.
4) Illustration of Priority matrix for the water distribution networks.

1.5 Thesis Organization

Chapter 2 summarizes a detailed literature review to illustrate the water supply systems and risk management. It also covers the factors that influence the criticality and performance of water distribution networks. The literature review describes the previous models and research regarding the criticality of water distribution networks. “Paprika” and “Swing” are the weighting techniques used in this study to determine the criticality and priority indices. Chapter 3 presents the research methodology and process. It includes the criticality factors identification to develop the criticality index with the assistance of Paprika and Swing techniques. Priority index, priority scale, matrix development and process procedures are also explained in this chapter.

Chapter 4 presents the data collection method for this study and the analysis done on the collected data. Chapter 5 describes the case study and the priority model implantation. It illustrates a detailed procedure to develop the criticality index. The criticality index and the performance index are inserted into the priority model to define the priority index of the referred pipeline in specific locations. The priority index guides municipalities to arrange their maintenance and rehabilitations plans. Finally, chapter six presents the research conclusion, limitation and future work possibilities.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter consists of 10 sections as shown in Figure 2.1. Section 2-2 provides a definition of water supply distribution networks, including the components, types and the pipeline material used in the water main systems. Section 2-3 gives an overview of asset management and its principles and the benefits of applying it to the water supply systems. Section 2-4 talks about risk management. It defines the risk process, risk rates and how to measure and quantify the risk. Section 2-5 discusses the criticality of pipelines. It describes the term "critical assets" and explains the important factors that affect the criticality of water distribution network. There are several factors found and most of them can be categorized into four main groups: Economic, social, operational and environmental aspects.

Section 2-6 defines the performance of water distribution networks and the deterioration factors that affect the condition of water pipelines. Section 2-7 illustrates El Chanati performance factors and performance index. Section 2-8 and Section 2-9 explain the Paprika and Swing methods respectively. These methods are used in the development of criticality models to determine the weight of the criticality factors of water distribution networks. Section 2-10 gives an overview of previous research work and models on the evaluation of water disruption networks. Some researchers have developed a risk index while others have developed criticality index as it is explained below.

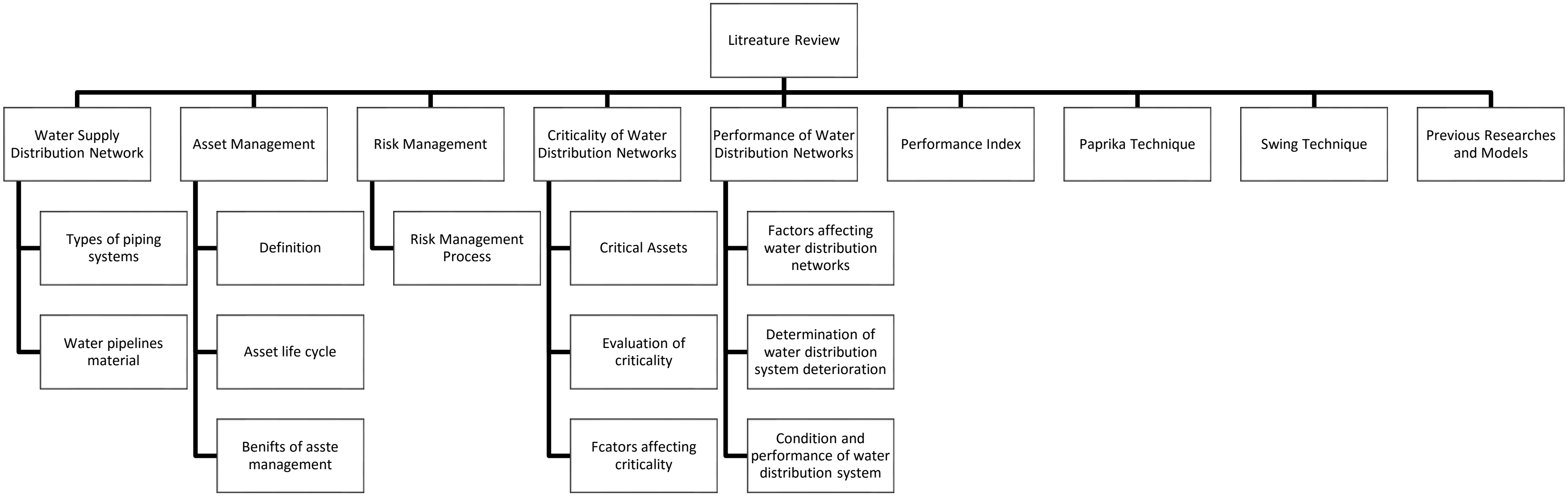


Figure 2-1 Literature review diagram

2.2 Water Supply Distribution Network

Water is one of the key elements to sustain life and without it life can never exist. Over the centuries, surface water and ground waters have been a source of water supplies for human activities such as domestic use, agriculture and industrial fields (Loucks and Van Beek 2005).The water supply system forms a fundamental part of the development of civilizations and it is a challenge to keep the supply of fresh water to different consumers (Bhave 2003). The primary goal of the water system is to carry the water under the designed pressure from the treatment plant or pump stations to the distributing system. The distribution system consists of an interconnecting pipes network and loops. These networks should deliver the water from the source to the demand point (Gupta 2001). The water supply system has many components or subsystems, according to Tarrant Regional Water District Integrated Water Supply Plan published 2013, it divides the water supply system as follows:-

I. Pump stations: described as the plumbing capacity and number of plumbs.
II. Pipelines: described by size, length, location.
III. Reservoirs: described by yield, capacity and water right.
IV. Other Water Supply rights/contracts: defined by annual yield.
V. Water Treatment Plants: specified by treatment capacity and location.

2.2.1 Types of piping systems

The piping system can be classified into four main categories; it is described as follows:-

a) Transmission lines

The transmission lines are pipes that transport water from its resource to the treatment plants or from the treatment plants to pump stations or from pump stations to the distribution network or reservoirs. These pipelines are usually long and large, and usually, their diameters are above 400 mm (Bhave 2003).

b) In-Plant piping system.

These pipes are found in the treatment plants and pump stations. They are usually big in size but small in length. These pipes are attached to many different accessories such as valves and meters to monitor the characteristics of the water (Bhave 2003).

c) Distribution mains

The Distribution mains pipes carry the water from the treatment plants and service reservoirs to be distributed to the community. Manholes are often built near or between the pipes for servicing and to make the maintenance of the pipes much easier. The size of these pipes are ranged from 100 mm to 250 mm and in some occasions may increases above 250 mm.

d) Service lines

The service lines pipes deliver the water from the distribution networks to the customers. These pipes are small and usually their diameter below 100 mm (Bhave 2003).

2.2.2 Water pipelines materials.

Water pipelines can be made of different materials in different sizes. According to the Deterioration and Inspection of water distribution system dated 2003. It is mentioned that two-thirds of the existing water mains in use across Canada are cast iron and ductile iron, while Steel, Polyvinyl chloride (PVC), high-density polyethylene (HDPE), asbestos cement (AC) and concrete pressure pipes (CPP) may also be used in the construction of water pipelines. Table 2-1 shows the conventional water main materials and their period of installation.

Table 2-1 Common water main material (Deterioration and Inspection of water distribution system 2003)

Pipe Material	Range of Diameter	Period of Installation	CSA Standard	AWWA Standard	AWWA Manual
Pit Cast Iron (CI)	75-1,500 mm	1850s-1940s		C100	
Spun Cast Iron (CI)	75-1,500 mm	1930s-1960s		C100	
Ductile Iron (DI)	75-1,600 mm	Since 1960s		C151	M41
Steel	> 150 mm	Since 1850s	Z245.1	C200	M11
Polyvinyl Chloride (PVC)	100-1,200 mm	Since 1970s	B137.3	C900/905	M23
High Density Polyethylene (HDPE)	100-1,575 mm	Since 1980s	B137.1	C906	
Asbestos Cement (AC)	100-1,050 mm	1930s to 1980s		C400	
Concrete Pressure Pipe (CPP)	250-3,660 mm	Since 1940s		C300/301/ 302/303	M9

With the reference to Table 2-1, Ductile Iron, Steel, PVC and Concrete pipes are the current conventional materials that are being utilized till our present date in the United Kingdom and Canada. While Asbestos and Cast are not being used from the mid of the last century due to health, environmental and maintenance problems Rajani and Kleiner (2004) Clarified that the types of pipes material used in water supply vary from country to country or even city from the city. The major types of materials used in water pipes manufacture are Cast iron, Asbestos Cement, and plastic in Europe. Figure 2-2 shows the distribution pipe materials among different European countries within the existing water supply networks at 1990.

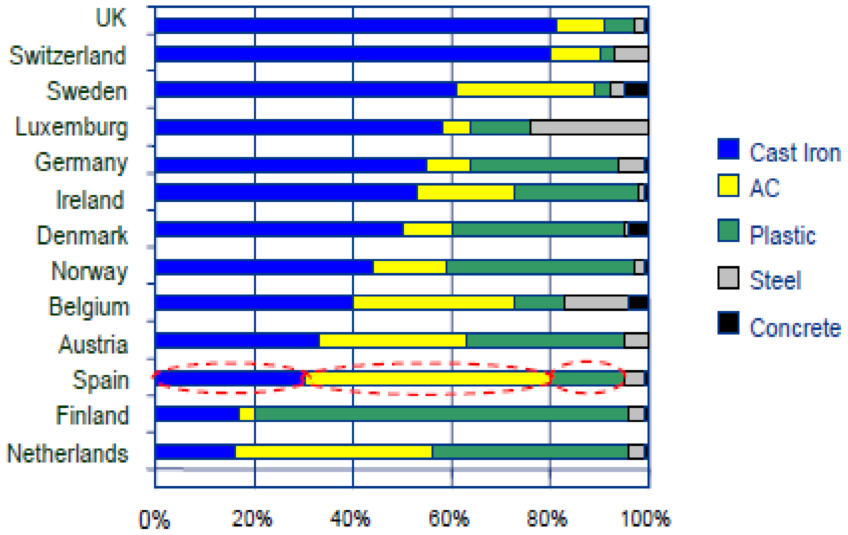


Figure 2-2 Pipe materials in Europe Rajani and Kleiner (2004)

In UK and Switzerland almost 80 % of water supply pipes are made of cast iron, however in Finland, most of the pipes are made of plastic. Spain, Belgium, and Netherlands have the largest proportion among the other European countries in using asbestos cement in their water supply pipes.

2.3 Asset Management

Assets can be explained as any physical components that have a value. The assets can provide services and usually has an economic life cycle greater than 12 months. An example of an asset is a pipeline connects two valves together. In other hands, Infrastructure asset can be defined as a stationary system forming a network and serving communities or societies, where the system as whole is projected to be operated at optimum capacity for its life cycle (New Zealand Pipe Inspection Manual, 2006). To maintain the system working at the best capacity, it is needed to be inspected and monitored and in some conditions replacement and refurbishment are required to keep the asset operates in an acceptable status during its lifecycle (New Zealand Pipe Inspection Manual, 2006).

2.3.1 Definition

New Zealand Pipe Inspection Manual (2006), defines asset management as the combination of managements, inspections, financial, engineering and other practices to keep a physical asset working at an approved quality by providing the required level of service with the respect of the cost effective manner is called asset management. Mitchell and Carlson (2001) have defined asset management as mix or integration set of the process (Engineering, financial, operating, maintenance) to keep the asset to working for the longest lifetime with the minimum cost value. Haider (2012) Has mentioned that the scope of asset management extends from the creating of the asset until its disposal. The asset management process must identify the objectives of the referred asset and keeping it works efficiently under various conditions, while managing the asset relationship with external factors and stakeholders.

2.3.2 Asset life cycle

Haider (2012) describes the asset life cycle and illustrates the different stages of an asset over time. These scenes consist of creating, commissioning, operation, maintenance and decommission. The final stage includes renewal or disposal of an asset; mainly it depends whenever if the asset is still required to the stakeholders or not. Schuman and Brent (2005) divide the life cycle into two primary phase Acquisition phase and Utilization phase. Acquisition phase starts from the creating an idea of the asset followed by the preliminary designs and later the construction of the proposed asset. In other hands, Utilization phase includes the maintenance of an asset during its process and the retirement of an asset at the end of its life cycle. Figure 2-3 explains the lifecycle of an asset adopted from Blanchard and Fabrycky (1998).

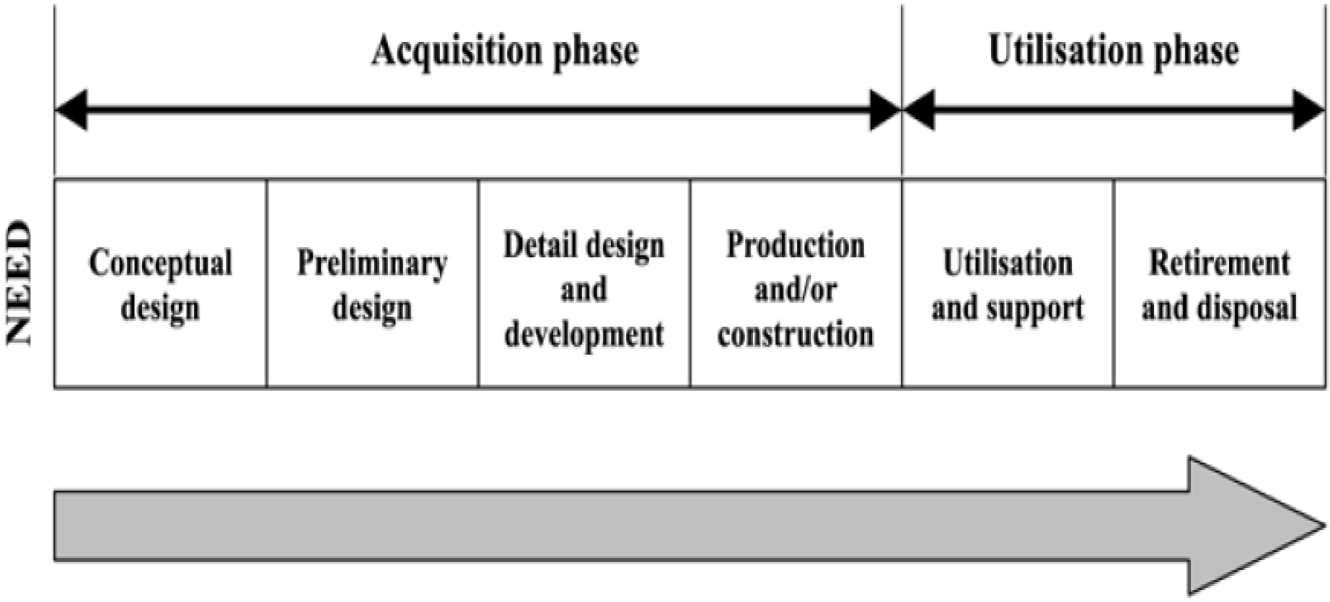


Figure 2-3 Lifecycle of an asset (Blanchard and Fabrycky, 1998).

2.3.3 Benefits of Asset Management.

The asset management main advantage is to make the asset perform its required service with minimum maintenance cost. Infra Guide, (2005) defines that primary benefit of asset management is providing a transparent, managerial and cost efficient manners to the asset, which results in an accurate evaluation to the asset with saving a lot of unnecessary expenses. Infra Guide, (2005) has also mentioned some specified benefits which are described as follows:

- Monitoring and measuring the performance of an asset is much easier.
- Helps in avoiding problems, crashes and disasters.
- Minimize the risk to the municipality.
- Improve the communication with the public.
- Better evaluation of asset regarding money.
- Reduce asset life cycle costs.

- Improve the performance and service of the asset.
- Choosing the best available scenario regarding resource allocation.
- Increase the accuracy of financial strategies and planning.
- More efficient in data collecting and management.

2.4 Risk Management.

It considers as one of the main principals of asset management, in which it identifies, analyzes and solves a potential hazard, threat or problem to an asset. ISO Guide 73 has defined the term risk as follows "Risk the chance of something happening (an event) that will have an impact on objectives." Hasting, (2000) has divided the risk into three main categories; "Hazard" explained as a source of potential harm or threat. "Consequence of failure" described as the outcome or the result of the risk occurring regarding loss, gain, disadvantages or injuries. "Likelihood" explained as the probability or rate of occurrence for an event or a risk. Risk can decompose into two main components: (i) Probability of failure and (ii) Consequence of failure as shown in Figure 2-4. The probability and consequence of failure analysis become more powerful when both results are quantified and later converted to a value of money (Harlow and Stewart 2006).

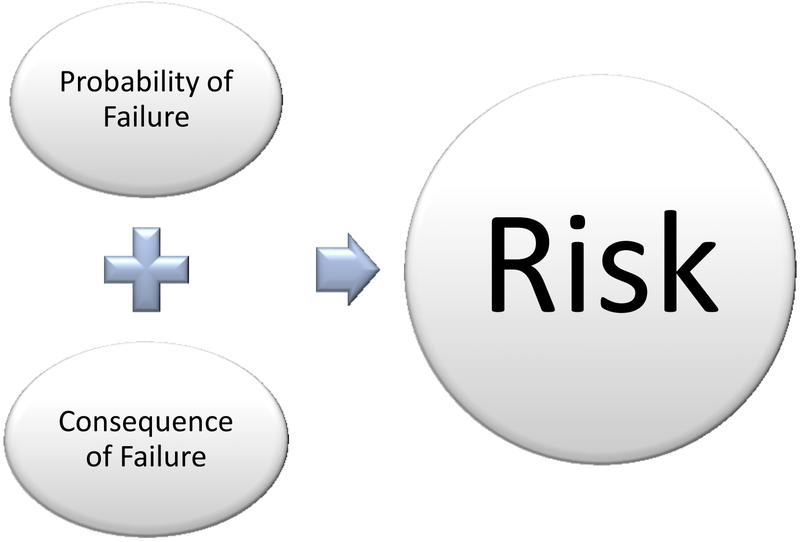


Figure 2-4 Risk main features.

2.4.1 Risk Management Process

In GWRC report no 08/RG/05/25 divide the risk process into four main stages, the following paragraph describes the steps as follows:

a) Setting a framework (Establishing a context)

It is the first step of the risk management process, in which the methodology of the whole process is defined, and it ensures the risk management process is compatible with the overall asset system or business. Also, it describes the relationship between the risk process with the key elements of the asset system such as asset's objectives, stakeholders, and main criteria.

b) Identify risks.

All types of risks that may affect the asset system are mentioned in this stage whatever if it is financial, utility or global risk. A detailed register must be created to define these risks and explaining the situation when the risks occurred. This will increase the awareness of the number of risks and reduce their rate of occurrences. Table 2-2 gives an example of a risk register adopted from Hastings, 2000. Table 2-3 shows some types of different risk that may affect an irrigation system. It also gives the score of the hazard consequences regarding safety, cost, and environment. The risk rating is the total risk score for the danger; the risk rating is calculated differently from one facility to another by risk priority and effect.

Table 2-2 An example for risk register adopted from Hastings 2000

Risk Register		Compiled by	NAJH				Date	
Title	Irrigation system	Revised by					Date	
Ref	Hazard	Current Controls	Rate	Safety	Cost	function	Environment	Risk Rating= R*(S+C+F+E)
1	Unable to supply water due to leak in rising main resulting	None	2	1	5	5	1	24
2	Unable to supply water due to pipework seal failure.	Inspect annually	2	2	3	3	2	20
3	Unable to supply water due to pump failure	Routine maintenance	3	1	4	5	1	33
4	Flooding of property.	Operating procedures	1	3	2	2	2	9
5	Unable to supply treated water to town due to control failure.	Communication link	1	3	3	3	5	14
6	Unable to supply water due to switchboard minor failure.	None	1	1	2	5	1	9
7	Unable to supply water due to switchboard major failure.	None	1	2	5	5	1	13

c) Evaluation risks.

After the whole risks are identified, the evaluation stage begins. The risks are divided into likelihood and consequences so they can be evaluated as a measurable value. The risk is then ranked and sorted according to their magnitude and prioritization.

d) Treating risks.

Various options and strategies are suggested to solve the risk or a problem. The optimum solution will be chosen with respect to the economic value of each solution. After the risk has been resolved, the asset will be monitored and tested, later the risk data are registered to increase the awareness of the same risk. The following figure 2-5 shows the relationship between the cause and consequence of risk-adopted from GWRC report no 08/RG/05/25.

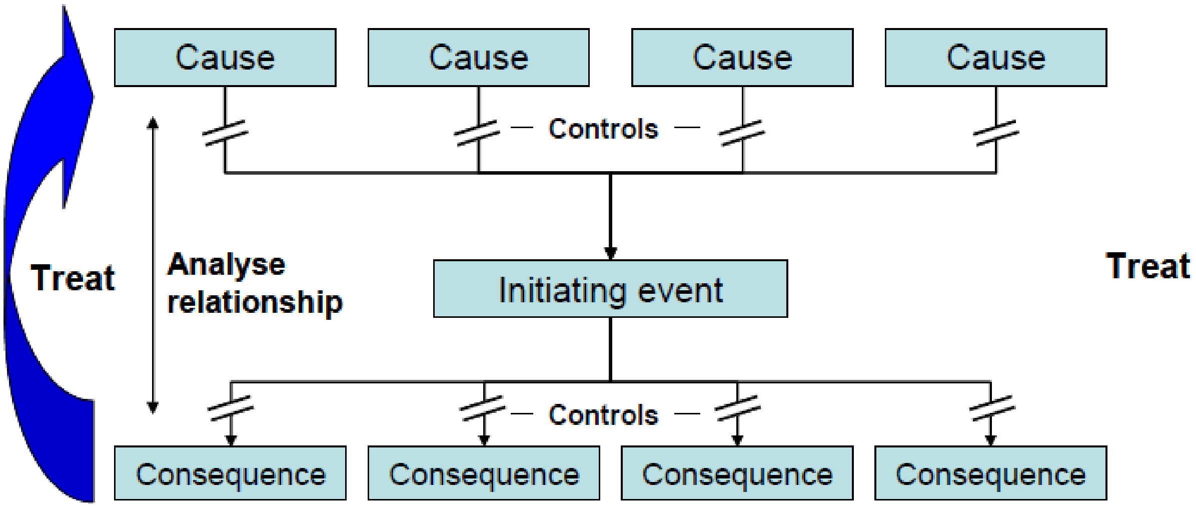


Figure 2-5 Relationship between cause and consequence of risk GWRC report no 08/RG/05/25.

2.5 Criticality of Water Distribution Networks.

Criticality is a part of the infrastructure management, an essential factor to rate and prioritize the maintenance and rehabilitation of the proposed infrastructure system. Criticality can be defined as the consequence of an asset failing to perform its intended function (Council 2006). To date, there is neither a standard nor a database to evaluate the criticality of infrastructure. Therefore, criticality is still a subjective matter and requires a lot of research and substantial involvement of support municipalities to determine its process and factors (Salman, 2011).

2.5.1 Critical Assets

The concept of critical assets has been developed to help the municipalities and managers to identify assets with high strategic importance. The critical assets usually have a high level of consequence regarding economic, political and social values if they have been damaged or didn't execute their jobs probably (Infrastructure Asset Grading Guidelines, 1999). Infrastructure Asset Grading Guidelines (1999) propose another definition for critical assets, describing it as "an asset where failure would have significant consequences, either in the ability of a system to provide services to customers or failure effect on the environment". In our current date, there are no specific rules or specifications for the determination of critical assets. It is a matter of technical studies and judgment to identify key assets, based on their level of risks and their consequence of failure value (Infrastructure Asset Grading Guidelines, 1999). Salman (2011) also define criticality as the failure impact of water pipelines when crashes occur.

Water Supply Asset Management Plan (2012) defines critical assets as those with a high consequence of failure if they are damaged or they fail. The critical assets should be managed through regular maintenance and monitoring to ensure their probability of failure remain at a minimum level or an acceptable value. According to Hastings (2000), criticality is a term used in asset planning. This term refers to assets with potential production losses, safety or environmental effects when they fail. Criticality techniques serve municipalities in developing maintenance and contingency plans for the assets.

2.5.2 Evaluation of Criticality

As mentioned previously, there is no particular rule to identify critical assets. However, in real life, municipalities assign the critical assets with a high grade (e.g. 4 or 5) for the high consequence of failure, while the non-critical assets are graded as low (e.g. 1 or 2) for the profound consequence of failure. For example, a primary water supply pipe that serves a huge city with a large number of customers and demands has a higher grade regarding criticality than a water supply pipe that serves a small village with a smaller number of clients. Therefore, the municipalities must keep the condition rating for critical assets above good shape to avoid any severe damage to the property by regular planned maintenance schedules. Conversely, the non-critical assets may stay in a poor condition or even collapse before municipalities take a due action because these assets have a low consequence of failure when damaged and the priority is always given to the critical assets (Infrastructure Asset Grading Guidelines, 1999).

2.5.3 Factors affecting criticality

There are several factors affect the criticality of pipelines; these factors can be related to economic, environmental or social aspects. Water supply asset management plan, (2012) has characterized five factors that affect the consequence of failure, and they are discussed as follows:

1. Diameter: The size of pipeline
2. Properties affected: How the surrounding building and properties are affected due to the consequence of failure
3. Critical Customer: Such as governmental building, hospitals, and authorities buildings
4. Land use zone: If the affected area is residential, commercial or industrial
5. Proximity to key sites: How does the consequence failure of water pipeline will affect key sites such as highway or important road intersection

Another clarification is made by Institute for water resources, 2013 for the criticality factors. It categorized the criticality into three main factors:

1. Social Factor: How does the consequence of failure will affect the society regarding social aspect such as safety, third party losses, loss of service and damaging public image

2. Environmental factor: How does the consequence of failure affect the surroundings and nearby environment.
3. Economic Factor: How much amount of money is lost due to the consequence of Failure. This cost can be generalized as direct and indirect cost.

Miles et al. , 2007 stated that the environmental impacts, the size of the pipeline, the transportation impact and ease of repair are all important factors that affect criticality as shown in Figure 2-6.

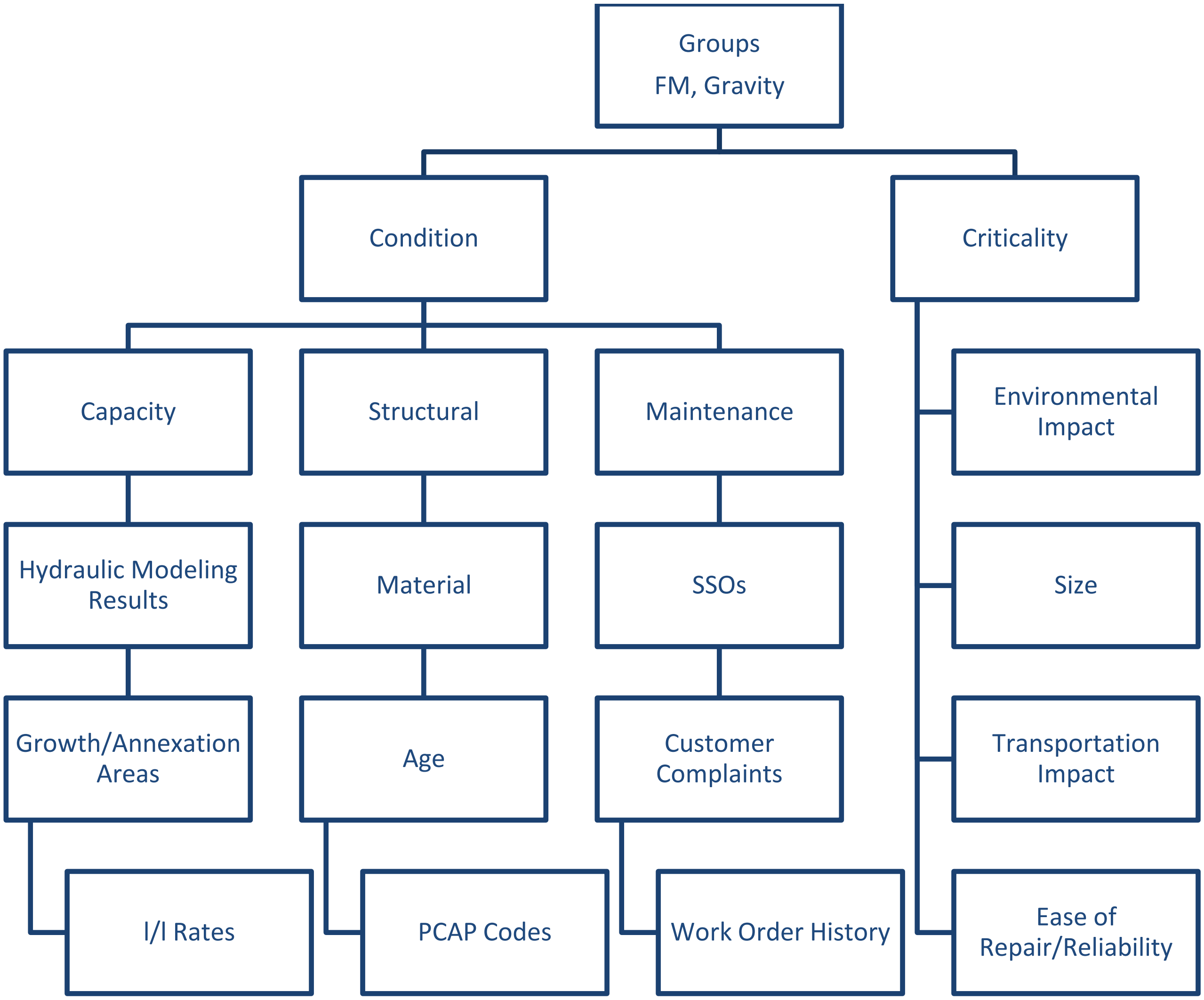


Figure 2-6 Condition and criticality factors adopted from Miles et al. 2007

The UMA,2007 developed a criticality model for city of Hamilton, the model categorized the criticality factors into four main factors and discussed as follow:

1. Economic: Influence of water main's failure in term of cost and resources
    a. Pipe Size: The consequences of failure on the water main are directly proportional to its size, due to an increase in repair cost.
    b. Depth of Pipe: The consequences of failure on the water main are directly proportional to its size, due to an increase in repair cost.
    c. Material: The consequences of failure on the water main depend on its manufacturing material type.
    d. Low Accessibility: The consequences of failure on the water main depend on the ease of reaching the pipelines for repairing
2. Operational: Influence of water main's failure on operation service
    a. Critical Location: The consequences of failure consider to be huge if it is near a critical location such as a hospital
    b. Material: The consequences of failure on the water main depend on its manufacturing material type
    c. Pipe Size: The consequences of failure on the water main are directly proportional to its size, due to an increase in repair cost.
3. Social: Influence of water main's failure on the society
    a. Road Type: The consequences of a failed water main depend on its road location due to public disruption. Pipes that are located under an expressway, highway, or major urban roads have large impacts in comparison to other roads.

   b. No Diversion: The consequences of failure consider to be huge to the public when there is no alternative route
   c. Pipe Size: The consequences of failure on the water main are directly proportional to its size, due to an increase of social impact.
4. Environmental: Influence of water main’s failure on the environment.
   a. Water Body Proximity: Failure consequences of water main are gradually increased when it is located close to surface water, such as a lake or a river.
   b. Locality: The consequences of failure consider to be huge when it located to a sensitive location.
   c. Pipe Size: The consequences of failure on the water main are directly proportional to its size, due to an increase of environment impact.

2.6 Performance of Water Distribution Networks

The term performance is explained as the capability of an asset to meet its clear objectives without any restrictions or errors (Infrastructure Asset Grading Guidelines, 1999). Pipe failure is part of the deterioration process. However, failure does not happen at once but numerous factors can affect the deterioration process of the pipes through time (Misiunas 2008). Figure 2-7 describes the pipe failure development over a specific period of time. The illustration below shows two critical stages during the deterioration process. The first is a partial failure stage, caused by a leak or burst; in this stage, however, the pipe still functions. The second stage is a complete failure, when the pipe cannot perform its services and thus, repair or replacement is needed to rectify the failure (Misiunas 2008). Makar and Kleiner (2000) have mentioned that pipes deteriorate as time passes. However, the deterioration rate depends on several factors such as the pipe’s material, its location and operational conditions.

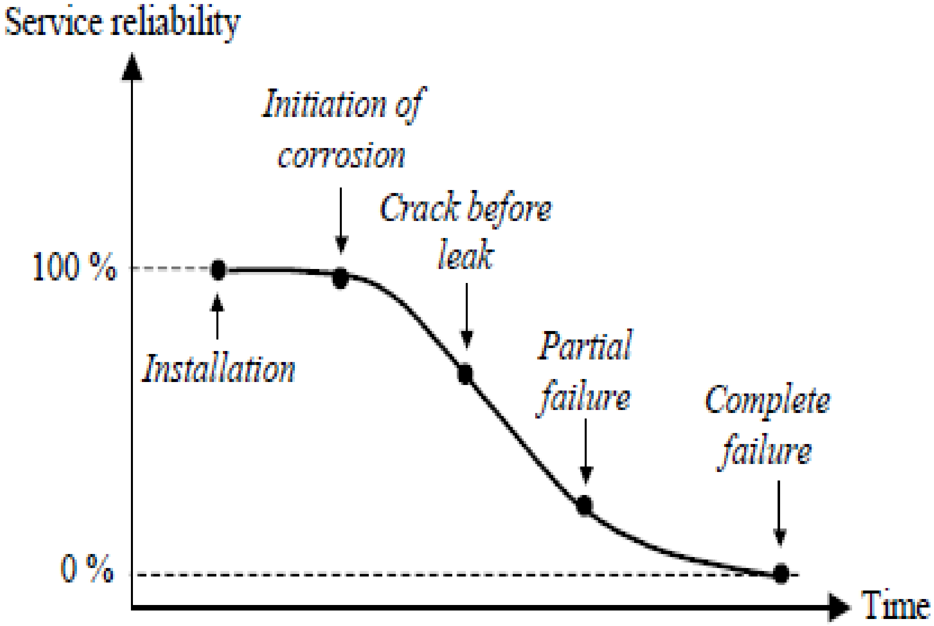


Figure 2-7 Pipe failure development adopted from Misiunas (2008)

2.6.1 Factors affecting water distribution networks

Several factors can affect the deterioration process of water distribution networks. Kleiner and Rajani (2001) have divided these factors into three broad categories, operational, environmental and physical. Also, they have reported that the buried pipes can be subjected to other loads and factors such as climate condition, soil shrinkage behavior, and the traffic loads. Figure 2-8 shows a cross section of a pipeline subjected to various types of loads adopted from (O'Day et al.,1986).

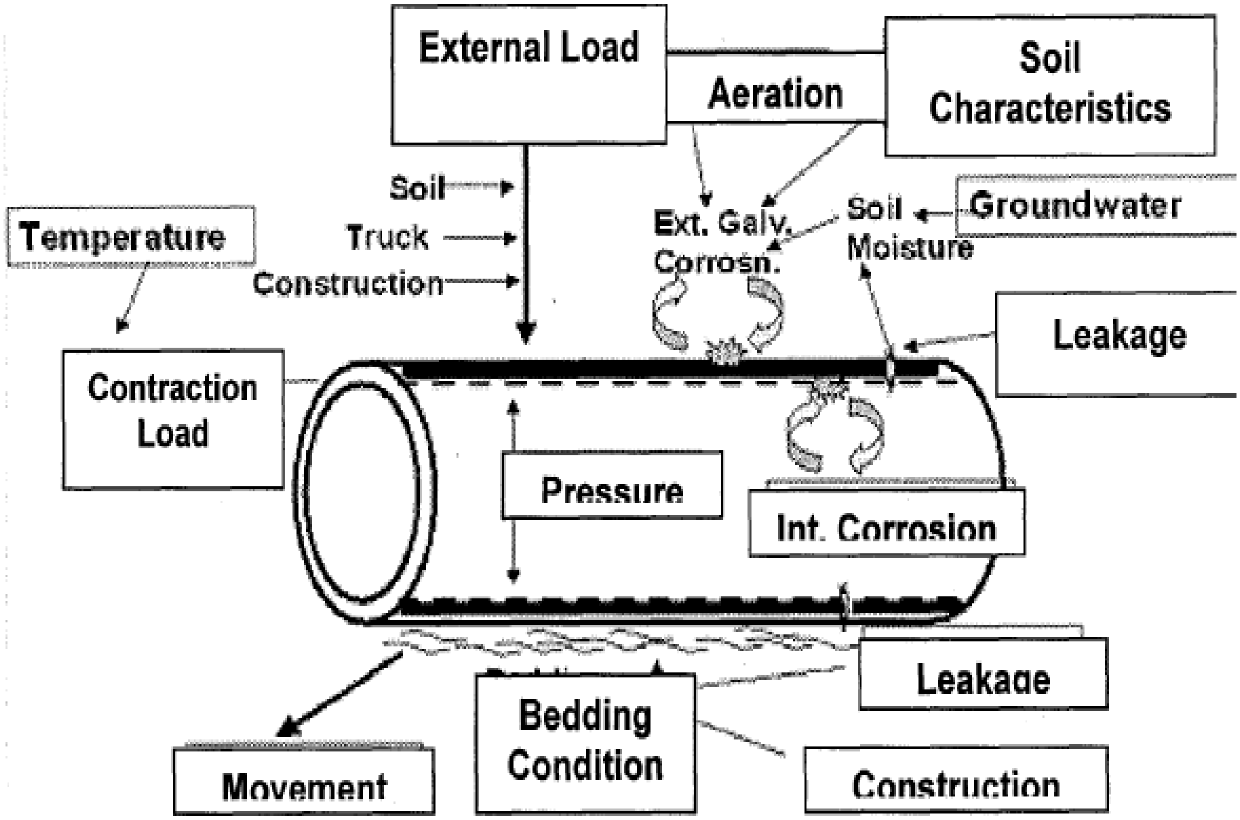


Figure 2-8 Pipe deterioration factors adopted from (O'Day et al.1986).

Kleiner and Rajani (2002) have classified water main deterioration factors into three types:

1. Static factors: They are elements that remain constant as time passes. These factors include pipe material, backfilling type and installation method
2. Dynamic factors: They are factors that are related to the pipe surrounding and environment. These factors include age, soil properties, dynamic loading and climate conditions.
3. Operational factors: They are the elements that describe the operation status of the pipes. Such as maintenance rate and protection method.

Walski and Male, (2000) have reported that the pipe breaks are caused by several defects. Failure of the pipeline can result from one factor or by interacting of several defects combined. The succeeding section describes the defects as follow:

1. Corrosion: The corrosion considers one of the primary defects that causes pipe breaks. This is due to unprotect external wall, and the inner wall is not lined well.
2. External loads: These external loads can be characterized into three categories
    a. Loads during excavation.
    b. Loads during installation and backfilling.
    c. Changes in the surface loads
3. Poor Tapping: Pipe tapping could weaken the pipe and causes a break. Manufacture's manuals should be followed because some pipes only can be with specific materials such as tapping saddles.
4. Pressure-Relate Breaks: This is caused due to the pipe cannot withstand the internal pressure of water inside it.

Another classification is made by Best Practices (2003b) divides the primary water deterioration into three group as shown in Table 2-3.

1. Physical factors: They are the physical characteristic of the pipeline such as pipe material, Pipe age, pipe thickness, pipe diameter, types of joints, thrust restraint, Pipelining and coating, dissimilar metals, pipe vintage and manufacturing process.
2. Environmental factors: They are the factors caused by the effect of environment or surrounding in which the pipe is placed. Such as soil type, soil moisture, pipe location in the road, trench backfill material, pipe bedding, underground disturbances, stray electric currents, seismic activity, and installation practices climate condition, ground water.
3. Operational factors: They are the operational conditions in which the pipe execute its services, such as water pressure, flow velocity, leakage, backflow potential and operational and maintenance practices.

2.6.2 Determination of water distribution system deterioration

Best Practices (2003b) explains that degradation of water distribution system become noticeable through one or more of the following effects:

1. Reduction of water quality: The main reason for this factor is internal corrosion of pipeline, due to the corrosion components dissolved in the water.
2. Reduce hydraulic capacity: This event happened due to the internal corrosion, the diameter of the pipeline is decreased due to the internal corrosion
3. High leakage rate: Due to several corrosion holes in the pipeline.
4. Frequent number of breaks: The breaks can happen due to several factors such as corrosion, poor installation, external loads and operating condition.

Most of the municipalities monitor the state of the pipeline by various methods and techniques (such as CCTV system) to avoid the condition of the pipeline to decrease below the proper status and to reduce complaints from the consumers.

2.6.3 Condition and performance of water distribution system

The asset condition shows the status asset regarding physical aspect, for example if the pipe is rusted or damaged from the surrounding effects. However, these effects may or may not affect the performance of the asset. The performance (as it is mentioned previously) is the ability to execute the asset service or function without any errors or receiving any complaints from the consumers (IPWEA Condition Assessment & Asset Performance Guidelines).

2.7 Performance Index

El Chanati (2014) has developed a performance index of water distribution networks by integrating its components, i.e. pipelines and accessories. This performance index is categorized into three main factors with each of the main factors divided into sub-factors. The main factors are identified as physical, environmental and operational as shown in the hierarchy diagram in Figure 2-9.

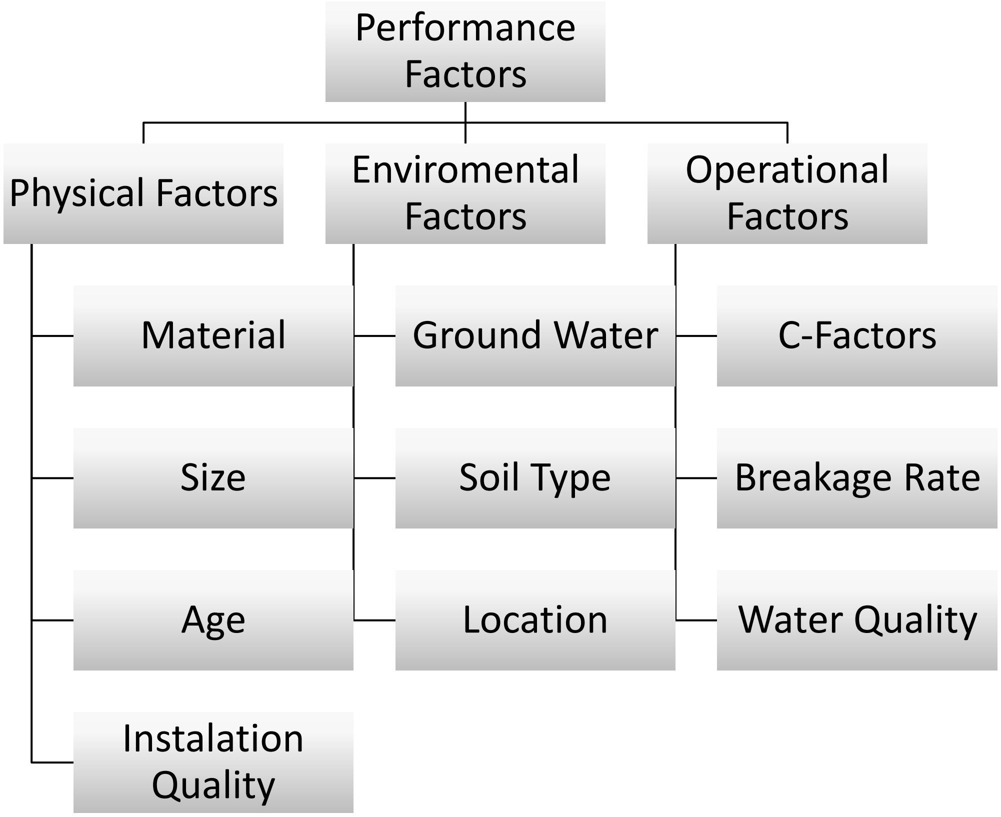


Figure 2-9 Performance factor of water distribution networks (El Chanati 2014)

Table 2-3 Deterioration factors affecting water systems (adopted from best practices, 2003b)

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

In El Chanati (2014), the Fuzzy Analytical Network Process (FANP) method is used to determine the relative weight of each subfactor. These weights are used along with their effect values to assess the performance index of the water distribution networks. Table 2-6 shows the weights and the effect values of the performance main and sub-factors. According to Table 2-4, each of the performance main factors is divided into several alternatives to estimate the performance of the pipeline. The total performance score varies from "0" to "10", where "0" and "10" indicate the pipeline is at its highest and lowest performance respectively. When the total performance score is "10", immediate action is required.

2.8 Paprika Technique

Paprika stands for "potentially all pairwise rankings of all possible alternatives", a new method developed by Paul Hansen and Franz Ombler. It is a multi-criteria decision making method (MCDM), where the decision maker executes a pairwise ranking of all undominated pairs of all possible alternatives represented by the model. Paprika is used to determine the point values for additive multi-attribute value models with performance criteria. Each criterion is defined in several categories and the pairwise comparison is run between these categories to epitomize the relative status of each criterion with the other. The categories are later ranked to enable the decision maker to prioritize the proposed alternatives (Hansen and Ombler 2008).

Due to the comparison of categories, pairs will be induced. The pair will at least contain one category from each criterion. In their comparison, if one of them contains a higher category value in the first criterion, the other pair contains a higher category value in the second criterion. Then, this pair can be defined as undominated. In contrast, the dominated pairs are naturally ranked because one pair has at least a higher category value in one criterion while other

Table 2-4 Performance weights and effect value (El Chanati 2014)

Main Factor	Sub-factors	Unit Of Measure	Qualitative Description (Parameters)	Weights	EV	Performance Score
PHYSICAL	Water Mains Age	(Years)	Old>50	0.0825	9.00	0.7427
			30-50		8.00	0.6601
			15-30		5.00	0.4126
			5-15		3.00	0.2476
			<5		0.00	0.0000
	Water Mains Size (Diameter)	mm	Small Size <200mm	0.0777	6.00	0.4660
			Medium Size (200-350)		4.00	0.3107
			Large Size>350		0.00	0.0000
	Material		PVC	0.1234	2.00	0.2468
			Concrete		3.00	0.3701
			Asbestos		4.00	0.4935
			Ductile		3.00	0.3701
			Cast Iron		0.00	0.0000
	Water Mains Installation Quality	(%)	Good	0.1276	0.00	0.0000
			Fair		4.00	0.5104
			Poor		8.00	1.0209
ENVIRONMENTAL	Ground Water Depth	(m)	Shallow depth	0.0955	8.00	0.7642
			Moderate depth		5.00	0.4776
			Deep depth		0.00	0.0000
	Soil Type	(% of Corrosiveness and Presence of hydrocarbons and Solvents)	Aggressive	0.0992	8.00	0.7934
			Moderate		5.00	0.4959
			Non-Aggressive		0.00	0.0000
	Location	Surface Type	Asphalt	0.0582	4.00	0.2329
			Seal		4.00	0.2329
			Foot Path		4.00	0.2329
			Unpaved		5.00	0.2911
OPERATIONAL	Pressure/Flow velocity and C factor	-	High> 101	0.1125	0.00	0.0000
			Medium(41 - 101)		4.00	0.4502
			Low< 41		7.00	0.7878
	Leakage/Breakage Rate	Breaks/km/year	High	0.1264	9.00	1.1374
			Medium		5.00	0.6319
			Low		0.00	0.0000
	Water Quality	(% of Impurity and added chemicals)	High	0.0970	8.00	0.7759
			Medium		5.00	0.4850
			Low		0.00	0.0000

categories of criteria are either of the same rank or lower than that of the intended. The decision maker begins to rank the undominated pairs until all the undominated pairs are ranked. Also, in the paprika process, some pairs are eliminated due to the transitivity property of additive value models, saving the decision maker plenty of time for (Hansen and Ombler 2008). Table 2-5 shows an example for a pairwise comparison between two categories adopted from Hansen and Ombler (2008). It shows a pairwise comparison of three criteria and two categories. The dominated pairs is illustrated as “^”. The undominated pairs is attached with italic numbers for identifications, while the shaded parts are the duplicate pairs. “a”, “b” and “c” represent the different categories of alternatives. The combination of two categories represents the second level, while the combination of three categories represents the third level.

Table 2-5 Pairwise comparison between two categories adopted from Hansen and Ombler (2008)

Alternatives	222	221	212	122	112	121	211	111
222		^	^	^	^	^	^	^
221			(i) b2 + c1 vs b1 + c2	(ii) a2 + c1 vs a1 + c2	(iv) a2 + b2 + c1 vs a1 + b1 + c2	^	^	^
212				(iii) a2 + b1 vs a1 + b1	^	(v) a2 + b1 + c2 vs a1 + b2 + c1	^	^
122					^	^	(vi) a1 + b2 + c2 vs a2 + b1 + c1	^
112						b1 + c2 vs b2 + c1	a1 + c2 vs a2 + c1	^
121							a1 + b2 vs a2 + b1	^
211								^
111								

The following equation, N(n,y,z), gives the total number of undominated pairs of degree z (z=2,3,.. n) that includes all the replicas. U(n,y,z) symbolizes the number of these pairs of degree z that are unique – excluding replicas (Hansen and Ombler 2008).

$N(n,y,z)={}^{n}C_{z}\,(2^{z-1}-1)({}^{y}C_{2})^{z}\,y^{n-z}$ ……………………………….…………………………[2-1]

$U(n,y,z)={}^{n}C_{z}\,(2^{z-1}-1)({}^{y}C_{2})^{z}$ ……………………………………………………….....[2-2]

Where **n** is the number of criteria, **y** is the number of categories and z is the level of degree. ${}^{n}C_{z}$ is the number of combinations of the **n** criteria taken **z** at a time and ${}^{y}C_{2}$ is the number of combinations of the **y** categories for each criterion taken two at a time (Hansen and Ombler 2008). Table 2-5 shows some undominated pairs for a range of value models adopted from Hansen and Ombler (2008). In Table 2-5, three criteria are used for illustration and each criterion is divided into three categories.

2.9 Swing Technique

Swing is a weighting technique (von Winterfeldt, D., Edwards 1986) that can judge the criteria in a series of driven questions. The decision maker assumes the best and worst hypothetical alternative for each criterion and makes a comparison between them (Balasubramaniam et al. 2007). The first step in the Swing method is to rank the value of each category in each criterion from 0 to 1, where 0 and 1 refer to the worst and the best decisions respectively. The next step is to arrange your alternatives in a table. The alternatives are inserted in each column and row. A dummy alternative "Benchmark" is added to the first row, containing the worst criterion of each category. The highest category of each alternative is included in the alternative's intersection of row and column. The remaining table is filled as the lowest category of each alternative. The decision maker ranks the rows from 0 to 100 and, as the first step, 0 is referred to the lowest score while 100 is referred to the highest. In this case, the benchmark always equals to 0 because it contains the worst category of each criterion. Next is to normalize all the scores to the relevant alternative for obtaining the weight of each factor. Finally, after obtaining the weights, you multiply them by the category value of the first step for achieving the total score for each criterion (Clemen, Robert T., and Terence Reilly 2001).

2.10 Previous Research Work and Models

Researchers have tried so far to develop a criticality model to rate the water distribution network. Wauthier et al. (2013) from Colorado State University have developed an equation to clarify the risk in the water system. The following formula explains the risk:

Risk = Probability of Failure x Consequences of Failure.

This equation consists of two parts:

1- The probability of failure (failure likelihood index)
2- Consequence of failure (criticality index)

The probability of failure is divided into three main factors, age, the number of breaks and service conditions. The age factor indicates the pipe's installation date, the number of breaks indicates the amount of breaks occurring to the pipeline at a particular time and service conditions indicates the degree of threat by other services such as traffic load and soil conditions affecting the pipeline. Out of these factors, the following equation is induced to calculate the probability of failure:

Total likelihood index $= W1 * Wa + W2 * Wb + W3 * Ws$ ……………………………………[2-3]

Where,

W1, W2 and W3 are the weight of each primary factor.

Wa = Likelihood of age

Wb = Likelihood of breaks

Ws= Likelihood of services

The decision maker assigns the weight of each factor in such a way that the total weight always equals 1. The main factors are divided into several attributes and ranked by the decision maker from 0 to 1, where 0 is at the lowest and 1 is at the highest risk. Table1 represents the age factor with different values to be ranked by the decision making expert (Wauthier et al. 2013).

The Consequence of failure is divided into three main parameters: Size, location and the cost of repair. The size parameter is defined as the potential flooding and the water amount that is lost if the pipeline breaks. Location parameter is defined as how critical the locality is, i.e. if the site is near a critical facility such as hospitals, governmental buildings, etc. or near a traffic-congested location such as downtown areas, highways, etc. The repair costs is the total cost for repairing the pipe itself and fixing damages caused by water flooding. Those costs are affected by several attributes such the pipe size, its accessibility, the number of people and the facilities affected by the flooding and the absence of water during the break. From these factors, the following equation is induced to describe the consequence of failure (Wauthier et al. 2013):

Total consequence of failure = W1 * Wcs + W2 * Wcl + W3 * Wcc……………………….[2-4]

Where,

Wcs = Consequence size

Wcl = Consequence location

Wcc= Consequence cost of repair

As it is stated in the preceding section, W1, W2, and W3 indicate the weight of each parameter and the decision maker has to weight each and also to rank the attribute of each of them (Wauthier et al. 2013). Piratla and Ariaratnam (2011) have developed a relative criticality index

(RCI), derived from the sum reliability effects, break repair cost and break repair energy consumption of the water distribution network (Piratla and Ariaratnam 2011). The following equation explains how the relative criticality index has been developed.

RCIj=Rj(x)+Cj(x)+Ej(x)……………………...[2-5]

Where,

x = water distribution system considered in the problem

RCIj= Relative criticality index of the pipeline

Rj(x)= reliability component, unavailability contribution toward the criticality for pipe type j

Cj(x) = cost function contributing toward the criticality for pipe type j

Ej(x) = energy function contributing toward the criticality for pipe type j

Reliability is defined as the probability of an individual element in an infrastructure system to perform its function in a given duration; in other words, it is the ability for non-failure or breakdown (Murray and Grubesic 2007). The cost functions can be defined as the cost of repairing the pipeline over a particular distance. Several models and techniques can be used to evaluate the repair costs and, due the scientific development of dynamic programming, simulation and genetic algorithms are implemented to produce the optimum solution (Piratla and Ariaratnam 2011). Kleiner and Rajani (2001) develop a statistical model to calculate the failure cost, while these methods are divided into deterministic and probabilistic models. Shahata and Zayed (2008) use a simulation called Monte Carleo to create a stochastic life-cost cycle model (SLCC) to make a comparison with the rehabilitation technique and produce the optimum solution. The Energy function is defined as the amount of energy required to fix a pipeline breakage. Water distribution systems are always under pressure and it is has been informed that 90 percent of the total energy cost for some facilities is mainly used for the pumping costs (Lansey et al. 1992). Filion et al.

(2004) develop a model to calculate the amount of energy consumed for repairing a break, by predicting the energy life cycle analysis of a network. Figure 2-10 illustrates the contribution of various pipes' materials towards criticality based on a case study in downtown Phoenix City, Arizona, adopted from Piratla and Ariaratnam (2011).

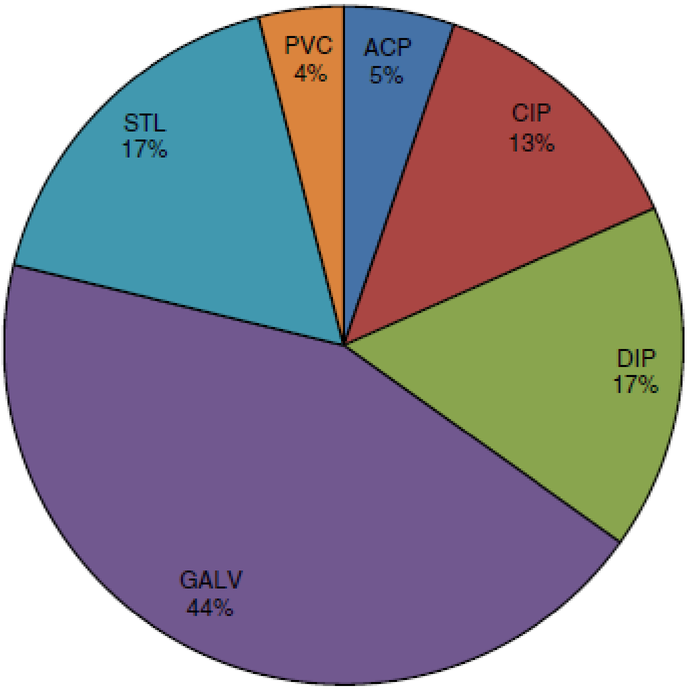


Figure 2-10 Contribution of various pipes towards criticality, adopted from Piratla and Ariaratnam (2011).

Salman (2011) develops a criticality model based on the critical factors of the city of Hamilton (UMA 2007). In this model, he categorizes the city according to the conditions of the land used, i.e. high density of the area and whether it is commercial, industrial or residential. In the next step, he implants AHP technique (Analytical Hierarchy Process) to determine the weight of critical factors and develops the following equation:

$CI_{pipe} = \sum_{i=1}^{n} \sum_{j=1}^{m} Wij \times Ii$……………………………………………………………….[2-6]

Where,

CIpipe: Criticality index of a pipe

Wij: Weight of a critical factor

Ii: Score of a critical factor

n: total category number

m: total factor number in each category

Rahman et al. (2014) develop a condition-based risk assessment model (RF) by the determination of the probability of failure (PF) with its degree of impact (DI) for each individual pipe segment as shown in the following equation:

RF = PF X DI ………………………………………………………………...............................[2-7]

Where,

RF = Risk of failure

PF = Probability of failure

DI = Degree of impact

The PF score is computed through the remaining life of each pipe; this score is affected by the pipe's installation date, the pipe's material type and the previous number of failure, such as the number of breaks, over the past years. Equation 2-8 illustrates the calculation of (RUL) remaining useful of pipe in years.

RUL= (ASL-Age) x P_{adj}…………………………………………………………………….[2-8]

Where,

ASL= Anticipated service life of pipe in years

Age = Current pipe age from date of installation

P_{adj} = Break history adjustment factors.

Table 2-6 illustrates different types of materials used in the manufacture of pipelines. The mean value for each type is taken as the ASL value. Table 2-7 explains the determination of break history adjustment factor.

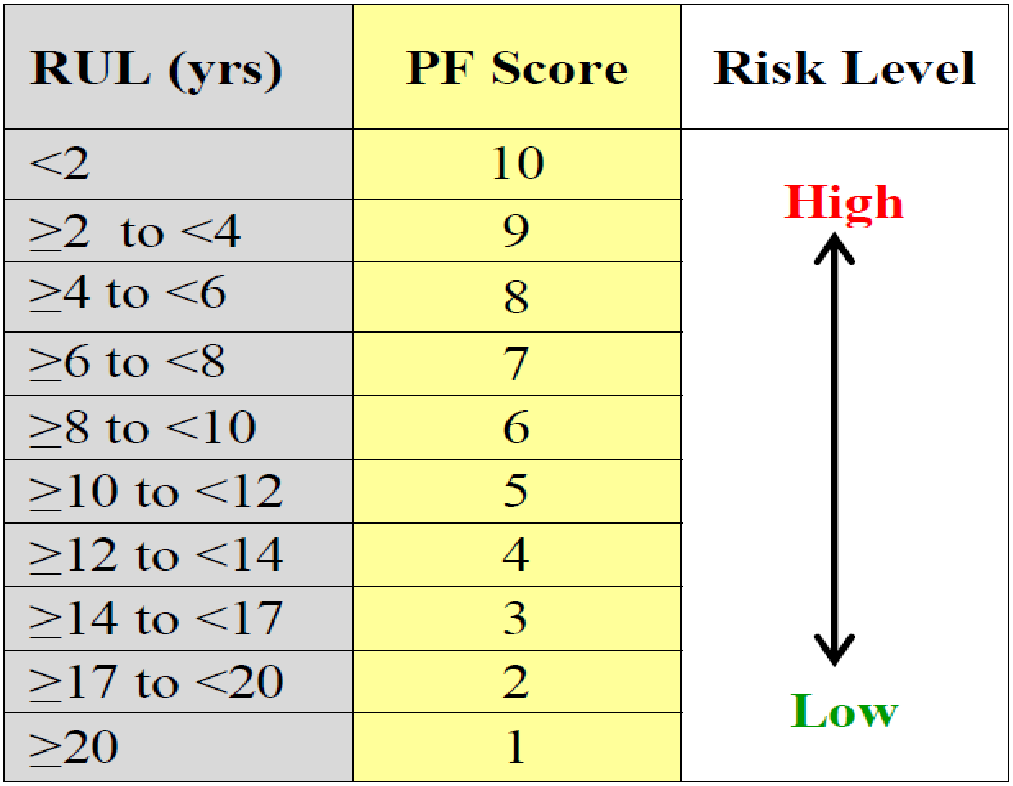
Table 2-6 Pipe material and anticipated service life, adopted from Rahman et al. (2014)

Pipe Material	Manufacturer's Service Life (yrs)	ASL (yrs)
Cast Iron (CI)	50-100	75
Ductile Iron (DI)	75-125	100
Galvanized Iron (GI)	40-60	50
Steel (STL)	30 - 75	50
Polyvinyl Chloride (PVC)	50-150	100
Composite (COMP)	50 -150	50
Asbestos Cement (ACP)	75-125	100

Table 2-7 Break history adjustment factor adopted from Rahman et al. (2014)

Number of Incidents	P_{adj}
0	1
1	0.3
2	0.2
≥3	0.1

Table 2-8 Probability of failure score (PF) adopted from Rahman et al. (2014)



RUL (yrs)	**PF Score**	**Risk Level**
<2	10	**High** ↕ **Low**
≥2 to <4	9	
≥4 to <6	8	
≥6 to <8	7	
≥8 to <10	6	
≥10 to <12	5	
≥12 to <14	4	
≥14 to <17	3	
≥17 to <20	2	
≥20	1	

Once the RUL of the pipe is determined, PF value is identified by matching its value with the RUL as shown in Table 2-8. The second part of the condition-based risk assessment model is the identification of the degree of impact (DI). The DI score varies based on different criteria, but Table 2-9 explains the most important criteria with their relative score. By identifying the two principles of the risk model (RF), the RF is calculated as per equation 2-5. Later, it is matched to the 4-level risk scale to determine the total risk of failure for the referred pipe as shown in Table 2-10 (Rahman et al. 2014).

Table 2-9 Degree of impact score (DI), adopted from Rahman et al. (2014)

Impact Criterion	Impact Score				
	1	2	3	4	5
Service Demand (gpm)	<160	160 to <320	320 to <480	480 to <640	≥640
Consumer Criticality	No critical consumers or pipe size < 8"	At least 1 Critical consumer	2 Critical consumers	3 Critical consumers	4 or more Critical consumers
Land Use	Agriculture or Open Space	Very low to low medium density Residential	Low medium to high density Residential	High to very high density Residential, Village core, or mixed use	Office professional, Commercial or Community Facility
Traffic Impact	Local Streets	Collector Street	Priority 2 Transit	Priority 1 Transit	Arterial Street
Material Phasing	PVC and ACP	Ductile Iron	Steel & Composite	Galvanized Iron	Unlined Cast Iron or unknown material
Estimated Cost for Repair	≤ $26,500	$26,501 - $53,000	$53,001- $80,000	$80,001 - $106,000	>$106,000

Table 2-10 Risk scale for ranges of RF scores, adopted from Rahman et al. (2014)

RF Score	Color	Failure Risk Level
≤ 20	Blue	Very Low
21 - 70	Green	Low
71 - 150	Orange	Medium
≥ 151	Red	High

2.11 Summary and Limitations of Previous Work

This literature review explains the water supply system, including the different types of pipelines, the pipelines' construction material and the liable risks for the pipelines. It also defines asset, risk management and how their principles influence the infrastructure system. Several factors affect the water distribution networks. These factors are grouped into two broad classifications: Criticality and Performance factors. Many researchers so far have identified the performance or the condition of pipelines. However, not a lot of research is allocated so far to the criticality of water distribution. Therefore, this topic is worth more consideration and research efforts; criticality is a subjective matter and to date, no general standard or database has evaluated it. As another limitation of the previous models, they mostly define criticality as a consequence of failure; in this project instead, it is defined as the asset's consequence of failure to perform its function, with the strategic importance of the referred asset, divided into economic, environmental/operational and social aspects.

This study aims to develop a priority assessment model based on the performance and criticality of water pipelines. Three main groups of factors, affecting the criticality of the water distribution network, are identified as follows: (i) Economic, (ii) environmental/operational and (iii) social. The economic factor is defined as the influence of failure on monetary resources and assets, e.g. pipeline diameter, pipeline depth, material and land use. Environmental/operational factors are described as the influence of failure on the environment and operational ability, e.g. operating pressure, water body proximity, buried assets proximity and soil type. The social factor is defined as the influence of failure on society, e.g. alternative routes, daily traffic, road types and nearby facilities.

“PAPRIKA and SWING” methods are the weighting techniques used to determine the weights of each criticality sub-factor. After identifying all the weights, they are inserted in the criticality model to estimate the criticality index. The criticality index is combined with the performance index to induce the priority index. The priority index serves municipalities as a guideline in their maintenance and rehabilitations plans.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Overview

This section explains the objective and methodology of criticality model. Figure 3-1 shows the model development flow chart. The model consists of consecutive steps, i.e. literature review to identify the criticality factors, data collection, Paprika and Swing implementation to determine the weights of each factor, sensitivity analysis of the factors, criticality and priority index development and conclusion and recommendation.

3.2 Literature Review

Literature review is discussed thoroughly in Chapter Two. A summary of what is discussed is as follows: Section 2-2 provides a definition of water supply distribution networks, covering the components, types and the pipeline material used in the water main systems. Section 2-3 gives an overview of asset management. Section 2-4 is on risk management and its process. Section 2-5 discusses the criticality of pipelines. It describes the critical term assets and explains the important factors affecting the criticality of water distribution network. Section 2-6 defines the performance of water distribution networks and the deterioration factors that affect the condition of water pipelines. Section 2-7 illustrates El Chanati performance factors and performance index. Section 2-8 and Section 2-9 explain the Paprika and Swing methods respectively. These methods are used in the development of criticality models, to determine the weight of the criticality factors of water distribution networks. Section 2-10 provides an overview of previous research on the evaluation of water disruption networks.

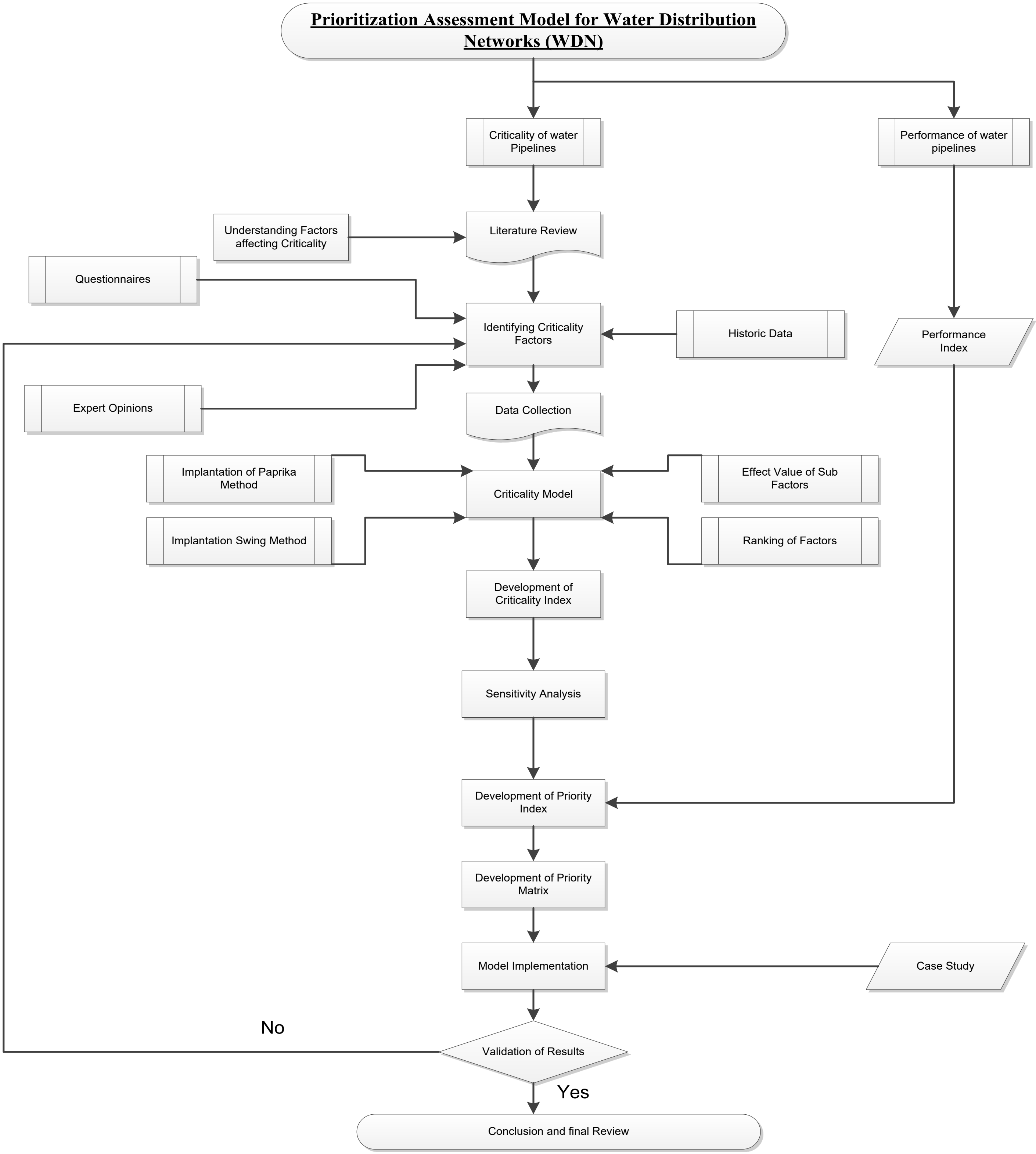


Figure 3-1 Research flow chart.

3.3 Factors Identification

Section 2-5 discusses an extensive overview of all criticality factors that affect the water distribution networks. Based on these factors, expert's opinions and Salman (2011) model a new criticality factor has been developed. The newly developed criticality factors are categorized into three main factors as it is illustrated in Figure 3.2. The main factors are economic, environmental/operational and social factors.

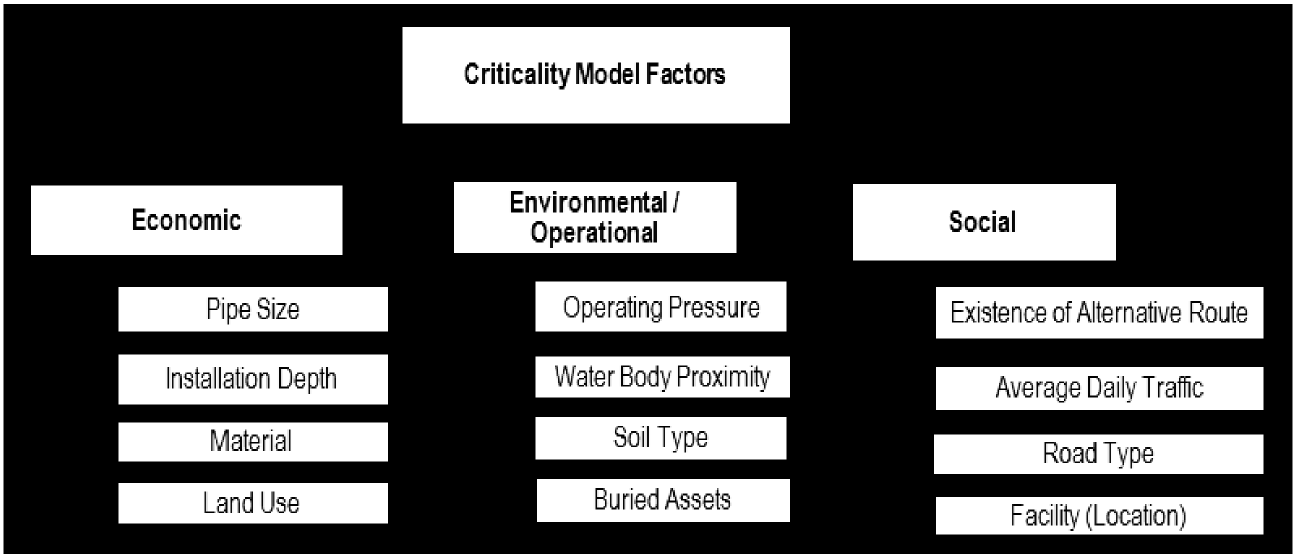


Figure 3-2 Criticality factors of water distribution networks.

Table 3-2 explains the description of criticality subfactors and their respective attribute values. Each main factor is divided into four subfactors which is allisturated in the following paragraph; The economic factor includes pipeline diameter, pipeline depth, material and land use.

- Pipeline Diameter: The consequences of failure on the water main are directly proportional to its size, due to an increase in repair cost. The pipline diameter can be identified from large to small.

- Pipeline Depth: The consequences of failure on the water main are directly proportional to its depth, due to an increase in repair cost. The pipeline depth is identified from deep to shallow.
- Material: Repair cost of water main depends on its type of manufacturing material. The pipeline can be manufactured from different materials, such as concrete, iron, PVC,…etc.
- Land Use: Without proper consideration towards various land uses during a pipeline repair, municipalities could suffer financial losses, project delays, and interruptions in daily operations. The land use can be classified as residential, industrial/commercial and high density area.

The environmental / operational factors include operating pressure, water body proximity, buried assets proximity, and soil type.

- Operating Pressure: The consequences of failure on the water main are directly proportional to its pressure. The pipeline pressure can be evaluated from high to low pressure.
- Water Body Proximity: Failure consequences of water main are gradually increased when it is located close to surface water, such as a lake or a river. The failure may cause sediment transport. This process will affect the nearby foundations and the beds of the canals.
- Buried Assets Proximity: Pipelines close to buried infrastructure (e.g. gas pipelines, electric cables) are more prone to failure thus are highly critical.
- Soil Type: Pipelines surrounded to high permeability soil, or lower density soil will cause more damages rather than other types of soil. Soil can be formed from different materials such as rock, clay, sand,…etc.

The social factor involves the existence of alternative route, Average daily traffic, road type and nearby facility.

- Existence of Alternative Route: Failure consequences of water main are considered huge due to public disruption when it has no alternative.
- Average Daily Traffic: A pipe repair operation may have detrimental effects on busy routes, which would cause indefinite delays for commuters and businesses. The average daily traffic can be evaluated from high to low value.
- Road Type: The consequences of a failed water main depend on its road location due to public disruption. Pipes that are located under an expressway, highway, or major urban roads have large impacts in comparison to other roads. The road type is classified into rural, urban and interstate areas.
- Nearby Facilities: Failure consequences of water main are considered huge when it is located near a critical location, such as a hospital, governmental building…etc.

After identifying all criticality factors that affect water distribution networks, a questionnaire is made to determine the degree of importance for each subfactor and their relationship to its main factor. A detailed overview of questioner development and data collection is explained in chapter four.

Table 3-1 Criticality subfactors description.

Main Factor	Sub-factors	Description	Attributes
Economic	Pipeline Diameter	The consequences of failure on the water main are directly proportional to its size, due to an increase in repair cost	a)Large b)Medium c)Small
	Pipeline Depth	The consequences of failure on the water main are directly proportional to its size, due to an increase in repair cost	a)Shallow b)Medium c)Deep
	Material	Repair cost of water main depends on its type of manufacturing material	a)Steel b)Concrete c)PVC d)Poly Ethylene e)Iron f)Copper
	Land Use	Without proper consideration towards various land uses during a pipeline repair, municipalities could suffer financial losses, project delays, and interruptions in daily operations.	a)Residential b)Industrial/Commercial c)High Density
Environmental/	Operating Pressure	The consequences of failure on the water main are directly proportional to its pressure.	a)High b)Medium c)Low
	Water Body Proximity	Failure consequences of water main are gradually increased when it is located close to surface water, such as a lake or a river.	a)Yes b)No
	Buried Assets Proximity	Pipelines close to buried infrastructure (e.g. gas pipelines, electric cables) are more prone to failure thus are highly critical.	a)Yes b)No
	Soil Type	Pipelines surrounded to high permeability soil, or lower density soil will cause more damages rather than other types of soil.	a)Clay b)Rock c)Silt d)Sand
Social	Existence of Alternative Route	Failure consequences of water main are considered huge due to public disruption when it has no alternative.	a)Yes b)No
	Average Daily Traffic	A pipe repair operation may have detrimental effects on busy routes, which would cause indefinite delays for commuters and businesses.	a)High b)Medium c)Low
	Road Type	The consequences of a failed water main depend on its road location due to public disruption. Pipes that are located under an expressway, highway, or major urban roads have large impacts in comparison to other roads.	a)Local b)Urban c)Interstate
	Nearby Facilities	Failure consequences of water main are considered huge when it is located near a critical location, such as a hospital	a)Yes b)No

3.4 Model Development

Upon the collection of questionnaires, the expert opinion is analyzed and incorporated into the multiple criteria methods to estimate the weight of each criticality factor and its subfactors. The following articles explain the analysis of the two approaches:

3.2.1 Paprika Method and the 1000Minds Software

For a small number of criteria, it is very easy to make a pairwise comparison while it is difficult to solve the pairwise comparison for a large number of criteria. Franz Omber and Paul Hansen (2008) address this issue by developing a decision-making software named "1000 Minds". 1000Minds ranks, prioritizes and compares alternatives in such a way that the criteria for each option are compared against others in a simultaneous method (1000Minds Software).

To use the software, the category in each criterion is first arranged based on the decision maker's opinion from the lowest to the highest rank. In this research, the criteria are the main criticality factors while the categories are the subfactors. Figure 3-3 shows the criteria view in 1000Minds. The economic factor is labeled as a criterion while its subfactors are ranked from the lowest to the highest rank.

Economic Factors

Dummy Economic

Pipeline Depth

Material

Pipeline Diameter

Land Use

Model: Criticality Main Factors – Q10

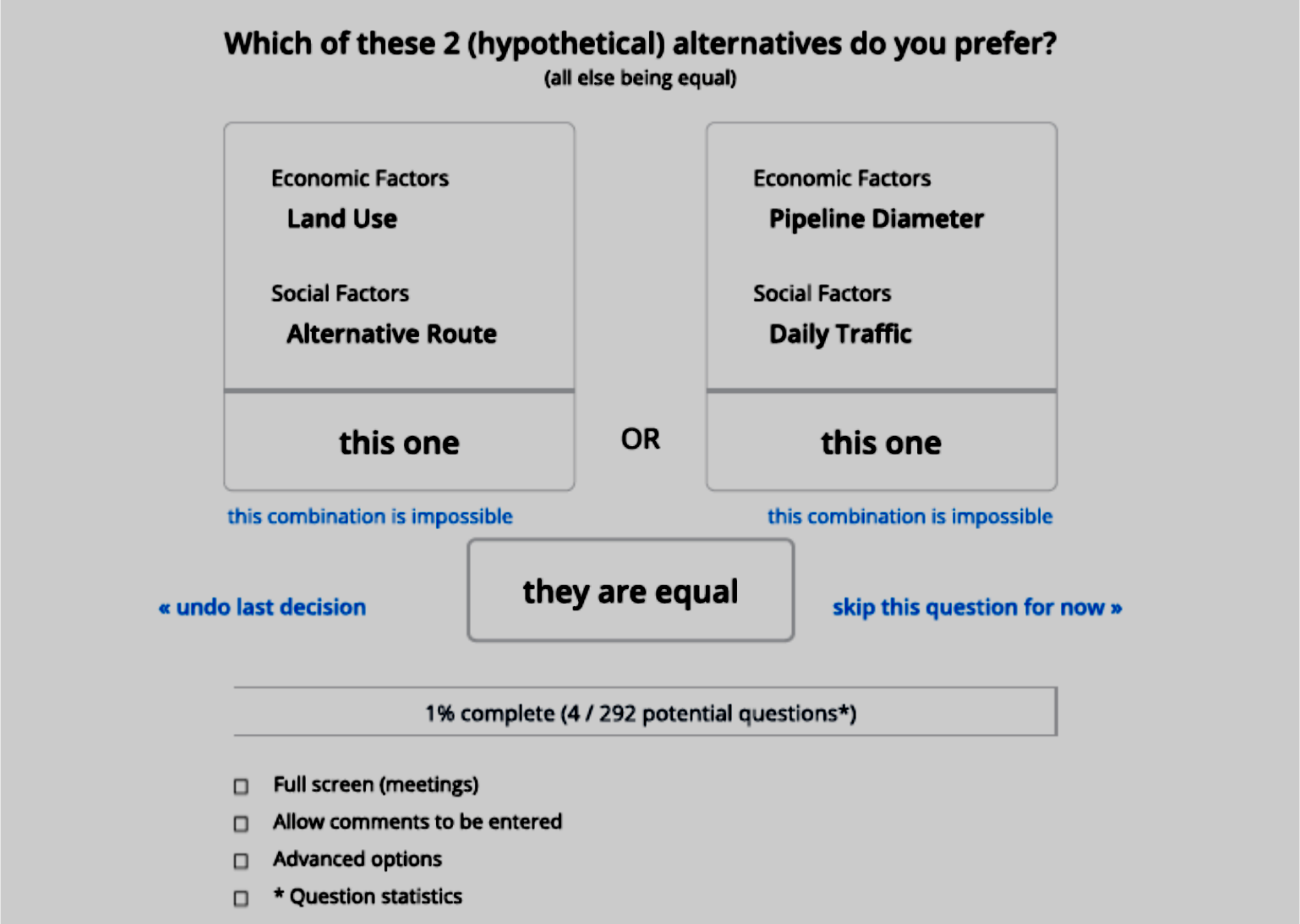
Criteria

Enter the **criteria** that matter – and make sure you enter the **levels** within each criterion down the page from **lowest** to **highest ranked**.

When entering levels for each criterion, it's essential that you enter the levels down the page from **lowest** to **highest ranked**. Otherwise the trade-off questions at the **decisions** step won't make sense.

Figure 3-3 Criteria view in 1000Minds Software adopted from 1000Minds Software

After the ranking process is completed, the decision maker proceeds to the decision phase. In this phase, two categories from a different criterion are integrated to the left-hand side (L.H.S) and another two categories from a different criterion are integrated to the right-hand side (R.H.S), as shown in Figure 3-4.



Which of these 2 (hypothetical) alternatives do you prefer?
(all else being equal)

Economic Factors: Land Use
Social Factors: Alternative Route

Economic Factors: Pipeline Diameter
Social Factors: Daily Traffic

1% complete (4 / 292 potential questions*)

Figure 3-4 Decision phase in 1000Minds Software adopted from 1000Minds Software

The decision maker has to choose between the right-hand side and the left-hand side or to choose that both criteria on both sides are equal in his point of view. When the decision is applied, the program jumps to another decision with different categories until all the undominated pairs in each level of the model are finished. As its main advantage, 1000Minds program saves the decision maker a lot of time by calculating itself the dominate and replicas criteria after each decision is made. After running the program for the full criteria, the weights are developed and the main factors are ranked in accordance with criticality. Also, another advantage of using the 1000Minds Software is the verity of the output data. Figure 3.5 shows a radar chart and criterion value function chart for an output example of the 1000Minds Software. As shown in this figure, the physical factors and the environmental factors have the highest and the lowest weights respectively.

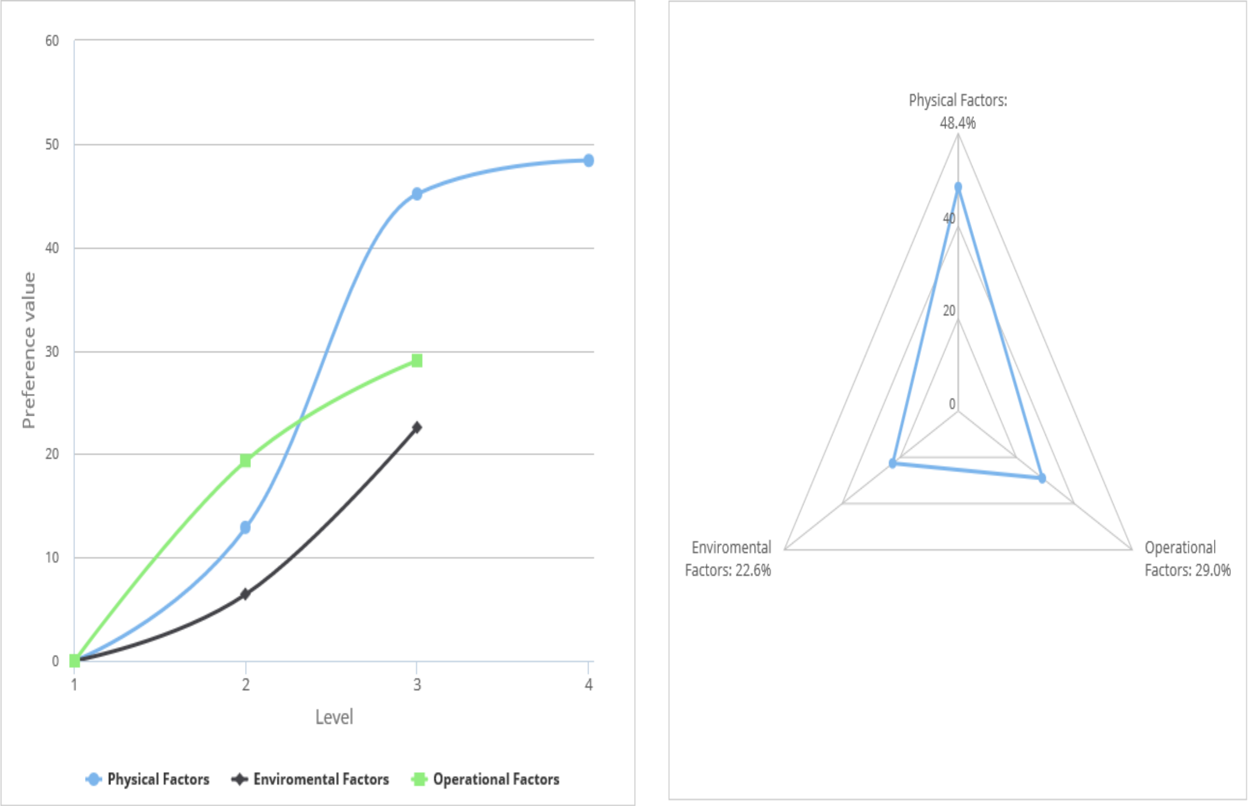


Figure 3-5 Radar and criterion value function charts adopted from 1000Minds Software

The 1000Minds outputs the weight of each alternative in a normalized criterion table. Table 3-2 shows the normalized criterion weights and single criterion scores of a provide example run by 1000 minds software. In Table 3-2, the physical factors are the dominant factors among the other criticality main factors and “Water Main Age” has the highest influence on criticality among the subfactors. In other hands, the environmental factors have the smallest impact on the criticality.

Table 3-2 Normalized criterion weights and single criterion scores adopted from 1000Minds Software

Criterion	**Criterion weight (sum to 1)**	**Level**	**Single criterion score (0-100)**
Physical Factors	0.484	Water Mains Material	0
		Water Main Size	26.7
		Installation Quality	93.3
		Water Main Age	100
Environmental Factors	0.226	Soil Type	0
		Location	28.6
		Ground Water	100
Operational Factors	0.29	C-Factor	0
		Water Quality	66.7
		Leakage Rate	100

3.2.2 Swing Method

Similar the first step in Paprika, the decision maker has to rank the categories from each criterion from 0 to 1. The most and the least favorable categories receive 1 and 0 respectively. The next step is to construct the Swing table and insert the main factors and subfactors of water criticality in it according to Section 2-5. Table 3-3 illustrates the criticality factors entering a Swing table based on the collected data.

Table 3-3 Criticality factors inserted into the Swing table

	Economic	**Environmental**	**Social**	**Rank**	**Value**	**Score/100**	**weight**
Benchmark	Pipeline Depth	Water Body Proximity	Daily Traffic	4	19	0.00	0.00
Economic	Pipeline Diameter	Water Body Proximity	Daily Traffic	3	27	11.76	0.07
Environmental	Pipeline Depth	Operating Pressure	Daily Traffic	2	59	58.82	0.34
Social	Pipeline Depth	Water Body Proximity	Road Type	1	87	100.00	0.59
	Total Value					170.58	1.00

In the Swing technique, a benchmark row is inserted into the table, containing the lowest attribute value in each main factor, as shown in Table 3-3. The decision maker once again ranks each row from 0 to 100, where 0 indicates the least important while 100 indicates the most important combination of categories. Each row is then evaluated and normalized to determine the weight of each criterion.

3.5 Developing the Criticality Index

According to Keeney and Raiffa (1976), multi-attribute value analysis generates an overall value for each alternative. This total value is obtained by the summation weight of each attribute multiplied by its attribute value (Pöyhönen and Hämäläinen 2001). Formula 3-1 shows the full value of V(x):

$V(x) = \sum_1^n Wi\ Vi(xi)$ …………………………………………………………………... [3-1]

Where

xi : The consequence of an alternative x for attribute *i* (*i*=1,…n)

Vi : The value of the consequence

Wi : The weight of the attribute *i*

The weight of each criticality subfactors was estimated in Chapter Two and the effect value of each subfactor is obtained from the expert opinion in Chapter Four.

To calculate the criticality index, a model is developed based on the previous multi-attribute equation and Salman (2011) criticality equation. The criticality index formula 3-2 is illustrated as follows:

$CI_{pipe} = \sum_{1}^{n} Wi \ x \ Ei$ ……………………………………………………………… [3-2]

Where,

CIpipe: Criticality index of a pipe

n: Total number of subfactors.

Wi: Weight of each subfactor

Ei: Effect value for each attribute of subfactors

The criticality index represents the criticality of water pipelines on an area-specific basis. The criticality index value is assessed from 0 to 10, where 10 and 0 indicate the highest and the lowest criticality respectively.

3.6 Criticality Index Scale

Upon knowing the pipeline criticality index, it is important to develop a scale to rank the proposed location according to criticality and to identify the failure consequence magnitude. Currently, a few research have developed a scale for water asset criticality. Strategic asset management of Sydney water (2010) developed a new severity scale illustrated in Table 3-4. This scale is divided into five main levels: Catastrophic, Critical, Moderate, Marginal and Minor. Each of these levels describes the actual status of the asset. The failure consequence is also identified in Table 3-4, where the total production loss, the effect of consequence on people and the total influence on the enterprise or plant are identified.

Table 3-4 Severity ranking according to Sydney water strategic asset management (2010)

Severity	Asset / Maintainable Unit	System / mission	People	Enterprise
5 CATASTROPHIC	Definite or presumed destruction or degradation of other functional Asset / Maintainable Unit	Complete loss of capability	Loss of life	Major plant and production loss Enterprise survival doubtful
4 CRITICAL	Complete failure of or damage to functional Asset / Maintainable Unit under consideration	40 % to 80 % loss of capability	Severe injury and long term damage	Moderate plant and production loss
3 MODERATE	Important degradation of functional Asset / Maintainable Unit under consideration or substantial increase in operator workload	10 % to 40 % loss of capability	Moderate injury with full recovery	Significant production loss
2 MARGINAL	Minor degradation of functional Asset / Maintainable Unit under consideration	Less than 10 % loss of capability	Moderate injury with full recovery	Minor production loss
1 MINOR	Negligible effect on performance of functional Asset / Maintainable Unit under consideration	No or negligible effect on success	No injury	No or negligible production loss

The newly developed criticality has five zones, each describing the criticality of the surroundings and the failure consequence if it occurs. The zones are scaled and ranged from 0 to 10, where 0 and 10 indicate the situations with the highest and the lowest criticality respectively, as shown in Table 3-5.

Table 3-5 Proposed criticality index scale

Scale	Category	Criticality “Consequence of failure.”
0-3	Non-Critical	Very low damages to the surrounding if asset fails, very low maintenance priority.
3-5	Fair	Low damages to the surrounding if asset fails, low maintenance priority.
5-7	Moderate	Moderate damages to the surrounding if asset fails, medium maintenance priority.
7-9	Critical	High damages to the surrounding if asset fails, high maintenance priority.
9-10	Very Critical	Catastrophic effect happened if asset fails, immediate maintenance priority

3.7 Performance Rating Scale

Infrastructure Asset Grading Guidelines (1999) develop a grade performance scale for water pipes, as shown in Table 3-6. The scale is ranged from 0 to 5, where grade 0 means the pipe’s performance is very good, with no evidence of defects or problems. However, grade 5 means the pipe performance is very poor and the pipe cannot function properly.

Table 3-6 Performance grade scale for water pipes adopted from Infrastructure Asset Grading Guidelines (1999)

Performance Grade	General Meaning
1	**Very Good** Smooth bored mains, not subject to degradation with sound factory applied linings; no measurable deterioration in the pipe bore; no performance problems.
2	**Good** As grade 1 but with loose deposits noticeable under abnormal flow conditions or slight deterioration of internal bore but with no significant reduction in cross sectional area; occasional flushing and/or scouring required to maintain adequate water quality, but with no significant effect on performance.
3	**Moderate** Some problems with loose deposits or deterioration of linings or water quality (resulting from the pipework system configuration or pipe wall deposits) leading to occasional complaints or inadequate design capacity for occasional peak demands or some deterioration of internal bore. Regular flushing or air scouring, required.
4	**Poor** Frequent problems with loose deposits or deterioration of linings or water quality (resulting from the pipework system configuration or pipe wall deposits) leading to regular complaints or inadequate design capacity for regular peak demands or some deterioration of internal bore. Regular flushing or air scouring required.
5	**Very Poor** Severe problems with deposits, deterioration of linings or water quality resulting from the pipework system configuration or pipe wall deposits. Water quality cannot be assured or inadequate design capacity for average flows or significant deterioration of internal bore.

Al Barqawi (2006) has developed a new condition scale for water networks to identify the pipelines' status and condition. The scale is between 0 and 10, indicating the conditions of "excellent" to "critical" respectively, as shown in Table 3-7. This scale can serve municipalities to choose the proper action based on the pipelines' condition.

Table 3-7 Al Barqawi condition rating scale (2006)

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

By studying the previous tables, a new performance scale is developed to establish the priority index and priority matrix. As shown in Table 3-8, the newly developed performance scale has five zones and each zone describes the pipe's performance. The performance scale ranges from 0 to 10, where 0 indicates the pipeline is in a perfect condition while 10 indicates the pipeline is in a severe condition and immediate action is required to restore the pipeline's performance.

Table 3-8 Proposed performance index scale

Scale	Category	Performance of the pipe
0-1	Excellent	The pipe can execute its function without any defects.
1-3	Good	The performance of the pipe is good with minor leakages.
3-5	Moderate	Average performance of the pipe with occurrence of some problems and complaints. Maintenance is required to increase the efficiency of the pipe.
5-7	Poor	Frequently problems occur to the pipe and its workability is low. Urgent maintenance is required to assume the pipe workability.
7-10	Severe	The pipe's functionality is unacceptable, immediate maintenance or replacement of the pipe is required

3.8 Priority Index and Matrix

The main purpose of prioritization is to identify where to assign the available resources in a damaged system for the most beneficial results. These resource can be explained as inspection, maintenance and rehabilitation process to the referred system (Nesbit 2007). To prioritize the available resources, there are a number of steps to follow, adopted from Nesbit (2007), as shown in Figure 3-6:

1. Identifying the criticality and performance factors: To understand all the factors that affect criticality and performance of water distribution networks. Sections 2-5 and 2-6 explain the indicated factors respectively.
2. Data collection: To study the actual status of water distribution network, e.g. the pipe's age, the network's location, material type, etc.
3. Calculating the criticality and performance indexes: To estimate the criticality and performance indexes of the pipeline.
4. Developing the priority index: When the main components of priority index are calculated, it is easy to prioritize the available resources and create a rehabilitation plan for the damaged asset.

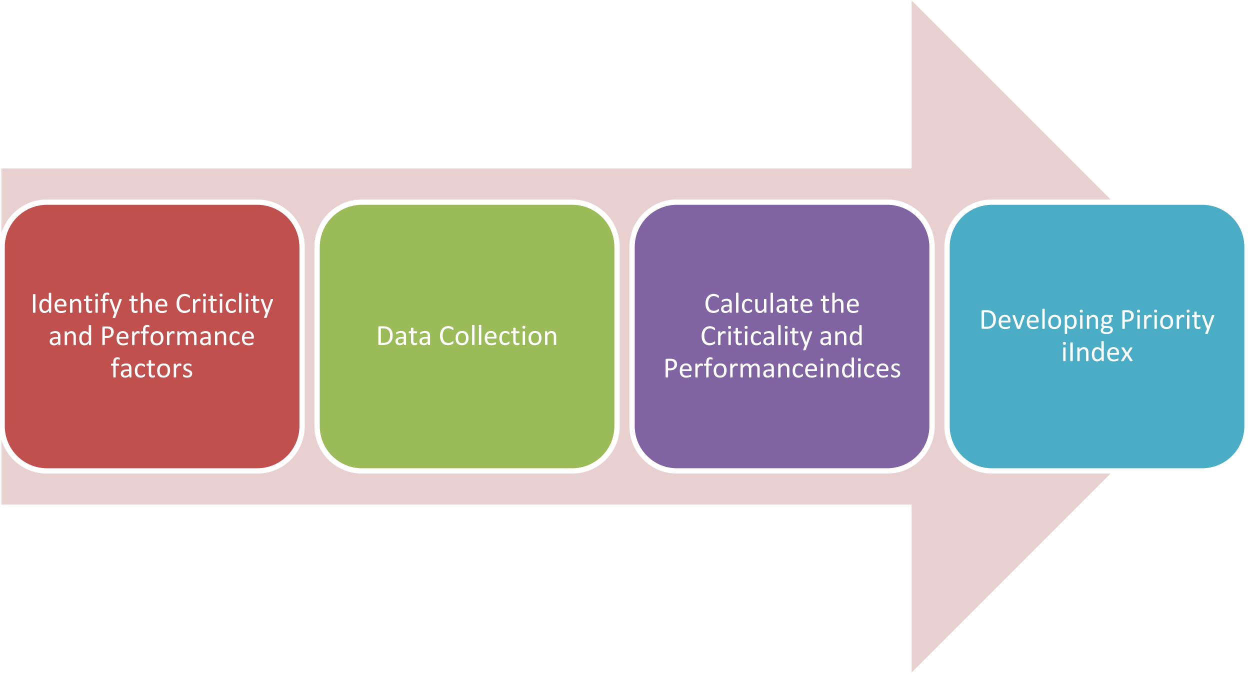


Figure 3-6 Prioritization process (Nesbit 2007)

The priority index can be estimated by using the equation 3-3:

$$P(i) = (Cri + Poi) / 2 \quad [3\text{-}3]$$

where,

P(i)= priority index of water pipe

Cri= criticality index of water pipe

Poi= performance index of water pipe

The priority index can be evaluated through utilizing the proposed priority scale or by illustration in a priority matrix similar to the risk matrix concept. Figure 3-7 shows the proposed priority scale, from 0 to 10, with 0 indicating the lowest priority and 10 indicating the highest priority when an immediate action is required to decrease the referred asset priority to an acceptable level by the best suitable rehabilitation method.

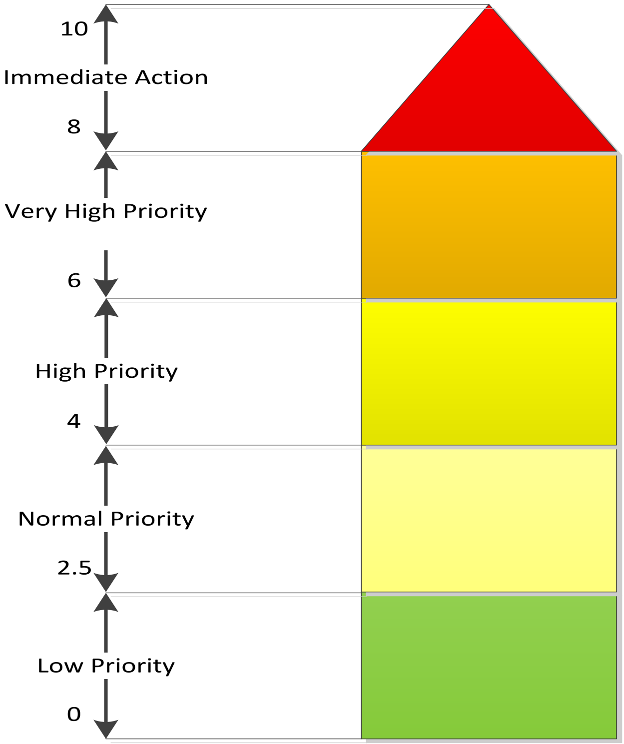
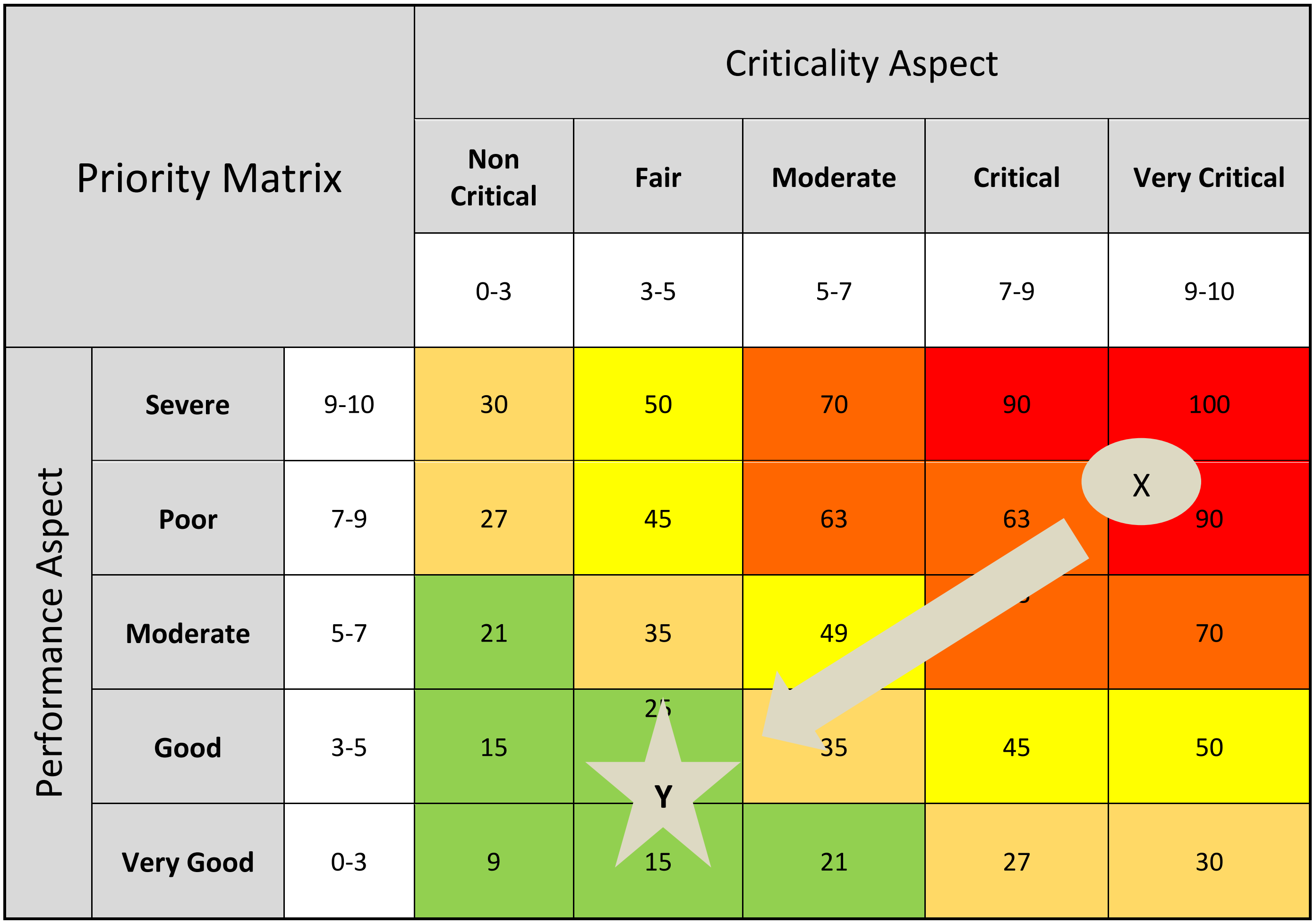


Figure 3-7 Proposed priority scale

Table 3-9 illustrates a proposed risk matrix diagram. The rows signifies the criticality aspect while columns signifies the performance aspect. The matrix is highlighted in various colors for more clarity, where red represents the highest priority and green represents the lowest priority. This matrix aims to assign the referred asset in the priority matrix (e.g. it is positioned at “x” in this scenario as shown in

the matrix) and to take all the necessary actions to decrease its priority index to position “y”, for instance.

Table 3-9 Proposed priority matrix



Priority Matrix			Criticality Aspect				
			Non Critical	**Fair**	**Moderate**	**Critical**	**Very Critical**
			0-3	3-5	5-7	7-9	9-10
Performance Aspect	**Severe**	9-10	30	50	70	90	100
	Poor	7-9	27	45	63	63	90
	Moderate	5-7	21	35	49	[illegible]	70
	Good	3-5	15	25	35	45	50
	Very Good	0-3	9	15	21	27	30

CHAPTER FOUR

DATA COLLECTION

This chapter explains the data collection method and the two types of collected data. The first type of data is collected for the identification of the criticality factors and their effect value through detailed questionnaires. The second type of data is obtained from Strategic Management Department of Water Networks in Montreal, Canada to implant the priority model in a real-life scenario. The data is collected through personal meetings, emails, online chats and printed forms. These data collection methods are designed for the opinion and judgment of the experts about the criticality factors. The following section explains the methods and techniques used in the data collection process.

4.1 Questionnaire Development

In order to develop a priority index model for water distribution network, a set of data is required. Accordingly, questionnaires are developed for collectiong expert opinion to calculate the criticality index. The questionnaire survey is conducted and supervised under Concordia University (Montreal, Canada) and Qatar University (Doha, Qatar). A digital and off-line survey is distributed among different experts and engineers working in water analysis systems and pipeline network management.

Fifteen sets of responded surveys are received from Qatar. The written responds were scanned and sent through emails. Online chats are sometimes used for data clarification and supplementary inquiries. Qatar's data is chosen as a part of this thesis, due to the mutual funding and collaboration between Concordia University and Qatar University in the field of research. An online survey is another method to distribute the criticality questionnaires. Nearly three hundred questionnaires are sent to water system experts across the world for their opinion. A total number of eighteen responses are collected from the experts. Only three questionnaires are rejected due to missing or incomplete data. The other fifteen surveys are responded by experts from Europe and North America. Figure 4-1 shows the number of acceptable questionnaires to their total number.

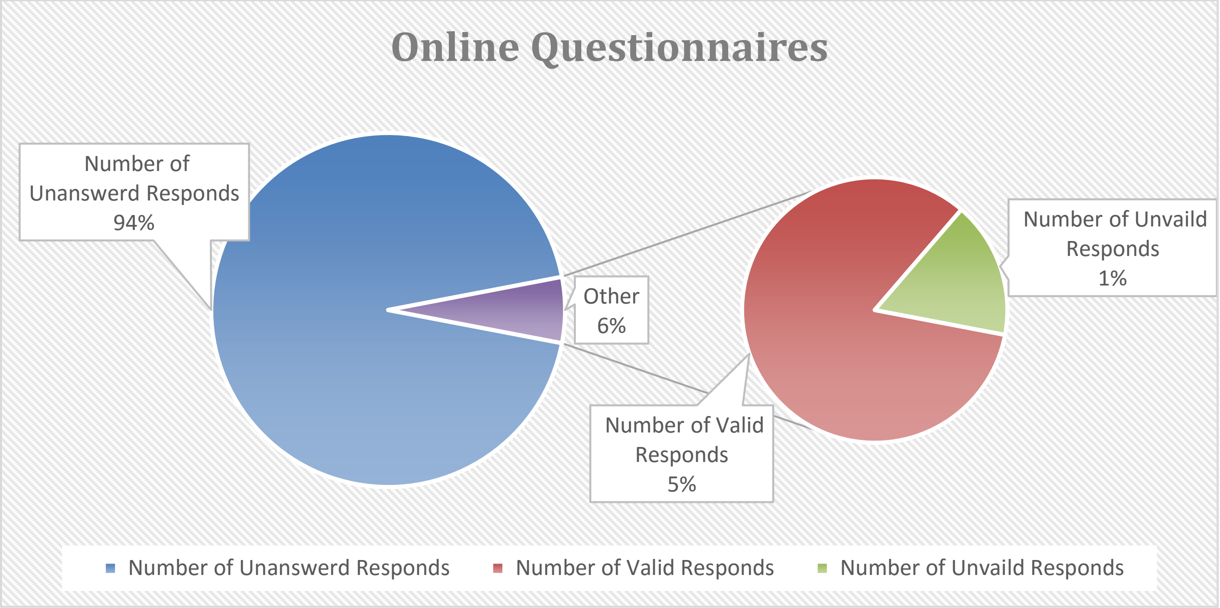


Figure 4-1 Online Questionnaires Status

4.1.1 Data Analysais

Most of the experts participating in this survey are pipeline engineers, planning engineers, material engineers and maintenance engineers. Figure 4-2 and Figure 4-3 display the number of responded questionnaires based on their years of experience. Figure 4-2 shows the number of responses received from Qatar University and Figure 4-3 shows those from Europe and North America. The questionnaire consists of two parts, each with a specific task described in the following articles.

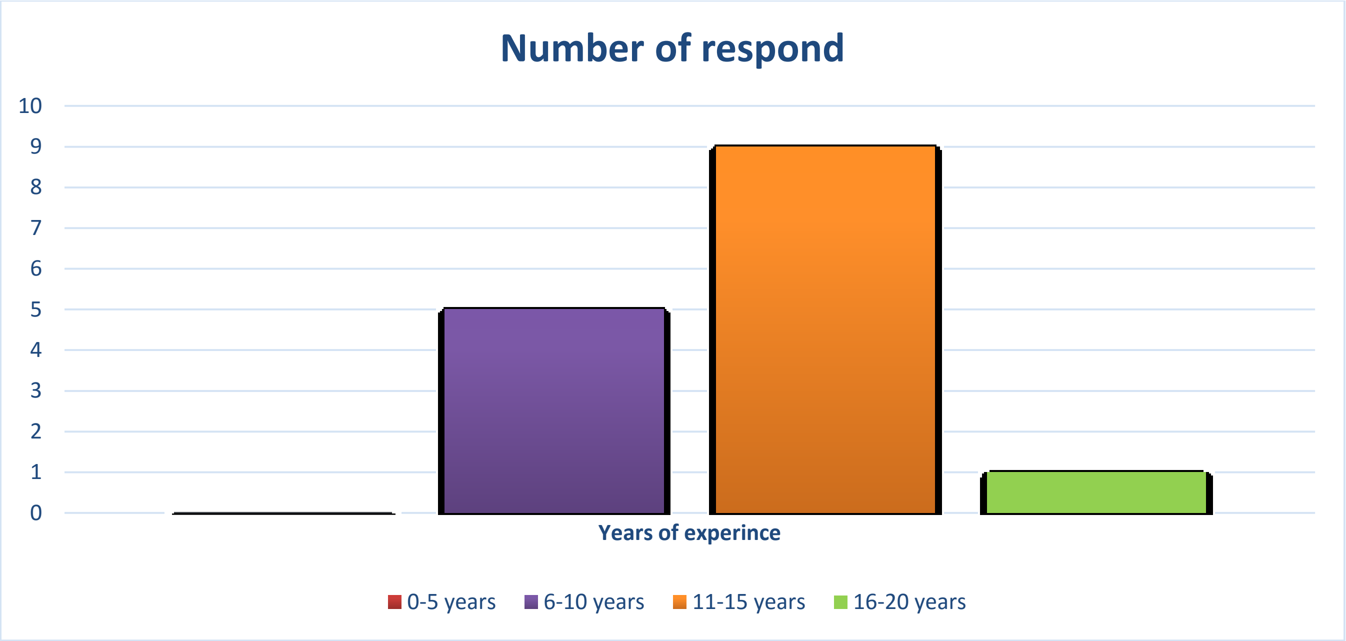


Figure 4-2 Number of responds received from Qatar

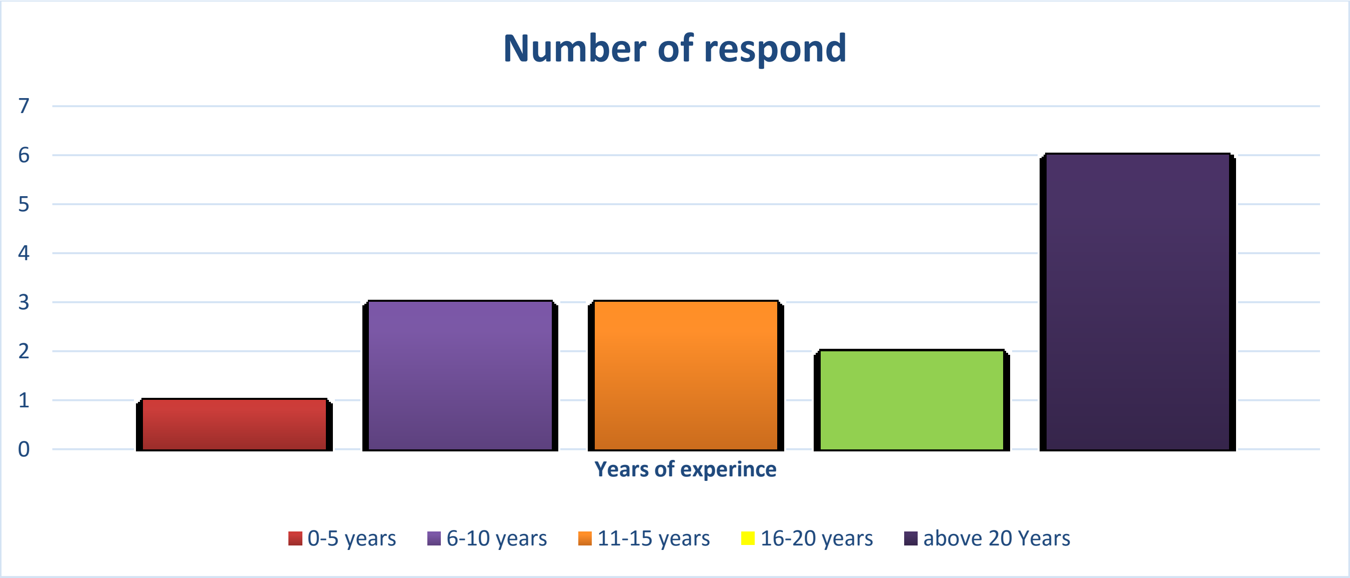


Figure 4-3 Number of responds received from Europe and North America

As another classification, the expert opinion is categorized based on the responders' profession. Here, the experts are categorized into three main groups: Group A for experts in the construction sites (e.g. civil engineers, pipeline engineers and maintenance engineers); Group B for experts in the planning, designing and management areas (e.g. planning engineers, designers and consultants); Group C for experts in the educational field (e.g. professors, lecturers and researchers). According to the responses from Qatar, 10 experts are classified into Group A and 5 experts are categorized into Group B. Based on the reviewed results, thirteen experts have chosen the Social main factor as dominant among the criticality factors. Meanwhile, the other two experts have selected the Environmental/Operational factor as the overwhelming factor among the criticality factors.

However, the online survey presents results different from those obtained from the Qatar responses. In the online survey, experts are evenly put into groups, each containing five responses. Group A experts have chosen the Economic factor as most influencing the criticality. The same results are also obtained from Group B, the experts selecting the Economic factor as the main dominant factor among others. Finally, Group C has similarly chosen the Economic factor as the most important among the other criticality factors. Figure 4-4 shows the dominant criticality factors based on the online survey results. Upon sorting and analyzing the collected data, it is concluded that the Social factor is the most preferable one among the Qatar experts. On the other hand, the experts from Europe and North America have selected the Economic factor as the most influential for the water distribution network criticality.

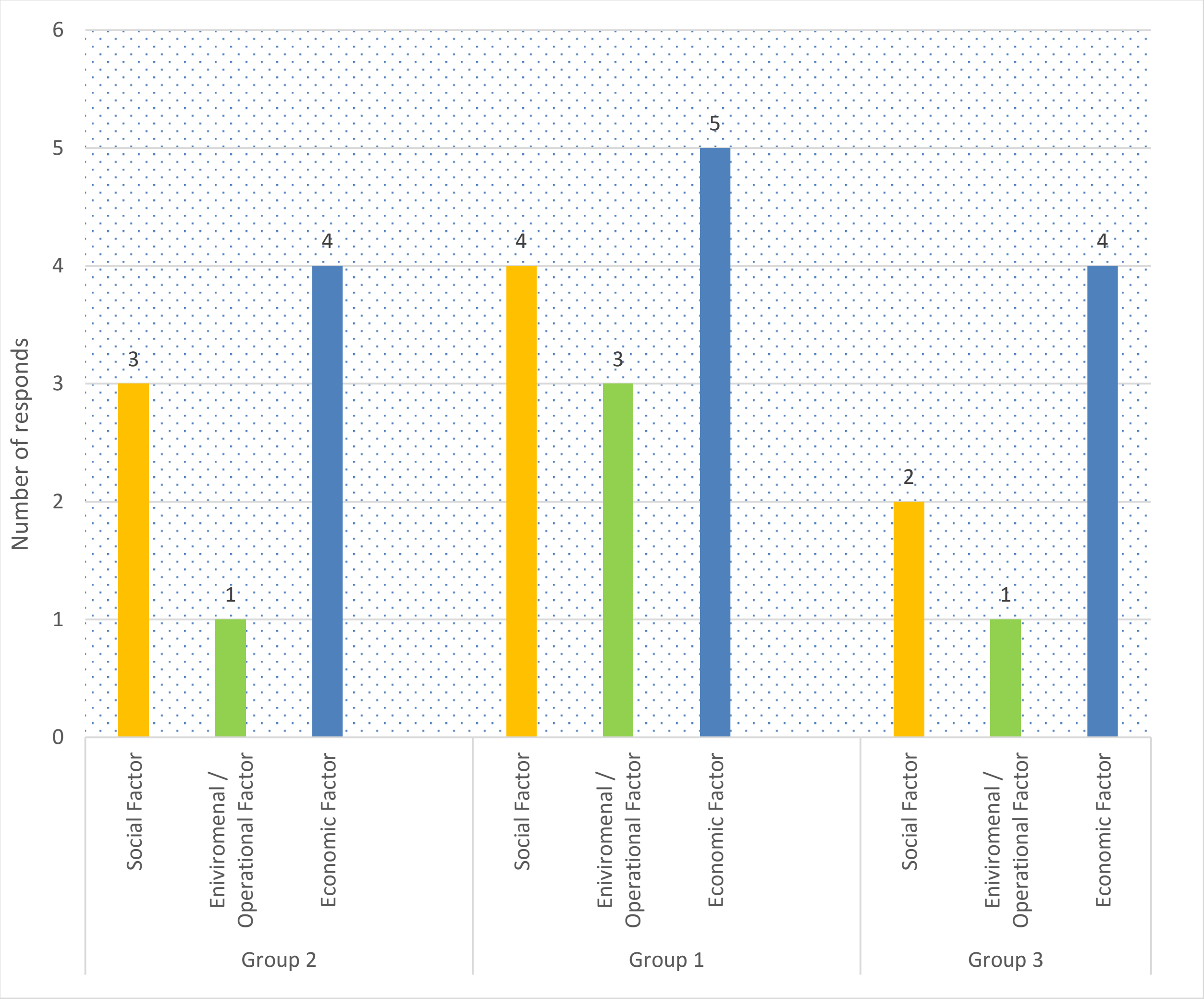


Figure 4-4 Criticality dominant factors from Europe and North America

4.1.2 Importance of Main factors for Criticality

The first part of the questionnaire represents the importance of the main factors for the total criticality of the possible failures of water pipelines from 1 to 10, where 1 and 10 indicate the least and the most factors respectively. Table 4-1 shows the importance of main factors for the criticality of water distribution networks.

Table 4-1 Importance of main factors to WDN criticality

Total criticality of pipe failure	**Main Factors**	**Importance with respect to total criticality (1-10)**
	Economic	
	Environmental	
	Social	

4.1.3 Importance of Subfactors to the Main factors

The second part of the questionnaire consists of several tasks. The first task represents the importance of each subfactor to the referred main factors from 1 to 10, where 1 and 10 inidcate the least and the most important factors respectively. Table 4-2 shows the importance of criticality subfactors to the main factor. In the second part, the expert fills the quantitative values for each subfactor's attribute. For instance, to evaluate the pipeline size from large to small, the expert must put a range (in inches or millimeters) to determine the value of each level. Table 4-3 shows various ranges for water pipeline size based on expert opinion.

Table 4-2 Importance of criticality subfactors to the main factor

Main Factor	**Sub-factors**	**Unit of Measure**	**Importance with respect to main factor (1-10)**	**Qualitative Description (Parameters)**	**Quantitative Value Range**	**Effect Value On Pipeline Condition (0 – 10)**
Economic	Pipeline Diameter	(Inches)		Large	( ) to ( )	( ) to ( )
				Medium	( ) to ( )	( ) to ( )
				Small	( ) to ( )	( ) to ( )
	Pipeline Depth	(Meters)		Shallow	( ) to ( )	( ) to ( )
				Medium	( ) to ( )	( ) to ( )
				Deep	( ) to ( )	( ) to ( )
	Land Use	NA		Residential	NA	( ) to ( )
				Industrial/Commercial		( ) to ( )
				High Density		( ) to ( )
	Material	NA		Steel	NA	( ) to ( )
				Concrete		( ) to ( )
				PVC		( ) to ( )
				Poly Ethylene		( ) to ( )
				Iron		( ) to ( )
				Copper		( ) to ( )
Environmental/ Operational	Operating Pressure	(kPa or psi)		High	( ) to ( )	( ) to ( )
				Medium	( ) to ( )	( ) to ( )
				Low	( ) to ( )	( ) to ( )
	Water Body Proximity	NA		Yes	NA	( ) to ( )
				No		( ) to ( )
	Buried Assets Proximity	NA		Yes	NA	( ) to ( )
				No		( ) to ( )
	Soil Type	NA		Clay	NA	( ) to ( )
				Rock		( ) to ( )
				Silt		( ) to ( )
				Sand		( ) to ( )
Social	Existence of Alternative Route	NA		Yes	NA	( ) to ( )
				No		( ) to ( )
	Average Daily Traffic	(AADT)		High	( ) to ( )	( ) to ( )
				Medium	( ) to ( )	( ) to ( )
				Low	( ) to ( )	( ) to ( )
	Road Type	NA		local	NA	( ) to ( )
				Urban		( ) to ( )
				Interstate		( ) to ( )
	Nearby Facilities	NA		Yes	NA	( ) to ( )
				No		( ) to ( )

4.1.4 Effect Value

The final part of the questionnaire is allocated to the effect value of each attribute. A column of empty score is attached to each subfactor's attributes as shown in Table 4-2. The expert must assign from 0 to 10 to each cell, 0 indicating the lowest effect value on the criticality and 10 indicating the highest effect value on the criticality as shown in Table 4-2.

Table 4-3 Water pipeline size

Responds	Pipe Diameter (Inch)					
	Large		Medium		Small	
	min	max	min	max	min	max
1	30	48	18	30	2	16
2	17.7	36	7.87	15.7	1.97	7.87
3	24	36	12	24	2	12
4	12	20	8	12	2	8
5	14	24	8	14	2	8

4.2 Data Collected for the Case Study

The second type of data is gathered from Strategic Management Department of Water Networks in Montreal, Canada to implant the criticality model in a real-life scenario. These data are obtained from different sectors of the city of Montreal. These sectors are “Ville Marrie”, “Bizard Island”, “Anjou” and “Lasalle”. The data contain the physical characteristics of Montreal pipeline network. Each pipe is recognized by its unique identification number and the pipe's location is identified by three roads. The first road shows the pipe's position and the other roads classify the beginning and the end node of the pipe, as shown in Figure 4-5.

The following illustration shows Pipe ID # 23194, located in the Ville Marrie sector; the pipe is positioned at De Bleury Road, with its start and end point located on Rene Levesque Road and Saint Catherine Road respectively. The physical characteristics of the pipe include the pipe's age, its diameter, its length, type of material, the number of breaks per year and other features used in the implantation of the criticality model.

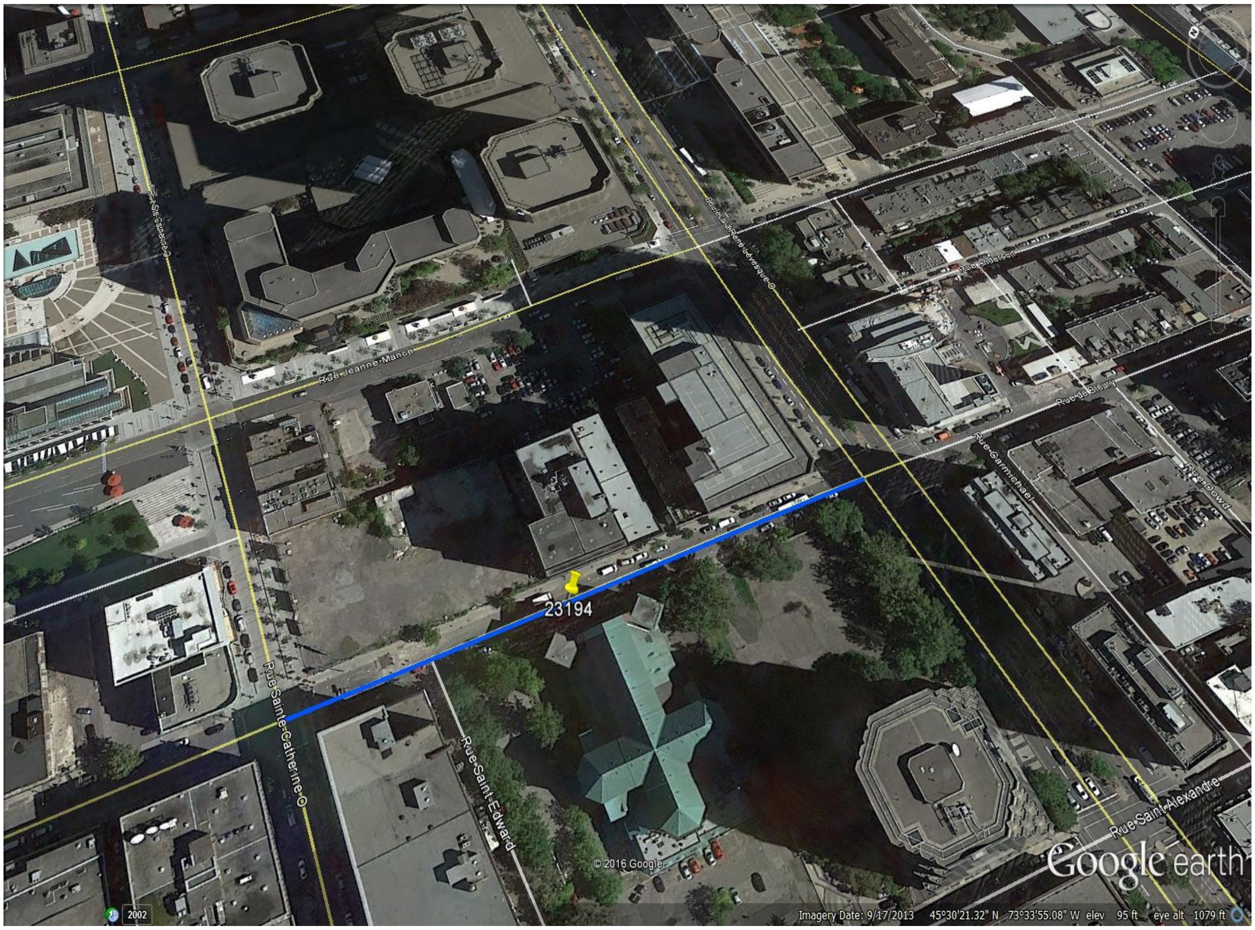


Figure 4-5 Location of Pipe 23194 at Ville Marrie sector (Google Earth)

CHAPTER FIVE

Model Implementation

This chapter describes the model implantation base on the research methodology discussed in Chapter Three. What follows describes the model implantation principal procedures:

1) Determining the criticality weights
2) Analysis of the criticality weights
3) Applying the criticality effect values
4) Development of criticality and performance indexes
5) Development of the priority index
6) Priority matrix implementation

The case study of this research is based on the city of Montreal, as the most metropolitan city in Quebec, Canada. The most populous part in Montreal is the Montreal Island, located between Saint Lawrence and Prairies Rivers, with an average population of 3.8 million. Laval and Longueuil regions are the second populous areas, located in the north and south of Montreal Island respectively. The Montreal contains different types of land in use areas, including residential, commercial, industrial and multi-use areas.

The data on the pipelines' characteristics are obtained from the Strategic Management Department of water network for the city of Montreal. These data include the pipelines' diameters, depth, material and other features used in clarifying the economic and operational subfactors. They determine the actual status of the pipeline. Canadian statistical data have also been employed in this research to determine the specification of the pipe's location, such as the land use and the soil type for the proposed locations. After achieving all the required data and inputs, calculating the criticality index is simple.

Later, the criticality index is combined with the performance index to form the priority index. The first step in developing the criticality index is to estimate the weights of criticality subfactors, calculated based on the expert opinion. All the responses and data are gathered and divided into three main categories for Qatar, Europe and North America. Each set of data is run in the model separately, once with the Paprika method and another time with the Swing method. However, prior to the data analysis, a detailed breakdown of response #1 is used to show the procedures of weights calculation.

5.1 Weights Calculation for Respond # 1

As mentioned in the research methodology, two weighting techniques are used in the determination of criticality weights. What follows explains the implementation of the Paprika and Swing methods to respond number one.

5.1.1 Paprika Implementation

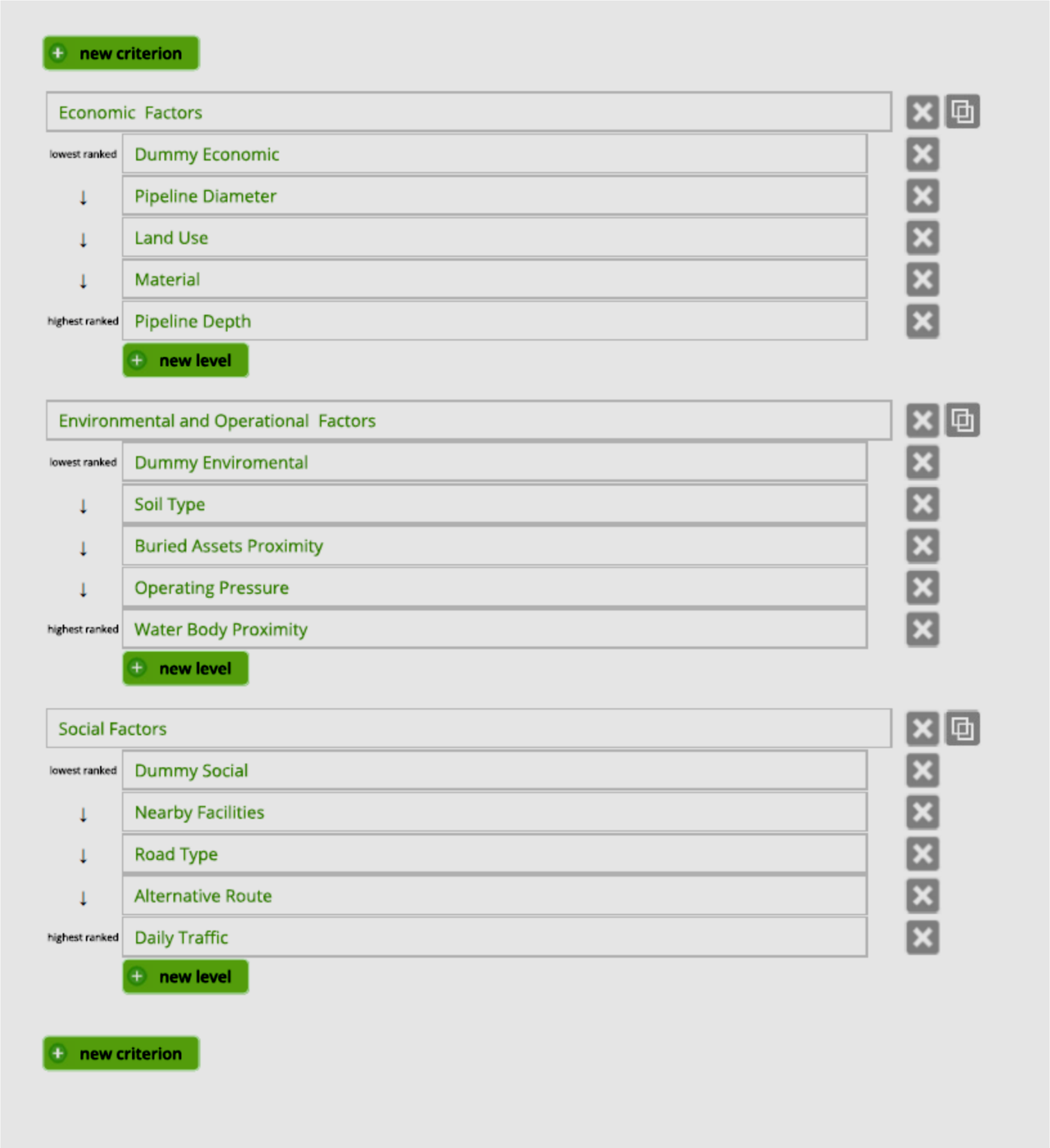
The first step in the Paprika technique is to construct a criticality table. As shown in Table 5-1, the main criticality factors and the criticality subfactors relevant to their main factor are listed in the first and the second columns respectively. A dummy subfactor is added to the main factors of each criticality. These dummies have no score or weights but are used in the Paprika processing. The importance of the subfactor to the main factor is filled into the third and the importance of the main factor to criticality is filled in the fourth column. These columns are filled with the data obtained from the expert opinion as described in the data collection chapter. The fifth column contains the "Total Value", that is the result of multiplying column three with column four. The

"Total Value" can be defined as the importance of each criterion to criticality based on the expert judgment.

Table 5-1 Criticality Table for Response #1 (Paprika method)

Main Factor	subfactors	Importance of the main Factor	Importance to the Criticality	Total Value	Scores	Weight
Economic	Dummy Economic	0	6.5	0	0	0.00%
	Pipeline Diameter	1		6.5	9	2.59%
	Pipeline Depth	3		19.5	23	6.61%
	Land Use	2		13	16	4.60%
	Material	2		13	17	4.89%
Environmental	Dummy Environmental	0	9	0	0	0.00%
	Operating Pressure	6		54	53	15.23%
	Water Body Proximity	7		63	64	18.39%
	Buried Assets Proximity	5		45	42	12.07%
	Soil Type	4		36	31	8.91%
Social	Dummy Social	0	2.5	0	0	0.00%
	Alternative Route	9		22.5	28	8.05%
	Daily Traffic	10		25	30	8.62%
	Road Type	8		20	25	7.18%
	Nearby Facilities	3		7.5	10	2.87%
	Total Value			325	348	100.00%

Meanwhile, all the criticality main and subfactors are inserted in the 1000Minds Software. Firstly, the main criticality factors are inserted in the program. Each of the main factors is divided into several attributes. The attribute or "the criticality subfactors" are arranged in an ascending order, according to their importance to the main factor, as shown in column 3. Figure 5-1 shows the arrangement of criticality factors in the 1000Minds Software.



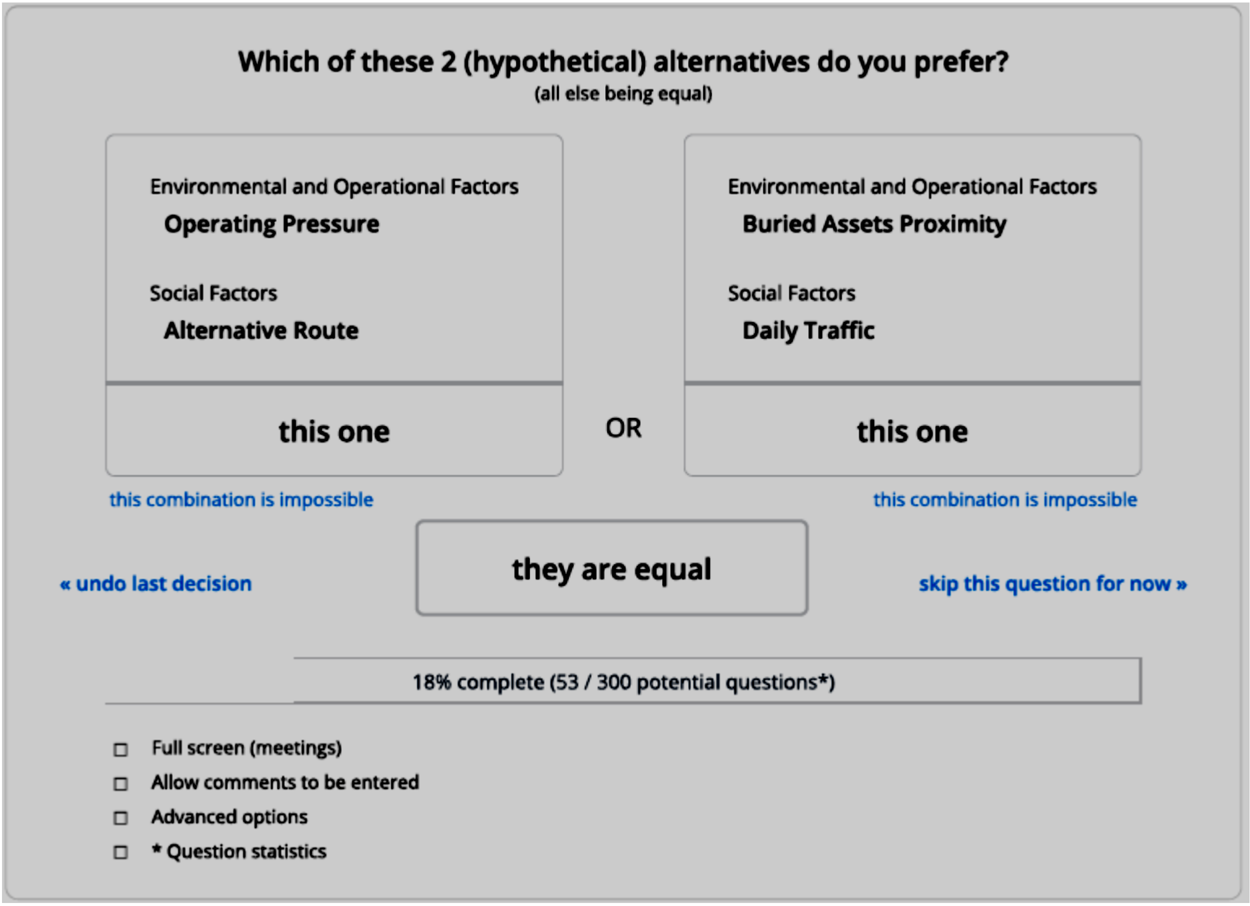
Economic Factors
Dummy Economic
Pipeline Diameter
Land Use
Material
Pipeline Depth

Environmental and Operational Factors
Dummy Enviromental
Soil Type
Buried Assets Proximity
Operating Pressure
Water Body Proximity

Social Factors
Dummy Social
Nearby Facilities
Road Type
Alternative Route
Daily Traffic

Figure 5-1 Arrangement of criticality factors in 1000Minds Software adopted from 1000Minds

The decision phase begins after all the criticality subfactors have been arranged. In this phase, two subfactors from different main factors are randomly chosen and inserted in the L.H.S while other subfactors from different main factors are chosen and inserted in the R.H.S. Figure 5-2 shows the comparison between the L.H.S and the R.H.S. The “Operating Pressure” and “Alternative Route” are inserted in the L.H.S while the “Buried Assets Proximity” and “Daily Traffic” are inserted in the R.H.S.



Which of these 2 (hypothetical) alternatives do you prefer?
(all else being equal)

Environmental and Operational Factors **Operating Pressure** Social Factors **Alternative Route**	Environmental and Operational Factors **Buried Assets Proximity** Social Factors **Daily Traffic**

18% complete (53 / 300 potential questions*)

Figure 5-2 Decision phase between criticality subfactors, adopted from 1000Minds

The total value of each side is calculated by using Table 5-1. In this scenario, the L.H.S equals to (54+22.5) 76.5; in the other hands, the total value of R.H.S equals to (45+25) 70. Therefore, the L.H.S has the higher value and the L.H.S in this scenario is chosen as the dominant side. Upon this selection, another combination of criticality subfactors is sorted in the R.H.S and

L.H.S until the combinations of all criticality subfactors finish. The next phase is the conclusion phase. One of the several advantages of the 1000Minds Software is the accuracy of its output results. The results can be obtained as scores, inserted in column six of Table 5-1. Later, these scores are normalized to obtain the weights of each criticality subfactor and are inserted in the final column of Table 5-1. Another illustration of the results can be made on a graph chart. Figure 5-3 shows radar and criterion value function charts, illustrating the output result of response #1.

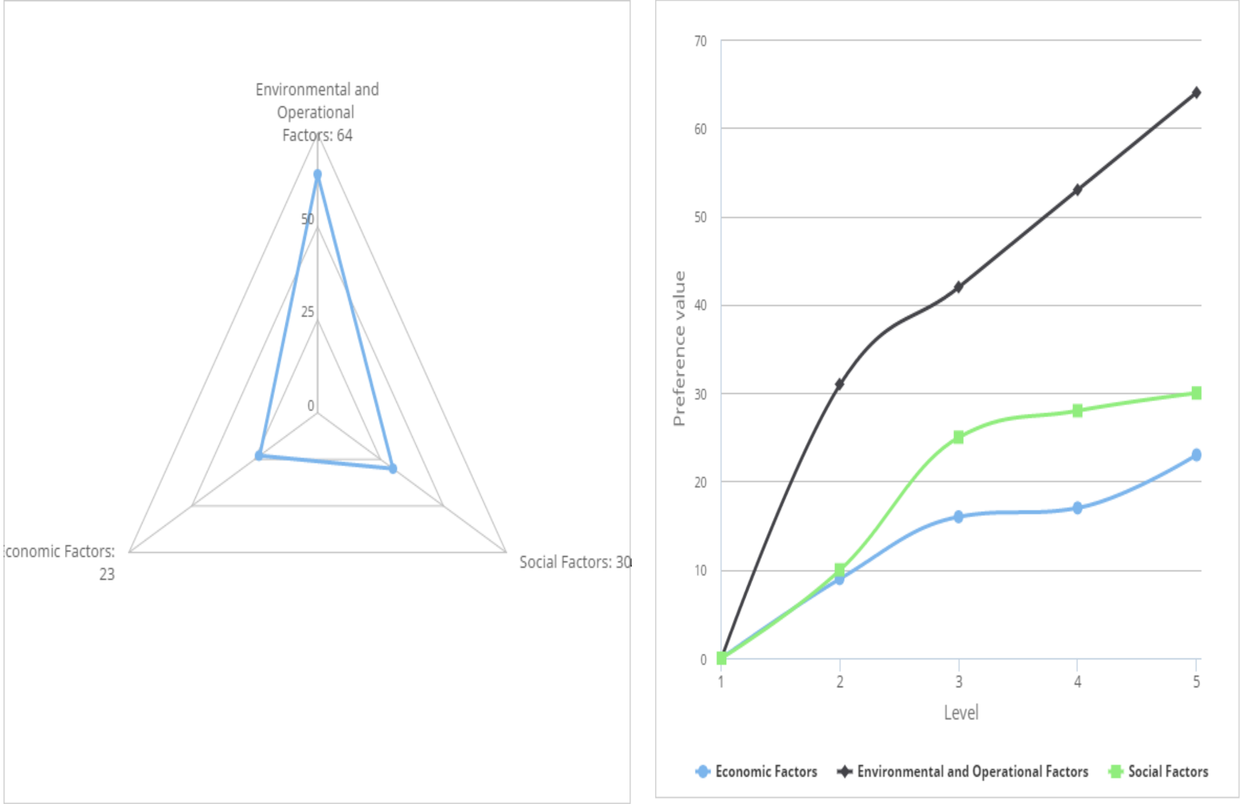


Figure 5-3 Radar and criterion value function charts adopted from 1000Minds

These charts clearly show which of the main factors have the highest influence on the criticality and the score of each criticality subfactor. The current scenario shows that the “Environmental/Operational” has the greatest effect on criticality, with “Water proximity” score equal to 64, while the highest score in the Economic and Social factors are 23 and 30 respectively.

5.1.2 Swing Implementation

Similar to the Paprika method, the first step in the Swing method is to construct another criticality table as shown in Table 5-2. The criticality main and subfactors are being inserted in the first and second columns. Also the "Total Value" is inserted in the third column with the same results as those of the previous criticality table. "Attribute Value" shows the relative importance of each subfactor to its main factor from 0 to 1, where 0 indicates the least important and 1 indicates the most important to the main factor.

Table 5-2 Criticality Table for Response #1 (Swing method)

Main Factors	Subfactors	Total Value	Attribute Value	Weight of main Factor	Total Importance	Total Weight
Economic	Pipeline Diameter	6.5	0	0.23	0	0.00%
	Land Use	13	0.5		0.115	5.30%
	Material	13	0.5		0.115	5.30%
	Pipeline Depth	19.5	1		0.23	10.59%
Environmental	Soil Type	36	0	0.47	0	0.00%
	Buried Assets Proximity	45	0.333		0.15651	7.21%
	Operating Pressure	54	0.667		0.31349	14.44%
	Water Body Proximity	63	1		0.47	21.65%
Social	Nearby Facilities	7.5	0	0.3	0	0.00%
	Road Type	20	0.714		0.2142	9.87%
	Alternative Route	22.5	0.857		0.2571	11.84%
	Daily Traffic	25	1		0.3	13.82%
	Total Value				2.1713	100.00%

The next step is to construct the Swing table as shown in Table 5-3. According to the Swing technique, a benchmark row is inserted, containing the lowest attribute value in each main factor, as described in Table 5-3. The rows are then ranked and evaluated according to their "Total Value" score. For example, the economic row contains the "Pipeline Depth", "Soil Type" and "Near facilities”. The value of economic row equals 19.5 + 36 + 7.5 = 63, as shown in Table 5-3. By using the results of the “Value” column, the rows are re-evaluated from 0 to 100 in the score column, where 0 indicates the lowest value that is the “Benchmark” row and 100 indicates the highest value that is the “Environmental” row. The score column is then normalized and the weights of each main factor are induced. When obtained from the Swing Table, the weights are inserted into Table 5-2 in the column “Weight of main factors”. The newly developed values are then multiplied by each subfactor’s attribute value and inserted in the “total importance” column. The final step is to normalize the total importance value and the weights of each criticality subfactors are implanted in the final column, as shown in Table 5-2.

Table 5-3 Swing Table for Response #1

Swing Table							
Main Factors	Economic	Environmental	Social	Rank	Value	Score/100	weight
Benchmark	Pipeline Diameter	Soil Type	Nearby Facilities	4	50	0.00	0.00
Economic	Pipeline Depth	Soil Type	Nearby Facilities	3	63	48.15	0.23
Environmental	Pipeline Diameter	Water Body Proximity	Nearby Facilities	1	77	100.00	0.47
Social	Pipeline Diameter	Soil Type	Daily Traffic	2	67.5	64.81	0.30
	Total Value					212.96	1.00

5.2 Qatar Data Analysis

Figure 5-4 and 5-5 represent the weight of criticality subfactors by using the responses received from Qatar. Figure 5-4 illustrate the weights by using Paprika method, while Figure 5-5 represent the weights by using Swing method. By utilizing the Paprika method, it has been concluded that the social factors have the highest attitude on the criticality, while the economic factors have the lowest attitude. “Road Type” subfactor has the highest weight equals to 21 %, followed by the “Alternative route” subfactor with weight equals to 15 %. “Nearby facilities” and

"Alternative route" subfactors have a high influence on the water criticality with weights equal to 14%. "Material" and "Water body proximity" subfactors have a low influence on the water criticality with weights equal to 3 %. Finally, the "Pipeline depth" has the lowest weight equals to 2 % as shown in Figure 5-4.

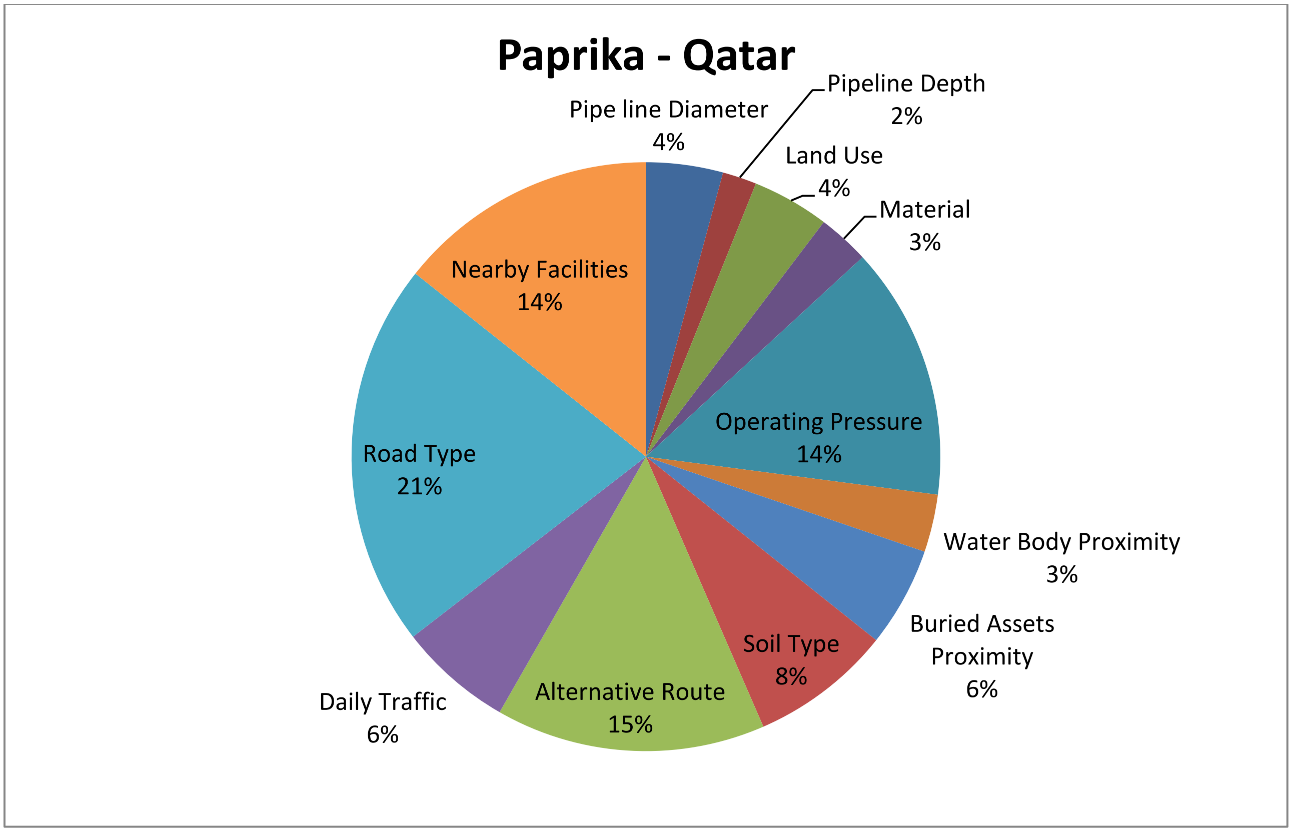


Figure 5-4 Criticality subfactors weights by utilizing Paprika method- Qatar.

Through using the Swing method, the weights of the criticality subfactors were similar to Paprika method with minor changes. Same as in the previous method, "Road Type" subfactor has the highest weight equals to 26 %. Followed by the "Operating pressure" subfactor with weight equals to 19 %. "Nearby facilities" and "Alternative route" subfactors also have a high influence on the water criticality with weight equal to 13% and 15% respectively. "Material" and "Water body proximity" subfactors have a low influence on the water criticality with weights equal to 2

%. Finally, the “Pipeline depth” and “Daily traffic” have the lowest weights equal to 1 % as shown in Figure 5-5.

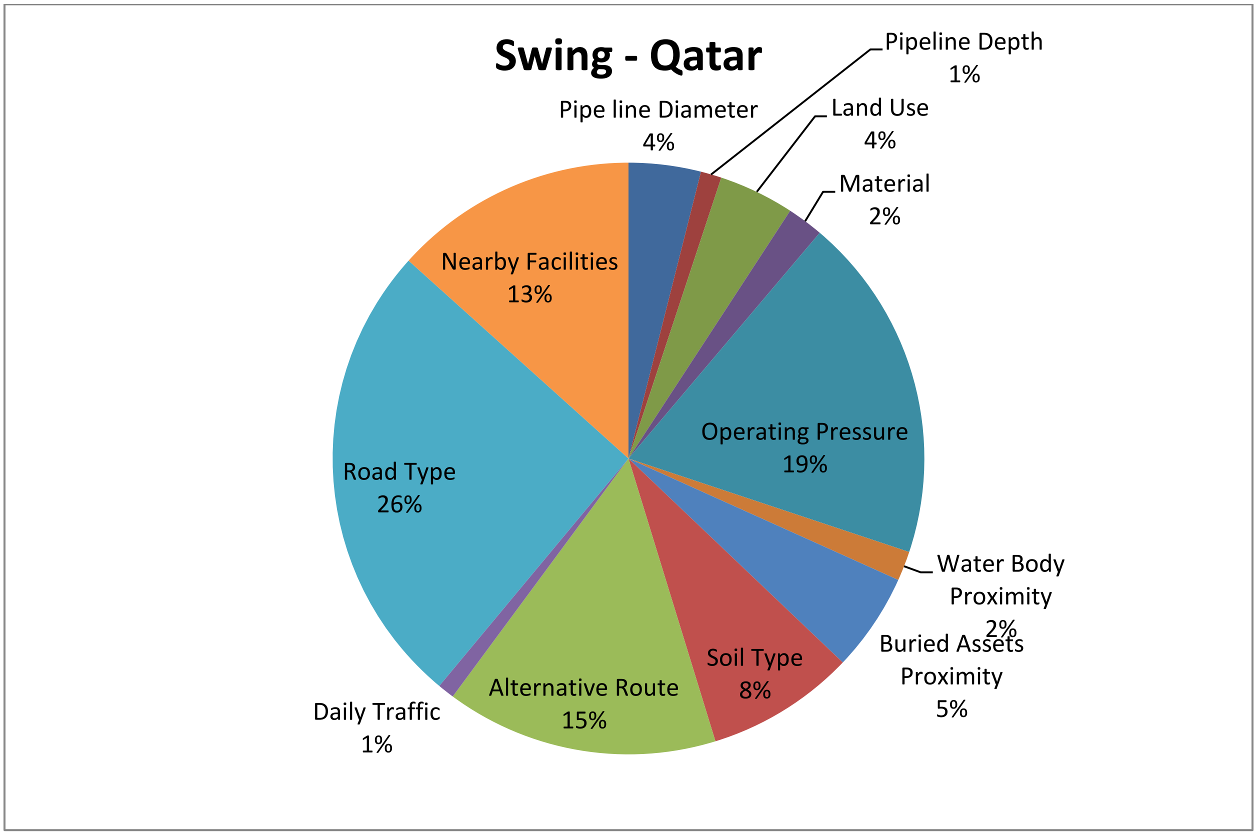


Figure 5-5 Criticality subfactors weights by utilizing Swing method-Qatar.

5.3 Europe Data Analysis

Similar to Qatar data process, the European data set were inserted into the model. Figure 5-6 and 5-7 represent the weights of criticality subfactors based on the European responds. Figure 5-6 shows the weights by using Paprika method, while Figure 5-7 represent the weights by using Swing method. By utilizing the Paprika method, it has been concluded that all weights of subfactors are ranged from 6 % to 10 %. “Pipeline diameter” and “Material” subfactor have the highest weights equal to 10 %. In the other hands “Nearby facilities” and “Water body proximity” have the lowest weights equal to 6 % as shown in Figure 5-6.

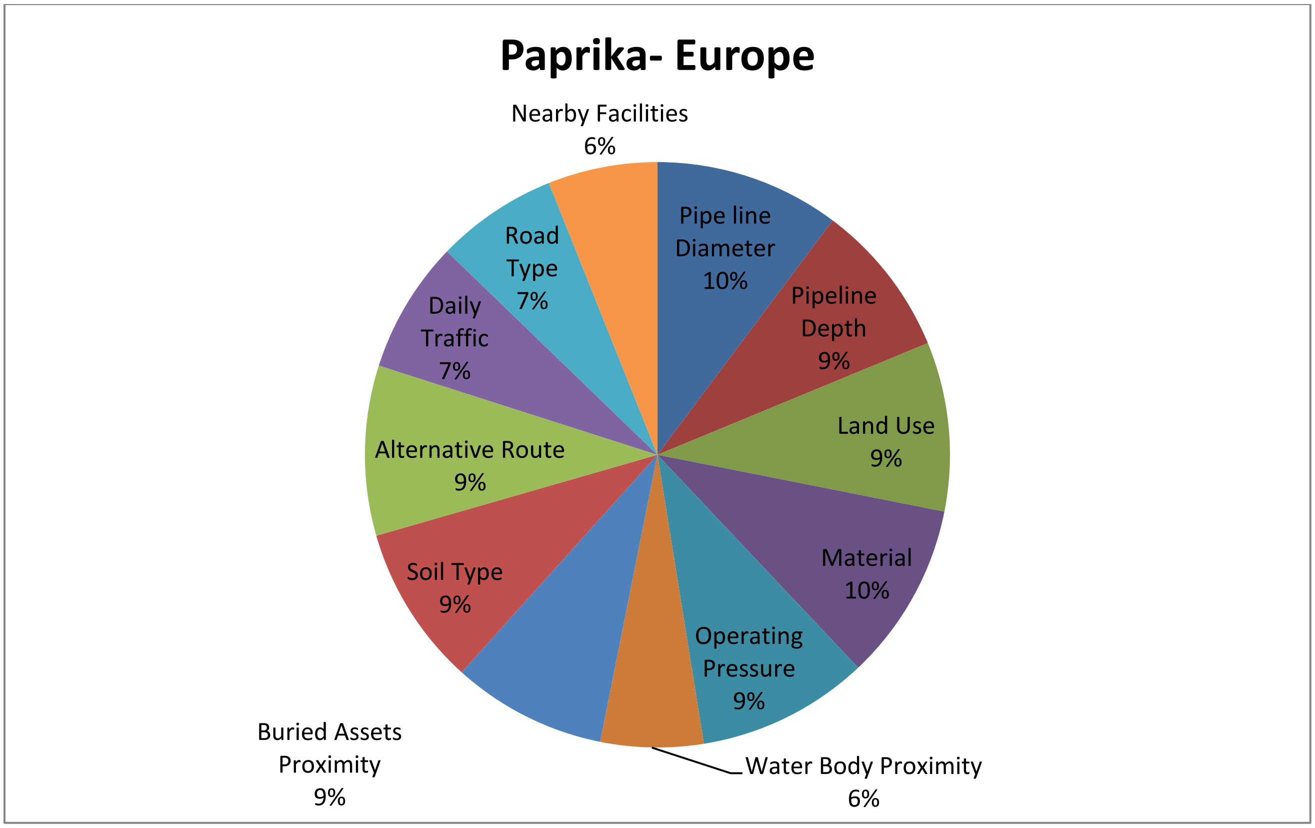


Figure 5-6 Criticality subfactors weights by utilizing Paprika method - Europe.

By applying the Swing method to the European data, the range of the weights is different from the Paprika method, in which the highest weight value was 13 %, while the lowest value was 3 %. “Pipeline diameter”, “Material” and “Operating pressure” subfactor have the highest weights equal to 13 %. Followed by the “Soil type” subfactor with a weight equals to 11 %. “Land use” and “Buried asset proximity” subfactors also have a high influence on the water criticality with weights equal to 10% and 15% respectively. Lastly the “Road type”, “Water body proximity” and “Nearby facilities” have the lowest weights equal to 3 % as shown in Figure 5-7.

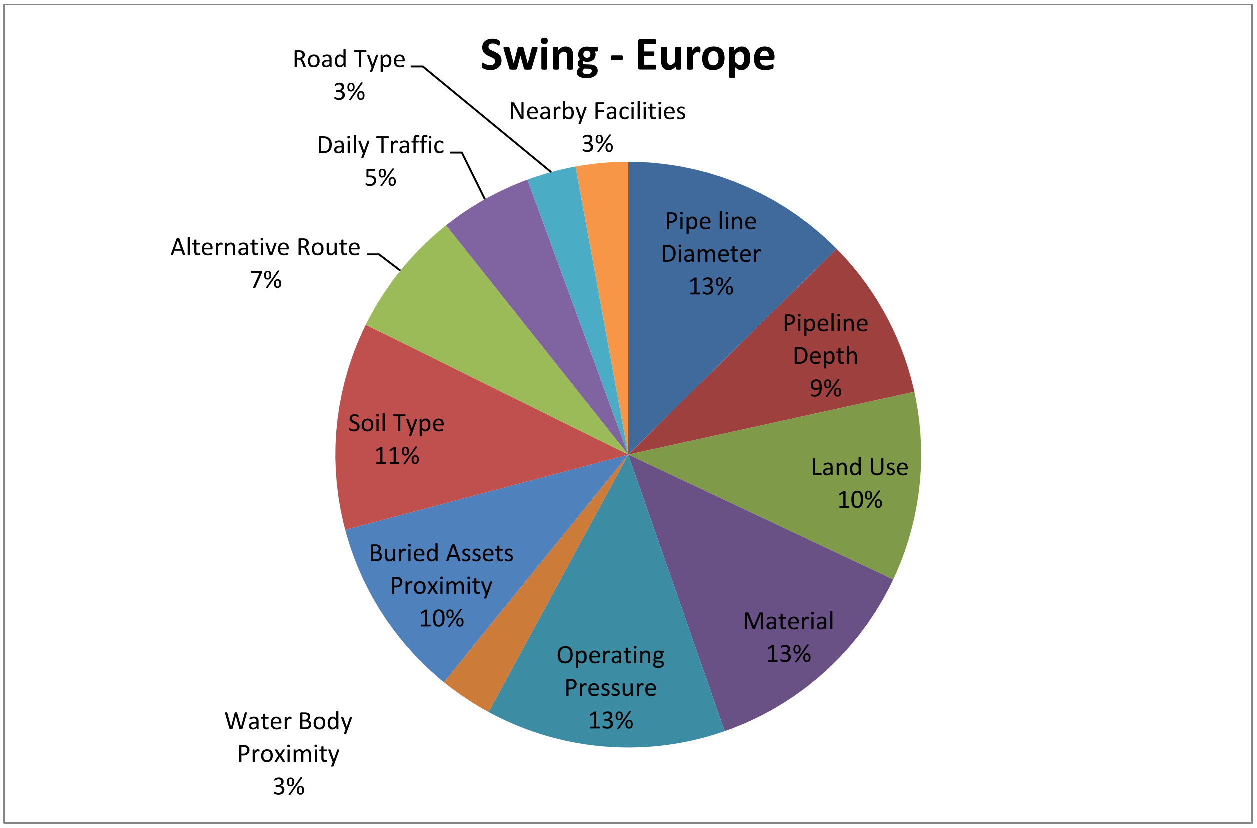


Figure 5-7Criticality subfactors weights by utilizing Swing method - Europe.

5.4 North America data analysis

Figure 5-8 and 5-9 represent the weight of criticality subfactors by using the responses received from North America. Figure 5-8 illustrate the weights by using Paprika method, while Figure 5-9 represents the weights by using Swing method. By utilizing the Paprika method, it has been concluded that the social and economic factors have the highest influence on water criticality with a total weight of 75 %. “Nearby Facilities” subfactor has the highest weight equals to 12 %, followed by the “Daily traffic”, “Road type”, “Pipeline Diameter” and “Land use” subfactors with each has a weight equals to 11 %. Finally the “soil type” has the lowest weight equals to 5 % as shown in Figure 5-8.

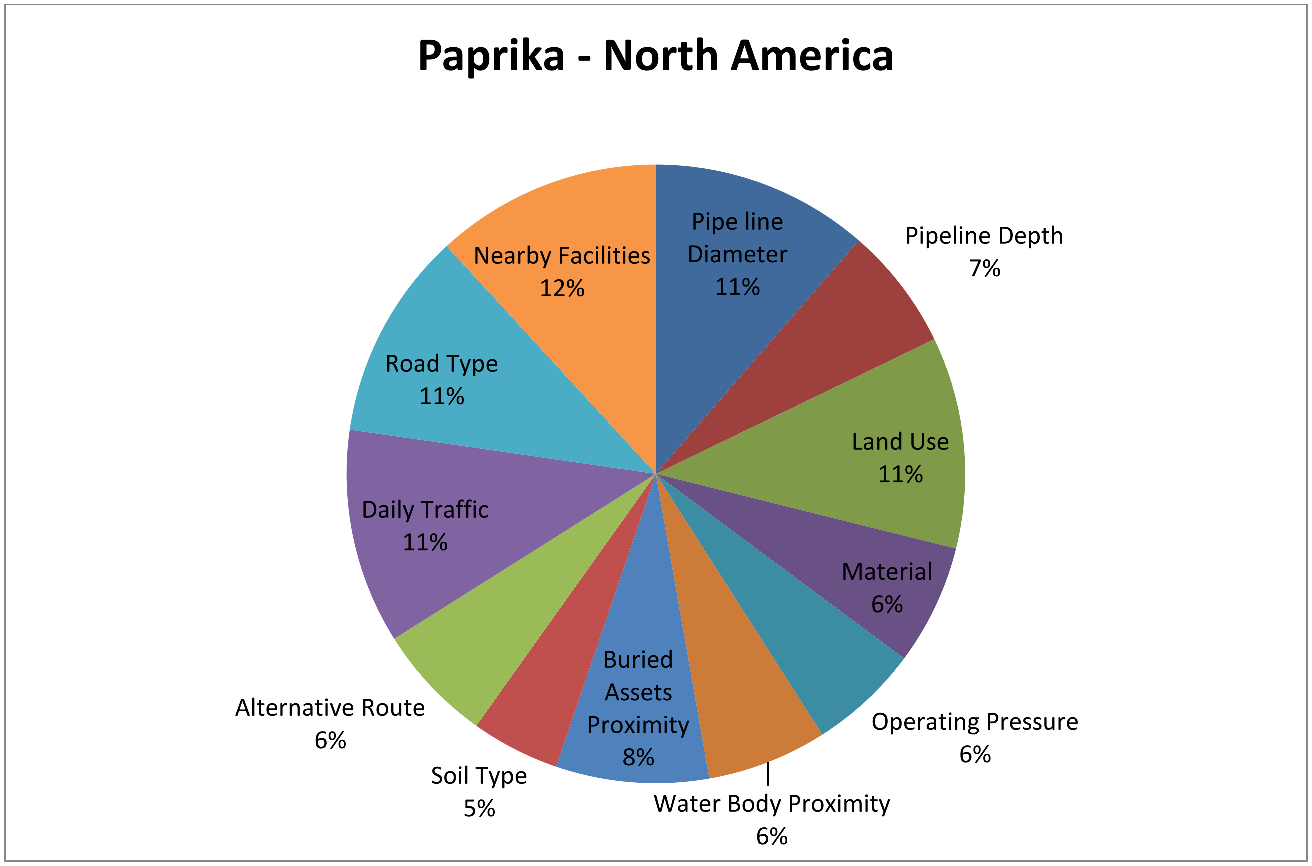


Figure 5-8 Criticality subfactors weights by utilizing Paprika method – North America.

Through using the Swing method and similar to Paprika method results, it has been concluded that the social and economic factors have the highest influence on water criticality with a total weight of 78 %. “Pipeline diameter” subfactor has the highest weight equals to 18 %. Followed by the “Land use” subfactor with weight equals to 16 %. “Nearby facilities” and “Daily traffic” subfactors also have a high influence on the water criticality with weight equal to 12% and 10% respectively. “Operating pressure” and “soil type” subfactors have a weak impact on the water criticality with weights equal to 4 %. And 3 % respectively. Finally, the “Alternative route” has the lowest weight equals to 1 % as shown in Figure 5-9.

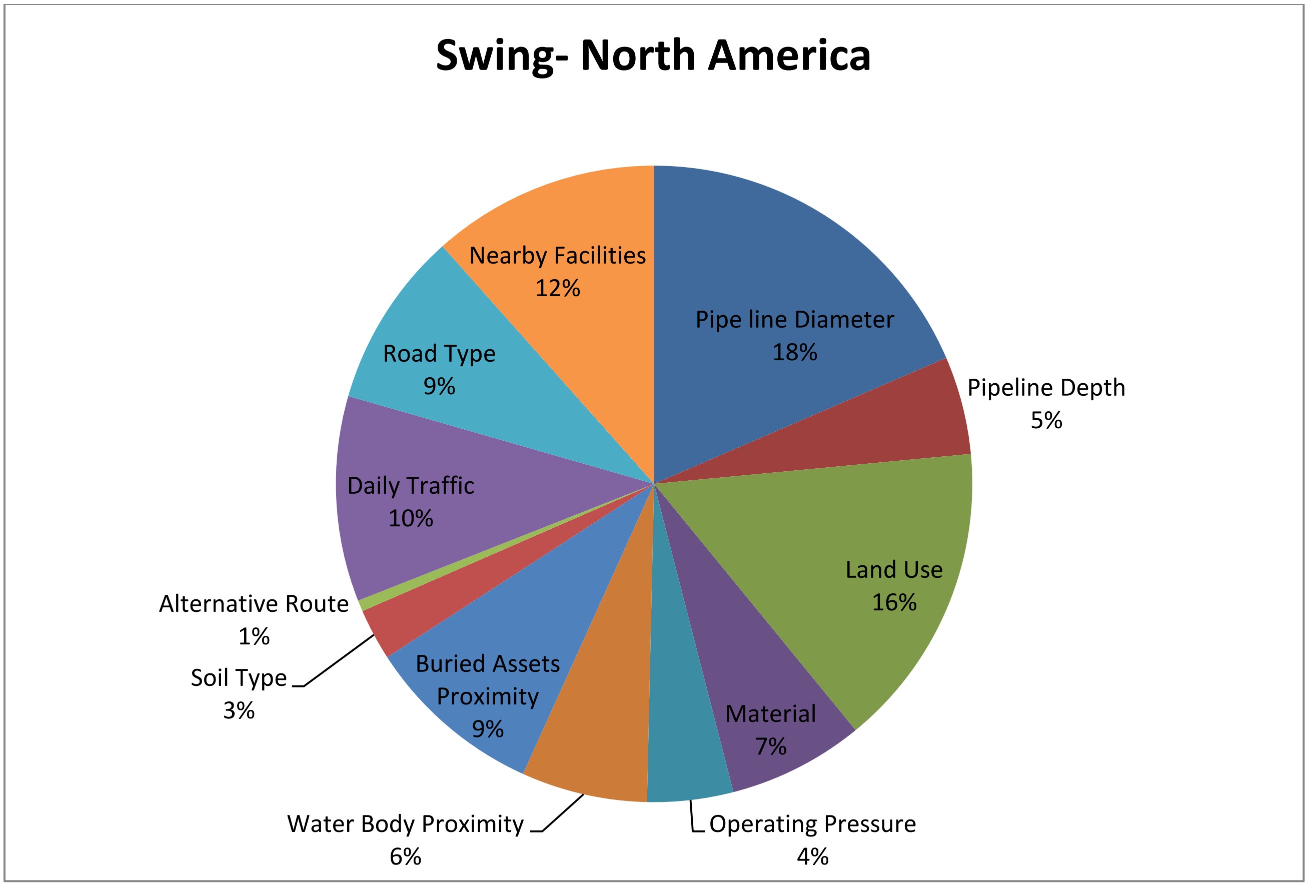


Figure 5-9 Criticality subfactors weights by utilizing Swing method – North America.

5.5 Sensitivity Analysis

A sensitivity analysis is executed to define which factors have the highest and the lowest impact on the criticality index. A series of "What if Scenarios" are performed to measure the influence of changing the subfactors on the criticality index results. Qatar Paprika data set is used in the sensitivity analysis to clarify the conclusions made in the previous section. Figure 5-10 illustrates a tornado graph that compares the effect of each criticality subfactor on the overall criticality index value. The X- axis displays the percentage change in the criticality index value. Each of the criticality subfactors is listed on the Y axis and each bar is drawn by using ± 10 percent to its attribute value.

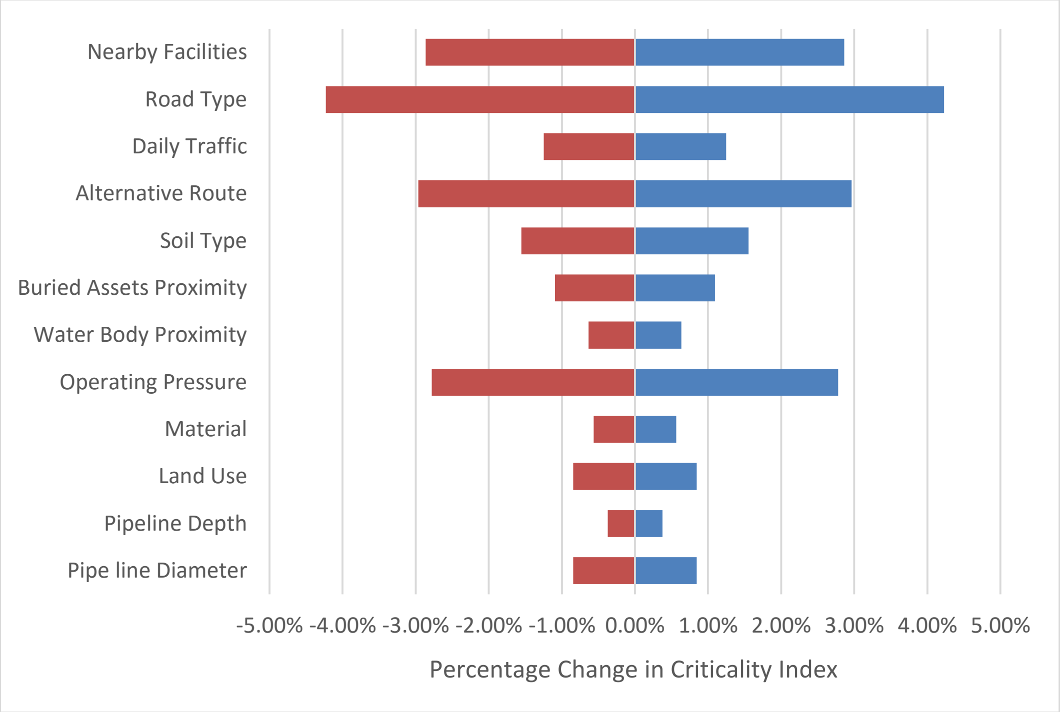


Figure 5-10 Criticality subfactors' impact on criticality index

As shown in Figure 5-10, the "Road type" has the highest influence on the criticality index with the percentage of ± 4, followed by the "Alternative route", "Nearby facilities" and "operating pressure" with the approximate percentage of ±3. Meanwhile, "Water body proximity", "Material" and "Pipeline depth" have the lowest influence on the criticality index with a percentage range below ± 1. Figure 5-11 shows another illustration graph for sensitivity analysis. Percentage change in criticality subfactors are drawn on the X-axis while the percentage change in criticality index is plotted on the Y –axis. This graph shows how the criticality subfactors have an effect on the criticality index. The more diversion of the subfactor lines from the 0 value, the higher the influence on the criticality index value. For Instance, the "Road type" subfactor has the highest diversion among the other lines, which means the largest effect on the criticality index while the "Pipe depth" has the lowest effect on the criticality index.

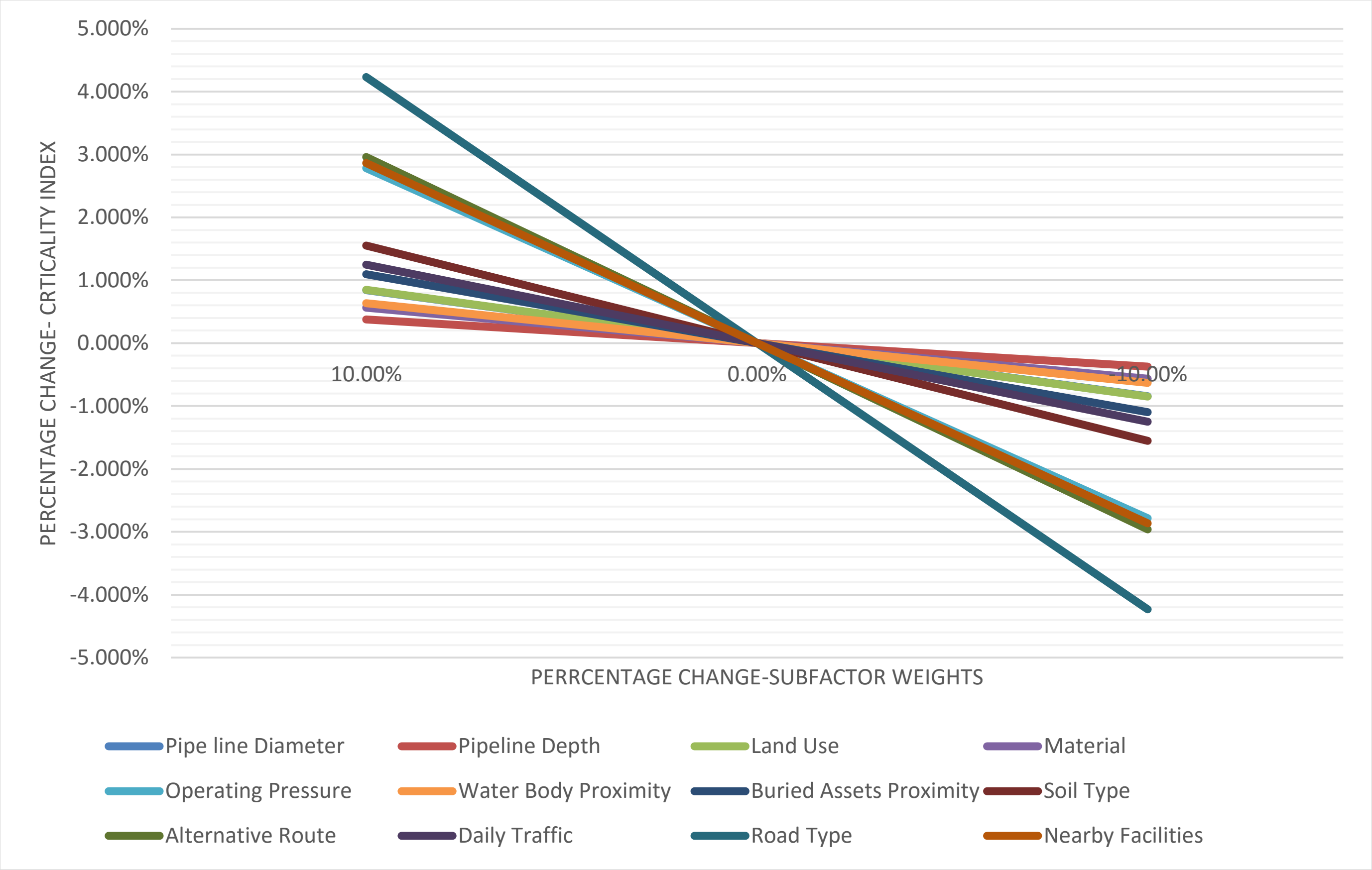


Figure 5-11 Sensitivity analysis for criticality subfactors

5.6 Data Comparison Analysis

A comparison is made with all received responses to evaluate the difference between sets of the expert opinion. Figures 5-12 and 5-13 describe the comparison between the three sets of data in a cluster graph. Figure 5-12 shows the result of the Paprika method while Figure 5-13 shows the results of the Swing method.

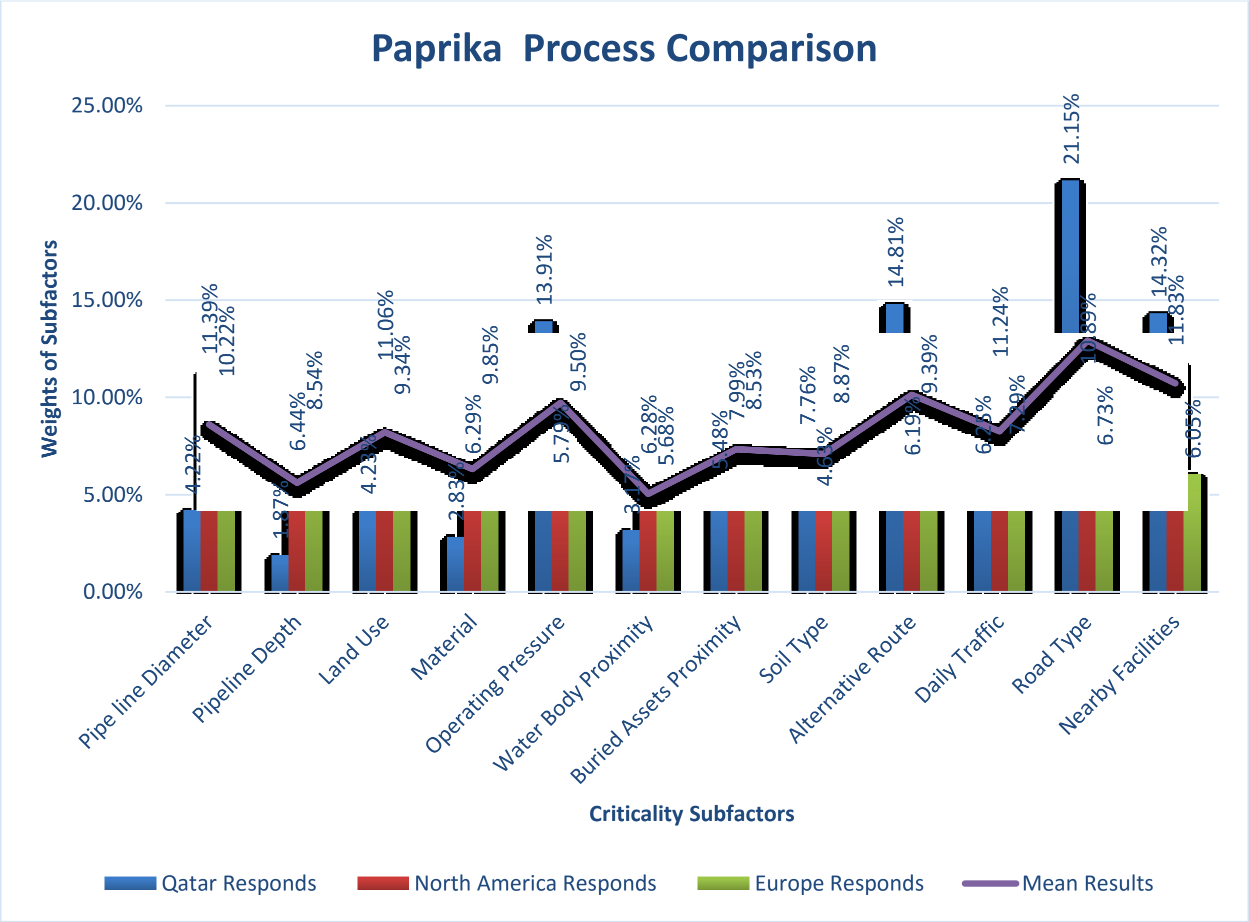


Figure 5-12 Paprika process comparison

The “X” axis shows the criticality subfactors while the “Y” axis describes the weight of each subfactor. Weight averaging is also drawn in the curves for a more accurate comparison illustration. Table 5-4 shows the mean value of the subfactors’ weights. It gives a comparison between the criticality subfactors by utilizing the Paprika and Swing methods. The “Variation” column represents the weight difference values between Paprika and Swing methods. The highest variation value is equal to 3.07%, while the lowest variation value is equal to 0.31%. Both methods are MCDM, but their methodology are different. That is the reason of the variance in the criticality subfactors weights.

Table 5-4 Subfactors average weights

Sub-Factor	Paprika Method	Swing Method	Variation
Pipeline Diameter	8.61%	11.68%	3.07%
Pipeline Depth	5.62%	5.03%	0.59%
Land Use	8.21%	10.05%	1.84%
Material	6.32%	7.18%	0.86%
Operating Pressure	9.73%	12.18%	2.45%
Water Body Proximity	5.04%	3.65%	1.39%
Buried Assets Proximity	7.33%	8.16%	0.83%
Soil Type	7.09%	7.40%	0.31%
Alternative Route	10.13%	7.48%	2.65%
Daily Traffic	8.26%	5.48%	2.78%
Road Type	12.92%	12.43%	0.49%
Nearby Facilities	10.73%	9.27%	1.46%

According to the Paprika method, the “Road type” has the highest influence on an average value of 12.92 percent. “Nearby facilities” and “Alternative route” subfactors have a high impact on an average weight of 10.73 percent and 10.13 percent. “Water Body proximity” considers the lowest factor with an impact on the criticality index with a value of 5.04 percent. Similar to the Paprika method, the “Road type” is also the dominant subfactor in the Swing method with an average weight of 12.43. Meanwhile, the “Water Body proximity” has the lowest weight of 3.65 percent.

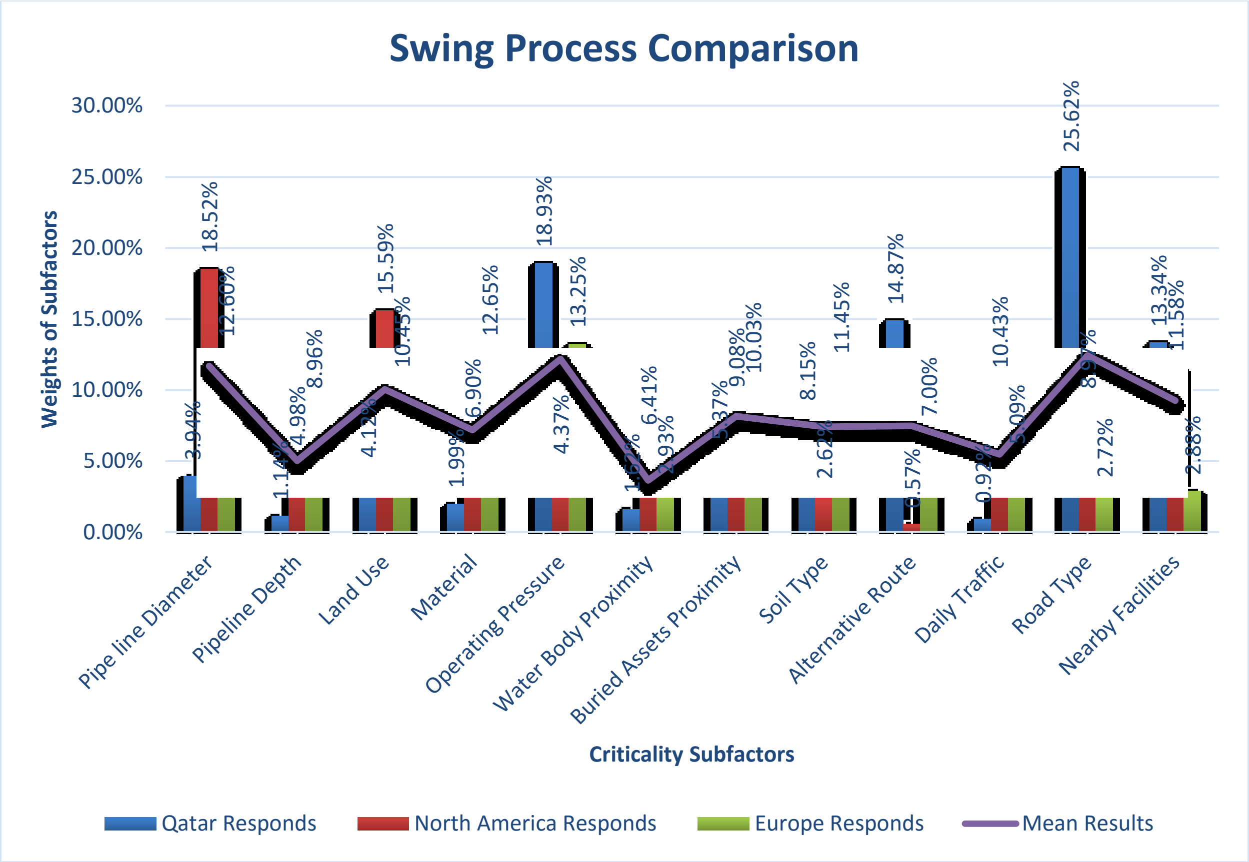


Figure 5-13 Swing process comparison

Table 5-5 shows the ranking of criticality subfactors through utilizing Paprika and Swing techniques from the lowest to the highest value. In accordance to Paprika technique the “Water Body Proximity”, “Pipeline Depth” and “Material” subfactors have the lowest influence on criticality. Meanwhile, the “Alternative Route”,” Nearby Facilities” and “Road Type” have the highest impact on criticality. Through utilizing Swing technique, it has been discovered that the “Water Body Proximity”, “Pipeline Depth” and “Daily Traffic” subfactors have the lowest effect on the criticality. In other hands, the “Pipeline Diameter”,” Operating Pressure” and “Road Type” have the highest influence on the criticality.

After data comparison and analysis, it has been revealed that Paprika technique is more conservative and accurate than the Swing technique. The main reason of preferring to work with Paprika, because its methodology is based on comparing of each criticality subfactors with each other. However, the Swing technique compares only the best and the worst categories with the other criticality subfactors.

Table 5-5 Ranking of criticality subfactors.

Ranks	Sub-Factor	Paprika Method	Sub-Factor	Swing Method
1	Water Body Proximity	5.04%	Water Body Proximity	3.65%
2	Pipeline Depth	5.62%	Pipeline Depth	5.03%
3	Material	6.32%	Daily Traffic	5.48%
4	Soil Type	7.09%	Material	7.18%
5	Buried Assets Proximity	7.33%	Soil Type	7.40%
6	Land Use	8.21%	Alternative Route	7.48%
7	Daily Traffic	8.26%	Buried Assets Proximity	8.16%
8	Pipeline Diameter	8.61%	Nearby Facilities	9.27%
9	Operating Pressure	9.73%	Land Use	10.05%
10	Alternative Route	10.13%	Pipeline Diameter	11.68%
11	Nearby Facilities	10.73%	Operating Pressure	12.18%
12	Road Type	12.92%	Road Type	12.43%

5.7 Criticality Score and Effect Value

The effect value is obtained from the expert opinion as shown in section 4.1.4. It is used to determine the criticality score by using equation 3-2. The summation of the criticality score of each factor results in the total criticality index of the pipeline. Table 5-6 and 5-7 represent the effect value, inserted in the Paprika and Swing tables respectively.

Table 5-6 Paprika table with the final criticality score

Main Factor	Subfactors	Weight	Attribute	Effect Value	Criticality Score
Economic	Pipe line Diameter	0.04	Large	8.23	0.34
			Medium	4.47	0.19
			Small	1.2	0.05
	Pipeline Depth	0.02	Shallow	5.67	0.12
			Medium	4.13	0.08
			Deep	3.40	0.04
	Land Use	0.04	Residential	1.80	0.08
			Industrial/Commercial	4.43	0.20
			High Density	7.33	0.31
	Material	0.03	Steel	1.10	0.03
			Concrete	6.37	0.18
			PVC	4.23	0.12
			Poly Ethylene	8.63	0.24
			Iron	4.30	0.14
			Copper	7.13	0.20
Environmental	Operating Pressure	0.14	High	7.93	1.10
			Medium	3.50	0.49
			Low	2.33	0.34
	Water Body Proximity	0.03	Yes	7.10	0.24
			No	2.57	0.09
	Buried Assets Proximity	0.05	Yes	7.20	0.38
			No	2.83	0.18
	Soil Type	0.08	Clay	3.30	0.28
			Rock	0.97	0.08
			Silt	8.30	0.68
			Sand	5.97	0.50
Social	Alternative Route	0.15	Yes	2.30	0.35
			No	7.33	1.09
	Daily Traffic	0.06	High	7.63	0.46
			Medium	4.40	0.27
			Low	1.8	0.12
	Road Type	0.21	Rural	1.43	0.24
			Urban	4.00	0.85
			Interstate	7.57	1.67
	Nearby Facilities	0.14	Yes	7.63	1.08
			No	2.73	0.38

Since El Chanati (2014) use Qatar expert opinion to develop the performance index, Qatar criticality responses are also used in Tables 5-6 and 5-7 for more contingency of the final results. Final criticality scores vary from 0 to 10, where 0 indicates that the pipeline has the lowest criticality value and 10 indicates it has the highest criticality value.

Table 5-7 Swing table with the final criticality score

Main	Subfactors	Weight	Attribute	Effect Value	Criticality
Economic	Pipe line Diameter	0.04	Large	8.23	0.32
			Medium	4.47	0.17
			Small	1.2	0.05
	Pipeline Depth	0.01	Shallow	5.67	0.09
			Medium	4.13	0.05
			Deep	3.40	0.02
	Land Use	0.04	Residential	1.80	0.08
			Industrial/Commercial	4.43	0.20
			High Density	7.33	0.29
	Material	0.02	Steel	1.10	0.02
			Concrete	6.37	0.11
			PVC	4.23	0.09
			Poly Ethylene	8.63	0.17
			Iron	4.30	0.10
			Copper	7.13	0.14
Environmental	Operating Pressure	0.19	High	7.93	1.52
			Medium	3.50	0.69
			Low	2.33	0.44
	Water Body Proximity	0.02	Yes	7.10	0.13
			No	2.57	0.05
	Buried Assets Proximity	0.05	Yes	7.20	0.39
			No	2.83	0.16
	Soil Type	0.08	Clay	3.30	0.31
			Rock	0.97	0.09
			Silt	8.30	0.73
			Sand	5.97	0.54
Social	Alternative Route	0.15	Yes	2.30	0.36
			No	7.33	1.11
	Daily Traffic	0.01	High	7.63	0.07
			Medium	4.40	0.04
			Low	1.8	0.01
	Road Type	0.26	Rural	1.43	0.29
			Urban	4.00	1.03
			Interstate	7.57	2.2
	Nearby Facilities	0.13	Yes	7.63	0.99
			No	2.73	0.34

5.8 Criticality and Performance Indices Implantation

GPS technology and Google maps are used to determine the piplelines' locations and their characteristics. Figure 5-14 shows a sample map from "Ville Marrie" by Google map. The integration of data from the Strategic Management Department of Water Network for the city of Montreal with the Canadian statistics and Google maps data clarify all the input needed to determine the current status of water pipelines.

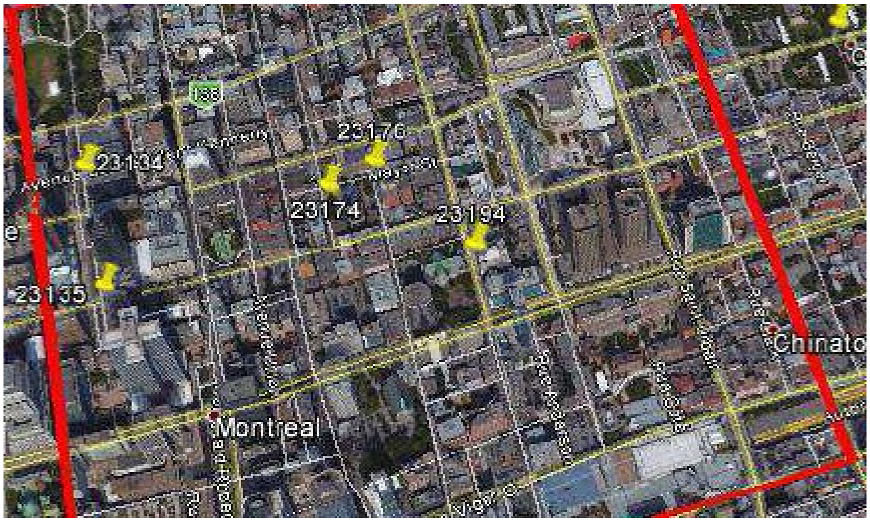


Figure 5-14 Ville Marrie map Google 2016

After obtaining all the input and requirements for the criticality and performance subfactors, the model is run. Some different sectors of the city of Montreal are also assessed as part of the current research, divided based on their general land use. "Ville Marrie", "Bizard Island", "Anjou" and "Lasalle" are the four different sectors at stake: Ville Marrie represents a mixed-used area, Bizard Island accounts for a rural area, "Anjou" embodies an industrial area and lastly, Lasalle accounts for a residential area.

5.8.1 Criticality Index Implementation

Several pipelines across the city of Montreal are taken as an implementation for the Criticality Index. Each of the previously referred sectors is divided into several land use. For example, “Bizard Island” is an island that contains both rural and residential areas. To simplify the model implantation, the pipeline samples are taken from a location according to their sectors types, as shown in Table 5-8.

Table 5-8 Land use according to sectors.

Location	Type of Land use
Ville Marrie	Mixed-used area
Bizard Island	Rural area
Anjou	Industrial area
Lasalle	Residential area

In this case study, five random pipeline samples are taken from each sector (except Anjou, only three samples are taken due to data shortage) to implant into the criticality model by using both the Paprika and Swing methods. The pipes’ locations are identified by the street names; then, Google Maps located them on the Montreal map. After determining the economic, environmental and social factors of the pipeline, they are inserted in the criticality model to estimate the criticality index of each one.

Figure 5-15 and 5-16 illustrate the criticality indexes of random pipelines taken from different sectors of the city of Montreal. Figure 5-15 shows the criticality index induced by the Paprika method, while Figure 5-16 shows the criticality index induced by the Swing method.

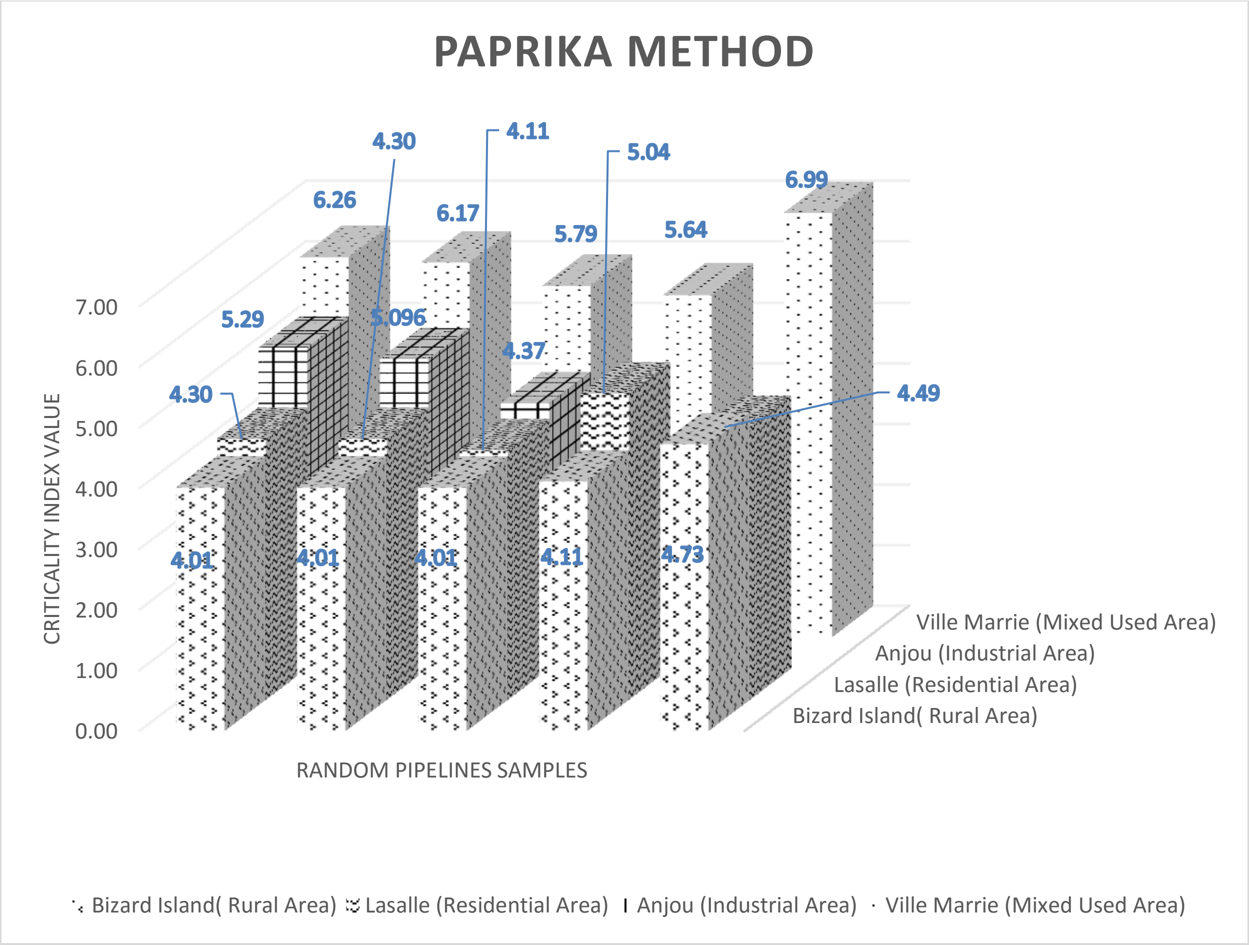


Figure 5-15 Criticality index for random pipelines samples using the Paprika method.

According to Figure 5-15, "Ville Marrie" sector has the highest criticality index. The maximum value at "Ville Marrie" is 6.99 and the lowest value is 5.64. "Anjou" sector has the highest criticality value after "Ville Marrie" with an average criticality value of 4.92. "Lasalle" sector is ranked in the middle of the sectors with an average criticality value of 4.45. Finally "Bizard Island" has the lowest criticality average value equal to 4.17, as shown in Figure 5-15.

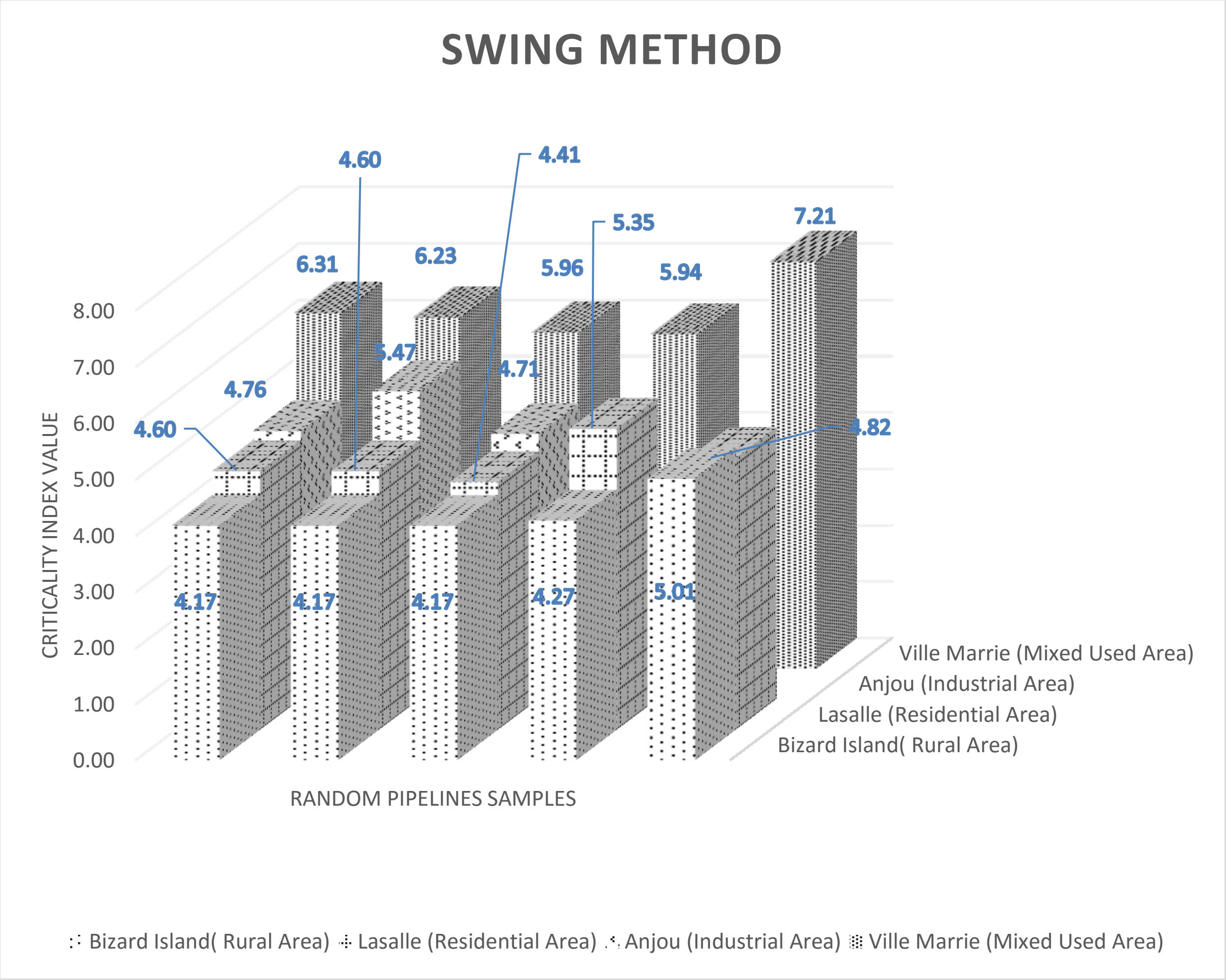


Figure 5-16 Criticality index for random pipeline samples using the Swing method.

Similar to the Paprika results, the ranking of city sectors are the same in the Swing method. “Ville Marrie” sector has the highest average criticality index with a value equal to 6.33. Followed by “Anjou” sector, an average criticality value of 4.98. “Lasalle” sector is ranked in the middle of the sectors with an average criticality value of 4.76. Finally, “Bizard Island” has the lowest criticality average value equal to 4.36, as shown in Figure 5-16.

5.8.2 Performance Index Implantation

By using El Chanati (2014) performance values of water distribution networks as shown in Table 2-6, the performance index of each pipeline can be estimated. The same pipe used in the criticality model is used once again to estimate the performance index, as shown in Figure5-17.

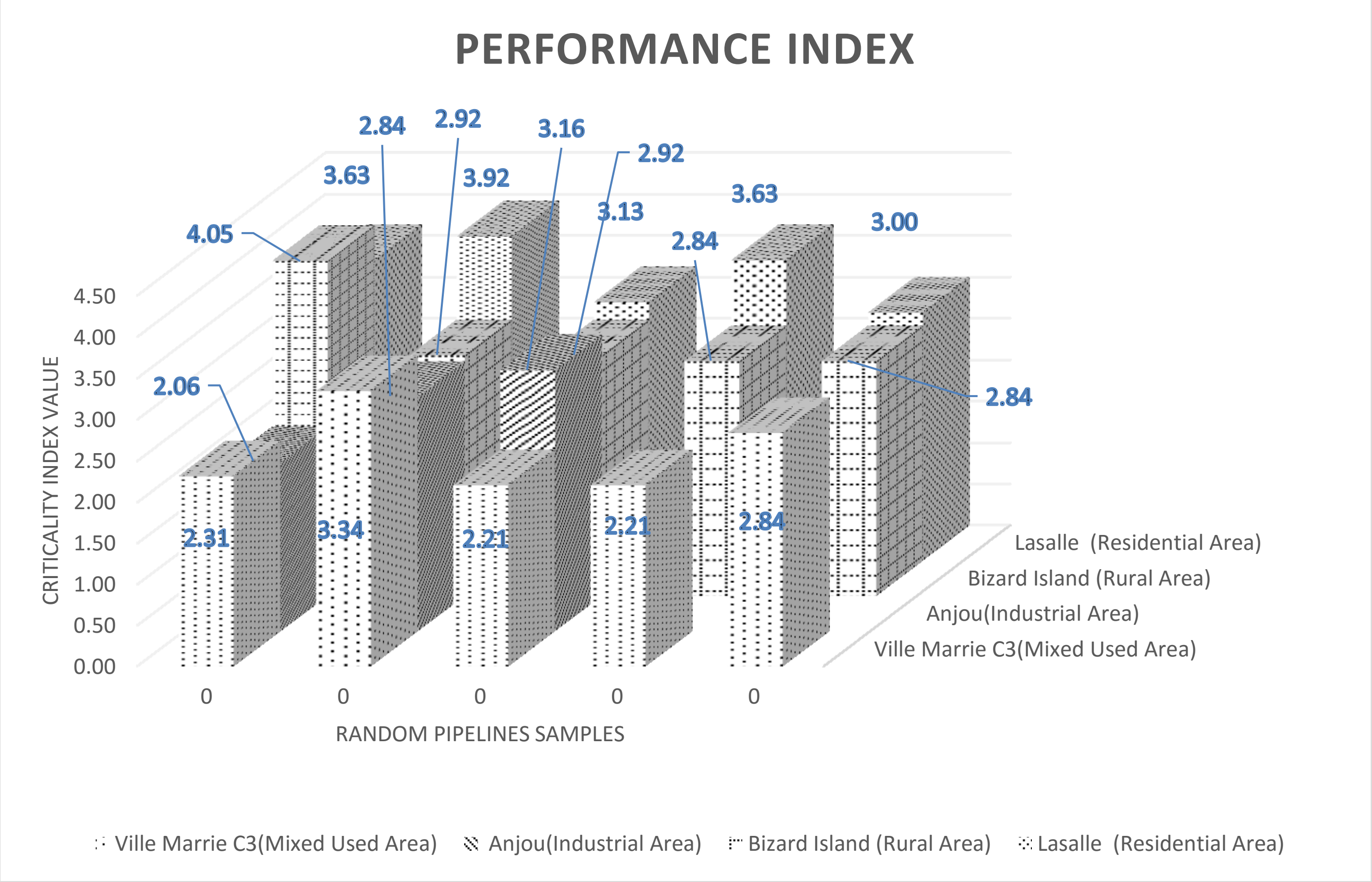


Figure 5-17 Performance index for random pipeline samples

According to Figure 5-17, the average value of the performance indexes for “Ville Marrie” and “Anjou” sectors are equal to 2.58 and 2.69 respectively. In the performance scale, these pipes are in “Good condition”. However, the average value of the performance index for “Lasalle” is equal to 3.46, which is the highest value among the other sectors and the pipes at this sector are in “Moderate condition”.

5.9 Priority Index Development

After identifying the criticality indexes of the referred pipelines across the city of Montreal, they are combined with the performance indexes to form the priority index as already shown in equation 3-3. Figures 5-18 and 5-19 show the priority indexes for the previous pipeline samples used in the implantation of the criticality indexes. Figure 5-18 represents the priority index 1, developed from the combination of Paprika criticality index and performance index. Figure 5-19 represents the priority index 2, generated from the combination of the Swing criticality index and performance index.

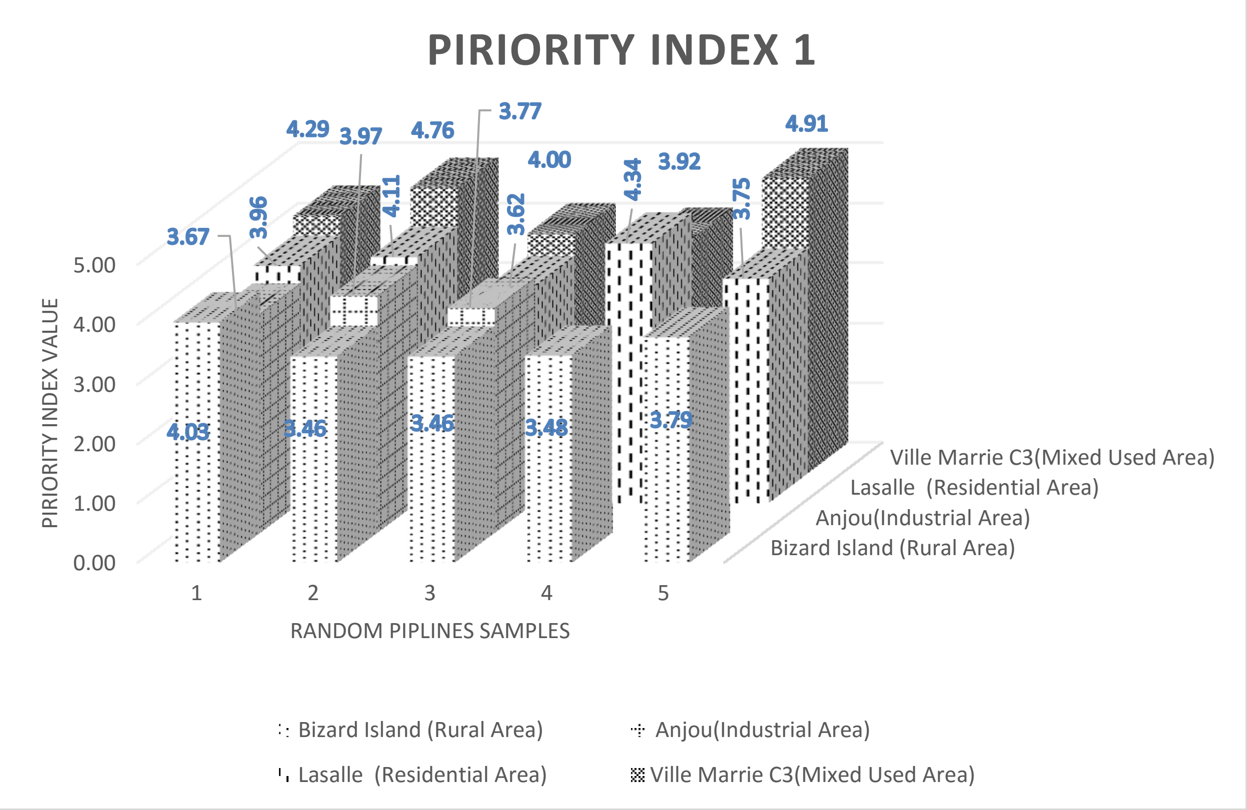


Figure 5-18 Priority Index 1.

In both scenarios (Priority indexes 1 & 2), the "Ville Marrie" sector has the highest mean priority index while "Bizard Island" has the lowest mean priority index. In the proposed priority scale, the "Ville Marrie" sector lies in the high priority scale while the remaining areas lie in the normal priority scale. As calculated, the "Ville Marrie" sector is the highest vital area of the city with the highest demand for repairs and maintenance scheduling among the other referred sectors of the city.

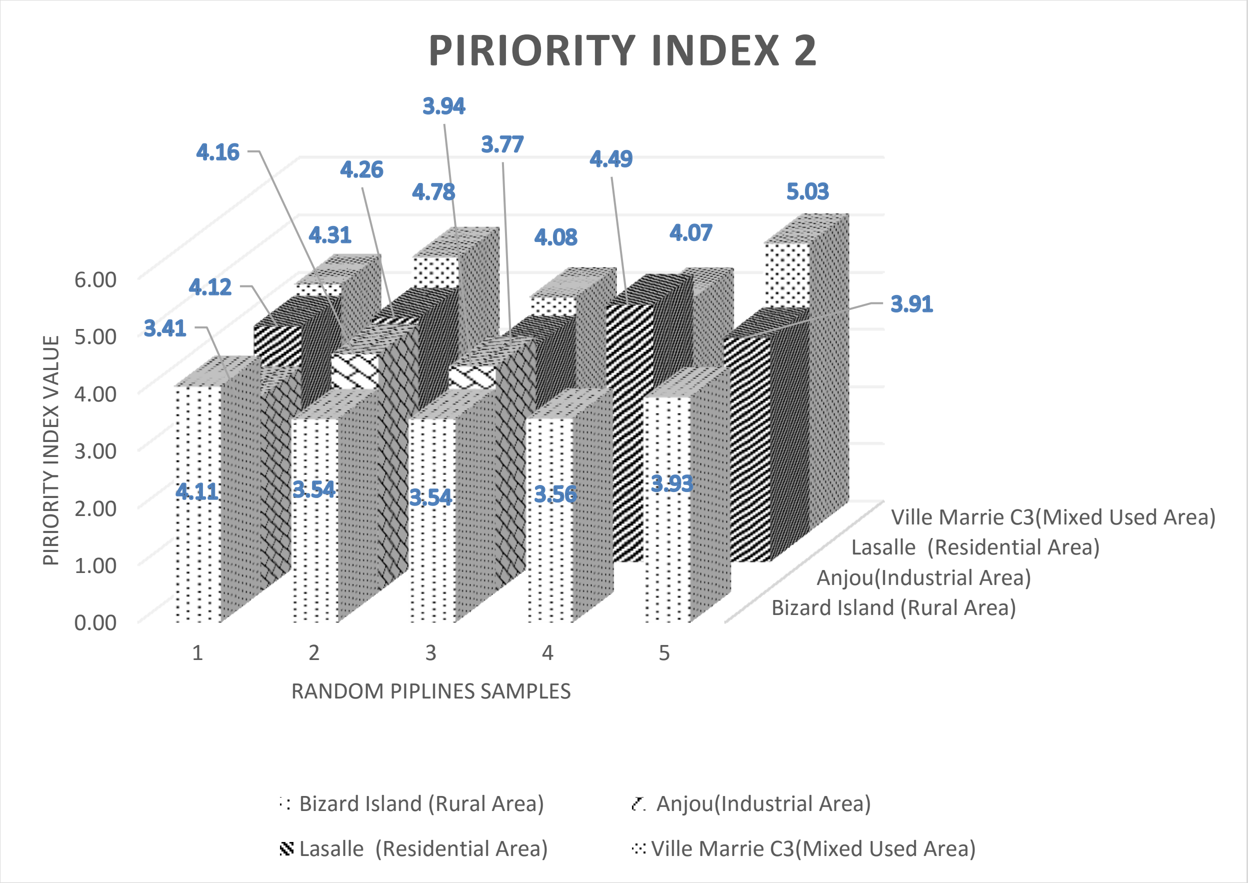


Figure 5-19 Priority Index 2.

5.10 Priority Matrix Implementation

As mentioned in section 3.5, priority matrix is another method to illustrate the importance of the referred water pipelines. Table 5-9 shows the average priority index for the previous pipeline samples among the different city sectors.

Table 5-9 Average priority index.

Sector location	CI Average 1	CI Average 2	Po.I FANP	Priority Score 1	Priority Score 2
Ville Marrie C3(Mixed Used Area)	6.17	6.33	2.58	4.38	4.46
Lasalle (Residential Area)	4.45	4.76	3.46	3.96	4.11
Bizard Island (Rural Area)	4.17	4.36	3.11	3.64	3.74
Anjou(Industrial Area)	4.92	4.98	2.69	3.80	3.84

A bubble chart is much better for data illustration than a normal matrix diagram, to show all the data indexes of this case in one diagram. Figure 5-20 shows a priority matrix bubble chart, where the X-axis describes the performance index and Y axis represents the criticality index. The priority scale appears as the background color of the bubble chart. Green at 0 represents the lowest priority while red at 10 represents the highest priority. The diameter of the bubble represents the actual value of the priority index value. The higher the value, the greater the diameter of the bubble. In the bubble chart, the priority index of the "Ville Marrie" sector is the highest value in the city equals to 4.42. In the other hands, the priority index of "Bizard Island" has the lowest value in the city equals to 3.69.

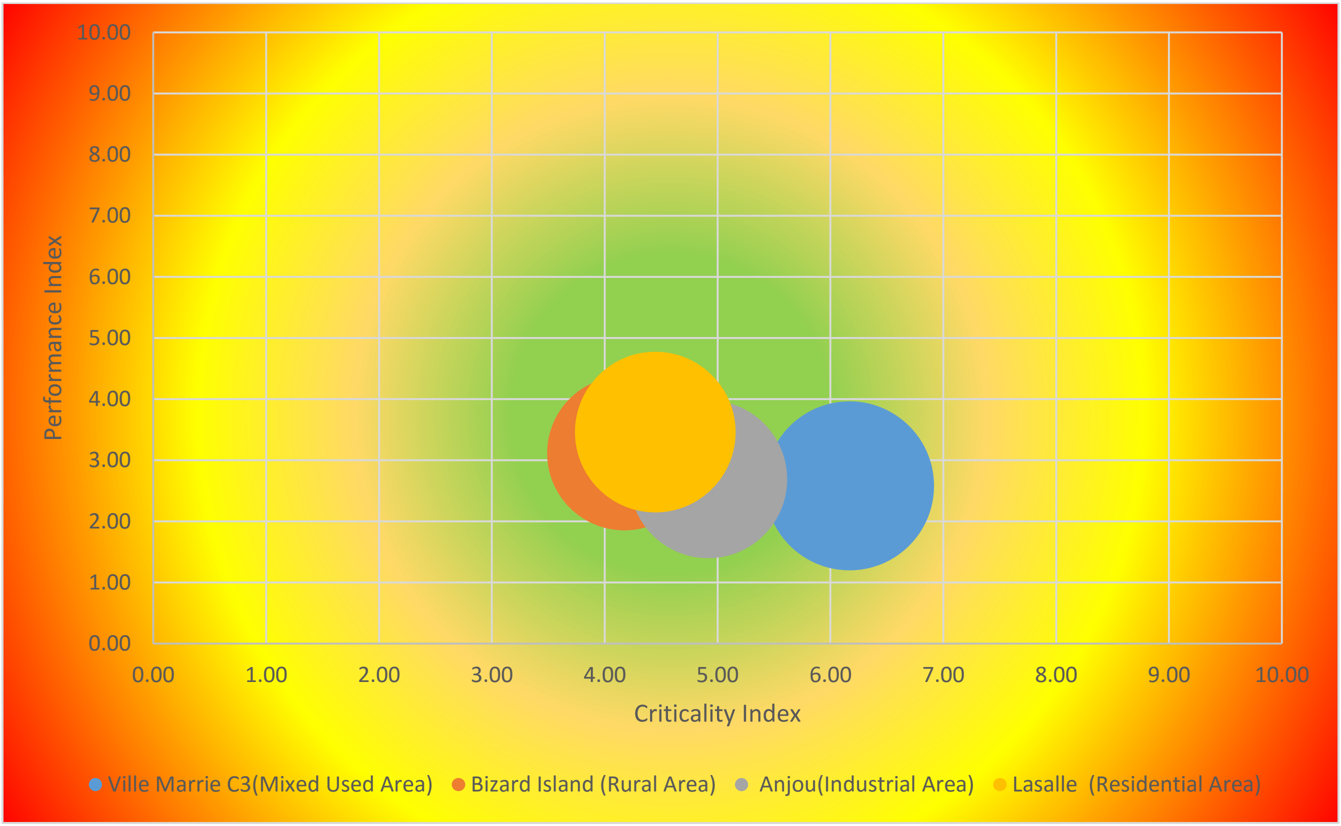


Figure 5-20 Priority bubble chart (Montreal city).

Figure 5-21 shows an imaginary case for the city of Montreal, intended for a better data illustration. In this scenario, the "Ville Marrie" sector has the highest priority index equal to 5.5 and the "Bizard Island" sector has the lowest priority index equal to 3. According to Figure 5-21, the greater bubble size refers to a higher priority index value and the smaller bubble size refers to a lower priority index. This technique facilitates to evaluate the assets based on their priority index and guides municipalities to arrange their maintenance and rehabilitation plans in the most effective manner.

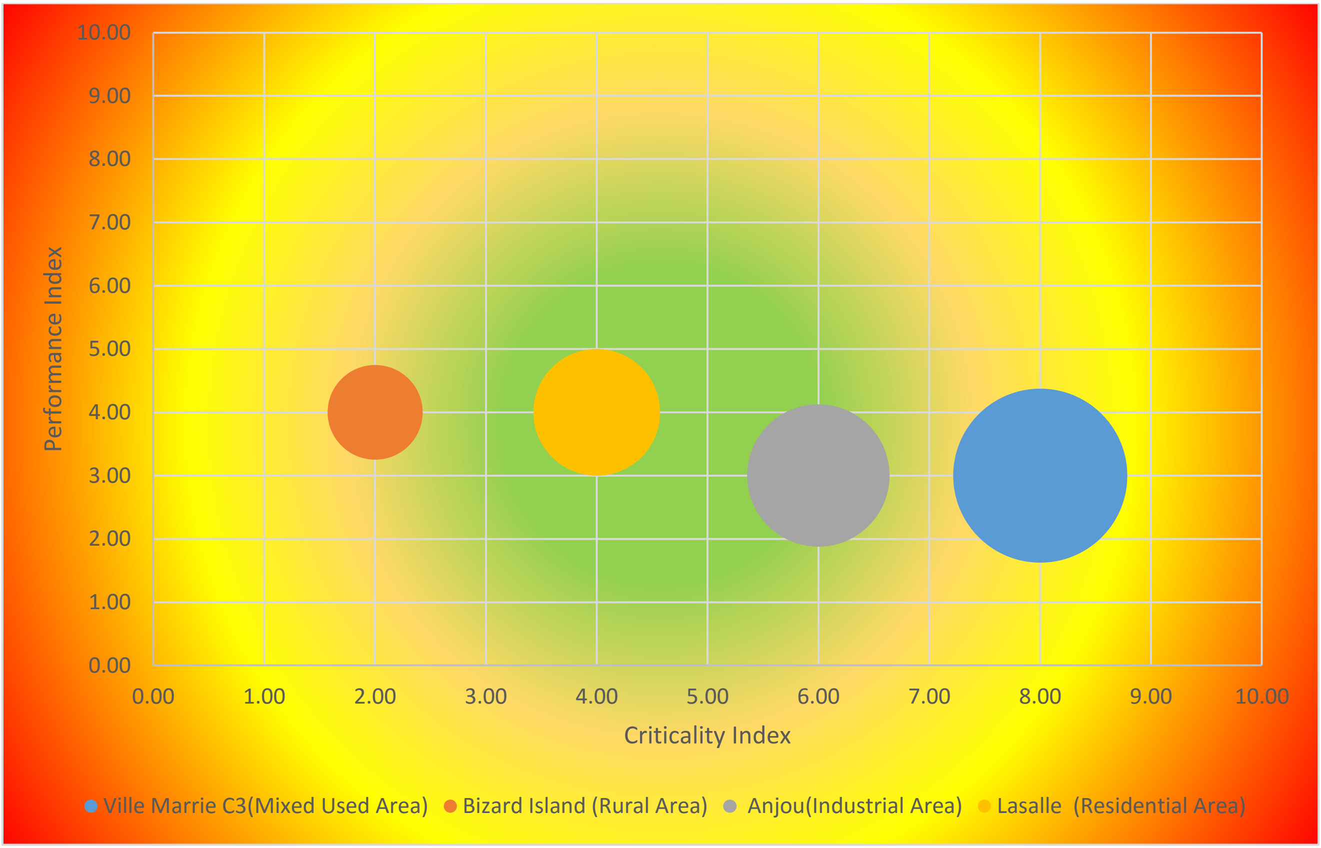


Figure 5-21Imaginary priority bubble chart (Montreal city).

CHAPTER SIX

Conclusion and Recommendation

6.1 Summary and Conclusion

This research mainly aims to calculate a priority index for water distribution networks and use this index to prioritize the maintenance and rehabilitation schedule of the pipeline networks. The priority index is divided into two main indexes: “Criticality Index” and “Performance Index”. Criticality index development is also mentioned explicitly in this study, while the performance index is adopted from El Chanati (2014).

The subfactors affecting the criticality of the water distribution network are identified. They are grouped into three main factors, economic, environmental/operational and social factors. The Paprika and Swing methods are implemented to calculate the weights of each subfactor, supported by the 1000Minds Software. Two types of questionnaires are sent to water distribution experts in Qatar, Europe and North America. The experts have estimated the scores of the subfactors and the effect values of their attributes.

According to the Qatar data set and by means of the Paprika method, social subfactors have the highest impact on criticality with a total weight of 56 percent. “Road type” has the highest weight value equal to 21 percent; besides, “Nearby facilities”, “Alternative route” and “Operating pressure” have a strong influence on criticality with an approximate weight of 14 percent. Finally, the “Pipeline depth” has the lowest weight equal to 2 percent. The output results of the Swing method are similar to those of the Paprika method with some minor difference in the weight distribution. The social factors are still dominant with a total weight of 55 percent. Also, the “Road type” has the highest weight equals to 26 percent while the “Pipeline depth” and “Daily traffic” have the lowest weight equal to 1 percent.

According to the Europe data set and by means of the Paprika method, all subfactor weights lie between 6 to 10 percent. “Pipeline diameter” and “Material” have the highest weight value equal to 10 percent while “Nearby facilities” and “Water body proximity” have the lowest weight equal to 6 percent. The subfactors’ weight range is different according to the Swing method; the range varies from 13 to 3 percent. Also, “Pipeline diameter”, “Material” and “Operating pressure” have the highest weight, equal to 13 percent while “Nearby facilities”, “Water body proximity” and “Road type” have the lowest weight equal to 3 percent.

According to the North America data set and by means of the Paprika method, the Economic and Social subfactors have the highest effect on criticality with a total weight of 75 percent. “Nearby facilities” has the highest weight value equal to 12 percent; besides, “Pipeline diameter”, “Land use”, “Daily traffic” and “Road type” have a high influence on criticality with an approximate weight of 11 percent. Finally, the “Soil Type” has the lowest weight equal to 5 percent. The Economic and Social subfactors were also dominant based on the Swing method with a total weight of 78 percent. The “Pipeline diameter” has the highest weight equal to 18 percent followed by “Land use” with a weight equal to 16 percent. Lastly, “Alternative route” has the lowest weight equal to 1 percent.

After all subfactors’ weight values are determined, they are multiplied by their attribute effect value to estimate the criticality index, as shown in equation 3-2. Later, it is combined with El Chanati (2014) performance index to form the priority index. A new scale and matrix are developed to assess the priority index and to schedule the maintenance and rehabilitation of the water pipeline network.

The city of Montreal is used for the model implementation. Various Pipe samples are taken from different sectors and locations of the city. By using the available data and through executing the priority model, each pipeline's priority index is identified and "Ville Marrie" sector is found to have the highest priority index, equals to 4.42.While "Bizard Island" has the lowest priority index value in the city equals to 3.69.

6.2 Research Contributions

The current research has made a contribution in the field of criticality and performance assessment of water distribution networks by developing:

- A Priority index model for water distribution networks
- A Criticality index for water distribution networks.
- A Priority scale and matrix to assess the Priority index of water distribution networks. This will help the municipalities to schedule their maintenance and rehabilitation plans.

6.3 Research Limitation

This research estimates the priority index of the water distribution networks using the Paprika and Swing methods. The priority index is calculated through the combination of the criticality and performance indexes. The limitation this research has dealt with are as follows:

- The criticality subfactors of' weights have been computed based on the questionnaires collected from the expert opinion. However, a limited number responses were received from Europe and North America; thus, for more accurate data results, an increase in the number of responses is highly recommended.

- “Daily traffic” in the criticality subfactors is assumed according to the population density and average traffic volume of district when the information is not sufficient.
- Ground water level in Montreal city is assumed by 5 meter depth, which is equivalent to “Moderate” depth. However, the locations near to rivers or canals are assumed by 1 meter depth which is equivalent to “Shallow” depth.
- “Water installation quality” and “Water quality” in the performance subfactors are assumed to be in good condition due to the lack of data.
- The selected factors may not apply to all countries and all cases.
- The Priority index of a city’s sector is calculated by averaging the priority indexes of its pipelines.

6.4 Recommendation and Future work.

The recommendations for future research can be summarized as follows:

6.4.1 Research Enhancement

- The criticality index is based only on the pipelines of water distribution network, as the effect of pipeline accessories adds to the precision of criticality index.
- Considering public transport modal spilt to enhance the obtaining of “Daily traffic” results.
- Consider more factors affecting the water distribution network to make the model adoptable in all the cases and conditions in different countries.
- Apply advanced data collection techniques for water pipelines for higher sensing and detecting of changes.
- A detailed criticality and performance scale will enhance the evaluation of the pipeline status.

6.4.2 Research Extensions

- The priority index is developed from two indexes: “Criticality” and “Performance”. Adding the “Condition” index will increase the accuracy of the priority model.
- It is possible to develop a 3-D Priority Matrix, including criticality, performance and condition.
- It is possible to calculate the priority index for the whole water supply system.
- A budget allocation model could be used to distribute the available funds according to their priority index value.
- Priority Index model may apply to other infrastructure systems, such as sewer and road systems. It is possible to combine all the systems to help the municipalities have a general overview of their infrastructure systems.

References

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

American Water Works Association et al. (2002). "Managing Public Infrastructure Assets to Minimize Cost and Maximize performance." Alexandria, VA.

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

Asset Management Planning (2013), "Portland Water Bureau", Portland water Bureau Asset Management steering committee, 7-8.

Balasubramaniam, A., Boyle, A. R., and Voulvoulis, N. (2007). "Improving petroleum contaminated land remediation decision-making through the MCA weighting process." *Chemosphere*, 66(5), 791-798.

Best Practices. (2003b). "Deterioration and inspection of water distribution systems." Best Practice by the National Guide to Sustainable Municipal Infrastructure, Issue No. 1.1, Ottawa.

Bhave, P. R. (2003). *Optimal design of water distribution networks*, Alpha Science Int'l Ltd, 1-6.

Blanchard, B.S. and Fabrycky, W.J. (1998). "Systems Engineering and Analysis, 3rd ed", Prentice-Hall, Upper Saddle River, NJ, 566-579.

CIRC. (2016). "Canadian Infrastructure Report Card" www.canadainfrastructure.ca.

Council, C. C. (2006). "Water Supply Asset Management Plan." *prepared by Rationale Limited, June*, 6-9,45-49,55.

Dalius Misiunas (2008) "FAILURE MONITORING AND ASSET CONDITION ASSSESSMENT IN WATER SUPPLY SYSTEMS"Vilnius Gediminas Technical University, Faculty of Environmental Engineering, Sauletekio al. 11, Vilnius, Lithuania, 648-655.

Deterioration and Inspection of water distribution system (2003). "A BEST PRACTICE BY THE NATIONAL GUIDE TO SUSTAINABLE MUNICIPAL INFRASTRUCTURE. "Federation of Canadian Municipalities and National Research Council. 3-4

El Chanati, H. (2014). "Performance Assessment of Water Network Infrastructure." Concordia University.

EPA.(2013). " Drinking Water Distribution Systems" US Environmental Protection Agency www.epa.gov/dwsixyearreview/drinking-water-distribution-systems#Legionella_section

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

Filion, Y. R., MacLean, H. L., and Karney, B. W. (2004). "Life-cycle energy analysis of a water distribution system." *Journal of Infrastructure systems*, 120-130.

Gupta, R. S. (2001). *Hydrology and hydraulic systems*, Waveland Press Long Grove, Ill, 659.

Haider, A. (2012). *Information systems for engineering and infrastructure asset management*, Springer Science & Business Media, 21.

Hansen, P., and Ombler, F. (2008). "A new method for scoring additive multi-attribute value models using pairwise rankings of alternatives." *Journal of Multi-Criteria Decision Analysis*, 15(3-4), 87-107.

Hansen & Ombler (2008). "1000Minds software, implementing the PAPRIKA method" www.1000minds.com

Harlow, V. K., and Stewart, D. (2006). "Condition assessment: should you risk it?" *Water asset management international*, 2-4.

Hastings, N. A. J. (2000). *Asset management and maintenance*, Queensland University of Technology, 164-165, 251-252, 258.

InfraGuide. (2005). "Managing Infrastructure Assets". Canada: InfraGuide best practice, National Guide to Sustainable Municipal Infrastructure.

InfraGuide. (2006). "Managing Risk". Canada: InfraGuide best practice, National Guide to Sustainable Municipal Infrastructure.

IIMM (2006). "International Infrastructure Management Manual, International edition 2006"

IPWEA "Condition Assessment & Asset Performance Guidelines " Australia ,4-6,16-18. http://www.ipwea.org/search?executeSearch=true&SearchTerm=Preamble+Document#sthash.gzw0hLKy.dpuf)

Keeney, R.L., Raiffa, H., (1976). "Decisions with Multiple Objectives: Preferences and Value Trade-offs." Wiley, New York.

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

Institute for water resources (2013). "Best Practice in Asset Management" US Army Corps of Engineers www.iwr.usace. Army.mil

Kleiner, Y., and Rajani, B. (2002). "Forecasting variations and trends in water-main breaks." *J. Infrastruct. Syst.*, 8(4), 122–131.

Lansey, K., Basnet, C., Mays, L., and Woodburn, J. (1992). "Optimal maintenance scheduling for water distribution systems." *Civil Engineering Systems*, 9(3), 211-226.

Makar, J. M., and Kleiner, Y. (2000). "Maintaining water pipeline integrity." Proc., AWWA Infrastructure Conf. and Exhibition, Baltimore,1-13.

Mitchell, J., and Carlson, J. (2001). "Equipment asset management–what are the real requirements." *Reliability magazine*, 4, 14.

Miles, S. W., Styers, F. C., and Nesbit, C. M. (2007). "Setting pipeline rehabilitation priorities to achieve "best" results—A case study using condition and criticality criteria." Proc., Pipelines 2007: Advances and Experiences with Trenchless Pipeline Projects, ASCE, Reston, VA, 1–10.

Murray, A. T., and Grubesic, T. (2007). *Critical infrastructure: reliability and vulnerability*, Springer Science & Business Media, 1-8.

Najafi, M., and Kulandaivel, G. "Pipeline condition prediction using neural network models." *Proc., Pipelines 2005@ sOptimizing Pipeline Design, Operations, and Maintenance in Today's Economy*, ASCE, 767-781.

Neil S. Grigg, Darrell G. Fontane, and Johan van Zyl (2013). "Water Distribution System Risk Tool for Investment Planning-Web Report #4332".Water Research Foundation. http://www.waterrf.org/Pages/Index3.aspx

Nesbit, C. M. (2007). "Setting Pipeline Rehabilitation Priorities to Achieve "Best" Results–A Case Study Using Condition and Criticality Criteria S. Wayne Miles, PE, BCEE Frank C. Styers, PE 2."

New Zealand Water and Wastes Association Inc (2006). "New Zealand Pipe Inspection Manual 3rd Edition", Wellington, New Zealand, Email water@NZWWA.org.nz, ii-1-ii-4,2-6-2-7,4-1-4-2.

New Zealand Water and Wastes Association Inc (1999). "Infrastructure Asset Grading Guidelines". Wellington 6140 New Zealand. www.nzwwa.org.nz , 20-22,49,59

Organization, W. H. (2004). *Guidelines for drinking-water quality: recommendations*, World Health Organization.

O'Day, D.K, Weiss, R., Chiavari, S., and Blair, D. (1986). "Water main evaluation for renewal /replacement." American water work association research foundation (90509), Denver, Colorado.

Piratla, K. R., and Ariaratnam, S. T. (2011). "Criticality Analysis of Water Distribution Pipelines." *Journal of Pipeline Systems Engineering and Practice*, 2(3), 91-101.

P. Klingel (2010) "Von intermittierender zu kontinuierlicher Wasserverteilung in Entwicklungsländern",PhD thesis, Karlsruhe Institute of Technology, Department of Civil Engineering Geo and Environmental Sciences, Karlsruhe, Germany.

Porirua City Council (2012), "Water supply asset management plan". Porirua City, Newzeland 47-48

Pöyhönen, M., and Hämäläinen, R. P. (2001). "On the convergence of multiattribute weighting methods." *European Journal of Operational Research*, 129(3), 569-585.

Rahman, S., Devera, J. and Reynolds, J., (2014) . "Risk Assessment Model for Pipe Rehabilitation and Replacement in a Water Distribution System". InPipelines 2014@ sFrom Underground to the Forefront of Innovation and Sustainability (pp. 1997-2006). ASCE.

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.

Salman, A. (2011). "Reliability-based management of water distribution networks." Concordia University.

Schuman, C. A., and Brent, A. C. (2005). "Asset life cycle management: towards improving physical asset performance in the process industry." *International Journal of Operations & Production Management*, 25(6), 566-579.

Shahata, K., and Zayed, T. "Simulation as a tool for life cycle cost analysis." *Proc., Proceedings of the 40th conference on winter simulation*, Winter Simulation Conference, 2497-2503.

Shamir, U., and Howard, C. D. D. (1979). "An analytical approach to scheduling pipe replacement." J. Am. Water Works Assoc., 71(5), 24–258.

Stapelberg, R. (2006). "Professional Skills Training in Integrated Asset Management: How to Develop and Implement the Essential Organisational Asset Management Functions." *Engineering Asset Management*, Springer, 1243-1251.

Sydney water Business Management system (BMIS), (2010) " BMIS Number : AMQ0008" http://www.sydneywater.com.au

Tarrant Regional Water District (2013). "Tarrant Regional Water District Integrated Water Supply Plan", ES-7-ES-8,1-13-1-14,2-1-2-3.

UMA Engineering Ltd.(AECOM) (2007). "Water Main Management Framework: technical report" UMA Engineering Ltd.(AECOM), Mississauga, Ontario, Canada.

U.S. Department of Transportation (2006). “Freight in America , A New national picture” U.S. Department of Transportation Research and Innovative Technology Administration Bureau of Transportation Statistics, 1-4.

Twort, A. C., Ratnayaka, D. D., and Brandt, M. J. (2000). *Water supply*, Butterworth-Heinemann, 569.

Walski, T. M., and Male, J. W. (2000). "Maintenance and rehabilitation/replacement." *Water distribution system handbook (LW Mays)*17.10 .

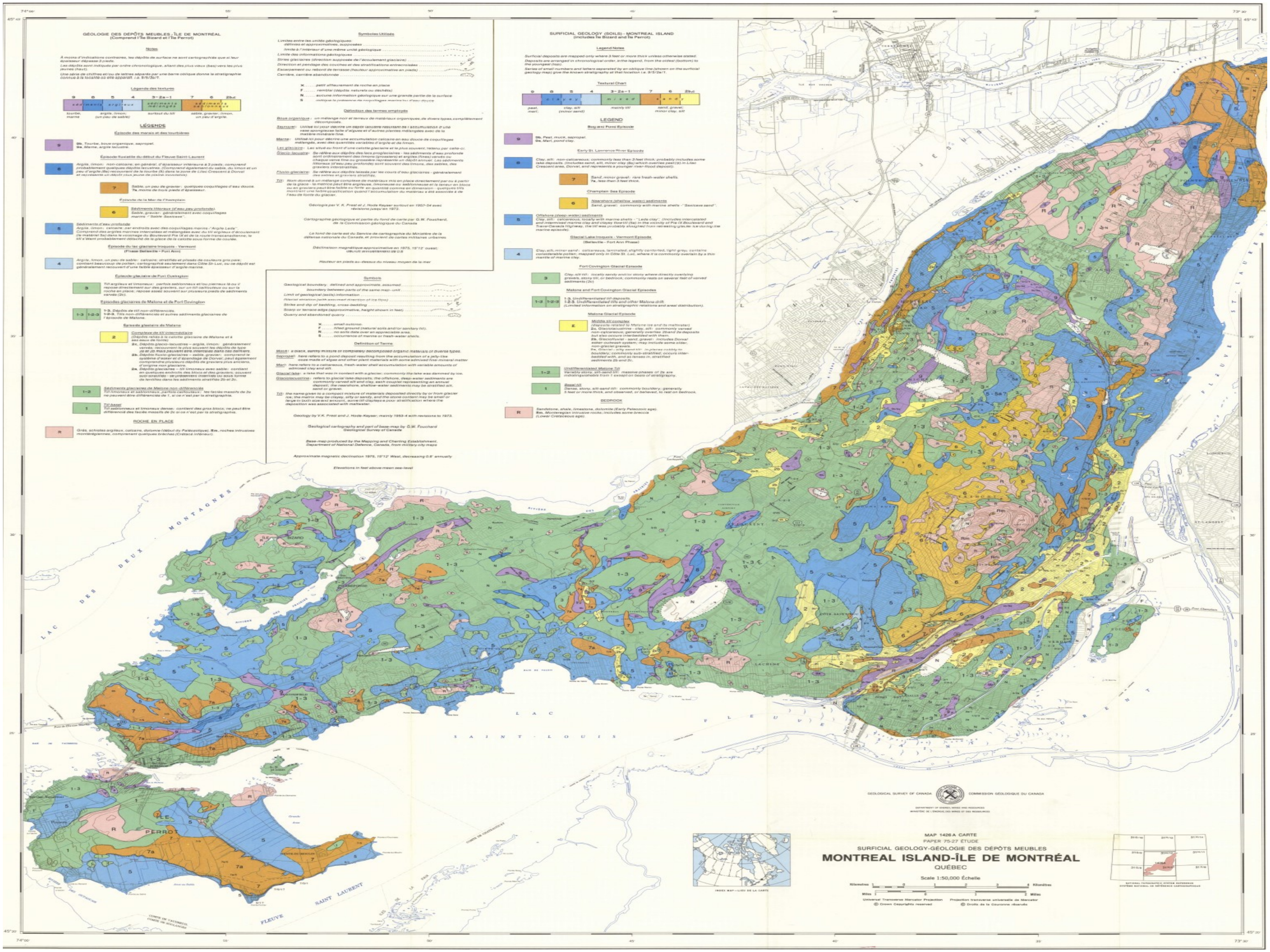
Von Winterfeldt, D., Edwards, W(1986). "Decision Analysis and Behavioral Research. " Cambridge University Press, Cambridge.

Water Environment Research Foundation (2011). SIMPLE: Water and wastewater sustainable infrastructure management program learning environment. http://simple.werf.org/.

Y. Kleiner and B. Rajani (2001). "Comprehensive review of structural deterioration of water mains: statistical models." Urban water 3(3): 131-150.

Appendix 1

Maps and Diagrams



GÉOLOGIE DES DÉPÔTS MEUBLES - ÎLE DE MONTRÉAL
(Comprend l'Île Bizard et l'Île Perrot)

Notes

À moins d'indications contraires, les dépôts de surface ne sont cartographiés que si leur épaisseur dépasse 3 pieds.

Les dépôts sont indiqués par ordre chronologique, allant des plus vieux (bas) vers les plus jeunes (haut).

Une série de chiffres et/ou de lettres séparés par une barre oblique donne la stratigraphie connue à la localité où elle apparaît, i.e. 9/5/2a/1.

Légende des textures

9	8	5	4	3–2a–1	7	6	2b,c
sédiments argileux				sédiments mélangés	sédiments sablonneux		
tourbe, marne	argile, limon; (un peu de sable)			surtout du till	sable, gravier; limon, un peu d'argile.		

LÉGENDE

Épisode des marais et des tourbières

9 — **9b**, *Tourbe, boue organique, sapropel.* **9a**, *Marne, argile lacustre.*

Épisode fluviatile du début du Fleuve Saint-Laurent

8 — *Argile, limon: non-calcaire; en général, d'épaisseur inférieure à 3 pieds; comprend probablement quelques dépôts lacustres. (Comprend également du sable, du limon et un peu d'argile (8a) recouvrant de la tourbe (9) dans la zone de Lilac Crescent à Dorval et représente un dépôt plus jeune de plaine inondable).*

7 — *Sable, un peu de gravier: quelques coquillages d'eau douce.* **7a**, *moins de trois pieds d'épaisseur.*

Épisode de la Mer de Champlain

6 — *Sédiments littoraux (d'eau peu profonde).* *Sable, gravier: généralement avec coquillages marins - "Sable Saxicava".*

5 — *Sédiments d'eau profonde* *Argile, limon: calcaire; par endroits avec des coquillages marins - "Argile Leda". Comprend des argiles marines intercalées et mélangées avec du till argileux d'écoulement (le matériel 5a) dans le voisinage du Boulevard Pie IX et de la route transcanadienne; le till s'étant probablement détaché de la glace de la calotte sous forme de coulée.*

Épisode du lac glaciaire Iroquois - Vermont
(Phase Belleville - Fort Ann)

4 — *Argile, limon, un peu de sable: calcaire; stratifiés et plissés de couleurs gris pâle; contient beaucoup de pollen; cartographié seulement dans Côte St-Luc, ou ce dépôt est généralement recouvert d'une faible épaisseur d'argile marine.*

Épisode glaciaire de Fort Covington

3 — *Till argileux et limoneux: parfois sablonneux et/ou pierreux là ou il repose directement sur des graviers, sur un till caillouteux ou sur la roche en place; repose assez souvent sur plusieurs pieds de sédiments varvés (2c).*

Épisodes glaciaires de Malone et de Fort Covington

1–3 | 1–2–3 — **1-3**, *Dépôts de till non-différenciés.* **1-2-3**, *Tills non-différenciés et autres sédiments glaciaires de l'épisode de Malone.*

Épisode glaciaire de Malone

2 — *Complexe de till intermédiaire* *(Dépôts reliés à la calotte glaciaire de Malone et à ses eaux de fonte)*
- **2c**, *Dépôts glacio-lacustres — argile, limon: généralement varvés; recouvrent le plus souvent les dépôts de type 2a et 2b mais peuvent être intercalés dans ces derniers.*
- **2b**, *Dépôts fluvio-glaciaires — sable, gravier: comprend le système d'esker et d'épandage de Dorval; peut également comprendre plusieurs dépôts de graviers plus anciens, d'origine non glaciaire.*
- **2a**, *Dépôts glaciaires — till limoneux avec sable: contient en quelques endroits des blocs et des graviers; souvent sub-stratifiés; se présentent intercalés ou sous forme de lentilles dans les sédiments stratifiés 2b et 2c.*

1–2 — *Sédiments glaciaires de Malone non-différenciés* *Till limoneux et sablonneux, parfois caillouteux: les faciès massifs de 2a ne peuvent être différenciés de 1, si ce n'est par la stratigraphie.*

1 — *Till basal* *Till sablonneux et limoneux dense: contient des gros blocs; ne peut être différencié des faciès massifs de 2c si ce n'est par la stratigraphie.*

ROCHE EN PLACE

R — *Grès, schistes argileux, calcaire, dolomie (début du Paléozoïque).* **Rm**, *roches intrusives montérégiennes, comprenant quelques brèches (Crétacé inférieur).*

Symboles Utilisés

Limites entre les unités géologiques:
définies et approximatives, supposées
limite à l'intérieur d'une même unité géologique
Limite des informations géologiques
Stries glaciaires (direction supposée de l'écoulement glaciaire)
Direction et pendage des couches et des stratifications entrecroisées
Escarpement ou rebord de terrasse (hauteur approximative en pieds)
Carrière, carrière abandonnée

X....... *petit affleurement de roche en place*
F....... *remblai (dépôts naturels ou déchets)*
N....... *aucune information géologique sur une grande partie de la surface*
S....... *indique la présence de coquillages marins ou d'eau douce*

Définition des termes employés

Boue organique: *un mélange noir et terreux de matériaux organiques de divers types complètement décomposés.*

Sapropel: *Utilisé ici pour décrire un dépôt lacustre résultant de l'accumulation d'une vase spongieuse faite d'algues et d'autres plantes mélangées avec de la matière minérale fine.*

Marne: *Utilisé ici pour décrire une accumulation calcaire en eau douce de coquillages mélangés, avec des quantités variables d'argile et de limon.*

Lac glaciaire: *Lac situé au front d'une calotte glaciaire et le plus souvent, retenu par celle-ci.*

Glacio-lacustre: *Se réfère aux dépôts des lacs proglaciaires - les sédiments d'eau profonde sont ordinairement des limons (grossiers) et argiles (fines) varvés ou chaque varve fine ou grossière représente un dépôt annuel. Les sédiments littoraux (d'eau peu profonde) sont souvent des limons, des sables, des graviers interstratifiés.*

Fluvio-glaciaire: *Se réfère aux dépôts laissés par les cours d'eau glaciaires - généralement des sables et graviers stratifiés.*

Till: *Nom donné à un mélange complexe de matériaux mis en place directement par ou à partir de la glace - la matrice peut être argileuse, limoneuse ou sablonneuse et la teneur en blocs ou en graviers peut être faible ou forte en quantité comme en dimension - quelques tills montrent une faible stratification quand l'accumulation du matériau a été associée à de l'eau de fonte du glacier.*

Géologie par V. K. Prest et J. Hode Keyser surtout en 1953-54 avec révisions jusqu'en 1973.

Cartographie géologique et partie du fond de carte par G.W. Fouchard, de la Commission géologique du Canada

Le fond de carte est du Service de cartographie du Ministère de la défense nationale du Canada, et provient de cartes militaires urbaines.

Déclinaison magnétique approximative en 1975, 15°12' ouest; décroît annuellement de 0.6'

Hauteur en pieds au-dessus du niveau moyen de la mer

Symbols

Geological boundary: defined and approximate, assumed
boundary between parts of the same map-unit
Limit of geological (soils) information
Glacial striation (with assumed direction of ice flow)
Strike and dip of bedding, cross-bedding
Scarp or terrace edge (approximative, height shown in feet)
Quarry and abandoned quarry

X....... *small outcrop.*
F....... *filled ground (natural soils and/or sanitary fill).*
N....... *no soils data over an appreciable area.*
S....... *occurrence of marine or fresh-water shells.*

Definition of Terms

Muck: *a black, earthy mixture of completely decomposed organic materials of diverse types.*

Sapropel: *here refers to a pond deposit resulting from the accumulation of a jelly-like ooze made of algae and other plant materials with some admixed fine-mineral matter.*

Marl: *here refers to a calcareous, fresh-water shell accumulation with variable amounts of admixed clay and silt.*

Glacial lake: *a lake that was in contact with a glacier; commonly the lake was dammed by ice.*

Glaciolacustrine: *refers to glacial lake deposits; the offshore, deep-water sediments are commonly varved silt and clay, each couplet representing an annual deposit; the nearshore, shallow-water sediments may be stratified silt, sand or gravel.*

Till: *the name given to a compact mixture of materials deposited directly by or from glacier ice; the matrix may be clayey, silty or sandy, and the stone content may be small or large in both size and amount; some till displays a poor stratification where the deposition was associated with meltwater.*

Geology by V.K. Prest and J. Hode-Keyser; mainly 1953-4 with revisions to 1973.

Geological cartography and part of base-map by G.W. Fouchard Geological Survey of Canada

Base-map produced by the Mapping and Charting Establishment, Department of National Defence, Canada, from military city maps

Approximate magnetic declination 1975, 15°12' West, decreasing 0.6' annually

Elevations in feet above mean sea-level

SURFICIAL GEOLOGY (SOILS) - MONTREAL ISLAND
(includes Île Bizard and Île Perrot)

Legend Notes

Surficial deposits are mapped only where 3 feet or more thick unless otherwise stated.

Deposits are arranged in chronological order, in the legend, from the oldest (bottom) to the youngest (top).

Series of small numbers and letters separated by an oblique line (shown on the surficial geology map) give the known stratigraphy at that location i.e. 9/5/2a/1.

Textural Chart

9	8	5	4	3–2a–1	7	6	2b,c
	clayey			mixed	sandy		
peat, marl;	clay, silt (minor sand)			mainly till	sand, gravel; minor clay, silt		

LEGEND

Bog and Pond Episode

9 — **9b**, *Peat, muck, sapropel.* **9a**, *Marl, pond clay.*

Early St. Lawrence River Episode

8 — *Clay, silt: non-calcareous; commonly less than 3 feet thick; probably includes some lake deposits. (includes sand, silt, minor clay (8a) which overlies peat (9) in Lilac Crescent area, Dorval, and represents a younger river-flood deposit).*

7 — *Sand, minor gravel: rare fresh-water shells.* **7a**, *less than 3 feet thick.*

Champlain Sea Episode

6 — *Nearshore (shallow water) sediments* *Sand, gravel: commonly with marine shells - "Saxicava sand".*

5 — *Offshore (deep-water) sediments* *Clay, silt: calcareous; locally with marine shells - "Leda clay". (includes intercalated and intermixed marine clay and clayey flow till (5a) in the vicinity of Pie IX Boulevard and Trans-Canada Highway, the till was probably sloughed from retreating glacier ice during the marine episode).*

Glacial Lake Iroquois - Vermont Episode
(Belleville - Fort Ann Phase)

4 — *Clay, silt, minor sand: calcareous, laminated, slightly contorted, light grey; contains considerable pollen; mapped only in Côte St. Luc, where it is commonly overlain by a thin mantle of marine clay.*

Fort Covington Glacial Episode

3 — *Clay-silt till: locally sandy and/or stony where directly overlying gravels, stony till, or bedrock; commonly rests on several feet of varved sediments (2c).*

Malone and Fort Covington Glacial Episodes

1–3 | 1–2–3 — **1-3**, *Undifferentiated till deposits.* **1-2-3**, *Undifferentiated tills and other Malone drift.* *(Limited information on stratigraphic relations and areal distribution).*

Malone Glacial Episode

2 — *Middle till complex* *(deposits related to Malone ice and its meltwater)*
- **2c**, *Glaciolacustrine - clay, silt: commonly varved non-calcareous; generally overlies 2b and 2a deposits but also occurs interbedded with them.*
- **2b**, *Glaciofluvial - sand, gravel: includes Dorval esker-outwash system; may include some older, non-glacial gravels.*
- **2a**, *Glacial - silty sand till: in places cobbly to bouldery; commonly sub-stratified; occurs interbedded with, and as lenses in, stratified sediments 2b and 2c.*

1–2 — *Undifferentiated Malone Till* *Variably stony, silt-sand till: massive phases of 2a are indistinguishable from 1 except on basis of stratigraphy.*

1 — *Basal till* *Dense, stony, silt-sand till: commonly bouldery; generally 5 feet or more thick, and observed, or believed, to rest on bedrock.*

BEDROCK

R — *Sandstone, shale, limestone, dolomite (Early Paleozoic age).* **Rm**, *Monteregian intrusive rocks; includes some breccia (Lower Cretaceous age).*

GEOLOGICAL SURVEY OF CANADA — COMMISSION GÉOLOGIQUE DU CANADA
DEPARTMENT OF ENERGY, MINES AND RESOURCES
MINISTÈRE DE L'ÉNERGIE, DES MINES ET DES RESSOURCES

MAP 1426A CARTE
PAPER 75-27 ÉTUDE

SURFICIAL GEOLOGY-GÉOLOGIE DES DÉPÔTS MEUBLES
MONTREAL ISLAND-ÎLE DE MONTRÉAL
QUÉBEC

Scale 1:50,000 Échelle

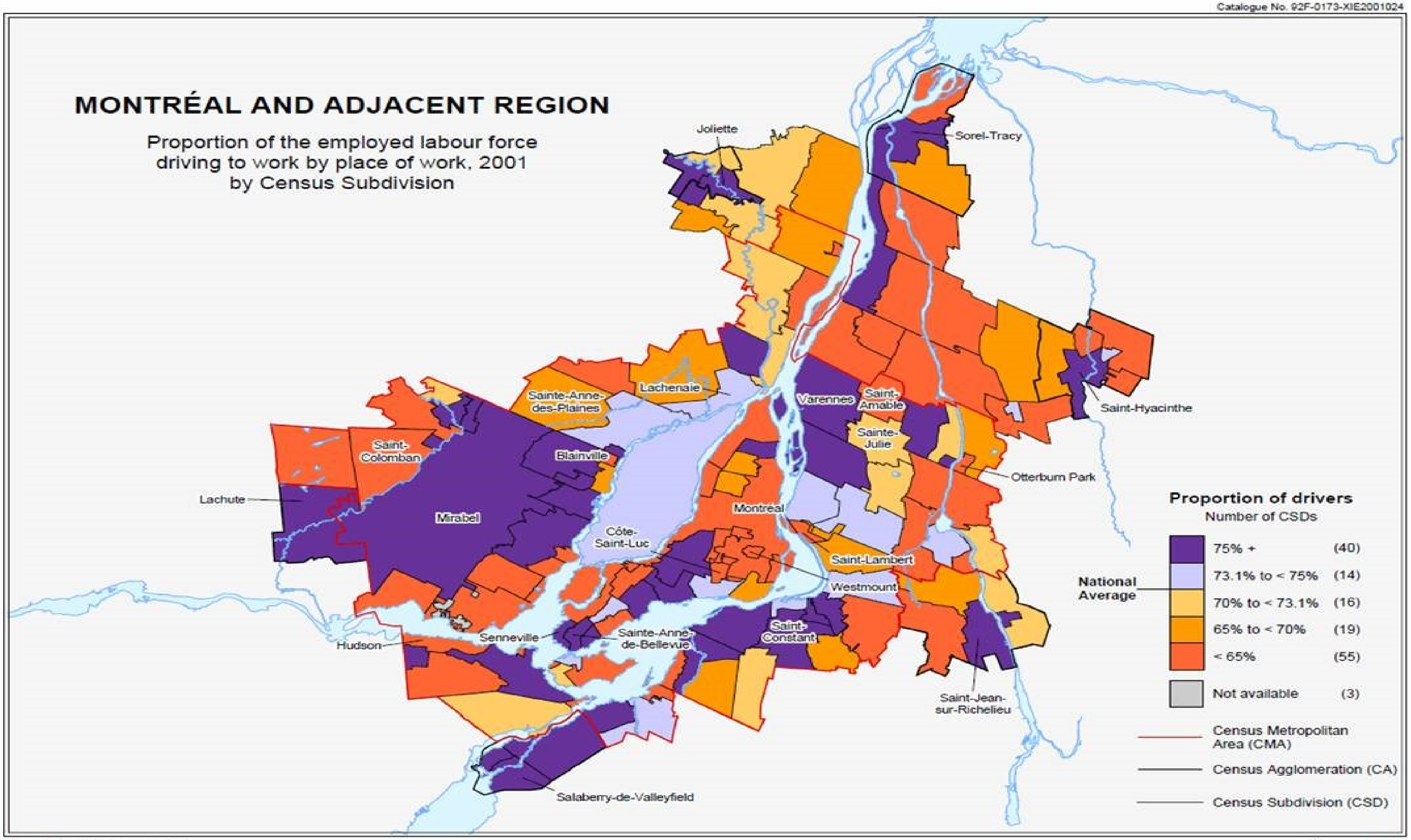
Kilometres 1 0 1 2 3 4 Kilomètres
Miles 1 0 1 2 Milles

Universal Transverse Mercator Projection — Projection transverse universelle de Mercator

NATIONAL TOPOGRAPHIC SYSTEM REFERENCE
SYSTÈME NATIONAL DE RÉFÉRENCE CARTOGRAPHIQUE

INDEX MAP—LIEU DE LA CARTE

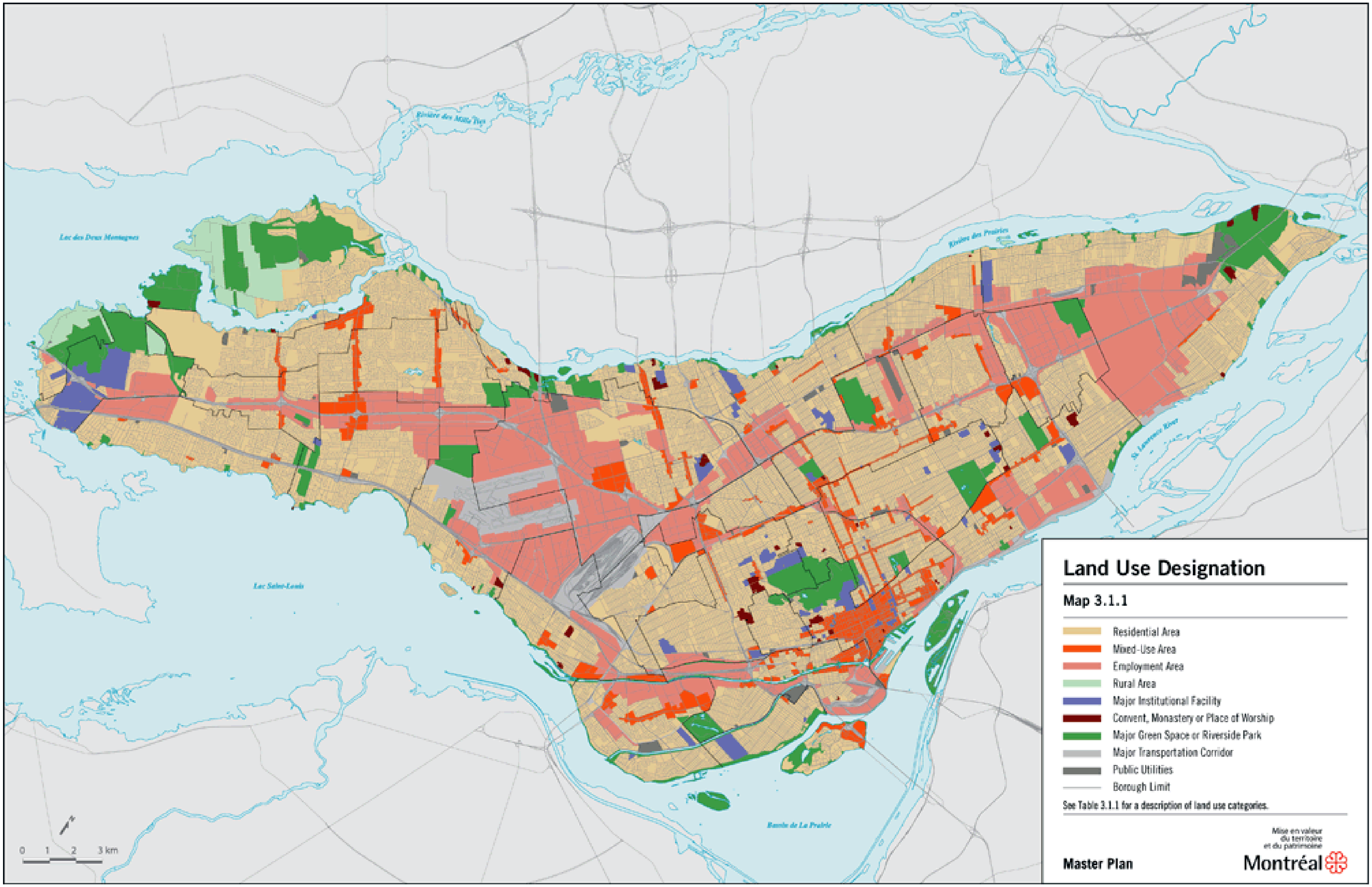
Catalogue No. 92F-0173-XIE2001024



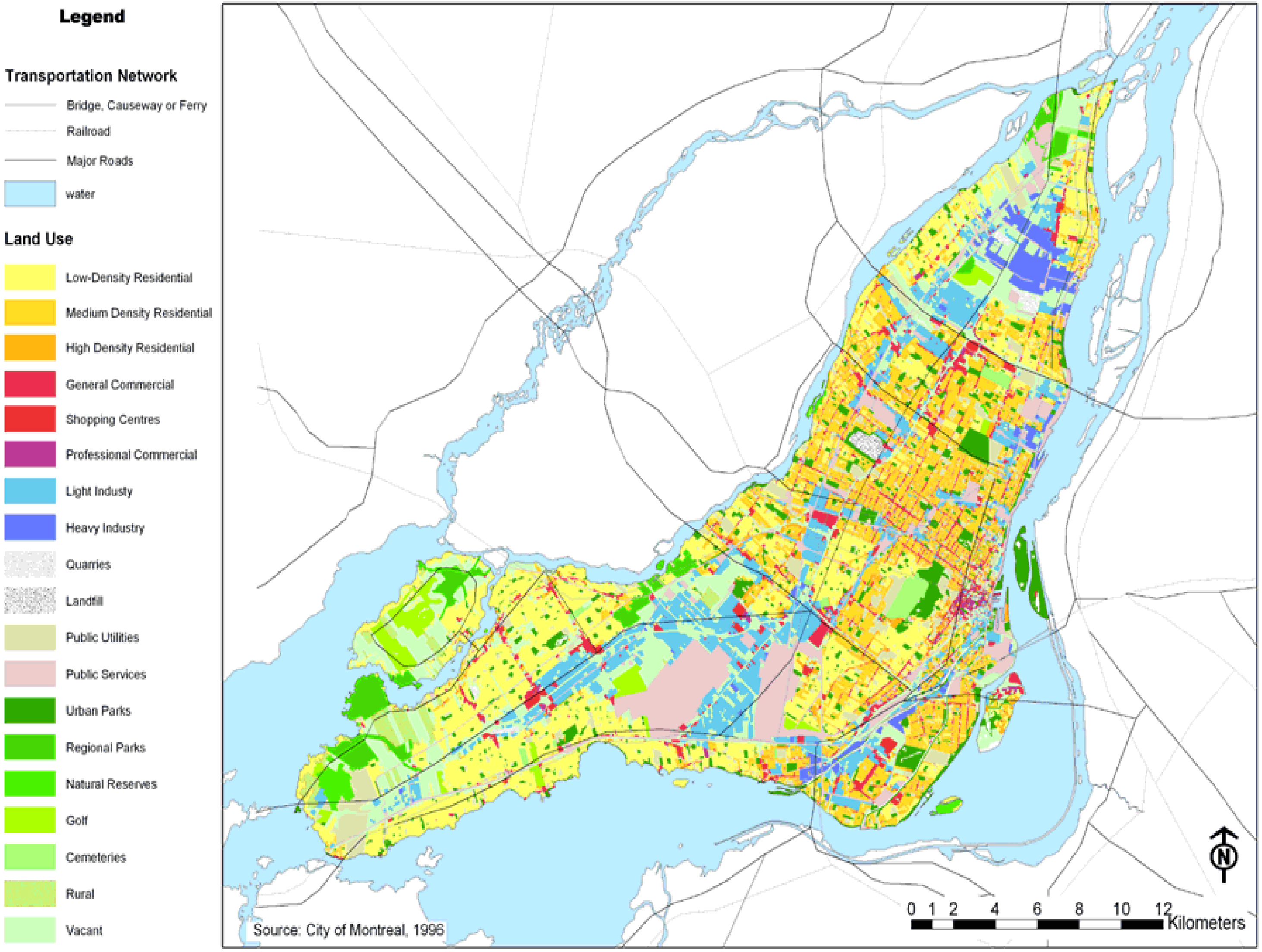
Statistics Canada Statistique Canada

Source: 2001 Census of Canada. Produced by the Geography Division, Statistics Canada, 2002.

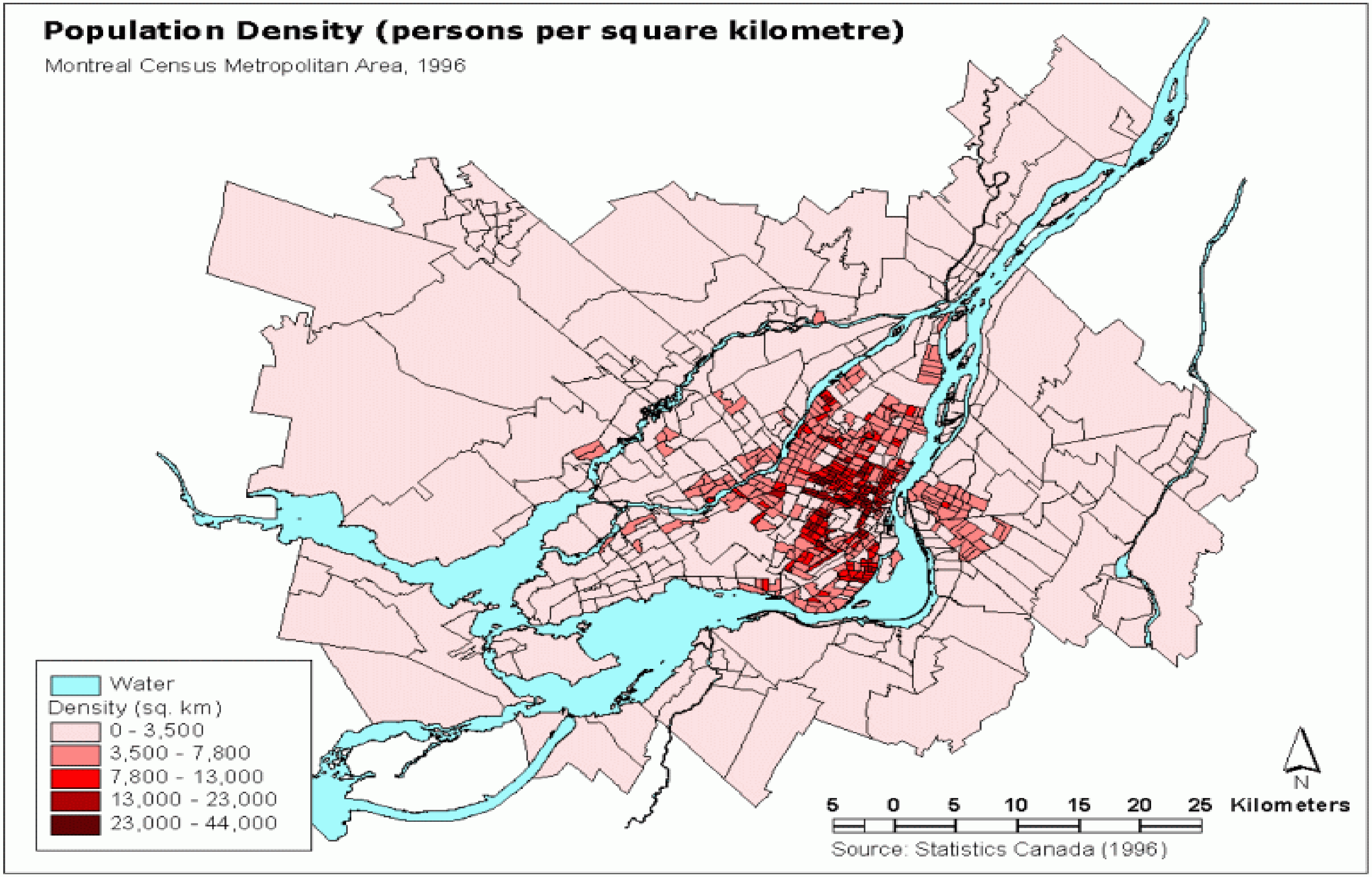
Canada


Land Use Designation
Map 3.1.1
Residential Area
Mixed-Use Area
Employment Area
Rural Area
Major Institutional Facility
Convent, Monastery or Place of Worship
Major Green Space or Riverside Park
Major Transportation Corridor
Public Utilities
Borough Limit
See Table 3.1.1 for a description of land use categories.
Master Plan
Mise en valeur du territoire et du patrimoine
Montréal
Lac des Deux Montagnes
Rivière des Mille Îles
Rivière des Prairies
Lac Saint-Louis
St. Lawrence River
Bassin de La Prairie
N
0 1 2 3 km

Montreal Island Land Use 1996



Source: City of Montreal, 1996


Population Density (persons per square kilometre)
Montreal Census Metropolitan Area, 1996
Water
Density (sq. km)
0 - 3,500
3,500 - 7,800
7,800 - 13,000
13,000 - 23,000
23,000 - 44,000
N
5 0 5 10 15 20 25 Kilometers
Source: Statistics Canada (1996)

Appendix 2

Questionnaires Samples

Concordia University

جامعة قطر
QATAR UNIVERSITY

Department of Civil & Architectural Engineering

RELIABILITY AND CRITICALITY ASSESSMENT OF WATER NETWORK

Dear Sir/Madam

We would like to present our appreciation and thanks to you for taking part of your time to complete this questionnaire that aims to identify the degree of importance for the factors affecting water **networks' reliability**[1] **and criticality**. The questionnaire is a part of the requirements for an academic research that is funded by Qatar National Research Fund (QNRF) and performed under the supervision of Qatar and Concordia Universities to build a reliability and criticality assessment models for water networks. The information in the questionnaire will be used for academic research with complete commitment of confidentiality to your information.

To meet the above mentioned purpose, each network of water pipelines will be divided into segments which include the pipes and accessories between two isolation valves. A model is developed based on the score of segment importance and the in-accessibility of the components in the segments (i.e. pipe, valve, and hydrant). This model considers, as well, the effect of failure and working conditions on the water accessibility of customers and the **reliability of the components**[2] by applying previous developed models. Accordingly, aggregation of the segments' reliability considering their importance score will constitute the reliability of a water network.

PART (1): GENERAL INFORMATION

1) How do you describe your occupation?

- ☐ Pipeline Inspection Expert
- ☐ Pipeline Department Manager
- ☑ Pipeline Engineer
- ☐ Others _______________

2) Which best describes your working experience?

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

---

[1] **Network reliability**: Reliability of the network as a result of the aggregation of the components' reliability, their failure effect on segment accessibility, and the weight of importance of the segments

[2] **Component reliability**: Performance of components calculated from the previous models

A: RELIABILITY ASSESMENT MODEL

PART (A-1): SEGMENTS' IMPORTANCE FACTORS

The segments of a water network are classified into 7 area types such as commercial, educational, etc. Each area has components. In the following table, you need to evaluate the level of importance for each component by giving a percentage. The higher the percentage the more importance is the component. The outcome will be used to prioritize **segments**[3] accordingly.

Table 2: Evaluation of area components

Area	**Example(s)**	**Importance in %**
Agriculture	- Crops - Pastures	10
Commercial	-Shops (restaurants, supermarkets, retail stores … etc.) -Business offices - Hotels, guesthouses, motels	15
Institutional	- Schools, colleges and universities	10
Industrial	- Factories	5
Health Care Facilities	- Medical centers and hospitals	40
Residential	- Buildings, housing sets	20

/100

Giving the importance level in percentages from the above, provide a value range as described in the following table. This range will define the final score of the component. The score will show the importance level on a scale of 10 where 10 is the highest value. The result from this part is to find the **segments' weights of importance**[4].

Table 3: Defining the importance level

	1	**2**	**3**
	Qualitative Description	**Quantitative Value Range**	**Effect Value On Importance Level (0 – 10)**
Importance Level	Extremely high	(9) to (10)	10*
	Very high	(8) to (9)	
	High	(7) to (8)	
	Average	(4) to (6)	
	Below average	(0) to (3)	

* Extremely high importance is scored as 10 which presents the highest Value for the importance level of an area component within a network segment.

---

[3] **Segment:** Part of the water network between two isolation valves

[4] **Segments' weights of importance**: Calculated based on importance of the buildings that are being served and the consumption rates

PART (A-2): ACCESSIBILITY IMPORTNACE LEVELS

In-accessibility[5] of the components of a water network in case of working and failing conditions will be measured from very low to very high levels. A very low in-accessibility level means that the component has the highest contribution level with respect to the reliability of the network and vice versa. Accordingly, please define the unit of measure of in-accessibility (i.e. hours or days) for each level of in-accessibility as well as the quantitative value range of in-accessibility. In addition insert an effect value for each level of in-accessibility to measure the effect of various components on the reliability of the water network.

Table 4: Level of in-accessibility

?

	1	2	3	4
	Qualitative Description	**Unit of Measure (Hours or days)**	**Quantitative Value Range**	**Effect Value On Water Network Reliability 0 – 10**
In-Accessibility	**Very Low "VL"**	4 HOUR BLOCKS	( ) to ( )	10*
	Low "L"	12 HOURS	( ) to ( )	
	Moderate "M"	1 DAY	( ) to ( )	
	High "H"	3 DAYS	( ) to ( )	
	Very High "VH"	7 DAYS	( ) to ( )	
* Very High accessibility's effect value on the reliability of the network is scored as 10 which presents the highest Value for the accessibility- based reliability assessment of a component of a network.				

The research group has developed some models which can measure the performance of the components of a water network including the pipes and the accessories. The performance is measured from zero to ten. Ten shows the best condition of the component; while, zero presents the lowest. These models will be used for the reliability assessment of the networks. In the following tables assign a level of in-accessibility to the failure condition of the components for each level of performance.

Table 5: Level of in-accessibility with respect to the performance score of the water network components

	Level of in-accessibility of component in case of failure "VL", "L", "M", "H" or "VH"		
Performance score	**Pipes**	**Hydrants**	**Valves**
10-8	M	VH	VH
8-6	L	VH	VH
6-4	L	VH	H
4-2	VL	VH	H
2-0	VL	VH	H

---

[5] **In-accessibility**: Is the opposite of the accessibility and is the measure of how much the customers will not have access to the water. **Accessibility**: Is a measure of how reachable can water be to a customer in a segment. **Segment accessibility**: Accessibility of the segment considering the belief degree of the failure and working conditions of the components. **Network accessibility**: Aggregation of the segments' accessibility after considering the segments' weights of importance.

B: CRITICALITY ASSESSMENT MODEL

This part of the questionnaire aims to assess the degree of importance of the factors affecting the criticality of the potential failures of water pipelines. Figure 1 presents the main factors and sub-factors that will be used in the criticality assessment model.

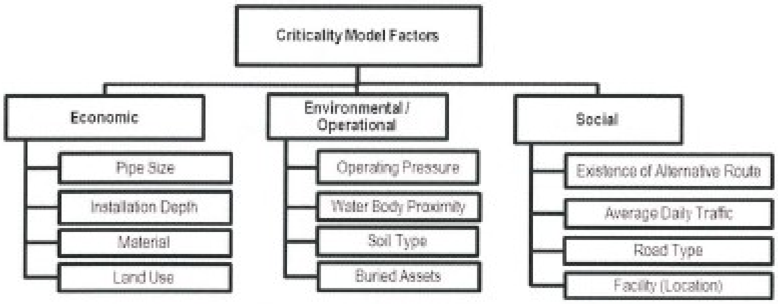


Figure 1: Factors Affecting the Condition of Water Pipelines

PART (B-1): WATER PIPELINES OVERALL WEIGHTING AND ASSESSMENT

In the following table determine the importance of the main factors with respect to the total criticality of the possible failures of pipelines from 1 to 10, where "1" represents the least important and "10" represents the most important factor.

	Main Factors	Importance with respect to total criticality (1-10)
Total Criticality of pipe failure	Economic	2 – 6
	Environmental	4 – 7
	Social	8 – 10

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

In order to determine the criticality index of pipelines; it is required to determine the score of factors. As a result, please kindly fill the table in the next page by identifying for each factor based on your experience:

- Importance score of each sub-factor *with respect to their associated main factor from 0 to 10, where* **"0"** represents the least important and **"10"** represents the most important factor.
- A corresponding **quantitative value range** for each parameter
- An **effect value range on pipeline criticality** from 0 to 10, where **"0"** represents the most critical and **"10"** represents the least critical possible failure.

Example:

*In the table below, consider evaluating the **"Pipeline Diameter"** factor.*

Main Factor	Sub-factors	Unit of Measure	Importance with respect to main factor	Qualitative Description (Parameters)	Quantitative Value Range *(if applicable)*	Effect Value Range On Pipeline Criticality (0 – 10)
E*	Pipeline Diameter	(Inches)		Large	( ) to ( )	( ) to ( )
				Medium	( ) to ( )	( ) to ( )
				Small	( ) to ( )	( ) to ( )

E*: Economic factors

*Please evaluate the importance of ~~the sub-factors~~ with respect to their ~~associated~~ main factor within the range of **"one to ten"** in this box.*

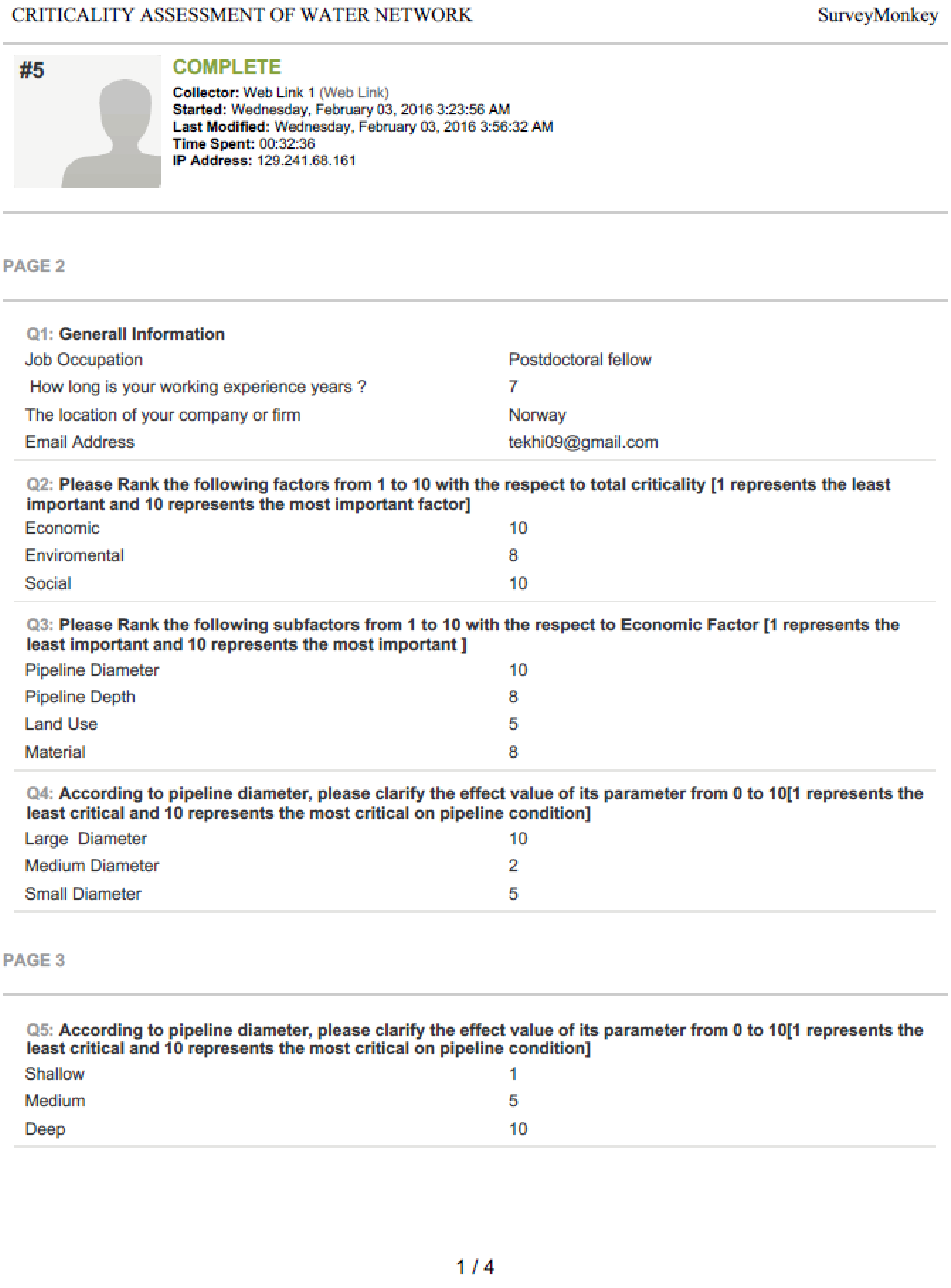
*The "Quantitative Value Range" can be **"36 to 50 inches","18 to 36 inches"**, and **"3 to 18 inches"** for the "Large", "Medium", and "Small" parameters respectively.*

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

~~what are these~~,
(~~sub-factors~~.

Note: why isnt the unit of measure in mm? This is what is used by kahramaa and Ashghal

Main Factor	Sub-factors	Unit of Measure	Importance with respect to main factor (1-10)	Qualitative Description (Parameters)	Quantitative Value Range	Effect Value On Pipeline Condition (0 – 10)
Economic	Pipeline Diameter	mm (~~Inches~~)	3	Large	(450) to (∞)	(8) to (10)
				Medium	(200) to (400)	(4) to (7)
				Small	(50) to (200)	(0) to (3)
	Pipeline Depth	(Meters)	1	Shallow	(0) to (1)	(0) to (3)
				Medium	(1) to (3)	(4) to (7)
				Deep	(3) to (∞)	(8) to (10)
	Land Use	NA	5	Residential	NA	(8) to (10)
				Industrial/Commercial		(4) to (7)
				High Density		(0) to (3)
	Material	NA	1	Steel	NA	(8) to (10)
				Concrete		(0) to (3)
				PVC		(4) to (7)
				Poly Ethylene		(0) to (3)
				Iron		(0) to (3)
				Copper		(0) to (3)
Environmental/ Operational	Operating Pressure	(kPa ~~or psi~~)	7	High	(60) to (120)	(8) to (10)
				Medium	(21) to (59)	(4) to (7)
				Low	(0) to (20)	(0) to (3)
	Water Body Proximity	NA	0	Yes	NA	(0) to (0)
				[✓ No]		(0) to (0)
	Buried Assets Proximity	NA	5	Yes	NA	(5) to (10)
				No		(0) to (4)
	Soil Type	NA	0	Clay	NA ✓	( ) to ( )
				Rock		( ) to ( )
				Silt		( ) to ( )
				Sand		( ) to ( )
Social	Existence of Alternative Route	NA	5	Yes	NA	(5) to (10)
				No		(0) to (4)
	Average Daily Traffic	(AADT)	3	High	(5000) to (∞)	(9) to (10)
				Medium	(1000) to (5000)	(6) to (8)
				Low	(0) to (1000)	(0) to (5)
	Road Type	NA	8	Rural	NA	(0) to (3)
				Urban		(4) to (9)
				Interstate		(10) to (10)
	Nearby Facilities	NA	3	Yes	NA	(3) to (10)
				No		(0) to (2)



#5

COMPLETE

Collector: Web Link 1 (Web Link)
Started: Wednesday, February 03, 2016 3:23:56 AM
Last Modified: Wednesday, February 03, 2016 3:56:32 AM
Time Spent: 00:32:36
IP Address: 129.241.68.161

PAGE 2

Q1: **Generall Information**

Job Occupation	Postdoctoral fellow
How long is your working experience years ?	7
The location of your company or firm	Norway
Email Address	tekhi09@gmail.com

Q2: **Please Rank the following factors from 1 to 10 with the respect to total criticality [1 represents the least important and 10 represents the most important factor]**

Economic	10
Enviromental	8
Social	10

Q3: **Please Rank the following subfactors from 1 to 10 with the respect to Economic Factor [1 represents the least important and 10 represents the most important]**

Pipeline Diameter	10
Pipeline Depth	8
Land Use	5
Material	8

Q4: **According to pipeline diameter, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]**

Large Diameter	10
Medium Diameter	2
Small Diameter	5

PAGE 3

Q5: **According to pipeline diameter, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]**

Shallow	1
Medium	5
Deep	10

Q6: According to land use, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]

Residential	5
Industry/ Commercial	8
High Denisty	10

Q7: According to material, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]

Steel	8
Concrete	5
PVC	5
Poly Ethylene	5
Iron	8
Copper	10

Q8: Please Rank the following subfactors from 1 to 10 with the respect to Environmental/Operational Factor [1 represents the least important and 10 represents the most important]

Operating Pressure	10
Water Body Proximity (is defined by if the location is close to surface water, such as a lake, river etc...)	5
Buried Assets Proximity(is defined by if the location is close to another infrastructure services such as gas pipelines, sewers pipelines etc...)	8
Soil Type	5

PAGE 4

Q9: According to operating pressure, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]

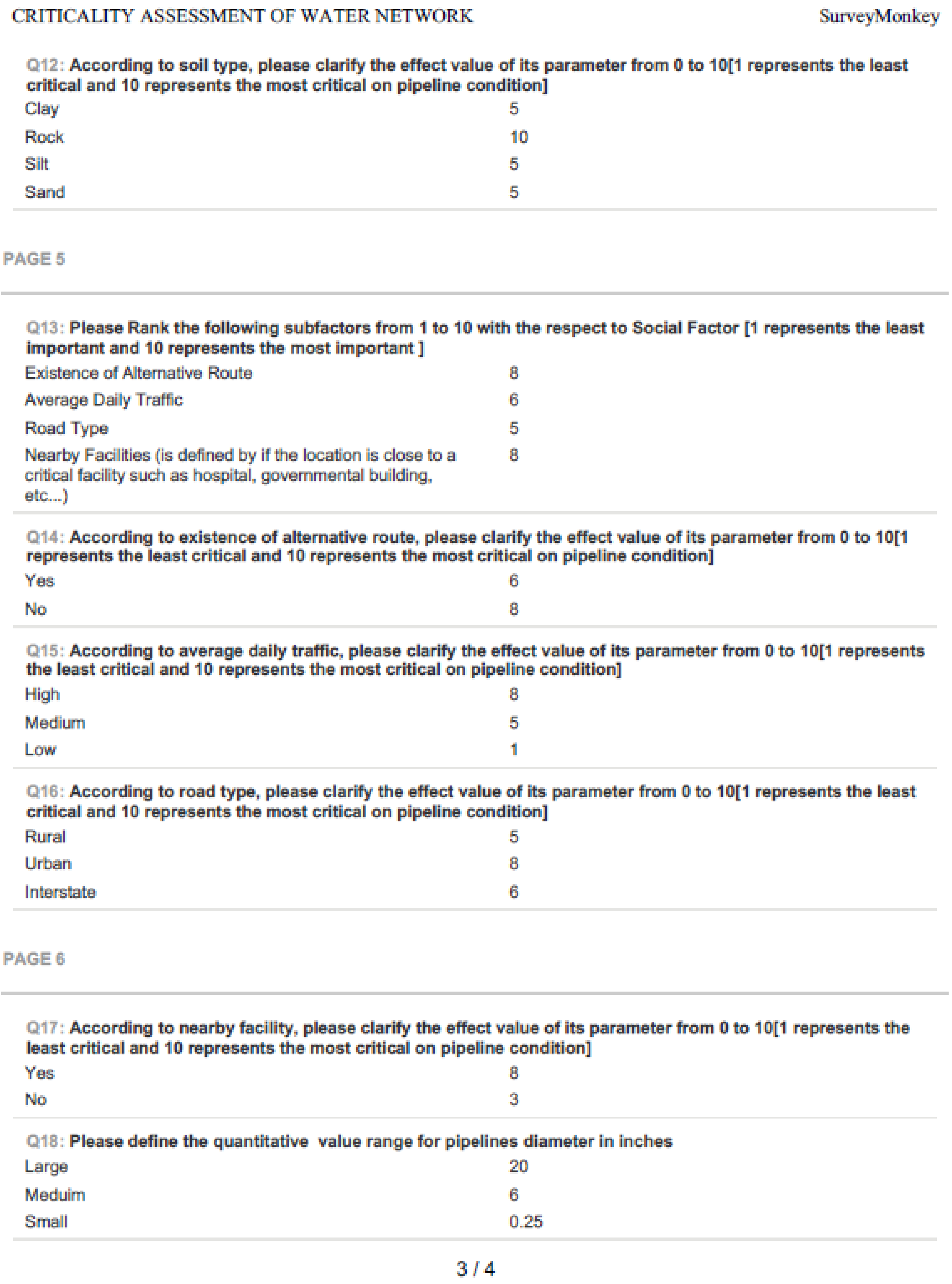
High	8
Medium	5
Low	10

Q10: According to water body proximity, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]

Yes	5
No	5

Q11: According to buried assets proximity, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]

Yes	8
No	1



Q12: According to soil type, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]

Clay	5
Rock	10
Silt	5
Sand	5

PAGE 5

Q13: Please Rank the following subfactors from 1 to 10 with the respect to Social Factor [1 represents the least important and 10 represents the most important]

Existence of Alternative Route	8
Average Daily Traffic	6
Road Type	5
Nearby Facilities (is defined by if the location is close to a critical facility such as hospital, governmental building, etc...)	8

Q14: According to existence of alternative route, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]

Yes	6
No	8

Q15: According to average daily traffic, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]

High	8
Medium	5
Low	1

Q16: According to road type, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]

Rural	5
Urban	8
Interstate	6

PAGE 6

Q17: According to nearby facility, please clarify the effect value of its parameter from 0 to 10[1 represents the least critical and 10 represents the most critical on pipeline condition]

Yes	8
No	3

Q18: Please define the quantitative value range for pipelines diameter in inches

Large	20
Meduim	6
Small	0.25

Q19: Please define the quantitative value range for pipelines depth in meters

Shallow	0.4
Meduim	0.8
Deep	1.3

Q20: Please define the quantitative value range for pipelines depth in meters

Shallow	0.4
Meduim	0.8
Deep	1.3

Q21: Please define the quantitative value range for operating pressure in psi

High	1200
Meduim	500
Low	120

Q22: Please define the quantitative value range for average daily traffic in (AADT)

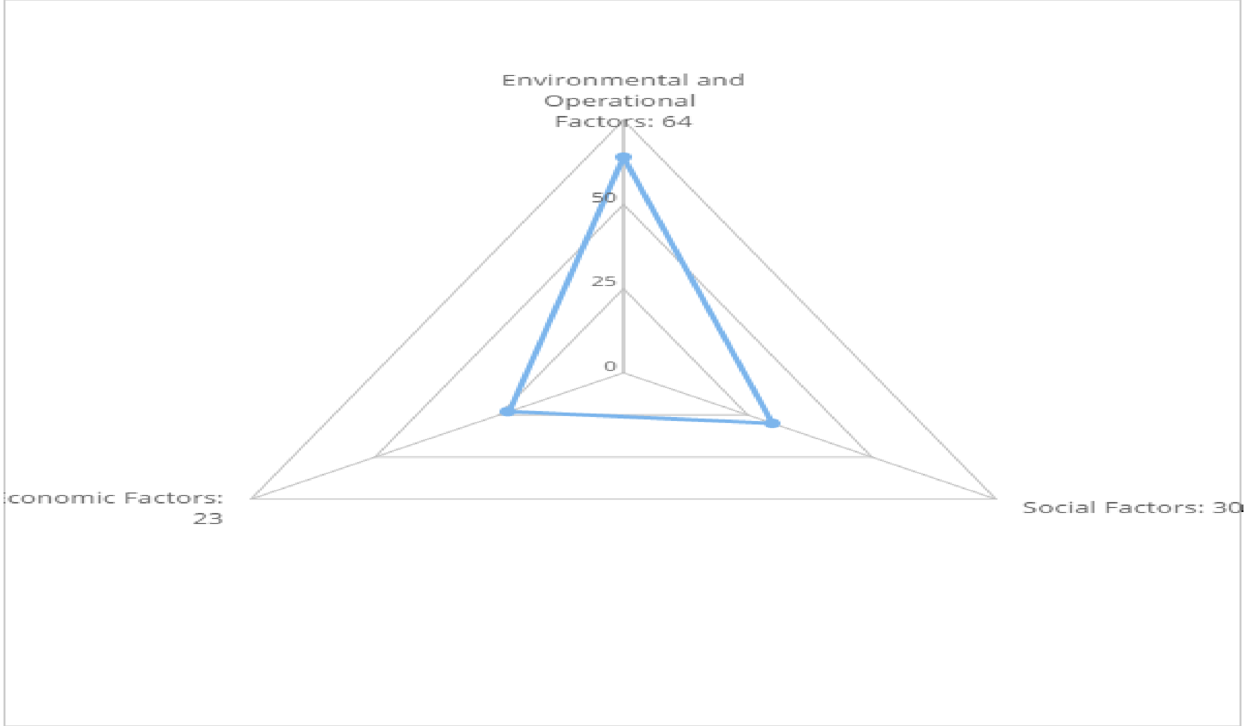
High	7000
Meduim	5000
Low	2000

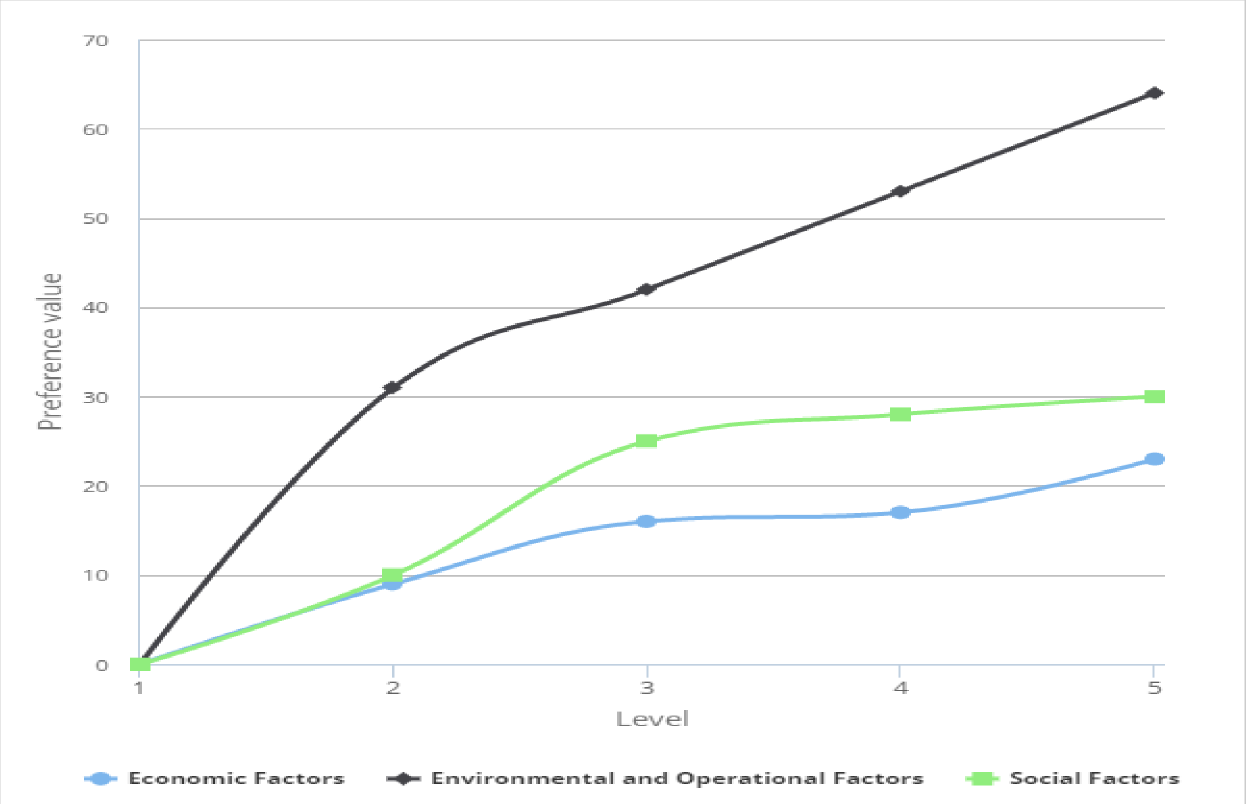
Appendix 3

1000 Minds Software Results

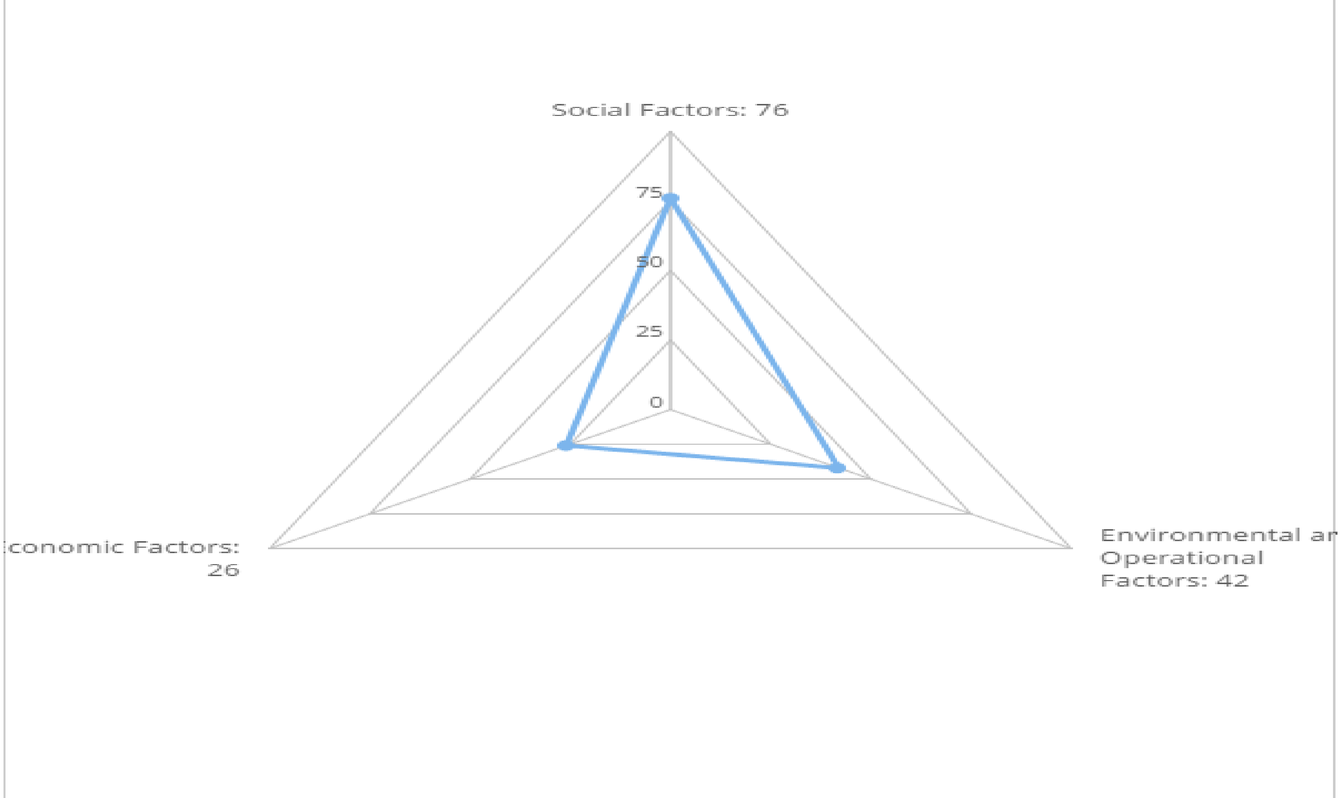
Qatar-Data Responds (1-5)

Response # 1

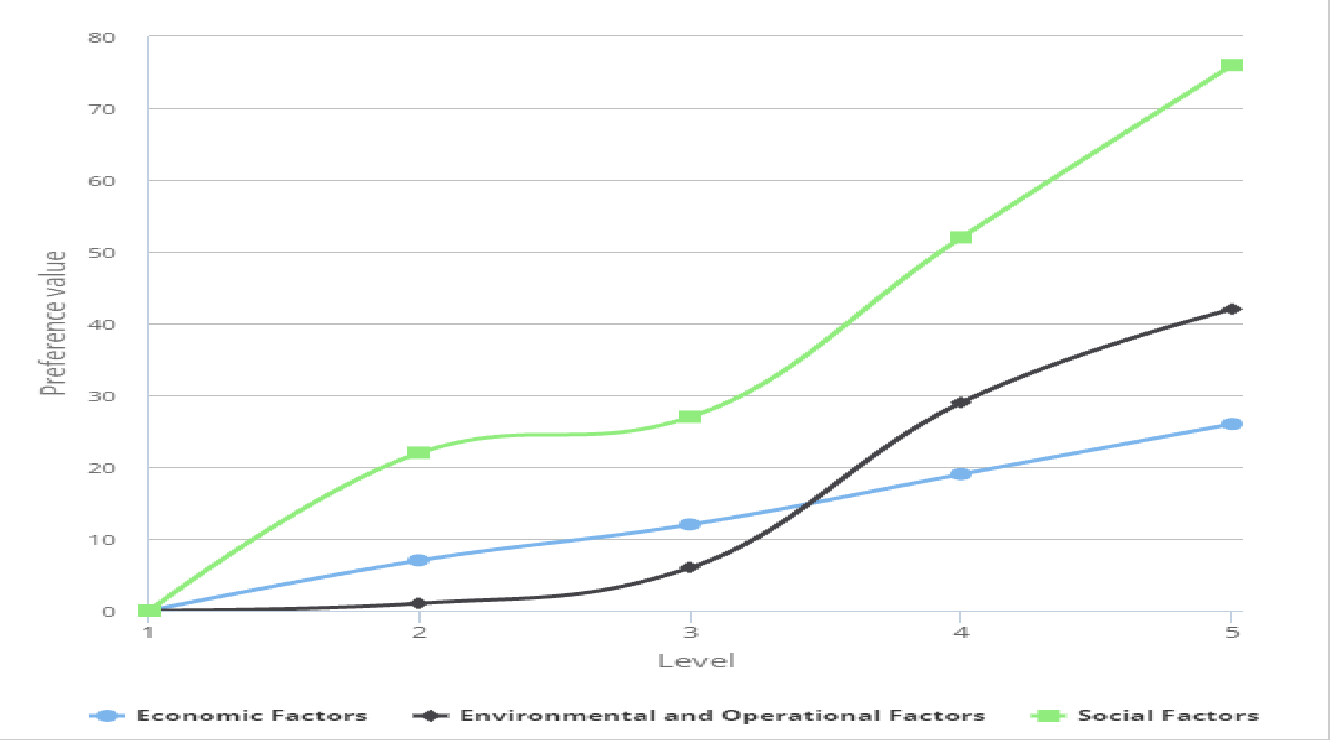

Environmental and Operational Factors: 64
50
25
0
conomic Factors: 23
Social Factors: 30


70
60
50
40
30
20
10
0
Preference value
1
2
3
4
5
Level
Economic Factors
Environmental and Operational Factors
Social Factors

Response # 2

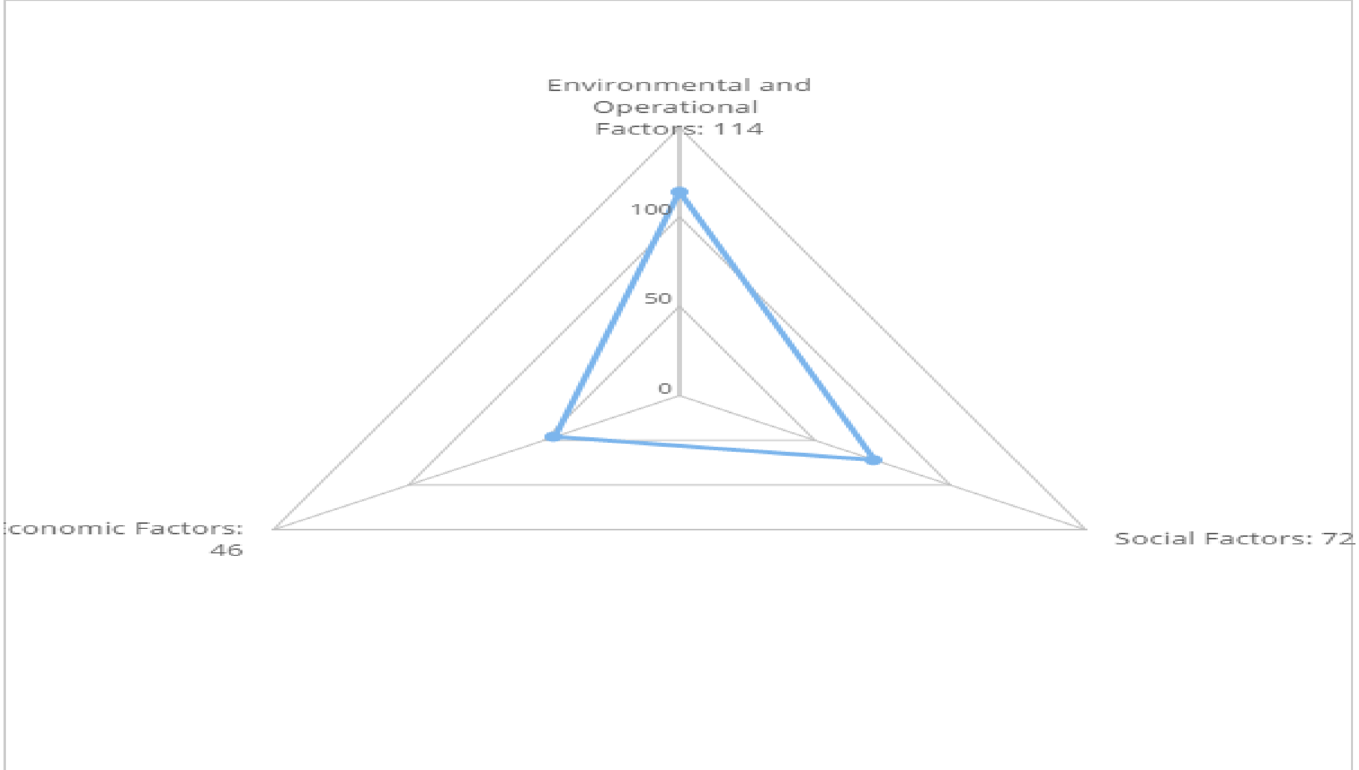


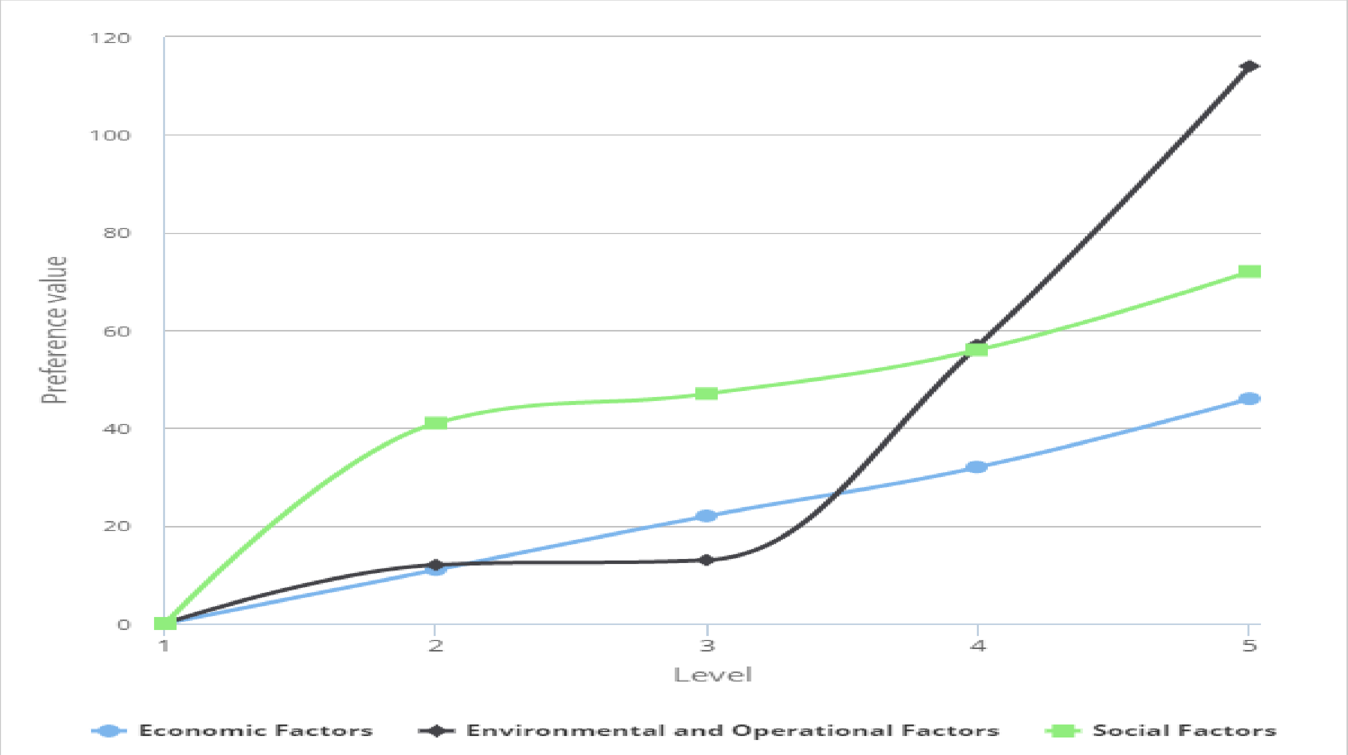
Social Factors: 76
75
50
25
0
conomic Factors: 26
Environmental ar Operational Factors: 42



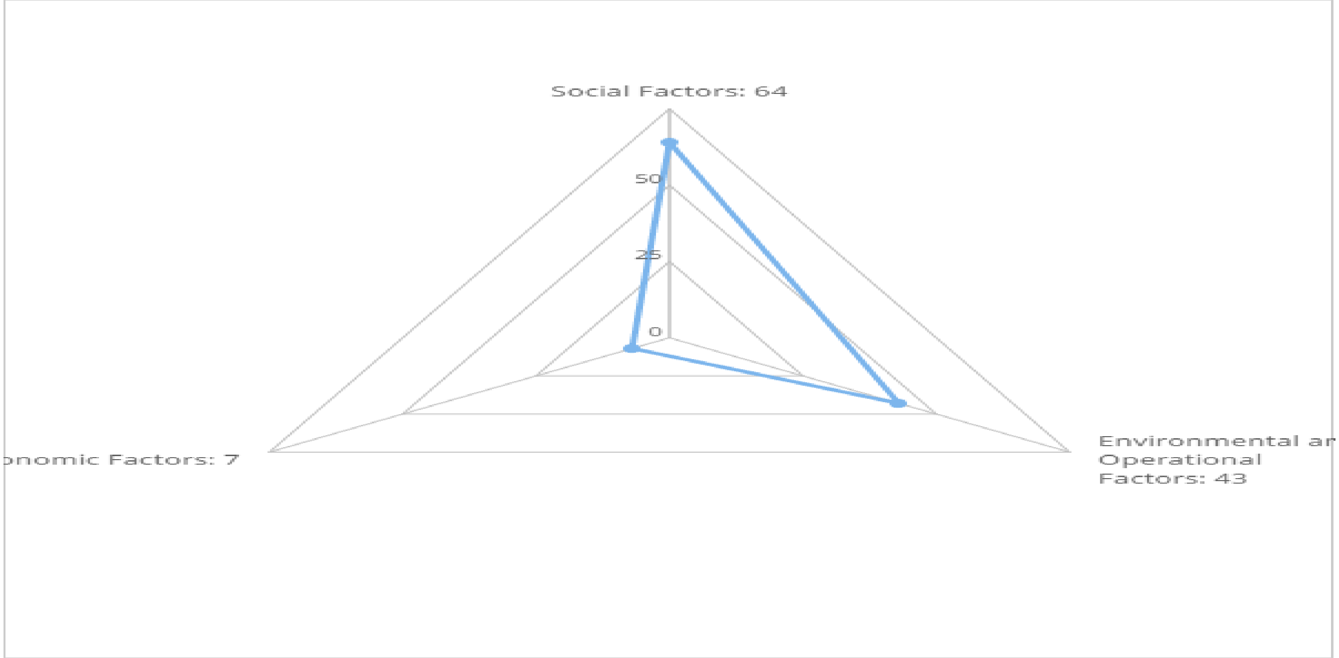
80
70
60
50
40
30
20
10
0
Preference value
1
2
3
4
5
Level
Economic Factors
Environmental and Operational Factors
Social Factors

Response # 3

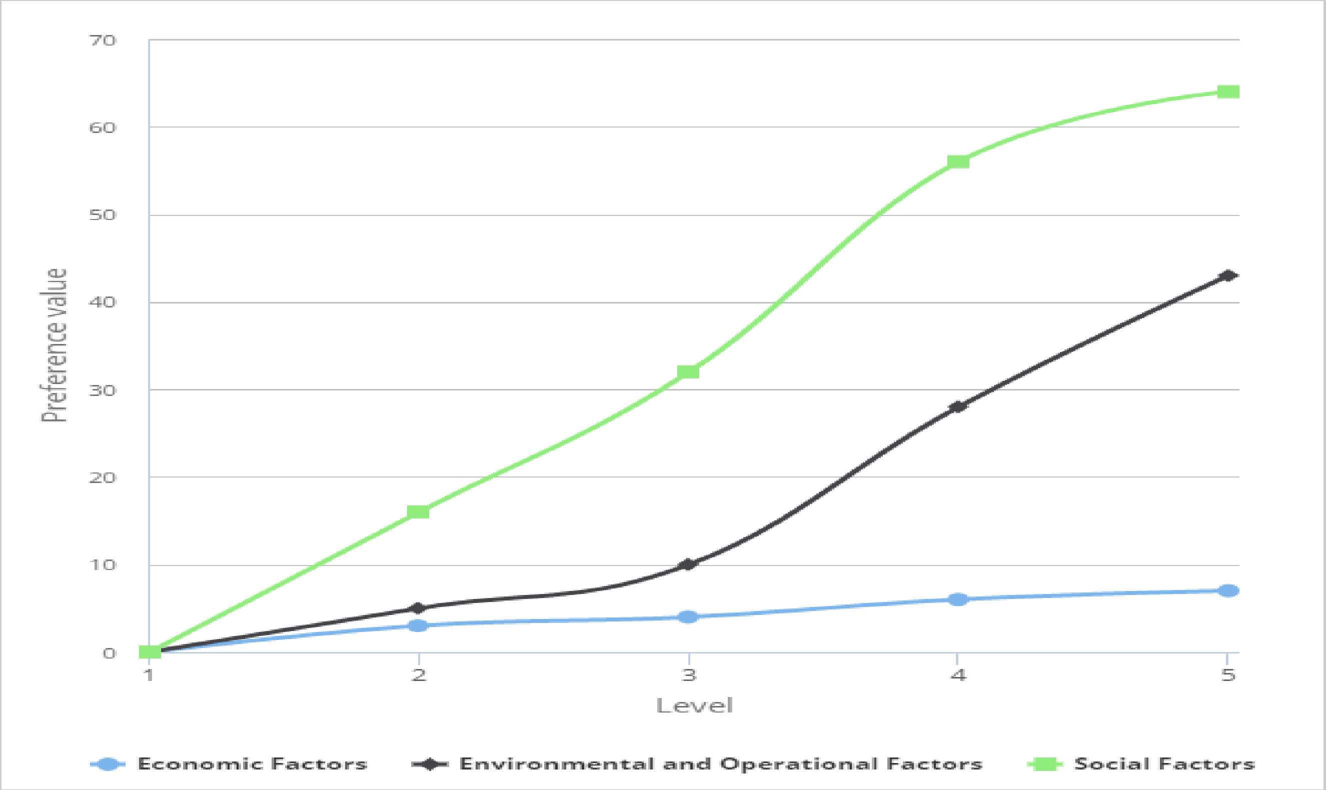

Environmental and Operational Factors: 114
100
50
0
conomic Factors: 46
Social Factors: 72


120
100
80
60
40
20
0
Preference value
1
2
3
4
5
Level
Economic Factors
Environmental and Operational Factors
Social Factors

Response # 4

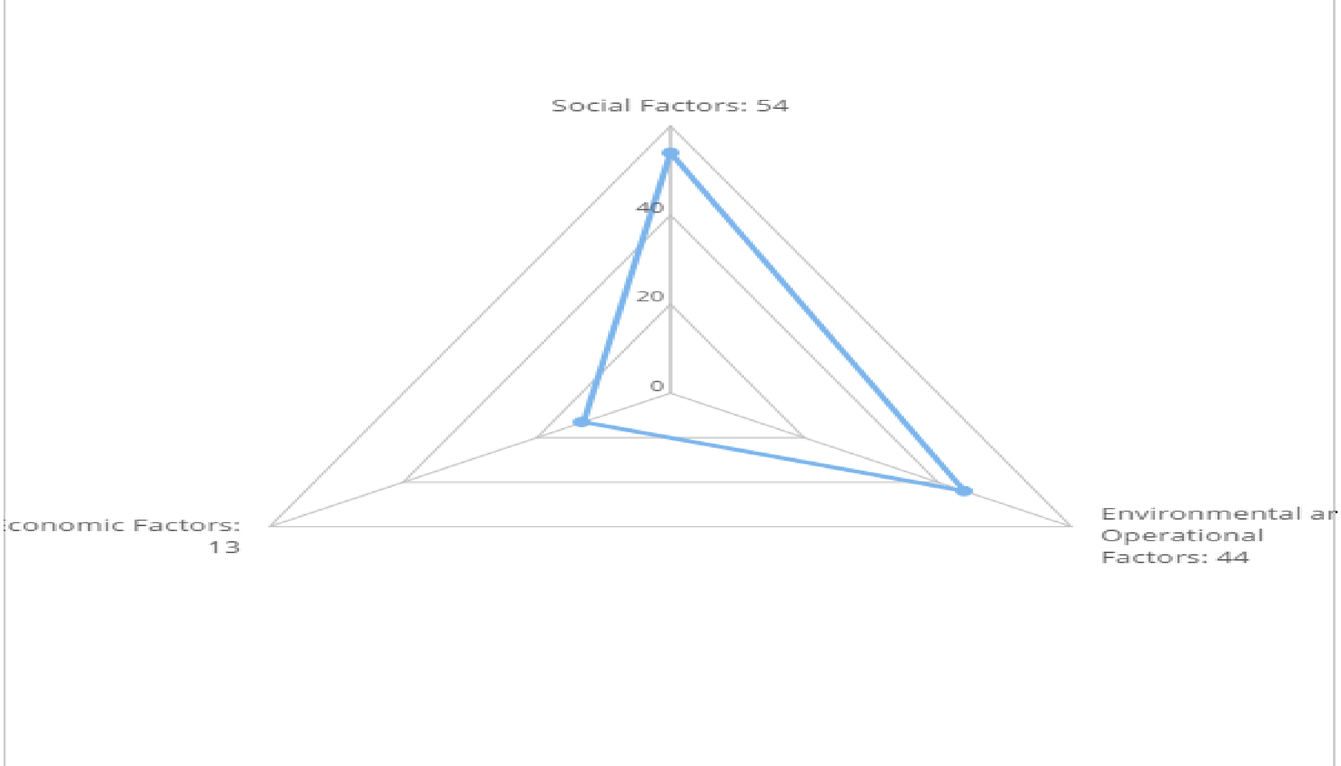


Social Factors: 64
50
25
0
onomic Factors: 7
Environmental ar
Operational
Factors: 43

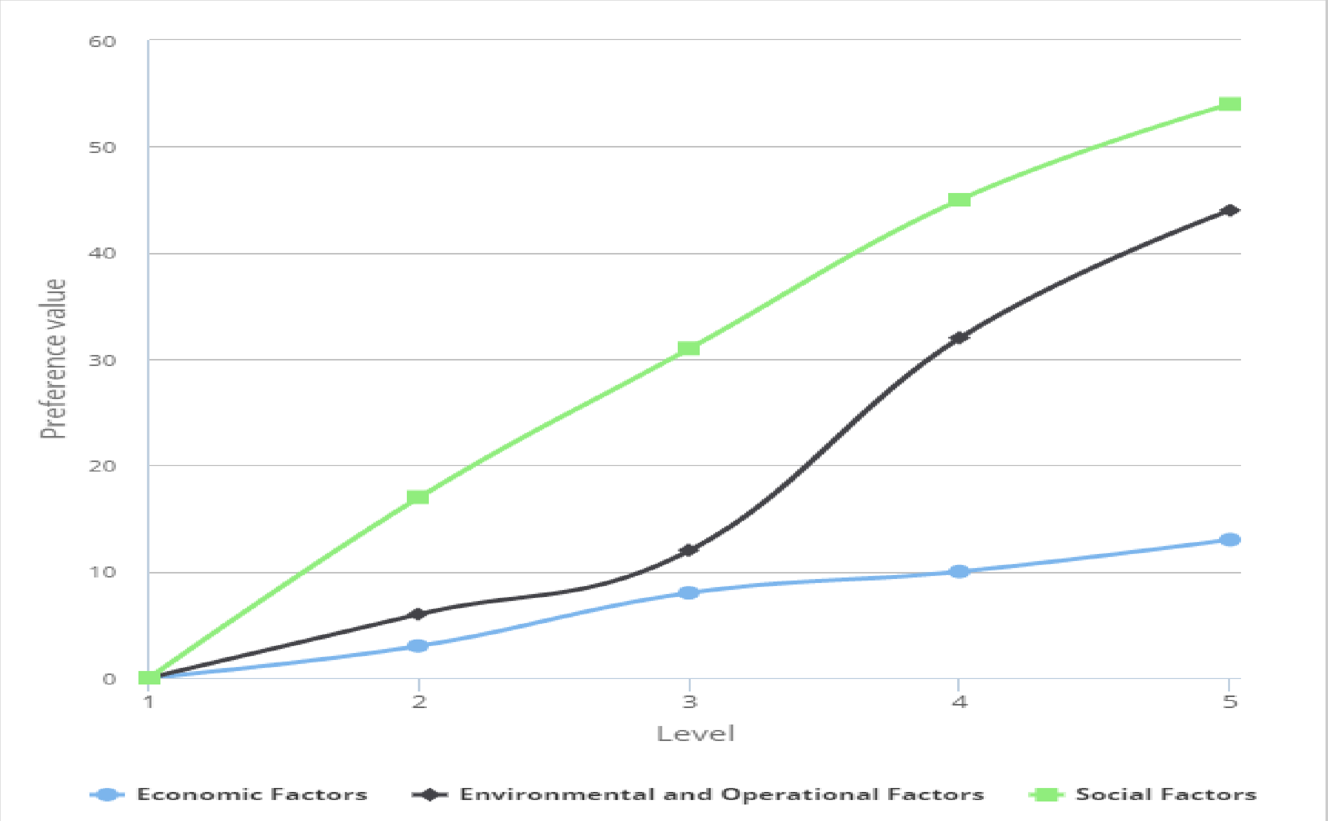


70
60
50
40
30
20
10
0
Preference value
1
2
3
4
5
Level
Economic Factors
Environmental and Operational Factors
Social Factors

Response # 5



Social Factors: 54
40
20
0
conomic Factors: 13
Environmental ar Operational Factors: 44



60
50
40
30
20
10
0
Preference value
1
2
3
4
5
Level
Economic Factors
Environmental and Operational Factors
Social Factors

Appendix 4

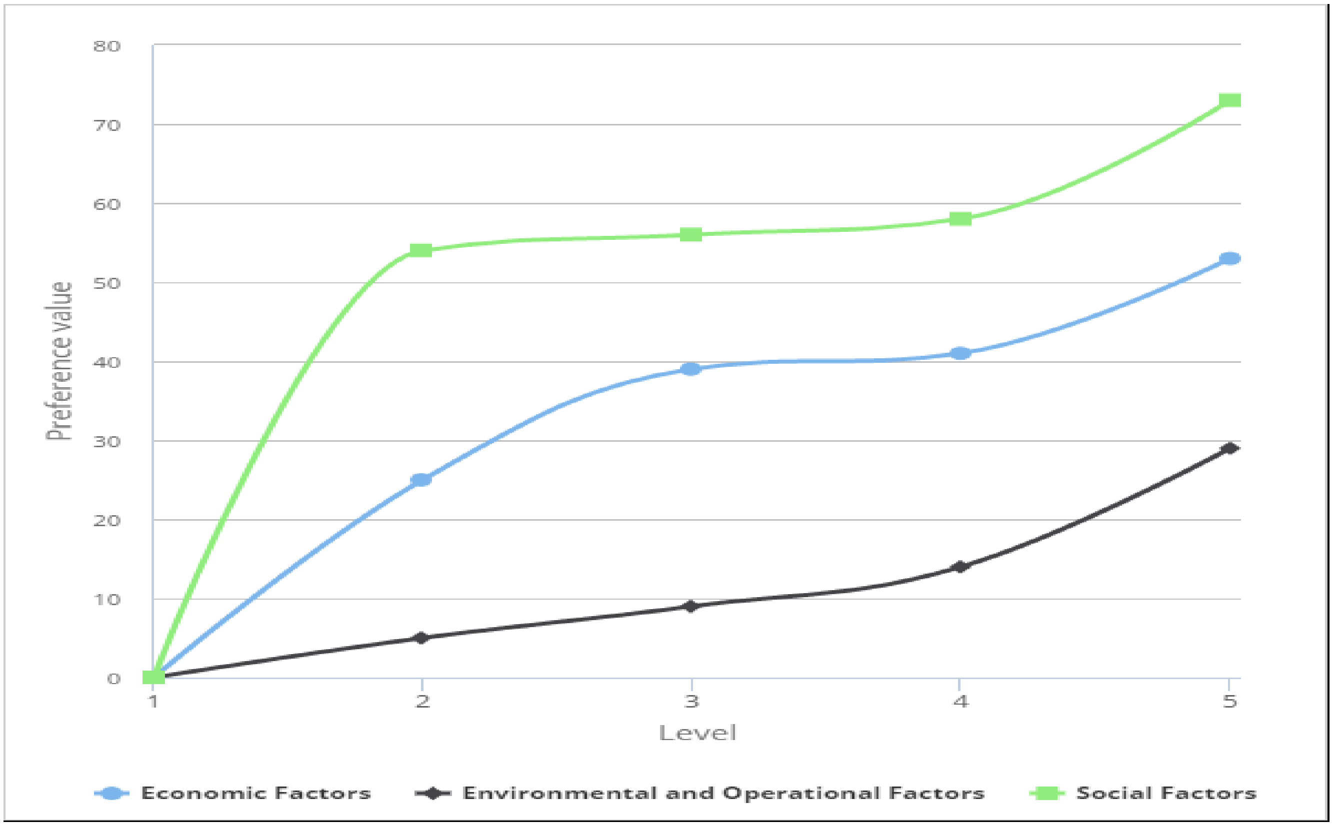
1000 Minds Software Results

NA & Europe-Data Responds

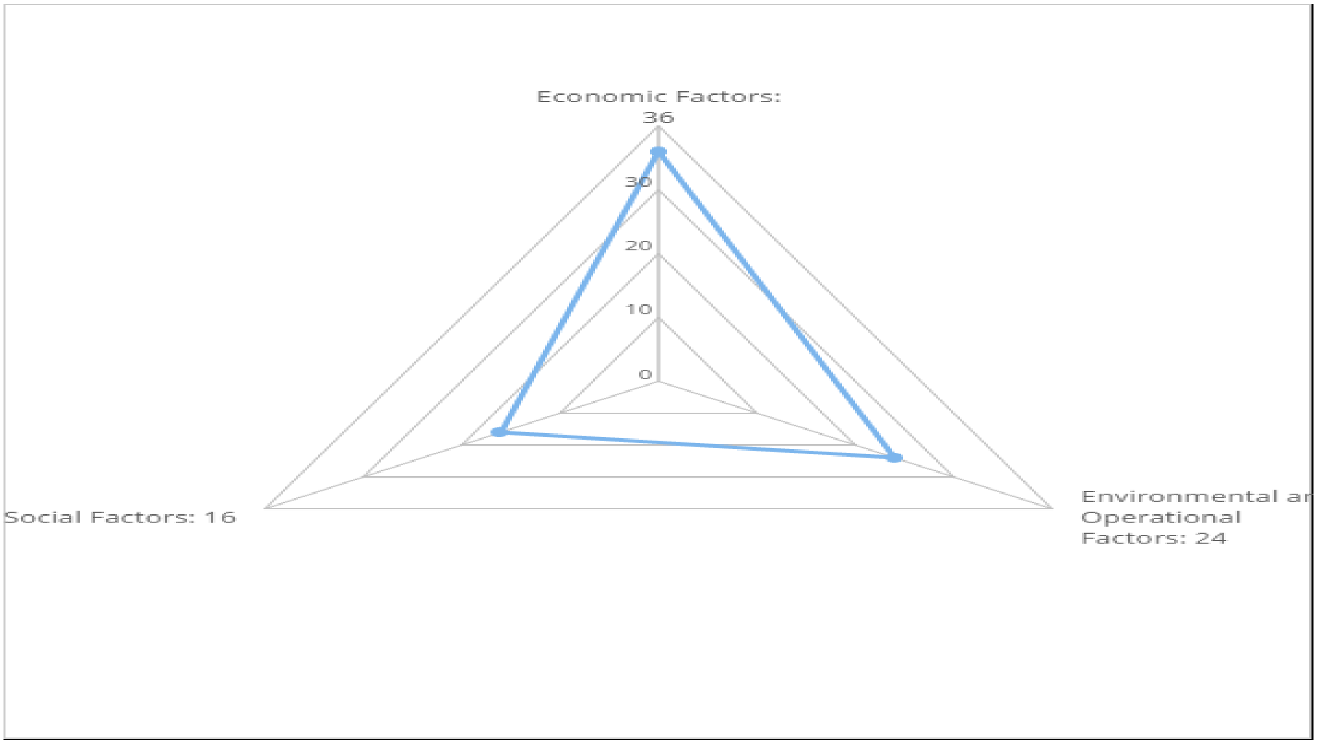
(16-20)

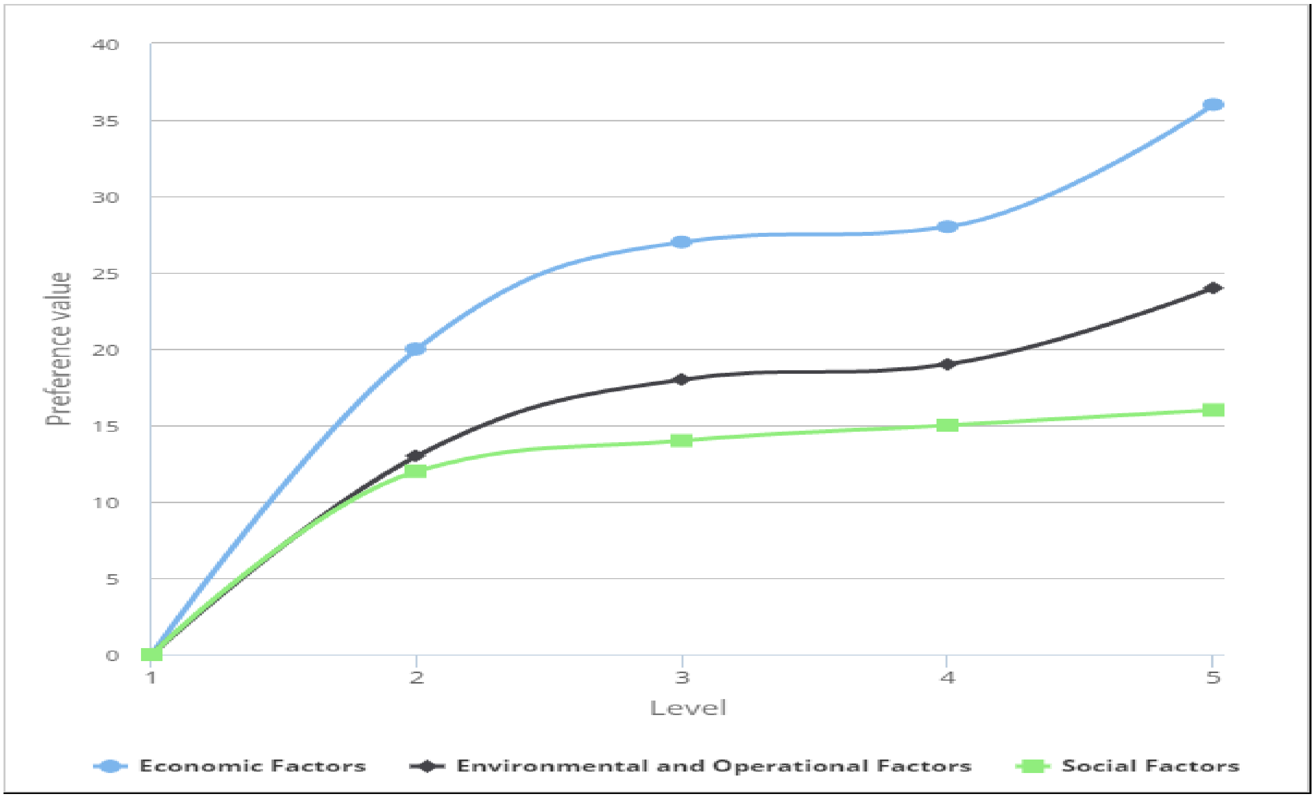
Response # 16


Social Factors: 73
75
50
25
0
nvironmental and Operational Factors: 29
Economic Factors 53

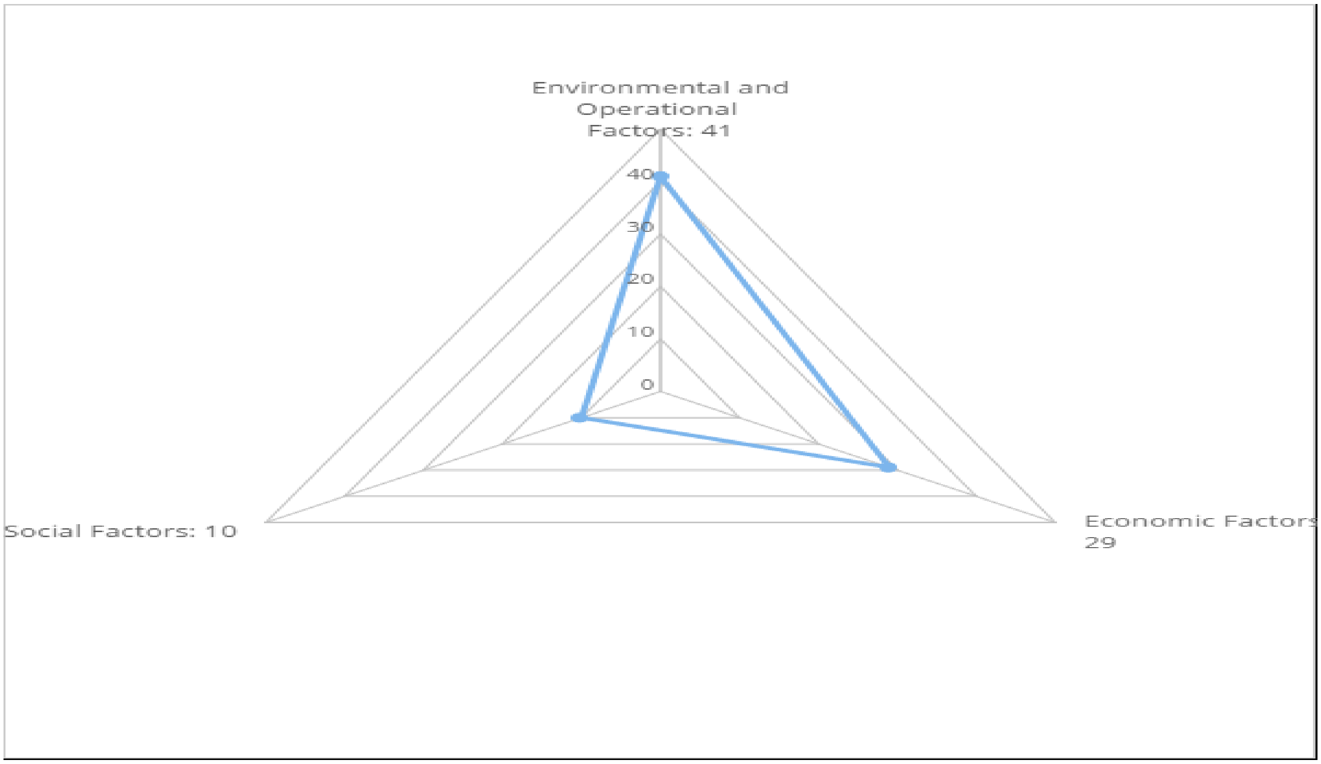

Preference value
80
70
60
50
40
30
20
10
0
1
2
3
4
5
Level
Economic Factors
Environmental and Operational Factors
Social Factors

Response # 17

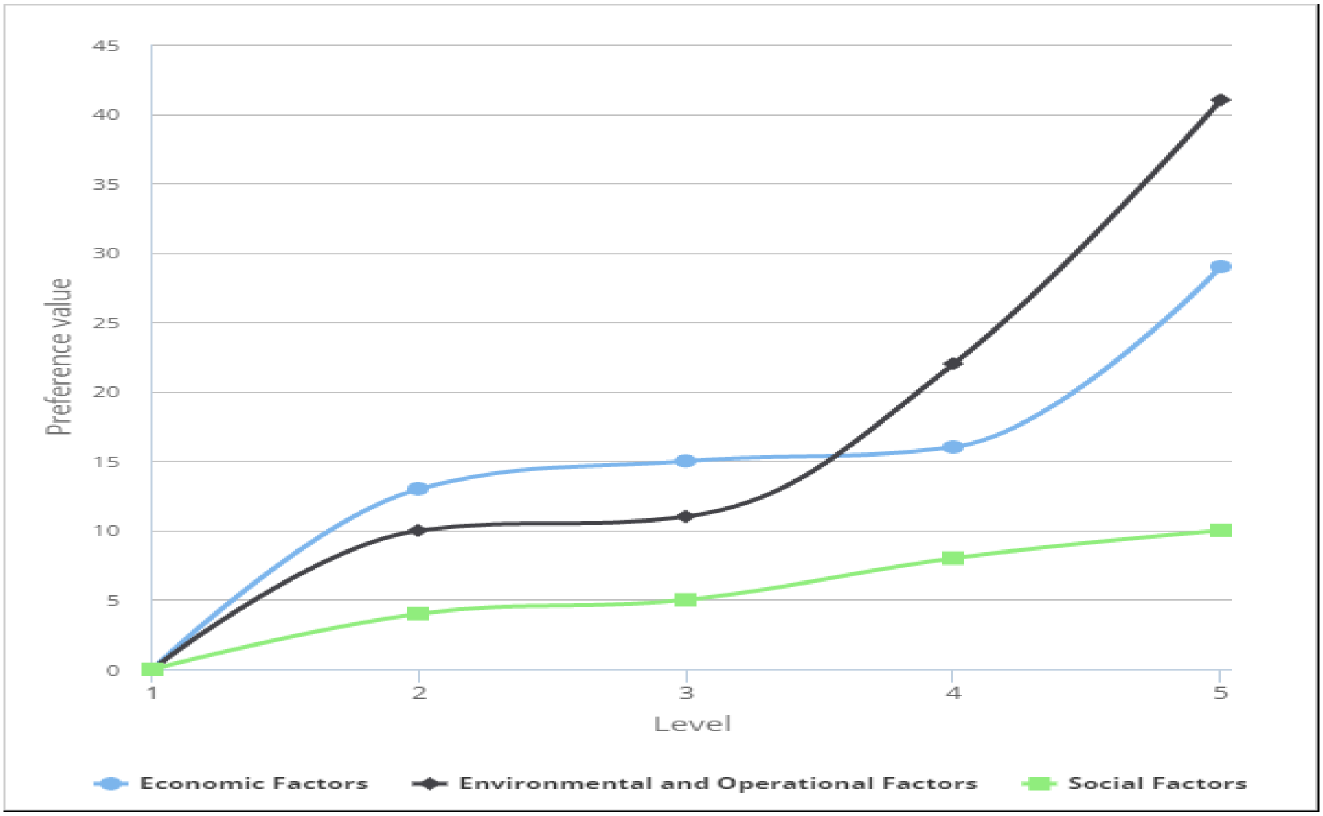

Economic Factors: 36
30
20
10
0
Environmental ar
Operational
Factors: 24
Social Factors: 16


40
35
30
25
20
15
10
5
0
Preference value
1
2
3
4
5
Level
Economic Factors
Environmental and Operational Factors
Social Factors

Response # 18

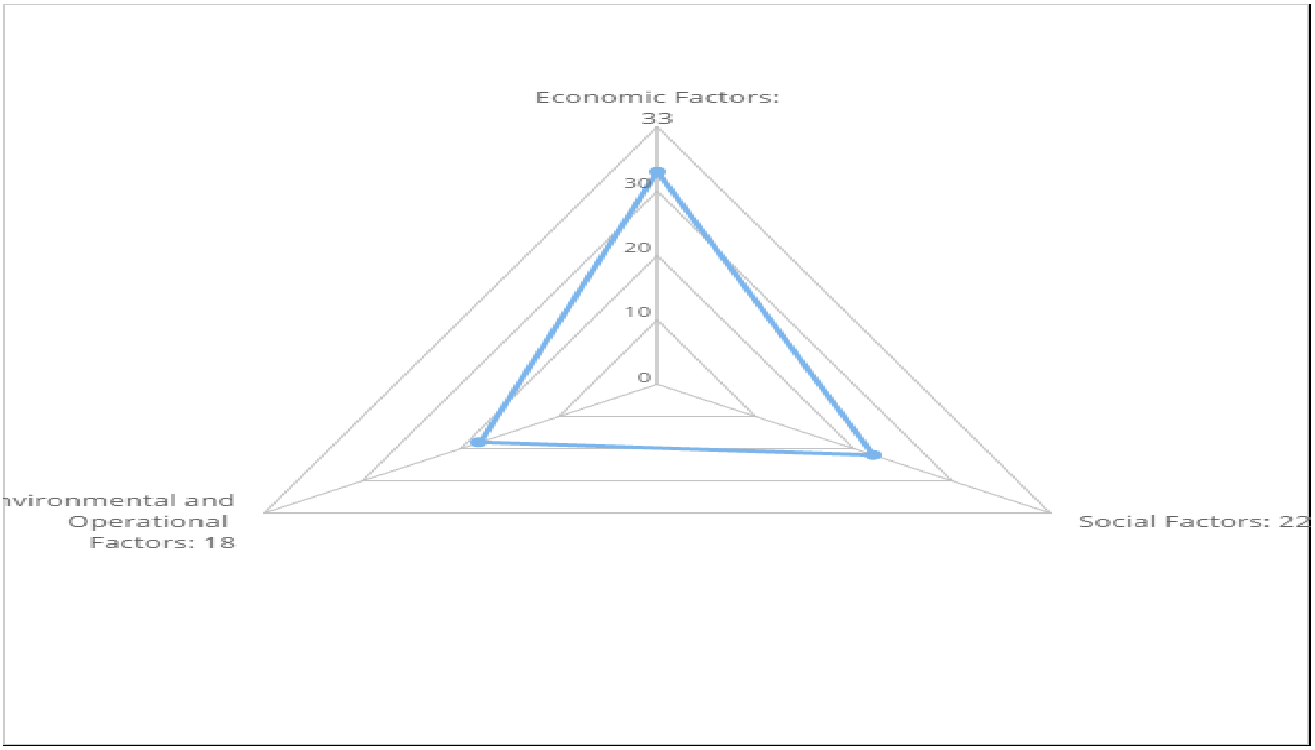


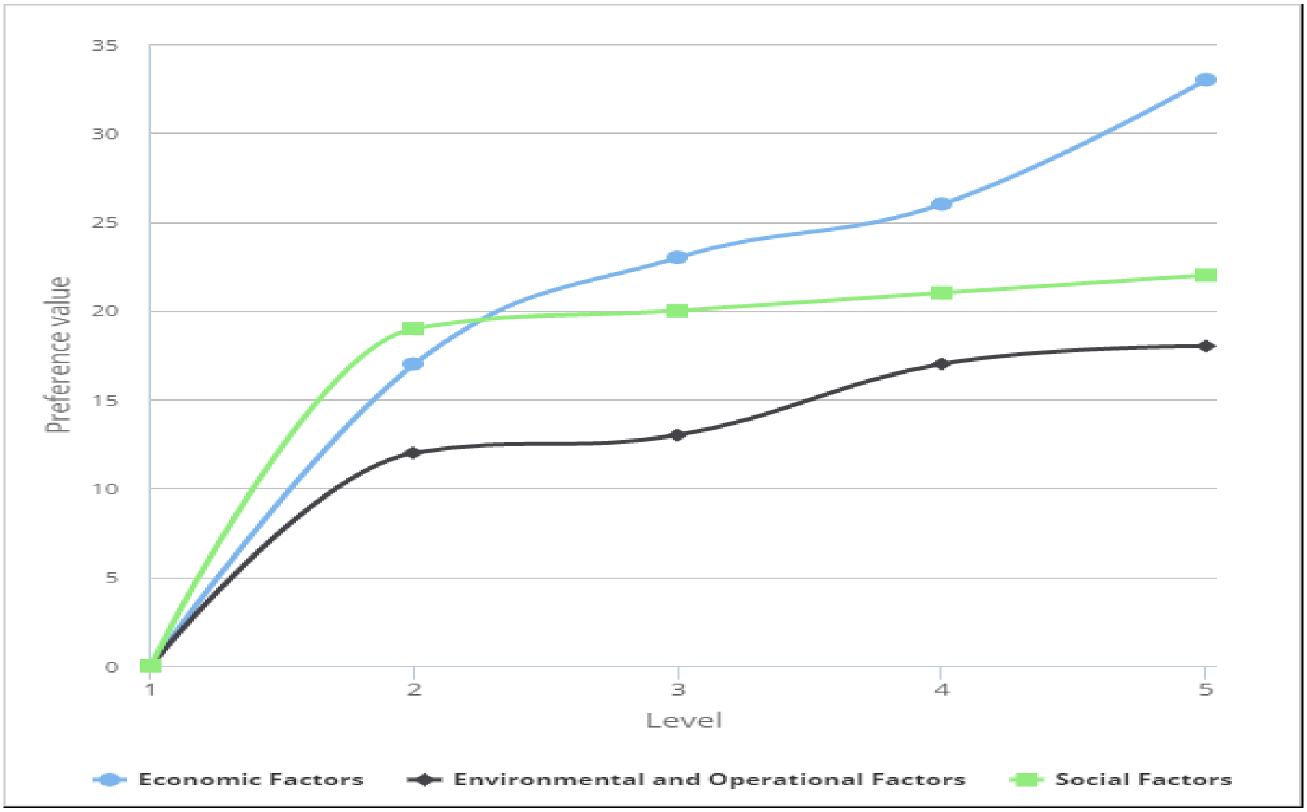
Environmental and Operational Factors: 41
40
30
20
10
0
Economic Factors
29
Social Factors: 10



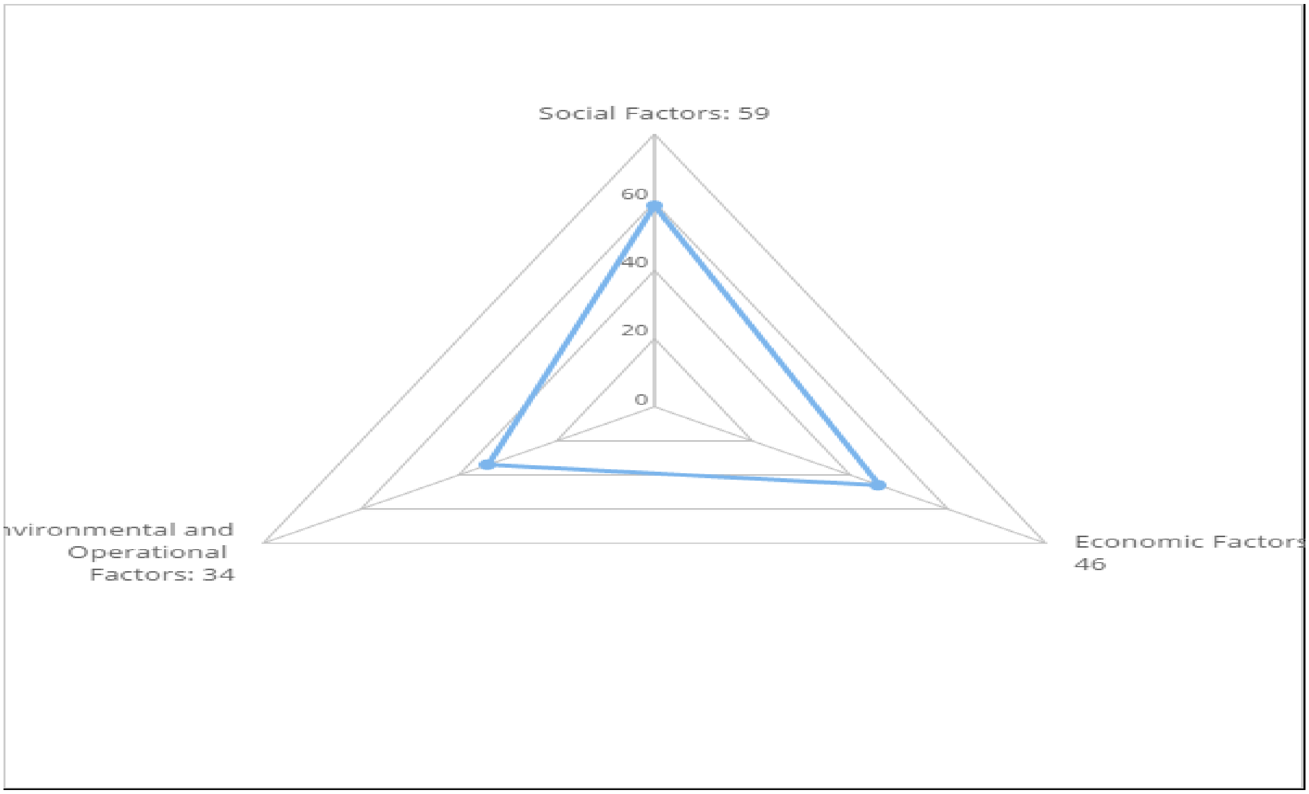
45
40
35
30
25
20
15
10
5
0
Preference value
1
2
3
4
5
Level
Economic Factors
Environmental and Operational Factors
Social Factors

Response # 19

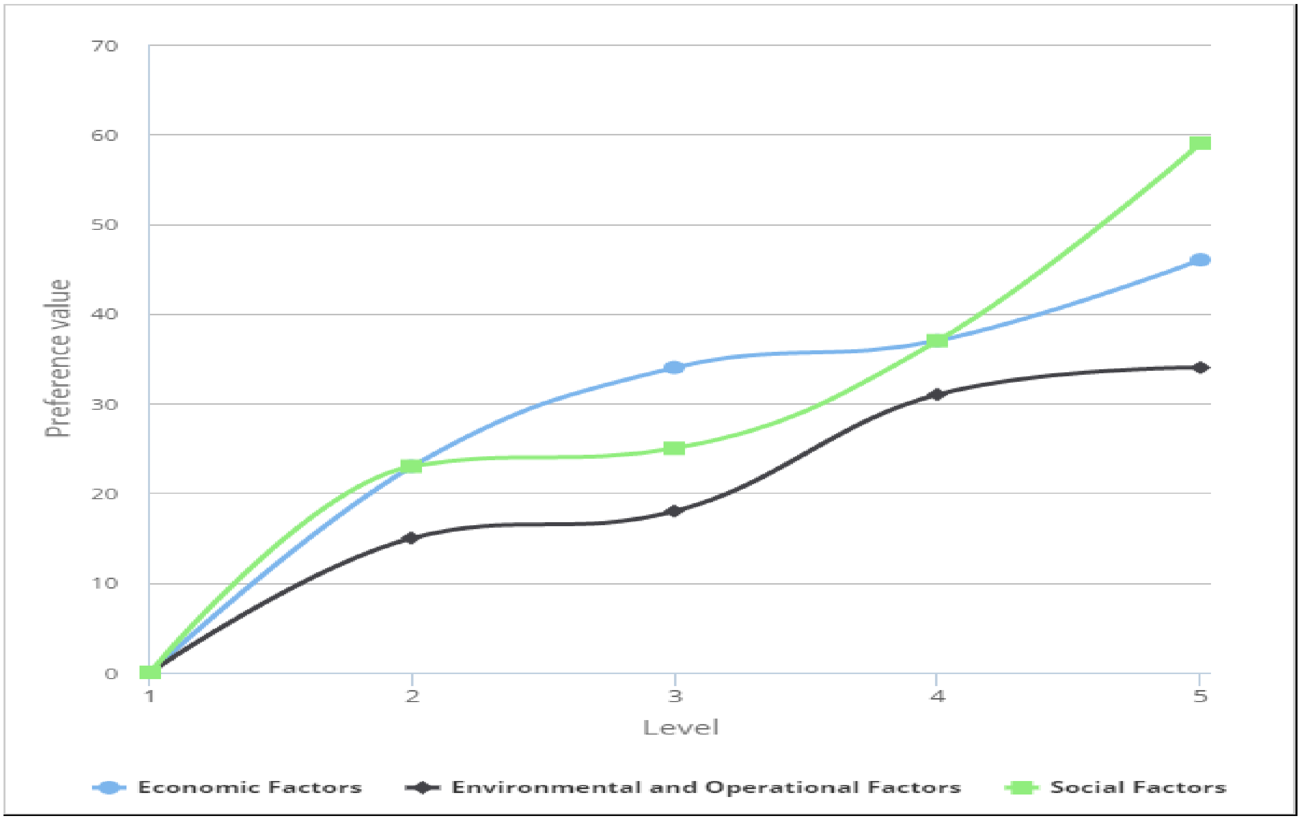

Economic Factors: 33
30
20
10
0
nvironmental and Operational Factors: 18
Social Factors: 22


35
30
25
20
15
10
5
0
Preference value
1
2
3
4
5
Level
Economic Factors
Environmental and Operational Factors
Social Factors

Response # 20



Social Factors: 59
60
40
20
0
nvironmental and Operational Factors: 34
Economic Factors 46



70
60
50
40
30
20
10
0
Preference value
1
2
3
4
5
Level
Economic Factors
Environmental and Operational Factors
Social Factors