Reliability-Based Management of Water Distribution Networks

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ABSTRACT

Reliability-Based Management of Water Distribution Networks

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Canada's civil infrastructure systems have been in use for over 79 % of their expected service life. Municipalities in Canada have noted that 59% of their water systems needed repair and the condition of 43% of these systems is unacceptable. Therefore, a significant volume of rehabilitation projects are necessary to improve infrastructure performance. Reliability and criticality assessments (RCA) as well as the ability to determine the most suitable methods of rehabilitation are urgently needed in order to allocate the available budget efficiently. The research presented in this thesis aims at developing a priority index (PI) for intervention that considers the combination of RCA for water networks. Sound techniques are utilized to develop the PI such as reliability theory, simple multi-attribute rating technique (SMART), and Analytical Hierarchy Process (AHP).

The reliability assessment encompasses two levels: (1) segment and (2) sub-network reliabilities. The priority index (PI) for intervention is crucial to schedule segment rehabilitation. Simple Multi Attribute Rating Technique (SMART) is used to select the most suitable methods of rehabilitation for these components. Selection of a rehabilitation method is based on several factors: (1) technical feasibility, (2) whether the selection is contractually acceptable, (3) cost effectiveness, (4) environmental impact, and (5) whether the rehabilitation method is a new technology or not. The output of rehabilitation selection model is the method of rehabilitation for components coupled with the associated costs and durations for rehabilitation activities for each sub-network.

The final stage of this research is to schedule these rehabilitation activities. Scheduling of the rehabilitation activities related to water main networks depends mainly on available budget and planning time. Other factors, such as network reliability, criticality, location, contract size, and rehabilitation method(s), also affect the scheduling process.

This research presents a method for optimizing the scheduling of rehabilitation work for water distribution networks. The method utilizes unsupervised neural networks (UNNs) and Mixed Integer Non Linear Programming (MINLP) and performs the scheduling in two stages. In the first stage, UNNs are used to group water mains according to their locations and rehabilitation methods. In the second stage, MINLP is used to determine the number of rehabilitation contract packages and to generate an optimized schedule based on these packages considering network reliability, criticality, contract size, and planning time. Data on water network are collected from the city of Hamilton, Ontario, Canada. Four sub-networks are selected randomly from the entire network to represent four types of land use; undeveloped, residential, park, and commercial/industrial. The data is used as a test bed to validate and demonstrate the use of the developed research methodology. An automated tool (DSSWATER), based on the developed methodology, is developed to assist users and decision makers. The developed models and tools are expected to be beneficial to municipal engineers and managers as well as to academics.

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NOMENCLATURE

λ: The average failure rate, transition rate, or hazard rate

AHP: Analytical Hierarchy Process

ANN: Artificial Neural Network

A.R: Accessory replacement

BPNN: Back-Propagation Neural Network

C: Cost Constraint

CEPA: Canadian Environment Protection Act

CI: Criticality Index

CIPP: Cured In Place Pipes

DP: Dynamic Programming

DPA: Deterioration Point Assignment

DSS: Decision Support System

EAUC: Equivalent Annual Uniform Cost.

Ei: Experience factor

f/y: Failure rate

HDD: Horizontal Directional Drilling

I_j**:** Impact Score

IoE: Impact on Environnement

L: Length

MAUT: Multi-Attribute Utility Theory

MFC: Microsoft Foundation Classes

MIP: Mixed Integer Programming

MINLP: Mixed Integer Nonlinear Programming

NBS: Network Break down Structure

NRC: National Research Council, Canada

$T_{ins.}$: Installation time

$N_{failure}$: Number of failure

P [ ]: represents the probability that at least one of the m paths will be operable;

PI: Priority index for intervention

Pipe Type:

> **HYP:** High Polyvinylchloride Pipe; **LEAD:** Lead Pipe; **CAST1:** Cast Iron spheroidal Pipe, type 1; **COPP**: Copper Pipe; **CIPIT1:** Cast Iron Pipe, first generation; **CIPIT2:** Cast Iron Pipe, second generation; **CIPIT3:** Cast Iron Pipe, third generation; **DUCT:** Ductile Iron Pipe; **STEEL:** Steel; **PCP:** Precast Concrete Pipe; **CONCW:** Concrete Pipe

Q (t): Failure density function

R(t): Reliability function

Road Type:

> **RC:** Rural Collector Road; **RA:** Rural Arterial Road; **UC:** Urban Collector Road; **UAMI:** Urban Minor Arterial Road; **UAMJ:** Urban Major Arterial Road; **HWY:** Highway; **EXPWY:** Expressway

SMART: Simple Multi Attribute Rating Technique

T: Time constraint

T_i: a minimal path, one in which no node is traversed more than once in going along the path;

$T_{analyzing}$: Analyzing time

TT: Trenchless Technology

UNN: Unsupervised Neural Network

VBA: Visual Basic Language

W_j: Decomposed Relative Weight

x,y: Segment coordinates

CHAPTER 1

INTRODUCTION

1.1 Overview

Water distribution networks are among the most important municipal infrastructure assets, and vital to the public. Billions of dollars are spent worldwide every year to rehabilitate and renew these networks. In Canada, it was estimated that $34 billions is needed to rehab the 112,000 km of water mains (NRC: National Guide to Sustainable Municipal Infrastructure, 2002). It was also estimated that $100 to $325 billion is needed urgently to replace aging water distribution pipelines in the USA over 20 years (Grablutz et al., 2000). Therefore, it is important to conduct research on effective management of these valuable assets. Management in this case should address budget allocation, selection of rehabilitation methods, and scheduling of rehabilitation works.

1.2 Current Practices and Their Limitations

Interviews conducted as part of this research reveal that decisions pertinent to the scheduling of rehabilitation or replacement and/or renewal of watermains, within a short time horizon (1 to 3 years), depend on factors such as their respective locations, available budget, type of rehabilitation work, and expected level of service. Scheduling of such work is performed intuitively without the support of tools that optimize this process. In fact, there are no standard procedures used by municipalities to prioritize and schedule rehabilitation works.

Municipalities, however, use priority-based ad hoc scheduling; driven by the condition ratings of individual pipe segments as described by Loganathan *et al.*, (2001). Optimum scheduling is necessary to (1) allocate available budget efficiently, (2) achieve targeted level of service, (3) decrease complaints of local residents, (4) integrate and efficiently coordinate asset rehabilitation works, and (5) decrease the operation and maintenance cost.

Moreover, most trenchless technologies, which have been used since the middle of the 20th century (Iseley *et al.,* 1999), are not used widely in North American cities. The open cut method is used for most projects, even in downtown areas, with significant social and environmental impacts. Therefore, a decision support system can be useful in selecting the most suitable rehabilitation methods. NRC (Infraguide: Best practices, 2003) and Al-aghbar (2005) developed decision support systems which aid in selecting rehabilitation methods and consider the status of water mains. These systems select one or more suitable rehabilitation methods. The cost of rehabilitation or installation is dependent on the selected method.

Most previous researchers (Shahata and Zayed (2008), Al-Aghbar (2005), Moselhi and Sigurdaottir (1998), Zayed et al. (2011), NRC-Infraguide: Best practices (2003), and Mohamed and Zayed (2008)) studied condition, rehabilitation selection, and scheduling of water distribution revitalization projects as it relates to individual components of the network and not taking into account the important relationships between components in the network and the network as a whole. According to Australian Department of Environment and Resource

Management (2010), network modeling is a key component for performing a capital project plan (including condition, rehabilitation selection, and scheduling) of water distribution networks because *"(1) it allows existing infrastructure to be utilized to its maximum capacity (2) It will support the development of an optimised capital works program (3) It provides service providers with the information necessary to make optimal decisions in relation to system operation and planning to achieve the desired service standards and (4) It will lead to value for money to customers*."

Hence, the limitations of current practice can be improved by performing the following activities: (1) assess network reliability and criticality, (2) select cost effective rehabilitation method(s), and (3) optimize scheduling of rehabilitation activities.

1.3 Research Objectives

The main purpose of this research is to address the limitation cited in the literature and depicted in current practices and to study the processes needed to effectively manage the operation and maintenance of water main networks. The research sub-objectives can be summarized as follows:

1. Study and analyze the limitations of current management framework related to water distribution networks based on current practices and related literature.
2. Develop a priority index (PI) for intervention model for water networks based on reliability and criticality assessments.

3. Develop a scheduling model for rehabilitation works.
4. Design and code an automated decision support system that implements the developed models.

1.4 Research Methodology

The research methodology deals with studying the state of the art and current practices related to efficient management of water distribution networks with a focus on priority index (PI) for intervention based selection of suitable rehabilitation strategy(ies) and scheduling of rehabilitation activities. In this respect, the proposed methodology aids and addresses the following three main issues.

1.4.1 Model Development of Priority Index (PI) for Intervention

A methodology for grouping the priority index (PI) for intervention of rehabilitation works is studied and developed which accounts for (1) the water distribution network and its characteristics, (2) the reliability assessment of basic components, (3) the criticality aspects of various zones in the network as a risk source to the services provided by the network.

1.4.2 Selection of Rehabilitation Methods

A wide range of rehabilitation methods are studied including those described by NRC (Infraguide: Best practices, 2003) and those in use in current practice. A selection methodology is developed to account for: (1) technical feasibility, (2) contractual acceptability, (3) cost effectiveness and (4) other factors such as environmental impact and new promising technologies.

1.4.3 Scheduling Model

A scheduling model based on the developed methodology, which accounts for constraints and factors used in current practices, is developed and applied to a case study.

1.5 Thesis Organization

Chapter 2 presents a literature review on water main condition assessment techniques, reliability theory, criticality, decision making theory, and rehabilitation methods for water mains. Chapter 3 presents the developed methodology, which encompasses the development of three models; a priority index (PI) for intervention model, a model for the selection of rehabilitation methods, and a scheduling model. The priority index (PI) for intervention model is described in two sections; a reliability assessment model and a criticality index model. Chapter 4 explains the sources of the data collected. The data are collected from four sources: (a) literature; (b) city of Hamilton, Ontario, Canada, database, (c) asset management team of the city of Hamilton, and (d) two consulting teams. Chapter 5 implements the automated tool (DSSWATER) which helps a user apply the developed models of reliability assessment, criticality index, priority index (PI) for intervention, rehabilitation selection, and optimum scheduling. Chapter 6 presents a simple case study to demonstrate the application of the developed models using the collected data. Chapter 7 presents the thesis conclusions, contributions and recommendations. It also includes limitations and enhancement and recommendations for future research.

CHAPTER 2

Literature Review

2.1 The Components of Water Distribution System

Water distribution systems consist of several components such as pumps, motors, power transmission, valves, controls, hydrants, pipes and tanks (Cullinane, 1989). The typical distribution network, as shown in Figure 2.1, includes pipes, hydrants, as well as numerous types of valves, joints, and other components.

M: Main pipe

RH: Residential Home

B: Branch

⊗: Isolation valve

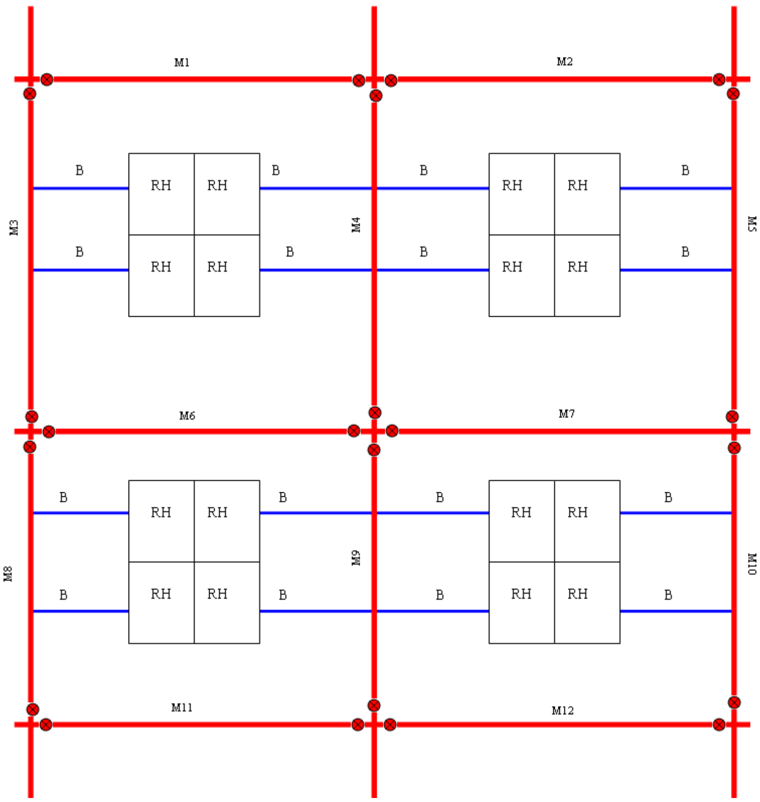


Figure 2.1: Typical Water Distribution System

A pipeline is divided into several segments, which are located between two or more isolation valves. During maintenance, isolation valves are closed to isolate a segment from the entire network. Isolation is important in order to drain the water inside the segment during maintenance processes.

2.1.1 Segment

Figure 2.2 shows a typical water main segment, which includes several components.

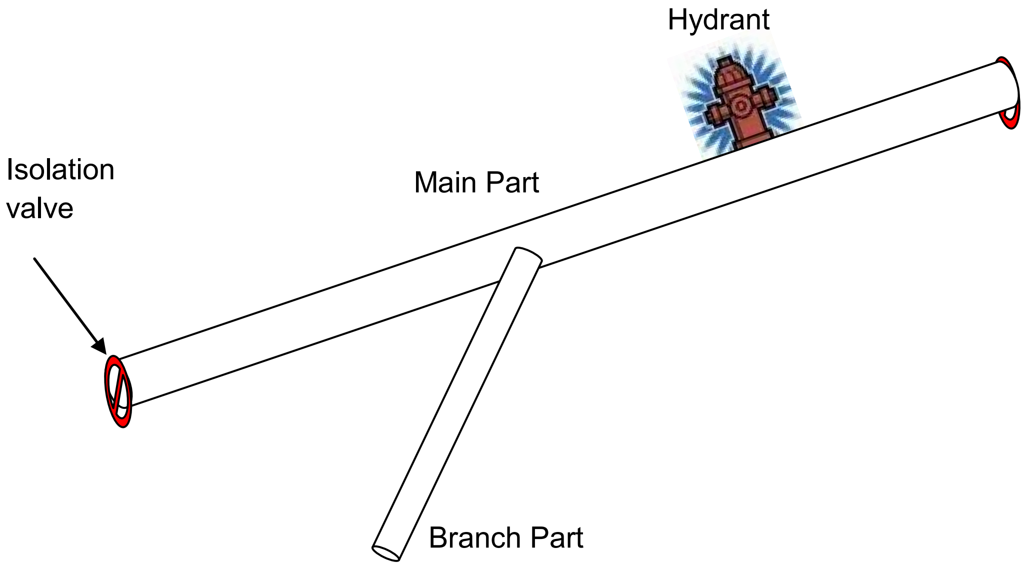


Figure 2.2: A Water Main Segment

Australian National Audit Office (Better Practice Guide 2010) reported that “to determine the effectiveness and efficiency of assets in supporting the delivery of specified service outcomes, an Asset Portfolio should be segmented into largest groupings that allow worthwhile analysis.” Walski (1993) defined a segment as a pipe or a collection of pipes. In addition, a segment can be used to obtain a quick assessment of the susceptibility of a system to a single pipe break. June *et al.* (2004) defined a segment as a set of pipes which should be closed when maintenance is performed. Bouchart and Goulter (1991) defined a new segment as “starting whenever the demand along the link or the diameter changes (cited in Walski, 1993)”. The first and second definitions are included in this research because of the need to isolate each segment at an intersection (when an isolation valve exists at the intersection). The segment might be extended to another block due to the lack of an isolation valve at the first intersection (Figure 2.3).

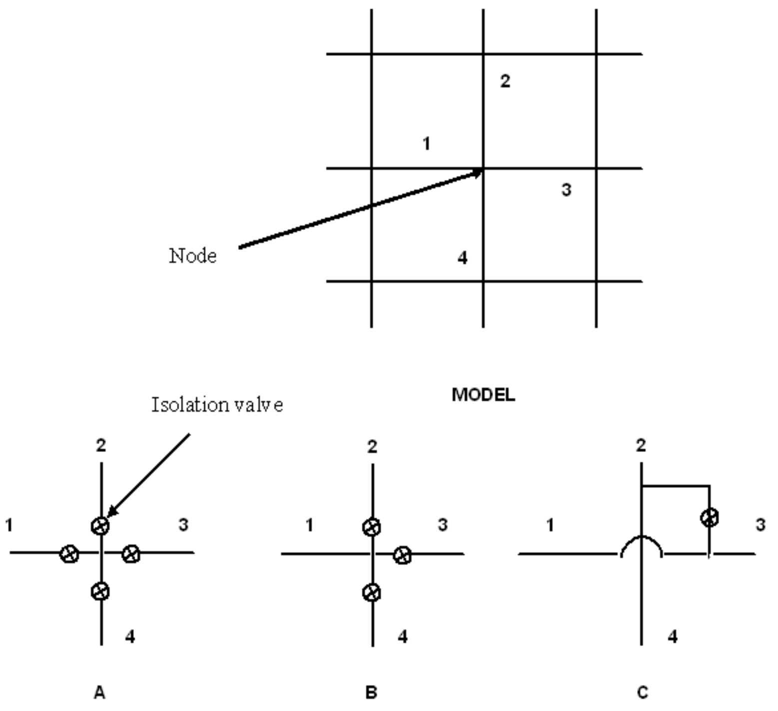


Figure 2.3: Alternative Valving at a Node
(Adapted From Walski, 1993)

Therefore, in this thesis a segment is defined as: a single water main pipe or a group of connected pipes (along with all the associated components) which is located between the two nearest intersections at which isolation valves exist and the operation of these valves leads to the isolation of the segment in case of breakage or for regular maintenance of a component in the segment. Hence, each segment includes pipes which are connected in series and contain accessories (valves, hydrants, joints, etc.) and branched pipes, which extend to residences, factories, shops and other endpoints. These endpoints are attached to the segment as shown in Figure 2.3.

2.1.2 Isolation Valves

Walski (1993) and June *et al.* (2004) described the importance of isolation valves within the water distribution network as follows:

1. Closing valves at the two ends will isolate a pipe. By isolating the pipe, it can be repaired easily.
2. Valves are the key components to water system reliability.
3. A water distribution network would be disabled for every maintenance action if there are no valves.
4. Valves control the flow of water.

2.2 Condition Rating and Assessment Techniques for Water Mains

2.2.1 Condition Rating Of Water Mains

The establishment of a condition rating for water mains is important in order to aid municipalities in the categorization of their assets and the allocation of their limited budget (Wang, 2006). Al Barqawi and Zayed (2006) reported that the purpose of a condition rating for a water mains system is to objectively rate or scale the current condition of the buried pipes. The condition rating is obtained by measuring and analyzing a set of factors which deteriorate with the age of a component. Hence, knowledge of these factors and their behavior when deterioration occurs will lead to a satisfactory condition rating. Fahmy (2010) developed a DSS to select inspection methods to evaluate the condition assessment of water mains whether if they are destructive or non-destructive methods. Karaa and Marks (1990) reported that the performance or condition rating of water distribution networks can be measured using a number of factors such as the cost of maintaining and operating the system, quality of water supply, serviceability of the system, structural integrity and safety of the system operation and reliability of the water supply. The NRC (Infraguide: Best practices, 2003) listed three categories of factors, namely physical, environmental and operational (Table 2.1). Each category is divided into sub-factors which represent a portion of the condition rating. The combination of these sub-factors represents the condition rating of a component after using several modelling techniques. Al Barqawi and Zayed (2006) performed a condition assessment model using AHP and ANN. Wang (2006) determined the condition assessment of a water main using regression analysis, and Geem (2003) developed a decision support system (DSS) for pipe condition assessment using a back-propagation neural network (BPNN). Kleiner and Rajani (2001) divided models that are used for assessment and use historical data divided into three categories; deterministic, probabilistic multi- variant, and probabilistic. The next section discusses the condition assessment techniques for water mains based on several categories.

Table 2.1: Factors Affecting Deterioration of Water Mains
(NRC-Infraguide, 2002)

	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.
	Pipe lining and coating	Lined and coated pipes are less susceptible to corrosion.
	Dissimilar metals	Dissimilar metals are susceptible to galvanic corrosion.
	Pipe installation	Poor installation practice can damage pipes, making them vulnerable to failure.
	Pipe manufacture	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure. This problem is most common in older pit cast pipes.
Environmental	Pipe bedding	Improper bedding may result in premature pipe failure.
	Trench backfill	Some backfill materials are corrosive or frost susceptible.
	Soil type	Some soils are corrosive; some soils experience significant volume changes in response to moisture changes, resulting in changes to pipe loading. Presence of hydrocarbons and solvents in soil may result in some pipe deterioration.
	Groundwater	Some groundwater is aggressive toward certain pipe materials.
	Climate	Climate influences frost penetration and soil moisture. Permafrost must be considered in the north.
	Pipe location	Migration of road salt into soil can increase the rate of corrosion.
	Disturbances	Underground disturbances in the immediate vicinity of an existing pipe can lead to actual damage or changes in the support and loading structure on the pipe.
	Stray electrical currents	Stray currents cause electrolytic corrosion.
	Seismic activity	Seismic activity can increase stresses on pipe and cause pressure surges.
Operational	Internal water pressure, transient pressure	Changes to internal water pressure will change stresses acting on the pipe.
	Leakage	Leakage erodes pipe bedding and increases soil moisture in the pipe zone.
	Water quality	Some water is aggressive, promoting corrosion
	Flow velocity	Rate of internal corrosion is greater in unlined dead-ends mains.
	Backflow potential	Cross connections with systems that do not contain potable water can contaminate water distribution system.
	O&M practices	Poor practices can compromise structural integrity and water quality

2.2.2 Condition Assessment Techniques for Water Main Network

Loganathan *et al.* (2001) divided the assessment approaches for a water main network using mathematical models into five categories: a) deterioration point assignment methods (DPA), b) break-even analysis, c) mechanistic methods, d) regression methods, and e) failure probability methods. These quantitative tools have been developed to prioritize and renew pipeline operation (Rogers and Grigg, 2006).

i) Deterioration Point Assignment (DPA) Methods (Current Practice)

Cities in North America are using Deterioration Point Assessment (DPA) methods. They are simple, easy to apply, and rely on the scores of a set of deterioration factors. The summation of these scores represents the condition assessment of a water main. A more detailed description of these methods is shown in current practices and their limitations are dealt with in Section 1.2.

ii) Break-Even Analysis

The goal of this method is to find a suitable time for replacement instead of rehabilitation. Economic equations are utilized, taking into consideration the time, interest rate, and present value to forecast the time of replacement. The maintenance cost of an individual pipe increases with time due to the increased probability of failure, while the cost of replacement (or capital recovery cost) decreases due to a reduction in the present value of the replacement with time. The total cost is the summation of both costs based on the equivalent annual uniform cost (EAUC), which has an optimal value at a specific time. Therefore, this specific time represents the ideal time for replacement (Figure 2.4). Shamir and Howard (1997) used this method to find the optimal time of replacement for a pipe. Historical data were collected to determine this optimal time. The break rates are measured in breaks per year per 1000 ft (Equation 2.1).

$$N(t) = N(t_o)e^{A(t-t_o)} \quad (2.1)$$

Where:

t: time in years.

t_o: base year for the analysis (the year the pipe was installed, or the first year for which data are available).

N(t): number of breaks per 1000-ft length of pipe in year (t).

A: growth rate of coefficient (dimension is 1/year).

Shamir and Howard (1997) mentioned that care should be taken to aggregate only data that are considered to be homogeneous with respect to the cause of breakage. Therefore, it is not an easy task to generalize the regression equation due to the variables involved some of which include pipe material, soil type and temperature conditions. Also, it requires another model to determine the costs of future breaks (Shamir and Howard, 1997).

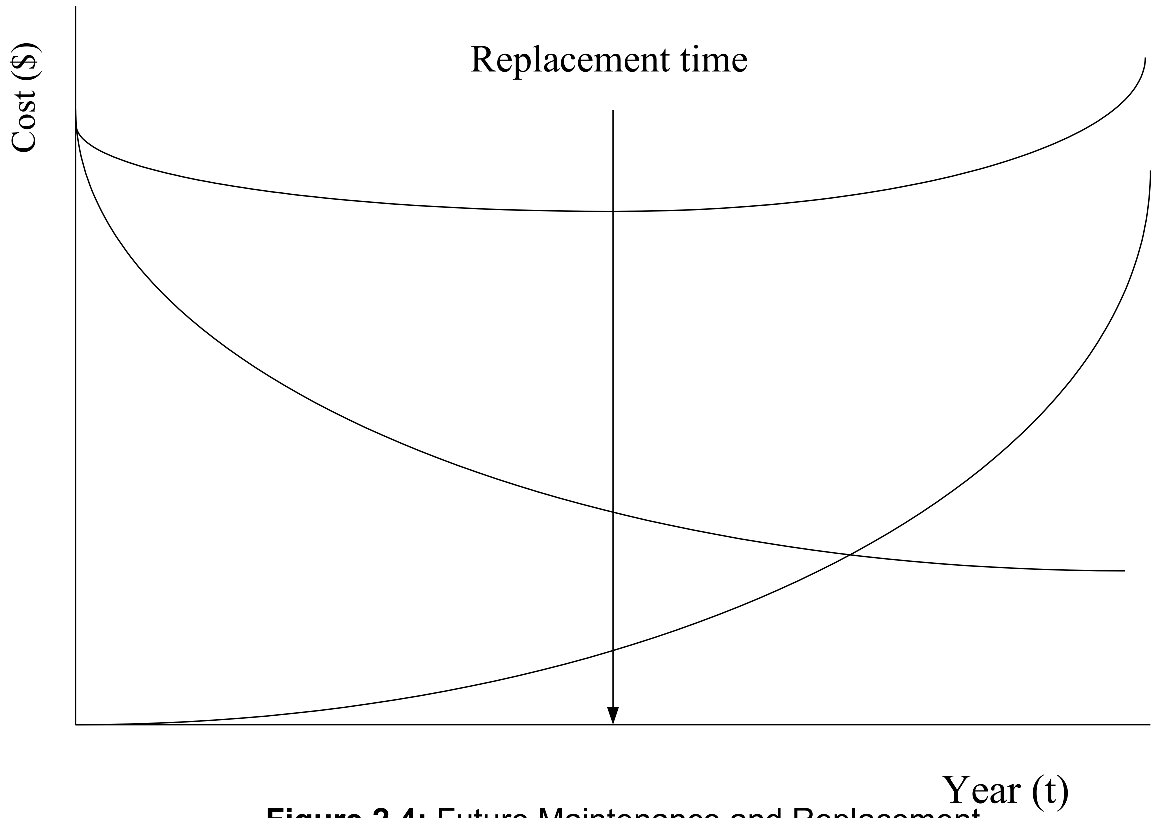


Figure 2.4: Future Maintenance and Replacement
(Shamir and Howard, 1997)

Shahata and Zayed (2008) developed a stochastic life cycle cost modeling approach for water mains. The process of the model is divided into four steps: a) input parameters, b) simulation, c) sensitivity analysis, and d) output. The input includes the cost of new construction and rehabilitation elements, deterioration parameters (i.e. number of breaks), economic parameters (i.e. interest rate), and new construction and rehabilitation alternatives. Using simulation to compute the equivalent annual uniform cost (EAUC), they developed cash flow for the suggested scenarios after generating random values for the previous parameters (Figure 2.5) The EAUC represents the equivalent annual uniform cost of different rehabilitation scenarios such as open cut, pipe bursting, horizontal directional drilling, etc.

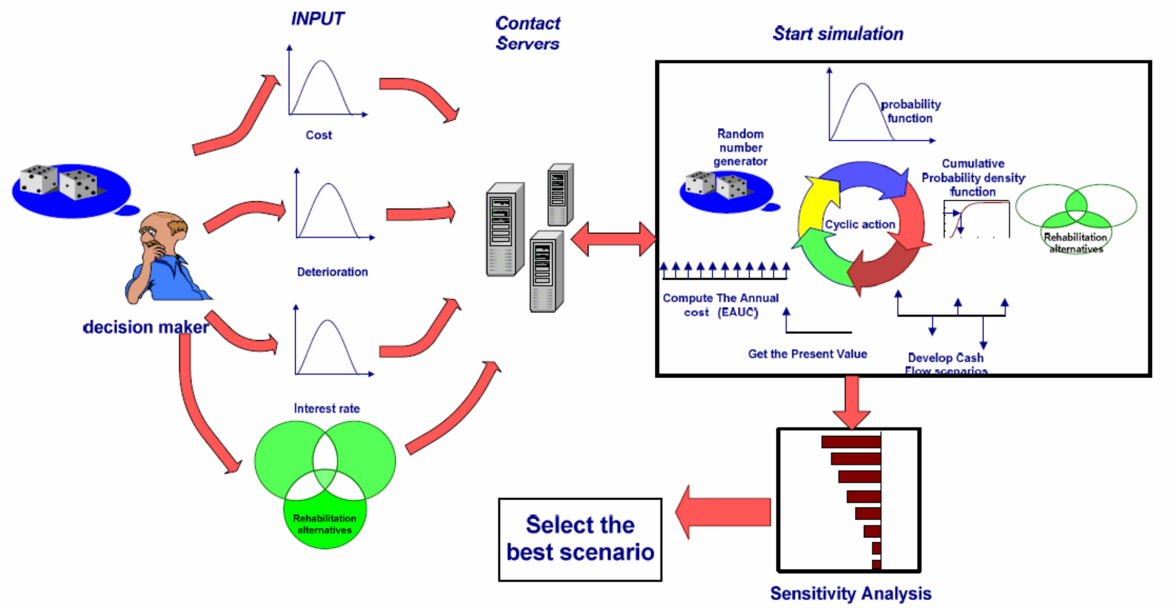


Figure 2.5: Framework for Stochastic Life Cycle Cost (SLCC) Model (Shahata and Zayed, 2008)

iii) Mechanistic Methods

This method relies on the structural analysis of a pipe. The analysis includes calculation of the strength of a pipe against the external and internal loads. Rogers and Grigg (2006) stated that mechanistic methods are implemented as physical models. The physical mechanisms of pipe failure include three categories (Makar and Kleiner, 2000):

a) Pipe structural properties, pipe–soil interaction and the quality of installation.

b) Internal and external loads.

c) Material deterioration.

Hadzilacos *et al.,* (2000) developed software to determine the structural performance, hydraulic reliability, water quality, and service reliability. The authors calculated the deterioration first, which decreases the resistance of a pipe against the interior load (water pressure) and the exterior loads (soil, temperature, traffic, etc.). Figure 2.6 depicts the expected loads (interior and exterior).

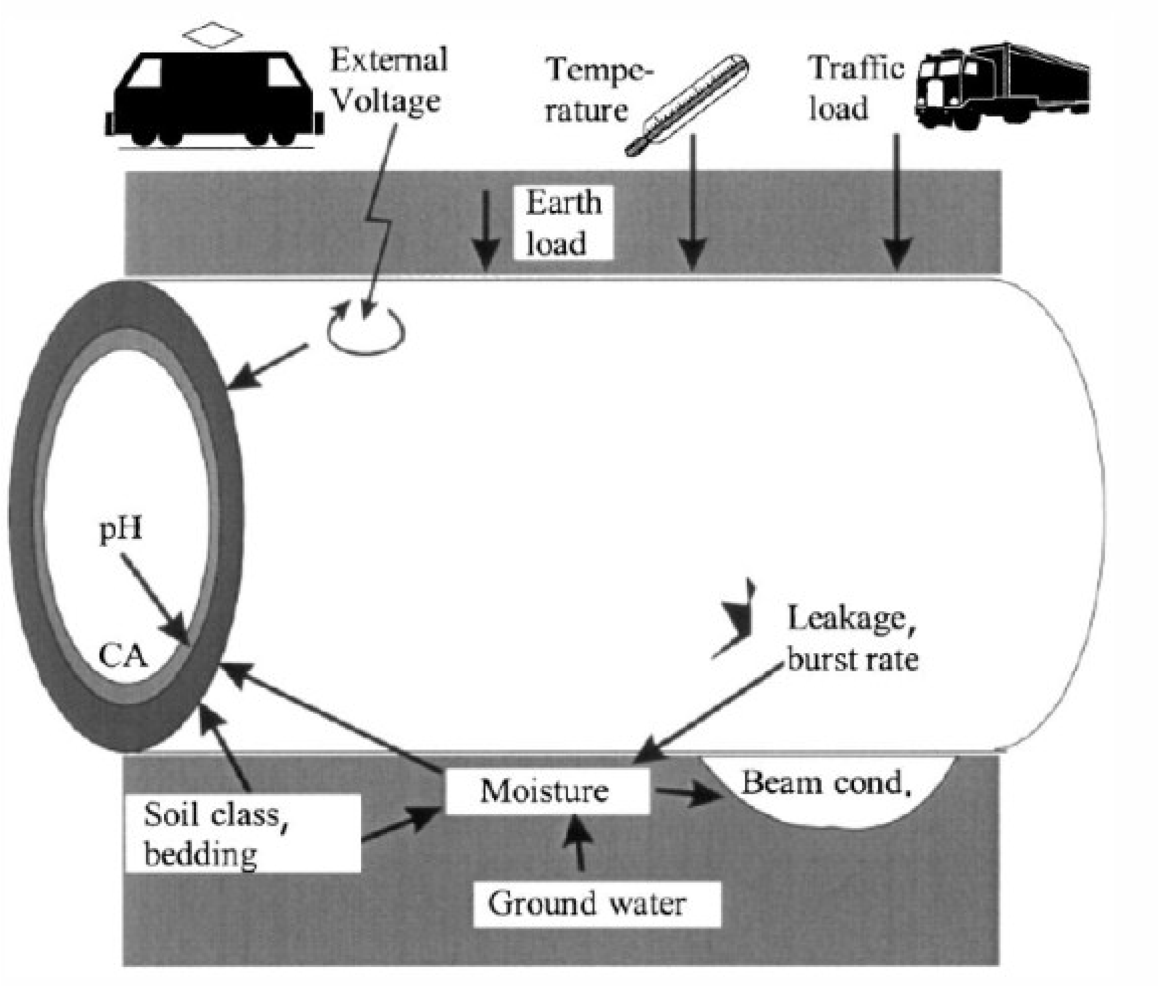


Figure 2.6: Loads That May be Applied to a Pipe
(Hadzilacos et al., 2000)

iv) Regression Methods

Regression methods are correlated to the Deterioration Point Assessment (DPA) methods by using the same deterioration factors (Loganathan *et al.,* 2001). Researchers applied regression methods to find relationships among several deteriorated factors of water main networks (Loganathan *et al.,* 2001). The relationship between breakage rates of a pipe with time is determined by the methods outlined in Shamir and Howard (1979). Wang (2006) used regression methods to study the relationship between annual break rates of individual water mains and independent variables, such as pipe age, diameter, length, and depth. Figures 2.7 and 2.8 present two examples of Wang's results using regression method.

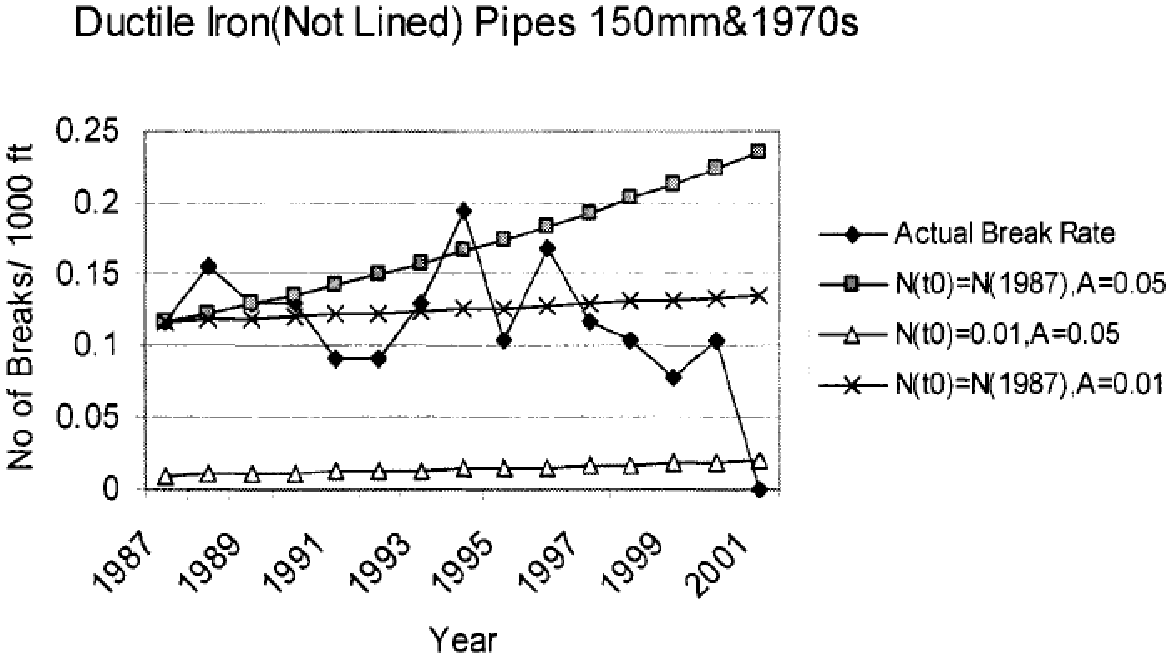


Figure 2.7: Ductile Iron (Not Lined) Pipe Actual versus Forecasted Break Rates (Diameter=150mm, Decade of installation=1970s), (Wang, 2006)

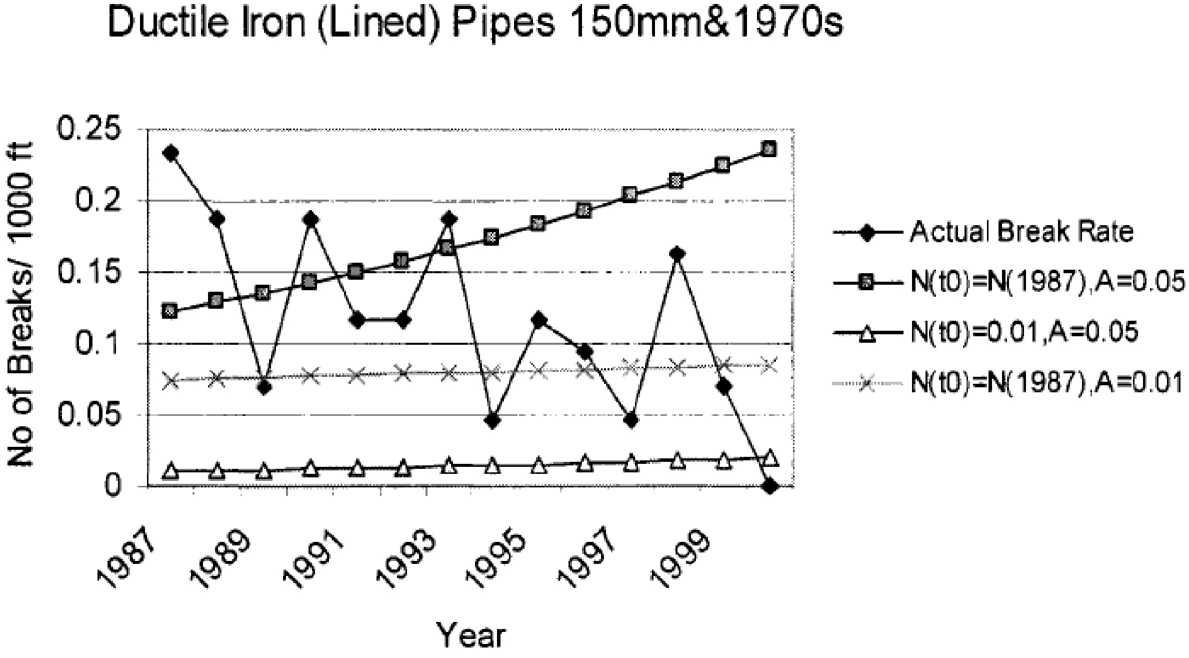


Figure 2.8: Ductile Iron (Lined) Pipe Actual versus Forecasted Break Rates (Diameter=150mm, Decade of installation=1970s), (Wang, 2006)

v) Failure Probability Methods

The failure probability is also related to DPA methodology. Both methods can be built on the same deterioration factors, but failure probability methods can be brought by assessing the probability of survival. These methods are explained extensively by researchers with their advantages and disadvantages (Rogers and Grigg, 2006). The methodology can be demonstrated by fitting the available data related to the breakage history of a pipe and finding the most suitable distribution (e.g. Exponential, Poisson, or Weibull) to predict the probability of the next failure (Rogers and Grigg, 2006). The condition assessment of a pipe can be found by modeling the results of these methods (reliability theory is one of these methods) into a numerical or subjective scale. This research aims to add the new concept of calculating failure probability using reliability theory.

2.3 Reliability of Infrastructure

2.3.1 Reliability Assessment of Distribution Water Networks

Reliability is the probability of a component to perform the intended objective for a specific time under stated conditions (Ramakumar, 1993). Govil (1983) defined the reliability of an item as the probability of this item to perform its work within a specific time, under certain operating conditions. Water main reliability is divided into hydraulic reliability and mechanical reliability. Cullinane (1989) defined hydraulic reliability as the availability and ability of the water main to provide water at required pressures, for a certain time and location. Therefore, hydraulic failure can be caused by failing to deliver a prescribed quantity of water. The mechanical reliability of a water main is the probability of that main meets its specified requirements for a given period of time. The mechanical reliability of a water main is a function of several factors such as external and internal loads, environmental and operational conditions and pipe characteristics (Kleiner and Rajani, 2001). The failure of a pipe due to mechanical breakdown is a complex process because it may have occurred due to one or more of the previously stated factors or an interaction among them. Moreover, hydraulic reliability is also affected by mechanical reliability (Cullinane, 1989). Reliability Assessment of water distribution networks is measured relative to failure (Quimpo, 1996). After installation, the reliability is equal to 100% (no failure occurs at that time and the condition of the water main is considered perfect). With time, the reliability decreases due to a hydraulic and/or mechanical problem.

Reliability of water main accessories can be treated in a manner similar to water mains in terms of mechanical reliability. Hydrants and isolation valves work with high reliability when their interior valves open and close properly. Problems associated with valve function, decreases their reliability. In conclusion, the properties related to the reliability of a water main and an accessory can be represented in the following manner (Govil, 1983):

(i) $0 \leq R(t) \leq 1$

(ii) $R(0)=1$ and $R(\infty)=0$

(iii) R(t) in general, is a decreasing function of time

The mathematical expression of reliability assessment for an element, such as a component of a water network, can be represented as follows (Cullinane, 1989).

$$R(t) = \int_{t}^{\infty} f(t)dt \quad \text{(2.2)}$$

Where f(t) is the probability density function of the component's failure, which can be found using statistical data.

2.3.2 Average Failure Rate (λ)

Failure rate (f/y) is the number of failures that occur within a specific time interval. As an example, the failure rate of a pipe for a period of 10 years with 1 failure is 1f/10y, which is equal to (0.1 f/y). This is called the first failure. If a second failure occurs 5 years after the first tenth year, the failure rate will be (1f/5y), which equals 0.2 f/y. The average failure rate, transition rate, or hazard rate (λ) in this case is (2 f/15y), which is equal to (0.133 f/y). Billinton and Allan (1983) described the difference between hazard rate (λ) and failure rate (f/y) as follows: “the basic concept of a transition rate is perhaps easiest to explain from a failure point of view. It should be noted that a transition rate has a much wider significance and is used in conjunction with the occurrence of other events such as repair”. The shape of a hazard rate curve is often referred to as a bathtub curve for self-evident reasons and can generally be divided into 3 distinct phases (Figure 2.9).

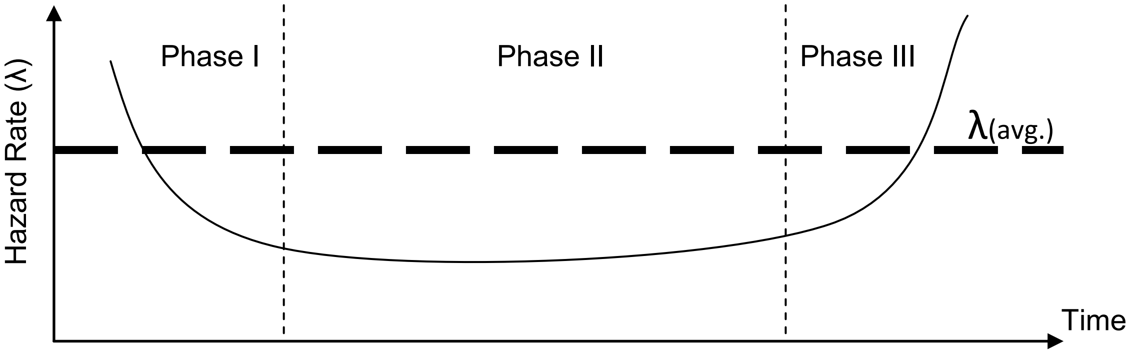


Figure 2.9: Hazard Rate Curve
(Adapted from Billinton and Allan, 1983)

Phase (I) is known by various names, such as infant mortality or the de-bugging phase. The availability of a hazard rate (λ) in this region is very high due to manufacturing errors or improper design. Phase (II) is distinguished by a constant hazard rate. In this region, failures occur purely by chance. Phase (III) represents the wear-out or fatigue phase and is characterized by a rapidly increasing hazard rate with time. Phase (II) is considered as the useful life, to which the negative exponential distribution is applicable (Billinton and Allan, 1983).

The average failure rate (λ) can be measured in terms of failure per unit time (as mentioned above), and this relation is described in Equation 2.3 (Govil, 1983).

$$\lambda = \frac{f}{t} \quad \text{……………………………………} \quad (2.3)$$

Where: λ =the average failure rates,

f = number of failures during the test interval, and

t = total test time.

2.3.3 Exponential Reliability Functions

Reliability is a function of the average failure rate (λ). This function takes a negative exponential shape when λ is constant as shown in equation 2.4.

$$R(t) = e^{-\lambda t} \quad \text{……………………………………} \quad (2.4)$$

While the failure rate, f (t), is:

$$f(t) = \frac{-dR(t)}{dt} = \lambda e^{-\lambda t} \quad \text{……………………………………} \quad (2.5)$$

And the failure density function, Q (t), is:

$$Q(t) = \int_0^t f(t) = \int_0^t \lambda e^{-\lambda t} dt = 1 - e^{-\lambda t} \quad \text{……………………………………} \quad (2.6)$$

From equations 2.5 and 2.6, the relationship between R(t) and Q(t) can be expressed as follows:

$$R(t) = 1 - Q(t) \quad \text{……………………………………} \quad (2.7)$$

Figure (2.10) shows the reliability functions when an exponential function is used.

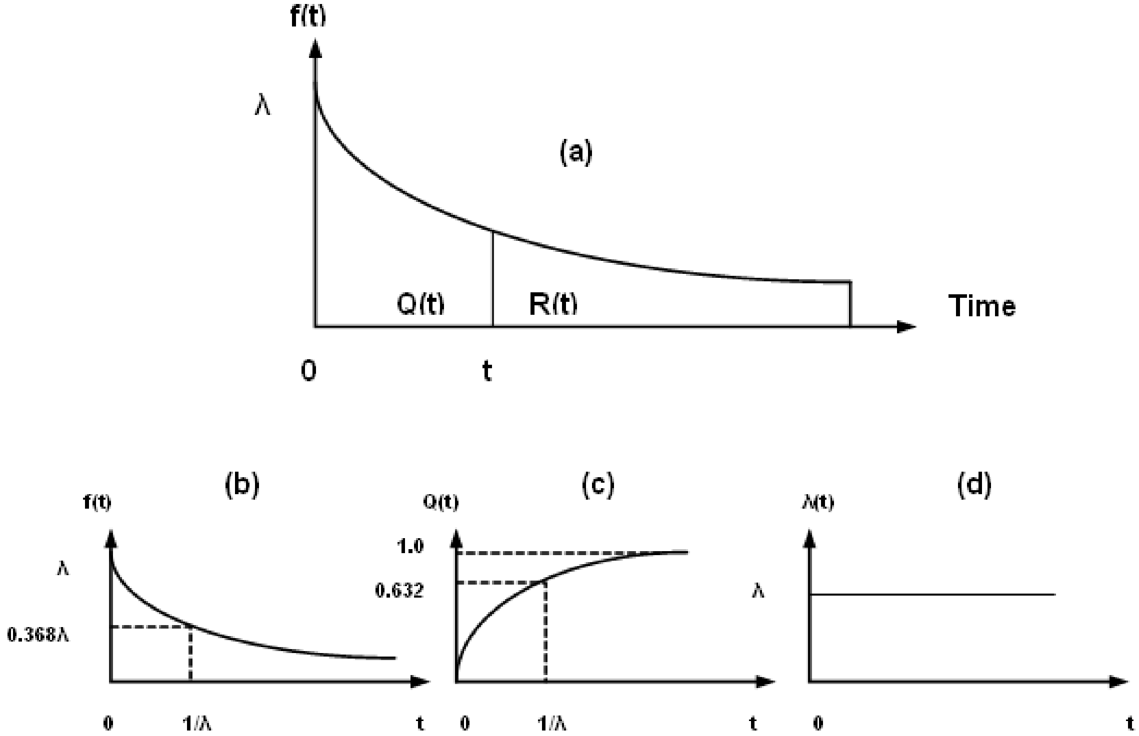


Figure 2.10: Exponential reliability functions

a) Areas Showing Q(T) and R(T). b) Failure Density Function. c) Cumulative Failure Distribution. d) Hazard Rate (Billinton and Allan, 1983)

2.3.4 Network Reliability Analysis

When the water mains are connected so that they constitute a network, the network reliability can be found depending on their connection configuration (series, parallel and series-parallel systems) (Billinton and Allan, 1983). For a series system, which is shown in Figure 2.11, the system reliability will be equal to the multiplication of each water main’s reliability within the system (Equation 2.8).

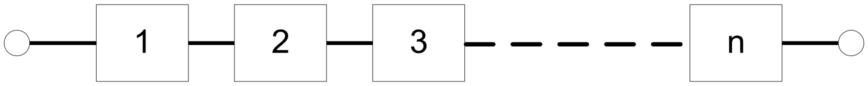


Figure 2.11: Series Network
(Billinton and Allan, 1983)

$$R_s = R_1 . R_2 . R_3 ....R_n = \prod_{i=1}^{n} R_i \qquad (2.8)$$

Where:

R_s: System reliability, R_i: component reliability, i: segment i^{th}, n: total number of segment.

When the water mains in the network are connected in parallel, as shown in Figure 2.12, system reliability can be calculated using Equation 2.9.

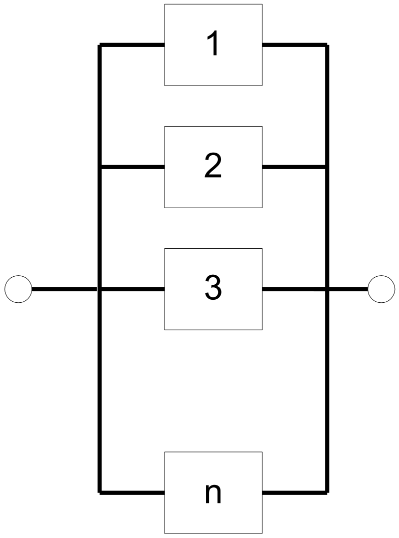


Figure 2.12: Parallel Network
(Billinton and Allan, 1983)

$$R_s = 1 - Q_1 . Q_2 . Q_3 ....Q_n = 1 - \prod_{i=1}^{n} Q_i \qquad (2.9)$$

Where:

Q_i: Component failure

Finally, when the water mains are connected in a series-parallel network, which is shown in Figure 2.13, network reliability can be calculated as indicated by Equations (2.10) to (2.14):

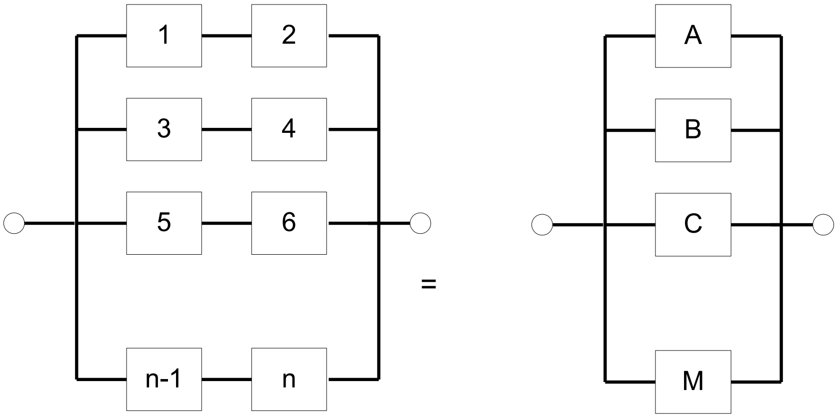


Figure 2.13: Series-Parallel Network
(Billinton and Allan, 1983)

$$R_A = R_1.R_2 \qquad (2.10)$$

$$R_B = R_3.R_4 \qquad (2.11)$$

$$R_C = R_5.R_6 \qquad (2.12)$$

$$R_M = R_{n-1}.R_n \qquad (2.13)$$

$$R_S = 1 - Q_A.Q_B.Q_C.........Q_M = 1 - \prod_{i=1}^{n} Q_i \qquad (2.14)$$

The previous techniques can be applied for simple networks. For complex networks, system reliability can be calculated using other techniques (Quimpo, 1996), which are listed below:

1. Fault-tree analysis
2. Cut-set
3. Path-set (Cut/Tie Set)
4. Spanning-tree analysis
5. Polygon-to-chain reduction
6. Method of bounds
7. Connection matrix technique.

Quimpo (1996) reported that dealing with a large network is not easy to manage, even with high-speed computers. Choosing the most suitable method requires an analysis of each of the previous methods. However, when the network is large, Cut-set and Path-set techniques will be appropriate in conjunction with existing software.

2.3.5 Tie Set Method

By evaluating the methods, as explained in section 2.5.4, it is determined that Cut-set and Path-set are the most suitable methods when dealing with a large network. Other methods can be used with smaller networks. However, the Cut-set and Path-set (Equations 2.15 and 2.16) techniques work with the software in order to achieve satisfactory final results.

$$R = P[\bigcup_{i=1}^{m} T_i] \qquad (2.15)$$

$$T_i = \{N_1 \cap N_2 \cap .... \cap N_{K-n}\} \qquad (2.16)$$

where:

R: System reliability;

P [ ]: represents the probability that at least one of the m paths will be operable;

T_1: a minimal path, one in which no node is traversed more than once in going along the path;

and N_k: the nonfailure of the k-th pipe link in the network.

Figure 2.14 shows a minimal tie set diagram of a simple network (Li and Zhao, 2005). The reliability of the network can be calculated using Equations (2.15) and (2.16) as follows:

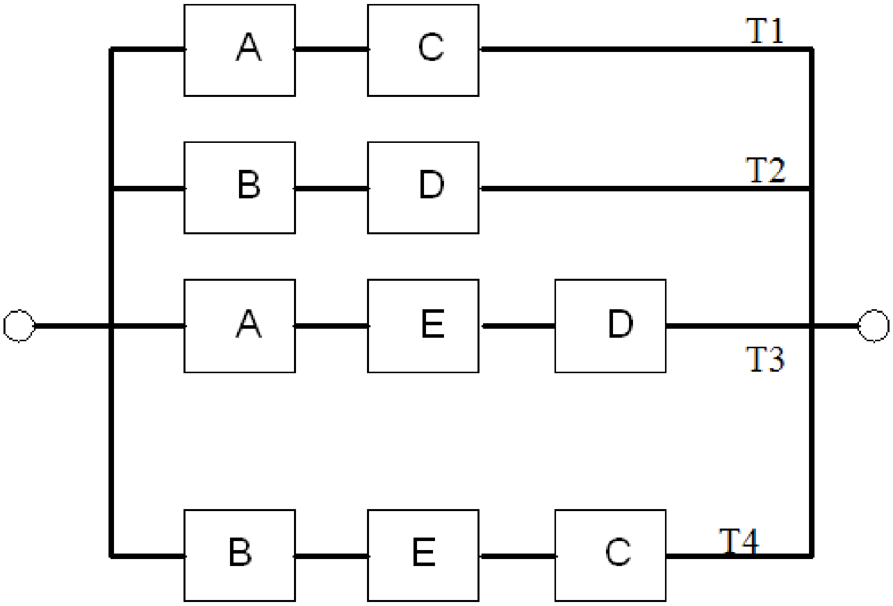


Figure 2.14: Series-Parallel Network
(Billinton and Allan, 1983)

$$P(T_1) = P(A).P(C)$$
$$P(T_2) = P(B).P(D)$$
$$P(T_3) = P(A).P(E).P(D)$$
$$P(T_4) = P(B).P(E).P(C)$$
$$\therefore R = P(T_1) + P(T_2) + P(T_3) + P(T_4) - [(4-1)\{P(A).P(B).P(C).P(D).P(E)\}]$$

2.4 Water Main Rehabilitation Methods

2.4.1 Rehabilitation Method Classification

Hoffman (2004) divided the pipeline system rehabilitation methods into: (1) repair, (2) renovation (maintenance), and (3) replacement (on-line and off-line). On-line replacement includes pipe bursting and sliplining. The renovation of water main systems is divided into cleaning and non-structural sprayed linings (epoxy resin and cement mortar) and structural linings (close-fit PE and CIPP). Close-fit PE includes concentric reduction.

2.4.2 Decision Support System (DSS) for the Rehabilitation Of Water Main Networks

Researchers have contributed a significant amount of work related to this field. They have studied the known factors affecting water mains to select the most suitable rehabilitation method, using different techniques, such as simulation (Shahata and Zayed, 2008), AHP (Al-Aghbar, 2005), MAUT (Moselhi and Sigurdaottir, 1998), AHP and SMART (Zayed *et al.*, 2011), and based on the cause of failure (NRC (Infraguide: Best practices, 2003)); and Mohamed and Zayed, 2008)). The variety of rehabilitation methods, location characteristics, available budget, surrounding environment and societal tendencies and traditions led to the need for the development of new decision support systems. Therefore, decision support systems are required to cover most of the criteria. The following decision support systems (DSS) are examples of selecting the most suitable rehabilitation method.

The NRC (Infraguide: Best practices, 2003) developed DSS to provide a detailed technique allowing for a selection of the best rehabilitation method(s) from among alternative water main technologies (Figure 2.15). The final output is more likely to be a set of rehabilitation methods instead of one method. Alagbar (2005) introduced a methodology (Figures 2.16 and 2.17) to determine the most suitable method of rehabilitation and the output also consisted of a set of rehabilitation methods. The selection of a rehabilitation method must be performed according to technical feasibility, contractual acceptance and cost effectiveness. The first and second conditions function as a filter for the selection. Other factors may be added to the third condition (cost effectiveness) in order to render a comparison of several types of rehabilitation more logical and economical.

Mohamed and Zayed (2008) determined the most suitable rehabilitation method (Figure 2.18) based on the breakage rate. This scenario rests on yes/no decisions, which lead to certain limitations: (1) the location (near or far from the source) of a pipe inside the network is not considered, (2) the cost of rehabilitation is not calculated and compared with other methods, and (3) the impact on the environment is not considered.

Shahata and Zayed (2008) proposed a maintenance plan for the best rehabilitation scenario based on stochastic life cycle cost analysis (Figure 2.19). The model has limitations as it does not account for environmental impacts.

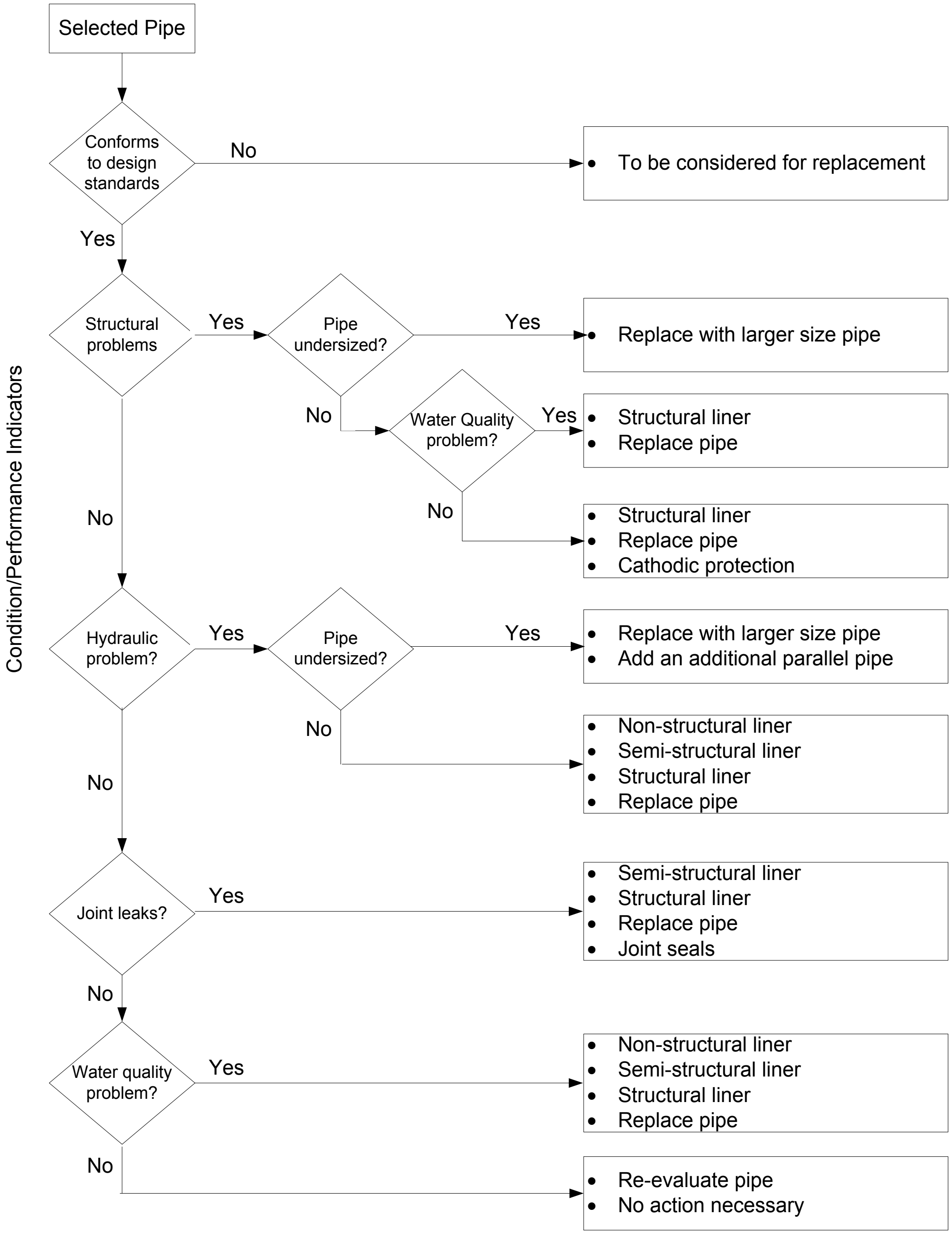


Figure 2.15: Selection Alternative Water Main Renewal Technologies (Adapted from NRC (Infraguide: Best practices, 2003))

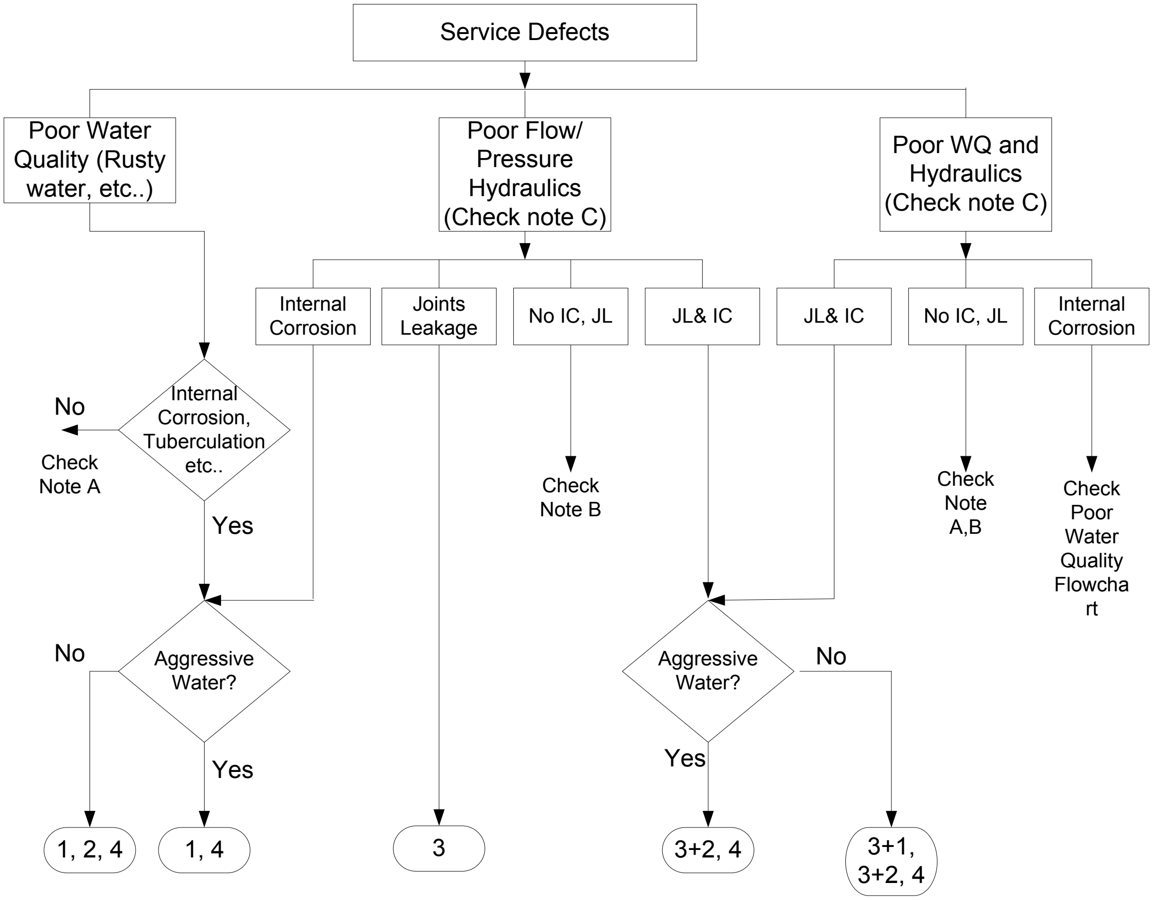


Figure 2.16: Water System Rehabilitation Selection Service Defects Flowchart (Alaghbar, 2005)

Non-structural or Semi-structural Rehabilitation Options:

(1) Epoxy Lining; (2) Cement Lining; (3) Internal Joint Sealing; and (4) Close Fit Sliplining, Swaged Lining Fold & Formed Lining, and Cured In Place Pipes (CIPP)

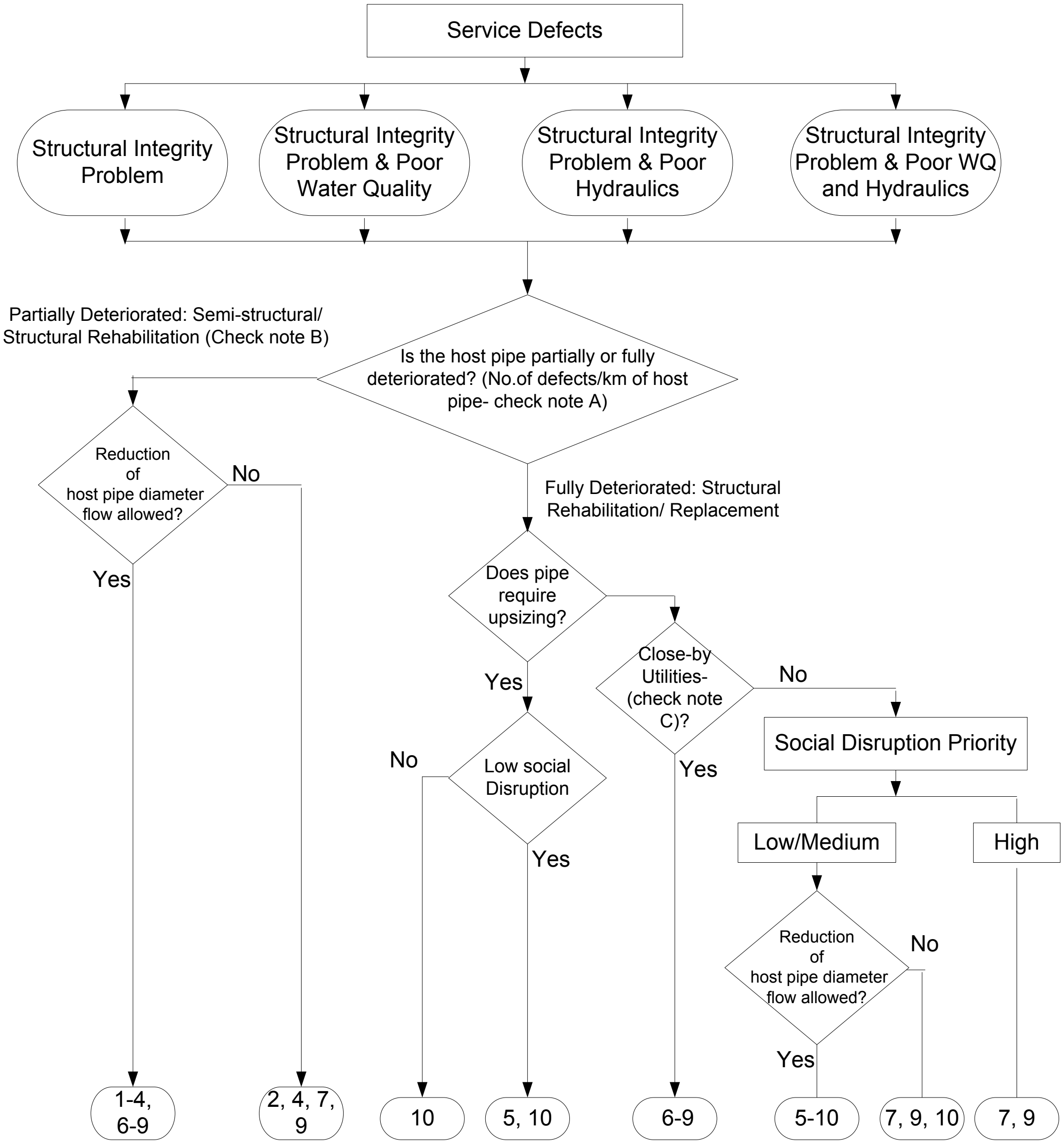


Figure 2.17: Water System Structural Defects Rehabilitation Selection Flow Chart (Alaghbar, 2005)

Semi-structural Rehabilitation Options:
(1) Swaged Lining (Reduced Diameter); (2) Folded and Formed Lining; (3) Sliplining; and (4) Cured In Place Pipes (CIPP).

Structural Rehabilitation Options:
(5) Conventional Open Cut Replacement; (6) Swaged Lining (Reduced Diameter); (7) Folded and Formed Lining; (8) Sliplining; (9) Cured In Place Pipes (CIPP); and (10) Pipe Bursting.

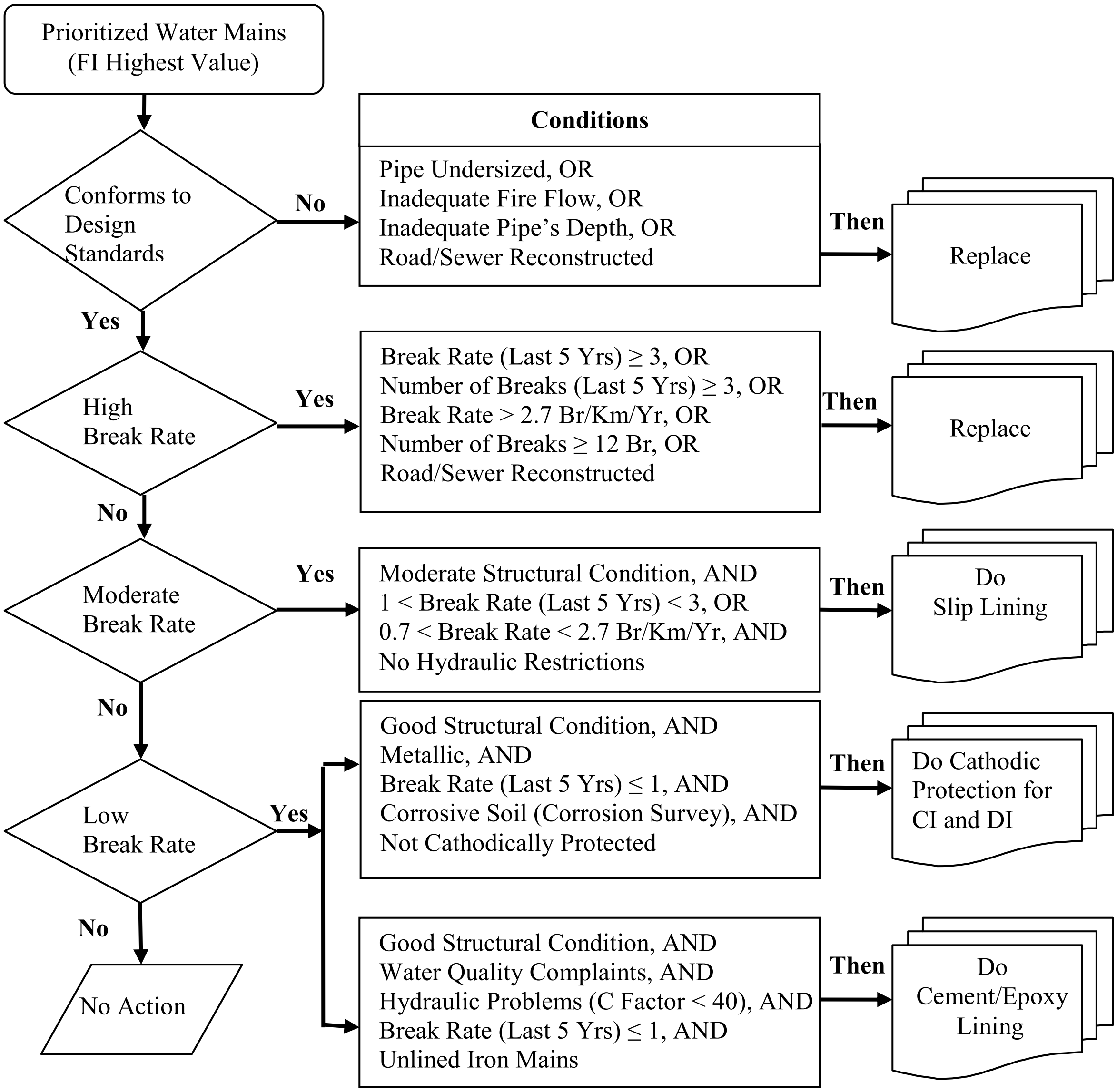


Figure 2.18: Decision Making Tree of Rehabilitation/Replacement Selection - Scenario I (Breakage rate)-(Adapted from Mohamed and Zayed, 2008)

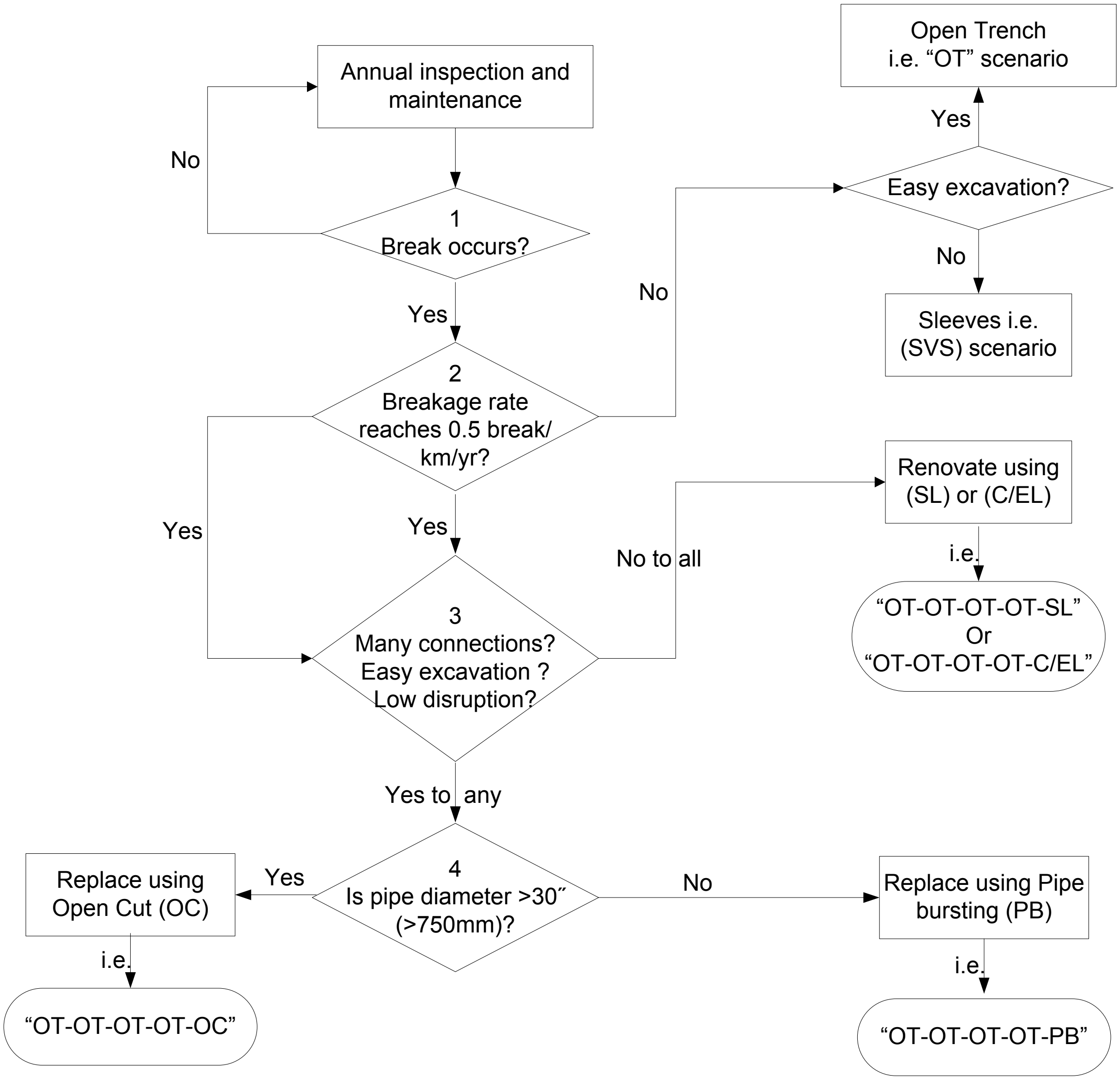


Figure 2.19: Maintenance Plan Procedure Flowchart (Shahata and Zayed, 2008)

2.4.3 Cost elements of Rehabilitation Methods (TCReh)

i) Cost Element Classifications

Based on Najafi (2004), the life-cycle cost of a project can be categorized into three branches: (1) pre-construction, (2) construction, and (3) post-construction. The first branch includes land acquisition, easements, permits, design fees, planning, legal fees, and preparation of contract drawings. The second branch includes the direct and indirect construction cost and the social cost(s). The final branch includes the operation and maintenance costs, depreciation and loss of revenue due to emergency repairs. These factors could be major or minor according to the method of construction (open cut or trenchless). Harbuck (2000) divided the types of costs into three stages: (1) Primary costs, (2) Secondary costs, and (3) Risk costs. The following shows the subdivisions within each category:

1. Primary costs:
    a) Planning
    b) Engineering
    c) Design management
    d) Right-of-way costs (permanent takes and temporary easements)
    e) Construction costs associated with pipe installation
    f) Life cycle costs (if requested by the owner).
    g) Secondary costs: costs that can be paid as compensation for damages to land property.
    h) Loss of business and resulting tax revenue

        i) Impact of construction on residents and environmental impacts.

2. Risk costs:
    a) Impact on geotechnical conditions.
    b) Unforeseen obstructions.
    c) Disposal of contaminated soil or ground water.

ii) Impact on Environment (IoE) (Zayed, Salman, and Basha; 2011)

Environmental concerns represent a national priority for the Government of Canada and these concerns are enforced through the Canadian Environment Protection Act (CEPA), 1999 (c.33). The construction sector is a source of adverse environmental impact. A proper assessment of environmental impact should therefore be performed prior to selecting the method of construction, which is greatly affected by site conditions (Langan, 2003). This would save costs by minimizing environmental impact. The IoE is defined as the systematic identification and evaluation of the potential impacts (effects) of proposed projects, plans, programs or legislation to the physical-chemical, biological, cultural and socio-economical components of the total environment (Canter, 1996). It is also the systematic identification and evaluation of the potential impacts (effects) of proposed projects, plans, programs or legislation to the physical-chemical, biological, cultural and socio-economical components of the total environment (Canter, 1996). The impact of construction projects on these factors and their interrelationships should be studied and analyzed.

2.5 Decision Making and Scheduling of Rehabilitation Activities in Water Networks

2.5.1 Scheduling the Rehabilitation of Water Main Networks

Scheduling the rehabilitation of water main networks can be accomplished with a model, which is a crucial tool to decision makers who must schedule the rehabilitation within an allotted time and budget. The optimum scheduling is necessary to (1) allocate the available budget sufficiently, (2) increase the level of service, (3) decrease the level of complaint by local residents, (4) integrate asset rehabilitations, and (5) decrease the operation and maintenance cost. The objective of the optimized scheduling is the integration of the previous points which is very difficult task for a decision maker. In general, the decision maker might impose a decision according to his/her experience in this field without considering one or more than one factors, and therefore the optimum process of scheduling using mathematical modeling is crucial to collect the objectives, variables, and constraints. Several mathematical models have been developed as suitable scheduling models for such rehabilitation work. Dandy and Engelhardt (2001), Al-Battaineh and AbouRizk (2005), Hong et al. (2006), Halhal, D. et al. (1999), and Alvisi and Franchini (2006) developed optimized scheduling methods for water main rehabilitations. Their work, however, is limited to individual pipe sections without: (1) including the pipe network and its accessories, (2) accounting for pipe location, (3) considering the impact of scheduled work on the network priority index (PI) for intervention, and (4) clustering the rehabilitation work of individual pipes, segments and segment groups to generate practical work packages.

Table 2.2 summarizes several previous studies of scheduling rehabilitation work of water mains. It includes factors and techniques used to develop different scheduling models. With different type of modeling methods, the final objective is to schedule rehabilitation works of water mains. The two main constraints that are used by the previous studies are the available budget and the planning time of rehabilitation.

Table 2.2: Summary of Different Research works of Water Main Scheduling

No.	Reference	Year	Technique	Factors
1	Dandy and Engelhardt	2001	Genetic algorithms	• Pipe ID • Time of the replacement • Size of the new pipe
2	Al-Battaineh and AbouRizk	2005	Genetic algorithms	• Section ID • Pipe material • Pipe diameter • Cleaning level • Pipe length • Number of combination crews • Number of preparation crews • Number of lining crews • Productivity information
3	Alvisi and Franchini	2006	multi-genetic algorithm	• Pipe ID • Time intervals • Budget s allocation/ time interval
4	Halhal et al.	1999	messy genetic algorithms	• Pipe ID • Planning period • Available budget • Benefit (system improvement)
5	Hong et al.	2006	Total cost	• Pipe ID • Planning period • Available budget

Adding more constraints is making the optimization process more complete. However, a decision maker can add a lot of constraints which lead to several problems, such as (1) complexity of forming the mathematical model to include added constraints, (2) difficulty to implement the developed model using specific software, and (3) difficulty of collecting required data that are costly and time consuming. As such, in building a scheduling mathematical model one should consider the availability of the required data and the feasibility of implementing such model in practical software. The research presented in this paper addresses the limitation cited in the literature and develops reliability based optimized scheduling method for rehabilitation work of water networks. The method is developed using unsupervised neural networks (UNNs) and Mixed Integer Non Linear Programming (MINLP). It generated schedules that provide most suitable rehabilitation plans accounting for a number of factors and respecting budget constraints of municipalities.

2.5.2 Decision Making Techniques

Researchers have studied crucial factors, which affect the assessment of water mains, using different techniques, in order to obtain a condition rating result for each pipe. Three methods will be utilized for this research:

i. Analytical Hierarchy Process (AHP)

The AHP method is used to convert subjective assessments of relative importance to a set of overall scores or weights (Saaty, 2001). This method deals with a complex decision according to the weight of selected criteria. It is suitable for decisions with both quantitative and qualitative criteria (Backer *et al.,* 2001).

Alternatives are scored using a pair-wise comparison matrix according to a unified scale (i.e. 1-9). The AHP application procedure passes through several steps (Zayed and Halpin, 2004; Zayed and Chang, 2002): (1) building pair-wise comparison matrices for factors and their sub-factors, (2) checking the consistency of the matrices, and (3) determining the relative weight of factors and sub-factors (decomposed weight). The model that quantifies the qualitative factors is shown in Equation 2.17 (Zayed and Halpin, 2004; Zayed and Chang, 2002):

$$Index = \sum_{j=1}^{n} V_j (x_j).W_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.17)}$$

Where:

V_j (x_j) = Score of sub-factors in factor j.

W_j = Decomposed relative weight of factor j.

ii. Simple Multi-Attribute Rating Technique (SMART)

The SMART is a multi-criteria decision analysis method developed by Von Winterfeldt in 1986 (Lootsma 1997). The SMART method is a simple implementation of the multi-attribute utility theory (MAUT) in linear format (Backer *et al.* 2001). The application procedure consists of the following actions (Lootsma 1997; Backer 2001; Zayed et al. 2011): (1) determine the various alternatives that should be evaluated; (2) set the list of criteria that will be considered in the evaluation process; (3) assign a value to each criteria on a unified scale; (4) determine the overall 'score' of an alternative using the weighted sum of its rating against each criteria as shown in Equation 2.18; and (5) rank the alternatives by their relative scores.

$$Index = \sum_{i=1}^{n} W_i \times I_i \quad \text{……………………………………………………} \quad (2.18)$$

Where: W_i: Weight of factor i, I_i: Score of factor i (0 .01- 1.00), n: total factor number

iii. Unsupervised Neural Network (Kohonen)

An unsupervised neural network, also known as a Kohonen network (Fausett, 1994), consists of two layers, input and output layers. Other types of neural networks consist of at least three layers. The extra layers represent those that are hidden, which are not found in an unsupervised neural network. The most important reason of using an unsupervised neural network is to cluster the data; therefore, the output should be checked carefully. The architecture of the Kohonen network is shown in Figure 2.20. Fausett, (1994) described the Kohonen algorithm as follows:

Step 0: (a) Initialize weights w_{ij}, (b) Set topological neighborhood parameters, and (c) Set learning rate parameters.

Step 1: While stopping condition is a false, do step 2-8.

Step 2: For each input vector x, do steps 3-5.

Step 3: For each j, compute: $D(j) = \sum_i (w_{ij} - x_i)^2$ ……………………………… (2.19)

Step 4: For index J such as that D (J) is a minimum.

Step 5: For all units j within a specified neighborhood of J, and for all i:

$$w_{ij}(new) = w_{ij}(old) + \alpha[x_i - w_{ij}(old)] \tag{2.20}$$

Step 6: Update learning rate.

Step 7: Reduce radius "R" of topological neighborhood at specified times.

Step 8: Test stopping condition.

Alternative structures are possible for reducing R and α. It should be noted that the learning rate α is a slowly decreasing function of time (or training epochs). The results of clustering process are several groups of pipes where each group includes several pipes that are located in a specific zone in the city. These pipes might require different methods of rehabilitations.

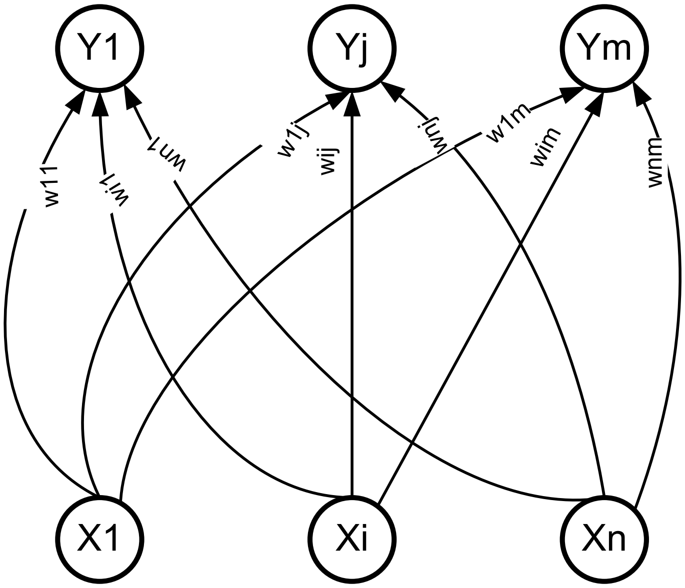


Figure 2.20: Kohonen Self-organizing Map
(Fausett, 1994)

iv. Criticality

Accounting for criticality is an important strategy that has been followed by several municipalities and cities in North America, in order to prioritize water mains. A criticality is defined as the failure consequences of water main when the failure occurs (UMA, 2007). In field applications, there is currently no standard model of criticality that can be implemented to municipal water networks. Therefore, criticality is still a subjective matter which requires heavy involvement of city managers in order to decide on a criticality process.

The relationship between criticality and condition assessment is still not clear to several engineers and managers because they share most of the same factors (i.e. pipe diameter, material). However, a pipe break might be used as a function of condition assessment, while the total affect of pipe failure is a function of criticality.

Miles et al. (2007) reported that environmental impacts, sizes, transportation impact, ease of repair/reliability are the factors that affect criticality of sewers, as shown in Figure 2.21. The process of dividing these factors should be avoided due to the existence of several factors common to both groups. For instance, pipe material is an important factor to be considered for criticality (failure results of concrete pipes are larger than the failure results of PVC pipes). In addition, pipe size is an important factor to be considered for condition assessment.

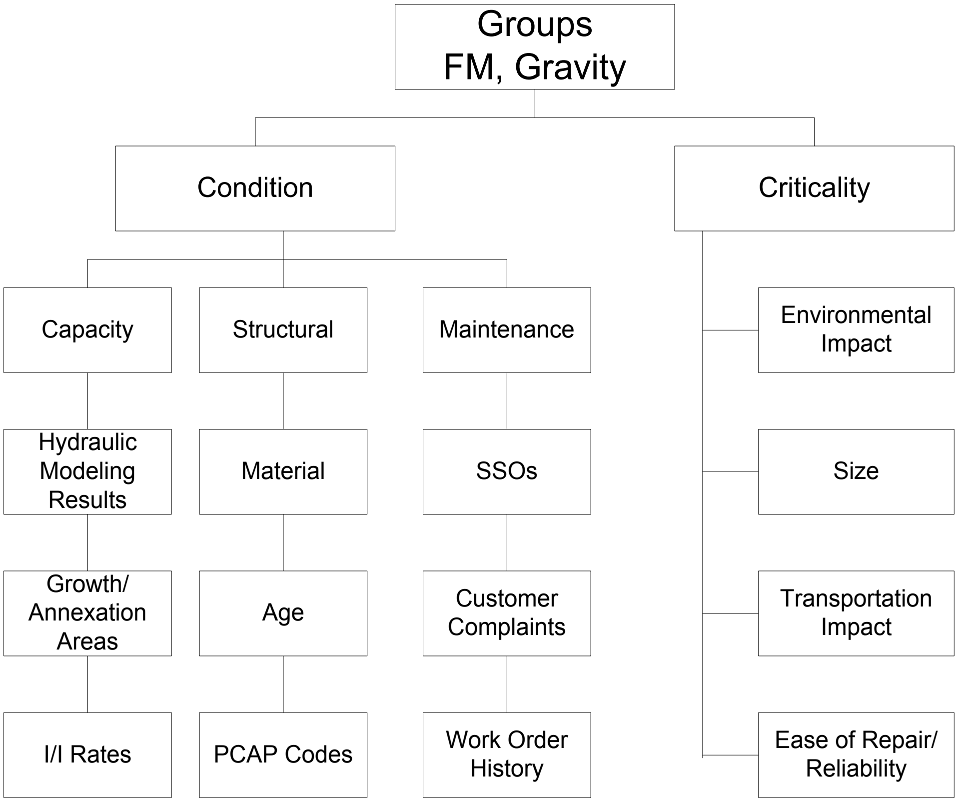


Figure 2.21: Examples of Condition and Criticality Factors
(Adapted from Miles et. al, 2007)

The UMA (2007) developed a criticality model for the city of Hamilton. The model considers four main categories, which are the high-level categories that represent the water main's failure consequences based on experts' opinions. The categories are economic, operational, social, and environmental while their factors (Table 2.3) are as follows:

- **Economic**: influence of the main's failure on monetary resources.
    - Pipe Size (mm): The consequences of failure on the water main are directly proportional to its size, due to an increase in repair cost.

    - Depth (m): According to expert opinion, the consequences of water main failure are huge when its buried depth exceeds 4 m, due to the dramatic increase in repair cost.
    - Material: The consequences of failure on the water main depend on its manufacturing material, due to an increase in repair cost. Concrete pipes have large impacts in comparison to other materials.
    - Low Accessibility: The consequences of water main failure create large impacts when it is not accessible, due to increase of repair cost.
- **Operational:** influence of the main's failure on operational ability.
    - Critical Location: Failure consequences of a water main are considered huge when it is located near a critical location, such as a hospital.
    - Material: Failure consequences of a water main depend on its manufacturing material, due to impacts on the client.
    - Pipe Size (mm): Failure consequences of a water main gradually increase with its size due to an increase on client impact.
- **Social:** influence of the main's failure on society.
    - 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.

  - No Diversion: Failure consequences of a water main are considered huge due to public disruption when it has no alternative.
  - Pipe Size (mm): Failure consequences of water main are gradually increased with its size due to the increase of social impact.

- **Environmental:** influence of the main's failure on the environment.
  - Water Body Proximity: Failure consequences of a water main are gradually increased when it is located close to surface water, such as a lake.
  - Locality: Failure consequences of a water main are considered huge when it is located within a sensitive area.
  - Pipe Size (mm): The consequences of a failed water main gradually increased with its size, due to an increased environmental impact.

Table 2.3: Criticality Factors (UMA, 2007)

Category (First Level)	Economic (Repair Cost)	Operational (Customer Impact)	Social		Environmental (Environmental Impact)
			Public Disruption	Visibility	
Factor (Second Level)	Pipe size	Critical location	Road type	Pipe size	Water body proximity
	Depth	Material	No diversion	Land use	Locality (Sensitive area)
	Material	Discharge			Affected pipe diameter
	Land use				
	Low accessibility				

Scores were assigned to the identified categories and their factors according to a scale of 1-100 where 100 represents the most critical and 1 represents a noncritical or less critical. Factor weights were assigned according to experts' opinions. During the implementation of this model, the city encountered several problems and therefore decided to validate and enhance the model (Salman *et. al*, 2010).

Table 2.4: Criticality Factor Scores (UMA, 2007)

Pipe Size (mm)		**Depth (m)**		**Material**	
Value	**Score**	**Value**	**Score**	**Value**	**Score**
0-299	1	0-3.9	1	Other	1
300-449	5	4+	100	HYP, LEAD	5
450-749	10			CAST1, CIPIT1, CIPIT2, CISP1, CISP2, CISP3, COPP, DUCT, STEEL	10
750-1199	50				
1200+	100				
				PCP,CONCW	100
Low Accessibility		**Critical Location**		**Road Type**	
Value	**Score**	**Value**	**Score**	**Value**	**Score**
No	1	No	1	Other	1
Yes	100	Yes	100	RC	5
				RA, UC	10
				UAMI	25
				EXPWY, HWY, UAMJ	100
No Diversion		**Water Body Proximity**		**Locality**	
Value	**Score**	**Value**	**Score**	**Value**	**Score**
No	1	200+	1	No	1
Yes	100	101-200	5	Yes	100
		51-100	10		
		1-50	25		
		0	100		

2.6 Mixed Integer Non Linear Programming (MINLP)

The MINLP is used in this research to schedule these rehabilitation works. It is important to note here that “The MINLP method has attracted attention because of their modeling capability and because powerful solvers are available commercially” (Earl and D’Andrea, 2005). The concept of this method is not limited to linear relations among the variables; it can be extended to include non linear relations. Bussieck and Pruessner (2003) reported that the use of Mixed Integer Nonlinear Programming (MINLP) has grown recently to cover several areas, such as financial, engineering, management science, and operations research sectors. The general form of a MINLP according to Bussieck and Pruessner (2003) is:

$$\text{Minimize} \quad f(x, y)$$

$$\text{Subject to } g(x, y) \leq o$$

$$x \in X$$

$$y \in Y \qquad \text{Integer}$$

The f(x, y) is a nonlinear objective function, and g(x, y) is a nonlinear constraint function. The x, y are the decision variables, where y is integer value. Caution must be considered when MINLP is used due to its difficulty to solve because of the combination of mixed integer programs (MIP) and the nonlinear programs (NLP), which have difficulties in both of their subclasses (Bussieck and Pruessner, 2003). Letchford (2010) stated two important facts related to the

MINLP, these facts are (1) the MINLP may be a challenge to be solved (i.e. harder than NP) and (2) the optimal solution can be inside the convex area of feasible solutions.

The MINLP has not been used to schedule the rehabilitation of water mains. Genetic algorithm based methods are used by others (see Table 1). It has been recognized that MINLP can be faster than genetic algorithm due to prematurity and the requirement of several runs from different starting points (Young et al., 2007).

2.7 Summary of the Limitations of Previous Research

Reliability assessment of water main networks provides a real assessment based on the failure rates of the components within water networks. It is simple to apply when the failure data of these components is applicable. Otherwise, an assessment of water main networks can be done while considering the contribution of several factors (described in Table 2.1) that lead to failure (Al Barqawi and Zayed (2006); Karaa and Marks (1990); and Geem (2003)). The limitations of previous research are summarized as follows:

- At the time of this research, not all factors, which lead to failure, are known.
- A failure can occur due to one or more factors, and it is not easy to know the reason(s) behind a failure due to the complex interrelationship among the factors.
- The relations among factors have not been studied comprehensively.

- There still is a difficulty related to the collection of the required data for each factor.
- It is limited to individual pipe sections without considering the entire network.

In conclusion, reliability assessment gives a more realistic assessment as compared to relying on an assessment that utilizes a combination of several factors. In addition, reliability assessment of a water main component is not a new concept but the reliability assessment of a segment has not been studied yet. The reliability assessment of a segment is based on the reliability of its components (i.e. valves, hydrants, pumps and pipes).

The criticality model (UMA, 2007) of the City of Hamilton has encountered several problems since it was implemented, due to different factors, which are as follows:

- The model was generic to all land uses.
- Factor weights were assigned directly by experts.

However, this model covered the most critical factors that affect the criticality of a water main such as economic, operational, social, and environmental factors.

The selection of rehabilitation methods have been studied extensively by many researchers (Shehab-Eldeen, 2002; Shahata and Zayed , 2008; Alagbar, 2005; NRC (Infraguide: Best practices, 2003); and Mohamed and Zayed, 2008). These studies focused on cost, duration and failure problems. Research has not included the impact of rehabilitation methods on the environment. With increased concern related to the environment, the environmental impact due to a rehabilitation method must be considered. Therefore, the method chosen should be based on cost, duration, failure problem and the impact on the environment.

The optimum scheduling of rehabilitation based on the added value to network reliability has not been studied. Most of the previous studies (Dandy and Engelhardt, 2006; Hong et al., 2006; Alvisi and Franchini, 2006) dealt with the scheduling of water main rehabilitation as follows:

- Individual pipe sections were considered and the accessories within each pipe network were not considered,
- They did not account for pipe locations,
- They did not consider the impact of the scheduled work on the priority index (PI) for intervention of the network, and
- They did not cluster the rehabilitation work of individual pipes, segments and segment groups to generate practical work packages.

Therefore, the current research intends to solve the previous limitations by considering scheduling rehabilitation methods as work packages instead of individual scheduling entities. In addition, scheduling of accessories that are attached to the pipes is considered. Finally, with respect to the available time and the maximum budget of a municipality (an owner), the optimum scheduling will be based on the maximum priority index (PI) for intervention, that considers the combination of reliability and criticality (RCA) for water distribution networks. The maximum priority index (PI) for intervention can be obtained by executing one or more work packages simultaneously.

CHAPTER 3

Research Methodology

3.1 Introduction

This chapter describes the methodology adapted in this study. The methodology encompasses the modeling aspects of PI assessment, selection of most suitable rehabilitation method(s), and optimizing multi-objective scheduling for rehabilitation work on water distribution networks. Figure 3.1 depicts the steps of the proposed approach.

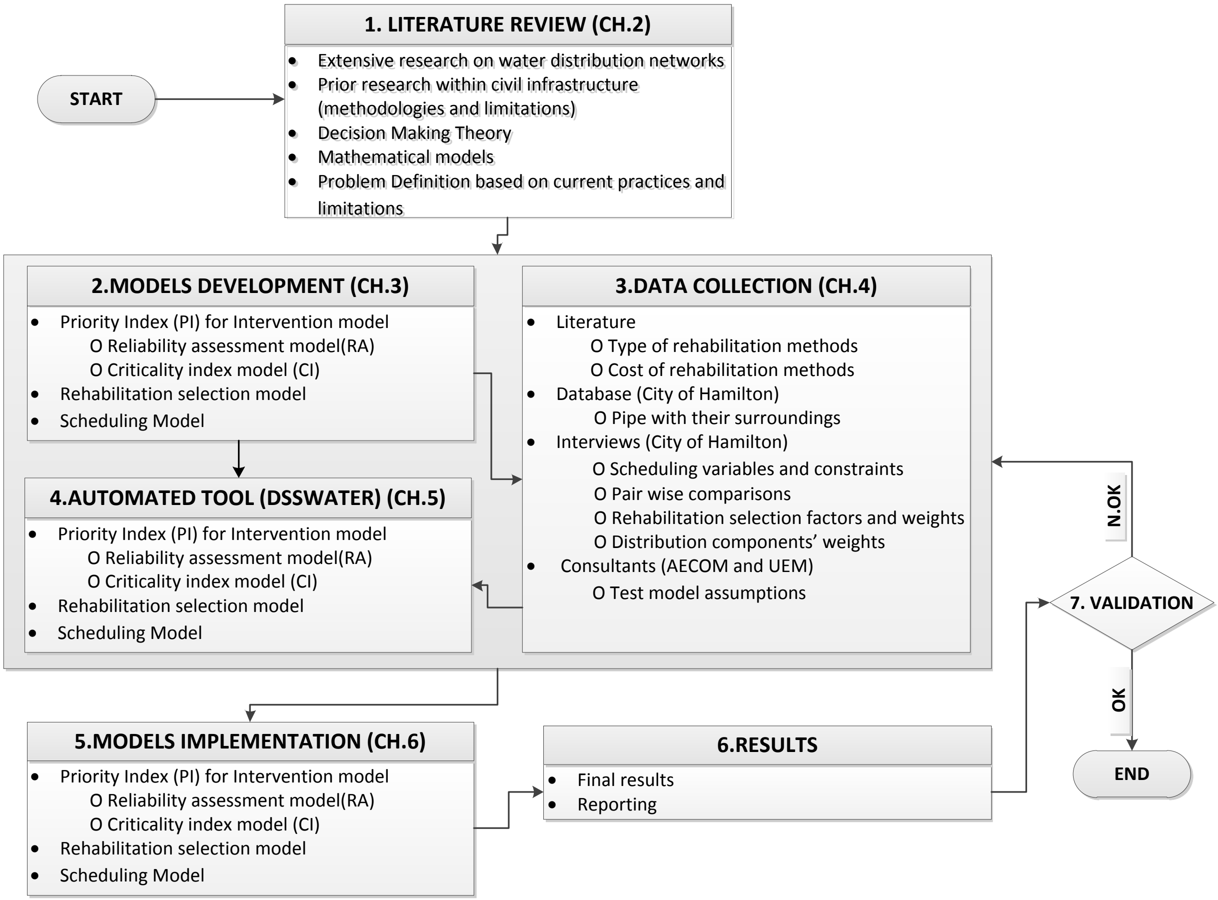


Figure 3.1: General Flow of the Developed models

The literature review covers all major disciplines that are necessary in evaluation of the developed models. Chapter 2 summarizes the main literature review. Chapter 3 summarizes the model developments. PIs are generated at both segment and network levels using the developed PI. This model is described subsequently in section 3.3. At that end of that stage, most of suitable rehabilitation method(s) are evaluated (considering a number of factors). This is explained in Section 3.4. At this stage, the decision maker is well informed regarding (1) the condition of water distribution network, (2) the rehabilitation techniques that can help to minimize the negative impact of failure at the pipe segment level. As a result, it is imperative that rehabilitation work should be scheduled. In this respect, the decision maker is faced with a limited budget and reasonable rehabilitation packages phased in the time domain. The optimum scheduling which is developed in this thesis accounts for such real life constraints. It is described in detailed in Section 3.5. Chapter 4 describes the process of data collection needed for the model. This can be done directly from the municipal operation and maintenance records. Upon completion of data collection, an automated tool (DSSWATER), which is explained in detailed in Chapter 5, is developed to implement the developed methodology. Finally, a case study is presented in Chapter 6 to depict the application of the developed models.

3.2 Limitations and Assumptions of the Developed Models

The developed models are limited to the following:

- They are suitable for small (less than 300 mm) and medium (300mm-750mm) diameter pipes due to their limited effects of criticalities. Large diameter pipes (more than 750mm) and transmission pipes should be avoided due to huge effects of criticalities.
- A hydraulic model is necessary to determine the direction of water flow through the mains, which can be used to determine the connectivity among these mains to determine a network/ sub-network reliability.
- Soil contamination is not considered as a critical factor due to difficulties in data collection.
- Assumptions can be improved if a comprehensive survey is made and sent to relevant decision makers and experts related to:
  - Number of failures of accessories.
  - Maximum contract price.
  - Size (minimum and maximum) of rehabilitation work packages.
  - Weights of rehabilitation criteria (cost, impact on environment, and trial of new technologies).
- The quality of rehabilitation cost data can be improved by updating the rehabilitation cost used in this research according to market value.
- Reliability value after rehabilitation of components of water distribution network can be obtained using manufacturing manuals.

3.3 PI Model

Figure 3.2 depicts the proposed approach to develop a PI for water networks. The developed model utilizes reliability theory and measures consequences of failure, driven by the captured condition data, for the entire network. In this respect, the Network Breakdown Structure (NBS) is mapped in a highest order progressively from network to component levels.

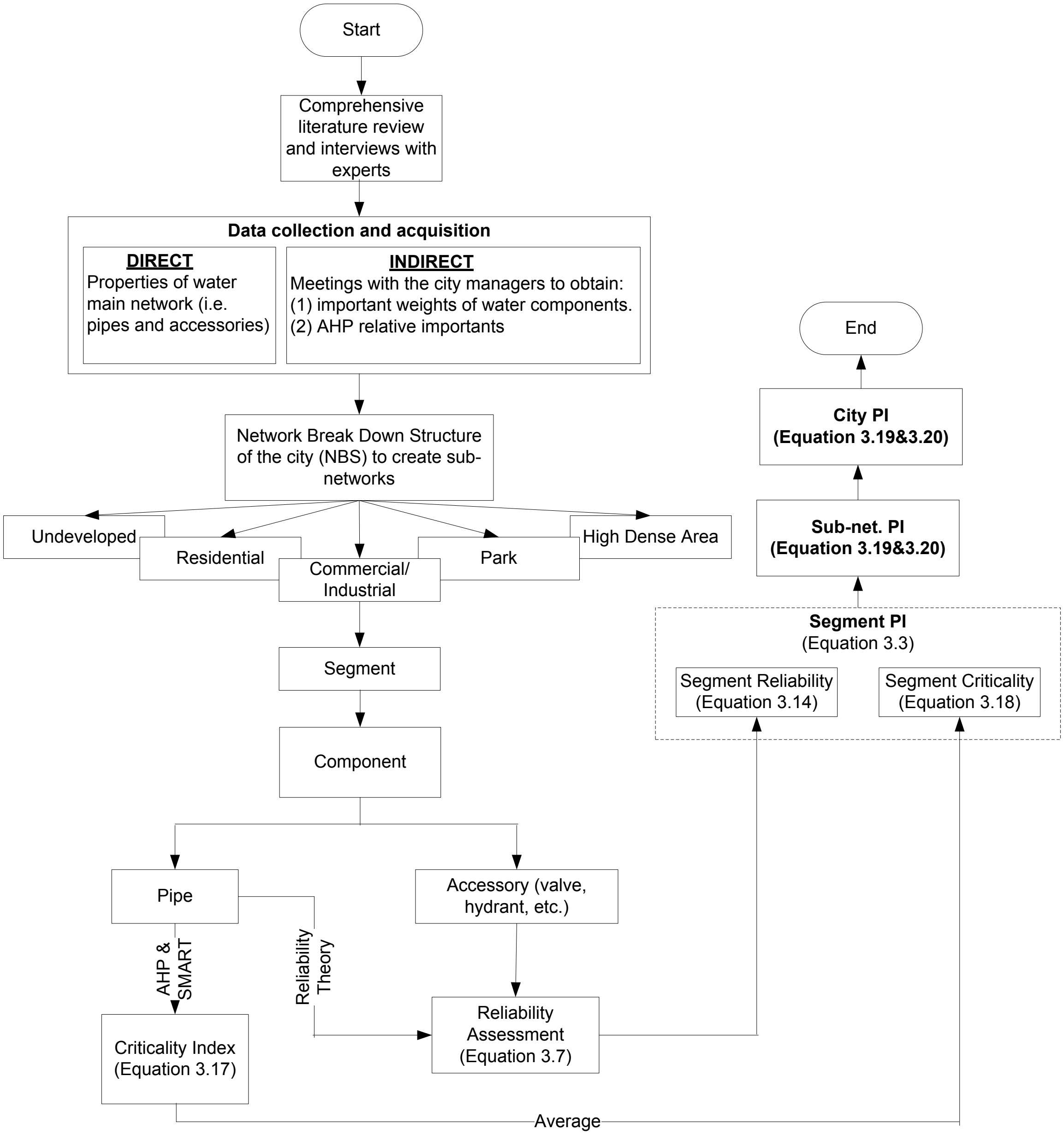


Figure 3.2: PI Development

The NBS is developed in various levels within the water network starting from component, segment, sub-network, to network levels. Land use is a main factor that the entire network is divided based upon. Five main categories of land use are considered: residential, undeveloped, park, commercial/industrial, and high dense. The water network of a city or municipality is divided into sub-networks. Each sub-network consists of several segments that include water main components, such as pipelines and their accessories. Reliability assessment is calculated for each component and segment using reliability theory, while criticality index is calculated for each pipe and segment using Analytical Hierarchy Process (AHP) and Simple Multi Attribute Rating Technique (SMART). The PI is determined based on reliability and criticality assessments (RCA) of segments and sub-networks.

The PI is defined on a scale from 0 to 1.0, where 1.0 is the highest priority index (PI) for intervention and 0 is the lowest. When the PI is small, the pipe is assigned high priority for rehabilitation need and vice versa. The PI might be simply represented using breakage rates and the consequences of failure when failure occurs. As explained earlier, the pipe reliability value, which ranges between “0” and “1”, can be expressed as a function of the breakage rate of the pipe. When breakage rate of a pipe is high, the pipe is not reliable and is assigned a high priority for rehabilitation. Therefore, the relation between PI and reliability is proportional (Equation 3.1).

$$\mathrm{PI}\ \alpha\ R \qquad (3.1)$$

The second consideration of PI is the consequence of pipe failure, which is a crucial factor to prioritize pipe rehabilitations. Criticality Index (CI) is used to represent the severity of consequence of pipe failure. A scale of “0.0” to “1.0” is used to represent the CI. When the failure consequence of a pipe is huge, the CI approaches 1.0, and consequently, this pipe is assigned the utmost priority for rehabilitation. As such, the relation between criticality index and PI is an inverse relation (Equation 3.2).

$PI \propto (1-CI)$ ……………………...…….................................…........................ (3.2)

Breakage rate and failure consequences are not influencing each other and therefore they are two individual categories. For instance, a pipe might have high breakage rate with small failure consequences or vice versa. Hence, Reliability and criticality indices are considered two independent variables, and the multiplication rule for independent variables can be applied as in Equation 3.3.

$$PI_{seg.} = R_{seg.} \times (1 - CI_{seg.}) \quad \text{……………..................…………........……} \quad (3.3)$$

Where: $CI_{seg} \neq 1.0$; (assume: CI=0.99 when CI>0.99)

The right hand side of the equation represents (1) the reliability assessment ($R_{seg.}$) of a segment, which is a function of a breakage rate and (2) the criticality index ($CI_{seg.}$) of a segment, which is a function of the consequences of pipe failure. The highest value of CI is equal to 1.00; however this value doesn’t represent the highest priority of rehabilitation when R is very high. This case can be avoided by assuming CI value equals to 0.99 instead of 1.00. Both indicators have reverse scales, lowest reliability assessment and highest criticality index represent a segment with highest priority for rehabilitation as shown in Figure 3.3. Caution should be exercised when a segment is critical but has high reliability. In this case, a new monitoring program must be specified for these pipes, which is out of the scope of this research.

0.0	**R:** Low **CI:** Low **PI:** Urgent need to be rehabilitated	**R:** Medium **CI:** Low **PI:** Medium need to be rehabilitated	**R:** High **CI:** Low **PI:** No need to be rehabilitated
Criticality Index	**R:** Low **CI:** Medium **PI:** Urgent need to be rehabilitated	**R:**Meduim **CI:** Medium **PI:** Medium need to be rehabilitated	**R:** High **CI:** Medium **PI:** No need to be rehabilitated
1.0	**R:** Low **CI:** High **PI:** Urgent need to be rehabilitated	**R:** Medium **CI:** High **PI:** Medium need to be rehabilitated with monitoring	**R:**High **CI:** High **PI:** No need to be rehabilitated with monitoring
	0.0	**Reliability Assessment**	**1.0**

Figure 3.3: Reliability versus Criticality Decision Matrix

3.3.1 Break Down Structure of the City Network (NBS)

Figure 3.2 shows the procedure of data flow from NBS to the calculated PI at sub-network, segment, and component level. The model breaks the network into zones or a number of networks which are in term of sub-network. Each sub-network is also divided into pipe segments. In this level, each segment consists of serious of pipe sections along with their accessories (i.e. hydrants and valves).

From current practice, it became clear that the process of NBS depends on several factors such as population density, zoning type (i.e. residential, commercial, industrial, park, undeveloped, etc.), tax rate, limitation supporting of major infrastructure such as pumps need to be considered.

3.3.2 System Reliability

Reliability theory is used in depicting the condition to find the reliability assessment of each component in the distribution networks. In the next sections, component, segment and sub-network reliability are described.

3.3.2.1 Component Reliability

To calculate the reliability of a component deterministically, the average failure rate (λ) of a component can be calculated first, as shown in Equation 3.4 (Ramakumar, 1993):

$$\lambda = \frac{N_{failure}}{Time} \quad \text{(3.4)}$$

For a water main pipe, the average number of failures that have occurred from the time of installation can be calculated, as shown in Equation 3.5:

$$\lambda_{pipe} = \frac{N_{failure/km}}{T_{analyzing} - T_{inst.}} \quad \text{(3.5)}$$

To calculate the average failure rate (λ) of a hydrant, a valve, etc., Equation 3.6 can be utilized:

$$\lambda_{hydrant, valve, etc.} = \frac{N_{failure}}{T_{analyzing} - T_{inst.}} \quad (3.6)$$

After determining the average failure rate of a component, the reliability of the component can be found. The simple form of calculating the reliability (R) is shown in Equation 3.7, (Billinton and Allan, 1983). Reliability is considered to follow the negative exponential function, which means that reliability decreases exponentially with time due to the average failure rate increases with time.

$$R(t) = e^{-\lambda t} \quad (3.7)$$

In this case, average failure rate (λ) means the hazard rate, while failure rate, f(t), is :

$$f(t) = \frac{-dR(t)}{dt} = \lambda e^{-\lambda t}$$

(3.8)

Failure numbers and ages of water network components are collected to determine their reliabilities. Segment reliability ($R_{seg.}$), sub-network reliability ($R_{sub\text{-}net.}$), and network reliability are determined after finding component reliability as follows.

3.3.2.2 Segment Reliability

Figure 2.3 shows a typical segment of a water main network. The segment has components attached to it, such as hydrants, isolation valves, and branch pipes. To calculate segment reliability, the average failure rate should be calculated. The unit for the average failure rate is (Failure/Km/yr), which is used by most researchers, Fahmy and Moselhi (2008), Shahata and Zayed (2008), Al-Barqawi and Zayed (2006), and Kleiner and Rajani (2002). This unit is useful when the expression is employed for continuous large pipes or transmission pipes. For example, if a main street is 5 km in length, this unit (Failure/Km/yr) can be understood easily. However, if this street is divided into 30 segments and some of these segments are less than 1 km in length, this unit is not appropriate for expressing the failure rate of this specific segment. Therefore, there is a need to use a smaller length unit to express the average failure rate of this segment. The suggested units are (Failure/m/yr), (Failure/5.0m/yr), or (Failure/10.0 m/yr). To select a suitable unit that makes the results well understood, a sensitivity analysis is required. As an assumption, (Failure/m/yr) is selected and therefore Equation 3.5 can be changed into Equation 3.9 by changing the km (a large unit) to m (a small unit).

$$\lambda_{pipe} = \frac{N_{failure/m}}{T_{analyzing} - T_{inst.}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.9)$$

The average failure rates of hydrants and valves can be identified based on each meter of segment. As an example, if there are H hydrants and V valves attached to a segment having a length L (m), the average failure rate of the hydrant and valve can be estimated as follows, Equations 3.10 and 3.11.

$$\lambda_{hydrant} = \frac{\sum_{h=1}^{H} \left[\frac{N_{failure}}{T_{analyzing} - T_{inst.}} \right]_h}{L} = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.10)$$

$$\lambda_{valve} = \frac{\sum_{v=1}^{V} \left[\frac{N_{failure}}{T_{analyzing} - T_{inst.}} \right]_v}{L} = \qquad (3.11)$$

Where, N is failure number since installation, Vis total number of valves, T is year, and L is length of segment.

Walski (1993) reported that the reliability analysis for a large main should take into consideration the outage in laterals and service lines. Therefore, for each meter of segment that has several failure rates, some of these could be due to different components. Adding the average failure rates together, the average failure rate of the segment per meter increases as depicted in Equation 3.12.

$$\lambda_{seg} = \lambda_{pipe} + \lambda_{b.p} + \lambda_{hydrant} + \lambda_{valve} + \lambda_{others} = \sum_{i=1}^{n} \lambda_i \qquad (3.12)$$

Equation 3.12 represents a breakage rate of a segment where components of the segment have the same weight. To be more specific, a component weight (w_i) is added to the equation to adjust it (Equation 3.13).

$$\therefore \lambda_{segment} = \frac{\sum_{i=1}^{n} \lambda_i . w_i}{\sum_{i=1}^{n} w_i} = \qquad (3.13)$$

Where, i is water main component, n is total number of water main component, w is relative weight of component ith.

By adapting Equation 3.7, the segment reliability can be expressed as Salman *et al.,* (2009) as shown (Equation 3.14):

$$R_{segment} = e^{-(\lambda t)_{Segment}} \quad \text{...} \quad (3.14)$$

Where:

λ: is weighted summation of the average failure rate of each component within the segment, and is not to be considered a function of time (λt= λ), and R: is segment reliability.

Segment reliabilities in each sub-network are utilized to find sub-network reliabilities of a city to be used for scheduling process.

3.3.2.3 Network/ Sub-Network Reliability

Equations 2.8 and 2.9 can be used to determine the reliability of a sub-network when its segments are connected in series and/or parallel respectively. The size of a sub-network plays an important factor of selecting the most suitable length unit. Sub-network reliability might be very small and can’t be well understood by the user; and he/she can change the length unit into higher length. In this case, sensitivity analysis is crucial to aid the decision maker in this selection. The reliabilities of the city network, which is base on the combination of Equations 2.8 and 2.9, decrease when the accumulative failure numbers of their components increase consequently. The Equations 2.8 and 2.9 are modified by (1) adding 1, 2, and 3 failure(s) to the original accumulative failure components and (2) by testing three length units (1 m, 5 m, 10 m) as shown in Equations 3.15 and 3.16. Component reliability, segment reliability, and sub-network reliability will be decreased consequently.

$$R_y = R_1.R_2.R_3.......R_n = \prod_{i=1}^{n} e_i^{-\frac{(f+x)}{l}} \text{ ....(3.15)}$$

$$R_y = 1 - Q_1.Q_2.Q_3.......Q_n = 1 - \prod_{i=1}^{n} [1 - e_i^{-\frac{(f+x)}{l}}] \text{ ....(3.16)}$$

Where: R_y: System reliability, R_i: component reliability, Q_i: component unreliability ($1-R_i$), i: segment ith, n: total number of segment, f: accumulative failure number, x: 0, 1, 2, and 3, and l: segment length (1 m, 5 m, 10 m).

As result, the decision maker can select the suitable unit according to the sufficient range values of sub-network reliability.

Three length units can be tested which are 1 m, 5 m, and 10 m. Sub-network reliability decreases when the number failures of sub-network components increases. The 0 represents the original accumulative failure numbers and +1, +2, and +3 are the added value to the original failure of each component in the network. Based on the sensitivity analysis chart, a decision maker might consider the suitable unit length due to the sufficient range of values between the maximum and the minimum values. Selecting the suitable unit length is important to the use of the scheduling model.

3.3.3 Criticality Model

Figure 3.4 depicts the procedure for criticality model development. The test basis of the criticality model provided in this thesis is that of the City of Hamilton, which was described by Salman *et al.,* (2010). The model accounts for zoning types and other factors as described in Chapter 2. In addition, the criticality model is described below:

- The city is divided according to its land use (High Density, Commercial/Industrial, Residential, Park, and Undeveloped/ Other).
- The relative weights of categories and factors must be determined using the Analytical Hierarchy Process (AHP)
- The overall criticality index must be determined instead of a maximum criticality index.
- The scale of factor score is modified to 0.01-1.00 instead of 1-100 to fit the PI equation.

3.3.3.1 Criticality According to Land Use

The first improvement step to the model of the City of Hamilton was made by dividing the city according to land use (High Density, Commercial/Industrial, Residential, Park, and Undeveloped/ Other). Using such a break down allows the decision maker to sufficiently manage and control zoning based on their properties (i.e. expand industrial zone, increase/ decrease tax base).

3.3.3.2 Application of AHP

The weights of critical factors in the UMA (2007) model were directly assigned based on expert opinions.

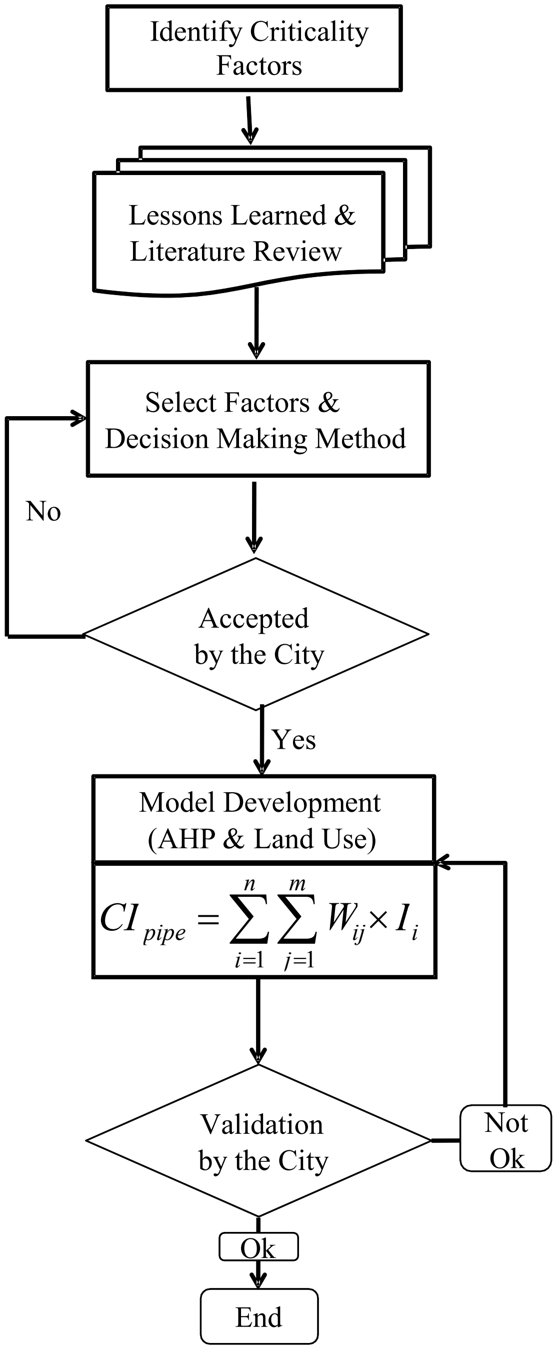


Figure 3.4: Criticality Methodology

The model in this thesis is built using the Analytical Hierarchy Process (AHP). The AHP was selected in an effort to maintain the consistency of reliable weights because (1) it is an easy mature technique that attempts to simulate human decision process, (2) it aids decision makers in solving complex problems by organizing thoughts, experiences, knowledge and judgments, into a hierarchical framework, and guiding them through a sequence of pair-wise comparison judgments, (3) it allows decision-makers incorporate both qualitative and quantitative considerations of human thought and intuition in a logical fashion and (4) it converts subjective assessments of relative importance to a set of overall scores or weights. The AHP was implemented five times to calculate the critical factor weights. This application allows the user to be more specific to assign the pair wise comparison among the critical factors based on the land use. For example, a low accessibility weight for high density zone should be more than for undeveloped zone. Consequently, a decision maker should participate in assigning the pair-wise comparison during the AHP procedure.

3.3.3.3 Overall Criticality Index

The criticality index of the UMA (2007) criticality model is equal to the maximum critical category (Economic, Operational, Social, and Environmental). The result of original model expresses bias results in leading or depicting the criticality index value of water distribution mains of the City of Hamilton. In the improved model, introduced here, pipe criticality index is determined using the weighted average criticality of the four categories (Equation 3.17).

$$CI_{pipe} = \sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij} \times I_i \quad \text{……………………………………………………………….. (3.17)}$$

Where:

CI_{pipe}: Criticality index of a pipe.

W_{ij}: Weight of critical factor.

I_i: Score of critical factor.

$_n$: total category number (4).

$_m$: total factor number in each category.

By considering the average criticality weight of the four categories, the bias of the UMA (2007) model (considering the maximum category only) is avoided (according to the validation of the developed model).

Segment criticality index is determined using the average criticality index of its pipes (Equation 3.18) while ignoring criticalities of segment accessories due to their typically small consequences of failure, in comparison to the pipe consequences.

$$CI_{seg.} = \frac{\sum_{k=1}^{K} CI_k}{K} \quad \text{...} \quad (3.18)$$

Where:

Where: CI_k: Criticality index of the k^{th} pipe in the segment, and $CI_{seg.}$: Criticality index of a segment.

3.3.4 Network /Sub-Network PI

According to Equation 3.1, a PI includes reliability and criticality. The reliability value will be increased after rehabilitation, while the criticality value remains constant when the pipe properties (i.e. size, material, buried depth, etc.) are not changed after rehabilitation. Therefore, the PI is changed only if the rehabilitation occurs by increasing the reliability value. This fact leads to the adaptation of Equations 2.9 and 2.14 in order to determine the PI of a network in the both cases (series and parallel), which are depicted in Equations 3.19 and 3.20.

$$PI_{sub} = PI_1.PI_2.PI_3........PI_n = \prod_{i=1}^{n} PI_i \quad (3.19)$$

$$PI_{sub} = 1 - \left[(1-PI_1)(1-PI_2)(1-PI_3).......(1-PI_n)\right] = 1 - \prod_{i=1}^{n} (1-PI_i) \quad (3.20)$$

3.4 Selection of Rehabilitation Methods

It is well known that a segment rehabilitation is governed by their respective reliability, criticality and serviceability, as well as budget constraints. The developed model of the selection of rehabilitation methods is shown in Figure 3.5. The methodology consists of three important factors; (1) total cost of rehabilitation, (2) impact on environment, and (3) trial use of new technologies. In addition, a rehabilitation method must be technically feasible and contractually acceptable to be considered for any rehabilitation work. The selection methodology presented in this section utilizes the best practice flow chart methodology of the Canadian InfraGuide (NRC, 2003). The flow chart helps a decision maker to select rehabilitation methods based on pipes' defects. In fact, with this chart, the output presents a set of methods that can be used depending on the conditions of this pipe segment. As an example, to replace a pipe that is not structurally sound, one can use one of the following methods: (1) open cut or (2) trenchless technology (TT). The TT includes sliplining, close-fit sliplining (i.e.

diameter reduction and factory or site-folded), cured-in-place pipe (CIPP), pipe bursting, horizontal directional drilling (HDD), and microtunnelling.

In reality, not all of these methods are suitable for use in the field due to several limitations. Selecting suitable methods should be done on a case-by-case basis; insuring that the method is technically feasible and contractually acceptable.

Both of these conditions function only as a filter to the suitably acceptable methods. To select the most suitable method, Simple Multi Attribute Rating Technique (SMART) is utilized. This method provides the user with the option of weighting the three criteria (cost, trial of new technologies and environmental impact). The output of this model is a rating for rehabilitation methods, which has a specific cost and time that can be used in the scheduling process as described later in Section 3.5.

3.4.1 Impact on the Environment (IoE)

The construction work might have an adverse chemical, physical and/or biological impact on the environment (Tchobanoglous et al., 2003; Zayed et al., 2011). This work might have a chemical impact on the soil, water, and air. Also, it may have a physical impact on livestock; temperature, odour and noise. In addition, it can have an adverse biological impact on animals and plants. The type and extent of the environmental factors and sub-factors depend mainly on whether open cut or trenchless rehabilitation methods are used (Atalah et al., 2002).

When employing trenchless techniques, the environmental impact will be less, since most trenchless methods require a very small amount or no excavation. In the present study, a scoring scale is used to identify the impact on environment (IoE). A score of 1.0 represents a minimum effect on environment while 9.0 represents a maximum effect.

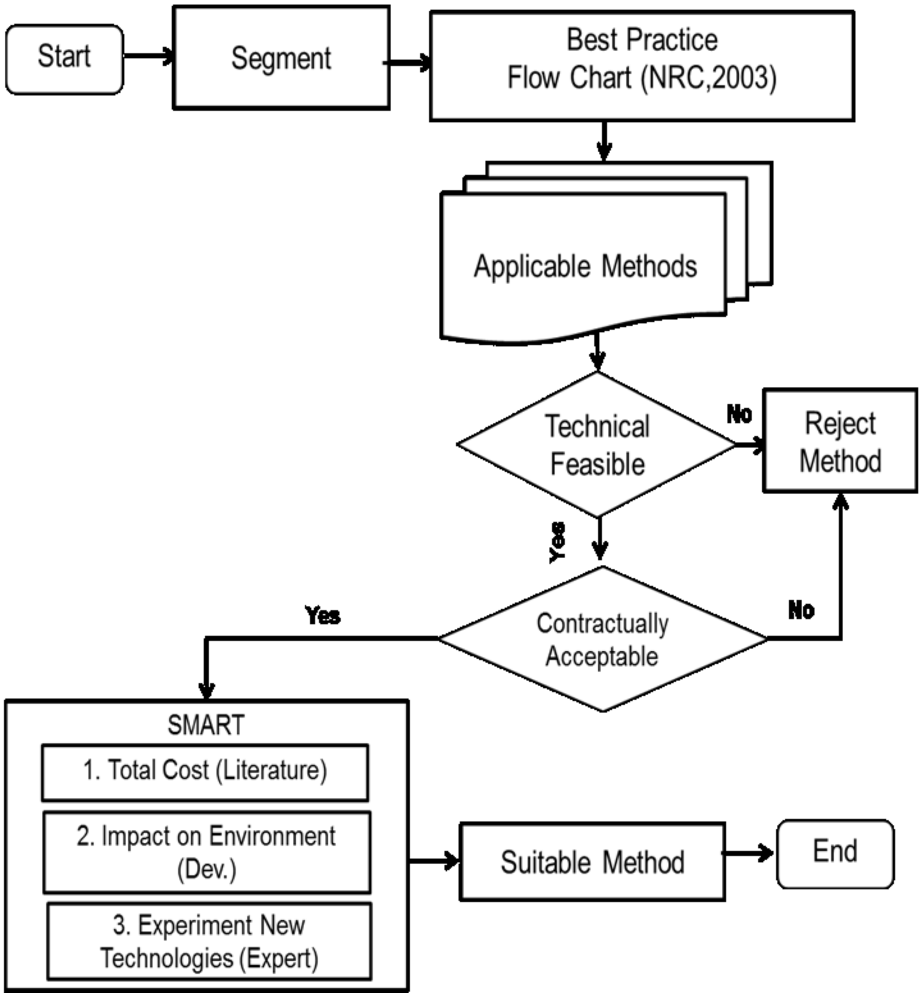


Figure 3.5: Rehabilitation Selection Methodology

3.4.2 Trial Use of a New Technology

Shahab Eldeen (2002) stated that when a decision maker selects a traditional method for rehabilitation he may have deprived himself from utilizing more practical and cost effective rehabilitation technology. Also, a decision maker may not be willing to accept the risk associated with the implementation of an unproven technology (Al-aghbar, 2005). A scoring scale is also used here; a score of 1.0 represents least preference to experiment with new technology, while 9.0 represents most preference to try new technology.

3.4.3 Method Selection Model

Simple multi-attribute rating technique (SMART) is selected among other decision support methods due to its simplicity. In applying SMART for selection of rehabilitation method, three objectives are used: (1) cost of rehabilitation, (2) impact on environment (IoE), and (3) experimentation of new technologies related to the rehabilitation method (Moselhi et al., 2009). The utility of each rehabilitation method (i.e. alternative) can be determined using Equation 3.21.

$$U_a = \sum_{i=1}^{n} a_i \times W_i \quad \text{……………………………………………………………} \quad (3.21)$$

Where: U_a: Overall relative utility score of alternative (rehabilitation method), a_i: The value assigned to the ith alternative, W_i: weight.

Therefore, one method is preferred over other rehabilitation methods where its overall relative utility has higher value than other methods. Similarly, the SMART is applied to all segments that are being considered for rehabilitation.

3.5 Scheduling Model

Figure 3.6 depicts the main components of the developed scheduling method, which is performed in two stages; (1) dividing the water distribution network of a city into several groups using UNN and (2) optimizing the scheduled work of these groups using MINLP.

The objective of the first stage is to cluster the water mains of the water distribution network of a city into several groups based on their geographical locations and rehabilitation methods. Each resulted group includes several pipe segments. Neuroshell 2 is used to implement the process of clustering because it is commercially available and easy to use. The resulted groups are utilized in the second stage to determine rehabilitation work packages (WPs) based on user-defined package size. A work package includes a group of segments that share same rehabilitation method. The developed work packages are scheduled using MINLP. Lingo 12 (Lindo, 2011) is used for the scheduling process because it is a software that has the capability to implement the developed MINLP method in a relatively fast processing time.

The method expands upon developments presented earlier by the authors (Salman, et al., 2009-b, Moselhi, et al. 2009, Salman et.al 2010, Salman, et al. 2009-a). It also integrates elements of those developments and introduces a methodology for optimized scheduling of rehabilitation work that accounts for reliability and criticality of water mains.

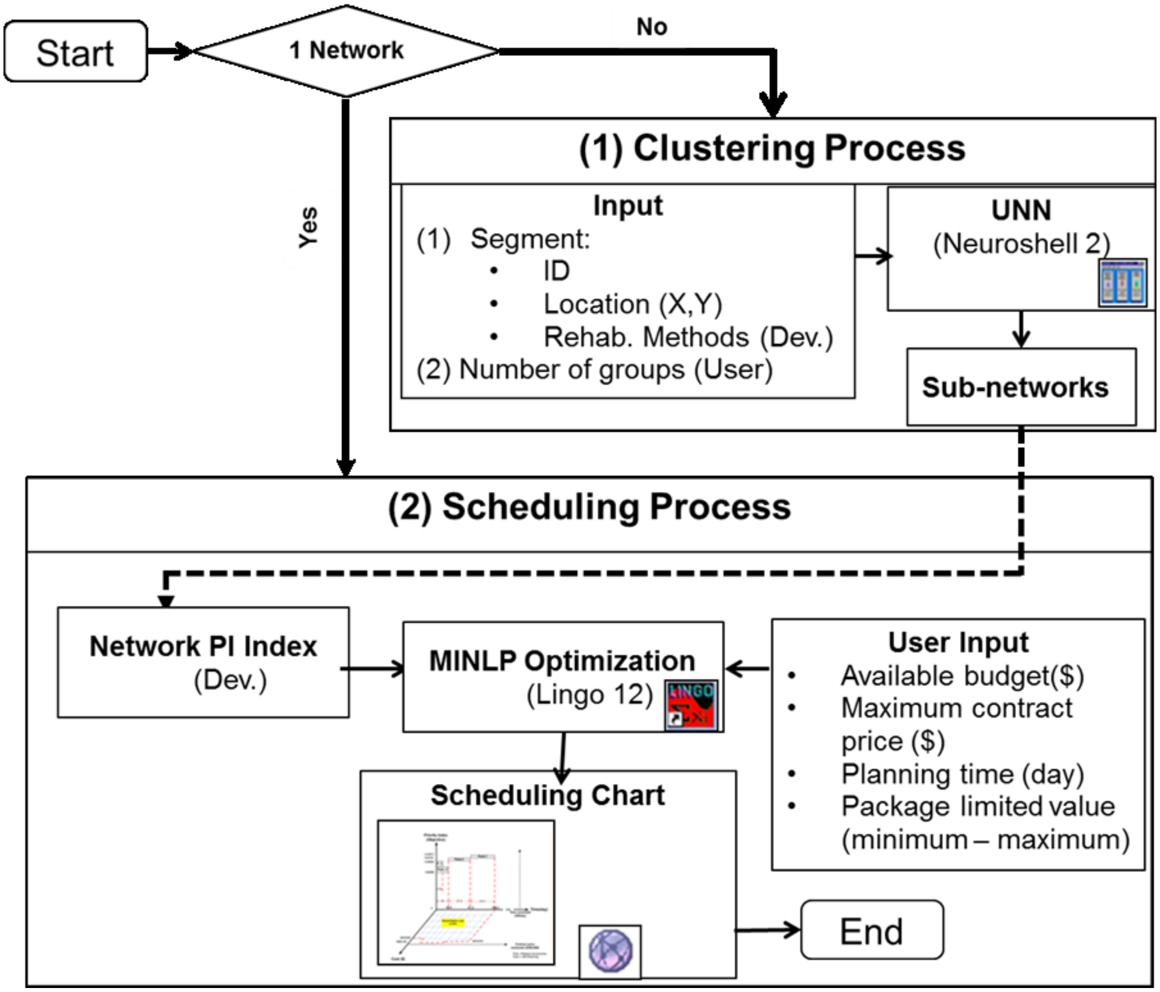


Figure 3.6: Methodology of Scheduling Model

The input data needed in the first stage encompasses (1) the segment ID, (2) the rehabilitation method for each segment, (3) location of each segment (x, y), and (4) the number of pipe segment groups. The latter number is to be initially provided by the user based on his preference. Unsupervised neural networks are then used to cluster individual pipes considering the number of groups defined initially by the user. The output of this stage is a number of groups where each one includes a number of pipe segments, which are located in a specific geographical location and share one or more than one rehabilitation method. The benefit of this stage is to control the scheduling process by limiting the segment locations and rehabilitation methods. As such, the process of clustering aids the decision maker to create the work packages for rehabilitations (WPs), which is part of the second stage as depicted in Figure 3.7.

In the second stage, work packages (WPs) are formed directly by including the segments, within each of the groups formed in the first stage that shares the same rehabilitation method, and accounting for the upper and lower limits values specified by the user for the size of WPs. Upon formation of the individual work packages, and inputting the maximum contract price and the scheduling horizon, the optimized schedule of these packages is performed using mixed integer nonlinear programming (MINLP). The final scheduling is divided into several intervals, and each interval includes one or more than one work package that maximizes the PI by increasing its reliability.

The input of the second stage is divided into two types; direct data from the database and indirect data that are generated in the first stage of the proposed method. The direct data is entered by the user and includes: (1) available budget, (2) planning time of rehabilitation, (3) maximum value of contract price, and (4) package size or maximum and minimum values of rehabilitation work package.

The indirect data includes: (1) the results of PI model, which include segment reliability and criticality as well as PI for each segment, each sub-network, and the entire network; and (2) the result of rehabilitation selection model which includes segment rehabilitation method, cost, and duration.

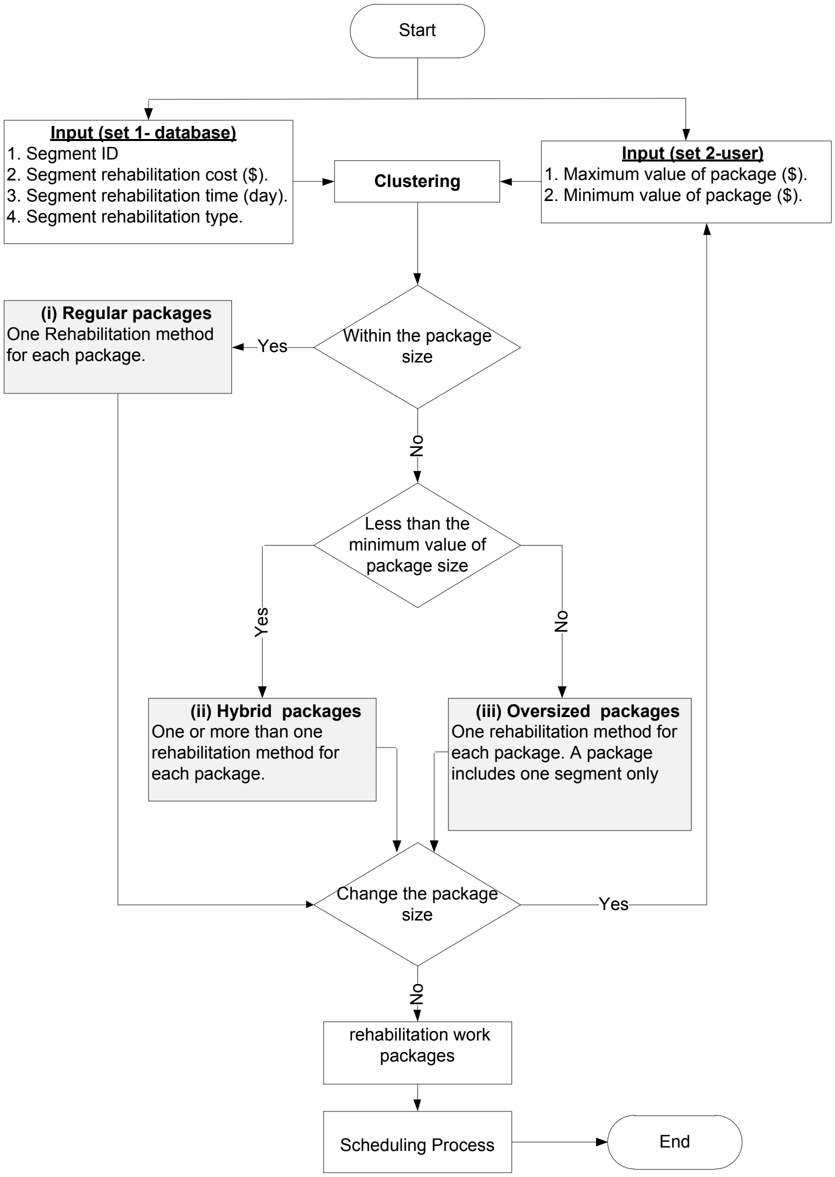


Figure 3.7: Methodology of Rehabilitation Work Packages

It should be noted that the inclusion of the maximum value of contract price is necessary to conform with fare business practice and city regulations in utilizing local contractors and in allowing for competition among them. The maximum value of a contract price is changeable and depends on several factors, such as the type of work, number of bidders, economic conditions and available budget.

As well, two exceptional package types can be generated by the developed method; hybrid and oversized packages which should be dealt with individually on a case-by-case basis. This process is crucial to monitor and control rehabilitation work based on type of work, total budget, number of pipe segments, complexity of work, etc. The indirect data, which include the results of PI model and rehabilitation selection method, are explained in the next sections.

Mixed Integer Non Linear Programming (MINLP)

The objective of this formulation, which is depicted in Figure 3.8, is to maximize the PI of segment groups as shown in Equation 3.22:

$$Max.PI_{group} = PI_{i}. \otimes PI_{i+1} \otimes PI_{i+2} .... \otimes PI_{n} \; .... \; (3.22)$$

$Max.PI_{group}$ is calculated according to the segment connections in a similar manner to that used in Equations 3.19 and 3.20. For example, when the segments are connected in series, $Max.PI_{group}$ is calculated as follows:

$$Max.PI_{group} = \prod_{i=1}^{n} PI_{i} \; .... \; (3.23)$$

And if the segments are connected in parallel, $Max.PI_{group}$ is calculated as follows:

$$Max.PI_{group} = 1 - \prod_{i=1}^{n} (1 - PI_{i}) \; .... \; (3.24)$$

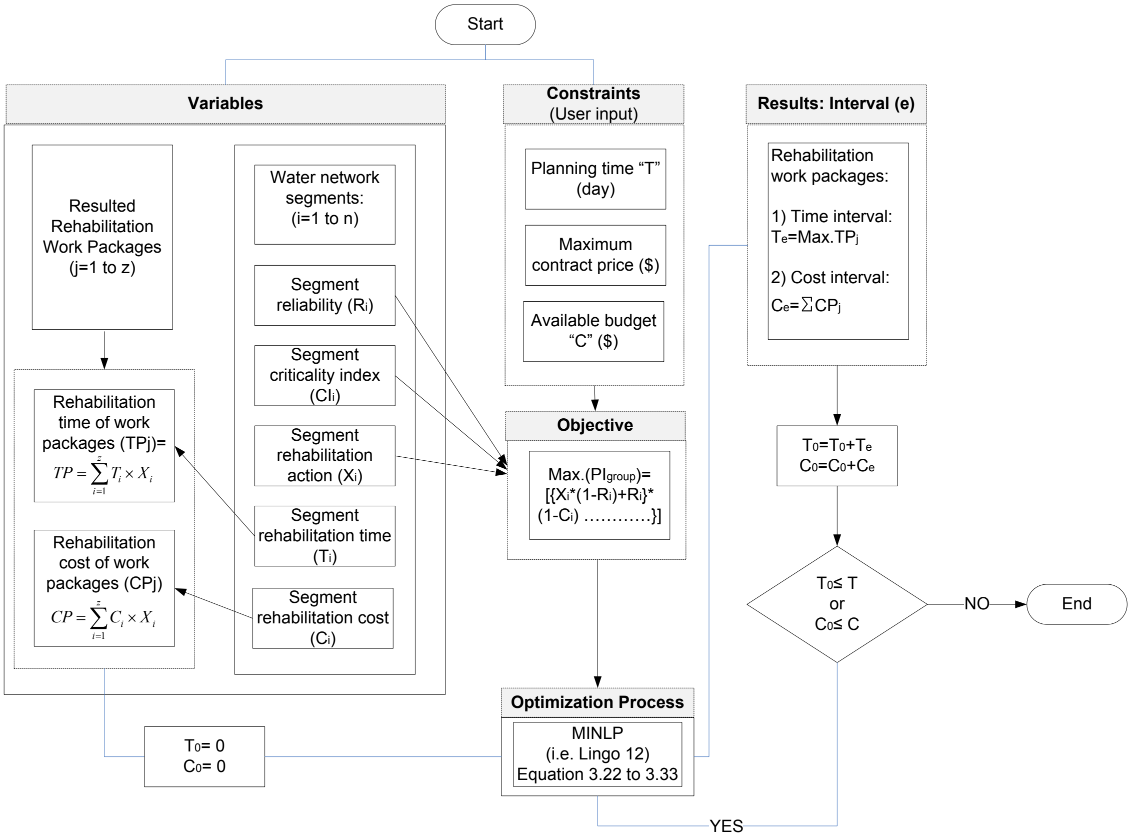


Figure 3.8: MINLP Scheduling Methodology

The configurations such as star and delta are not considered in this thesis. Combining the rehabilitation option (X_i), reliability (R_i), and criticality index (CI_i) of a segment; the PI of the group is equal to:

$$PI_i = \{(X_i \times (1 - R_i)) + R_i\} \times (1 - CI_i) \quad \text{..} \quad (3.25)$$

Where:

- Criticality Index (CI) has a constant value after and before rehabilitation if the pipe's properties are not changed.
- R_i is equal to 1.0 if it is rehabilitated, otherwise R_i is equal to the original value and therefore the term $(X_i \times (1 - R_i))$ is added to the equation to

represent the adding value to the PI of the group due to rehabilitation. The rehabilitation status is $X_i = [0,1]$ “0” for no action and “1” for rehabilitation.

- For a package that has more than one segment is expressed as:

$$X_1 - X_2 = 0; \quad (3.26)$$

In this case, a similar action is made for both segments in term of rehabilitated or not. When, another segment(s) is added to the same package, a new equation(s) should be added as:

$$X_2 - X_3 = 0; \quad (3.27)$$

- Rehabilitation cost (CP) and time (TP) of package works are equal to:

$$CP = \sum_{i=1}^{z} C_i \times X_i \quad (3.28)$$

$$TP = \sum_{i=1}^{z} T_i \times X_i \quad (3.29)$$

Where, C_i and T_i are the rehabilitation cost and time of the i^{th} segment, and z is the number of segments in the package being considered for scheduling. In addition, CP and TP are package rehabilitation cost and time, respectively. The assumption of linear schedule within each work package is made and therefore, a package rehabilitation time is equal to the summation of its segments rehabilitation time.

The constraints of this optimization are the contract price and rehabilitation time horizon as follows:

- The cost constraint (C) which represents a maximum contract price for each rehabilitation interval should not be exceeded and is expressed as:

$$\sum_{j=1}^{y} CP_j \leq C; \qquad (3.30)$$

Time interval is equal to the maximum package time when more than one packages are executed concurrently.

$$T_e = Max.(TP_j, TP_{j+1}, TP_{j+2}, \ldots\ldots\ldots, TP_{j+e}); \qquad (3.31)$$

- Time constraint (T) stands for rehabilitation planning time which should be equal or larger than the total time intervals as.

$$\sum_{e=1}^{m} T_e \leq T; \qquad (3.32)$$

Finally, the available budget constraint (A.Budget) is equal to the summation of rehabilitation cost of rehabilitation intervals in the scheduling process as.

$$\sum_{e=1}^{m}\sum_{j=1}^{y} CP_{ej} \leq A.Budg.;$$

(3.33)

Where CP_{ej}: Rehabilitation cost of the package j^{th} in the interval e^{th} , and A.Budg.: Available budget of the city.

The final optimized scheduling model can be summarized as follows:

Objective: $Max.PI_{group} = PI_i . \otimes PI_{i+1} \otimes PI_{i+2} \ldots\ldots\ldots\ldots \otimes PI_n$

Subject to constraints:

$$\sum_{j=1}^{y} C_e \leq C;$$

$$\sum_{e=1}^{m} T_e \leq T;$$

$$PI_i = \{(X_i \times (1 - R_i)) + R_i\} \times (1 - CI_i)\};$$

$$CP = \sum_{i=1}^{z} C_i \times X_i$$

$$TP = \sum_{i=1}^{z} T_i \times X_i$$

For package j=1 to z: $X_i - X_{i+1} = 0;$

$$T_e = Max.(TP_j);$$

$$C_e = \sum_{i=1}^{z} CP_j;$$

End

3.6 Summary

Table 3.1 shows a summary of the research methodology. As mentioned previously, the research methodology is divided into PI, rehabilitation selection, and scheduling models. Each model encompasses several topics to be covered for each level of a water main network.

Table 3.1: Summary of Research Methodology

Level Model	City Network	Sub-network	Segment	Component
PI	(i) Break Down Structure (NBS), (ii) Reliability Sensativity Analysis, and (iii) City PI.	Sub-network PI.	(i) Segment reliability, (ii) criticality, and (ii) PI.	(i) Component reliability and (ii) Pipe criticality
Selection of Rehabilitation method.	Total cost of rehabilitation of a city.	Total cost of rehabilitation of a sub-network.	(i) IoE, (ii) Rehabilitation cost of a segment, and (iii) Select rehabilitation method.	Rehabilitation cost of component.
Scheduling	City Scheduling	Sub-network scheduling	Grouping into packages	NA

CHAPTER 4

Data Collection

4.1 Introduction

The data are collected from four sources: (a) literature; (b) the database of the Canadian city of Hamilton, (c) asset management team of the city of Hamilton, and (d) two consulting teams. The properties of pipes in the water distribution network and those of their surrounding soil were extracted from city of Hamilton database.

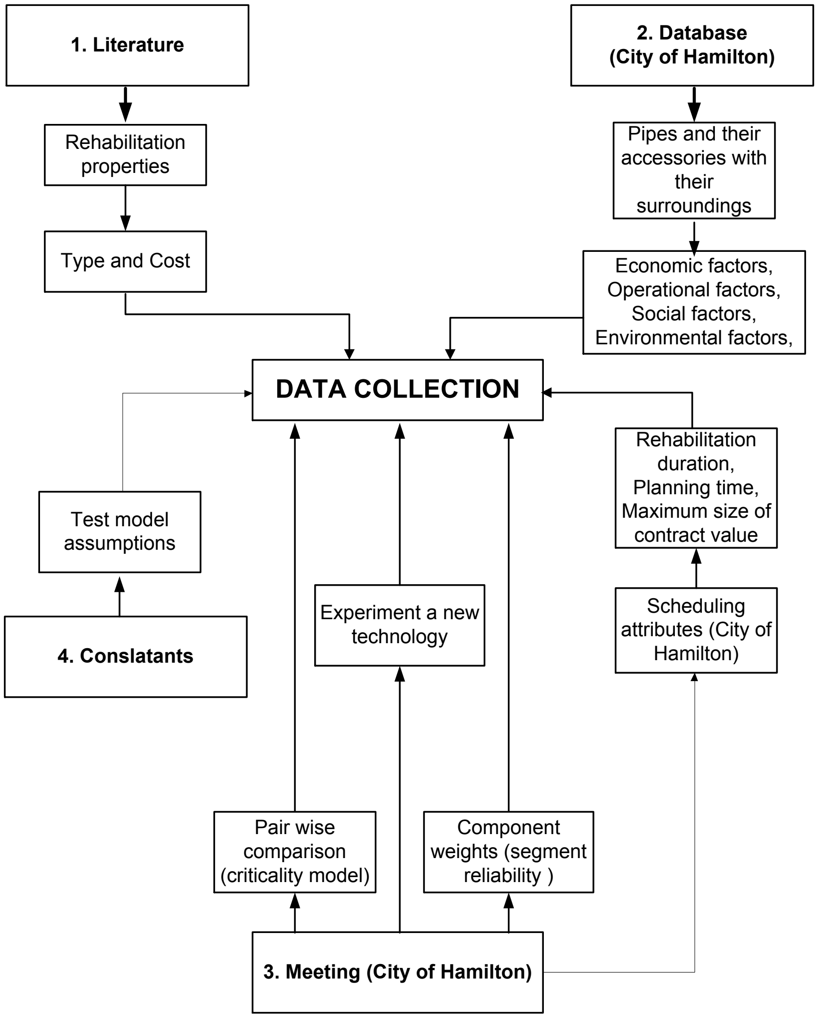


Figure 4.1: Data Collection Sources

Table 4.1: Data sources and types

Attribute Name	Units/Limits	Source
Pipe Length	m	City of Hamilton
Pipe Material	PVC, CONC, Steel	City of Hamilton
Pipe Age	Syear	City of Hamilton
Pipe Diameter	mm	City of Hamilton
Pipe Depth	m	City of Hamilton
Pipe Land Use	Undeveloped, Residential, Park,	City of Hamilton
Pipe Low Acc.	0/1	City of Hamilton
Road Type	RC; RA, UC; UAMI; EXPWY, HWY,	City of Hamilton
Criticality Location	0/1	City of Hamilton
Water Body Proximity	m	City of Hamilton
No Diversion	0/1	City of Hamilton
Locality	0/1	City of Hamilton
Pipe Coordination (X)	mm	City of Hamilton
Pipe Coordination (Y)	mm	City of Hamilton
Score of Critical Factor	1-100	City of Hamilton
Rehabilitation Method Cost	$/m	Zhao and Rajani
Component Weights	1% - 100%	Consultants & City of Hamilton
Experiment a new technology	1-9	Consultants & City of Hamilton
Impact on Environment	1-9	Consultants & City of Hamilton
Planning time of rehabilitation	day	Consultants & City of Hamilton
Time of Rehabilitation Method	day	Consultants & City of Hamilton
Maximum size of a contract value	$	Consultants & City of Hamilton
Pair Wise Comparison for AHP Process	1/9 - 9	Consultants & City of Hamilton

The cost of several rehabilitation methods were collected from the literature. Water network properties (e.g. pipes with their soundings) were taken directly from a criticality model (UMA, 2007), which was described in Chapter 2. To determine the impact on the environment, a questionnaire was designed and sent to several municipalities in Canada and the USA. Meeting with the asset management team from Hamilton was crucial in making reasonable assumptions related to scheduling attributes, network component weights, which reflect their respective importance in the overall PI of the network and the values assigned to pair wise comparisons of the criticality model.

4.2 Sources of Data Collection

4.2.1 Literature

Zhao and Rajani (2002) prepared a comprehensive study to determine an average cost of several rehabilitation methods (Table 4.2). The study is a suitable reference for calculation and analysis, though it was prepared eight years ago; an expert could modify these costs based on current market value.

The data is used in this thesis as the most comprehensive study found in literature. The cost of the rehabilitation methods ($/m) have been used in conjunction with other factors (e.g. environmental impact, and experimentation with a new technology), in order to determine the most suitable type of rehabilitation.

Table 4.2: Average Cost of Trenchless Techniques with More than Five Data Records (Zhao and Rajani, 2002)

Method	Overall average cost($/mm/m)	Diameter range (mm)				# of data records from Trenchless Technology magazine
		Small (≤300) [$/m]	Medium (330-940) [$/m]	Large (960-1,830) [$/m]	Very large (>1,830) [$/m]	
Microtunneling	9.52	2,614	4,770	15,399	46,898	51
Tunneling	3.74	-	1,962	7,093	7,969	24
CIPP	1.38	299	531	2,654	-	39
HDD	2.97	265	1,791	6,239	-	10
Sliplining	1.38	231	988	2,441	2,567	16
Pipe Bursting	2.20	726	1,165	-	-	11
Pipe Jacking	4.29	-	-	7,540	9,515	6
Relining	0.95	295	-	-	-	6
Open Cut	3.85	609	2,314	2,225	-	14

The objective of this research is to study current practice, design and select a suitable decision making model using sufficient management for the water distribution network. Data collected from the City of Hamilton shows that most of the pipe sizes are classified as small to medium. Therefore, other trenchless methods, such as pipe jacking, were not considered.

4.2.2 City of Hamilton, Ontario, Canada

The application example was selected according to land use (Salman et al., 2010) in the City of Hamilton, Ontario, Canada. The City of Hamilton (Figure 4.2) is located on the west end of Lake Ontario and has a population of 504,599 people. The city covers a land area of 1,117.21 square kilometres. Hamilton has over 1,900 kilometres of water lines (City of Hamilton, 2010). Four sub-networks are selected according to the type of land use within Hamilton. These sub-networks represent Undeveloped, Residential, Park, and Commercial/ Industrial land use types. The application example demonstrates the capabilities of the developed models with respect to a PI, rehabilitation work and scheduling of these rehabilitations. The case considers four sub-networks; pertinent to each land use.

The total number of pipe segments in the network is 34,560 which are divided according to pipe size, material, and land use (Table 4.3). More than 70% of the total number of pipes are less than 300mm; while large diameter pipes represents 0.1% of the city network. Also, metallic pipes such as steel, ductile, and cast iron pipe represents 83% of the total number of the pipes. Moreover, 74% of these pipes are located in residential zone.

Figure 4.2: Selected Sub-networks- City of Hamilton

Table 4.3: Number of Pipes According to Various Categories

Pipe size					
Pipe size (mm)	0-299	300-449	450-749	750-1199	1200 +
No. of Pipes	24,529	8,028	988	974	41
Pipe Material					
Pipe Material	HYP, LEAD	CAST1, CIPIT1, CIPIT2, CISP1, CISP2, CISP3, COPP, DUCT, STEEL		PCP, CONCW	Others
No. of Pipes	1,799	28,699		778	3,284
Land Use					
Land Use	Parks	Residential	Commercial/Industrial	High Density	Others
No. of Pipes	372	25,691	5,333	1,005	2,159

In order to develop a criticality model, original data consisting of water network properties were collected from the City of Hamilton and used by UMA (2007). Table 4.4 shows these categories and their respective factors. Data from the City of Hamilton dealing with network properties are divided into four categories which include pipe attributes with its surroundings as shown in Tables 4.5 to 4.8.

Table 4.4: Classification of Critical Factors (UMA, 2007)

Categories	Economic (Repair Cost)	Operational (Customer Impact)	Social		Environmental (Environmental Impact)
			(Public Disruption)	(Visibility)	
Factors	Pipe size	Critical location	Road type	Pipe size	Water body
	Depth	Material	No diversion	Land use	Locality
	Material	Discharged			Affected Pipe
	Land use				
	Low accessibility				

Each attribute was given a score 1 to 100 based on its criticality (i.e. low accessibility is given a score of 100 when a pipe to be rehabilitated is located in an area that is difficult to be reached, otherwise it is given 1). Table 2.4 depicts scores of attributes that are considered for each critical factor. These scores are adapted for the calculation of this thesis.

Table 4.5: Attributes of Economic Factor (UMA, 2007)

Economic Category					
Factor	**Pipe size**	**Depth**	**Material**	**Land use**	**Low accessibility**
Unit	**mm**	**m**	**Type**	**Type**	**Yes/ No**
Valid Entries	0-300	0-3.9	OTHER	Other	No
	300-449	4+	HYP, LEAD	Park	Yes
	450-749		CAST1, CIPIT1, CIPIT2, CISP1, CISP2, CISP3, COPP, DUCT, STEEL	Residential	
	750-1199		PCP, CONCW	Comm./ Indst.	
	1200+			High Density	

Table 4.6: Attributes Of Operational Factor (UMA, 2007)

Operational Category			
Factor	**Critical Location**	**Material**	**Discharged**
Unit	**Yes/ No**	**Type**	**mm**
Valid Entries	No	OTHER	0-300
	Yes	HYP, LEAD	300-449
		CAST1, CIPIT1, CIPIT2, CISP1, CISP2, CISP3, COPP, DUCT, STEEL	450-749
		PCP, CONCW	750-1199
			1200+

Table 4.7: Attributes of Social Factor (UMA, 2007)

Social Category				
Factor	**Public Disruption**		**Visibility**	
	Road Type	**No Diversion**	**Pipe size**	**Land use**
Unit	**Type**	**Yes/ No**	**mm**	**Type**
Valid Entries	OTHER	No	0-300	OTHER
	RC	Yes	300-449	Park
	RA, UC		450-749	Residential
	UAMI		750-1199	Comm./ Indst.
	EXPWY, HWY, UAMJ		1200+	High Density

Table 4.8: Attributes of environmental factor (UMA, 2007)

Environmental Category			
Factor	**Water Body Proximity**	**Locality**	**Affected diameter**
Unit	**Value**	**Yes/ No**	**mm**
Valid Entries	200+	No	0-300
	101-200	Yes	300-449
	51-100		450-749
	1-50		750-1199
	0		1200+

4.2.3 Interviews with the Asset Management Professionals- City of Hamilton and Consulting Teams

To perform component weights, experimentation with a new technology and scheduling parameters, several meetings with the asset management team of the City of Hamilton, AECOM, and UEM were required to develop a PI model, rehabilitation selection model, and scheduling model. Table G.1, Appendix G, shows the interviewees contact information. It includes the title, position and number of interviewees conducted to collect the required data.

4.2.3.1 Component Weights (Segment Reliability)

Meetings with the asset management team of the City of Hamilton and two consultant expert teams in municipal infrastructure were crucial in making reasonable assumptions related to network component weights, which reflect their respective importance in the overall PI of the network, and the values assigned to the components of the criticality model. A hypothetical water main segment has been developed, in order to identify its component weights (Table 4.9).

Table 4.9: Component Weights

Segment	**Water main component**	**Weight (%)**
Hypothetical	Pipe	38
	Hydrant	31
	Isolation valve	28
	Control valve	3
Total		100

4.2.3.2 Experiment a New Technology

The City of Hamilton is capable of adapting to a new technology which will decrease the impact on the environment, decrease cost, and lower construction time. Therefore, a score of “1" is given to open cut method and “5” to trenchless technology methods.

4.2.3.3 Planning Time of Rehabilitation

Planning time for rehabilitation is a constraint of performing the scheduling model. Work rehabilitation packages might be overlapped due to limited time of rehabilitation and therefore it is necessary to assume a suitable time of rehabilitation. The City of Hamilton has specific requirements to perform planning time of rehabilitation such as the place of rehabilitation (land use) and rehabilitation time (i.e. summer, winter). For this reason, two years is the assumed time required to perform rehabilitation activities.

4.2.3.4 Maximum Size of a Contract Value

The maximum size of a contract value is another constraint of executing the scheduling model. Applying this constraint allows for the breakdown of the total work required for rehabilitation into smaller packages, which allows for effective monitoring and control of these packages. After extensive discussion with the City of Hamilton, the assumption of a maximum size of a contract value was selected.

4.2.3.5 Pair Wise Comparison (Criticality Model)

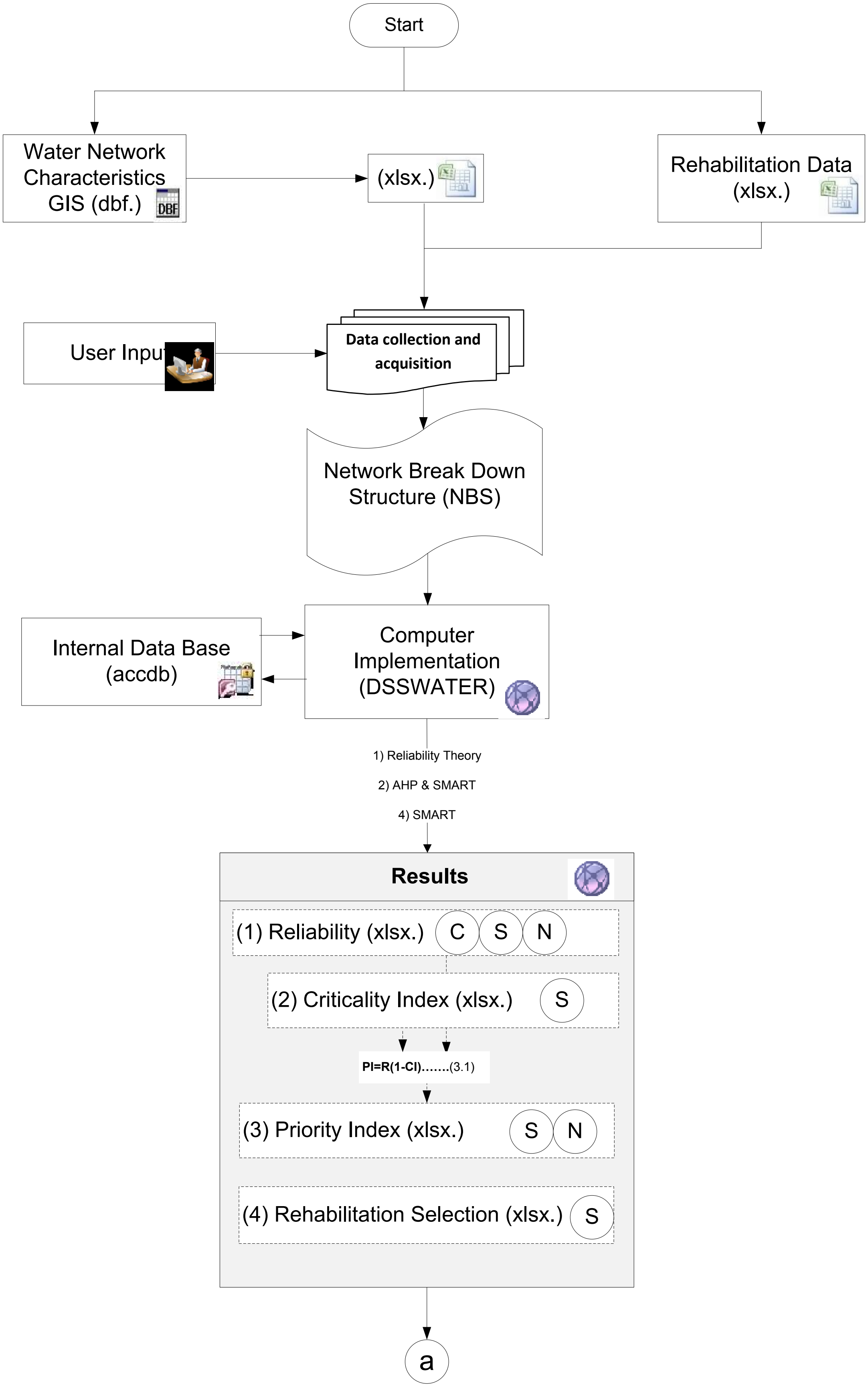
The City of Hamilton has performed the pair-wise comparison matrices in order to determine the weights of critical factors which are tested by expert teams from AECOM and UEM. The AHP model has been applied five times according to the land use as shown in Appendix I. Therefore, the team evaluated the pair-wise comparison of the criticality model five times. Through these comparisons and evaluations, the weights of critical factors are developed according to land use.

CHAPTER 5

Automated Tool Development

5.1 Introduction

This chapter describes the implementation of the developed models, mentioned in Chapter 3 into prototype software which is called DSSWATER. The DSSWATER is developed using object-oriented programming and Microsoft Office Framework.net, coded using visual Basic (VBA) and Lingo 12 (Lingo 12, 2011), and Microsoft Access is utilized as the database management system as shown in Figure 5.1. The DSSWATER has three main components: (1) PI model, (2) rehabilitation selection model, and (3) scheduling model supported by a relational database. The PI model is developed using the following calculations (1) reliability assessment of water main components and segments, (2) criticality indices of water pipes and segments, and (3) PI of segments and networks. The rehabilitation methods of water main components (pipes and accessories) are the output of the rehabilitation selection model which is the second model. In addition to the PI and rehabilitation selection models, the following additional factors are used in the scheduling needed for the rehabilitation work (model 3). These factors are: (1) rehabilitation package limits (minimum and maximum), (2) rehabilitation planning time, and (3) maximum contract price. As stated earlier, the scheduling model using Mixed Non Linear Integer Programming (MNLP) which was developed in Section (3.5).


Start
Water Network Characteristics GIS (dbf.)
DBF
(xlsx.)
Rehabilitation Data (xlsx.)
User Input
Data collection and acquisition
Network Break Down Structure (NBS)
Internal Data Base (accdb)
Computer Implementation (DSSWATER)
1) Reliability Theory
2) AHP & SMART
4) SMART
Results
(1) Reliability (xlsx.)
C
S
N
(2) Criticality Index (xlsx.)
S
PI=R(1-CI).......(3.1)
(3) Priority Index (xlsx.)
S
N
(4) Rehabilitation Selection (xlsx.)
S
a

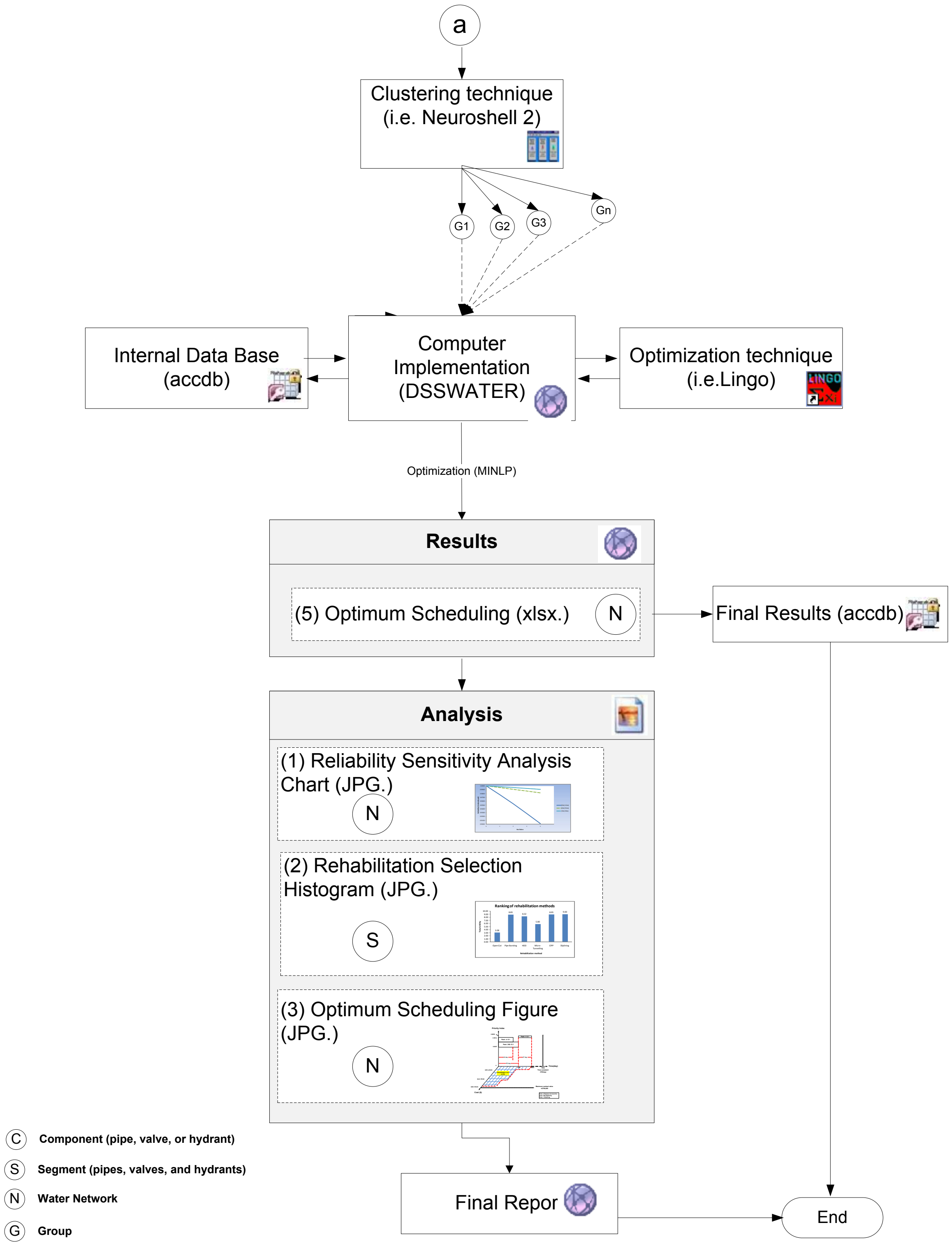


Figure 5.1: Input and Output of DSSWATER

The scheduling model output consists of rehabilitation scheduling of water network components.

5.2 Characteristics of DSSWATER

DSSWATER uses a Graphical User Interface (GUI); written in VBA language and Lingo 12 in an ACCESS 2007 environment, which is available and used widely. The program includes a procedure that allows a user to enter water component properties and scheduling constraints as shown in Figure 5.2.

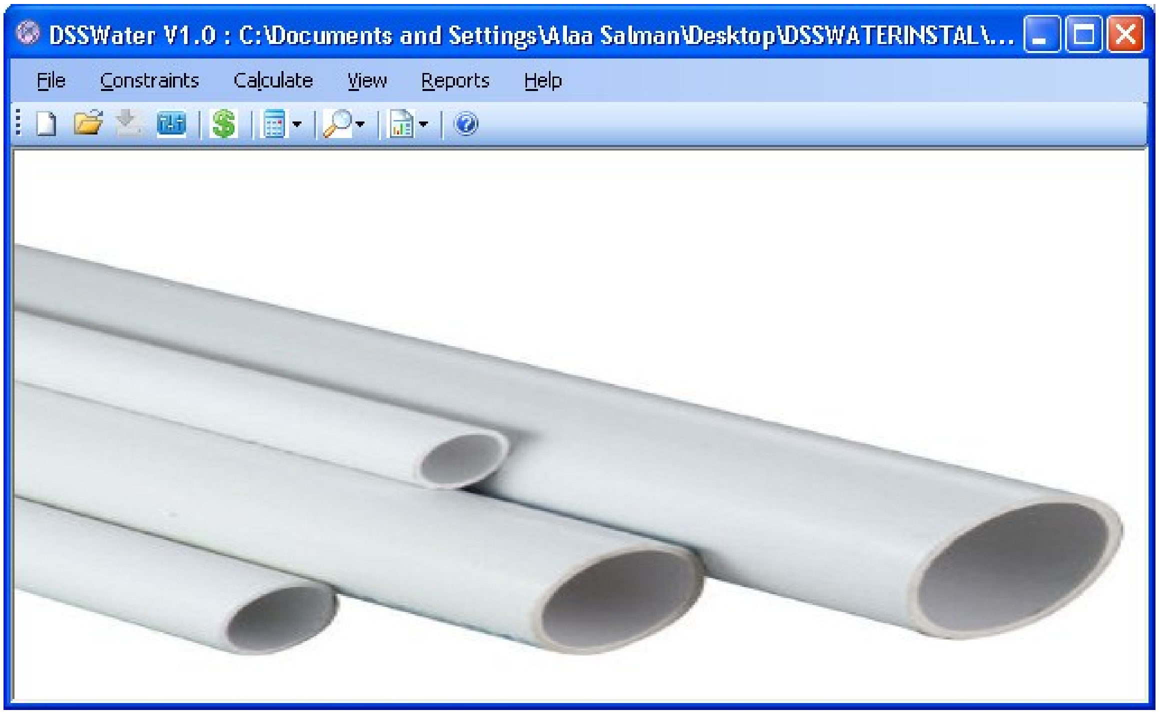


Figure 5.2: DSSWATER: Main Page

The DSSWATER-Prototype software is limited for one network only to provide a proof of concept demonstrating the developed models in this thesis (Chapter 3). It should be noted that the Unsupervised Neural Network (UNN) is not automated and therefore clustering must be done when a user intends to divide a city network into groups or sub-networks. In order to utilize the developed software, a user must have the capability to understand the system structure and the relationship between them and the three models; (1) PI, (2) rehabilitation selection, and (3) scheduling. Data and calculations are saved and processed from model (1), model (2) to model (3) accordingly and will be used in rehabilitation selection and scheduling models.

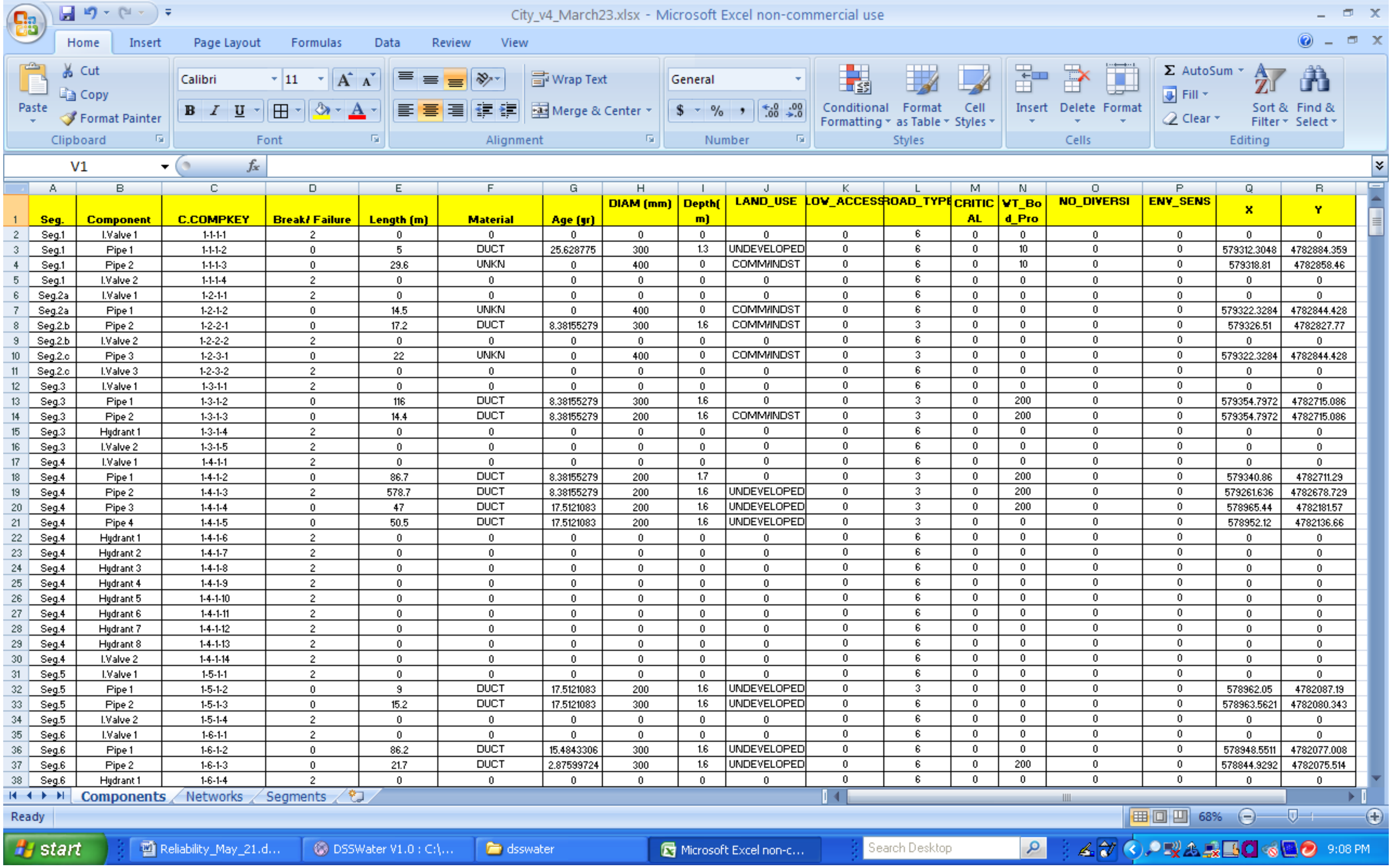
The flow direction of the software starts from the component level to the network level through to the segment level. With the required data, the results of each component are directly transferred to segment and network attributes.

5.2.1 DSSWATER: Set Up

Three important requirements are needed to set up the DSSWATER; first, Microsoft Framework.net must be downloaded in the machine using Microsoft web-page (Microsoft, 2011). This process is very important to install dynamic link libraries (dll.). Secondly, Lingo 12 (Lingo 12, 2011) should be installed to perform the optimum scheduling of each group. Finally, an Excel template sheet should be created, in order to include the required data of a distribution network. The required data consists of three sets which are component, network, and segment tables.

(1) Component table, which includes properties of network components as depicted in Table 5.1. The required data in this set is divided into 18 columns as follows:

Table 5.1: Required Data-components (xlxs. Template)



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Seg.	Component	C.COMPKEY	Break/ Failure	Length (m)	Material	Age (yr)	DIAM (mm)	Depth(m)	LAND_USE	LOW_ACCESS	ROAD_TYPE	CRITIC AL	WT_Bo d_Pro	NO_DIVERSI	ENV_SENS	X	Y
2	Seg.1	I.Valve 1	1-1-1-1	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
3	Seg.1	Pipe 1	1-1-1-2	0	5	DUCT	25.628775	300	1.3	UNDEVELOPED	0	6	0	10	0	0	579312.3048	4782884.359
4	Seg.1	Pipe 2	1-1-1-3	0	29.6	UNKN	0	400	0	COMM/INDST	0	6	0	10	0	0	579318.81	4782858.46
5	Seg.1	I.Valve 2	1-1-1-4	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
6	Seg.2a	I.Valve 1	1-2-1-1	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
7	Seg.2a	Pipe 1	1-2-1-2	0	14.5	UNKN	0	400	0	COMM/INDST	0	6	0	0	0	0	579322.3284	4782844.428
8	Seg.2.b	Pipe 2	1-2-2-1	0	17.2	DUCT	8.38155279	300	1.6	COMM/INDST	0	3	0	0	0	0	579326.51	4782827.77
9	Seg.2.b	I.Valve 2	1-2-2-2	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
10	Seg.2.c	Pipe 3	1-2-3-1	0	22	UNKN	0	400	0	COMM/INDST	0	3	0	0	0	0	579322.3284	4782844.428
11	Seg.2.c	I.Valve 3	1-2-3-2	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
12	Seg.3	I.Valve 1	1-3-1-1	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
13	Seg.3	Pipe 1	1-3-1-2	0	116	DUCT	8.38155279	300	1.6	0	0	3	0	200	0	0	579354.7972	4782715.086
14	Seg.3	Pipe 2	1-3-1-3	0	14.4	DUCT	8.38155279	200	1.6	COMM/INDST	0	3	0	200	0	0	579354.7972	4782715.086
15	Seg.3	Hydrant 1	1-3-1-4	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
16	Seg.3	I.Valve 2	1-3-1-5	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
17	Seg.4	I.Valve 1	1-4-1-1	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
18	Seg.4	Pipe 1	1-4-1-2	0	86.7	DUCT	8.38155279	200	1.7	0	0	3	0	200	0	0	579340.86	4782711.29
19	Seg.4	Pipe 2	1-4-1-3	2	578.7	DUCT	8.38155279	200	1.6	UNDEVELOPED	0	3	0	200	0	0	579261.636	4782678.729
20	Seg.4	Pipe 3	1-4-1-4	0	47	DUCT	17.5121083	200	1.6	UNDEVELOPED	0	3	0	200	0	0	578965.44	4782181.57
21	Seg.4	Pipe 4	1-4-1-5	0	50.5	DUCT	17.5121083	200	1.6	UNDEVELOPED	0	3	0	0	0	0	578952.12	4782136.66
22	Seg.4	Hydrant 1	1-4-1-6	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
23	Seg.4	Hydrant 2	1-4-1-7	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
24	Seg.4	Hydrant 3	1-4-1-8	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
25	Seg.4	Hydrant 4	1-4-1-9	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
26	Seg.4	Hydrant 5	1-4-1-10	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
27	Seg.4	Hydrant 6	1-4-1-11	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
28	Seg.4	Hydrant 7	1-4-1-12	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
29	Seg.4	Hydrant 8	1-4-1-13	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
30	Seg.4	I.Valve 2	1-4-1-14	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
31	Seg.5	I.Valve 1	1-5-1-1	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
32	Seg.5	Pipe 1	1-5-1-2	0	9	DUCT	17.5121083	200	1.6	UNDEVELOPED	0	3	0	0	0	0	578962.05	4782087.19
33	Seg.5	Pipe 2	1-5-1-3	0	15.2	DUCT	17.5121083	300	1.6	UNDEVELOPED	0	6	0	0	0	0	578963.5621	4782080.343
34	Seg.5	I.Valve 2	1-5-1-4	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
35	Seg.6	I.Valve 1	1-6-1-1	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0
36	Seg.6	Pipe 1	1-6-1-2	0	86.2	DUCT	15.4843306	300	1.6	UNDEVELOPED	0	6	0	0	0	0	578948.5511	4782077.008
37	Seg.6	Pipe 2	1-6-1-3	0	21.7	DUCT	2.87599724	300	1.6	UNDEVELOPED	0	6	0	200	0	0	578844.9292	4782075.514
38	Seg.6	Hydrant 1	1-6-1-4	2	0	0	0	0	0	0	0	6	0	0	0	0	0	0

Column A- Segment:

Column “A” represents segment number.

Column B- Component:

Column “B” represents component type and number for each segment.

Column C- CompKey:

Column “C” represents the identity number of each component; it is divided into four sections (#, #, #, #). The first section represents network number; the second number is to identify the segment number, the third number depicts the branch number of the segment; while the fourth number represents the component number. By adapting this numbering methodology, each component in a network can be identified and located easily.

Column D- Break (Failure):

Column “D” represents the Break number of a pipe or Failure number of an accessory (valve or hydrant) since its installation.

Column E- Length (m):

Column “E” depicts pipe’s length. NA might be written for an accessory.

Column F- Material:

Column “F” depicts pipe’s material (i.e. ductile, steel, concrete, etc.). NA might be written for an accessory.

Column G- Age (year):

Column “G” describes pipe and accessory ages.

Column H- Diameter (mm):

Column “H” depicts pipe diameter. NA might be written for an accessory.

Column I- Depth (m):

Column “I” depicts pipe depth. NA might be written for an accessory.

Column J- Land use:

Column “J” illustrates pipe land use (i.e. residential, undeveloped, etc.). NA might be written for an accessory.

Column K- Low Accessibility:

Column “K” depicts pipe accessibility whether it is accessible (0) or not (1). NA might be written for an accessory.

Column L- Road Type:

Column “L” depicts pipe road type (i.e. RC: Rural Collector; HWY: Highway, etc.). NA might be written for an accessory.

Column M- Critical Location:

Column “M” depicts pipe location whether it is critical, such as a hospital (1) or not a critical (0). NA might be written for an accessory.

Column N- Water Body Proximity:

Column “N” depicts pipe distance from the surface water (i.e. lake). NA might be written for an accessory.

Column O- No Diversion:

Column “O” depicts pipe alternative whether it exists (0) or not (1). NA might be written for an accessory.

Column P- Locality:

Column “P” depicts pipe location within a sensitive area (1) or not (0). NA might be written for an accessory.

Column Q- X (m):

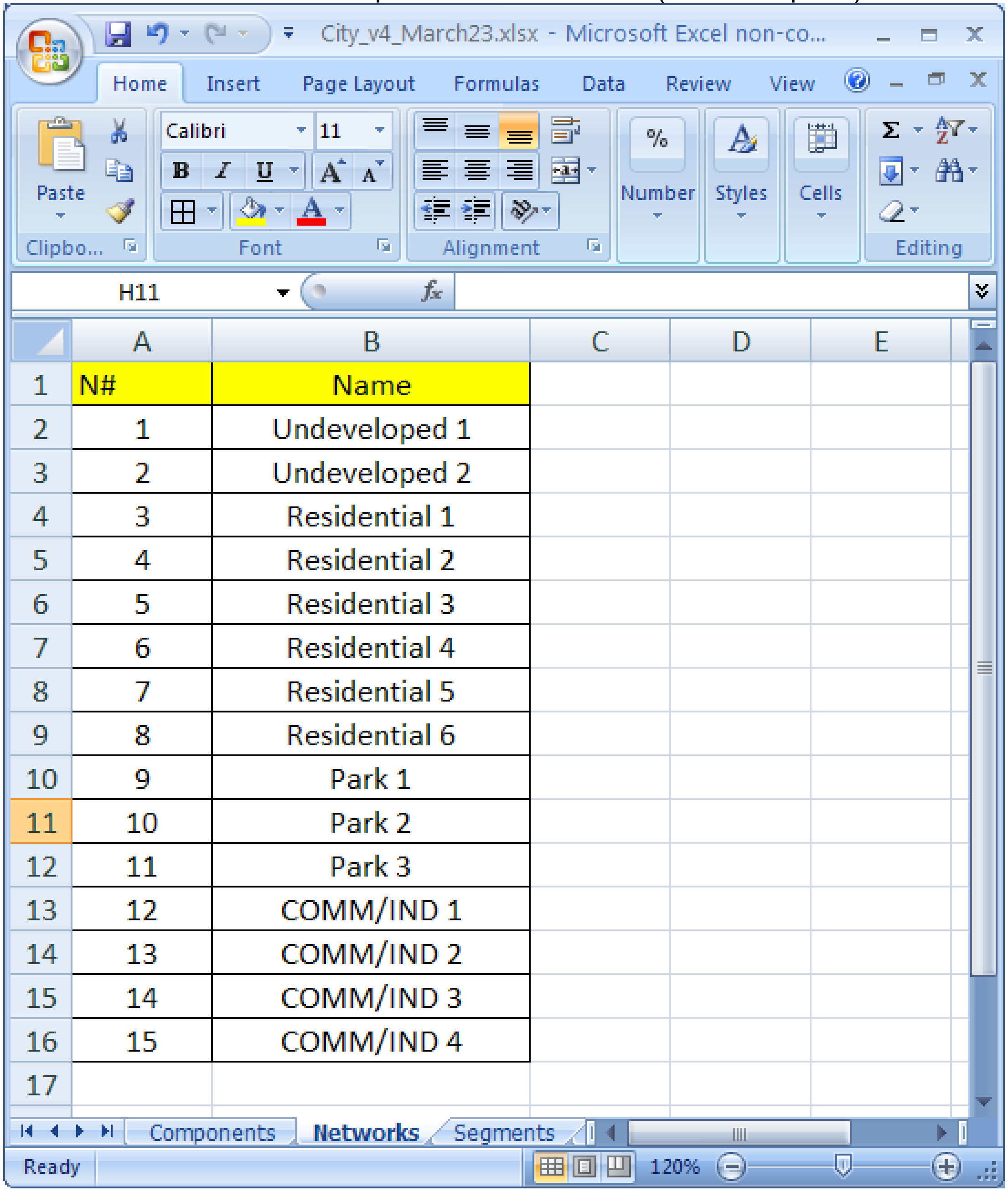
Column “Q” depicts the coordination of pipe X in the network. NA might be written for an accessory.

Column R- Y (m):

Column “R” depicts the coordination pipe Y in the network. NA might be written for an accessory.

(2) The second set of required data is the network name as depicted in Table 5.2. The network name represents land use to be utilized for the analytical hierarchy process (AHP).

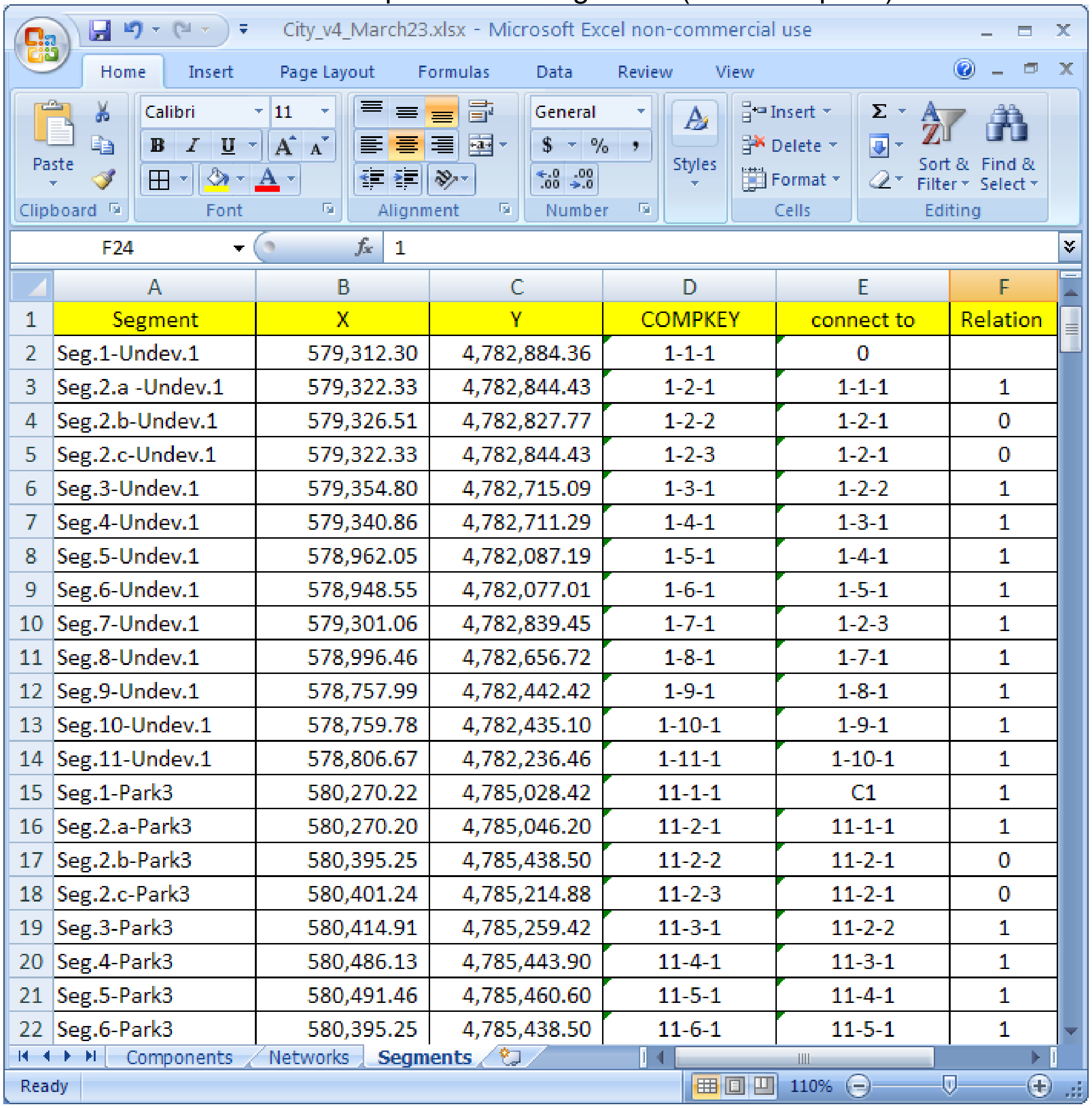
Table 5.2: Required Data-Networks (xlxs. Template)



N#	Name
1	Undeveloped 1
2	Undeveloped 2
3	Residential 1
4	Residential 2
5	Residential 3
6	Residential 4
7	Residential 5
8	Residential 6
9	Park 1
10	Park 2
11	Park 3
12	COMM/IND 1
13	COMM/IND 2
14	COMM/IND 3
15	COMM/IND 4

(3) The third set of data is the segment table. The logical relations among segments are identified to construct a network (Table 5.3). The relations among segments are limited in series, parallel and series-parallel. Other relations such as delta and star are not considered.

Table 5.3: Required Data-segments (xlxs. Template)



F24 f_x 1

	A	B	C	D	E	F
1	Segment	X	Y	COMPKEY	connect to	Relation
2	Seg.1-Undev.1	579,312.30	4,782,884.36	1-1-1	0	
3	Seg.2.a -Undev.1	579,322.33	4,782,844.43	1-2-1	1-1-1	1
4	Seg.2.b-Undev.1	579,326.51	4,782,827.77	1-2-2	1-2-1	0
5	Seg.2.c-Undev.1	579,322.33	4,782,844.43	1-2-3	1-2-1	0
6	Seg.3-Undev.1	579,354.80	4,782,715.09	1-3-1	1-2-2	1
7	Seg.4-Undev.1	579,340.86	4,782,711.29	1-4-1	1-3-1	1
8	Seg.5-Undev.1	578,962.05	4,782,087.19	1-5-1	1-4-1	1
9	Seg.6-Undev.1	578,948.55	4,782,077.01	1-6-1	1-5-1	1
10	Seg.7-Undev.1	579,301.06	4,782,839.45	1-7-1	1-2-3	1
11	Seg.8-Undev.1	578,996.46	4,782,656.72	1-8-1	1-7-1	1
12	Seg.9-Undev.1	578,757.99	4,782,442.42	1-9-1	1-8-1	1
13	Seg.10-Undev.1	578,759.78	4,782,435.10	1-10-1	1-9-1	1
14	Seg.11-Undev.1	578,806.67	4,782,236.46	1-11-1	1-10-1	1
15	Seg.1-Park3	580,270.22	4,785,028.42	11-1-1	C1	1
16	Seg.2.a-Park3	580,270.20	4,785,046.20	11-2-1	11-1-1	1
17	Seg.2.b-Park3	580,395.25	4,785,438.50	11-2-2	11-2-1	0
18	Seg.2.c-Park3	580,401.24	4,785,214.88	11-2-3	11-2-1	0
19	Seg.3-Park3	580,414.91	4,785,259.42	11-3-1	11-2-2	1
20	Seg.4-Park3	580,486.13	4,785,443.90	11-4-1	11-3-1	1
21	Seg.5-Park3	580,491.46	4,785,460.60	11-5-1	11-4-1	1
22	Seg.6-Park3	580,395.25	4,785,438.50	11-6-1	11-5-1	1

5.2.2 DSSWATER: Working on a New Project

The first drop down menu on the upper left of the DSSWATER screen is “File” which includes several options; “New Project” is the first option to be selected to open a new project as shown in Figure (5.3).

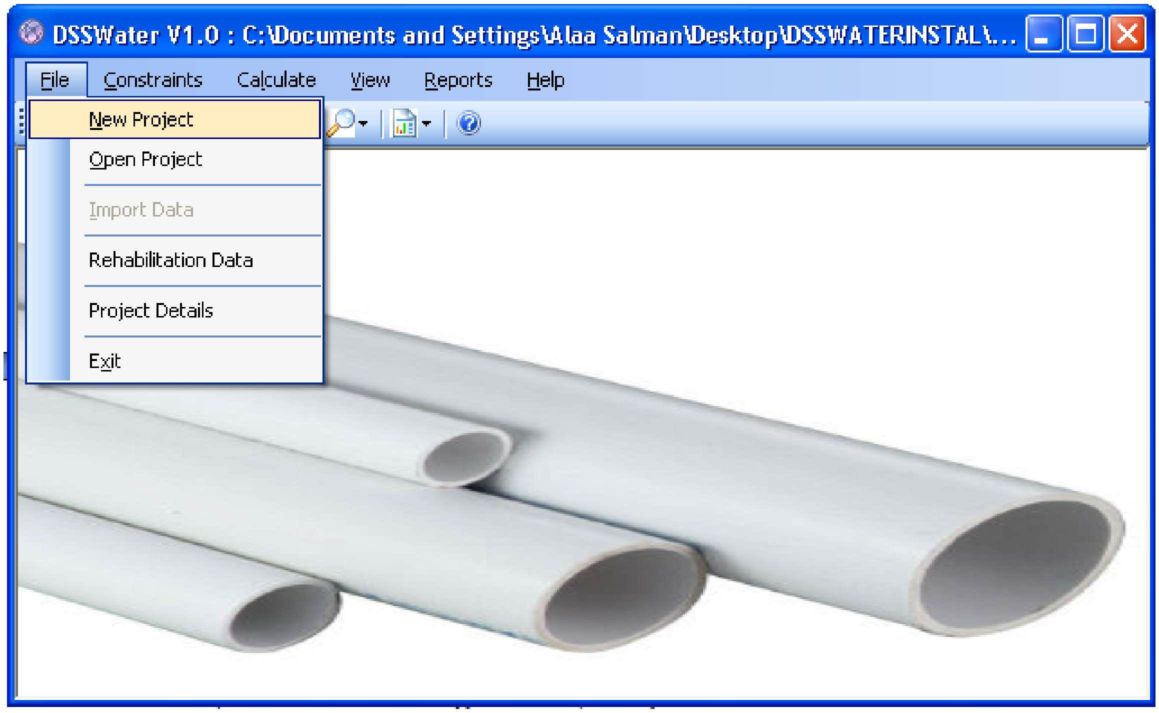
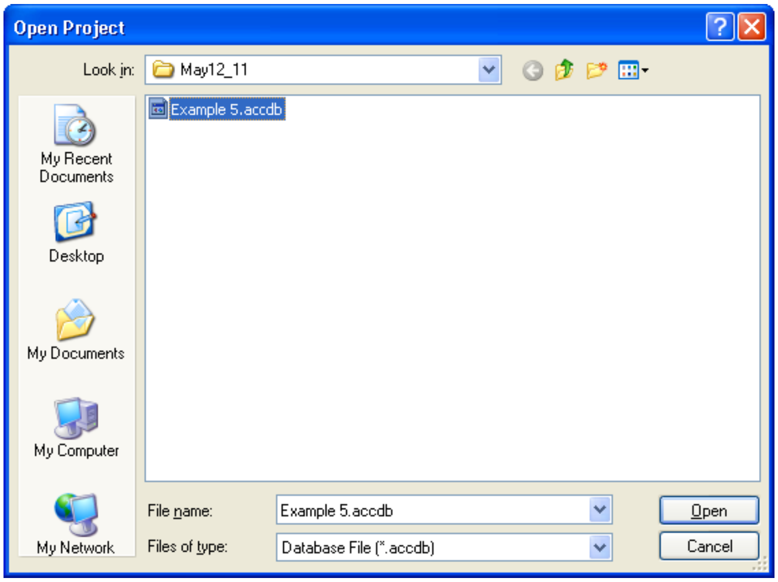


Figure 5.3: DSSWATER: Open New Project

A new screen, as shown in Figure 5.4, is open to write a name of the new file (Example 5) and save it as an access data base file (.accdb).



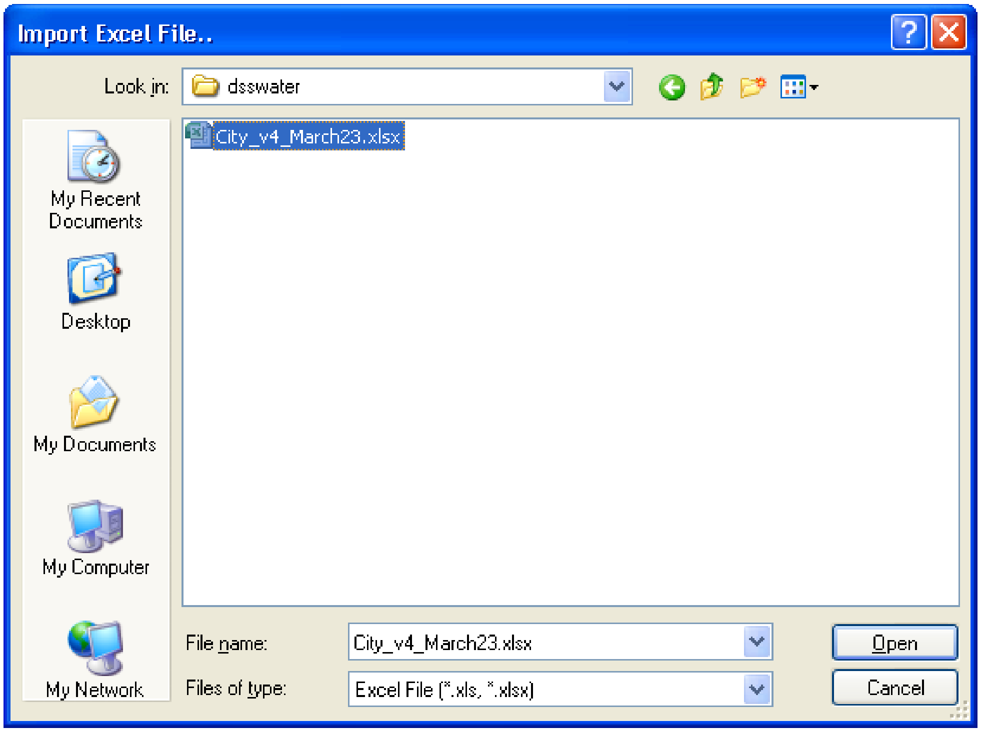
Look in: May12_11

File name: Example 5.accdb

Files of type: Database File (*.accdb)

Figure 5.4: DSSWATER: Select an access data base file (.accdb)

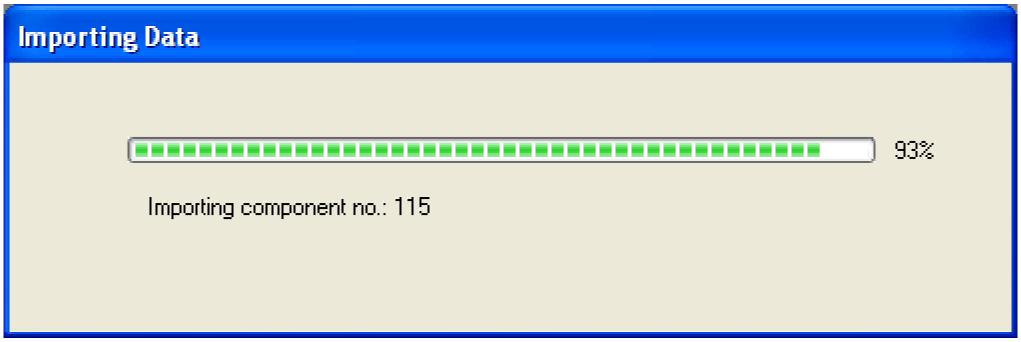
In this stage, a new project template is built using an Access environment but without data and therefore a new file is required to upload the data (City_v4_March23.xlsx) using the third option of “File” drop down menu (Import) as shown in Figure 5.5. The required data should be saved in (xlsx.) file. This process might take a few minutes until data are imported to DSSWATER (Figure 5.6).



File name: City_v4_March23.xlsx

Files of type: Excel File (*.xls, *.xlsx)

Figure 5.5: DSSWATER: Import Data (.xlxs)

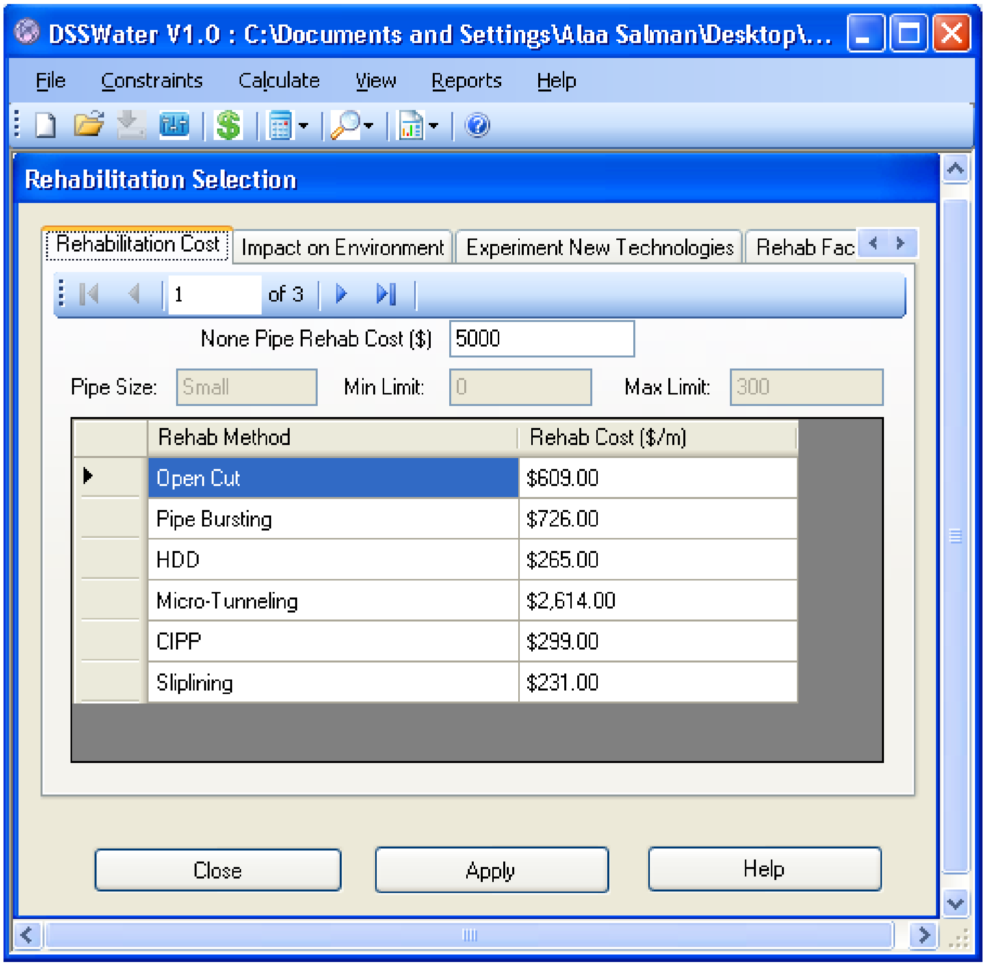


93%

Importing component no.: 115

Figure 5.6: DSSWATER: Importing Data

The ‘File’ dropdown menu also gives the user access to the ‘Rehabilitation Data’ window. Rehabilitation Data window (Figure 5.7) is composed of four tabs; Rehabilitation Cost, Impact on Environment, Experiment New Technologies, and Rehabilitation Factors. A user can modify or change the default values directly.



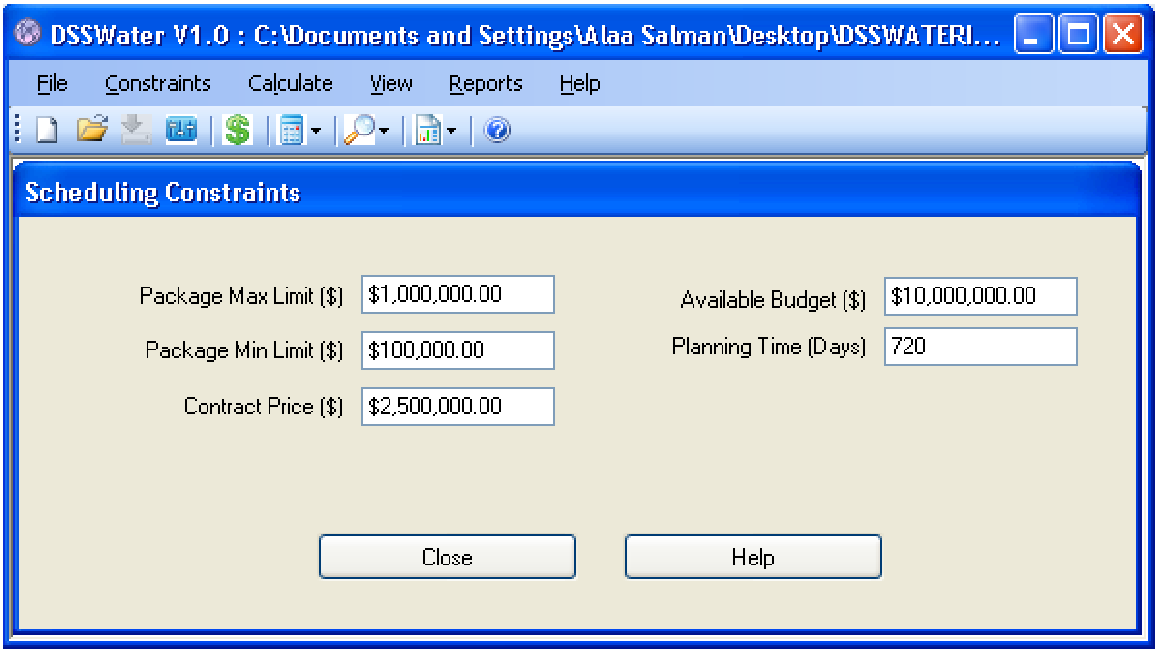
None Pipe Rehab Cost ($) 5000

Pipe Size: Small Min Limit: 0 Max Limit: 300

Rehab Method	Rehab Cost ($/m)
Open Cut	$609.00
Pipe Bursting	$726.00
HDD	$265.00
Micro-Tunneling	$2,614.00
CIPP	$299.00
Sliplining	$231.00

Figure 5.7: DSSWATER: Rehabilitation Selection- Constraints

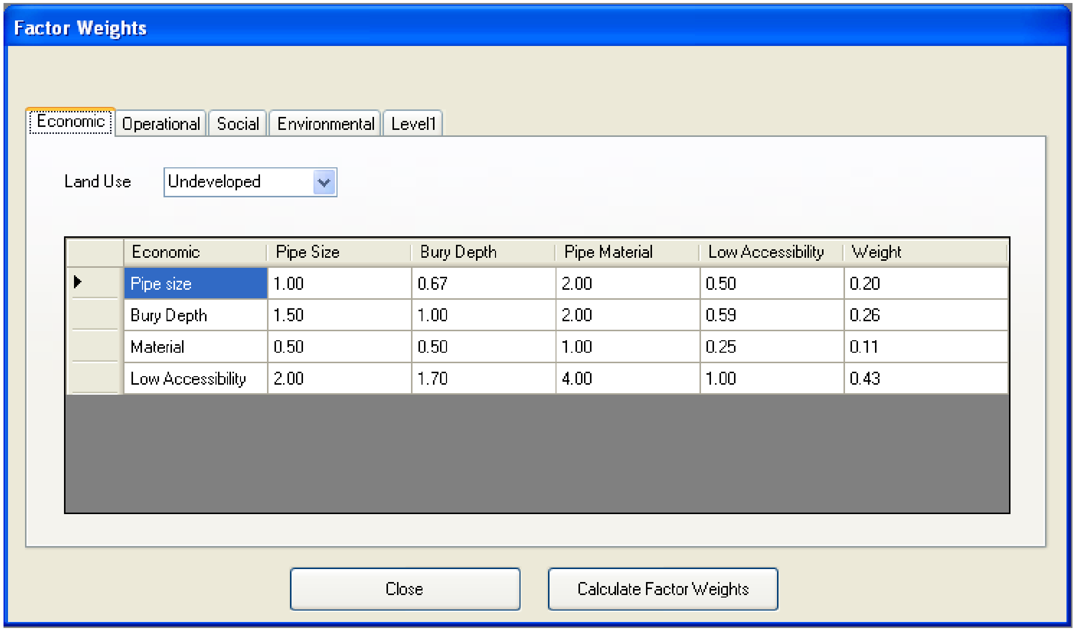
The second dropdown menu is “Constraints” which includes one option: Scheduling. The Scheduling Constraints window (Figure 5.8) includes packages size, rehabilitation time, contract price, and available budget. A user has an option to change the default values of scheduling constraints.



Package Max Limit ($) $1,000,000.00
Package Min Limit ($) $100,000.00
Contract Price ($) $2,500,000.00
Available Budget ($) $10,000,000.00
Planning Time (Days) 720

Figure 5.8: DSSWATER: Scheduling Constraints

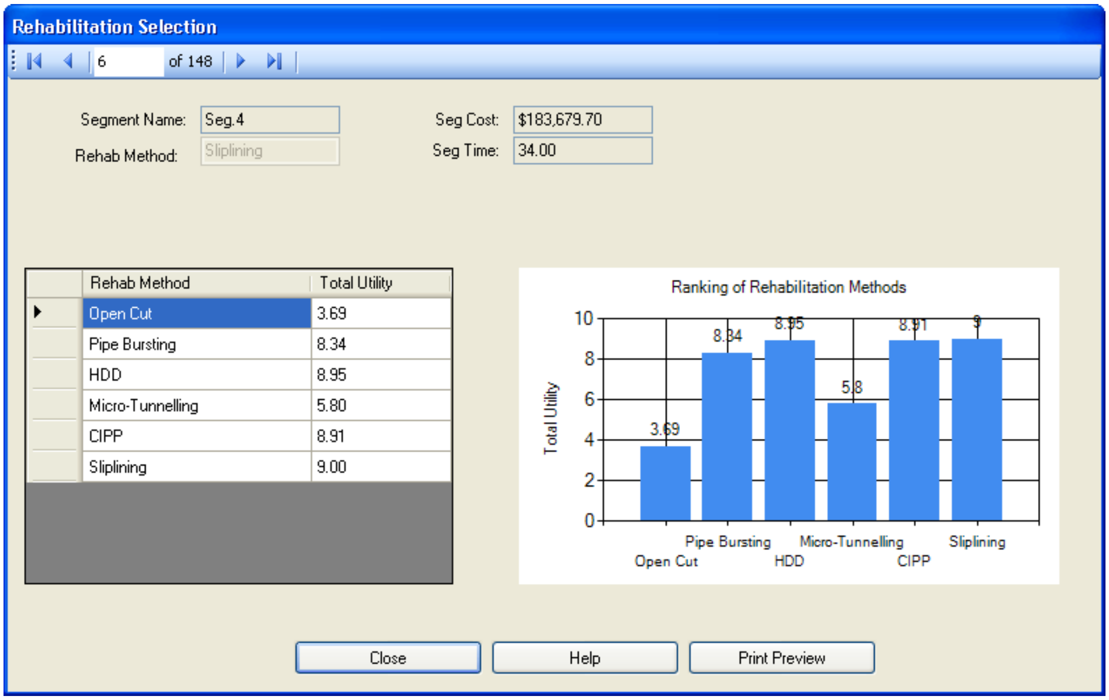
The third dropdown menu is “Calculate” which includes the options (1) Factor Weights to calculate the weight of critical factors using AHP (Figure 5.9), (2) Component Reliability of each component using reliability theory, (3) Component Criticality to determine the criticality index of each pipe, (4) Segment Criticality to determine the criticality index of each segment, (5) Segment PI to determine the PI of each segment, (6) Rehabilitation Selection to depict the ranking of rehabilitation methods of each segment (Figure 5.10), (7) Group PI to determine the PI of the group, (8) Packages to determine the number of packages of the group according to the scheduling constraints (Figure 5.11), and (9) Scheduling to depict the optimum rehabilitation scheduling with respect to scheduling constraints (Figure 5.12). The previous options should be performed consecutively.



Land Use: Undeveloped

Economic	Pipe Size	Bury Depth	Pipe Material	Low Accessibility	Weight
Pipe size	1.00	0.67	2.00	0.50	0.20
Bury Depth	1.50	1.00	2.00	0.59	0.26
Material	0.50	0.50	1.00	0.25	0.11
Low Accessibility	2.00	1.70	4.00	1.00	0.43

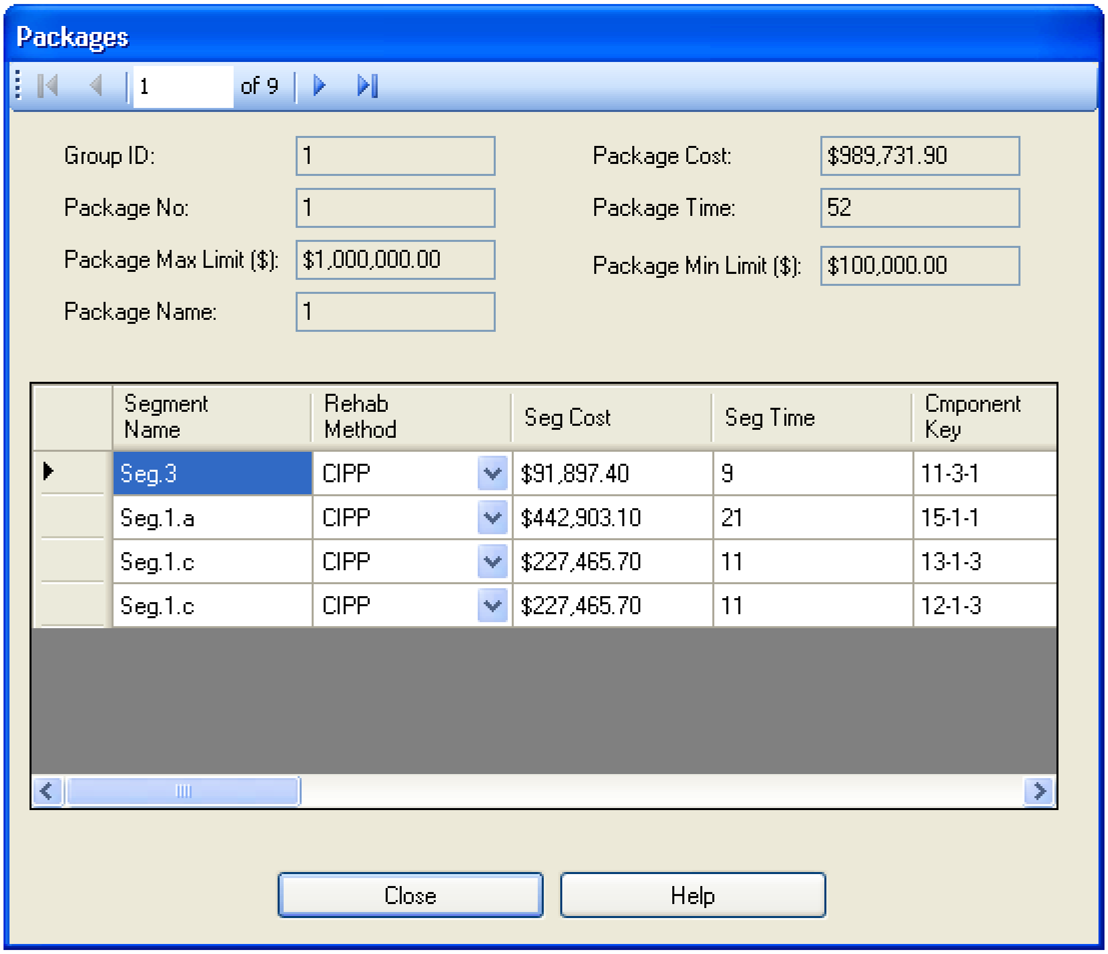
Figure 5.9: DSSWATER: Factor Weights



Segment Name: Seg.4
Rehab Method: Sliplining
Seg Cost: $183,679.70
Seg Time: 34.00

Rehab Method	Total Utility
Open Cut	3.69
Pipe Bursting	8.34
HDD	8.95
Micro-Tunnelling	5.80
CIPP	8.91
Sliplining	9.00

Figure 5.10: DSSWATER: Rehabilitation Selection- Ranking

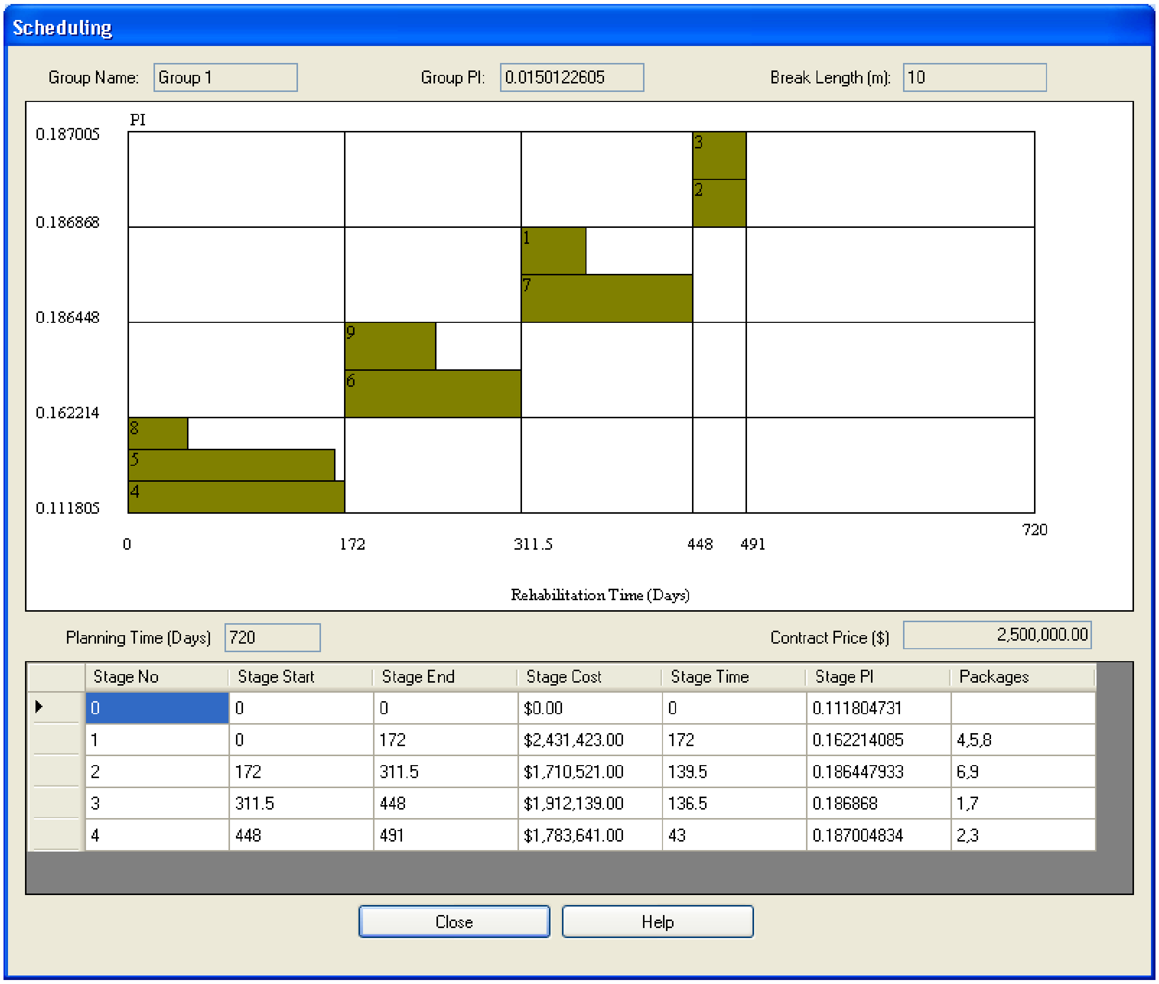


Group ID:	1
Package No:	1
Package Max Limit ($):	$1,000,000.00
Package Name:	1
Package Cost:	$989,731.90
Package Time:	52
Package Min Limit ($):	$100,000.00

Segment Name	Rehab Method	Seg Cost	Seg Time	Cmponent Key
Seg.3	CIPP	$91,897.40	9	11-3-1
Seg.1.a	CIPP	$442,903.10	21	15-1-1
Seg.1.c	CIPP	$227,465.70	11	13-1-3
Seg.1.c	CIPP	$227,465.70	11	12-1-3

Figure 5.11: DSSWATER: Rehabilitation Selection- Ranking

Testing the data that is imported to the DSSWATER in the previous step requires using the fourth dropdown menu "View". The first option in the "View" menu is "components". By selecting this option, a new screen depicts the data as shown in Figure 5.13. DSSWATER records 725 components in the network, and each component has several attributes. A user in this stage can modify or change component's attributes directly in this screen.



Group Name: Group 1

Group PI: 0.0150122605

Break Length (m): 10

Planning Time (Days) 720

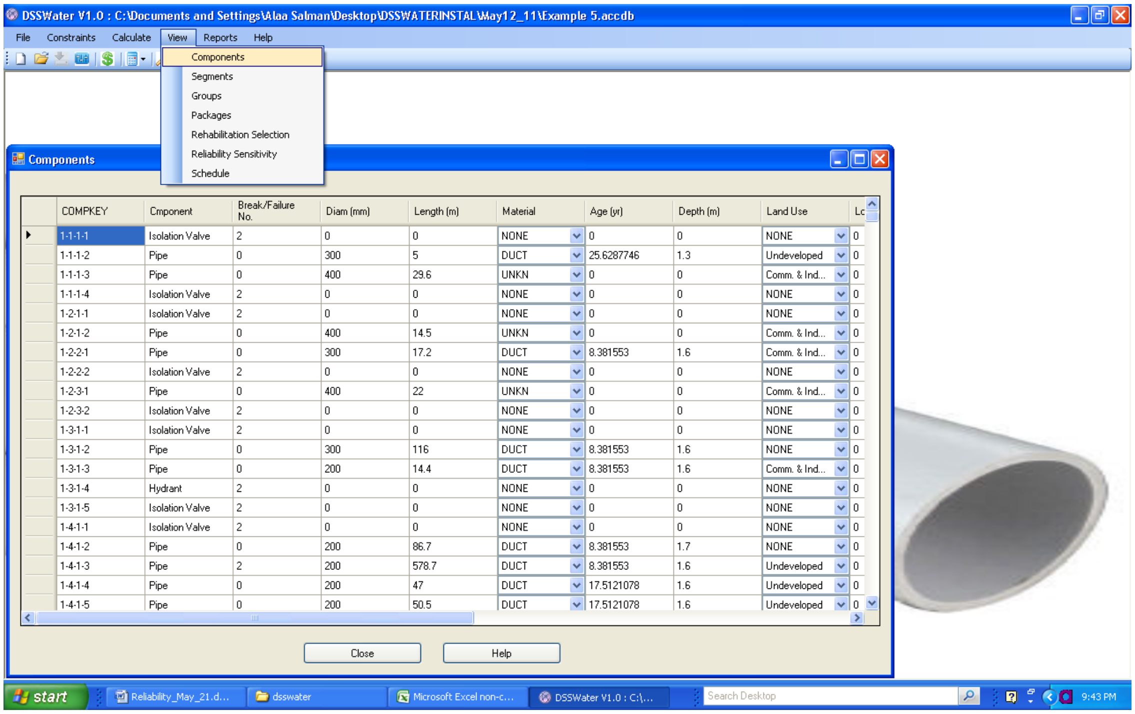
Contract Price ($) 2,500,000.00

Stage No	Stage Start	Stage End	Stage Cost	Stage Time	Stage PI	Packages
0	0	0	$0.00	0	0.111804731	
1	0	172	$2,431,423.00	172	0.162214085	4,5,8
2	172	311.5	$1,710,521.00	139.5	0.186447933	6,9
3	311.5	448	$1,912,139.00	136.5	0.186868	1,7
4	448	491	$1,783,641.00	43	0.187004834	2,3

Figure 5.12: DSSWATER: Optimum Scheduling Chart

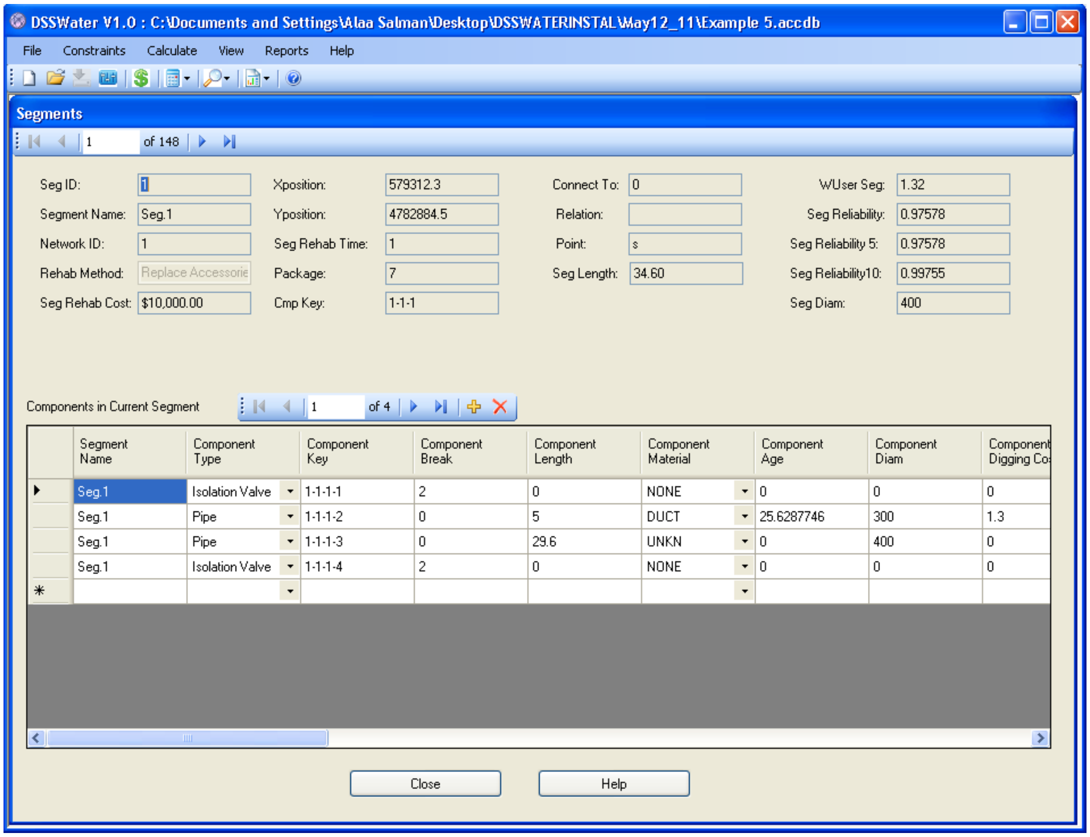
The second option in the “View” menu is “Segments” as shown in Figure 5.14. The network records 149 segments in the network, and each segment has its components. In this window, a user can modify the segment’s attributes (i.e. component types, relation among components, etc.).

The logical relations among segment can be depicted in the following example (Figure 5.15).



COMPKEY	Cmponent	Break/Failure No.	Diam (mm)	Length (m)	Material	Age (yr)	Depth (m)	Land Use	Lc
1-1-1-1	Isolation Valve	2	0	0	NONE	0	0	NONE	0
1-1-1-2	Pipe	0	300	5	DUCT	25.6287746	1.3	Undeveloped	0
1-1-1-3	Pipe	0	400	29.6	UNKN	0	0	Comm. & Ind...	0
1-1-1-4	Isolation Valve	2	0	0	NONE	0	0	NONE	0
1-2-1-1	Isolation Valve	2	0	0	NONE	0	0	NONE	0
1-2-1-2	Pipe	0	400	14.5	UNKN	0	0	Comm. & Ind...	0
1-2-2-1	Pipe	0	300	17.2	DUCT	8.381553	1.6	Comm. & Ind...	0
1-2-2-2	Isolation Valve	2	0	0	NONE	0	0	NONE	0
1-2-3-1	Pipe	0	400	22	UNKN	0	0	Comm. & Ind...	0
1-2-3-2	Isolation Valve	2	0	0	NONE	0	0	NONE	0
1-3-1-1	Isolation Valve	2	0	0	NONE	0	0	NONE	0
1-3-1-2	Pipe	0	300	116	DUCT	8.381553	1.6	NONE	0
1-3-1-3	Pipe	0	200	14.4	DUCT	8.381553	1.6	Comm. & Ind...	0
1-3-1-4	Hydrant	2	0	0	NONE	0	0	NONE	0
1-3-1-5	Isolation Valve	2	0	0	NONE	0	0	NONE	0
1-4-1-1	Isolation Valve	2	0	0	NONE	0	0	NONE	0
1-4-1-2	Pipe	0	200	86.7	DUCT	8.381553	1.7	NONE	0
1-4-1-3	Pipe	2	200	578.7	DUCT	8.381553	1.6	Undeveloped	0
1-4-1-4	Pipe	0	200	47	DUCT	17.5121078	1.6	Undeveloped	0
1-4-1-5	Pipe	0	200	50.5	DUCT	17.5121078	1.6	Undeveloped	0

Figure 5.13: DSSWATER: Network Components



Seg ID: 1	Xposition: 579312.3	Connect To: 0	WUser Seg: 1.32
Segment Name: Seg.1	Yposition: 4782884.5	Relation:	Seg Reliability: 0.97578
Network ID: 1	Seg Rehab Time: 1	Point: s	Seg Reliability 5: 0.97578
Rehab Method: Replace Accessorie	Package: 7	Seg Length: 34.60	Seg Reliability10: 0.99755
Seg Rehab Cost: $10,000.00	Cmp Key: 1-1-1		Seg Diam: 400

Segment Name	Component Type	Component Key	Component Break	Component Length	Component Material	Component Age	Component Diam	Component Digging Co
Seg.1	Isolation Valve	1-1-1-1	2	0	NONE	0	0	0
Seg.1	Pipe	1-1-1-2	0	5	DUCT	25.6287746	300	1.3
Seg.1	Pipe	1-1-1-3	0	29.6	UNKN	0	400	0
Seg.1	Isolation Valve	1-1-1-4	2	0	NONE	0	0	0

Figure 5.14: DSSWATER: Network Segments

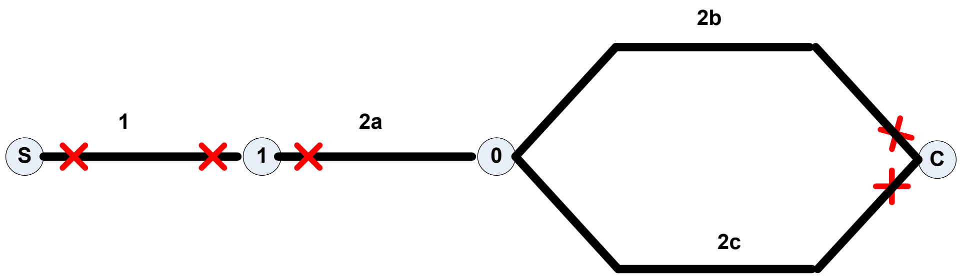


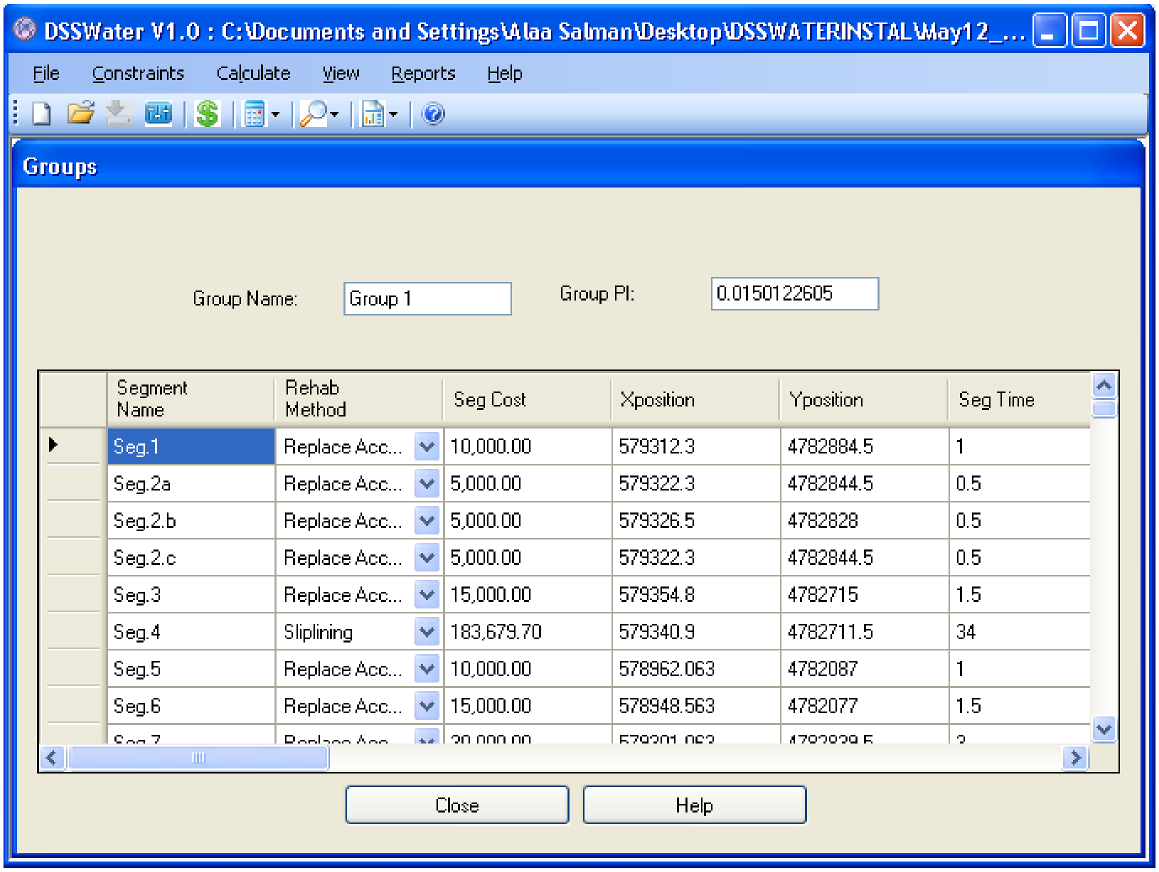
Figure 5.15: DSSWATER: Network Segments

The first segment (1) is connected to the point source (S). The second segment is divided into (2a, 2b, and 2c). 2a is connected in series with segment (1), the relation between segments (1) and (2a) can be represented by a numerical number "1". Segments 2b and 2c are connected in parallel; in addition, they are connected to the last point in the network, "0" represents the starting point of the both segments and "C" represents the last point in the network. Table 5.4 depicts the logical relations among segments of the network.

Table 5.4: Logical Relations among Segments

Segment	CompKey	connect to	Relation	Point	Note
1	1-1-1	0		S	Connect to the first point in the network
2a	1-2-1	1-1-1	1		Series connection
2b	1-2-2	1-2-1	0	C	Parallel connection &Connect to the last point in the network
2c	1-2-3	1-2-1	0	C	Parallel connection &Connect to the last point in the network

The third option in the “View” Dropdown menu is “Group”. This option depicts the collection of segments in the group with their connections and rehabilitation methods, costs, time, and location as shown in Figure 5.16.



Group Name: Group 1

Group PI: 0.0150122605

	Segment Name	Rehab Method	Seg Cost	Xposition	Yposition	Seg Time
▶	Seg.1	Replace Acc...	10,000.00	579312.3	4782884.5	1
	Seg.2a	Replace Acc...	5,000.00	579322.3	4782844.5	0.5
	Seg.2.b	Replace Acc...	5,000.00	579326.5	4782828	0.5
	Seg.2.c	Replace Acc...	5,000.00	579322.3	4782844.5	0.5
	Seg.3	Replace Acc...	15,000.00	579354.8	4782715	1.5
	Seg.4	Sliplining	183,679.70	579340.9	4782711.5	34
	Seg.5	Replace Acc...	10,000.00	578962.063	4782087	1
	Seg.6	Replace Acc...	15,000.00	578948.563	4782077	1.5

Figure 5.16: DSSWATER: Network Segments

Also in the “View” Dropdown menu, “Reliability Sensitivity” can be selected. The Reliability Sensitivity Window is depicted in Figure 5.17 to show the reliability sensitivity of the network according to three unit lengths (1m, 5m, and 10m).

The Report Dropdown menu gives access to a report which contains the final results of the three models (PI, rehabilitation selection, and scheduling) as shown in Figure 5.18. The Final dropdown menu is “Help” which gives access to a tutorial related to using DSSWATER and information about the author (5.19).

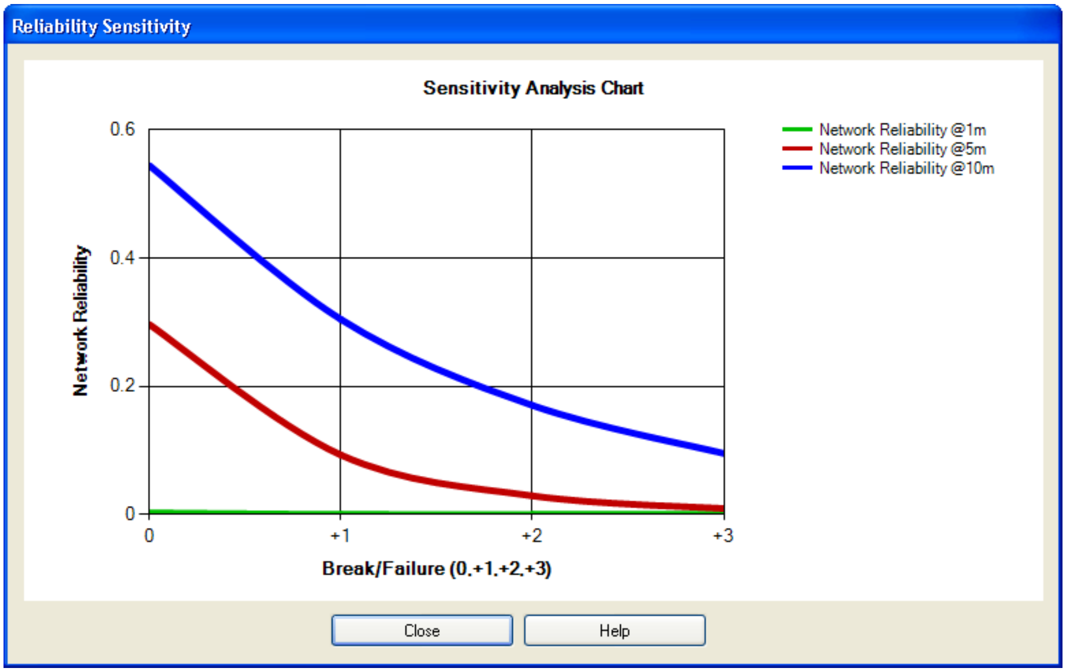
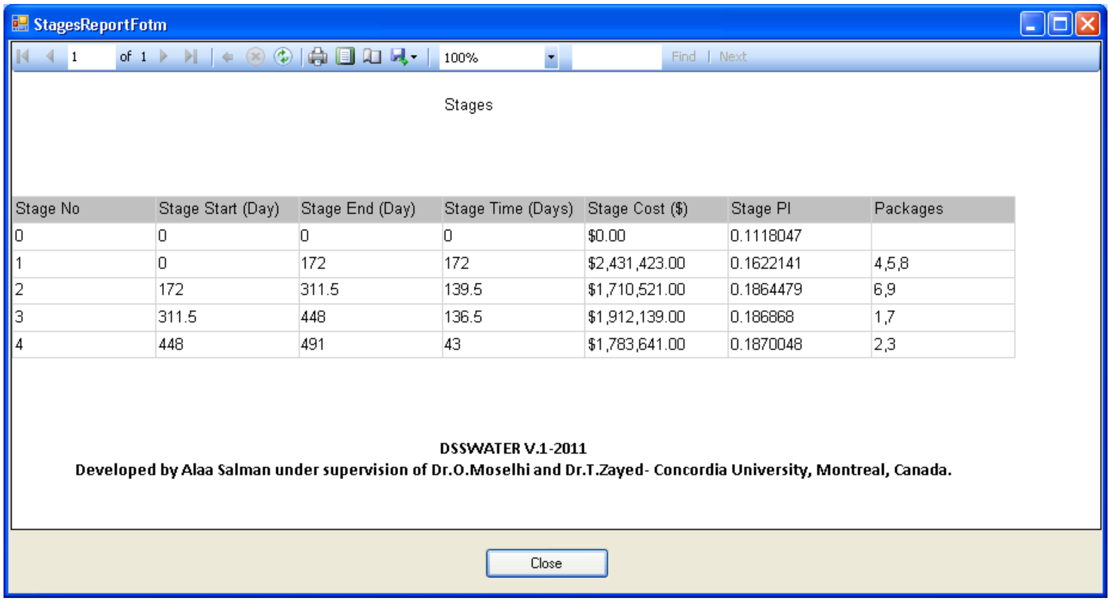


Figure 5.17: DSSWATER: Reliability Sensitivity for Checking a Unit Length

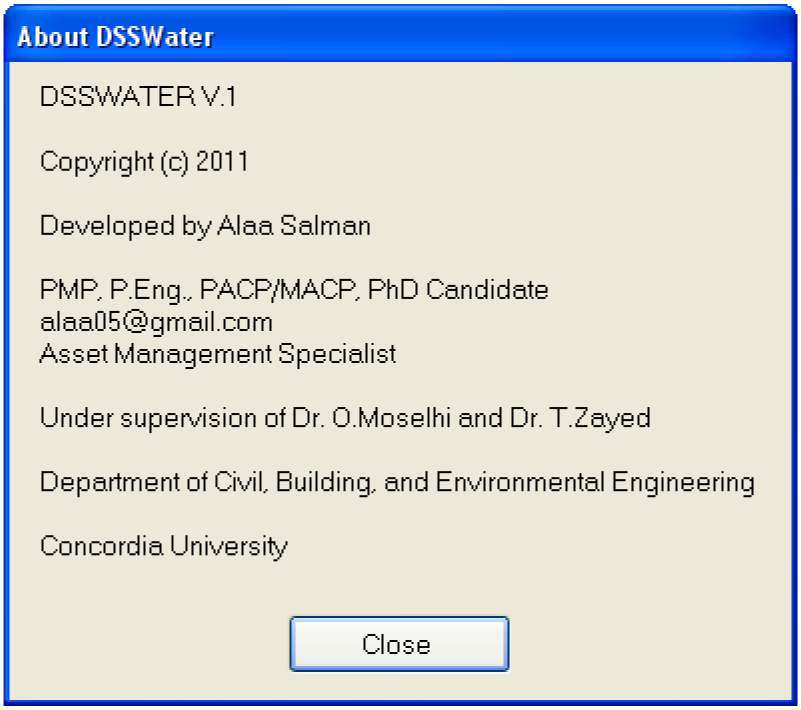


Stages

Stage No	Stage Start (Day)	Stage End (Day)	Stage Time (Days)	Stage Cost ($)	Stage PI	Packages
0	0	0	0	$0.00	0.1118047	
1	0	172	172	$2,431,423.00	0.1622141	4,5,8
2	172	311.5	139.5	$1,710,521.00	0.1864479	6,9
3	311.5	448	136.5	$1,912,139.00	0.186868	1,7
4	448	491	43	$1,783,641.00	0.1870048	2,3

DSSWATER V.1-2011
Developed by Alaa Salman under supervision of Dr.O.Moselhi and Dr.T.Zayed- Concordia University, Montreal, Canada.

Figure 5.18: DSSWATER: Report- Scheduling



DSSWATER V.1

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Figure 5.19: DSSWATER: About

5.5 Summary

This chapter presented the implementation of the proposed methodology in prototype software. Object-oriented programming is employed to implement the developed system. The system models were coded in Visual Basic and Lingo 12, utilizing Microsoft foundation classes. The user interfaces incorporated a status bar and dialog windows. Microsoft Access 2003 is employed as a database management system. The optimized scheduling is implemented as a final table that represents scheduling stages, cost, time, and PI of a network for each stage.

CHAPTER 6

Implementation of Developed Models on Case Study

6.1 Introduction

This chapter presents an application example to test and validate the development models, which were implemented in three stages. In stage one, standard spreadsheet applications, using MS-Excel, is applied to implement the extracted data from GIS software (ArcMap, 2008). The data is acquainted and formatted according to the network break down structure to be ready for use in the next stage. In the second stage, a developed automated tool (DSSWATER), which is explained in detail in Chapter 5, is used to (1) calculate reliability assessment, criticality index, and PI, and (2) rank and select rehabilitation methods. The third stage requires a decision by the user. The user in this stage has an option to proceed to the next stage directly, which consists of optimizing rehabilitation scheduling using Mixed Non Linear Integer Programming (MINLP), or dividing the network, first, into groups or sub-networks and then proceeding to optimizing rehabilitation scheduling using MINLP for each group. An Unsupervised Neural Network (UNN) was carried out using Neuroshell2 (Neuroshell-2, 1996) to cluster these data into groups according to geographical location (x, y) and rehabilitation method (which is a part of the third stage). The next section describes the application of the developed models on the distribution network of a section of the City of Hamilton.

6.2.1 Application of the PI model

i) Reliability Assessment Model

Table 6.1 depicts the collected data and reliability calculation of segment 1 in sub-network 1 as shown in Figure 6.1. Segment 1 consists of four components (i.e. two pipes and two isolation valves) as shown in column 1 of Table 6.1. It has a length of 34.60 m (summation of column 3). The two isolation valves have two failures and there are no breaks in the two pipes (column 2). The weights of network components (column 5) are normalized based on components' weights in column 4 using Equation 3.13. These weights are generated by teams of experts. Table 6.1 shows that the weights of an isolation valve, a control valve, a pipe, and a hydrant in a typical segment to be 0.28, 0.03, 0.38, and 0.31, respectively. In the depicted example, segment 1 has two isolation valves and two pipes; therefore, the total weight of segment 1 equals to 1.32. The failure rate (column 7) is calculated based on Equations 3.9, 3.10, and 3.11 using the combination of weights of failure number (column 2), segment length (column 6), and component's relative weight (column 5) . In addition, based on Equation 3.7, the reliability of the two pipes is equal to 1.0 because they do not have any breaks through their history. Applying Equation 3.7, the component reliability (column 8) of the isolation valve is 0.9878, which is the negative exponential value of the weighted average of failure rate (column 7). Considering that all components in column 1 are connected in series, the segment reliability (column 9) is equal to 0.9758, which is a product value of its component reliabilities (column 8) according to 3.14.

Table 6.1: Component and Segment Reliability

Component	**Accumulative Failure No.**	**Length (m)**	**Weight (Expert judjment)**	**Relative Weight**	**Segment Length (m)**	**Failure Rate (Failure/m)**	**Component Reliability**	**Segment Reliability**
(1)	**(2)**	**(3)**	**(4)**	**(5)=** [(4)/sum(4)]	**(6)=** [sum(4)]	**(7)=** [(5)* (2)/ (6)] **[Equations 3.9, 3.10, and 3.11]**	**(8)=** Exp.[-(7)] **[Equation 3.7]**	**(9)=** Product [(8)] **[Equation 3.14]**
I. Valve 1	2	N.A	0.28	0.21	34.60	0.0123	0.9878	0.9758
Pipe 1	0	5.00	0.38	0.29		0.0000	1.0000	
Pipe 2	0	29.60	0.38	0.29		0.000	1.0000	
I. Valve 2	2	N.A	0.28	0.21		0.0213	0.9878	
Sum.		34.60	1.32	1.00				

To determine the reliability of sub-network 1, the connections (series, parallel, series-parallel, delta, and/or, star) of its segments must be considered as shown in Figure 6.2.

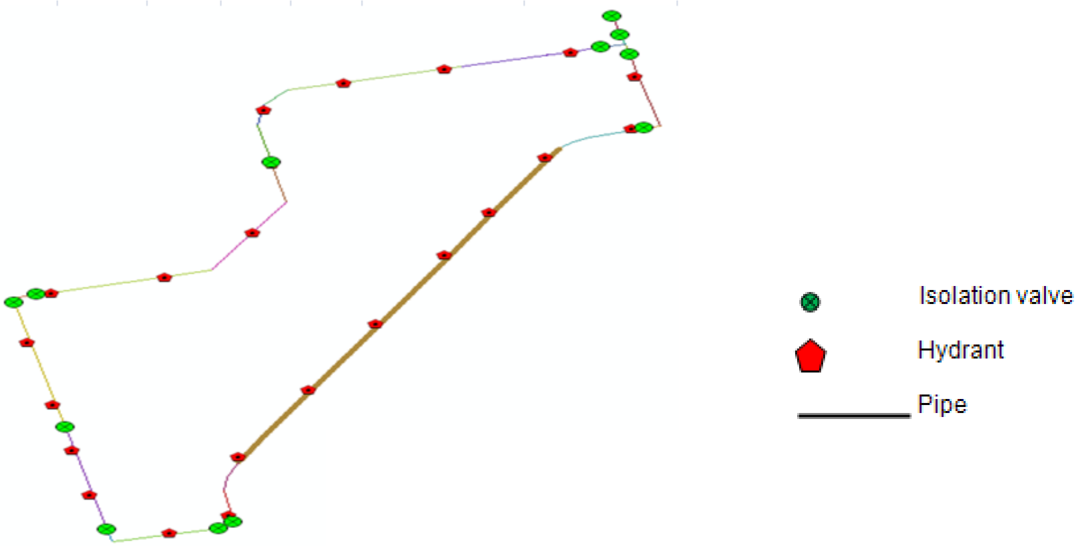


Figure 6.1: Sub-network 1- GIS Model

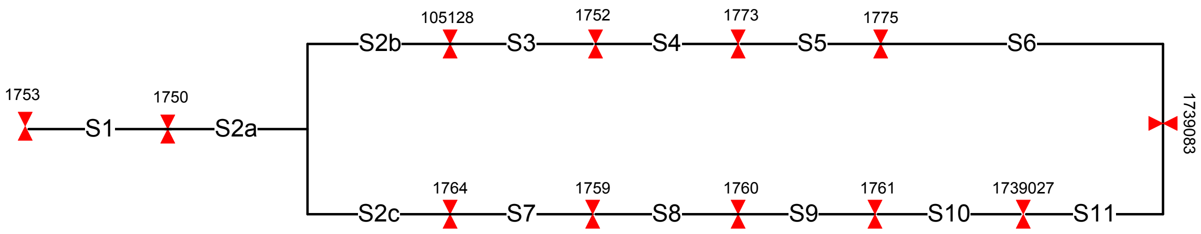


Figure 6. 2: Sub-network 1: Linear Connections

Applying the principle of series-parallel connections using on Equations 2.8 and 2.9, yields the reliability assessment of sub-network 1 equal to 0.9911. Similarly, reliability assessments of sub-networks 2, 3, and 4 were calculated to be 0.9858, 0.9914, and 0.9988, respectively. These results show that sub-network 2 has less reliability as compared to the others due to high rate of failure per meter length of its segments; however, incorporating criticality of each sub-network is necessary to consider the failure consequences of the breakage rate to get the PI of each sub-network.

ii) Sensitivity Analysis of Reliability Model(s)

Figure 6.3 depicts the sensitivity analysis for the reliability of the city distribution network using DSSWATER. The reliabilities increase when the weighted average failure rate of the components is calculated based on 5.00 m and 10.00 m segment lengths instead of 1.00 m. Sensitivity analysis was conducted to find the most suitable unit length for the entire calculations of the developed models (PI and scheduling). The cumulative number of failure (f) is expected to increase in the future, and hence the two parameters (l and f) are selected for the sensitivity analysis due to their effects on the network reliability value based on Equations 3.15 and 3.16.

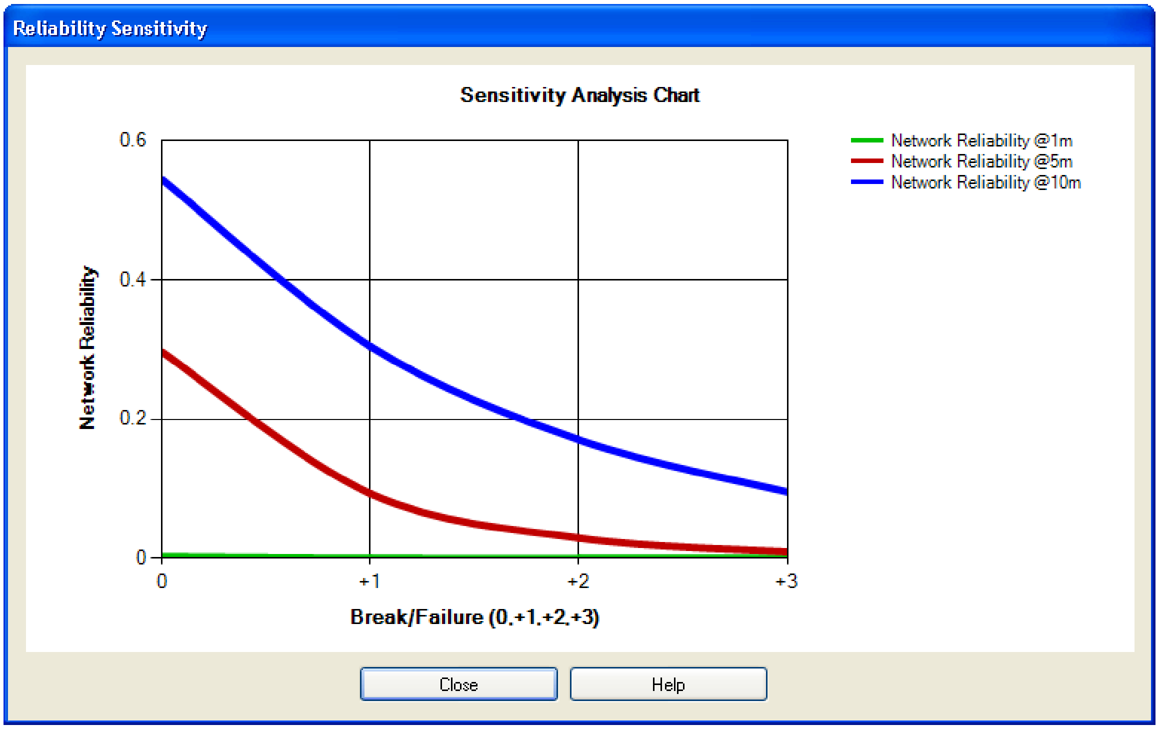


Figure 6. 3: Sensitivity Analysis of Reliability Assessment

In the current results, a 10.0 m length gives a sufficient range of network reliability between 0.10-0.55; while 1.0 m and 5.0 m lengths result in a small range which is not easy to recognize. Therefore, a length of 10.0 m is selected in the present study.

iii) Criticality Index Model

As mentioned in Chapter 3, the overall criticality index of a pipe is the weighted average of the four categories: economic, operational, social, and environmental. Tables 6.2, 6.3, and 6.4 illustrate criticality index data and calculation including scores, weights, and results of CI application. Segment 1 is composed of two pipes that are located in two different land uses. The first pipe is located in undeveloped land and the second is located in commercial/industrial land as depicted in Table 6.2. The scores of the two pipe attributes are considered low ("0.01" - "0.25"). The maximum scores for both pipes are "0.25" due to the "Water Body Proximity" factor (i.e. the two pipes are located within 10m of the lake). The weights of the two pipes are obtained using AHP according to their land uses, (see Table 6.3). Critical location factors of the first and second pipes are 0.18 and 0.56, respectively. This result reflects the point view of the asset management team of the City of Hamilton, who assigned the pair wise comparison of the AHP process for each land use.

Table 6.2: Criticality Data of segment 1

Critical Factor	Pipe 1	Pipe 2
Diameter (mm)	300	400
Depth (m)	1.30	0.00
Pipe Type	Ductile	Unknown
Land Use	Undeveloped	Commercial/Industrial
Low Accessibility	0	0
Road Type	Other	Other
Critical Location	0	0
Water Body Proximity (m)	10	10
No Diversion	0	0
Environment Sensitive	0	0

In fact, this result is considered logical as the location of the comm./ind. land is more critical than that of undeveloped land. The other factor weights that are depicted in Table 6.3 show the differences of the critical factors based on land use.

Table 6.3: Criticality Factor Weights

Category	Factor	UMA (2007) (Expert opinion)	Developed model: AHP with respect to land use			
			Com./Indus.	Residential	Park	Undeveloped / Other
Economic	Pipe size (mm)	0.25	0.31	0.20	0.19	0.20
	Depth (m)	0.25	0.22	0.26	0.25	0.26
	Pipe material	0.16	0.16	0.14	0.16	0.11
	Land use	0.17				
	Low accessibility	0.17	0.31	0.40	0.39	0.43
Operational	Critical location	0.60	0.56	0.48	0.12	0.18
	Pipe type	0.20	0.17	0.24	0.23	0.27
	Discharged (mm)	0.20	0.27	0.27	0.65	0.55
Social	Public Disruption	0.60				
	Road Type	0.40	0.20	0.25	0.25	0.25
	No Diversion	0.60	0.30	0.25	0.25	025
	Visibility	0.40				
	Pipe size (mm)	0.75	0.50	0.50	0.50	0.50
	Land use	0.25				
Environmental	Water Body Proximity (m)	0.50	0.22	0.28	0.20	0.21
	Locality	0.30	0.28	0.28	0.45	0.43
	Affected diameter (mm)	0.20	0.50	0.44	0.35	0.35

In order to calculate the overall criticality index of pipes 1 and 2, Equation 3.17 is applied as an application of SMART method which yields overall criticality scores of 0.050 and 0.041, for pipes 1 and 2, respectively as shown in Table 6.4. Using Equation 3.18, the criticality of segment 1 (CI_1) is determined to be equal to 0.045, which is considered not critical. Hence, this result shows segment 1 has few consequences of failure and recovery of its components after a failure can be done with less effort.

Table 6.4: Criticality of Segment 1, Sub-network 1

Pipe#	Pipe 1					Pipe 2				
Land Use	Undeveloped					Commercial/Industrial				
Categories / Factors	Economic Weight	Operational Weight	Social Weight	Environment Weight	Factor Score	Economic Weight	Operational Weight	Social Weight	Environment Weight	Factor Score
Category Weight	0.22	0.29	0.20	0.29	NA	0.26	0.21	0.32	0.21	NA
Diameter	0.20	0.55	0.50	0.35	0.05	0.31	0.27	0.4	0.50	0.05
Depth	0.26	NA	NA	NA	0.01	0.22	NA	NA	NA	0.01
Pipe Type	0.11	0.27	NA	NA	0.10	0.16	0.17	NA	NA	0.01
Low Accessibility	0.43	NA	NA	NA	0.01	0.31	NA	NA	NA	0.01
Road Type	NA	NA	0.25	NA	0.01	NA	NA	0.25	NA	0.01
Critical Location	NA	0.18	NA	NA	0.01	NA	0.56	NA	NA	0.01
Water Body	NA	NA	NA	0.21	0.25	NA	NA	NA	0.22	0.25
No Diversion	NA	NA	0.25	NA	0.01	NA	NA	0.35	NA	0.01
Environment	NA	NA	NA	0.43	0.01	NA	NA	NA	0.28	0.01
CRITICALITY (Equation 2.18)	0.0279	0.0536	0.030	0.0743		0.0224	0.0208	0.0260	0.0828	
Overall Criticality (Equation 3.17)	0.0500					0.0410				
Segment Criticality (Equation 3.18)	0.0445									
Segment Un-Criticality [1-(Equation 3.18)]	0.9555									

vi) PI

The PI of segment 1, which is a multiplication of reliability (R) assessment and un-criticality index (1.0 – CI_1), is equal to 0.9314 based on Equation 3.3. The PI value of segment 1 is very high due to its high value of reliability assessment (0.9785) and low value of criticality index (0.045). This result gives a chance for other segments that have lower PI values in the distribution network to be rehabilitated. In addition, a manager might consider this result for implementing a maintenance program by giving a priority for other segments in the network that have lower PIs. Similarly, the PI of other segments on sub-network 1 are calculated. The PI of sub-network 1 is equal to 0.7219 using the principle of series-connection (see Figure 6.3). Similar to sub-network 1, the PI of sub-networks 2, 3, and 4 are 0.9280, 0.8709, and 0.7633, respectively. Figure 6.4 depicts the final results of PIs compared to reliability indices of the four sub-networks. As a result, sub-network 1, which is located in an undeveloped zone, has the lowest PI. Obtaining PIs of the city's sub-networks including the calculated four sub-networks is a crucial step toward efficiently managed budget allocation and scheduling of rehabilitation work in the city.

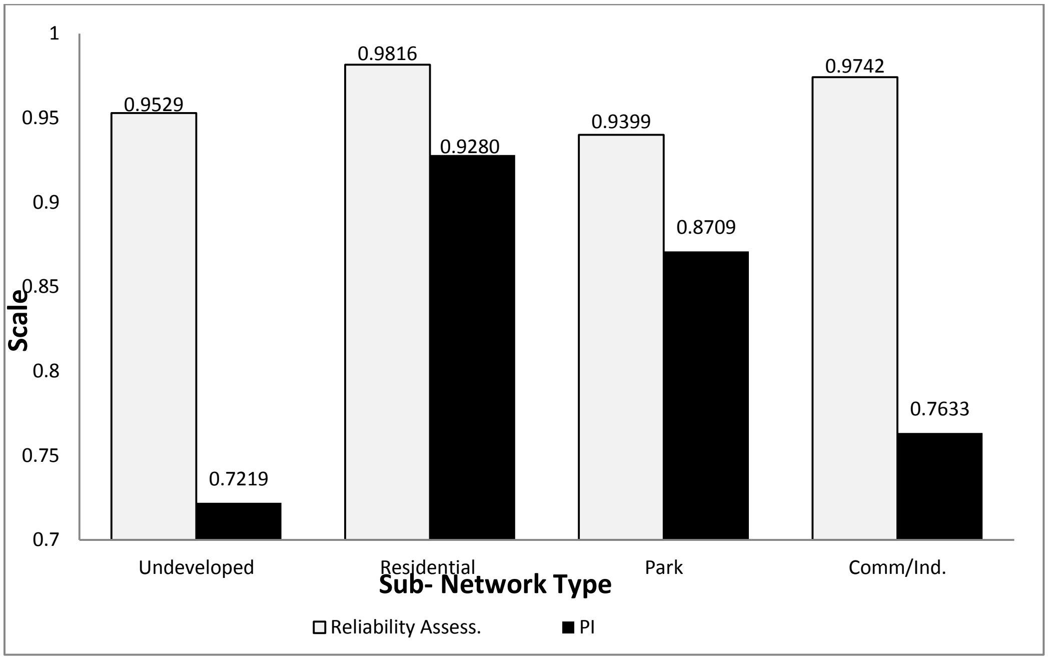


Figure 6.4: Reliability Assessment (R) vs. PI

6.2.2 Application of the Rehabilitation Selection Model

Pipe number 2 which is located in segment 4 (sub-network 1) has 2 breaks since its construction. To determine the most suitable method of rehabilitation, Table 6.5 depicts the ranking of rehabilitation methods using SMART technique (described in Chapter 3) on six rehabilitation methods (open cut, pipe bursting, HDD, micro-tunnelling, CIIP, and sliplining). These methods are considered technically feasible and contractually acceptable. In addition, three criteria are utilized to rank these methods as discussed earlier in Section 3.4; namely cost, environmental impact, and experiment with new technologies. The two parameters in Equation 3.21 are the weights of the criteria, which are considered generic, and the scores of the criteria are based on each rehabilitation method. It should be noted that the weights of the criteria were determined by three teams of experts. In the case study, the weights of rehabilitation cost, impact on environment (IoE), and the use of experimental new technology are 0.4, 0.4, and 0.2, respectively. The scores of these criteria were also established by the three teams of experts. The impact on environment (IoE) is obtained using a simple scale (1-9) where 1.0 represents a minimum impact on the surrounding environment caused by the rehabilitation method being considered; while 9.0 represents a maximum impact. The use of experimental new technologies, which is subjective, is determined according to the experience of the user. A scale of (1-9) is also used where 1.0 represents the lowest level of confidence in the rehabilitation method, and 9.0 depict the highest level of confidence. The final value of the total utility of each rehabilitation method is determined by multiplying the weight by the score of each factor as shown in Table 6.5.

A final rehabilitation ranking (Figure 6.5) shows that “sliplining” is preferred versus other rehabilitation methods. However, the total utility values of Sliplining, CIPP, Pipe Bursting, and HDD have close values. These results can assist decision makers in selecting the most suitable rehabilitation method(s) for a network as explained in Section 3.4.

Table 6.5: Ranking of Rehabilitation Methods

Rehab. Method	Weight						**Total Utility**	**Ranking**
	0.4		0.4		0.2			
	Cost [$] (user)	**1-9 (developed)**	Impact on Environment 1-9 (user)	**1-9 (developed)**	Experiment new Technologies 1-9 (user)	**1-9 (developed)**		
Open Cut	1,339,112	**6.2**	5.00	**1.00**	1.00	**1.00**	**3.08**	**6**
Pipe Bursting	674,186	**8.63**	3.00	**9.00**	5.00	**9.00**	**8.85**	**3**
HDD	1,036,452	**7.30**	3.00	**9.00**	5.00	**9.00**	**8.32**	**4**
Microtunneling	2,760,399	**1.00**	3.00	**9.00**	5.00	**9.00**	**5.80**	**5**
CIPP	607,290	**8.87**	3.00	**9.00**	5.00	**9.00**	**8.95**	**2**
Sliplining	571,756	**9.00**	3.00	**9.00**	5.00	**9.00**	**9.00**	**1**

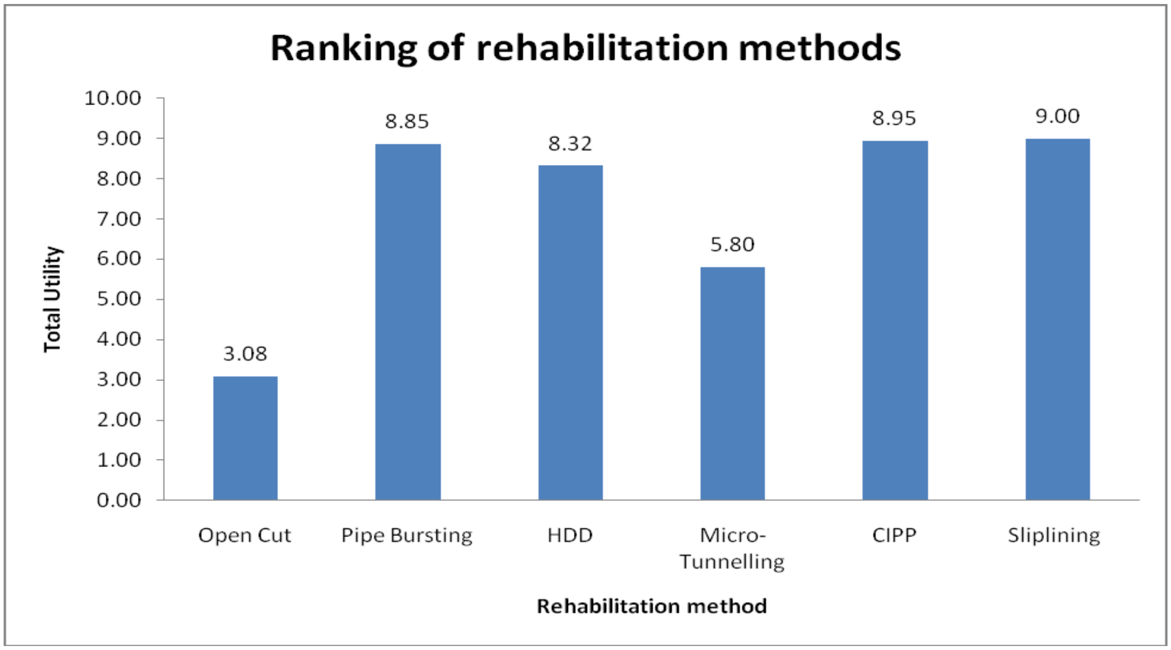


Figure 6.5: Ranking of Rehabilitation Methods

6.4 Application of the Scheduling Model

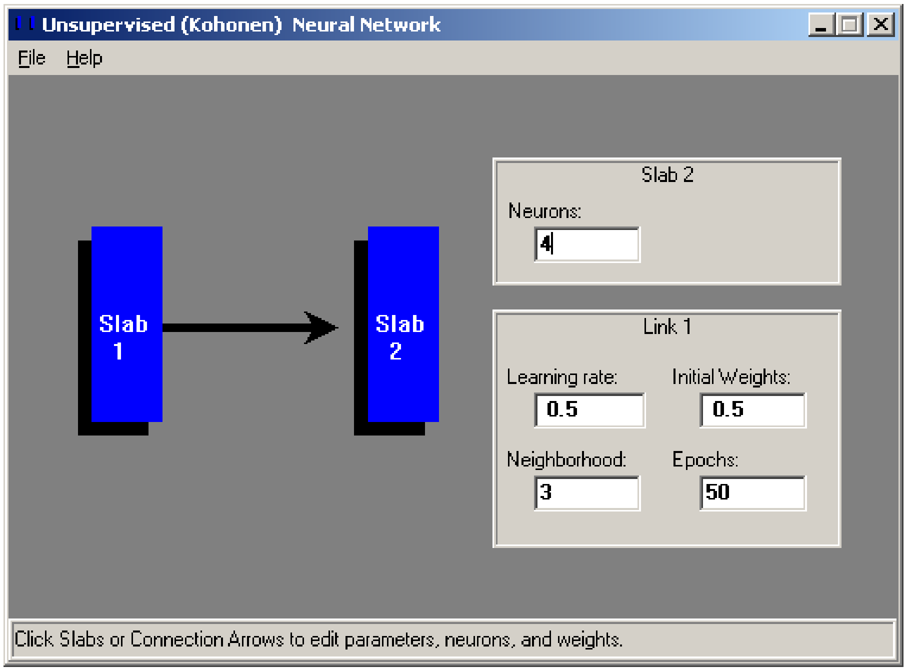
6.4.1 Unsupervised Neural Network (UNN)

The developed UNN was applied to a hypothetical large network to test it. The network was constructed using the four sub-networks referred earlier in Section 4.2.2. The four sub-networks were utilized in a fashion that would form a large network as shown in Figure 6.6. This was carried out by duplicating these sub-networks and subsequently connecting them.

The configuration was repeated and distributed to the area of the City of Hamilton as an assumption to allow for the use of the UNN application. The network integrates two of the undeveloped zones, six residential zones, three park zones, and four commercial/industrial zones.

Figure 6.6: UNN Application

NeuroShell-2 is used in the clustering process. It is easy to use, flexible, and commercially available. The main purpose of the clustering is to divide the water network segments into groups based on the geographic location and selected rehabilitation method of their respective segments. The UNN structure includes two layers as shown in Figure 6.7; input (Slab 1) and the output (Slab 2) only. The input variables (Slab 1) are segment ID, rehabilitation type, X, and, Y coordinates of each segment in the original four sub-networks and the 11 artificially generated sub-networks. The numerical ID of a segment is chosen based on the network number and its segment number (e.g. the ID of segment 1 of sub-network 1 is 11; while the ID of segment number 5 of sub-network 10 is 510). The numerical ID method should be avoided when numbers of sub-networks and/or their segments are very high due to the conflict between sub-network numbers and segment numbers. However, it is used in this case study to make it easier for the reader to follow.



Slab 2

Neurons: 4

Link 1

Learning rate: 0.5

Initial Weights: 0.5

Neighborhood: 3

Epochs: 50

Click Slabs or Connection Arrows to edit parameters, neurons, and weights.

Figure 6.7: UNN Structure- NeuroShell-2

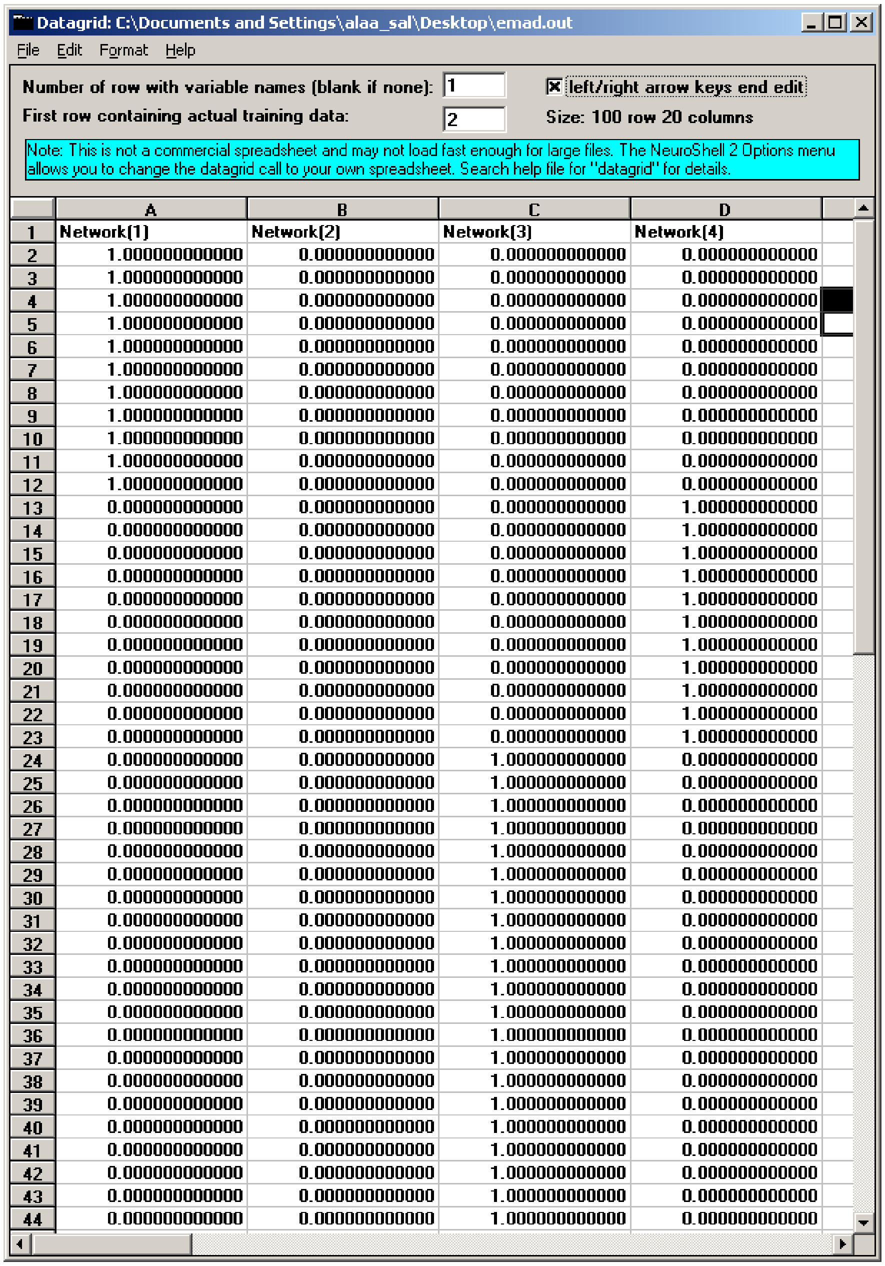
Segment ID 111 is used in sub-network 1 and 11, but it can be recognized easily based on the X and Y coordinates. Table 6.6 depicts the segment ID, which was used as input (Slab 1) for the UNN method. The 15 sub-networks were entered sequentially; starting from sub-network 1, segment 1 to the sub-network 15, segment 6. The second input is the rehabilitation method of a segment. It is obtained from the rehabilitation selection model, which is described in Section 6.2.2. The selected method of a segment is based on total cost of rehabilitation, impact on environment, and trial use of new technologies. The third and fourth input of the Slab 1 is the X and Y coordinates. They can be obtained using the GIS standard functions. The four parameters of the Slab 1 were used to cluster the water distribution network into groups.

The user can identify the number of groups that will be generated by the UNN by entering the number of Neurons (groups) as depicted in Figure 6.7. In addition, the user can identify the learning rate, initial weights, neighbourhood, and Epochs. The learning rate was set equal to the default value of 0.5, which means that the weight change is one half the errors (NeuroShell, 1996).

The data was generated by NeroShell into the data grid and the yes/no output indicates whether each segment is in one of the four groups or not (1 signifies “yes” and 0 signifies “no”). Training for this Kohonen network proceeds quite differently than training in a backpropagation network. It should be noted that the number of learning epochs and neighbourhood size decrease as training progresses.

Table 6.6: UNN Input- Segment ID

Sub-network	Seg.	Seg.ID	Sub-network	Seg.	Seg.ID	Sub-network	Seg.	Seg.ID
Undev.1	Seg.1-Undev.1	11	Res.3	Seg.3-Res.3	53	Park 2	Seg.3-Park2	103
Undev.1	Seg.2-Undev.1	12	Res.3	Seg.4-Res.3	54	Park 2	Seg.4-Park2	104
Undev.1	Seg.3-Undev.1	13	Res.3	Seg.5-Res.3	55	Park 2	Seg.5-Park2	105
Undev.1	Seg.4-Undev.1	14	Res.3	Seg.6-Res.3	56	Park 2	Seg.6-Park2	106
Undev.1	Seg.5-Undev.1	15	Res.3	Seg.7-Res.3	57	Park 2	Seg.7-Park2	107
Undev.1	Seg.6-Undev.1	16	Res.3	Seg.8-Res.3	58	Park 2	Seg.8-Res2	108
Undev.1	Seg.7-Undev.1	17	Res.4	Seg.1-Res.4	61	Park 3	Seg.1-Park3	111
Undev.1	Seg.8-Undev.1	18	Res.4	Seg.2-Res.4	62	Park 3	Seg.2-Park3	112
Undev.1	Seg.9-Undev.1	19	Res.4	Seg.3-Res.4	63	Park 3	Seg.3-Park3	113
Undev.1	Seg.10-Undev.1	110	Res.4	Seg.4-Res.4	64	Park 3	Seg.4-Park3	114
Undev.1	Seg.11-Undev.1	111	Res.4	Seg.5-Res.4	65	Park 3	Seg.5-Park3	115
Undev.2	Seg.1-Undev.2	21	Res.4	Seg.6-Res.4	66	Park 3	Seg.6-Park3	116
Undev.2	Seg.2-Undev.2	22	Res.4	Seg.7-Res.4	67	Park 3	Seg.7-Park3	117
Undev.2	Seg.3-Undev.2	23	Res.4	Seg.8-Res.4	68	Park 3	Seg.8-Park3	118
Undev.2	Seg.4-Undev.2	24	Res.5	Seg.1-Res.5	71	Com&Ind. 1	Seg.1-Com&Ind. 1	121
Undev.2	Seg.5-Undev.2	25	Res.5	Seg.2-Res.5	72	Com&Ind. 1	Seg.2-Com&Ind.1	122
Undev.2	Seg.6-Undev.2	26	Res.5	Seg.3-Res.5	73	Com&Ind. 1	Seg.3-Com&Ind.1	123
Undev.2	Seg.7-Undev.2	27	Res.5	Seg.4-Res.5	74	Com&Ind. 1	Seg.4-Com&Ind.1	124
Undev.2	Seg.8-Undev.2	28	Res.5	Seg.5-Res.5	75	Com&Ind. 1	Seg.5-Com&Ind.1	125
Undev.2	Seg.9-Undev.2	29	Res.5	Seg.6-Res.5	76	Com&Ind. 1	Seg.6-Com&Ind.1	126
Undev.2	Seg.10-Undev.2	210	Res.5	Seg.7-Res.5	77	Com&Ind. 2	Seg.1-Com&Ind.2	131
Undev.2	Seg.11-Undev.2	211	Res.5	Seg.8-Res.5	78	Com&Ind. 2	Seg.2-Com&Ind.2	132
Res.1	Seg.1-Res.1	31	Res.6	Seg.1-Res.6	81	Com&Ind. 2	Seg.3-Com&Ind.2	133
Res.1	Seg.2-Res.1	32	Res.6	Seg.2-Res.6	82	Com&Ind. 2	Seg.4-Com&Ind.2	134
Res.1	Seg.3-Res.1	33	Res.6	Seg.3-Res.6	83	Com&Ind. 2	Seg.5-Com&Ind.2	135
Res.1	Seg.4-Res.1	34	Res.6	Seg.4-Res.6	84	Com&Ind. 2	Seg.6-Com&Ind.2	136
Res.1	Seg.5-Res.1	35	Res.6	Seg.5-Res.6	85	Com&Ind. 3	Seg.1-Com&Ind.3	141
Res.1	Seg.6-Res.1	36	Res.6	Seg.6-Res.6	86	Com&Ind. 3	Seg.2-Com&Ind.3	142
Res.1	Seg.7-Res.1	37	Res.6	Seg.7-Res.6	87	Com&Ind. 3	Seg.3-Com&Ind.3	143
Res.1	Seg.8-Res.1	38	Res.6	Seg.8-Res.6	88	Com&Ind. 3	Seg.4-Com&Ind.3	144
Res.2	Seg.1-Res.2	41	Park 1	Seg.1-Park 1	91	Com&Ind. 3	Seg.5-Com&Ind.3	145
Res.2	Seg.2-Res.2	42	Park 1	Seg.2-Park1	92	Com&Ind. 3	Seg.6-Com&Ind.3	146
Res.2	Seg.3-Res.2	43	Park 1	Seg.3-Park1	93	Com&Ind. 4	Seg.1-Com&Ind.4	151
Res.2	Seg.4-Res.2	44	Park 1	Seg.4-Park1	94	Com&Ind. 4	Seg.2-Com&Ind.4	152
Res.2	Seg.5-Res.2	45	Park 1	Seg.5-Park1	95	Com&Ind. 4	Seg.3-Com&Ind.4	153
Res.2	Seg.6-Res.2	46	Park 1	Seg.6-Park1	96	Com&Ind. 4	Seg.4-Com&Ind.4	154
Res.2	Seg.7-Res.2	47	Park 1	Seg.7-Park1	97	Com&Ind. 4	Seg.5-Com&Ind.4	155
Res.2	Seg.8-Res2	48	Park 1	Seg.8-Park1	98	Com&Ind. 4	Seg.6-Com&Ind.4	156
Res.3	Seg.1-Res.3	51	Park 2	Seg.1-Park2	101			
Res.3	Seg.2-Res.3	52	Park 2	Seg.2-Park2	102			



Number of row with variable names (blank if none): 1

First row containing actual training data: 2

☒ left/right arrow keys end edit

Size: 100 row 20 columns

Note: This is not a commercial spreadsheet and may not load fast enough for large files. The NeuroShell 2 Options menu allows you to change the datagrid call to your own spreadsheet. Search help file for "datagrid" for details.

	A	B	C	D
1	Network(1)	Network(2)	Network(3)	Network(4)
2	1.000000000000	0.000000000000	0.000000000000	0.000000000000
3	1.000000000000	0.000000000000	0.000000000000	0.000000000000
4	1.000000000000	0.000000000000	0.000000000000	0.000000000000
5	1.000000000000	0.000000000000	0.000000000000	0.000000000000
6	1.000000000000	0.000000000000	0.000000000000	0.000000000000
7	1.000000000000	0.000000000000	0.000000000000	0.000000000000
8	1.000000000000	0.000000000000	0.000000000000	0.000000000000
9	1.000000000000	0.000000000000	0.000000000000	0.000000000000
10	1.000000000000	0.000000000000	0.000000000000	0.000000000000
11	1.000000000000	0.000000000000	0.000000000000	0.000000000000
12	1.000000000000	0.000000000000	0.000000000000	0.000000000000
13	0.000000000000	0.000000000000	0.000000000000	1.000000000000
14	0.000000000000	0.000000000000	0.000000000000	1.000000000000
15	0.000000000000	0.000000000000	0.000000000000	1.000000000000
16	0.000000000000	0.000000000000	0.000000000000	1.000000000000
17	0.000000000000	0.000000000000	0.000000000000	1.000000000000
18	0.000000000000	0.000000000000	0.000000000000	1.000000000000
19	0.000000000000	0.000000000000	0.000000000000	1.000000000000
20	0.000000000000	0.000000000000	0.000000000000	1.000000000000
21	0.000000000000	0.000000000000	0.000000000000	1.000000000000
22	0.000000000000	0.000000000000	0.000000000000	1.000000000000
23	0.000000000000	0.000000000000	0.000000000000	1.000000000000
24	0.000000000000	0.000000000000	1.000000000000	0.000000000000
25	0.000000000000	0.000000000000	1.000000000000	0.000000000000
26	0.000000000000	0.000000000000	1.000000000000	0.000000000000
27	0.000000000000	0.000000000000	1.000000000000	0.000000000000
28	0.000000000000	0.000000000000	1.000000000000	0.000000000000
29	0.000000000000	0.000000000000	1.000000000000	0.000000000000
30	0.000000000000	0.000000000000	1.000000000000	0.000000000000
31	0.000000000000	0.000000000000	1.000000000000	0.000000000000
32	0.000000000000	0.000000000000	1.000000000000	0.000000000000
33	0.000000000000	0.000000000000	1.000000000000	0.000000000000
34	0.000000000000	0.000000000000	1.000000000000	0.000000000000
35	0.000000000000	0.000000000000	1.000000000000	0.000000000000
36	0.000000000000	0.000000000000	1.000000000000	0.000000000000
37	0.000000000000	0.000000000000	1.000000000000	0.000000000000
38	0.000000000000	0.000000000000	1.000000000000	0.000000000000
39	0.000000000000	0.000000000000	1.000000000000	0.000000000000
40	0.000000000000	0.000000000000	1.000000000000	0.000000000000
41	0.000000000000	0.000000000000	1.000000000000	0.000000000000
42	0.000000000000	0.000000000000	1.000000000000	0.000000000000
43	0.000000000000	0.000000000000	1.000000000000	0.000000000000
44	0.000000000000	0.000000000000	1.000000000000	0.000000000000

Figure 6.8: UNN Output- NeuroShell-2

Figure 6.8 depicts the output of the NeuroShell-2 and Figure 6.9 shows a summary of UNN results. The vertical axis indicates the number of segments and the horizontal represents the four groups.

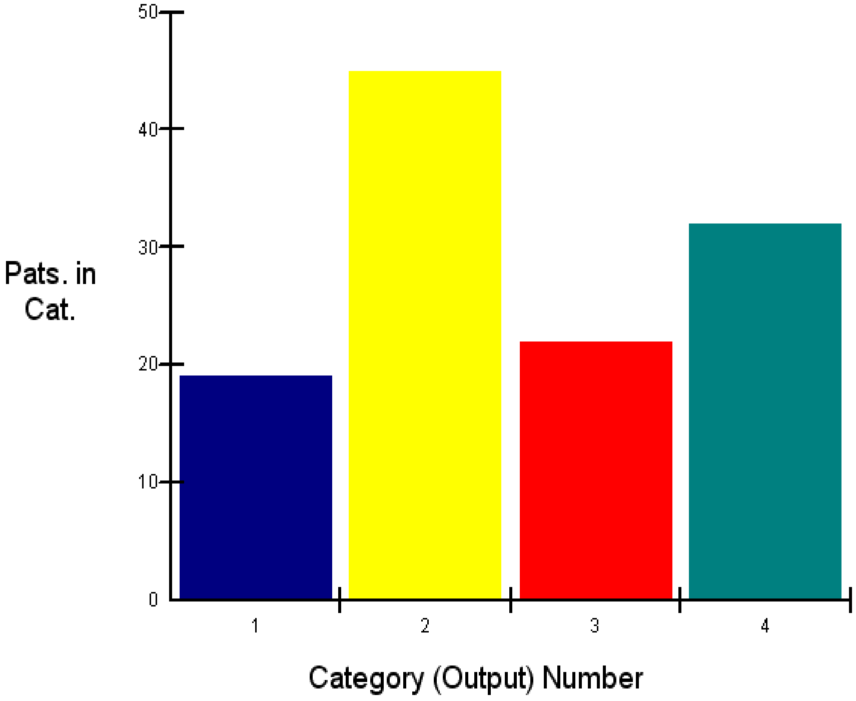
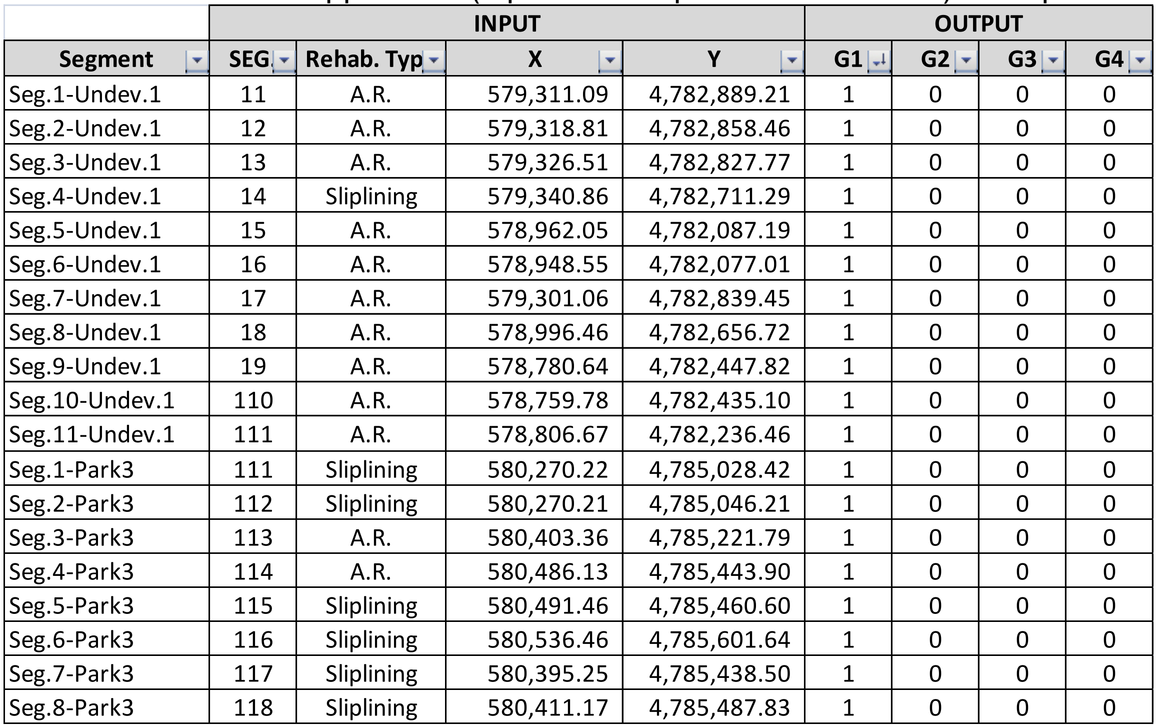


Figure 6.9: UNN Summary of Final Results- NeuroShell-2

Table 6.7 depicts the input and the output of the UNN- group 1. The input is rehabilitation methods, locations (x,y) of segments and number of groups, which is assumed to be four. The result is binary with either “0” representing a segment that is not within this group or “1”, representing a segment that is within this group.

The output shows the individual segments clustered within each of the four groups. The four groups represent four geographical zones which are easy to be monitored and controlled. This process is necessary to form the rehabilitation work packages in the second stage. Each group contains several segments with different rehabilitation methods. Also, the total cost of rehabilitation of all segments in groups can’t be monitored and controlled easily. As such, dividing the four groups into small groups or rehabilitation work packages (WPs) makes the process of monitoring and controlling more efficient in since scheduling can be completed based on the developed work packages instead of scheduling individual segments. Each group is divided into work packages according to the rehabilitation method and with respect to the minimum and maximum values identified by the user.

Table 6.7: UNN Application (Input and Output of Neuroshell 2): Group 1



	INPUT				OUTPUT			
Segment	SEG	Rehab. Typ	X	Y	G1	G2	G3	G4
Seg.1-Undev.1	11	A.R.	579,311.09	4,782,889.21	1	0	0	0
Seg.2-Undev.1	12	A.R.	579,318.81	4,782,858.46	1	0	0	0
Seg.3-Undev.1	13	A.R.	579,326.51	4,782,827.77	1	0	0	0
Seg.4-Undev.1	14	Sliplining	579,340.86	4,782,711.29	1	0	0	0
Seg.5-Undev.1	15	A.R.	578,962.05	4,782,087.19	1	0	0	0
Seg.6-Undev.1	16	A.R.	578,948.55	4,782,077.01	1	0	0	0
Seg.7-Undev.1	17	A.R.	579,301.06	4,782,839.45	1	0	0	0
Seg.8-Undev.1	18	A.R.	578,996.46	4,782,656.72	1	0	0	0
Seg.9-Undev.1	19	A.R.	578,780.64	4,782,447.82	1	0	0	0
Seg.10-Undev.1	110	A.R.	578,759.78	4,782,435.10	1	0	0	0
Seg.11-Undev.1	111	A.R.	578,806.67	4,782,236.46	1	0	0	0
Seg.1-Park3	111	Sliplining	580,270.22	4,785,028.42	1	0	0	0
Seg.2-Park3	112	Sliplining	580,270.21	4,785,046.21	1	0	0	0
Seg.3-Park3	113	A.R.	580,403.36	4,785,221.79	1	0	0	0
Seg.4-Park3	114	A.R.	580,486.13	4,785,443.90	1	0	0	0
Seg.5-Park3	115	Sliplining	580,491.46	4,785,460.60	1	0	0	0
Seg.6-Park3	116	Sliplining	580,536.46	4,785,601.64	1	0	0	0
Seg.7-Park3	117	Sliplining	580,395.25	4,785,438.50	1	0	0	0
Seg.8-Park3	118	Sliplining	580,411.17	4,785,487.83	1	0	0	0

Note: A.R= Accessory replacement

Figure 6.10 shows group1 which includes several segments. The segments are located into two different sub-networks. Groups two, three, and four are constructed. Similarly, it is assumed that the four groups are connected in series to simplify the calculation. The limiting values (minimum and maximum cost) of a work package can be defined by a user; however default values ($100,000-$1,000,000) are made particularly for the case study to determine the work packages using DSSWATER as shown in Figure 6.11. The limiting values can be provided according to the need of a city and capacity of local contractors. Therefore, the default values of work packages can be changed for other cities.

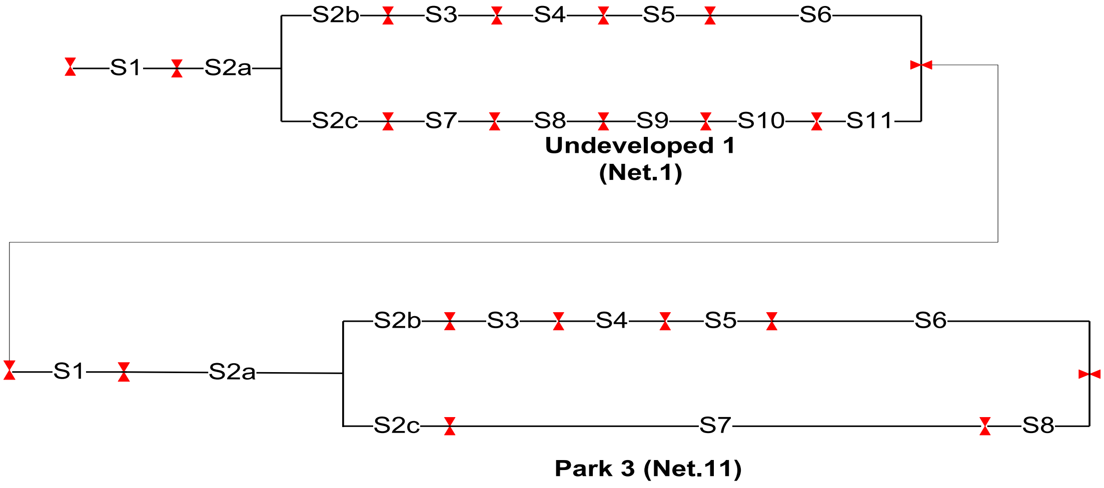
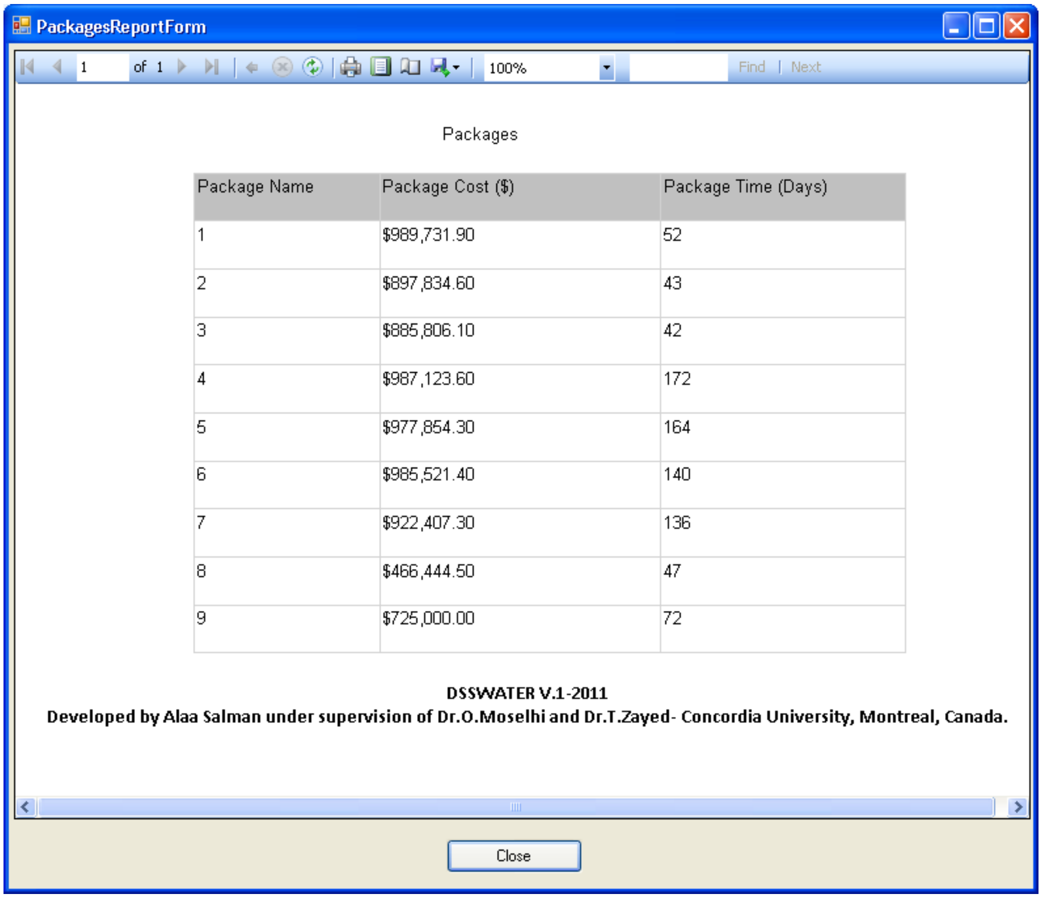


Figure 6.10: Group 1- Linear Connections



Packages

Package Name	Package Cost ($)	Package Time (Days)
1	$989,731.90	52
2	$897,834.60	43
3	$885,806.10	42
4	$987,123.60	172
5	$977,854.30	164
6	$985,521.40	140
7	$922,407.30	136
8	$466,444.50	47
9	$725,000.00	72

DSSWATER V.1-2011
Developed by Alaa Salman under supervision of Dr.O.Moselhi and Dr.T.Zayed- Concordia University, Montreal, Canada.

Figure 6.11: Resulted Rehabilitation Work Packages

Based on the input provided, the developed computer system identified nine packages as shown in Figure 6.11.

6.4.2 Schedule Optimization Model

After deciding on the work packages, the developed MINLP model is then applied using Lingo 12 (Lingo, 2011) to determine the optimum schedule for the nine work packages. The objective is to maximize the PI of the city's water distribution network respecting the maximum contract price of rehabilitation and planning time, which are assumed to be $2,500,000 and 720 days, respectively.

Figure 6.12 depicts the results of the scheduling model. The work packages are phased over four time periods with total cost and time of $ 7,837,724.00 and 491 days, respectively. The optimum scheduling starts with rehabilitation packages 4, 5, and 8 (sliplining). The PI of the city's network increases after rehabilitation Period 1 from 0.111805 to 0.162214 according to the Equations 3.23 and 3.24. The cost and time of rehabilitation period 1 are $2,431,423 and 172 days, respectively, which are within the time and cost constraints/limits based on Equations 3.30 and 3.32 respectively. Rehabilitation period 2 includes the rehabilitation of packages 6 and 9 using sliplining and accessory replacement. The PI increases after rehabilitation Period 2 from 0.162214 to 0.186448. The cost and time of rehabilitation of Rehabilitation period 2 are $ 1,710,521 and 139.5 days, respectively, which are within the cost and time constraints/limits as well. As a result of rehabilitation of the nine packages, the maximum value of PI reaches 0.187005.

The improvement of PI for the city's distribution network is due to the increase of the reliability values of all segments that are within the nine work packages. While the reliability values increase, the criticality of these segments remains the same; it is assumed that the pipe properties such as material, diameter, depth, etc. will not be changed after rehabilitation.

6.4.3 Sensitivity Analysis

Tables 6.8 and 6.9 summarize supplemental information that is useful in the sensitivity analysis of the generated schedule model. Packages 2 and 3 are performed to complete the scheduling proces and to maximize the PI of the water distribution network of the city, (e.g. PI reached to 0.187 as shown in Table 6.9 and in Figure 6.12). Package 2 includes three water segments (127, 131, and 133); while package 3 includes two water segments (137 and 143). In the sensitivity analysis, a closer look is given to reduced cost, slack, and dual price. These indicators are generated automatically by the software to provide additional information of the generated optimized schedule. Based on Boyd *et al.* (2004), the three indicators can be defined as follows; the reduced dost is also called opportunity cost "is the amount by which an objective function coefficient would have to improve (so increase for maximization problem, decrease for minimization problem) before it would be possible for a corresponding variable to assume a positive value in the optimal solution". "The slack value is a variable that is added to an inequality constraint to transform it to equality.

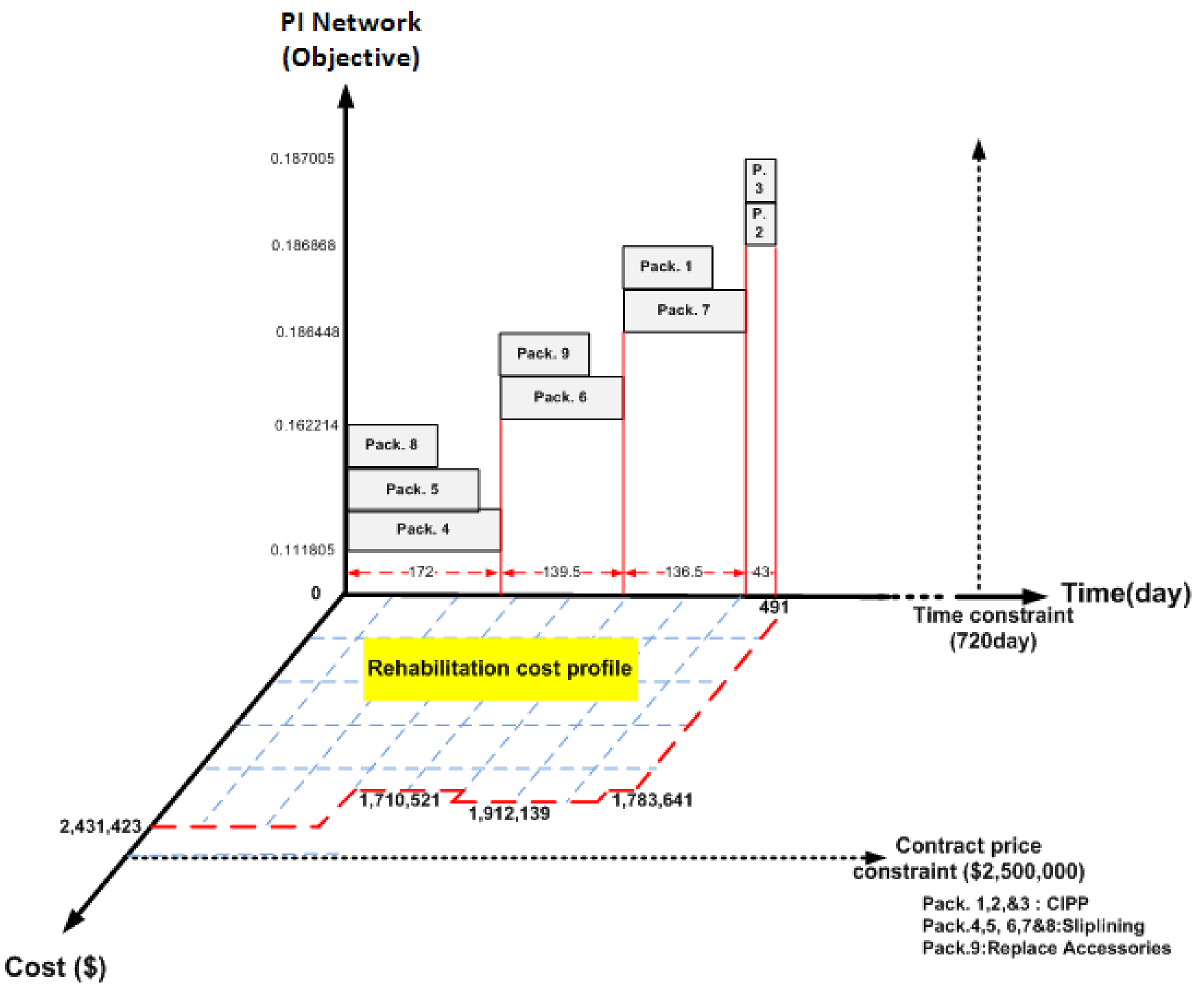


Figure 6.12: Optimum Scheduling

Introducing a slack variable replaces an inequality constraint with an equality constraint and a nonnegative constraint". The dual price is called also a shadow price and "is the change in the objective value of the optimal solution of an optimization problem obtained by relaxing the constraint by one unit – it is the marginal utility of relaxing the constraint, or equivalently the marginal cost of strengthening the constraint".

The reduced cost of the five segments (127, 131, 133, 137 and 143) are very small as shown in Table 6.8 and negative values, which can be ignored due to two reasons (1) X variable in the model represents an integer value; either 0 to represent no rehabilitation or 1 to represent rehabilitation and (2) the reduced cost of these segments are very small and have no effect on the PI of the city's distribution network. The output of the model shows clearly that all other variables such as reliability, criticality, and rehabilitation cost and time have no reduced costs and consequently they have no effect on the PI of the city's distribution network. The optimum scheduling solution leaves zero slack except the following three constraints; Available Budget, Rehabilitation Time, and Contract Price which are shown in Table 6.9.

Table 6.8: Output of the Optimum Scheduling Model: Reduced Cost

Variable	Package	Reduced Cost
X127	2	-0.183E-04
X131	2	-0.334E-04
X133	2	-0.183E-04
X137	3	-0.334E-04
X143	3	-0.334E-04
All other variables(i.e. reliability , criticality, rehabilitation cost and time)		0

The available budget of rehabilitation is $10,000,000, while only $7,837,724 is used for the rehabilitation process and therefore $2,162,276 is left as a slack value. The total rehabilitation time is 491 days, as shown in Figure 6.12, after completing the rehabilitation of the nine packages. As such, 229 days are left as a slack value of the rehabilitation planning time which is 720 days. Finally, the slack value of the contract price constraint is $716,359. The contract price constraint is $2,500,000, while the total cost of rehabilitation of the fourth rehabilitation period (package 2 and 3) is $1,783, 641; therefore the slack value of the contract price constraint is $716,359, the difference between $2,500,000 and $1,783, 641.

The dual prices are values associated with each constraint in the optimization model. The output of the optimum scheduling model shows four set of values as depicted in Table 6.8. (1) Segment Criticality (CI) has negative value; increasing the criticality index one unit will decrease the objective, or the PI of the city's distribution network. This result is logical due to the negative sign of criticality index in the objective equation. (2) Segment Rehabilitation option (X) has a positive value when its value is set equal to 1.0; the dual price of the rehabilitation option is considered very small and can be ignored. Particularly, when X is equal to 1.0, it means that rehabilitation will occur, and as a result it is impossible to change this value. (3) Segment PI has positive value, increasing the PI of each segment will increase the PI of the city's distribution network. At the end of the fourth rehabilitation period, the PI of a segment increases to the maximum level of rehabilitation. This result is due to two factors; reliability is equal to one after rehabilitation, and criticality index has fixed value before and after rehabilitation. (4) All the other constraints such as segment combinations to perform packages, and rehabilitation cost and time have zero value of dual price. A zero dual price of a constraint equation means changing the right-hand side a small amount will have no effect on the objective, which is the PI of a city's distribution network.

Table 6.9: Output of the Optimum Scheduling Model: Slack and Dual Price

Constraint	Slack	Dual Price
City PI (STAGE_PI)	0.1870048	1
Av_Budget	2,162,276.00	0
T_Planning	229	0
contract price	716,359.30	0
Segment Criticality (CI)	0	Negative
Segment Rehabilitation option (x)	0	Positive
Segment PI	0	Positive
Rehabilitation Cost (CC)	0	0
Rehabilitation Time (TC)	0	0
Package (segment combination)	0	0

In conclusion, the sensitivity analysis of the optimum schedule shows that (1) more cost and time are left to perform more rehabilitation works, (2) increasing criticality index of a segment effects negatively the PI of the city's distribution network, (3) Segment combinations to perform packages, and rehabilitation cost and time have no effect on the PI of the city's distribution network (4) Segment PI has positive effect on the PI of the city's distribution network due to increasing values of reliability and rehabilitation activity works, (5) all variables have no practical reduced costs, and therefore the contributions of the variables can't be improved more and the model is fit to perform the objective, which is to maximize the PI of the city.

CHAPTER 7

Conclusions and Recommendations

7.1 Summary

This thesis presented and integrated methodology that encompasses developments made on three major fronts: (1) a methodology for reliability assessment and criticality evaluation of various segments of an entire water distribution network, (2) structured and multi attributed decision support methodology for selection of suitable rehabilitation methods, considering a wide range of factors that include (a) technical feasibility (b) contractual compliance, and (c) cost effectiveness, and (3) an optimized scheduling methodology that integrates the developments made in the two previous fronts. In addition, the thesis includes prototype software (DSSWATER), designed to implement the developed methodology. In summary, three models are developed; (1) PI model, (2) rehabilitation selection model, and (3) scheduling model. DSSWATER is built to allow researchers and municipal engineers to test, implement and utilize the developed models.

The PI model is used to set the priorities of rehabilitation works and it consists of:

1. Breaking down the structure of a city area into sub-networks (NBS), where each sub-network includes several segments which encompass pipes and their accessories.

2. Calculating reliability assessment of pipes with their accessories using reliability theory. Reliability is expressed as a negative exponential function of the breakage rate of pipes (or failure rate of accessories).

3. Identifying segments (i.e. a group of pipes and their accessories), by considering the isolation valves which are shut down when there is a need to monitor, maintain, or rehabilitate the pipes or their accessories.

4. Calculating segment's reliability after identifying them according to 3 above.

5. Calculating the criticality index of water mains according to economic, operational, social, and environmental factors. Each factor is given a score and weight according to its attributes. Factor scores are assigned by experts (UMA and the City of Hamilton), while factor weights are determined using AHP according to land use (i.e. high dense, residential, commercial/ industrial, park and undeveloped).

6. Calculating segment criticality by determining the average criticality index of its pipes.

7. Determining the PI of a segment by combining its reliability assessment and criticality index (RCA).

8. Utilizing PI in the scheduling model.

The second model is for selection of rehabilitation methods and consists of the following steps:

1. Selecting applicable rehabilitation methods.

2. Refining the selection by testing the applicability of the method, according to its technical feasibility and contractual acceptability.

3. Determining cost, environmental impact and experimenting with new technologies, if they are technically feasible and contractually acceptable.

4. Applying SMART to determine the most suitable method with respect to the weights and scores of cost, impact on the environment and experimenting with new technologies.

5. Utilizing rehabilitation methods of segments that are to be rehabilitated for the scheduling model.

The third model is a scheduling model and it:

1. Clusters the segments using UNN and inputs of segment ID, location (x,y), rehabilitation method and number of groups.

2. Utilizes the PI of the city.

3. Groups the segments into packages according to rehabilitation type. A constraint is added to limit the package size. As a result, some groups might have more than one package with the same rehabilitation method.

4. Accounts for the two constraints: (1) maximum contract price and (2) planning time of rehabilitation works.

5. Applies Mixed Integer Nonlinear Programming (MINLP) to schedule the rehabilitation packages based on the added value to the PI of the city's water distribution network.

The developed methodology addresses a number of limitations associated with methods presented in the literature review and provides capabilities to work at segment and network levels, accounting for contract size, rehabilitation method, and planning time horizon. It can be suitable for municipalities to perform a tactical watermain frame work by increasing the PI level of watermain networks based on three models; PI, rehabilitation selection, and scheduling. The PI developed in the present thesis is practical; accounting for reliability assessment and criticality index of water distribution networks. Reliability assessment is represented by the failure function of a pipe and its accessories, while the criticality index is a function of pipe failure consequences. The PI is a comprehensive index that is utilized to prioritize and schedule rehabilitation work of water distribution networks. The second developed model is the rehabilitation selection method, which accounts for technical feasibility, contractual acceptability, cost effectiveness, impact on environment, and trial use of experiment new technologies. The developed reliability based scheduling method is designed to maximize the PI of water distribution networks. A case study is analyzed to demonstrate the use and capabilities of the developed methodology.

7.2 Research Contributions

The contributions made in this thesis consist of the development of methodologies for PI assessment of required rehabilitation works, selection of suitable rehabilitation method(s), and for optimized scheduling. The developments made include:

1. Developing an integrated failure model for pipes and accessories to determine overall segment failure.
2. Determining water pipe and segment criticalities according to land use.
3. Developing PI that accounts for reliability and criticality assessments (RCA).
4. Selecting the cost effective rehabilitation method considering the impact on environment.
5. Optimizing the schedule for rehabilitation work packages based on the added value to the PI of the network, respecting to the maximum contract price value and planning rehabilitation time.
6. Developing an automated tool to implement the designed methodology and its models and algorithms, and applying it to real case studies.

7.3 Research Limitations

The limitations of the methodology developed in this thesis can be summarized as follows:

1. Reliability assessment can be performed for small to medium pipe diameters only. For large diameters and transmission pipes, failure probability can be implemented.

2. Criticality index is obtained according to the time of the collected data; it should be updated when data is changed.
3. Pipe materials and other critical factors (i.e. low accessibility, depth) do not change after rehabilitation works. Therefore, criticality index is assumed not to change after rehabilitation.
4. Reliability assessment is assumed equal to 1.0 after rehabilitation. In reality, reliability assessment might be less than 1.0 after rehabilitation works.
5. Water segment connections (series and parallel) are assumed in the present thesis. A hydraulic model should be incorporated to identify these connections based on the flow direction of water.
6. In view of absence of data pertained to the number of failures of pipe accessories, the related number is assumed.

7.4 Recommendations for Future Research

Below is a list of issues, which can be considered for future work to enhance and extend the developments, made in this research:

7.4.1 Enhancement for Future Research

1. Consider failure and reliability assessment of pipes with large diameters. Reliability assessment, which is a function of breakage rate, is suitable for small and medium pipe diameters, when the consequence of failure is limited. For large pipe diameters, reliability assessment must consider the probability of failure when the consequences are large.

2. Consider a dynamic criticality index model to cover pipe properties over their respective life cycle.

3. Study the cost effectiveness of rehabilitating the entire component of the segments or it’s an individual component.

4. Determine more accurate reliability values for various rehabilitation methods.

7.4.2 Extension for Future Research

1. Extend to the development made in this thesis to cover sewer networks.

2. Develop a budget allocation model based on the PI formulation developed in this thesis.

3. Build up an optimum rehabilitation scheduling of integrated water, sewer, and road networks.

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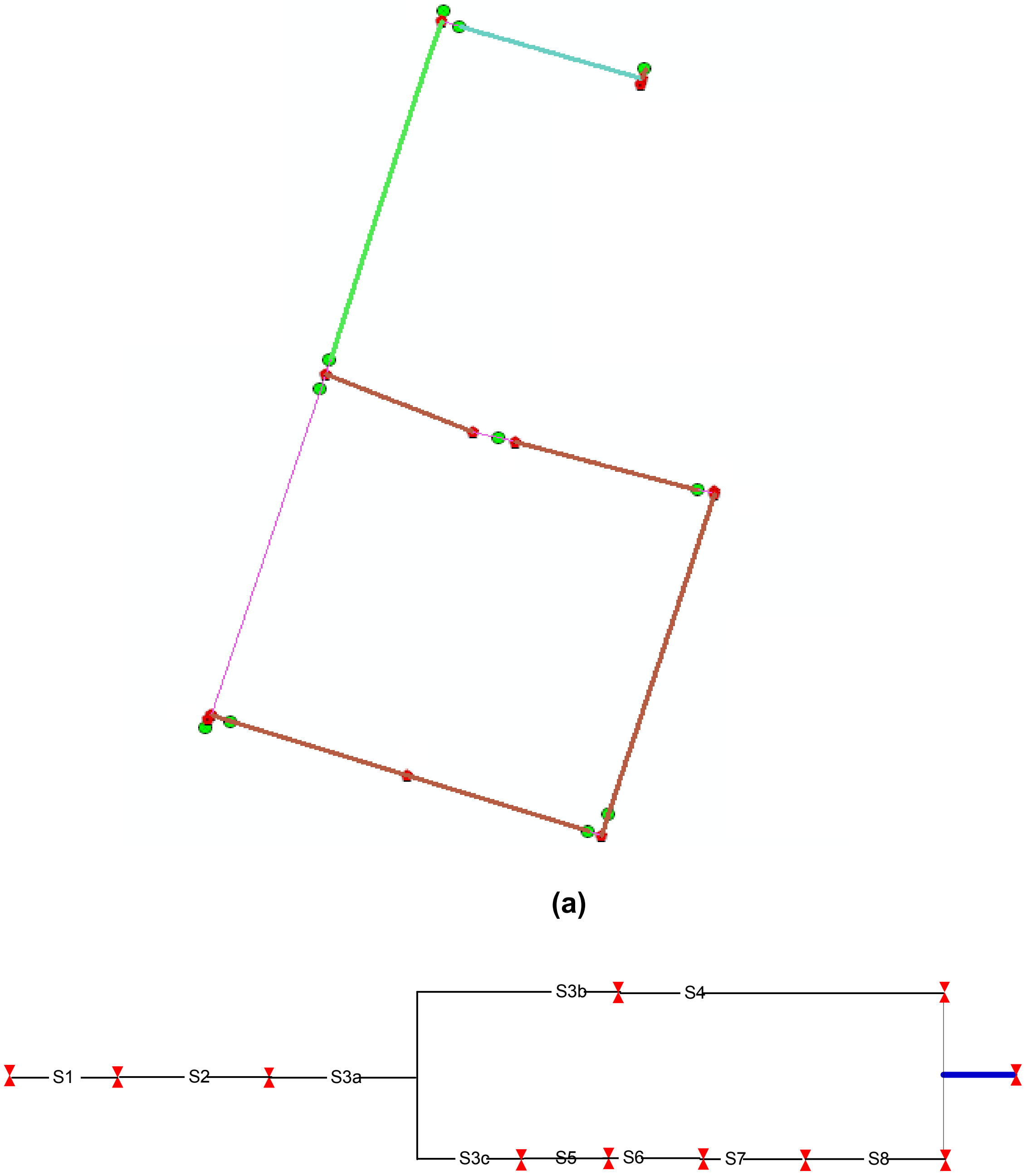
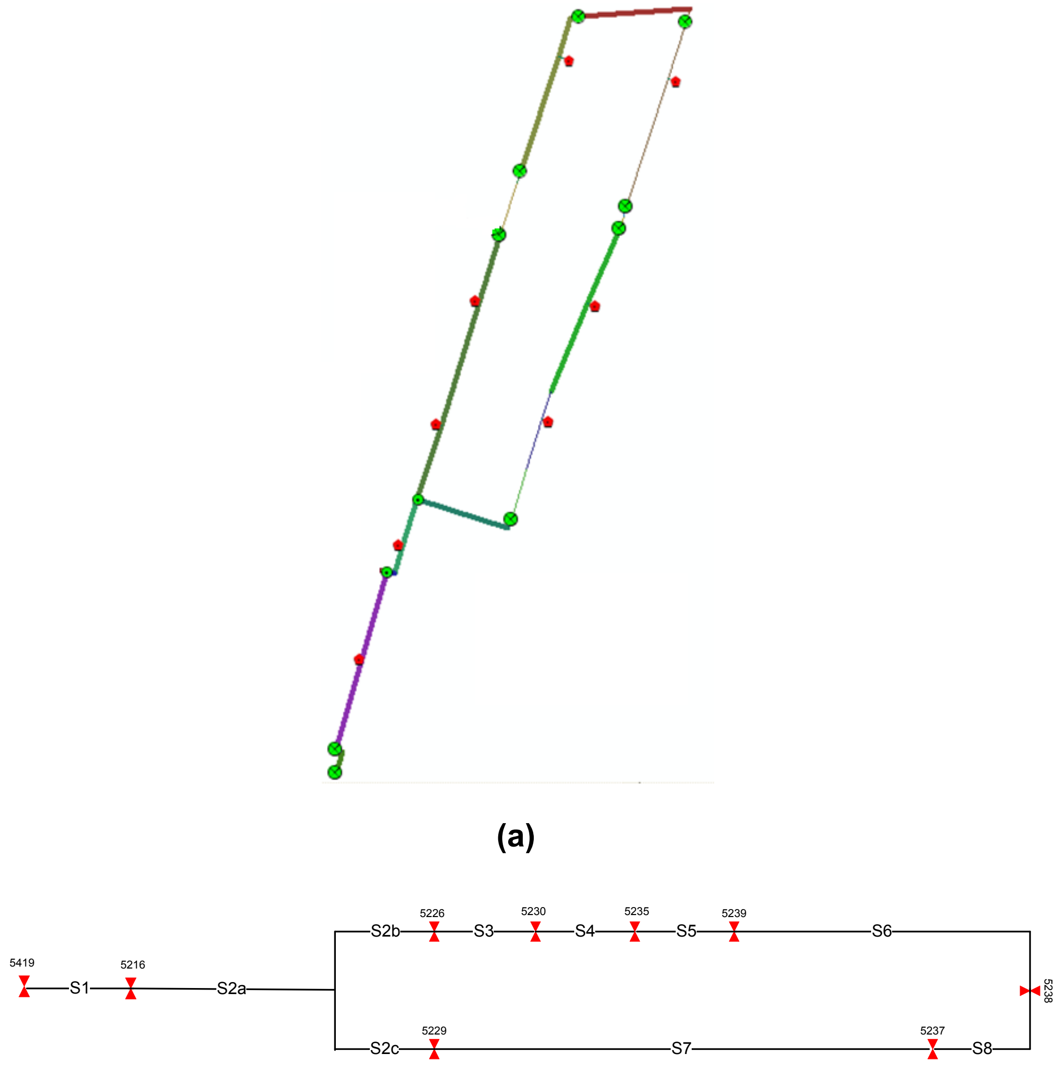
APPENDIX (A): Selected Sub-Networks



(a)

(b)

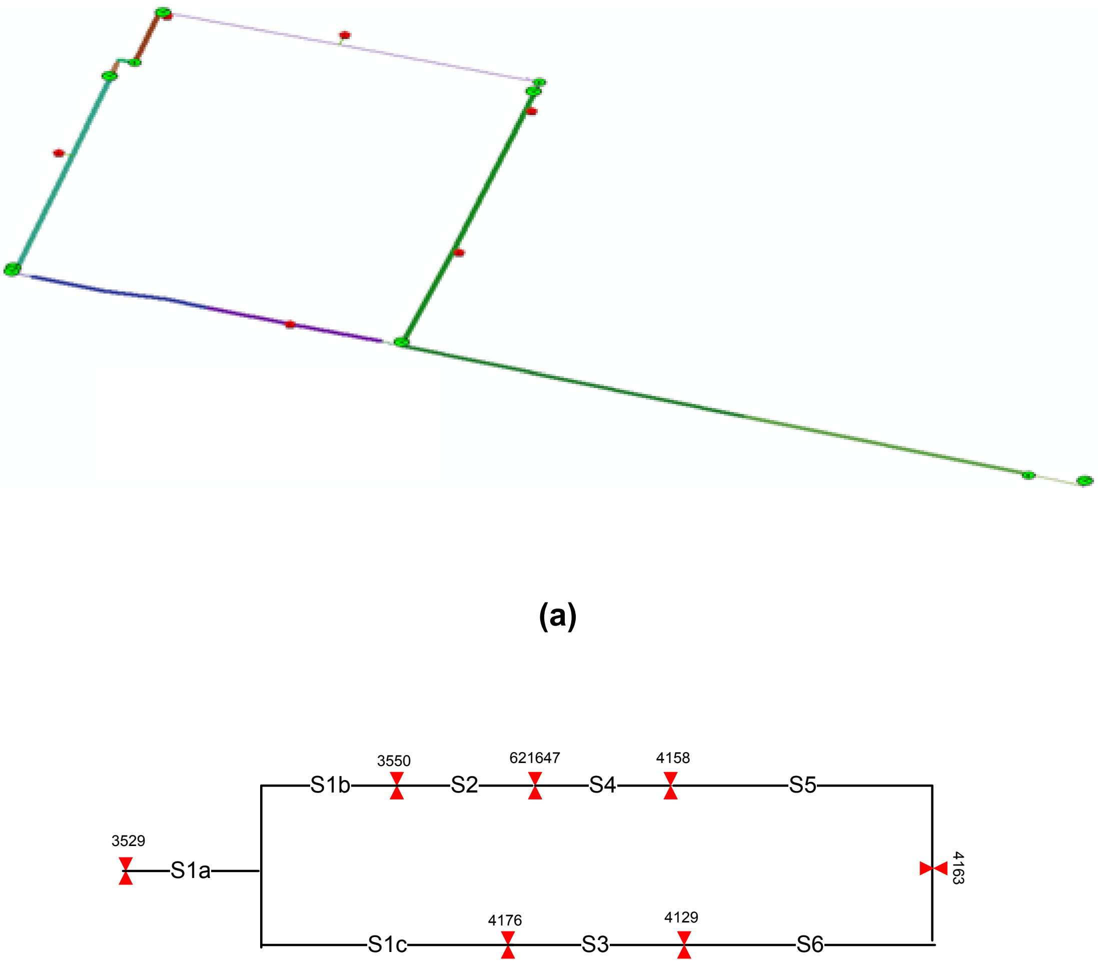
Figure A.1: Residential – a) GIS Map, b) Linear Connections



(a)

(b)

Figure A.2: Park – a) GIS Map, b) Linear Connections



(a)

(b)

Figure A.3: Comm./Ind.– a) GIS Map, b) Linear Connections

APPENDIX (B): Data Collection

Table B.1: Undeveloped Data

Seg.	Componen	Compkey	Failure	Length (m)	Material	Age (yr)	Diameter (mm)	Depth (m)	Land_Use	Low_Acess	Road_Type	Critical Location	WT_Bod Pro.(m)	No_Diversion	Locality	X	Y
Seg. 1	I. Valve 1	1-1-1-1	2	NA		NA	NA									-	-
	Pipe 1	1-1-1-2	0	5.00	DUCT	25.6	300	1.30	Undev.	0		0	10	0	0	579,312	4,782,884
	Pipe 2	1-1-1-3	0	29.60	UNKN	0.0	400	0.00	Com./Ind.	0		0	10	0	0	579,319	4,782,858
	I. Valve 2	1-1-1-4	2	NA		NA	NA									-	-
Seg. 2a	I. Valve 1	1-2-1-1	2	NA		NA	NA									-	-
	Pipe 1	1-2-1-2	0	14.50	UNKN	0.0	400	0.00	Com./Ind.	0		0	0	0	0	579,322	4,782,844
Seg. 2.b	Pipe 2	1-2-2-1	0	17.20	DUCT	8.4	300	1.60	Com./Ind.	0	RA,UC	0	0	0	0	579,327	4,782,828
	I. Valve 2	1-2-2-2	2	NA		NA	NA									-	-
Seg. 2.c	Pipe 3	1-2-3-1	0	22.00	UNKN	0.0	400	0.00	Com./Ind.	0	RA,UC	0	0	0	0	579,322	4,782,844
	I. Valve 3	1-2-3-2	2	NA		NA	NA									-	-
Seg. 3	I. Valve 1	1-3-1-1	2	NA		NA	NA									-	-
	Pipe 1	1-3-1-2	0	116.00	DUCT	8.4	300	1.60		0	RA,UC	0	200	0	0	579,355	4,782,715
	Pipe 2	1-3-1-3	0	14.40	DUCT	8.4	200	1.60	Com./Ind.	0	RA,UC	0	200	0	0	579,355	4,782,715
	Hydrant 1	1-3-1-4	2	NA		NA	NA									-	-
	I. Valve 2	1-3-1-5	2	NA		NA	NA									-	-
Seg. 4	I. Valve 1	1-4-1-1	2	NA		NA	NA									-	-
	Pipe 1	1-4-1-2	0	86.70	DUCT	8.4	200	1.70		0	RA,UC	0	200	0	0	579,341	4,782,711
	Pipe 2	1-4-1-3	2	578.70	DUCT	8.4	200	1.60	Undev.	0	RA,UC	0	200	0	0	579,262	4,782,679
	Pipe 3	1-4-1-4	0	47.00	DUCT	17.5	200	1.60	Undev.	0	RA,UC	0	200	0	0	578,965	4,782,182
	Pipe 4	1-4-1-5	0	50.50	DUCT	17.5	200	1.60	Undev.	0	RA,UC	0	0	0	0	578,952	4,782,137
	Hydrant 1	1-4-1-6	2	NA		NA	NA									-	-
	Hydrant 2	1-4-1-7	2	NA		NA	NA									-	-
	Hydrant 3	1-4-1-8	2	NA		NA	NA									-	-
	Hydrant 4	1-4-1-9	2	NA		NA	NA									-	-
	Hydrant 5	1-4-1-10	2	NA		NA	NA									-	-
	Hydrant 6	1-4-1-11	2	NA		NA	NA									-	-
	Hydrant 7	1-4-1-12	2	NA		NA	NA									-	-
	Hydrant 8	1-4-1-13	2	NA		NA	NA									-	-
	I. Valve 2	1-4-1-14	2	NA		NA	NA									-	-

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Seg. 5	I. Valve 1	1-5-1-1	2	NA		NA	NA									-	-
	Pipe 1	1-5-1-2	0	9.00	DUCT	17.5	200	1.60	Undev.	0	RA,UC	0	0	0	0	578,962	4,782,087
	Pipe 2	1-5-1-3	0	15.20	DUCT	17.5	300	1.60	Undev.	0		0	0	0	0	578,964	4,782,080
	I. Valve 2	1-5-1-4	2	NA		NA	NA									-	-
Seg. 6	I. Valve 1	1-6-1-1	2	NA		NA	NA									-	-
	Pipe 1	1-6-1-2	0	86.20	DUCT	15.5	300	1.60	Undev.	0		0	0	0	0	578,949	4,782,077
	Pipe 2	1-6-1-3	0	21.70	DUCT	2.9	300	1.60	Undev.	0		0	200	0	0	578,845	4,782,076
	Hydrant 1	1-6-1-4	2	NA		NA	NA									-	-
	I. Valve 2	1-6-1-5	2	NA		NA	NA									-	-
Seg. 7	I. Valve 1	1-7-1-1	2	NA		NA	NA									-	-
	Pipe 1	1-7-1-2	0	134.20	UNKN	0.0	400	0.00	Undev.	0		0	0	0	0	579,301	4,782,839
	Pipe 2	1-7-1-3	0	164.00	UNKN	0.0	400	0.00	Undev.	0	RA,UC	0	0	0	0	579,171	4,782,809
	Pipe 3	1-7-1-4	0	32.10	UNKN	0.0	400	0.00	Com./Ind.	0	RA,UC	0	200	0	0	579,012	4,782,772
	Pipe 4	1-7-1-5	0	33.20	UNKN	0.0	400	0.00	Com./Ind.	0	RA,UC	0	200	0	0	578,990	4,782,749
	Pipe 5	1-7-1-6	0	61.40	UNKN	0.0	400	1.50	Com./Ind.	0	RA,UC	0	200	0	0	578,984	4,782,717
	Hydrant 1	1-7-1-7	2	NA		NA	NA									-	-
	Hydrant 2	1-7-1-8	2	NA		NA	NA									-	-
	Hydrant 3	1-7-1-9	2	NA		NA	NA									-	-
	Hydrant 4	1-7-1-10	2	NA		NA	NA									-	-
	I. Valve 2	1-7-1-11	2	NA		NA	NA									-	-
Seg. 8	I. Valve 1	1-8-1-1	2	NA		NA	NA									-	-
	Pipe 1	1-8-1-2	0	64.60	UNKN	0.0	400	0.00	Com./Ind.	0	RA,UC	0	200	0	0	578,996	4,782,657
	Pipe 2	1-8-1-3	0	128.00	UNKN	0.0	400	0.00	Com./Ind.	0	RA,UC	0	200	0	0	579,010	4,782,594
	Pipe 3	1-8-1-4	0	166.30	UNKN	0.0	400	1.40		0	RA,UC	0	200	0	0	578,941	4,782,486
	Hydrant 1	1-8-1-5	2	NA		NA	NA									-	-
	Hydrant 2	1-8-1-6	2	NA		NA	NA									-	-
	Hydrant 3	1-8-1-7	2	NA		NA	NA									-	-
	Hydrant 4	1-8-1-8	2	NA		NA	NA									-	-
	I. Valve 2	1-8-1-9	2	NA		NA	NA									-	-
Seg. 9	I. Valve 1	1-9-1-1	2	NA		NA	NA									-	-
	Pipe 1	1-9-1-2	0	23.40	UNKN	0.0	400	0.00		0	RA,UC	0	0	0	0	578,758	4,782,442
	Pipe 2	1-9-1-3	0	7.50	DUCT	19.5	300	1.60		0		0	0	0	0	578,758	4,782,442
	I. Valve 2	1-9-1-4	2	NA		NA	NA									-	-

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Seg. 10	I. Valve 1	1-10-1-1	2	NA		NA	NA									-	-
	Pipe 1	1-10-1-2	0	204.70	DUCT	2.9	300	1.70	Com./Ind.	0		0	200	0	0	578,760	4,782,435
	Hydrant 1	1-10-1-3	2	NA		NA	NA									-	-
	Hydrant 2	1-10-1-4	2	NA		NA	NA									-	-
	I. Valve 2	1-10-1-5	2	NA		NA	NA									-	-
Seg. 11	I. Valve 1	1-11-1-1	2	NA		NA	NA									-	-
	Pipe 1	1-11-1-2	0	165.40	DUCT	2.9	300	1.60	Com./Ind.	0		0	0	0	0	578,807	4,782,236
	Hydrant 1	1-11-1-3	2	NA		NA	NA									-	-
	Hydrant 2	1-11-1-4	2	NA		NA	NA									-	-
	I. Valve 2	1-11-1-5	2	NA		NA	NA									-	-

Table B. 2: Residential Data

Seg.	Component	Compkey	Failu	Length (m)	Material	Age (yr)	Diameter (mm)	Depth (m)	Land_Use	Low_Access	Road_Type	Critical Location	WT_Bod_Pro (m)	No_Diversion	Locality	X	Y
Seg.1	I. Valve	3-1-1-1	2	NA	NA	NA											
	Pipe 1	3-1-1-2	3	95.70	CIS	47.95	150	1.60	Res.	0	RA,UC	0	200	0	0	591,570	4,787,136
	Pipe 2	3-1-1-3	1	5.20	CIS	47.95	150	1.60	Res.	0	OTHER	0	200	0	0	591,663	4,787,113
	I. Valve	3-1-1-4	2	NA	NA	NA											
Seg.2	I. Valve	3-2-1-1	2	NA	NA	NA											
	Pipe 1	3-2-1-2	1	190.70	CIS	47.95	150	1.60	Res.	0	OTHER	0	200	0	0	591,560	4,787,139
	Pipe 2	3-2-1-3	0	10.50	CIS	47.95	150	1.60	Res.	0	RA,UC	0	200	0	0	591,770	4,787,116
	I. Valve	3-2-1-4	2	NA	NA	NA											
Seg.3.a	I. Valve	3-3-1-1	2	NA	NA	NA											
	Pipe 1	3-3-1-2	0	8.00	CIS	47.95	150	1.60	Res.	0	OTHER	0	200	0	0	591,504	4,786,954
Seg.3.b	Pipe 1	3-3-2-1	1	81.00	CIS	47.95	200	1.60	Res.	0	OTHER	0	200	0	0	591,502	4,786,946
	Pipe 2	3-3-2-2	0	13.40	CIS	47.95	200	1.60	Res.	0	OTHER	0	200	0	0	591,576	4,786,915
	I. Valve	3-3-2-3	2	NA	NA	NA											
Seg.3.c	Pipe 1	3-3-3-1	0	9.00	CIS	47.95	150	1.60	Res.	0	OTHER	0	200	0	0	591,502	4,786,946
Seg.3.d	I. Valve 4	3-3-3-2	2	NA	NA	NA											
Seg.4	I. Valve	3-4-1-1	2	NA	NA	NA											
	Pipe 1	3-4-1-2	0	8.70	CIS	47.95	200	1.60	Res.	0	OTHER	0	200	0	0	591,589	4,786,911
	Pipe 2	3-4-1-3	1	95.10	CIS	47.95	200	1.60	Res.	0	RA,UC	0	200	0	0	591,598	4,786,909
	Hydrant	3-4-1-4	2	NA	NA	NA											
	I. Valve	3-4-1-5	2	NA	NA	NA											
Seg.5	I. Valve	3-5-1-1	2	NA	NA	NA											
	Hydrant	3-5-1-2	2	NA	NA	NA											
	Pipe 1	3-5-1-3	0	186.00	CIS	47.95	150	1.60	Res.	0	OTHER	0	200	0	0	591,499	4,786,938
	Pipe 2	3-5-1-4	1	11.60	CIS	47.95	150	1.60	Res.	0	OTHER	0	200	0	0	591,444	4,786,760
	I. Valve	3-5-1-5	2	NA	NA	NA											
Seg.6	I. Valve	3-6-1-1	2	NA	NA	NA											
	Hydrant	3-6-1-2	2	NA	NA	NA											
	Pipe 1	3-6-1-3	1	92.50	CIS	47.95	150	1.60	Res.	0	OTHER	0	200	0	0	591,455	4,786,756
	Pipe 2	3-6-1-4	1	97.00	CIS	47.95	150	1.60	Res.	0	OTHER	0	200	0	0	591,543	4,786,727
	I. Valve	3-6-1-5	2	NA	NA	NA											
Seg.7	I. Valve	3-7-1-1	2	NA	NA	NA											
	Pipe 1	3-7-1-2	0	6.60	CIS	47.95	150	1.60	Res.	0	EXPWY,	0	200	0	0	591,641	4,786,694
	Pipe 2	3-7-1-3	1	12.40	CIS	57.08	300	1.60	Res.	0	EXPWY,	0	200	0	0	591,641	4,786,694
	I. Valve	3-7-1-4	2	NA	NA	NA											
Seg.8	I. Valve	3-8-1-1	2	NA	NA	NA											
	Hydrant	3-8-1-2	2	NA	NA	NA											
	Pipe 1	3-8-1-3	1	183.30	CIS	57.08	300	1.60	Res.	0	EXPWY,	0	200	0	0	591,641	4,786,694
	I. Valve	3-8-1-4	2	NA	NA	NA											

Table B.3: Park Data

Seg.	Component	Compkey	Failu	Length (m)	Material	Age (yr)	Diameter (mm)	Depth(m)	Land_Use	Low_Acess	Road_Type	Critical Location	WT_Bod_Pro (m)	No_Diversion	Locality	X	Y
Seg. 1	I. Valve 1	9-1-1-1	2	NA	NA	NA											
	Pipe 1	9-1-1-2	0	1.30	DU	1.00	200	0.00	Park	0	OTHER	0	150	0	0	587,897	
	Pipe 2	9-1-1-3	4	14.40	CIS	57.10	150	1.60	Park	0	OTHER	0	200	0	0	587,901	
	Pipe 3	9-1-1-4	0	2.60	CIS	57.08	150	1.60	Park	0	OTHER	0	200	0	0	587,896	
	Pipe 4	9-1-1-5	1	4.00	CIS	47.95	150	1.60	Park	0	OTHER	0	200	0	0	587,896	
	I. Valve 2	9-1-1-6	2	NA	NA	NA											
Seg. 2.a	I. Valve 1	9-2-1-1	2	NA	NA	NA											
	Pipe 1	9-2-1-2	1	142.00	CIS	47.90	150	1.60	Res.	0	OTHER	0	200	0	0	587,897	
	C. Valve	9-2-1-3	2	NA	NA	NA											
	Hydrant 1	9-2-1-4	2	NA	NA	NA											
	Pipe 1	9-2-1-5	1	6.50	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	587,941	
	Pipe 2	9-2-1-6	3	59.00	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	587,959	
	Pipe 3	9-2-1-7	0	0.30	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	587,936	
Seg. 2.b	Hydrant 1	9-2-2-1	2	NA	NA	NA											
	Hydrant 2	9-2-2-2	2	NA	NA	NA											
	Pipe 1	9-2-2-3	4	212.10	CIS	65.62	150	1.60	Res.	0	OTHER	0	200	0	0	588,022	
	I. Valve 2	9-2-2-4	2	NA	NA	NA											
Seg. 2.c	Pipe 1	9-2-3-1	0	0.30	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	587,959	
	Pipe 2	9-2-3-2	2	72.30	CIS	57.08	150	0.00	Res.	0		0	200	0	0	588,028	
	Pipe 3	9-2-3-3	0	7.20	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	588,030	
	C. Valve	9-2-3-4	2	NA	NA	NA											
	I. Valve 3	9-2-3-5	2	NA	NA	NA											
Seg. 3	I. Valve 1	9-3-1-1	2	NA	NA	NA											
	Hydrant 1	9-3-1-2	2	NA	NA	NA											
	Hydrant 2	9-3-1-3	2	NA	NA	NA											
	Pipe 1	9-3-1-4	0	39.40	CIS	57.08	400	0.00	Und.	0		0	200	0	0	588,042	
	Pipe 2	9-3-1-5	0	62.60	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	588,060	
	Pipe 3	9-3-1-6	1	135.40	CIS	57.08	400	0.00	Res.	0		0	200	0	0	588,060	
	I. Valve 2	9-3-1-7	2	NA	NA	NA											

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Seg. 4	I. Valve 1	9-4-1-1	2	NA	NA	NA											
	Pipe 1	9-4-1-2	0	9.80	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	588,113	
	Pipe 2	9-4-1-3	0	7.70	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	588,116	
	I. Valve 2	9-4-1-4	2	NA	NA	NA											
Seg. 5	I. Valve 1	9-5-1-1	2	NA	NA	NA											
	Hydrant 1	9-5-1-2	2	NA	NA	NA											
	Pipe 1	9-5-1-3	0	148.00	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	588,118	
	I. Valve 2	9-5-1-4	2	NA	NA	NA											
Seg. 6	I. Valve 1	9-6-1-1	2	NA	NA	NA											
	Pipe 1	9-6-1-2	1	2.80	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	588,022	
	Pipe 1	9-6-1-3	0	9.80	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	588,035	
	Pipe 2	9-6-1-4	0	42.10	CIS	57.08	150	1.60	Res.	0	OTHER	0	200	0	0	588,023	
	I. Valve 1	9-6-1-5	2	NA	NA	NA											
Seg. 7	I. Valve 1	9-7-1-1	2	NA	NA	NA											
	Pipe 1	9-7-1-2	0	9.80	CIS	57.08	150	1.60	Res.	0	EXPWY,HW	0	200	0	0	588,163	
	Pipe 2	9-7-1-3	1	84.50	CIS	77.37	150	1.60	Res.	0	EXPWY,HW	0	200	0	0	588,166	
	I. Valve 2	9-7-1-4	2	NA	NA	NA											
Seg. 8	I. Valve 1	9-8-1-1	2	NA	NA	NA											
	Hydrant 1	9-8-1-2	2	NA	NA	NA											
	Pipe 1	9-8-1-3	0	6.20	CIS	77.37	150	1.60	Res.	0	EXPWY,HW	0	200	0	0	588,082	
	Pipe 2	9-8-1-4	1	122.90	CIS	77.37	150	1.60	Res.	0	OTHER	0	200	0	0	588,038	
	I. Valve 2	9-8-1-5	2	NA	NA	NA											

Table B.4: Commercial/ Industrial Data

Seg.	Component	Comp key	Break/Failure	Length (m)	Material	Age (yr)	Diameter (mm)	Depth(m)	Land_Use	Low_Access	Road_Type	Critical Location	WT_Bod_Pro (m)	No_Diversion	Locality	X	Y
Seg.1.a	I. Valve	12-1-	2	NA	NA	NA											
	C.Valve	12-1-	2	NA	NA	NA											
	Pipe 1	12-1-	0	5.10	CIPIT2	107.8	150	1.60	Cm./	0	OTHER	0	200	0	0	593,456	4,790,315
	Pipe 2	12-1-	0	32.44	NA	0.00	500	0.00	Cm./	0	EXPWY,H	0	200	0	0	593,426	4,790,325
	Pipe 3	12-1-	0	0.30	CIPIT2	107.8	200	1.60	Cm./	0	EXPWY,H	0	200	0	0	593,426	4,790,325
	Pipe 4	12-1-	1	200.91	NA	0.00	500	0.00	Res.	0	EXPWY,H	0	200	0	0	593,266	4,790,380
	Pipe 5	12-1-	2	206.72	NA	0.00	500	0.00	Res.	0	EXPWY,H	0	200	0	0	593,075	4,790,444
Seg.1.b	Pipe 1	12-1-	0	3.70	CIPIT1	107.8	150	1.50	Cm./	1	EXPWY,H	0	200	0	0	593,075	4,790,444
	Hydrant	12-1-	2	NA	NA	NA											
	Hydrant	12-1-	2	NA	NA	NA											
	I. Valve	12-1-	2	NA	NA	NA											
Seg.1.c	Hydrant	12-1-	2	NA	NA	NA											
	Pipe 1	12-1-	0	2.86	NA	0.00	500	0.00	Cm./	1	EXPWY,H	0	200	0	0	593,075	4,790,444
	Pipe 2	12-1-	0	11.06	NA	0.00	500	0.00	Cm./	0	EXPWY,H	0	200	0	0	593,063	4,790,448
	Pipe 3	12-1-	2	100.92	NA	0.00	500	0.00	Cm./	0	EXPWY,H	0	200	0	0	592,967	4,790,479
	Pipe 4	12-1-	1	103.85	NA	0.00	500	0.00	Cm./	0	EXPWY,H	1	200	0	0	592,868	4,790,508
	Pipe 5	12-1-	0	11.47	NA	0.00	500	1.50	Cm./	0	EXPWY,H	0	200	0	0	592,857	4,790,512
	Pipe 6	12-1-	0	3.00	DUCT	3.04	200	1.60	Cm./	1	EXPWY,H	0	200	0	0	592,857	4,790,512
	I. Valve	12-1-	2	NA	NA	NA											
Seg.2	I. Valve	12-2-	2	NA	NA	NA											
	Pipe 1	12-2-	1	242.40	CIPIT1	107.8	150	1.60	Cm./	1	UAMI	0	200	0	0	593,150	4,790,679
	I. Valve	12-2-	2	NA	NA	NA											
Seg.3	I. Valve	12-3-	2	NA	NA	NA											
	Pipe 1	12-3-	0	1.50	DUCT	3.04	200	1.60	Cm./	0	EXPWY,H	0	200	0	0	592,857	4,790,513
	Pipe 2	12-3-	0	1.30	DUCT	2.86	200	1.60	Cm./	0	EXPWY,H	0	200	0	0	592,858	4,790,514
	I. Valve	12-3-	2	NA	NA	NA											

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Seg.4	I. Valve	12-4-	2	NA	NA	NA											
	C.Valve	12-4-	2	NA	NA	NA											
	Hydrant	12-4-	2	NA	NA	NA											
	Hydrant	12-4-	2	NA	NA	NA											
	Pipe 1	12-4-	0	5.00	CIPIT1	107.8	150	1.60	Cm./	1	UAMI	0	200	0	0	593,150	4,790,679
	Pipe 2	12-4-	0	1.20	CIPIT1	107.8	150	1.60	Cm./	1	UAMI	0	200	0	0	593,152	4,790,685
	Pipe 3	12-4-	0	1.70	CIPIT1	107.8	150	1.60	Cm./	1	UAMI	0	200	0	0	593,152	4,790,687
	Pipe 4	12-4-	0	0.30	CIPIT2	107.8	150	1.60	Cm./	1	UAMI	0	200	0	0	593,152	4,790,687
	Pipe 5	12-4-	0	221.50	CIPIT2	107.8	150	1.60	Cm./	0	RA,UC	0	200	0	0	593,152	4,790,688
	I. Valve	12-4-	2	NA	NA	NA											
Seg.5	I. Valve	12-5-	2	NA	NA	NA											
	C.Valve	12-5-	2	NA	NA	NA											
	Pipe 1	12-5-	1	11.50	CIPIT2	107.8	150	1.60	Cm./	0	EXPWY,H	0	200	0	0	592,912	4,790,693
	Pipe 2	12-5-	0	3.70	CIPIT2	107.8	150	1.60	Cm./	0	EXPWY,H	0	200	0	0	592,916	4,790,704
	Pipe 3	12-5-	1	9.40	CIPIT2	107.8	150	1.60	Cm./	0	EXPWY,H	0	200	0	0	592,926	4,790,705
	Pipe 4	12-5-	2	49.60	CIPIT2	107.8	300	1.60	Cm./	0	EXPWY,H	0	200	0	0	592,940	4,790,753
	Pipe 5	12-5-	0	2.00	CIPIT2	107.8	150	1.60	Cm./	0	EXPWY,H	0	200	0	0	592,940	4,790,753
	Pipe 6	12-5-	0	0.30	CIPIT2	107.8	150	1.60	Cm./	0	EXPWY,H	0	200	0	0	592,926	4,790,705
	I. Valve	12-5-	2	NA	NA	NA											
Seg.6	I. Valve	12-6-	2	NA	NA	NA											
	Hydrant	12-6-	2	NA	NA	NA											
	Pipe 1	12-6-	0	4.80	DUCT	2.86	200	1.60	Cm./	0	EXPWY,H	0	200	0	0	592,859	4,790,517
	Pipe 2	12-6-	1	181.00	CIPIT2	107.8	150	1.60	Cm./	0	EXPWY,H	0	200	0	0	592,861	4,790,520
	I. Valve	12-6-	2	NA	NA	NA										593,456	4,790,315

APPENDIX (C): UNN Application

Table C.1: Segments of Group 2

Data				Result			
Seg.	**Rehab. Type**	**X**	**Y**	**G1**	**G2**	**G3**	**G4**
Seg.4-Undev.2	Sliplining	587,597.51	4,792,507	0	1	0	0
Seg.1-Res.3	Sliplining	587,449.45	4,786,166	0	1	0	0
Seg.2-Res.3	Sliplining	587,509.56	4,786,360	0	1	0	0
Seg.3-Res.3	Sliplining	587,594.68	4,786,317	0	1	0	0
Seg.4-Res.3	Sliplining	587,504.64	4,786,343	0	1	0	0
Seg.5-Res.3	Sliplining	587,575.30	4,786,541	0	1	0	0
Seg.6-Res.3	Sliplining	587,694.61	4,786,289	0	1	0	0
Seg.7-Res.3	Sliplining	587,649.69	4,786,289	0	1	0	0
Seg.8-Res.3	Sliplining	587,600.37	4,786,305	0	1	0	0
Seg.1-Res.4	Sliplining	583,855.52	4,786,597	0	1	0	0
Seg.2-Res.4	Sliplining	583,915.63	4,786,791	0	1	0	0
Seg.3-Res.4	Sliplining	584,000.75	4,786,748	0	1	0	0
Seg.4-Res.4	Sliplining	583,910.71	4,786,775	0	1	0	0
Seg.5-Res.4	Sliplining	583,981.37	4,786,973	0	1	0	0
Seg.6-Res.4	Sliplining	584,100.68	4,786,720	0	1	0	0
Seg.7-Res.4	Sliplining	584,055.76	4,786,720	0	1	0	0
Seg.8-Res.4	Sliplining	584,006.44	4,786,737	0	1	0	0
Seg.1-Res.5	Sliplining	583,531.04	4,787,775	0	1	0	0
Seg.2-Res.5	Sliplining	583,591.15	4,787,969	0	1	0	0
Seg.3-Res.5	Sliplining	583,736.38	4,788,120	0	1	0	0
Seg.4-Res.5	Sliplining	583,791.57	4,788,297	0	1	0	0
Seg.5-Res.5	Sliplining	583,917.42	4,788,673	0	1	0	0
Seg.6-Res.5	Sliplining	584,162.58	4,788,796	0	1	0	0
Seg.7-Res.5	Sliplining	584,362.82	4,788,919	0	1	0	0
Seg.8-Res.5	Sliplining	584,513.74	4,789,058	0	1	0	0
Seg.1-Res.6	Sliplining	582,691.38	4,792,463	0	1	0	0
Seg.2-Res.6	Sliplining	582,751.49	4,792,657	0	1	0	0
Seg.3-Res.6	Sliplining	582,836.61	4,792,614	0	1	0	0
Seg.4-Res.6	Sliplining	582,746.57	4,792,641	0	1	0	0
Seg.5-Res.6	Sliplining	582,817.23	4,792,839	0	1	0	0
Seg.6-Res.6	Sliplining	582,936.54	4,792,586	0	1	0	0
Seg.7-Res.6	Sliplining	582,891.62	4,792,586	0	1	0	0
Seg.8-Res.6	Sliplining	582,842.30	4,792,603	0	1	0	0
Seg.1-Park 1	Sliplining	587,897.12	4,789,437	0	1	0	0
Seg.2-Park1	Sliplining	587,897.11	4,789,454	0	1	0	0
Seg.5-Park1	Sliplining	588,118.36	4,789,869	0	1	0	0
Seg.6-Park1	Sliplining	588,163.36	4,790,010	0	1	0	0
Seg.7-Park1	Sliplining	588,022.15	4,789,847	0	1	0	0
Seg.8-Park1	Sliplining	588,038.07	4,789,896	0	1	0	0
Seg.1-Park2	Sliplining	587,883.13	4,788,457	0	1	0	0
Seg.2-Park2	Sliplining	587,883.12	4,788,475	0	1	0	0
Seg.5-Park2	Sliplining	588,104.37	4,788,889	0	1	0	0
Seg.6-Park2	Sliplining	588,149.37	4,789,030	0	1	0	0
Seg.7-Park2	Sliplining	588,008.16	4,788,867	0	1	0	0
Seg.8-Res2	Sliplining	588,024.08	4,788,916	0	1	0	0

Table C.2: Segments of Group 3

Data				Result			
Seg.	**Rehab. Type**	**X**	**Y**	**G1**	**G2**	**G3**	**G4**
Seg.1-Undev.2	A.R.	587,567.74	4,792,685	0	0	1	0
Seg.2-Undev.2	A.R.	587,575.46	4,792,654	0	0	1	0
Seg.3-Undev.2	A.R.	587,583.16	4,792,624	0	0	1	0
Seg.5-Undev.2	A.R.	587,218.70	4,791,883	0	0	1	0
Seg.6-Undev.2	A.R.	587,205.20	4,791,873	0	0	1	0
Seg.7-Undev.2	A.R.	587,557.71	4,792,635	0	0	1	0
Seg.8-Undev.2	A.R.	587,253.11	4,792,453	0	0	1	0
Seg.9-Undev.2	A.R.	587,037.29	4,792,244	0	0	1	0
Seg.3-Park1	A.R.	588,030.26	4,789,630	0	0	1	0
Seg.4-Park1	A.R.	588,113.03	4,789,852	0	0	1	0
Seg.3-Park2	A.R.	588,016.27	4,788,650	0	0	1	0
Seg.4-Park2	A.R.	588,099.04	4,788,873	0	0	1	0
Seg.3-Com&Ind.1	A.R.	592,857.50	4,790,513	0	0	1	0
Seg.4-Com&Ind.1	A.R.	593,149.67	4,790,679	0	0	1	0
Seg.3-Com&Ind.2	A.R.	592,087.81	4,789,813	0	0	1	0
Seg.4-Com&Ind.2	A.R.	592,379.98	4,789,979	0	0	1	0
Seg.3-Com&Ind.3	A.R.	590,828.32	4,790,233	0	0	1	0
Seg.4-Com&Ind.3	A.R.	591,120.49	4,790,399	0	0	1	0
Seg.3-Com&Ind.4	A.R.	591,178.18	4,789,463	0	0	1	0
Seg.4-Com&Ind.4	A.R.	591,470.35	4,789,629	0	0	1	0
Seg.10-Undev.2	A.R.	587,016.43	4,792,231	0	0	1	0
Seg.11-Undev.2	A.R.	587,063.32	4,792,032	0	0	1	0

Table C.3: Segments of Group 4

Data				Result			
Seg.	**Rehab. Type**	**X**	**Y**	**G1**	**G2**	**G3**	**G4**
Seg.1-Res.1	Sliplining	591,419	4,786,982	0	0	0	1
Seg.2-Res.1	Sliplining	591,504	4,786,954	0	0	0	1
Seg.3-Res.1	Sliplining	591,589	4,786,911	0	0	0	1
Seg.4-Res.1	Sliplining	591,499	4,786,938	0	0	0	1
Seg.5-Res.1	Sliplining	591,570	4,787,136	0	0	0	1
Seg.6-Res.1	Sliplining	591,689	4,786,883	0	0	0	1
Seg.7-Res.1	Sliplining	591,644	4,786,883	0	0	0	1
Seg.8-Res.1	Sliplining	591,595	4,786,900	0	0	0	1
Seg.1-Res.2	Sliplining	593,003	4,783,705	0	0	0	1
Seg.2-Res.2	Sliplining	593,063	4,783,899	0	0	0	1
Seg.3-Res.2	Sliplining	593,148	4,783,856	0	0	0	1
Seg.4-Res.2	Sliplining	593,058	4,783,883	0	0	0	1
Seg.5-Res.2	Sliplining	593,128	4,784,081	0	0	0	1
Seg.6-Res.2	Sliplining	593,248	4,783,828	0	0	0	1
Seg.7-Res.2	Sliplining	593,203	4,783,828	0	0	0	1
Seg.8-Res2	Sliplining	593,154	4,783,844	0	0	0	1
Seg.1-Com&Ind. 1	CIPP	593,458	4,790,320	0	0	0	1
Seg.2-Com&Ind.1	Sliplining	593,076	4,790,448	0	0	0	1
Seg.5-Com&Ind.1	Sliplining	592,942	4,790,752	0	0	0	1
Seg.6-Com&Ind.1	Sliplining	592,859	4,790,517	0	0	0	1
Seg.1-Com&Ind.2	CIPP	592,688	4,789,620	0	0	0	1
Seg.2-Com&Ind.2	Sliplining	592,306	4,789,748	0	0	0	1
Seg.5-Com&Ind.2	Sliplining	592,172	4,790,053	0	0	0	1
Seg.6-Com&Ind.2	Sliplining	592,089	4,789,817	0	0	0	1
Seg.1-Com&Ind.3	CIPP	591,429	4,790,040	0	0	0	1
Seg.2-Com&Ind.3	Sliplining	591,047	4,790,168	0	0	0	1
Seg.5-Com&Ind.3	Sliplining	590,913	4,790,472	0	0	0	1
Seg.6-Com&Ind.3	Sliplining	590,830	4,790,237	0	0	0	1
Seg.1-Com&Ind.4	CIPP	591,779	4,789,270	0	0	0	1
Seg.2-Com&Ind.4	Sliplining	591,397	4,789,398	0	0	0	1
Seg.5-Com&Ind.4	Sliplining	591,262	4,789,703	0	0	0	1
Seg.6-Com&Ind.4	Sliplining	591,179	4,789,467	0	0	0	1

APPENDIX (D): Segment Connections

Table D.1: Segment Connections of Group 1

Segment	X	Y	S.COMPKEY	connect to	Relation	Point
Seg.1-Undev.1	579,312	4,782,884	1-1-1	0		s
Seg.2.a -Undev.1	579,322	4,782,844	1-2-1	1-1-1	1	
Seg.2.b-Undev.1	579,327	4,782,828	1-2-2	1-2-1	0	
Seg.2.c-Undev.1	579,322	4,782,844	1-2-3	1-2-1	0	
Seg.3-Undev.1	579,355	4,782,715	1-3-1	1-2-2	1	
Seg.4-Undev.1	579,341	4,782,711	1-4-1	1-3-1	1	
Seg.5-Undev.1	578,962	4,782,087	1-5-1	1-4-1	1	
Seg.6-Undev.1	578,949	4,782,077	1-6-1	1-5-1	1	C1
Seg.7-Undev.1	579,301	4,782,839	1-7-1	1-2-3	1	
Seg.8-Undev.1	578,996	4,782,657	1-8-1	1-7-1	1	
Seg.9-Undev.1	578,758	4,782,442	1-9-1	1-8-1	1	
Seg.10-Undev.1	578,760	4,782,435	1-10-1	1-9-1	1	
Seg.11-Undev.1	578,807	4,782,236	1-11-1	1-10-1	1	C1
Seg.1-Park3	580,270	4,785,028	11-1-1	C1	1	
Seg.2.a-Park3	580,270	4,785,046	11-2-1	11-1-1	1	
Seg.2.b-Park3	580,395	4,785,438	11-2-2	11-2-1	0	
Seg.2.c-Park3	580,401	4,785,215	11-2-3	11-2-1	0	
Seg.3-Park3	580,415	4,785,259	11-3-1	11-2-2	1	
Seg.4-Park3	580,486	4,785,444	11-4-1	11-3-1	1	
Seg.5-Park3	580,491	4,785,461	11-5-1	11-4-1	1	
Seg.6-Park3	580,395	4,785,438	11-6-1	11-5-1	1	C2
Seg.7-Park3	580,536	4,785,602	11-7-1	11-2-3	1	
Seg.8-Park3	580,455	4,785,605	11-8-1	11-7-1	1	C2

Table D.2: Segment Connections of Group 2

Segment	X	Y	S.COMPKEY	connect to	Relation	Point
Seg.1	584,007	4,786,751	6-1-1	s		
Seg.2	583,997	4,786,755	6-2-1	6-1-1	1	
Seg.3.a	583,941	4,786,570	6-3-1	6-2-1	1	
Seg.3.b	583,939	4,786,562	6-3-2	6-3-1	0	
Seg.3.c	583,939	4,786,562	6-3-3	6-3-1	0	
Seg.4	584,026	4,786,526	6-4-1	6-3-2	1	C1
Seg.5	583,936	4,786,553	6-5-1	6-3-3	1	
Seg.6	583,892	4,786,372	6-6-1	6-5-1	1	
Seg.7	584,078	4,786,309	6-7-1	6-6-1	1	
Seg.8	584,078	4,786,309	6-8-1	6-7-1	1	C1
Seg.1	583,682	4,787,929	7-1-1	C1	1	
Seg.2	583,672	4,787,932	7-2-1	7-1-1	1	
Seg.3.a	583,617	4,787,747	7-3-1	7-2-1	1	
Seg.3.b	583,614	4,787,740	7-3-2	7-3-1	0	
Seg.3.c	583,614	4,787,740	7-3-3	7-3-1	0	
Seg.4	583,702	4,787,704	7-4-1	7-3-2	1	C2
Seg.5	583,612	4,787,731	7-5-1	7-3-3	1	
Seg.6	583,567	4,787,550	7-6-1	7-5-1	1	
Seg.7	583,753	4,787,487	7-7-1	7-6-1	1	
Seg.8	583,753	4,787,487	7-8-1	7-7-1	1	C2
Seg.1	582,843	4,792,617	8-1-1	C2	1	
Seg.2	582,833	4,792,620	8-2-1	8-1-1	1	
Seg.3.a	582,777	4,792,435	8-3-1	8-2-1	1	
Seg.3.b	582,775	4,792,428	8-3-2	8-3-1	0	
Seg.3.c	582,775	4,792,428	8-3-3	8-3-1	0	
Seg.4	582,862	4,792,392	8-4-1	8-3-2	1	C3
Seg.5	582,772	4,792,419	8-5-1	8-3-3	1	
Seg.6	582,728	4,792,238	8-6-1	8-5-1	1	
Seg.7	582,914	4,792,175	8-7-1	8-6-1	1	
Seg.8	582,914	4,792,175	8-8-1	8-7-1	1	C3
Seg.1	587,601	4,786,320	5-1-1	C3	1	
Seg.2	587,591	4,786,323	5-2-1	5-1-1	1	
Seg.3.a	587,535	4,786,138	5-3-1	5-2-1	1	
Seg.3.b	587,533	4,786,130	5-3-2	5-3-1	0	
Seg.3.c	587,533	4,786,130	5-3-3	5-3-1	0	
Seg.4	587,620	4,786,095	5-4-1	5-3-2	1	C4
Seg.5	587,530	4,786,122	5-5-1	5-3-3	1	
Seg.6	587,486	4,785,940	5-6-1	5-5-1	1	
Seg.7	587,672	4,785,878	5-7-1	5-6-1	1	
Seg.8	587,672	4,785,878	5-8-1	5-7-1	1	C4
Seg.4	587,596	4,792,512	2-4-1	C4	1	C5
Seg.1	587,897	4,789,437	9-1-1	C5	1	
Seg.2.a	587,897	4,789,454	9-2-1	9-1-1	1	
Seg.2.b	588,022	4,789,847	9-2-2	9-2-1	0	
Seg.2.c	587,959	4,789,644	9-2-3	9-2-1	0	
Seg.5	588,118	4,789,869	9-5-1	9-2-2	1	
Seg.6	588,022	4,789,847	9-6-1	9-5-1	1	C6
Seg.7	588,163	4,790,010	9-7-1	9-2-3	1	
Seg.8	588,082	4,790,013	9-8-1	9-7-1	1	C6
Seg.1	587,883	4,788,457	10-1-1	C6	1	
Seg.2.a	587,883	4,788,475	10-2-1	10-1-1	1	
Seg.2.b	588,008	4,788,867	10-2-2	10-2-1	0	
Seg.2.c	587,945	4,788,665	10-2-3	10-2-1	0	
Seg.5	588,104	4,788,889	10-5-1	10-2-2	1	
Seg.6	588,008	4,788,867	10-6-1	10-5-1	1	C7
Seg.7	588,149	4,789,030	10-7-1	10-2-3	1	
Seg.8	588,068	4,789,034	10-8-1	10-7-1	1	C7

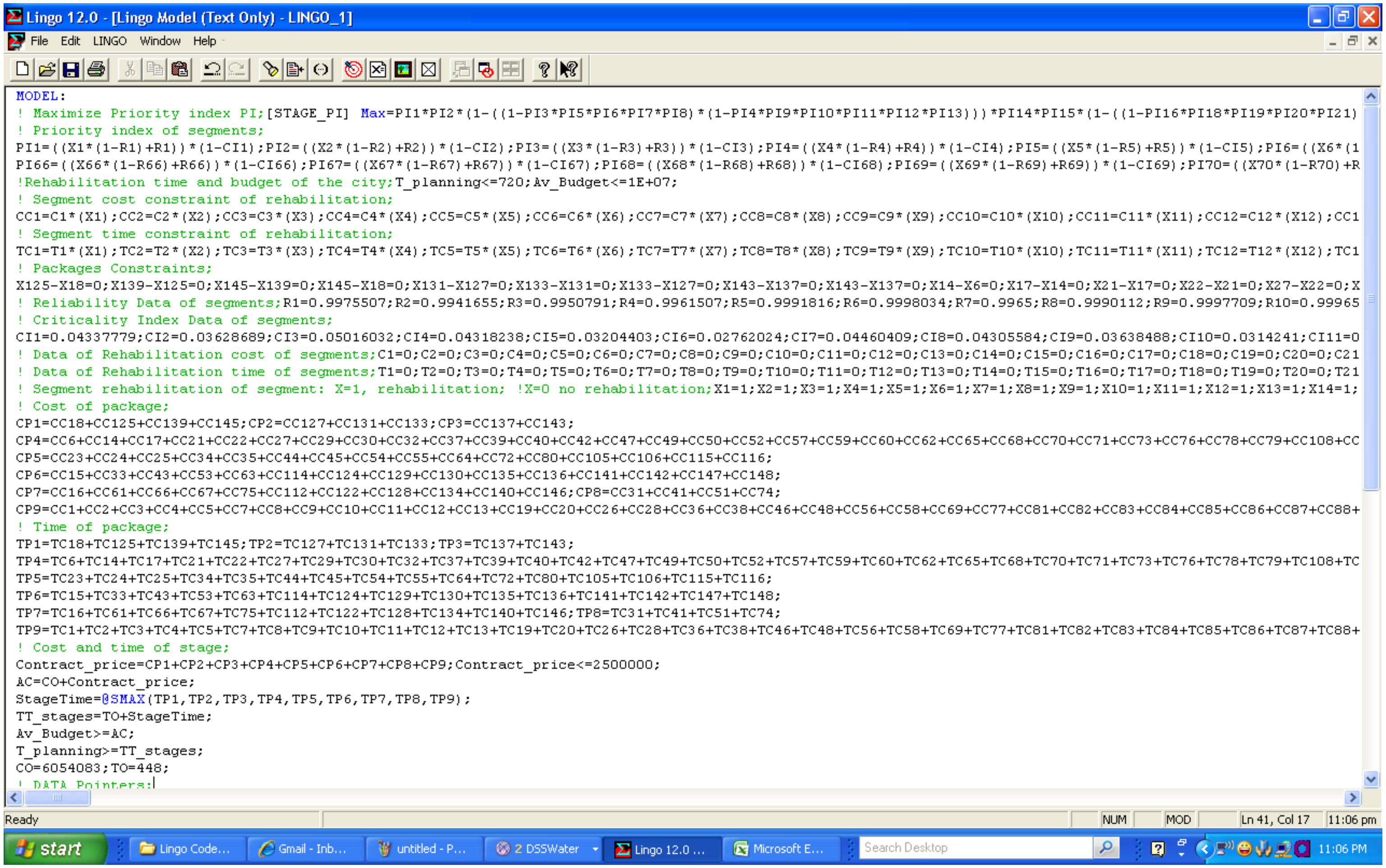
Table D.3: Segment Connections of Group 3

Segment	X	Y	COMPKEY	connect to	Relation	Point
Seg.1	587,567.74	4,792,685.23	2-1-1	s		
Seg.2a	587,577.76	4,792,645.30	2-2-1	2-1-1	1	
Seg.2.b	587,581.94	4,792,628.64	2-2-2	2-2-1	0	
Seg.2.c	587,577.76	4,792,645.30	2-2-3	2-2-1	0	
Seg.3	587,610.23	4,792,515.96	2-3-1	2-2-2	1	
Seg.5	587,217.48	4,791,888.06	2-5-1	2-3-1	1	
Seg.6	587,203.98	4,791,877.88	2-6-1	2-5-1	1	
Seg.7	587,556.49	4,792,640.32	2-7-1	2-2-3	1	
Seg.8	587,251.89	4,792,457.59	2-8-1	2-7-1	1	
Seg.9	587,013.43	4,792,243.29	2-9-1	2-8-1	1	
Seg.10	587,015.21	4,792,235.97	2-10-1	2-9-1	1	
Seg.11	587,062.10	4,792,037.33	2-11-1	2-10-1	1	C1
Seg.3	588,041.81	4,789,667.63	9-3-1	C1	1	
Seg.4	588,113.03	4,789,852.11	9-4-1	9-3-1	1	C2
Seg.3	588,027.81	4,788,688.02	10-3-1	C2	1	
Seg.4	588,099.03	4,788,872.50	10-4-1	9-3-1	1	C4
Seg.3	592,857.50	4,790,512.88	12-3-1	C4	0	
Seg.4	593,149.67	4,790,678.79	12-4-1	C4	0	C5
Seg.3	592,089.27	4,789,818.07	13-3-1	C5	0	
Seg.4	592,381.44	4,789,983.98	13-4-1	C5	0	C6
Seg.3	590,829.77	4,790,237.90	14-3-1	C6	0	
Seg.4	591,121.94	4,790,403.81	14-4-1	C6	0	C6
Seg.3	591,179.63	4,789,468.21	15-3-1	C6	0	
Seg.4	591,471.80	4,789,634.12	15-4-1	C6	0	C7

Table D.4: Segment Connections of Group 4

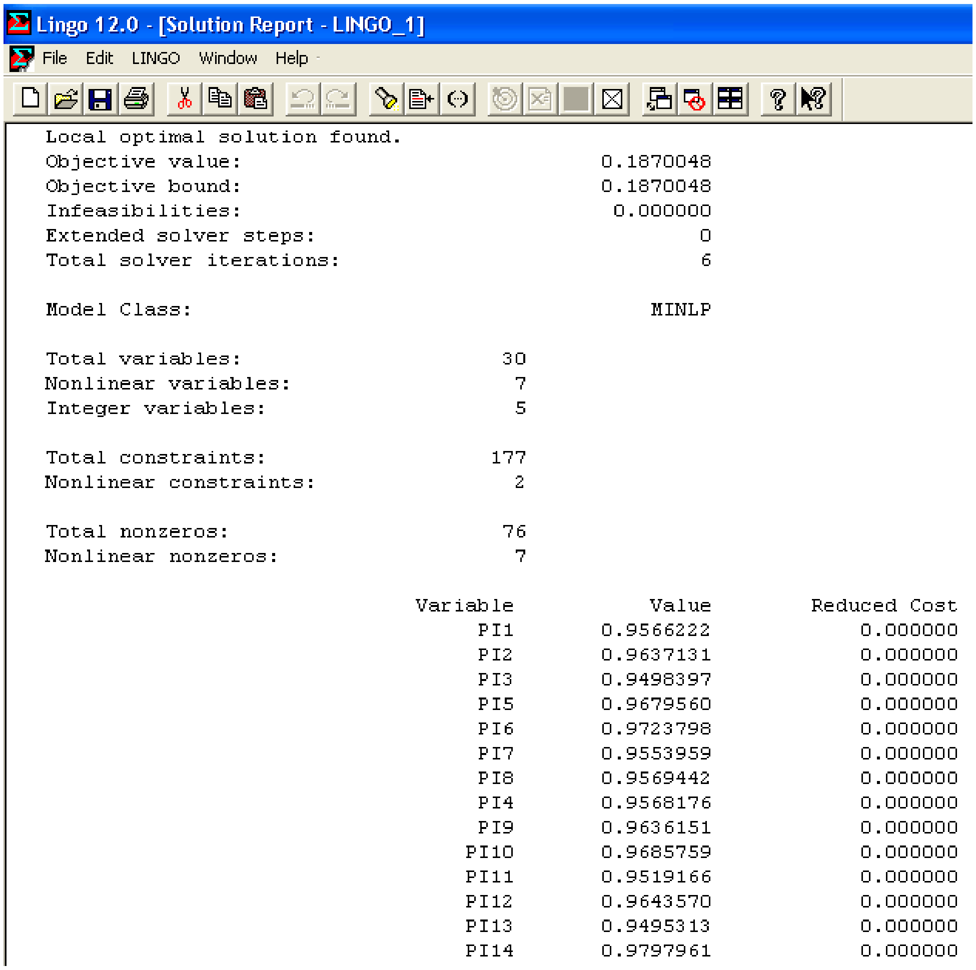
Segment	X	Y	COMPKEY	Connect to	Relation	Point
Seg.1	593,154	4,783,859	4-1-1	s		
Seg.2	593,144	4,783,862	4-2-1	4-1-1	1	
Seg.3.a	593,088	4,783,677	4-3-1	4-2-1	1	
Seg.3.b	593,086	4,783,670	4-3-2	4-3-1	0	
Seg.3.c	593,086	4,783,670	4-3-3	4-3-1	0	
Seg.4	593,173	4,783,634	4-4-1	4-3-2	1	
Seg.5	593,083	4,783,661	4-5-1	4-3-3	1	
Seg.6	593,039	4,783,479	4-6-1	4-5-1	1	
Seg.7	593,225	4,783,417	4-7-1	4-6-1	1	
Seg.8	593,225	4,783,417	4-8-1	4-7-1	1	C1
Seg.1	591,570	4,787,136	3-1-1	C1	1	
Seg.2	591,560	4,787,139	3-2-1	3-1-1	1	
Seg.3.a	591,504	4,786,954	3-3-1	3-2-1	1	
Seg.3.b	591,502	4,786,946	3-3-2	3-3-1	0	
Seg.3.c	591,502	4,786,946	3-3-3	3-3-1	0	
Seg.4	591,589	4,786,911	3-4-1	3-3-2	1	
Seg.5	591,499	4,786,938	3-5-1	3-3-3	1	
Seg.6	591,455	4,786,756	3-6-1	3-5-1	1	
Seg.7	591,641	4,786,694	3-7-1	3-6-1	1	
Seg.8	591,641	4,786,694	3-8-1	3-7-1	1	C2
Seg.1.a	591,779	4,789,270	15-1-1	C2	1	
Seg.1.b	591,397	4,789,400	15-1-2	15-1-1	0	
Seg.1.c	591,397	4,789,400	15-1-3	15-1-1	0	
Seg.2	591,472	4,789,634	15-2-1	15-1-2	1	
Seg.5	591,234	4,789,649	15-5-1	15-2-1	1	
Seg.6	591,181	4,789,472	15-6-1	15-1-3	1	C3
Seg.1.a	591,429	4,790,040	14-1-1	C3	1	
Seg.1.b	591,047	4,790,169	14-1-2	14-1-1	0	
Seg.1.c	591,047	4,790,169	14-1-3	14-1-1	0	
Seg.2	591,122	4,790,404	14-2-1	14-1-2	1	
Seg.5	590,885	4,790,418	14-5-1	14-2-1	1	
Seg.6	590,831	4,790,242	14-6-1	14-1-3	1	C4
Seg.1.a	592,688	4,789,620	13-1-1	C4	1	
Seg.1.b	592,307	4,789,750	13-1-2	13-1-1	0	
Seg.1.c	592,307	4,789,750	13-1-3	13-1-1	0	
Seg.2	592,381	4,789,984	13-2-1	13-1-2	1	
Seg.5	592,144	4,789,999	13-5-1	13-2-1	1	
Seg.6	592,090	4,789,822	13-6-1	13-1-3	1	C5
Seg.1.a	593,456	4,790,315	12-1-1	C5	1	
Seg.1.b	593,075	4,790,444	12-1-2	12-1-1	0	
Seg.1.c	593,075	4,790,444	12-1-3	12-1-1	0	
Seg.2	593,150	4,790,679	12-2-1	12-1-2	1	
Seg.5	592,912	4,790,693	12-5-1	12-2-1	1	
Seg.6	592,859	4,790,517	12-6-1	12-1-3	1	C6

APPENDIX (E): Optimum Scheduling Using Lingo 12



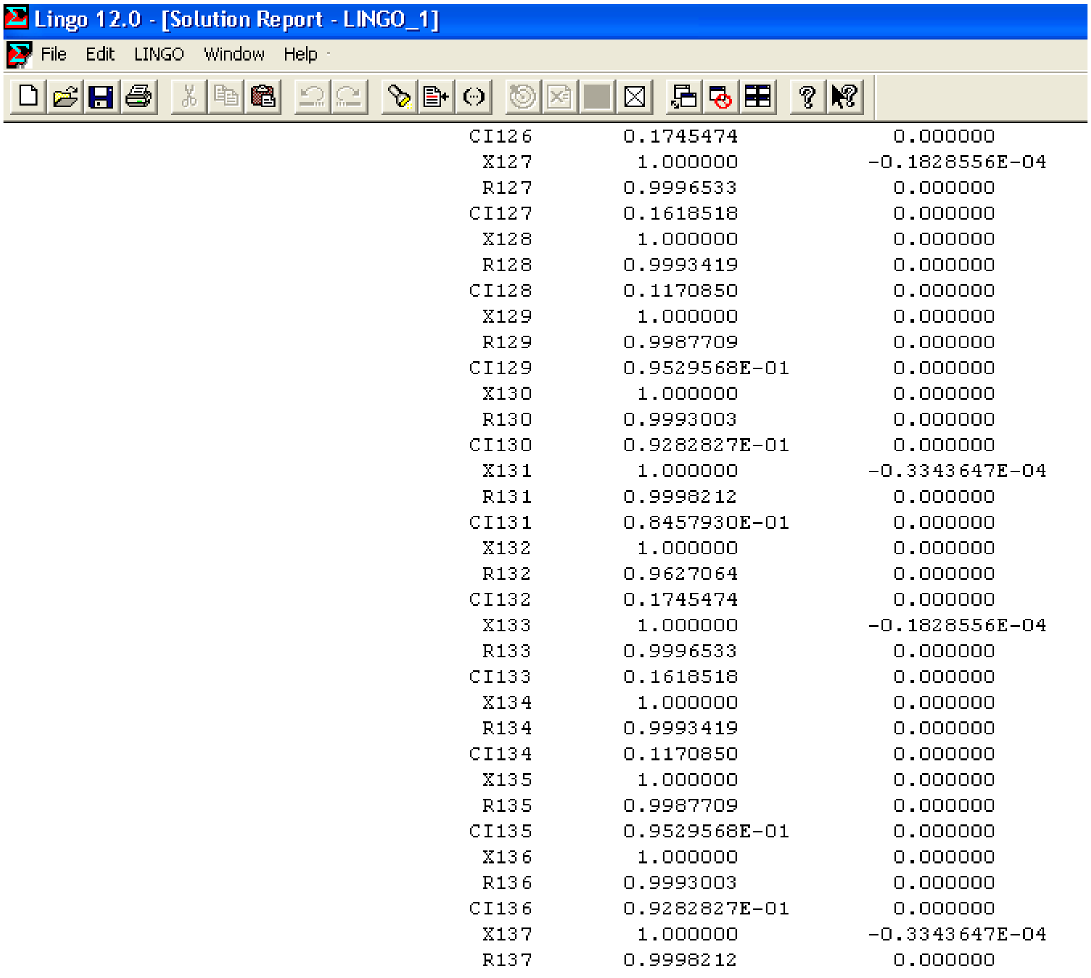
```
MODEL:
! Maximize Priority index PI;[STAGE_PI] Max=PI1*PI2*(1-((1-PI3*PI5*PI6*PI7*PI8)*(1-PI4*PI9*PI10*PI11*PI12*PI13)))*PI14*PI15*(1-((1-PI16*PI18*PI19*PI20*PI21)
! Priority index of segments;
PI1=((X1*(1-R1)+R1))*(1-CI1);PI2=((X2*(1-R2)+R2))*(1-CI2);PI3=((X3*(1-R3)+R3))*(1-CI3);PI4=((X4*(1-R4)+R4))*(1-CI4);PI5=((X5*(1-R5)+R5))*(1-CI5);PI6=((X6*(1
PI66=((X66*(1-R66)+R66))*(1-CI66);PI67=((X67*(1-R67)+R67))*(1-CI67);PI68=((X68*(1-R68)+R68))*(1-CI68);PI69=((X69*(1-R69)+R69))*(1-CI69);PI70=((X70*(1-R70)+R
!Rehabilitation time and budget of the city;T_planning<=720;Av_Budget<=1E+07;
! Segment cost constraint of rehabilitation;
CC1=C1*(X1);CC2=C2*(X2);CC3=C3*(X3);CC4=C4*(X4);CC5=C5*(X5);CC6=C6*(X6);CC7=C7*(X7);CC8=C8*(X8);CC9=C9*(X9);CC10=C10*(X10);CC11=C11*(X11);CC12=C12*(X12);CC1
! Segment time constraint of rehabilitation;
TC1=T1*(X1);TC2=T2*(X2);TC3=T3*(X3);TC4=T4*(X4);TC5=T5*(X5);TC6=T6*(X6);TC7=T7*(X7);TC8=T8*(X8);TC9=T9*(X9);TC10=T10*(X10);TC11=T11*(X11);TC12=T12*(X12);TC1
! Packages Constraints;
X125-X18=0;X139-X125=0;X145-X139=0;X145-X18=0;X131-X127=0;X133-X131=0;X133-X127=0;X143-X137=0;X143-X137=0;X14-X6=0;X17-X14=0;X21-X17=0;X22-X21=0;X27-X22=0;X
! Reliability Data of segments;R1=0.9975507;R2=0.9941655;R3=0.9950791;R4=0.9961507;R5=0.9991816;R6=0.9998034;R7=0.9965;R8=0.9990112;R9=0.9997709;R10=0.99965
! Criticality Index Data of segments;
CI1=0.04337779;CI2=0.03628689;CI3=0.05016032;CI4=0.04318238;CI5=0.03204403;CI6=0.02762024;CI7=0.04460409;CI8=0.04305584;CI9=0.03638488;CI10=0.0314241;CI11=0
! Data of Rehabilitation cost of segments;C1=0;C2=0;C3=0;C4=0;C5=0;C6=0;C7=0;C8=0;C9=0;C10=0;C11=0;C12=0;C13=0;C14=0;C15=0;C16=0;C17=0;C18=0;C19=0;C20=0;C21
! Data of Rehabilitation time of segments;T1=0;T2=0;T3=0;T4=0;T5=0;T6=0;T7=0;T8=0;T9=0;T10=0;T11=0;T12=0;T13=0;T14=0;T15=0;T16=0;T17=0;T18=0;T19=0;T20=0;T21
! Segment rehabilitation of segment: X=1, rehabilitation; !X=0 no rehabilitation;X1=1;X2=1;X3=1;X4=1;X5=1;X6=1;X7=1;X8=1;X9=1;X10=1;X11=1;X12=1;X13=1;X14=1;
! Cost of package;
CP1=CC18+CC125+CC139+CC145;CP2=CC127+CC131+CC133;CP3=CC137+CC143;
CP4=CC6+CC14+CC17+CC21+CC22+CC27+CC29+CC30+CC32+CC37+CC39+CC40+CC42+CC47+CC49+CC50+CC52+CC57+CC59+CC60+CC62+CC65+CC68+CC70+CC71+CC73+CC76+CC78+CC79+CC108+CC
CP5=CC23+CC24+CC25+CC34+CC35+CC44+CC45+CC54+CC55+CC64+CC72+CC80+CC105+CC106+CC115+CC116;
CP6=CC15+CC33+CC43+CC53+CC63+CC114+CC124+CC129+CC130+CC135+CC136+CC141+CC142+CC147+CC148;
CP7=CC16+CC61+CC66+CC67+CC75+CC112+CC122+CC128+CC134+CC140+CC146;CP8=CC31+CC41+CC51+CC74;
CP9=CC1+CC2+CC3+CC4+CC5+CC7+CC8+CC9+CC10+CC11+CC12+CC13+CC19+CC20+CC26+CC28+CC36+CC38+CC46+CC48+CC56+CC58+CC69+CC77+CC81+CC82+CC83+CC84+CC85+CC86+CC87+CC88+
! Time of package;
TP1=TC18+TC125+TC139+TC145;TP2=TC127+TC131+TC133;TP3=TC137+TC143;
TP4=TC6+TC14+TC17+TC21+TC22+TC27+TC29+TC30+TC32+TC37+TC39+TC40+TC42+TC47+TC49+TC50+TC52+TC57+TC59+TC60+TC62+TC65+TC68+TC70+TC71+TC73+TC76+TC78+TC79+TC108+TC
TP5=TC23+TC24+TC25+TC34+TC35+TC44+TC45+TC54+TC55+TC64+TC72+TC80+TC105+TC106+TC115+TC116;
TP6=TC15+TC33+TC43+TC53+TC63+TC114+TC124+TC129+TC130+TC135+TC136+TC141+TC142+TC147+TC148;
TP7=TC16+TC61+TC66+TC67+TC75+TC112+TC122+TC128+TC134+TC140+TC146;TP8=TC31+TC41+TC51+TC74;
TP9=TC1+TC2+TC3+TC4+TC5+TC7+TC8+TC9+TC10+TC11+TC12+TC13+TC19+TC20+TC26+TC28+TC36+TC38+TC46+TC48+TC56+TC58+TC69+TC77+TC81+TC82+TC83+TC84+TC85+TC86+TC87+TC88+
! Cost and time of stage;
Contract_price=CP1+CP2+CP3+CP4+CP5+CP6+CP7+CP8+CP9;Contract_price<=2500000;
AC=CO+Contract_price;
StageTime=@SMAX(TP1,TP2,TP3,TP4,TP5,TP6,TP7,TP8,TP9);
TT_stages=TO+StageTime;
Av_Budget>=AC;
T_planning>=TT_stages;
CO=6054083;TO=448;
! DATA Pointers;
```

Figure E.1: Optimum Scheduling: Generated Input using DSSWATER



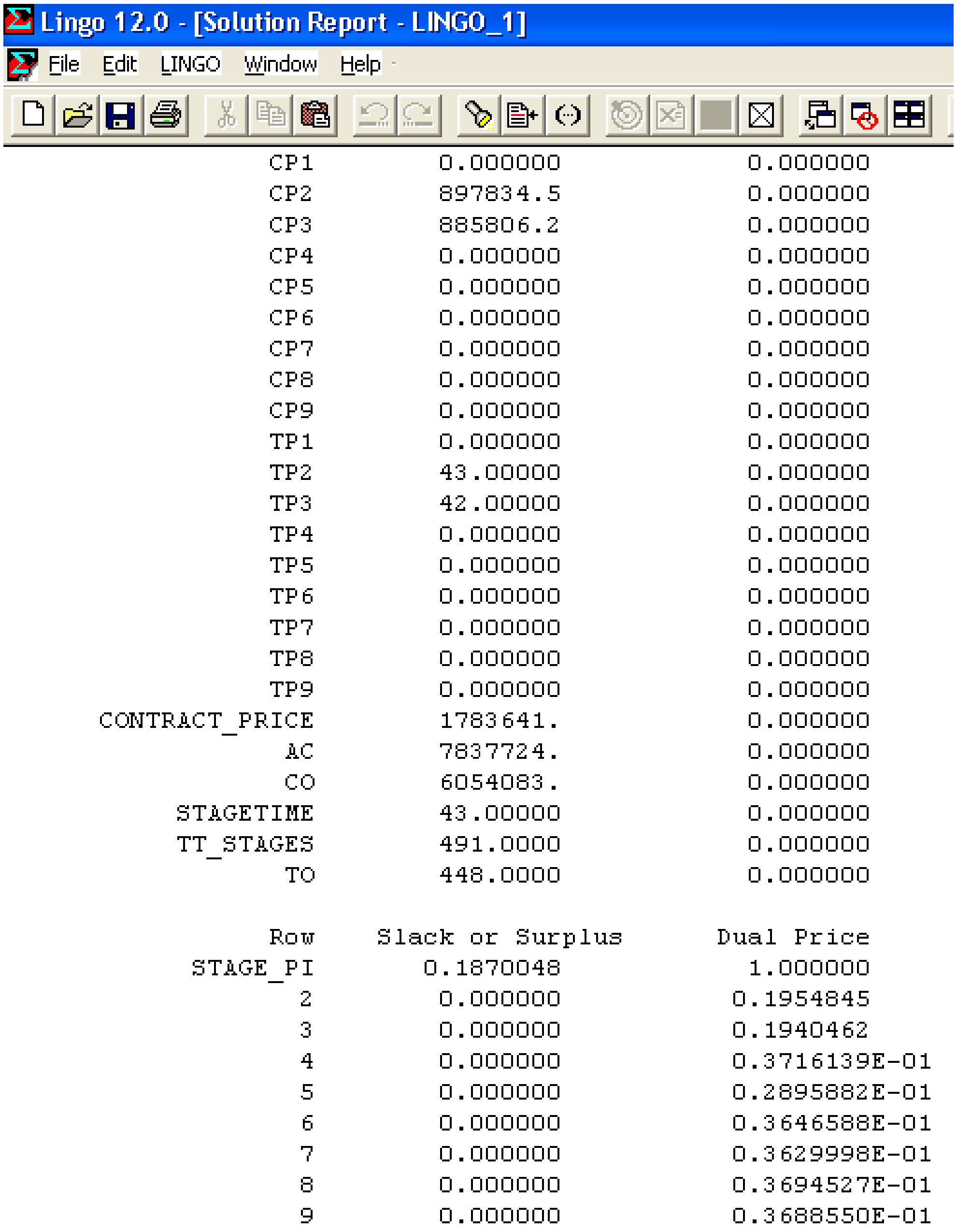
```
  Local optimal solution found.
  Objective value:                              0.1870048
  Objective bound:                              0.1870048
  Infeasibilities:                               0.000000
  Extended solver steps:                                0
  Total solver iterations:                              6

  Model Class:                                      MINLP

  Total variables:                    30
  Nonlinear variables:                 7
  Integer variables:                   5

  Total constraints:                 177
  Nonlinear constraints:               2

  Total nonzeros:                     76
  Nonlinear nonzeros:                  7

                                Variable           Value        Reduced Cost
                                     PI1       0.9566222            0.000000
                                     PI2       0.9637131            0.000000
                                     PI3       0.9498397            0.000000
                                     PI5       0.9679560            0.000000
                                     PI6       0.9723798            0.000000
                                     PI7       0.9553959            0.000000
                                     PI8       0.9569442            0.000000
                                     PI4       0.9568176            0.000000
                                     PI9       0.9636151            0.000000
                                    PI10       0.9685759            0.000000
                                    PI11       0.9519166            0.000000
                                    PI12       0.9643570            0.000000
                                    PI13       0.9495313            0.000000
                                    PI14       0.9797961            0.000000
```

Figure E.2-a: Optimum Scheduling: Output- Reduced Cost (PI)



```
           CI126        0.1745474          0.000000
            X127         1.000000       -0.1828556E-04
            R127        0.9996533          0.000000
           CI127        0.1618518          0.000000
            X128         1.000000          0.000000
            R128        0.9993419          0.000000
           CI128        0.1170850          0.000000
            X129         1.000000          0.000000
            R129        0.9987709          0.000000
           CI129        0.9529568E-01      0.000000
            X130         1.000000          0.000000
            R130        0.9993003          0.000000
           CI130        0.9282827E-01      0.000000
            X131         1.000000       -0.3343647E-04
            R131        0.9998212          0.000000
           CI131        0.8457930E-01      0.000000
            X132         1.000000          0.000000
            R132        0.9627064          0.000000
           CI132        0.1745474          0.000000
            X133         1.000000       -0.1828556E-04
            R133        0.9996533          0.000000
           CI133        0.1618518          0.000000
            X134         1.000000          0.000000
            R134        0.9993419          0.000000
           CI134        0.1170850          0.000000
            X135         1.000000          0.000000
            R135        0.9987709          0.000000
           CI135        0.9529568E-01      0.000000
            X136         1.000000          0.000000
            R136        0.9993003          0.000000
           CI136        0.9282827E-01      0.000000
            X137         1.000000       -0.3343647E-04
            R137        0.9998212          0.000000
```

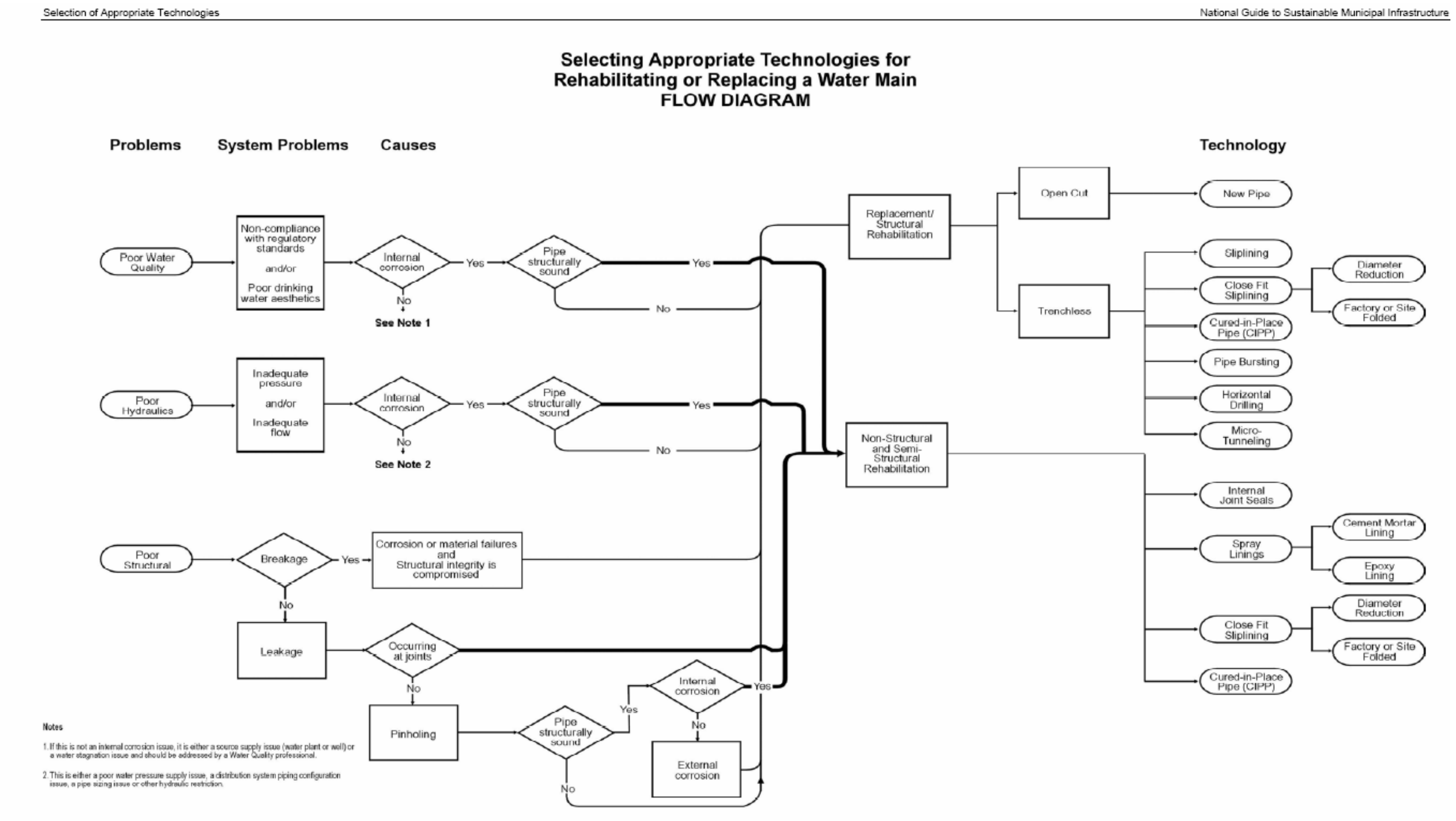
Figure E.3-b: Optimum Scheduling: Output- Reduced Cost (Reliability& Rehabilitation Options)



```
                  CP1        0.000000           0.000000
                  CP2        897834.5           0.000000
                  CP3        885806.2           0.000000
                  CP4        0.000000           0.000000
                  CP5        0.000000           0.000000
                  CP6        0.000000           0.000000
                  CP7        0.000000           0.000000
                  CP8        0.000000           0.000000
                  CP9        0.000000           0.000000
                  TP1        0.000000           0.000000
                  TP2        43.00000           0.000000
                  TP3        42.00000           0.000000
                  TP4        0.000000           0.000000
                  TP5        0.000000           0.000000
                  TP6        0.000000           0.000000
                  TP7        0.000000           0.000000
                  TP8        0.000000           0.000000
                  TP9        0.000000           0.000000
       CONTRACT_PRICE        1783641.           0.000000
                   AC        7837724.           0.000000
                   CO        6054083.           0.000000
            STAGETIME        43.00000           0.000000
            TT_STAGES        491.0000           0.000000
                   TO        448.0000           0.000000

                  Row    Slack or Surplus      Dual Price
             STAGE_PI        0.1870048           1.000000
                    2        0.000000           0.1954845
                    3        0.000000           0.1940462
                    4        0.000000           0.3716139E-01
                    5        0.000000           0.2895882E-01
                    6        0.000000           0.3646588E-01
                    7        0.000000           0.3629998E-01
                    8        0.000000           0.3694527E-01
                    9        0.000000           0.3688550E-01
```

Figure E.4: Optimum Scheduling: Output- Slack and Dual Price

APPENDIX (F): Flow Chart for Selecting the Rehabilitation or Replacement Technology



Notes

1. If this is not an internal corrosion issue, it is either a source supply issue (water plant or well) or a water stagnation issue and should be addressed by a Water Quality professional.
2. This is either a poor water pressure supply issue, a distribution system piping configuration issue, a pipe sizing issue or other hydraulic restriction.

Figure F.1: Flow Chart for Selecting the Rehabilitation or Replacement Technology (NRC: Best Practices, 2003)

Appendix (G): Survey Contact Information

Table G. 1: Survey Contact Information

Asset Management Teams (Organization)	Title	Position	No. of Employees
City of Hamilton (Ontario, Canada)	Asset Management Director	S.Engineer	1
	Asset Management Engineer	Engineer	6
AECOM (Ontario, Canada)	Asset Management Leader	S.Engineer	3
	Asset Management Engineer	Engineer	3
UEM (Ontario, Canada)	Asset Management Director	S.Engineer	1
	Asset Management Leader	S.Engineer	1
	Asset Management Engineer	Engineer	1
Total			**16**

APPENDIX (H): SAMPLE EXPERT SURVEY QUESTIONNAIRE

Dear Sir/ Madame,

My name is Alaa Salman, PhD student in the area of Construction Engineering and Management at Concordia University, Montreal, Canada. I am currently conducting a research on the reliability of water distribution networks.

I would like to seek your assistance in my research as I am currently trying to gather information about performance of water distribution networks to be used in my data base. I would be grateful if you could complete the attached questionnaire.

The information gathered from the questionnaire will be used in the data base of a computer system called “DSSWATER.” Please be assured that all information shared will be strictly confidential and used only for academic purposes. Please do not hesitate to contact me if you need any clarification or additional information. Sharing your valuable information is highly appreciated.

Best regards,

Alaa Salman

Graduate Student
PhD student- Construction Engineering and Management
Dep. Building, Civil, & Environmental Engineering – Concordia University
Montreal, Quebec
Canada

Osama Moselhi, PhD, Professor

Tarek Zayed, PhD, Associate Professor

1515 St. Catherine W.
H3G 1M8
Dep. Building, Civil, & Environmental Engineering – Concordia University
Montreal, Quebec
Canada

Questionnaire Form

All responses will remain **STRICTLY CONFIDENTIAL** and will be used for educational and research purposes only.

PART 1: COMPANY'S PROFILE

COMPANY'S NAME: --

TITLE OR POSITION OF RESPONDENT: --

ADDRESS:

TELEPHONE/ FAX / WEBSITE / E-MAIL:

How many years have you been in business; please specify?

PART 2: WATER DISTRIBUTION NETWORK'S CHARACTERISTICS

1. Water Components' Weights:

Assume that a hypothetical segment of water encompasses a pipe, an isolation valve, a control valve, and a hydrant. Please, try to complete the following table to show the importance of water components' weight. The total percentages should sum to 100.

Component	Important weight (%)
A Pipe	
An Isolation valve	
A Control valve	
A Hydrant	
Total	100

2. Pair-wise Comparison among Factors that Affects the Criticality of Water Mains:

Please, try to make a pair-wise comparison among factors based on your evaluation to the importance of this factor over the other. In other words, compare the importance of each factor against each of the other factors individually. This importance is evaluated regarding its effect on Criticality Index.

The following tables show the pair-wise comparison matrix among the different factors affecting the criticality of water mains based upon the proposed hierarchy (levels). For example, if the pipe size is worth 2 times as important as the pipe depth in affecting the criticality of water mains, just put 2 in the intersection cell of the pipe size row with the depth column. In contrast, the intersection cell between the depth and the pipe size will be the reverse (1/2). The matrices are as follows:

PART 3: FACTORS' WEIGHT of REHABILITATION METHOD

Water Components' Weight:

Please, try to complete the following table to show the factors' weight of rehabilitation methods. The total weight should be 100.

Component	Weight (%)
Rehabilitation cost	
Impact on environment	
Trial use of new technologies	
Total	100

Land USE (----------------)

Economic	Pipe size	Bury depth	Material	Low accessibility	**Weight**	**Consistency Ratio (CR)**	**EVALUATION**
Pipe size	1.00						
Bury depth		1.00					
Material			1.00				
Low accessibility				1.00			
Sum							

Operational	Critical customer	Material	Pipe size	**Weight**		**Consistency Ratio (CR)**	**EVALUATION**
Critical customer	1.00						
Material		1.00					
Pipe size			1.00				
Sum							

Social	Public Disruption	Visibility	**Weight**		**Consistency Ratio (CR)**	**EVALUATION**
Public Disruption	1.00					
Visibility		1.00				
Sum						

Public Disruption	Road type	No diversion	**Weight**		**Consistency Ratio (CR)**	**EVALUATION**
Road type	1.00					
No diversion		1.00				
Sum						

Environmental	Water body proximity	Sensitive area	Pipe size	**Weight**		**Consistency Ratio (CR)**	**EVALUATION**
Water body proximity	1.00						
Sensitive area		1.00					
Pipe size		2.00	1.00				
Sum							

Level 1	Economic	Operational	Social	Environmental	**Weight**	**Consistency Ratio (CR)**	**EVALUATION**
Economic	1.00						
Operational		1.00					
Social			1.00				
Environmental				1.00			
Sum							

PART 4: REHABILITATION SCHEDULE CHARASSTERISTICS AND CONSTRAINTS

1. Number of Sub-networks:

How many sub-networks you would like to consider for rehabilitation scheduling process; 1 sub-network represents a city distribution network, 2 sub-networks represent 2 sub-networks will be considered for scheduling process using clustering method, and so on.

--------------------- Sub-network

2. Rehabilitation Schedule Constraints:

Please complete the following table to consider the rehabilitation schedule constraints:

Constraint	Value	Unit	Note
Available budget of rehabilitation		$	
Planning time of rehabilitation		Year	
Maximum contract price		$	
Maximum limit of rehabilitation package size		$	
Minimum limit of rehabilitation package size		$	

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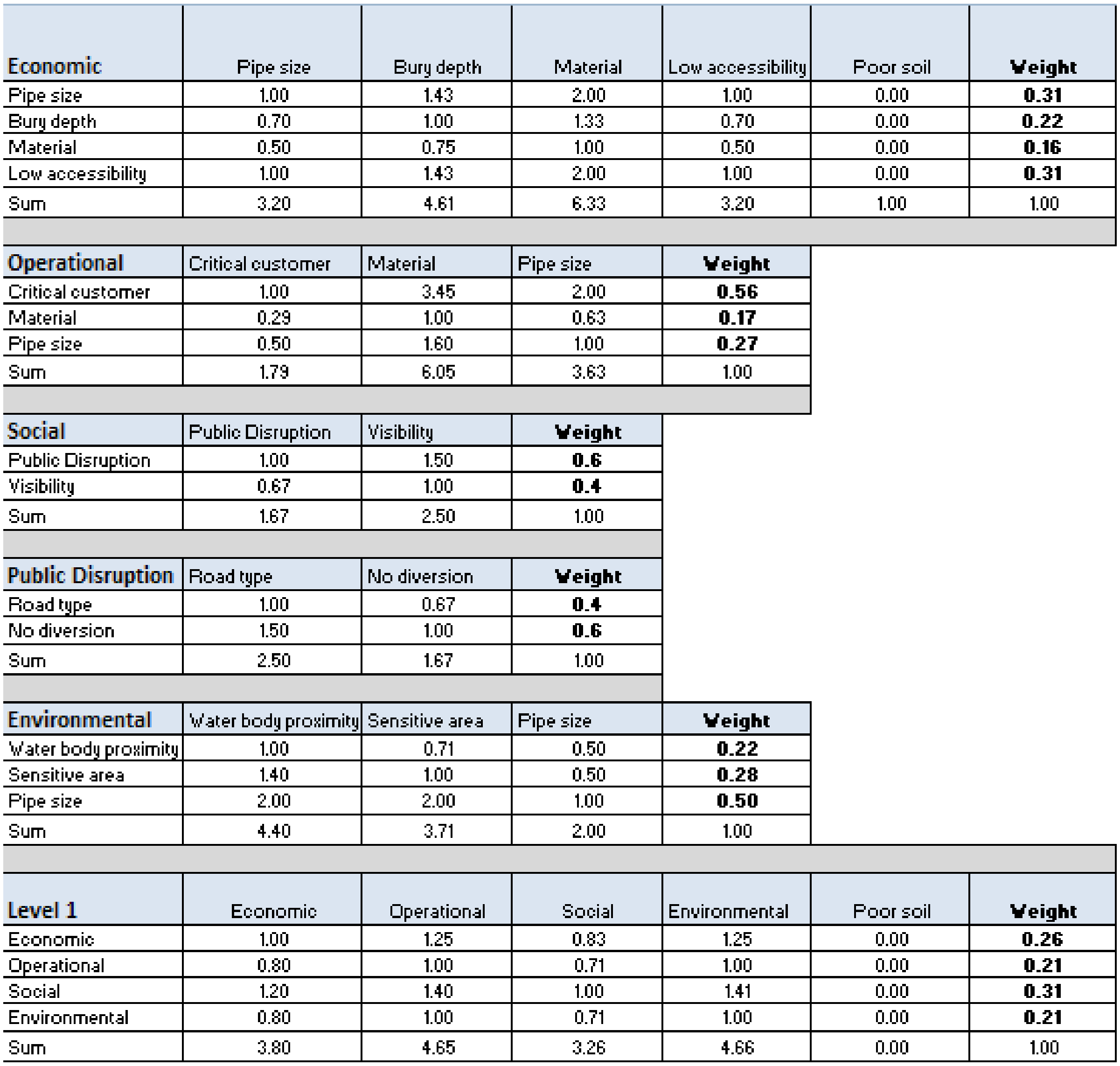
PART 5: ADDITIONAL COMMENTS

Thanking you for your assistance,
Alaa Salman

APPENDIX (I): Critical Factor Weights Using AHP

Table I.1: Critical Factor Weights for Commercial/Industrial using AHP



Economic	Pipe size	Bury depth	Material	Low accessibility	Poor soil	**Weight**
Pipe size	1.00	1.43	2.00	1.00	0.00	**0.31**
Bury depth	0.70	1.00	1.33	0.70	0.00	**0.22**
Material	0.50	0.75	1.00	0.50	0.00	**0.16**
Low accessibility	1.00	1.43	2.00	1.00	0.00	**0.31**
Sum	3.20	4.61	6.33	3.20	1.00	1.00

Operational	Critical customer	Material	Pipe size	**Weight**
Critical customer	1.00	3.45	2.00	**0.56**
Material	0.29	1.00	0.63	**0.17**
Pipe size	0.50	1.60	1.00	**0.27**
Sum	1.79	6.05	3.63	1.00

Social	Public Disruption	Visibility	**Weight**
Public Disruption	1.00	1.50	**0.6**
Visibility	0.67	1.00	**0.4**
Sum	1.67	2.50	1.00

Public Disruption	Road type	No diversion	**Weight**
Road type	1.00	0.67	**0.4**
No diversion	1.50	1.00	**0.6**
Sum	2.50	1.67	1.00

Environmental	Water body proximity	Sensitive area	Pipe size	**Weight**
Water body proximity	1.00	0.71	0.50	**0.22**
Sensitive area	1.40	1.00	0.50	**0.28**
Pipe size	2.00	2.00	1.00	**0.50**
Sum	4.40	3.71	2.00	1.00

Level 1	Economic	Operational	Social	Environmental	Poor soil	**Weight**
Economic	1.00	1.25	0.83	1.25	0.00	**0.26**
Operational	0.80	1.00	0.71	1.00	0.00	**0.21**
Social	1.20	1.40	1.00	1.41	0.00	**0.31**
Environmental	0.80	1.00	0.71	1.00	0.00	**0.21**
Sum	3.80	4.65	3.26	4.66	0.00	1.00

Table I.2: Critical Factor Weights for High Density using AHP

Economic	Pipe size	Bury depth	Material	Low accessibility	**Weight**
Pipe size	1.00	1.43	2.50	0.83	**0.31**
Bury depth	0.70	1.00	1.82	0.63	**0.22**
Material	0.40	0.55	1.00	0.50	**0.14**
Low accessibility	1.20	1.60	2.00	1.00	**0.33**
Sum	3.30	4.58	7.32	2.96	**1.00**

Operational	Critical customer	Material	Pipe size	**Weight**
Critical customer	1.00	3.00	1.25	**0.48**
Material	0.33	1.00	0.63	**0.18**
Pipe size	0.80	1.60	1.00	**0.34**
Sum	2.13	5.60	2.88	1.00

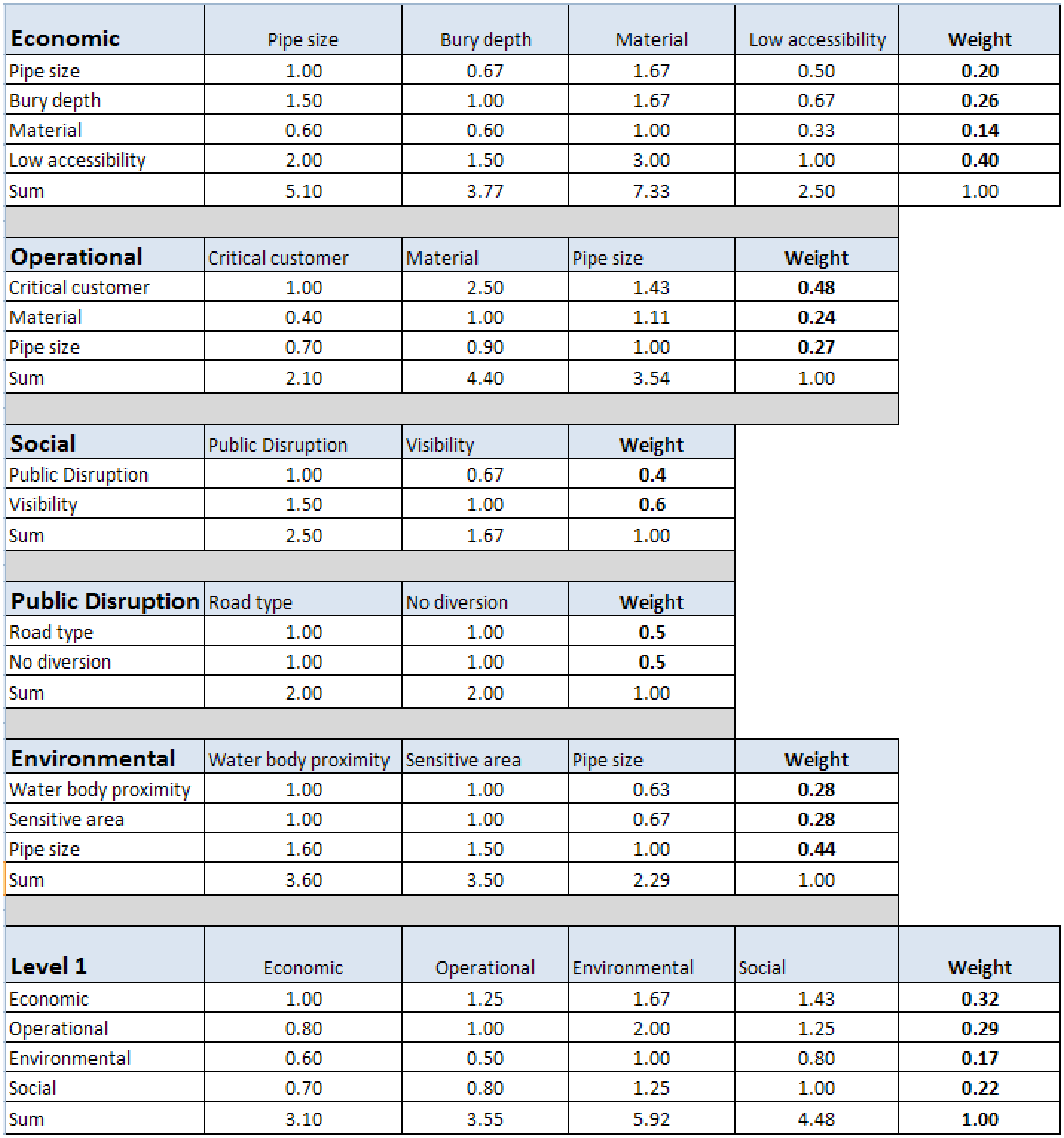
Social	Public Disruption	Visibility	**Weight**
Public Disruption	1.00	1.11	**0.53**
Visibility	0.90	1.00	**0.47**
Sum	1.90	2.11	1.00

Public Disruption	Road type	No diversion	**Weight**
Road type	1.00	0.67	**0.4**
No diversion	1.50	1.00	**0.6**
Sum	2.50	1.67	1.00

Environmental	Water body proximity	Sensitive area	Pipe size	**Weight**
Water body proximity	1.00	1.67	0.67	**0.33**
Sensitive area	0.60	1.00	0.50	**0.21**
Pipe size	1.50	2.00	1.00	**0.46**
Sum	3.10	4.67	2.17	1.00

Level 1	Economic	Operational	Environmental	Social	**Weight**
Economic	1.00	1.05	3.33	0.71	**0.29**
Operational	0.95	1.00	2.22	0.57	**0.24**
Environmental	0.30	0.45	1.00	0.43	**0.12**
Social	1.40	1.75	2.30	1.00	**0.36**
Sum	3.65	4.25	8.86	2.72	**1.00**

Table I.3: Critical Factor Weights for Residential using AHP



Economic	Pipe size	Bury depth	Material	Low accessibility	**Weight**
Pipe size	1.00	0.67	1.67	0.50	**0.20**
Bury depth	1.50	1.00	1.67	0.67	**0.26**
Material	0.60	0.60	1.00	0.33	**0.14**
Low accessibility	2.00	1.50	3.00	1.00	**0.40**
Sum	5.10	3.77	7.33	2.50	1.00

Operational	Critical customer	Material	Pipe size	**Weight**
Critical customer	1.00	2.50	1.43	**0.48**
Material	0.40	1.00	1.11	**0.24**
Pipe size	0.70	0.90	1.00	**0.27**
Sum	2.10	4.40	3.54	1.00

Social	Public Disruption	Visibility	**Weight**
Public Disruption	1.00	0.67	**0.4**
Visibility	1.50	1.00	**0.6**
Sum	2.50	1.67	1.00

Public Disruption	Road type	No diversion	**Weight**
Road type	1.00	1.00	**0.5**
No diversion	1.00	1.00	**0.5**
Sum	2.00	2.00	1.00

Environmental	Water body proximity	Sensitive area	Pipe size	**Weight**
Water body proximity	1.00	1.00	0.63	**0.28**
Sensitive area	1.00	1.00	0.67	**0.28**
Pipe size	1.60	1.50	1.00	**0.44**
Sum	3.60	3.50	2.29	1.00

Level 1	Economic	Operational	Environmental	Social	**Weight**
Economic	1.00	1.25	1.67	1.43	**0.32**
Operational	0.80	1.00	2.00	1.25	**0.29**
Environmental	0.60	0.50	1.00	0.80	**0.17**
Social	0.70	0.80	1.25	1.00	**0.22**
Sum	3.10	3.55	5.92	4.48	**1.00**

Table I.4: Critical Factor Weights for Parks using AHP

Economic	Pipe size	Bury depth	Material	Low accessibility	**Weight**
Pipe size	1.00	0.59	1.47	0.50	**0.19**
Bury depth	1.70	1.00	1.47	0.50	**0.25**
Material	0.68	0.68	1.00	0.50	**0.16**
Low accessibility	2.00	2.00	2.00	1.00	**0.39**
Sum	5.38	4.27	5.94	2.50	**1.00**

Operational	Critical customer	Material	Pipe size	**Weight**
Critical customer	1.00	0.50	0.20	**0.12**
Material	2.00	1.00	0.33	**0.23**
Pipe size	5.00	3.00	1.00	**0.65**
Sum	8.00	4.50	1.53	1.00

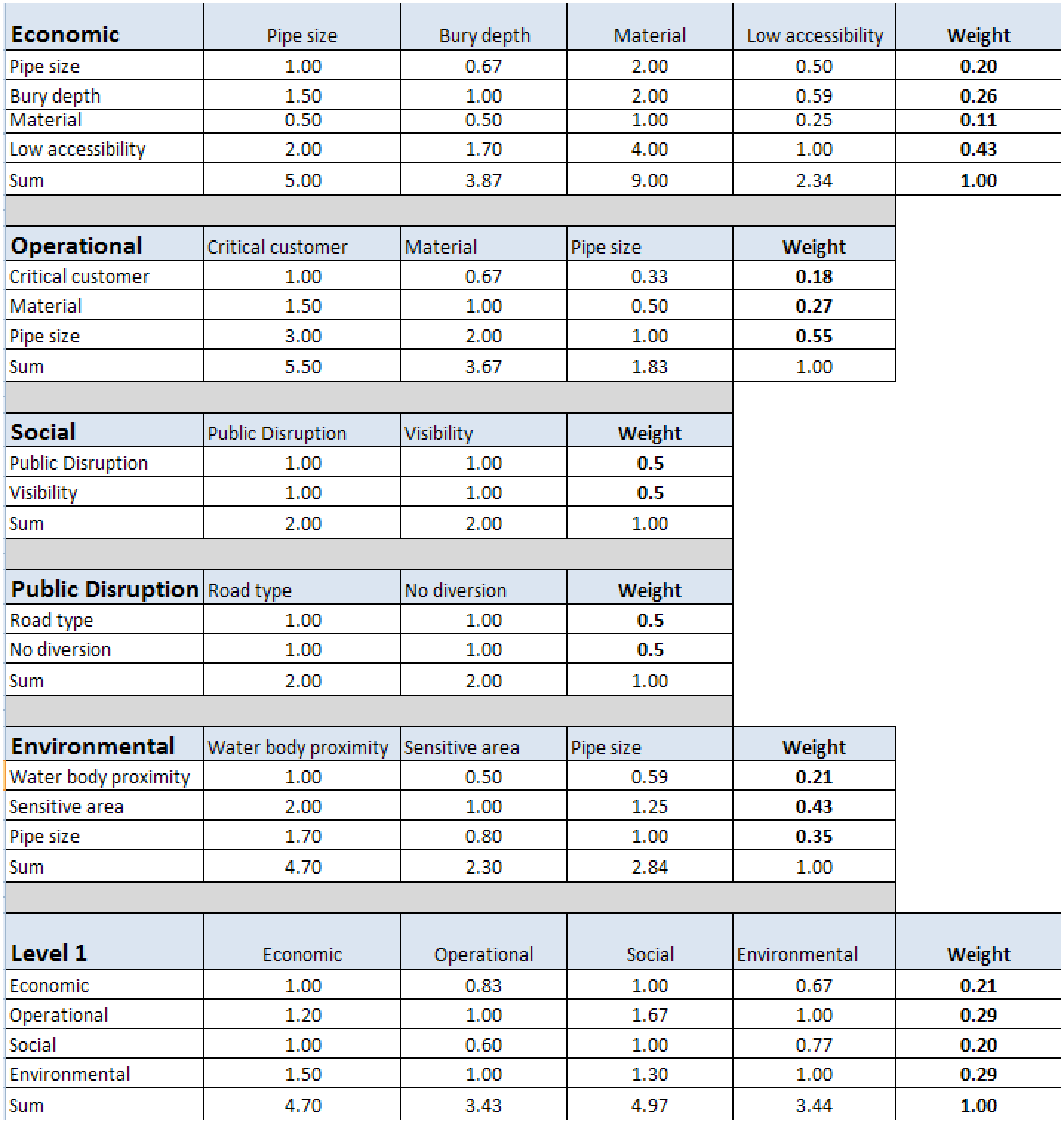
Social	Public Disruption	Visibility	**Weight**
Public Disruption	1.00	0.50	**0.33**
Visibility	2.00	1.00	**0.67**
Sum	3.00	1.50	1.00

Public Disruption	Road type	No diversion	**Weight**
Road type	1.00	1.00	**0.50**
No diversion	1.00	1.00	**0.50**
Sum	2.00	2.00	1.00

Environmental	Water body proximity	Sensitive area	Pipe size	**Weight**
Water body proximity	1.00	0.50	0.50	**0.20**
Sensitive area	2.00	1.00	1.43	**0.45**
Pipe size	2.00	0.70	1.00	**0.35**
Sum	5.00	2.20	2.93	1.00

Level 1	Economic	Operational	Social	Environmental	**Weight**
Economic	1.00	0.77	2.00	0.67	**0.24**
Operational	1.30	1.00	2.00	0.83	**0.29**
Social	0.50	0.50	1.00	0.77	**0.16**
Environmental	1.50	1.20	1.30	1.00	**0.30**
Sum	4.30	3.47	6.30	3.27	**1.00**

Table I.5: Critical Factor Weights for Undeveloped using AHP



Economic	Pipe size	Bury depth	Material	Low accessibility	Weight
Pipe size	1.00	0.67	2.00	0.50	**0.20**
Bury depth	1.50	1.00	2.00	0.59	**0.26**
Material	0.50	0.50	1.00	0.25	**0.11**
Low accessibility	2.00	1.70	4.00	1.00	**0.43**
Sum	5.00	3.87	9.00	2.34	**1.00**

Operational	Critical customer	Material	Pipe size	Weight
Critical customer	1.00	0.67	0.33	**0.18**
Material	1.50	1.00	0.50	**0.27**
Pipe size	3.00	2.00	1.00	**0.55**
Sum	5.50	3.67	1.83	1.00

Social	Public Disruption	Visibility	Weight
Public Disruption	1.00	1.00	**0.5**
Visibility	1.00	1.00	**0.5**
Sum	2.00	2.00	1.00

Public Disruption	Road type	No diversion	Weight
Road type	1.00	1.00	**0.5**
No diversion	1.00	1.00	**0.5**
Sum	2.00	2.00	1.00

Environmental	Water body proximity	Sensitive area	Pipe size	Weight
Water body proximity	1.00	0.50	0.59	**0.21**
Sensitive area	2.00	1.00	1.25	**0.43**
Pipe size	1.70	0.80	1.00	**0.35**
Sum	4.70	2.30	2.84	1.00

Level 1	Economic	Operational	Social	Environmental	Weight
Economic	1.00	0.83	1.00	0.67	**0.21**
Operational	1.20	1.00	1.67	1.00	**0.29**
Social	1.00	0.60	1.00	0.77	**0.20**
Environmental	1.50	1.00	1.30	1.00	**0.29**
Sum	4.70	3.43	4.97	3.44	**1.00**

Hamilton

City of Hamilton

City Hall, 71 Main Street West
Hamilton, Ontario,

Asset Management Section,
Environment and Sustainable Infrastructure Division, Public Works Department
Physical Address: 320 - 77 James St. N., Hamilton, ON, L8R 2K3
Phone: 905.546.2424, ext. 6397   Fax: 905.546.4494
Email: erika.waite@hamilton.ca

April 14, 2011

To Whom it may concern,

RE: Watermain Criticality Model Development Validation – Alaa Salman

This letter confirms the use of the Criticality Model, developed by Alaa Salman under supervision of Ross Homeniuk of AECOM Consultants and Drs.Osama Moselhi and Tarek Zayed of Concordia University, by the Asset Management Section of the City of Hamilton for the City's the entire water network distribution system in 2011. The model is embedded in a computerized system that utilizes the Analytical Hierarchy Process and accounts for land use in the city. Based on the application of the system and the results obtained, the team attests to the following:

1. The Criticality Model is practical, flexible and its generated results are reliable and support our asset management requirements for the water distribution network.
2. In general, the Criticality Model covers the scope of the project.
3. The selected factors and categories embedded in the system are comprehensive and represent the scope of the project satisfactorily.
4. The input and output of the model are in line with industry practice and are compatible with GIS tools such as GeoMedia.
5. The concept of criticality, according to land use, is useful and assists in eliminating bias in resource allocations needed to sustain the operating conditions of the entire distribution network.
6. The application of the Analytical Hierarchy Process (AHP) is particularly helpful to the Asset Management Team to fairly judge the weights of the critical factors.
7. The Criticality Model is flexible in view of its ability to account for a wide range of practical factors and parameters.
8. The Asset Management Team has found that the developed model can be integrated in our asset management operations.

Regards,

Erika Waite

Erika Waite
Senior Project Manager, Infrastructure Programming
Asset Management Section,
Environment and Sustainable Infrastructure Division,
Public Works Department,
City of Hamilton