Automated Selection of Trenchless Technology for Rehabilitation of Water Mains

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ABSTRACT

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The condition of the water distribution networks in Canada has been deteriorating over the past few decades due to the lack of preventive maintenance and asset management programs. It was reported that 60 percent of the water mains in Canada became unacceptable and inefficient for use. A study conducted by the Canadian Water and Wastewater Association (CWWA) estimates an outlay of $34 billion is needed to replace the existing 112,000 Km of water mains in Canada. Trenchless technology is one of the rapidly developing areas in rehabilitation and replacement of water mains. Selection of the most suitable trenchless method(s) is currently performed manually by a decision-maker, thus other more efficient and new methods may be overlooked. This thesis studies the methods used and the decision-making process involved in the rehabilitation of water mains with a focus on trenchless technology. A decision-support methodology has been developed using information gathered from the literature, a survey questionnaire form, and from a field investigation carried out by the author. The methodology incorporates Multi-Attribute Utility Theory and Analytical Hierarchy Process in its decision support system. The methodology has been implemented in an automated system composed of three modules: interactive flowcharts, Data Files and Query System, and a Decision Support System. The developed system automates the selection of the most suitable trenchless method for the rehabilitation of a specified water main project taking into consideration the project's characteristics and the decision-maker's preference. The system was tested using a case study of a water main rehabilitation project.

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CHAPTER 1

Introduction

1.1 Overview

In recent years, many researchers have documented the deteriorated condition of urban infrastructure facilities (Shehab Eldeen 2001). In spite of the increase in public infrastructure investments over the past few years, factors such as population growth and the poor condition of the infrastructure assets due to years of inadequate investment, lack of preventive maintenance and asset management programs have greatly affected the status of the civil infrastructure (InfraGuide 2004). In a number of cases, operation beyond design life and capacity of these assets has contributed to the deterioration of the civil infrastructure. Most municipalities agree that there is an urgent need for renewal of their infrastructure (Allouche et al. 2002). It is estimated that Canada needs to spend about $75 billion to restore the condition of its civil infrastructure systems (InfraGuide 2004). Currently, many Canadian municipalities are faced with the need to renew or rehabilitate extensive sections of their water and wastewater networks (Allouche et al. 2002). Water distribution networks are considered one of the major underground infrastructure facilities. For the past decades, the condition of the water distribution networks in Canada has extensively deteriorated, thereby impacting their performance (Infrastructure Canada 2004). It was reported that 60 percent of the water mains in Canada became unacceptable and inefficient for use, thus requiring immediate action (Mirza and Haider 2003). A study conducted by the Canadian Water and Wastewater Association (CWWA) in 1997 estimates an outlay of $34 billion is needed to replace the 112,000 Km of water mains in Canada. In addition, the CWWA's study estimates that an amount of $12.5 billion must be invested over a 15 year period to replace existing water mains and to construct new ones to service the expected population growth.

The conditions referred to above accelerate the aging process of water mains. The aging process begins as soon as the pipe is installed due, at times, to the aggressiveness of the surrounding environment. As the water main approaches its maximum design life, its deterioration causes ultimate failure and breakage, thus creating a malfunctioned distribution system (NRCC & FCM Sept. 2002). Assuming that the life cycle trend of a water main is similar to that of a sewer pipe, the average design life expectancy of a water main will be about 70 years if proper maintenance and asset management programs are implemented. Without preventive maintenance, the life expectancy of a water main is reduced to about 30 to 40 years (Shehab Eldeen 2001). Figure 1.1 depicts the impact of preventive maintenance on the life cycle of water mains.

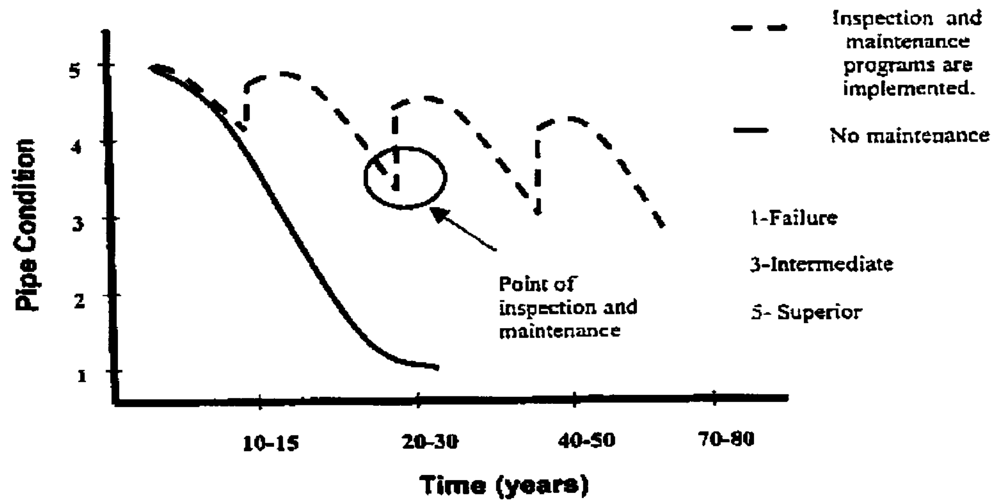

Figure 1.1 Pipe Life Cycles (Shehab Eldeen 2001)

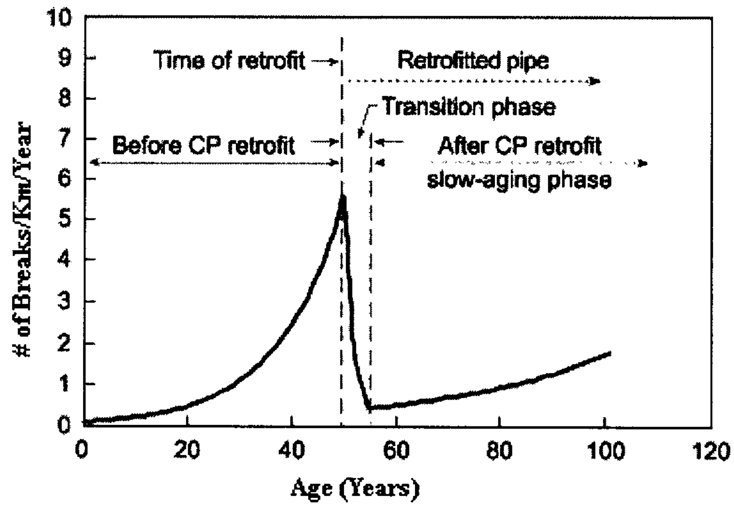

Figure 1.2 Grey Cast-Iron Water Main Life Cycles with Cathodic Protection Retrofit (Kleiner 2002)

Figure 1.2 shows that a simple cathodic protection retrofit could double the service life of grey cast-iron pipe, allowing it to reach, and even exceed, its life expectancy of 70 years. Beyond that it is more cost efficient to replace the pipe so as not to incur increased maintenance costs (Kleiner 2002). As was mentioned above, 60 percent of the water mains in Canada became unacceptable and inefficient, thus requiring immediate action (Mirza and Haider 2003). This is partially due to the fact that most of the water distribution networks were installed in the 1950's and 1960's. Thus the water mains have been in use for more than 40 years, hence exceeding their inadequately maintained service life. Figure 1.3 illustrates the age distribution of buried infrastructure in Canada.

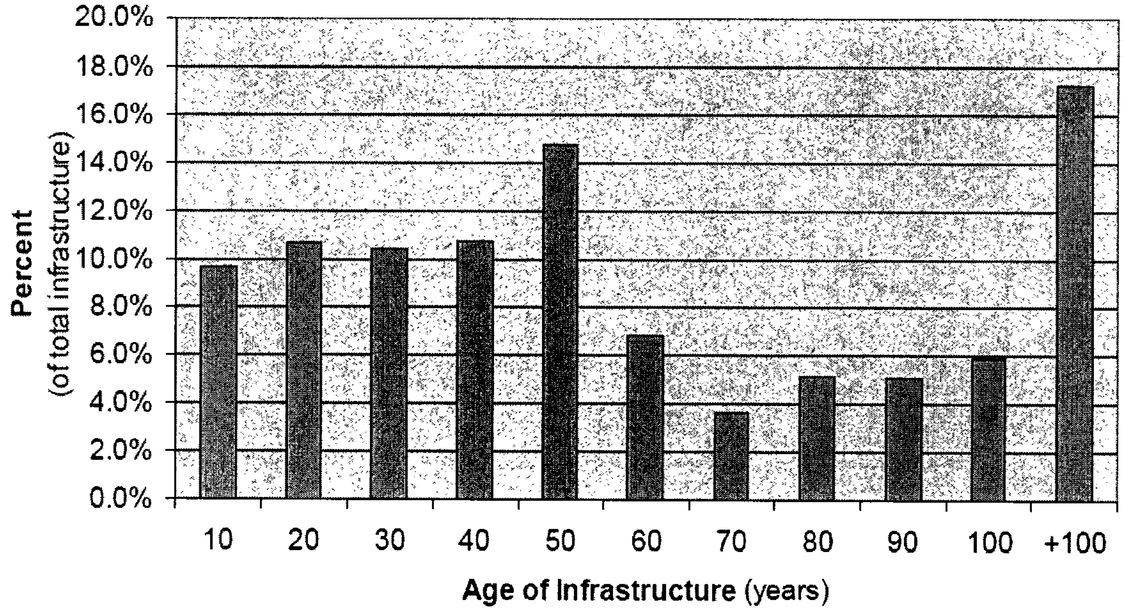

Figure 1.3 Age Profile of Buried Infrastructure in Canada (Andres 2003)

Canadian municipalities are currently operating and managing infrastructure that is 60 to 100 years old, but neglecting the infrastructure that ages 10 to 50 years (Andres 2003). This neglect will create a significant increase in water main replacement in the upcoming years. A study conducted by Jamie Powell in Canada indicates that large annual water main replacement will take place from 2005 to 2070 as shown in Figure 1.4. The data presented in that figure assumes that no preventive maintenance and rehabilitation programs will be applied.

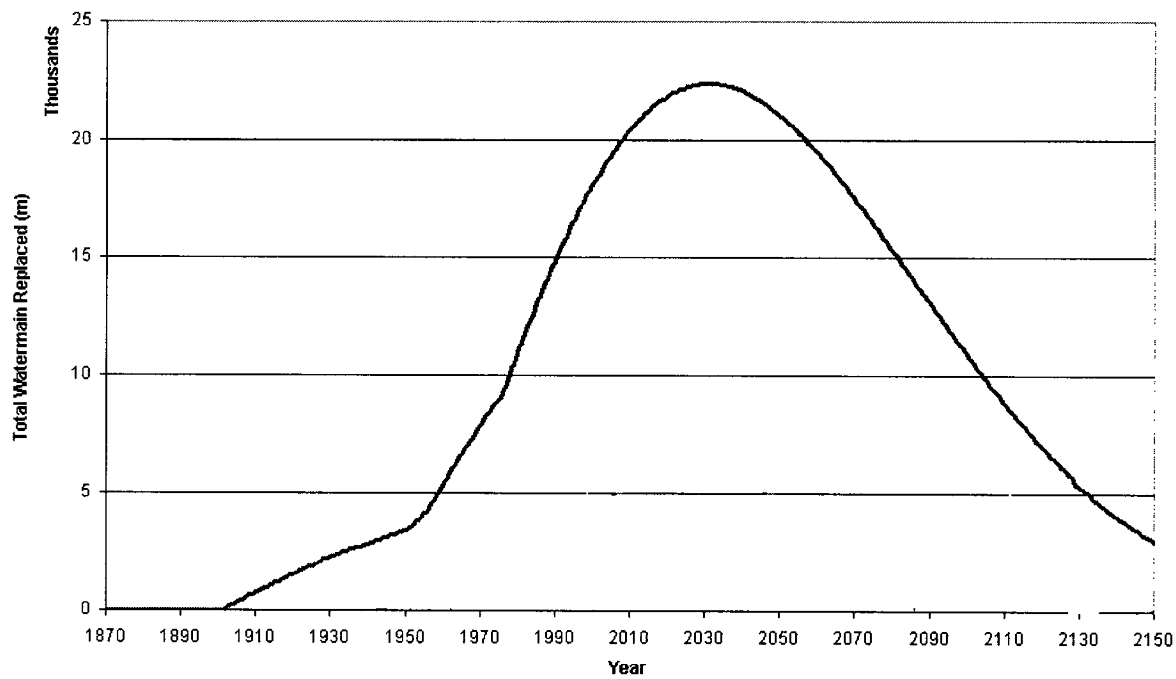

Figure 1.4 Water Main Replacement Demographics Based on Estimated Remaining Life (J. Powell 2003)

However, it should be noted that age alone is not always a good indicator of the condition of the water distribution networks since there are other physical, environmental, and operational factors that can impact the rate of deterioration.

In the past, most Canadian municipalities focused on expanding the water distribution networks to support the population growth. However, in recent years, more capital investment is being focused on renovating the distribution network because of an aging infrastructure, stringent water quality legislation, and shrinking financial resources (Collicott 2003). Current efforts are being focused on reducing the overall renewal costs, including social costs[1], through greater efficiency and the use of advanced technology.

[1] Social Costs are socio-economic costs associated with the open cut replacement method. Social costs include the costs of closing down a road and detouring traffic, the impact on surrounding businesses, and the disturbances caused to surrounding environment (Rahman 2004).

Particularly, cost savings will be optimized by developing and adopting more cost effective inspection and rehabilitation technology (Allouche et al. 2002). Water main rehabilitation or renewal is not an easy task since it involves the agreement of many stakeholders. Furthermore, as the majority of the water distribution networks are located underground, it is difficult to rehabilitate the system while offering a continuous and uninterrupted reliable service that responds to the needs of the community. Thus, municipalities are faced with the task of improving their water distribution infrastructure systems without disturbing the society and other nearby infrastructure systems. There are a number of methods used to repair, replace, and construct water distribution networks. These methods are constantly being developed, improved, and updated to reduce cost and time of project rehabilitation. One of the rapidly developing and expanding areas in the rehabilitation, construction, and replacement of water mains is trenchless technology (Ariaratnam et al. 1999). One survey (Allouche et al. 2002) has indicated that the utilization of trenchless technology by Canadian municipalities is on the rise, with 82% of municipalities using one or more lining techniques in the year 2000, as compared to 66% in 1996 and 32% in 1991.

1.2 Current Practices and Their Limitations

Billions of dollars have been spent on and invested in the installation and expansion of the water distribution networks to meet Canada's population requirements. To preserve this major capital investment, measures such as repair, rehabilitation, or replacement must be performed to bring the water distribution networks to their efficient working level (Allouche et al. 2002). The standard rehabilitation process of a water distribution network begins by inspecting and assessing its condition using Closed-Circuit Television (CCTV) cameras, acoustic leak detection, etc. According to this assessment, a section of the water distribution network is prioritized for repair, rehabilitation, or replacement. Subsequently, information about the project requirements, constraints, and environment is collected and analyzed. Based on the analyzed information, a rehabilitation method is chosen to suit the requirements of the project (NRCC & FCM Sept. 2002). In the past, most rehabilitation works were performed by using the traditional open trench replacement method, causing havoc to city streets, and disruption to businesses, environment, traffic and the community. Given the fact that socio-economic or social costs should be considered, there will be a substantial increase in the application of trenchless technology for renovating the water distribution networks. Currently, the selection process of the most suitable trenchless method is performed manually by the decision-maker, mostly a senior municipal engineer. Because this process is dependent on the decision-maker, other more efficient and new methods may be overlooked due to the lack of experience and knowledge (Shehab Eldeen and Moselhi 2001). Moreover, it may also be that the decision-maker disregards other methods because of his/her distrust in new technology.

The decision-maker manual selection of the method can have several limitations. The description and effects of these limitations are as follows (Shehab Eldeen 2001):

- Variety of methods: There are several water main rehabilitation methods available in the market. Each method is suitable for a certain type of project. Identifying the restrictions and applications of each method is a challenge for the decision-maker.
- Human capacity: Manual selection of the most suitable method is dependent on human capacity in being up-to-date with the fast developing trenchless technology. Since humans are not perfect, the decision-maker might overlook other more cost-and-time efficient methods that are available.
- Evaluation of new products: Recently developed products are often evaluated by their manufacturers and suppliers and by experimental tests. The availability of these evaluations could cause the decision-maker to disregard the new product due to the lack of real work historical data regarding the performance of the product. The level of confidence in the use of a newly developed product could increase/decrease with the type of warranty offered by the manufacturer or supplier.

The use of a computer automated selection system in the field of water main rehabilitation will save municipalities and especially decision-makers considerable time and money. In addition, using such a system provides the opportunity for junior engineers to participate in water main rehabilitation projects, thereby gaining experience and knowledge. It can also assist senior engineers in performing the selection process in a timely manner. The automated system will select the most cost efficient method that satisfies the project technical and contractual requirements, thus saving money for other infrastructure investments.

1.3 Research Scope and Objectives

The main scope of this research is to study the methods used and the decision-making processes involved in the rehabilitation of water mains with a focus on trenchless technology. The study was planned to include a field investigation of water main rehabilitation work. The field investigation is considered as an integral part of the scope of work in this research, so as to develop a better understanding of trenchless technology and the various on-site activities involved in the water main rehabilitation process. Specifically, the sub-objectives of the research are:

1. To develop a decision support methodology to rank different types of trenchless technology according to project characteristics and user requirements.
2. To implement the developed methodology in an automated system, which can assist in the water rehabilitation process by recommending the most suitable trenchless technology.
3. To develop understanding of the current practice in trenchless technology including on-site activities, crew composition, and productivity. And utilize the data collected in demonstrating the capabilities of developed system.

1.4 Thesis Organization

Chapter two presents a literature review on the prevailing status of the water distribution networks in Canada and the United States. It reveals the severity of the problems associated with the networks in the two countries. Chapter two, also, explains the properties of major types of water mains found in the Canadian network. It also explains the causes of water mains deterioration and the resulting defects.

Chapter three presents a literature review on different types of trenchless technology utilized in the rehabilitation of water mains. It explains the application procedure of each type of technology and its benefits and drawbacks as compared to other methods.

Chapter four presents the field investigation carried out on a pilot project conducted on the trenchless rehabilitation of a water main located at Blvd. Notre-Dame, Laval. It focuses on the study conducted to follow and analyze the fieldwork carried out on the application of a new lining technology. The study covers a number of issues related to crew composition and productivity, the work schedule, the rehabilitation procedure, and the difficulties encountered during the rehabilitation work. It describes field operations; mobilization, material preparation and installation, curing, monitoring and inspection, preparation for laterals, and commissioning. It also summarizes the experimental tests that were performed to evaluate the structural characteristics of the lining material. The findings of the study are briefly described and issues that require further attention are stated.

Chapter five presents the development of the methodology utilized in evaluating and ranking the available trenchless technology products. It describes the theoretical basis and the configuration of the developed decision support system. It also presents the implementation of the methodology in an automated system. A detailed design of the proposed system and its limitations are also presented. The last section of this chapter presents an application example to test and validate the developed system. The application example demonstrates the capabilities of the developed system. The findings of the field investigation are used to validate the developed system.

Chapter six summarizes the main activities of the work performed and highlights the contributions of the research conducted. It also provides recommendations for future research work.

CHAPTER 2

Literature Review

2.1 Introduction

Water distribution networks are large underground infrastructure systems consisting of water mains, service lines, hydrants, and valves. A water main is a branch in a water distribution network that supplies water to services and hydrants located at a specified land area (NRCC and FCM Sept. 2002 & March 2003). Municipalities are required to provide its populace with an adequate supply of safe and high quality potable water in a cost-effective and reliable network. The adequate supply of water is a necessity to sustain the economic and health viability of the community. The water distribution network accounts for 50 to 80 % of the expenses of an overall water infrastructure system (NRCC & FCM March 2003). Therefore, the water distribution system should be designed, constructed, operated, and maintained to fulfill the capacity and quality requirements referred to earlier.

The benefits of monitoring and maintaining an efficient water distribution network can be summarized into few points as follows (NRCC & FCM Sept. 2002):

- Provide safe and high quality potable water.
- Present up-to-date data about the condition of the water distribution network.
- Provide better capital planning.
- Assist municipalities in preparing strategic plans for cost effective inspection and repair.

- Prioritize mains in need of immediate repair or replacement.
- Provide input to risk analysis and the life time service of the network.
- Reveal any manufacturing and installation problems.
- Reduce water losses and costs associated with water distribution network failures.

This chapter discusses the prevailing status of major water mains found in the water distribution network in Canada. In addition, it explains their types and properties.

2.2 Status of the Water Distribution Network in Canada

The first water mains in Canada were installed in the 1850's and were mainly made of grey cast-iron pipes (NRCC & FCM Sept. 2002). Due to improper management and maintenance practices, the water distribution network deteriorated in unforeseen ways. Recent studies have shown an increase in the rate of water mains failure. The water distribution systems in Canada and the United States have been given near failing grades; D+ and D respectively (Infrastructure Canada 2004). A recent report released by McGill University and the Federation of Canadian Municipalities suggests that almost 60% of Canada's water and wastewater infrastructure can be classified as not meeting current municipal standards (Mirza and Haider 2003).

It has been reported that 40% of Canada's potable water is lost due to the leakage and deterioration in the water distribution network (NRCC 2002). Moreover the status of the water distribution networks has deteriorated by about 35% over the past 10 years (Infrastructure Canada 2004). Most segments of the water distribution network in Canada have approached or exceeded their design life expectancy. The picture is not much different in the United States, where it is estimated that an expenditure of about $11 billion per year is needed to repair and maintain its potable water infrastructure systems (Jeyapalan 2003).

Studies show that the lost water seeps into the soil creating many adverse effects to the water distribution network and other underground infrastructure systems such as the wastewater infrastructure. Water leakage reduces the efficiency of the water distribution network, impairs the quality of drinking water, and accelerates the corrosion effects on water mains and other underground infrastructure. Seeped water can also cause many problems, such as differential settlements and liquefaction effects, to adjacent utilities and the foundations of structures (AWWA 2003). Municipalities estimate that billions of dollars are needed to repair the damage caused by the water main leakages (Allouche et al. 2002). The direct costs associated with inadequate water infrastructure network include (Allouche et al. 2002):

- Higher purification costs due to loss of treated water to pipeline leakage.
- Higher energy costs incurred for pumping larger volume of water; considering the fact that pumping of potable water accounts for nearly 6% of overall electrical power consumption in North America.
- Ex-filtration (leakage) of water from the water mains can increase the amount of water infiltrating (seeping) into the sewer system, thus higher wastewater treatment costs are incurred.

Ideally, buried water mains should maintain their original status during their service life time. Unfortunately pipes begin deteriorating, in the some cases, as soon as they are installed under the ground due to the aggressive environmental nature of the bedding (e.g. soil type, soil acidity and aggressivity, ground water conditions, potable water quality, and undercurrents).

2.3 Types and Properties of Water Mains

According to the National Research Council of Canada (NRCC), two-thirds of Canada's water mains are made of grey cast-iron (GCI), ductile cast-iron (DI), and steel. The other one-third water mains are made of polyvinyl chloride (PVC), high density polyethylene (HDPE), asbestos cement (AC), and reinforced concrete (CPP).

2.3.1 Grey Cast-Iron Water Mains

Grey cast-iron water mains were the first efficient pipes installed in North America and the world since they could be manufactured in different sizes and properties. Each year Canada spends about 0.5% of the replacement value of its water distribution network to maintain or replace aging grey cast-iron mains (NRCC 2002). For the past few years, the installation of grey cast-iron mains has been reduced due to the development of other more efficient and durable mains made of PVC and HDPE. Grey cast-iron water mains are suitable for potable water pipes because they have a smooth inner surface, high compressive structural integrity, and low alkali reactivity. Furthermore they have low cost of production therefore making them suitable for long range water pipes (NRCC 2002).

2.3.2 Ductile Cast-Iron Water Mains

Ductile iron mains were first installed during the 1960's to replace its predecessor; the brittle grey cast-iron. Ductile iron (DI) preserves all cast-iron properties such as corrosion resistance and machineability, and provides additional strength, ductility and toughness. Since its introduction to the market place, DI mains have been recognized as the leading mains for the water distribution infrastructure (Ductile Iron Society 2001).

2.3.3 PVC Water Mains

Polyvinyl Chloride (PVC) pipes have been in use since the mid 70's. PVC pipes are much lighter than other types of pipes. In addition it has been shown that PVC pipes have a lower corrosion rate than other types of pipes (NRCC 2002). PVC pipes are more durable than iron or steel pipes, therefore more reliable and require less maintenance operations during its service lifetime (NRCC 2002). Table 2.1 summarizes the mechanical and hydraulic properties and the wear resistance mechanism of PVC and cast-iron pipes used in the Canadian water distribution network.

Table 2.1 Summary of PVC and Cast-Iron Properties (NRCC 2002 and Ductile Iron Pipe Association 2001)

Type of Pipe	**Mechanical Properties**	**Hydraulic Properties**	**Wear Resistance Mechanism**
Grey Cast-Iron	Have a brittle structure and low plastic deformations limits, Their low elasticity gives the iron its low ductility and toughness, Have low tensile strength but high compressive strength, and Can absorb low frequency vibrations without any damages.	The inner diameter of the grey cast-iron pipe has a smooth surface giving the surface a Hazen-William coefficient of about 150. The smooth surface of grey cast iron pipes prevents the occurrence of turbulence, thus providing a better water flow.	The graphite in the grey cast-iron structure helps in limiting its surface wear by providing a low wear interface. The graphite flakes form a protective barrier layer on the pipe's surface.
Ductile Cast-Iron	Have a minimum strength limit of 60000 psi for tensile strength, 42000 psi for yielding strength, and a 10% minimum elongation before yielding.	The hydraulic properties of ductile iron are very similar to that of cast-iron. Most of the DI pipes, used in the potable water distribution network, are internally lined to improve their hydraulic characteristics and their Hazen-William coefficient.	The spheroids graphite in the ductile iron structure helps in limiting its surface wear by providing a low wear interface and pitting region.
PVC	Have high resilience and flexibility, and Have high compressive and tensile yielding strengths.	The inner diameter of a PVC pipe has a smooth surface with an average Hazen-William coefficient of about 146.	Have high abrasion resistance thus reducing the wear effects.

2.4 Causes of Water Main Deterioration

Water mains have been deteriorating due to the following causes (NRCC & FCM Sept. 2002, NRCC & FCM July 2003, and Shehab Eldeen 2001):

1. Aging of water distribution infrastructure

   The deterioration of water mains begins as soon as it is installed due to the surrounding environmental factors. The design life expectancy of water mains with proper maintenance and management operations is about 70 years. However, the real average age of water mains is about 37 years (Shehab Eldeen 2001). Most water mains installed in Canada have exceeded their average service age thus speeding their deterioration rate.

   The following Table 2.2 shows the minimum and maximum design life expectancy values for grey cast-iron, ductile iron and PVC water pipes (J. Powell 2003)

Table 2.2 Pipe Design Life Expectancy (J. Powell 2003)

Pipe Material	Minimum (Years)	Maximum (Years)
Grey Cast-Iron	35	170
Ductile Iron	20	160
PVC	30	130

2. Inadequate preventive maintenance and asset management programs

   Without proper preventive maintenance and management operations, the life expectancy of the water distribution network decreases dramatically. Preventive maintenance assists in maintaining the integrity of the water main.

3. Inadequate funds and changed municipality priorities

   In recent years there has been a significant reduction in governmental grants for renewal of water distribution networks. Most of the funds assigned by the government are only used to install new water distribution network to meet the expected population rather than maintaining and repairing old ones. Thus the funds assigned are inadequate for the required maintenance and management operations (Shehab Eldeen 2001).

4. Lack of information and staff

   Most Canadian municipalities do not have a detailed inventory of their water distribution network. Thus they have no accurate inventory records regarding the status, capacity, performance, and needs of the water distribution network. This information assists the municipality engineering services in maintaining the status of the water distribution network. The lack of information is mainly due to the lack of staff assigned to inspect and analyze the status of the water distribution network. However, a study conducted by R. Andres in 2003 on seven Canadian municipalities show that it is possible to estimate the total length of water main in a certain region. The study shows that the total length of water main per capita is 4 to 6 meters with an annual total rehabilitation cost of about $3000 to $4000 per capita. Thus by using the Canadian population statistics it is possible to estimate the total length and cost of replacement of water mains available in a certain region.

The National Guide to Sustainable Municipal Infrastructure has identified three main factors that can affect the rate of deterioration of water distribution network and thus leading to their failure. These factors are physical, environmental, and operational. Each factor is sub-divided to show the effect of related minor factors. The following Table 2.3 summarizes these factors and their effects on the rate of deterioration of the water distribution network.

Table 2.3 Water Distribution System Deteriorating Factors (NRCC & FCM Sept. 2002)

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

2.5 Water Main Defects

Water main defects can be divided into two main categories: structural and service defects (NRCC & FCM Sept. 2002).

2.5.1 Structural Defects

Structural defects are those that affect the structural integrity of the water main. They are the primary reason for the failure of water mains. Any water main with a structural defect needs timely repair or rehabilitation because it decreases the efficiency of the system. A water main fails when it is unable to withstand the internal or external forces acting on it due to corrosion or degradation. The failure often happens in multiple stages in which the pipe experiences some defect and leakage for a while then it fails. The structural defects associated with cast-iron, ductile iron, and PVC pipes are as follows (NRCC & FCM Sept. 2002):

- Cracks: Hair like breaks visible on the pipe wall in which the walls pieces are still in place. There are five types of cracks as follows:
    1. Longitudinal Cracks: Cracks running along the axis of the pipe, as shown in Figure 2.1. Caused by radial internal water pressure and freezing water, ring stress from soil cover load, and ring stress from traffic load.

Figure 2.1 Longitudinal Crack (NRCC & FCM Sept. 2002)

2. Circumferential Cracks: Cracks running at a perpendicular angle to the axis of the pipe, as shown in Figure 2.2. Caused by flexural stresses due to traffic, bedding differential settlements, and frost actions. Thermal contraction and expansion also lead to circumferential cracking.

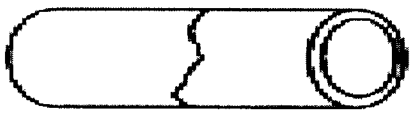

Figure 2.2 Circumferential Crack (NRCC & FCM Sept. 2002)

3. Multiple Cracks: Combination of 1 and 2.

4. Spiral Cracks: Cracks running spirally along the axis of the pipe, as shown in Figure 2.3. Caused by a combination of flexural and internal water radial stress

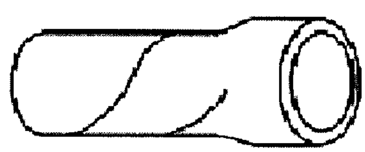

Figure 2.3 Spiral Crack (NRCC & FCM Sept. 2002)

5. Split Bell Cracks: Cracks at the bell of a pipe, as shown in Figure 2.4. Caused by differential thermal expansion between the bell and the seal.

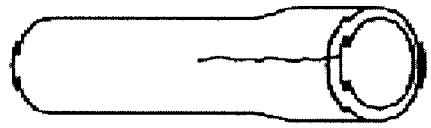

Figure 2.4 Split Bell Crack (NRCC & FCM Sept. 2002)

- Bell Shear: A shear slice in the bell of a pipe, as shown in Figure 2.5. Caused by over sizing the spigot into the bell of pipe and by flexural stresses.

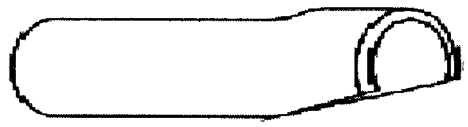

Figure 2.5 Bell Shear (NRCC & FCM Sept. 2002)

- Graphitization: This is a corrosion process product in which the iron ions in iron pipes are leached out leaving a weak graphite flakes matrix reducing the structural strength of the pipe. Graphitization requires special equipment such as X-rays to be noticed.

- Broken/Ruptured Pipes: Broken or ruptured pipes are pipes with displaced pipe pieces, shown in Figure 2.6, caused by internal radial water pressures.

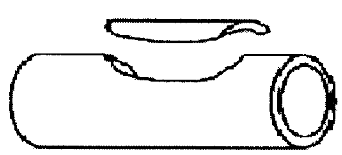

Figure 2.6 Ruptured Pipe (NRCC & FCM Sept. 2002)

- Holes: Punctures, shown in Figure 2.7, caused by localized wall pit corrosion.

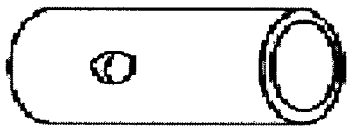

Figure 2.7 Hole in Pipe (NRCC & FCM Sept. 2002)

- Manufacturing Flaws & Inclusions: These are flaws unintentionally included during the manufacturing and casting process. Flaws weaken the structural integrity of the pipes. Examples include: Undissolved ferrosilicon, and iron phosphides.

2.5.2 Service Defects

Service defects are those that impact the hydraulic capacity, water quality, and assist in pipe degradation without jeopardizing the pipes structural integrity (NRCC & FCM Sept. 2002).

- Tuberculation, Scale Formation, and Encrustations: These are deposits clogging the pipe's interior, as shown in Figure 2.8. Often caused by poor water quality, corrosion and rust deposits.

Figure 2.8 Pipe Tuberculation (Ville de Laval: Notre-Dame 2003)

- Joint Leakage: This defect occurs when the spigot or joint of a main is not properly installed or constructed. Since water mains operate under pressure, water leaks from the pipe into the surrounding bedding causing pipe and bedding deterioration. The process of water leakage from the pipe joint is designated as ex-filtration (NRCC & FCM Sept. 2002).

CHAPTER 3

Trenchless Technology

3.1 Introduction

Trenchless technology is defined as the process of repairing, rehabilitating, replacing, or constructing in-ground conduits or pipes between two defined points without the use of continuous open-cut trenching or excavation (Shehab Eldeen 2001). Trenchless technology can be classified into three different categories depending on the type of rehabilitation it performs (AWWA 2001). The three types of rehabilitation are non-structural, semi-structural, and structural. Non-structural rehabilitation is used primarily to protect the inner surface of water pipes from corrosion and tuberculation. Semi-structural rehabilitation is used to protect the inner surface of the water pipes from corrosion and tuberculation and to provide additional structural resistance to the existing pipe. Structural rehabilitation is used to replace the existing pipe, thereby delivering a stand-alone pipe (Jeyapalan 2003).

3.2 Classification of Trenchless Technology Methods

The American Water Works Association (AWWA) classified trenchless technology into four classes according to the types of repair it performs.

Class I: Non-Structural Rehabilitation

1. Internal Joint Sealing
2. Spray Lining: Mortar Cement or Epoxy Resin Lining
3. Close-fit Slip Lining, Swaged Lining or Fold & Formed Lining

4.Cured-In-Place Pipe (CIPP) Lining

Class II/III: Semi-Structural Rehabilitation

1.Close-Fit Slip Lining, Swaged Lining or Fold & Formed Lining

2.Cured-In-Place Pipe Lining

3.Spray Lining: Mortar Cement

Class IV: Structural Rehabilitation/Replacement

1.Close-fit Slip Lining, Swaged Lining or Fold & Formed Lining

2.Cured-In-Place Pipe Lining

3.Pipe Bursting

The methods referred to above are described below.

3.2.1 Internal Joint Sealing (Class I: Non-Structural Repair)

This non-structural repair technique makes the internal surface of a leaking pipe joint watertight. It is applied when the structural integrity of the pipe is not an issue and the only problem is the ex-filtration of water at the pipe joints. The permanent leak-proof and flexible seal guarantees water tightness around the entire pipe joint. Most internal pipe joint seals are made of ethylene propylene monomer (EDPM) synthetic rubber, which has characteristics similar to those of natural rubber. The EDPM synthetic rubber offers a smooth, flushed and graded edge thus not causing any water tuberculation. The internal joint sealing method can repair pipes only with a diameter of 400 mm or greater. It can be used on most types of pipes such as grey cast-iron pipes and pre-stressed concrete cylindrical pipes (Kramer, McDonald & Thomson 1992, and NRCC & FCM March 2003).

The internal preparation of the pipe is important for internal joint sealing. The pipe must be completely cleaned and flushed from any debris to ensure maximum bonding between the seal and the pipe joint. Once the cleaning and flushing are completed, Portland cement is used to fill the joint gap and flush it with the internal surface of the water main. After curing the Portland cement, the area must be cleaned using a dry brush. It must then be coated with a lubricant soap compatible with the seal material. The lubricant soap is used to facilitate the installation of the joint seal. The seal is then positioned to span the gap of the pipe joint. The seals are locked into place with either carbon or stainless steel bands, which are installed at the grooves of each seal. A hydraulic expanding device is then used to apply the correct pressure to the retaining bands, thereby keeping the seals in position. Pressure tests must be performed before operating the pipe (AWWA 2001 and NRCC & FCM March 2003).

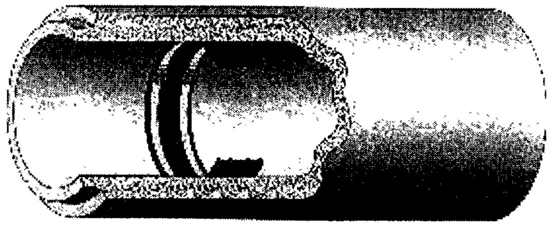

Figure 3.1 Internal Joint Sealing (Link Pipe 2001)

3.2.2 Spray Lining: Mortar Cement or Epoxy Lining

This non-structural or semi-structural repair technique is used to rehabilitate water pipe service defects such as tuberculation and internal corrosion. Spray lining is applied only to structurally or semi-structurally sound water pipes. This technique can be applied on water pipes with diameters ranging from 100 mm to 4500 mm (NRCC & FCM March

2003). Two materials can be used for spray lining; mortar cement and epoxy resin. Each is described subsequently.

Mortar Cement Lining is used in Class I: non-structural repair and in Class II/III: semi-structural repair. It is the most popular lining technique used in water mains, and was developed in the United States in 1905 to repair grey cast-iron pipes (AWWA 2001). At that time manual hand troweling was used to apply the cement. However, due to the advances in technology, a rotating head machine is now being used to line water pipes with much better control over the thickness of the applied mortar, which can range from 5 mm to 10 mm. Mortar cement is an alkaline chemical inhibitor that limits oxidation. In other words, it acts as a corrosion inhibitor. When the slightly acidic potable water passes through the cement lined water main, its acidity is neutralized. The neutralization effect acts as a de-oxidizing agent, thus protecting the host pipe from corrosion. In addition, the cement lining improves the hydraulic characteristics of the water pipe and reduces the need to flush the water main because of rusty water, also known as rusty water.

Lining water mains with cement mortar can be a semi-structural repair consisting of the following steps: first, the application of an initial cement coat followed by the installation of a wire mesh that runs along the section of the water main being rehabilitated, and then followed by a second mortar cement coat. The semi-structural repair requires the access of workers to install a wire mesh and therefore is only suitable for water mains with diameters of 600 mm or more. Most mortar cement equipment can negotiate 22.5° of bends or less, but special mortar cement lining equipment has been able to negotiate bends up to 45° (NRCC & FCM March 2003).

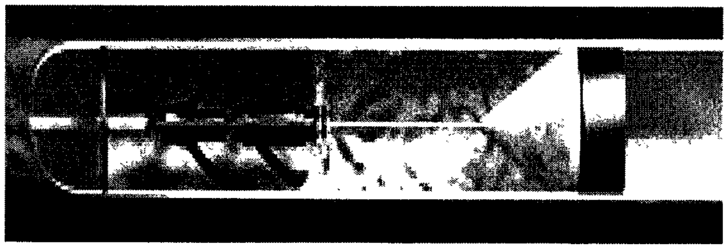

Figure 3.2 Mortar Cement Lining Equipment (Spiniello 2004)

The mortar cement can have a structural strength between 1 to 2 KPa. The application of mortar cement requires a completely cleaned and dewatered pipe since the water or debris might affect the composition of the cement. In the case of semi-structural repairs, water service connections must be excavated and exposed before installing the wire mesh. Moreover, all main valves must be cleaned or replaced to remove any cement mortar residue from the lining process. Once the water main is lined, water service lines are cleared by blowing compressed air throughout or by letting water run back through the service line. Curing the mortar cement is done by capping the ends of the main section for 12 to 24 hours under ambient temperature to prevent rapid drying and subsequent cracking of the lining (AWWA 2001, and NRCC & FCM March 2003).

After the mortar cement is cured, the water main must first be checked by a CCTV and then flushed to reduce the alkalinity of the flowing water, which can reach a PH of 10, due to the newly applied mortar cement liner (NRCC & FCM March 2003).

Epoxy Resin Lining, on the other hand, is used in Class I: non-structural repair. It is an alternative to non-structural cement mortar lining. Epoxy lining was developed to eliminate the mortar cement lining drawbacks (NRCC & FCM March 2003). Epoxy liner is a dielectric insulator that prevents the flow of negative ions (electrons) from the surface of the cast-iron into water thus creating a dielectric barrier. If any pinholes or voids are present in the cover, the liner loses its dielectric properties and corrosion can occur. In addition, epoxy liner improves the hydraulic characteristics of the water main because it provides a smooth flow surface (Kramer, McDonald & Thomson 1992).

The epoxy lining is composed of two materials: resin and hardener. The process of preparing the water main for epoxy lining is similar to the preparation undertaken in the mortar cement lining method in which the water main must be completely cleaned and dewatered. A rotating head machine is used to spray the inner diameter of the host pipe with a 1 mm thick epoxy resin. The composition of the resin and hardener, which is critical for the durability and cohesiveness of the liner, is controlled by a computer. Once the epoxy resin is applied, an ultra-violet (UV) ray machine is inserted to the water main to cure the epoxy liner. After completing the curing process, the lined main should be inspected visually or by a CCTV and then disinfected by utilizing high pressure chlorinated water flushing (AWWA 2001, and NRCC & FCM March 2003). Epoxy lining has three major advantages over cement lining as follows: it has a faster curing rate, there is no loss in the inner main diameter, and there is no need to clean the water service lines.

3.2.3 Close-Fit Slip Lining, Swaged Lining or Fold & Formed Lining

These trenchless rehabilitation methods can be used for non-structural, semi-structural or structural repairs (AWWA 2001). Each is described below.

In the Close-Fit Slip Lining method, the lining is carried out by the insertion of a smaller diameter pipe or liner into a larger diameter host pipe and filling the annular space with grout to achieve a close-fit lining (NRCC & FCM March 2003). The slip lining creates a new internal pressure pipe inside the host pipe without the need of open cut excavation. The slip liner is then connected to the water main valves at both ends. The outer diameter of the liner or the new pipe should be at most 90% of the inner diameter of the host pipe (Kramer, McDonald & Thomson 1992). Close-fit slip lining can be used for non-structural or semi-structural rehabilitations in which it improves the hydraulic characteristics of the water main, resists some internal and external loads, and provides watertight water mains (AWWA 2001). In addition, the close-fit slip lining can be used for structural rehabilitation in which it can resist the internal and external pressure loads by itself and provide the above-mentioned repairs. This technique can be applied on pre-stressed concrete pipes, PVC, and grey cast-iron pipes with diameters ranging from 100 mm to 1500 mm (NRCC & FCM March 2003).

Most slip liners are made of polyethylene (PE) for non-structural or semi-structural repairs and of high density polyethylene (HDPE) or fibre-reinforced plastics (FRP) for structural repairs. However the FRP is rarely used due to its high material cost (Kramer, McDonald & Thomson 1992).

The rehabilitation process begins with cleaning and inspection of the host pipe. Then the liner sections are joined to equal the length of the host pipe. The liner sections are joined together by either thermal butt fusion or couplers. These joining procedures reduce the cost and time of insertion but caution must be taken so as not to exceed the tensile strength of the liner and the capacity of the pulling or pushing equipment. The insertion of the slip liner must be done through excavated access pits only. The slip liner can be inserted into the host pipe by either pulling the butt fused sections or by pushing the coupled sections. A towing head is sometimes used to reduce the pulling stress on the liner. During the lining process, coupled lining sections can be inserted only by pushing them into the host pipe using jacking equipment or a back-hoe. In this case, the maximum pushing length and force must be determined so as not to exceed the liners compressive strength capacity. Sometimes pushing and pulling are utilized together to ease the insertion process. After inserting the liner into the host pipe, the service lateral lines are connected to the liner by using open cut excavation (AWWA 2001, and NRCC & FCM March 2003).

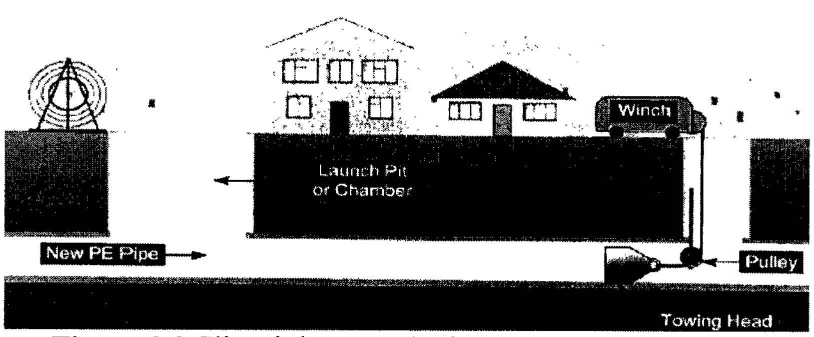

Figure 3.3 Slip Lining Installations (Hastak et al. 2000)

Grouting the annular space to create a close-fit slip lining is the final step of the installation process. The annulus grout can be structural grout with a strength ranging from 10 to 20 KPa, thus sharing the load pressure with the host pipe. It can also be non-structural grout with strength of 1 KPa, in which the pipe has to fully resist the load pressure. The main function of the grout is to increase the structural performance of the water main, to prevent sliding between the host and new pipes, and to prevent water, soil and roots getting between the host and new pipes. Care must be taken during grouting to avoid any pipe flotation (Kramer, McDonald & Thomson 1992).

Swaged (Reduced Diameter) Lining is performed by the insertion of a temporary reduced diameter thermoplastic liner into a host pipe (NRCC & FCM March 2003). The temporary diameter reduction allows sufficient clearance for the insertion process. The liner diameter is reduced using either a set of static dies or a group of compression rollers. The outside uncompressed diameter of the liner should be approximately equal to the inner host pipe diameter to create a close-fit. Swaged liners can be used for non-structural, semi-structural, and structural rehabilitation. This technique can be applied to any type of pipes, such as PVC and grey cast-iron pipes, having diameters ranging from 100 mm to 1000 mm. Most swaged liners are made of PVC, PE, or HDPE, depending on the type of repair required (NRCC & FCM March 2003).

Installation of swaged liner is carried out by first cleaning the water main in need of rehabilitation. Then the diameter of the liner is reduced by 5-15% of its original size. After the diameter reduction, the liner is winched into the host pipe using a towing head. Then the ends are sealed and water pressure is applied to revert the lining to its original diameter creating a close-fit liner (AWWA 2001, and NRCC & FCM March 2003).

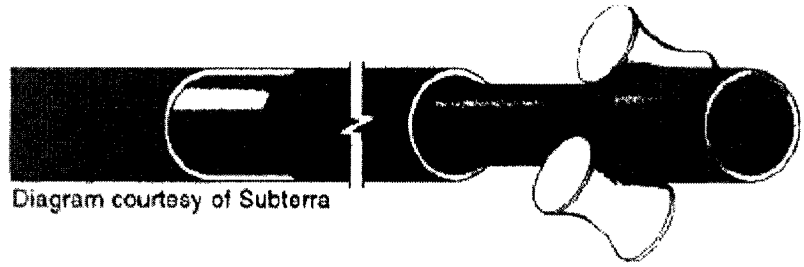

Figure 3.4 Swaged Lining (Subterra 2003)

The Fold & Formed Lining technique is based on the temporary folding and forming of the liner into a "U" or "C" shape to ease the insertion of the liner into the host pipe. This method can be used for non-structural, semi-structural, and structural rehabilitation of water mains (AWWA 2003). Fold and formed lining can be applied to almost all types of pipes such as PVC and grey cast-iron pipes with diameters ranging from 100 mm to 600 mm (NRCC & FCM March 2003). The liner is usually made of PVC or PE or HDPE depending on the type of repair required.

Preparation, i.e. folding and forming, of the liner can be performed either in the factory or on the site (AWWA 2001). The preparation of the work site begins by cleaning the water main in need of rehabilitation. Then the folded liner, which is retained by elastic straps, is inserted into the host pipe through an inspection chamber or an access pit. A winch is used to pull the liner along the host pipe. After insertion, the liner is heated using either external heaters or steam to increase its flexibility and thus ease the reverting process. If external heaters are used, a rounding device is inserted into the liner to revert the liner against the inner wall of the host pipe in order to create a close-fit liner. In this case, the liner ends should be capped and the air pressure should be maintained to cure the liner into a rigid state. If steam is used to revert the liner, no rounding device is required for the process, but the contractor still needs to cap the ends of the liner and maintain air pressure. After curing the liner, a robotic cutter is used to re-open the service lateral lines connections (AWWA 2001, and NRCC & FCM March 2003).

Some fold and formed liners have anchors to improve the gripping action between the host pipe and the liner. The annular space created from these anchors can then be filled with grout, but this will reduce the inner diameter of the water main, and open cut excavation will be required to re-open service lateral connections (Kramer, McDonald & Thomson 1992).

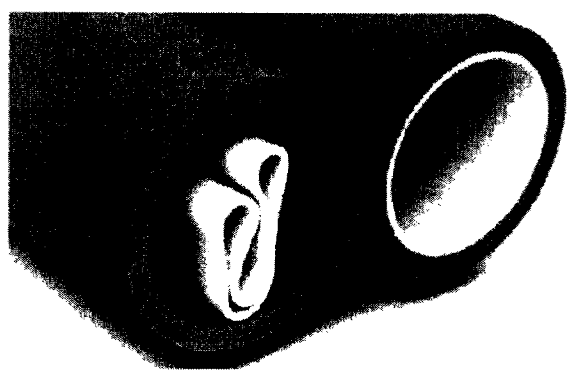

Figure 3.5 Fold and Formed Lining Before and After Reversion (Hastak, Makarand, and Ghokhale, Sanvij 2003)

3.2.4 Cured-In-Place Pipe Lining (Class I: Non-Structural Repair/Class II/III: Semi-Structural Repair/ Class IV: Structural Repair)

The cured-in-place pipe lining method consists of inserting a resin impregnated fabric tube into the host water main (NRCC & FCM March 2003). This method was originally developed in the early 1980's in Japan to rehabilitate deteriorated gas pipes or pipes that have been destroyed by a seismic event (Kramer, McDonald & Thomson 1992). The

CIPP creates a new close-fit rigid pipe inside the host pipe. The fabric and resin combination can be designed for non-structural, semi-structural, and structural rehabilitation. Most of the CIPP can be applied to all types of pipes such as PVC and grey cast-iron pipes with diameters ranging from 100 mm to 3000 mm (NRCC & FCM March 2003). CIPP pipes are known for their flexibility and thus can easily negotiate 90° bends (AWWA 2001).

There are four types of cured-in-place pipes available on the market (NRCC & FCM March 2003) as follows:

- Felt based Tubes: This type of tube is made of non-woven polyester felt used primarily for semi-structural or structural rehabilitation. Most of the felt based tubes used for structural rehabilitation are reinforced with fibers to increase their structural integrity capacity. The inner layer of the tube is coated with an elastomer polymer layer to create a smooth pipe surface thus providing a better Hazen-William coefficient[1].
- Woven Hose Tubes: This type of tube is made of woven fiberglass material used primarily for semi-structural or structural rehabilitation.
- Membrane System Tubes: This type of tube consists of a very thin membrane and was originally designed for non-structural repairs. This system offers internal corrosion protection and can patch joint gaps and pinholes for structurally sound water mains.

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[1] Hazen-Williams coefficients are used in the William-Hazen equation for friction loss calculation in ducts and pipes. As the Hazen-William coefficient increases the friction loss decreases, thus improving the hydraulic capacity i.e. the flow rate of the pipe (Hauser 1991).

- Felt and Woven Hose Tubes (Multi-layer Liner): This tube has a combination of three layers: a non-woven felt that acts as a resin absorbing layer to seal cracks, a woven fibreglass layer that provides the structural strength of the liner, and an internal layer of elastomer polymer. This type of tube is used only for structural rehabilitation since the layers provide an increase in its structural strength.

The resin performs an important role in ensuring the structural integrity of the host pipe, since it is the bonding agent between the CIPP and the host water main. Thermosetting epoxy resin is used in the rehabilitation of water mains since it provides a good adhesive force between the host pipe and the liner. In addition, the cured epoxy resin has a negligible reaction to the water in the water main; therefore it is in accordance with local health agency regulations (AWWA 2001).

The installation process begins with a careful CCTV inspection of the host pipe. The host pipe must then be carefully by-passed, cleaned, and dried of any water or debris because debris or water can compromise the adhesion of the liner to the host pipe. Any intruding connections, encrustation, hard deposits, loose pipe fragments should be removed to ease in the installation and to achieve a close-fit pipe. Then the host pipe must be checked again with a CCTV to record and define any available defects and the location of lateral service connections (AWWA 2001 and NRCC & FCM March 2003).

Small diameter liners are usually impregnated in the production plant and quickly delivered in refrigerated trucks to prevent any premature resin setting. On the other hand, large diameter liners are usually impregnated on site to reduce the probability of premature setting since a large quantity of resin is utilized. After the impregnation process, the liner is inserted into the host pipe through either an inspection chamber or an excavated pit. The insertion process is performed using inversion equipment, in which the liner is turned inside out to expose the resin to the inner diameter of the host pipe and to propagate the liner along the host pipe. The inversion is performed by pumping either water or air into the liner. Some types of CIPP require winching rather than inverting. When the host pipe is fully lined, the curing process is commenced by circulating either hot water or steam into the liner, or by using UV-rays equipment. The curing process often requires around 5 hours depending on the length and diameter of the host pipe, and the capabilities of the curing equipment. Once the curing has been completed, the liner ends are trimmed and the lateral service lines are re-opened using remote robotic cutters (AWWA 2001 and NRCC & FCM March 2003).

Figure 3.6 Cured-In-Place Pipe Inversion Process (NordiTUBE 2003)

3.2.5 Pipe Bursting (Class IV: Structural Replacement)

Pipe bursting is a trenchless technology used to replace deteriorated water mains rather than rehabilitating or repairing them. The replacement is performed by shattering the water main and dislodging its fragments to create a void that will be filled with a new pipe. This method can be applied only to structural replacements since the old host pipe is broken into bits. Pipe bursting can be applied to non-ductile types of pipes with diameters ranging from 50 mm to 1200 mm (NRCC & FCM March 2003).

Most of the pipes used to replace the old pipes are made of high density polyethylene (HDPE) (Kramer, McDonald & Thomson 1992). Sections of the HDPE new pipe are butt fused to equal the required host pipe length because the replacement is performed in a single application. Secondly, all lateral service lines and fire hydrants connected to the host water main must be excavated and uncovered before pipe bursting commences. The shattering is performed using either a pneumatic, hydraulic or static bursting head which is inserted through an excavation pit. The bursting breaks the old pipe into fragments and compresses the fragments into the surrounding soil creating the void. The new pipe is simultaneously pulled in to fill in the void. One of the main benefits of the pipe bursting method is its ability to upsize the existing pipe diameter by about 30% depending on the surrounding soil conditions, depth of cover, and the proximity of other underground infrastructure utilities (AWWA 2001).

Caution must be taken during the replacement to ensure that the pulling force is less than the new pipe tensile strength and that the outer diameter of the new pipe will not be damaged by the fragments of the host pipe. Sometimes, a protective sheet is pulled with the new pipe to shield the new pipe from the fragments. The bursting force of the bursting head must be checked to ensure its capability to break the host pipe or any repair clamps. In addition, any underground utility close to the host water main must be excavated and exposed to avoid any damage due to the bursting force (NRCC & FCM March 2003).

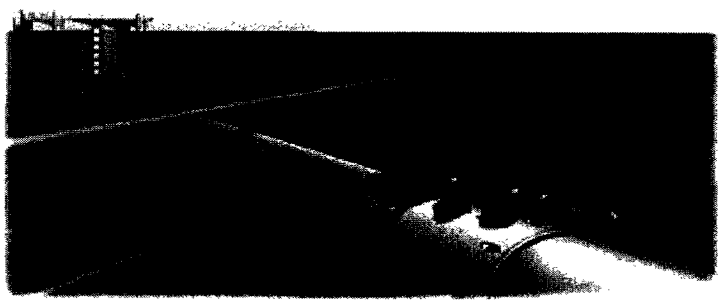


Figure 3.7 Pipe Bursting (Vermeer 2003)

Table 3.1 summarizes the types of available trenchless technology with their capabilities. The table was developed using information obtained from the National Research Council of Canada and the Federation of Canadian Municipalities (March 2003). Table 3.1 shows the method's rehabilitation capabilities, range of diameters for which it is applicable, maximum application distance by a single shot, and the maximum degrees of bends it can negotiate. Table 3.2 lists the benefits and drawbacks associated with the utilization of each trenchless method.

Table 3.1 - Trenchless Technology - Summary Table (NRCC & FCM March 2003)

Trenchless Technology		**Rehabilitation Capabilities**			**Range of Diameters (mm)**	**Maximum Installation Distance (m)**	**Max. Degree Bends Negotiated**	**Access Requirements**		**Application**	
		Class I: Non-Structural	Class II/ III: Semi-Structural	Class IV: Structural				Inspection Chamber	Access Pits	Cast-Iron	PVC
1	Internal Joint Sealing	X			400 or greater	Unlimited	Not Applicable	X	X	X	X
2.A	Spray Lining: Mortar Cement	X	X		100 to 4500	500	22.5	X	X	X	X
2.B	Spray Lining: Epoxy Resin	X			100 to 4500	500	25	X	X	X	X
3.A	Close-Fit Slip Lining	X	X	X	100 to 1500	100	2		X	X	
3.B	Swaged Lining	X	X	X	100 to 1000	100	2		X	X	
3.C	Fold & Formed Lining	X	X	X	100 to 600	600	10	X	X	X	
4	Cured-In-Place Pipes (CIPP)	X	X	X	100 to 3000	650	90	X	X	X	X
5	Pipe Bursting			X	50 to 1200	150	N.A.		X	X	X

N.A.: Not Applicable

Table 3.2 Benefits and Drawbacks of Trenchless Methods (NRCC & FCM March 2003)

Trenchless Method	Benefits	Drawbacks
Internal Joint Sealing	• Minimal working or excavation space. • End to any ex-filtration. • Quick and fast repair for pipe joint leakages.	• Can only be applied to man-accessible pipes, i.e. 400 mm or greater.
Mortar Cement Spray Lining	• Minimal excavation space is required. • Can accommodate a variety of diameters and bends. • Improves the hydraulic characteristics of the host pipe. • Inhibits and slows the rate of internal corrosion. • Reduces the number of maintenance flushing activities because it reduces the formation of rusty water. • Service connections do not have to be excavated in the case of non-structural repairs.	• The water main must be structurally sound. • Can not negotiate more than 45° bends. • The mains must be cleaned and dried. • Application below freezing point may cause severe damage to the mortar lining. • Water service lines must be cleaned after lining. • Can temporarily affect the PH value of the water. • There is a minor reduction in the internal diameter, therefore the flow rate, of the water main.
Epoxy Resin Spray Lining	• Minimal excavation space is required. • No loss in the inner diameter of the lined pipe. • Can accommodate a variety of diameters and bends. • Improves the hydraulic characteristics of the host pipe. • Slows the rate of internal corrosion. • Reduces the number of maintenance flushing activities because it reduces the formation of rusty water.	• The water main must be structurally sound. • May not be used below the water table while there is the presence of infiltration. • The mains must be fully cleaned and dried.
Close-Fit Slip Lining	• Improves the hydraulic characteristics of the host pipe. • Improves the structural integrity of the old pipe. • Reduces material cost by utilizing standard pipe diameters.	• Requires the excavation of lateral service line connections to be reconnected to the liner. • Can not negotiate bends. • Its use may be limited by excessive deflection.
Swaged Lining	• Creates a watertight water main. • Improves the hydraulic characteristics of the host pipe. • Improves the structural integrity of the old pipe. • Can be inserted through an inspection chamber. • Lateral service connections can be re-opened using remote robotic cutters thereby eliminating the use of open cut excavation.	• Swaged lining can not negotiate sharp bends. • It is not suitable for non-circular or deformed pipes. • It is not suitable for repairing joint displacements. • Its use depends on the friction between the liner and the host pipe to stay in place.

Table 3.2 – Cont'd Benefits and Drawbacks of Trenchless Methods (NRCC & FCM March 2003)

Trenchless Method	Benefits	Drawbacks
Fold and Formed Lining	• Improves the hydraulic characteristics of the host pipe. • Improves the structural integrity of the old pipe. • Can be inserted through an inspection chamber. • Lateral service connections can be re-opened using remote robotic cutters thereby eliminating the use of open-cut excavation (not in the case of anchored liners).	• May not negotiate sharp bends. • Not suitable for non-circular or deformed pipes. • Not suitable for repairing joint displacements (not in the case of anchored liners). • Infiltration could adversely affect the installation process. • Depends on the friction between the liner and the host pipe to stay in place (not in the case of anchored liners).
Cured-In-Place Pipe Lining	• Minimal working or excavation space is required. • Improves the hydraulic characteristics of the water main. • Improves the structural integrity of the old pipe. • Lateral service connections can be re-opened using remote robotic cutters thereby eliminating the use of open cut excavation. • Could negotiate 90° bends. • Could accommodate very long lengths.	• Requires extensive CCTV inspection. • Requires extensive cleaning and drying. • Inversion of liner may cause formation of sags. • If a section of the liner is not fully adhered to the host pipe, water or air bubbles may form, requiring replacement by open cut excavation.
Pipe Bursting	• Reduces the cost of replacement since it does not need any open cut excavation. • Could upsize the original host diameter up to 30% to accommodate population growth. • Applied in a single application thus reducing cost of labour and time needed for replacement. • Does not need any cleaning of host pipe.	• Requires excavation pits. • Requires the excavation of lateral service lines, fire hydrants, and any close-by underground utility. • May cause surface damage due to the bursting force. • No quality control on the pipe bedding and side fill support.

CHAPTER 4

Field Investigation

4.1 Introduction

To develop an understanding and appreciation of trenchless technology rehabilitation, it was decided to carry out a field investigation where site activities could be observed, monitored, and analyzed. The study conducted in this thesis is based on a pilot project carried out by City of Laval. The city of Laval, created in 1965 and located 12 miles north of Montreal, Quebec, is a major economic pole offering more than 122000 jobs at more than 1000 manufacturing companies. In 2003, its capital investment reached 1.2 billion dollars. With regards to civil infrastructure, Laval's water distribution network runs through 1192 km of pipe of which, 600 km are made of grey cast iron that was constructed in 60's and 70's. Most of the roads in Laval that were constructed in 1960s have achieved their design life expectancy of 40 years, thus requiring immediate repair. Records show that after compaction works, the chances that the existing grey cast iron pipe breaks are very high. Due to the increasing number of breaks in grey cast iron water mains immediately after road works, the City of Laval has adopted a new policy in its infrastructure rehabilitation. The "New Policy of Laval" is to rehabilitate water mains without carrying out any dynamic compaction work over the rehabilitated pipes. The municipality engineers have decided to rehabilitate the city's deteriorated water main network using trenchless technology. The rehabilitation work was governed by Section 1.3 of the "Travaux d'infrastructures Canada-Quebec 2000" program. The engineers have decided to use the 3200 feet 12-inch diameter water mains located at Blvd. Notre-Dame as a pilot project for the utilization of a new cured-in-place lining.

This chapter presents a case study on the above-mentioned pilot project. It focuses on the study conducted to follow and analyze the fieldwork carried out on the application of a new lining technology. The study covers a number of issues related to crew composition and productivity, the work schedule, the rehabilitation procedure, and the difficulties encountered during the rehabilitation work. The chapter also describes field operations; mobilization, material preparation and installation, curing, monitoring and inspection, preparation for laterals, and commissioning. As well, it summarizes the experimental tests that were performed to evaluate the structural characteristics of the lining material. The findings of the study are briefly described and issues that require further attention are stated. This year as well as in 2006, performance measurements will be taken on an experimental section of the pipe. This includes CCTV inspection, laboratory ripping tests, and water tightness tests primarily at the service connections. If the follow-up and monitoring tests produce positive conclusive data, the City of Laval will incorporate this method into its existing water mains rehabilitation program.

4.2 Case Study

This case study focuses on a pilot project carried out by City of Laval over a period of two months, starting from August 2003 and finishing in September 2003. The study was conducted on a 3200 feet (875 m) 12-inch (300mm) diameter water main located at Blvd. Notre-Dame, Laval. The condition of the water main was found to have deteriorated extensively directly after road works; requiring immediate rehabilitation. The water main had service and structural defects such as tuberculation, pit corrosions, and cracks mainly due to the dynamic compaction of the road bedding during road works. The aggressive clay bedding and high radial stress from soil bedding and traffic contributed respectively to the water main deterioration. These defects affected the potable water quality and the pipes' operating efficiency.

The leakage and the brittleness of grey cast iron water mains brought the City of Laval to look for trenchless technology as an alternative solution to the open cut replacement method. The City proceeded to experiment with a new lining technology, Tubetex L-1, with the objective of reducing the number of water main breaks, insuring the water tightness of the network, and most importantly improving the weak mechanical resistance of the grey cast iron pipe. The use of lining technology was considered to reduce the rehabilitation time and the total rehabilitation cost, including social costs, as compared to the open cut replacement method. Discussed below are the scope of work, the water main history, the issues related to site work and productivity, and the difficulties encountered during rehabilitation work.

4.2.1 Scope of Work

The main scope of the project is to rehabilitate the deteriorated water main in order to restore its structural integrity and functional condition to its normal working condition using cured-in-place trenchless technology. By restoring its condition the quality of drinking water improves, the deterioration of the water pipe and the leakage of water from the water distribution system is minimized or even halted. The rehabilitation work was governed by Section 1.3 of the "Travaux d'infrastructures Canada-Quebec 2000" program.

4.2.2 Blvd. Notre-Dame Water Main History

The water distribution system at Blvd. Notre-Dame was constructed in the 1960's. Until 2002, the water main had no previous break history i.e. 0 breaks / year / Km.

4.2.3 Site Work Issues

The work carried out on site included the following main activities:

1. Collection of data regarding the status of the water mains before rehabilitation works.
2. Installation of temporary bypass pipes.
3. Cleaning of host water main using power boring machines, resin pigs, and squeegees.
4. Inspection of pipes using Closed Circuit Television (CCTV) cameras before and after rehabilitation.
5. Lining the host pipe using cured-in-place structural liner.
6. Installation of measurement valves in inspection chambers.
7. Evaluation and monitoring of lining performance during service and after a year of installation.
8. Publication of monitoring and evaluation results.

The resources, allocated to the above activities, encompassed a team of engineering and construction personnel (labor resources), specialized equipment, and material. The team consisted of a site engineer, a site supervisor, CCTV and rotary cutter operators, a lining technician, two lining technician assistants, and three general workers. With respect to equipment and material, they are listed in Table 4.1. Figure 4.1 depicts the general site arrangement with the focus on the eversion process.

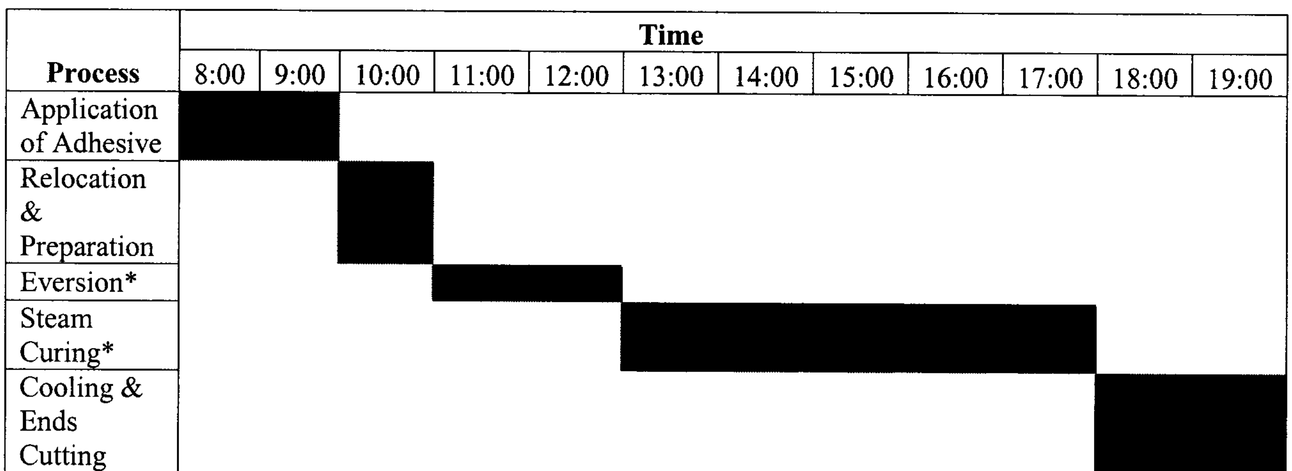
Table 4.1 List of Equipment and Material Utilized In the Rehabilitation Process (Notre-Dame 2003)

Equipment	Material
General equipment truck: Metal saws, winch, axe, cables and ropes, hoses, squeegees, cleaning pigs, water pumps (dewatering excavation pits), air and steam ventilation valves	Tubetex L-1 + Felt Liner
Power boring machine	Epoxy resin
CCTV and rotary cutter truck and its accessories	W 250 water valves
Lining truck and its accessories	W 250 coupler repair clamps
Air compressor and its accessories	Epoxy lined cast iron water main pipes
Backhoe	Water
Temporary bypass hoses	

Figure 4.1 Eversion Process (Mousset 2003)

4.2.4 Scheduling and Productivity

Figure 4.2 depicts the general installation schedule, developed for lining a 660 ft (200m), 12-inch (300mm) diameter pipe section. It captures the daily activities performed on the job site at Blvd. Notre Dame, and their respective sub-tasks. However, the time progress varies with different types of pipes, length and curvature of pipe sections, diameter of pipe, contractor and labor productivity, weather conditions, equipment's availability and capability. It should be noted that the schedule was developed based on the data collected on site along with the observations made throughout the lining process. As such it is a built schedule.



* Eversion and steam curing vary depending on the length and diameter of existing pipe

Figure 4.2 Schedule for a single lining of a 660 ft (200m), 12-inch (300mm) diameter cast iron pipe (Notre Dame 2003)

The time required to line each pipe segment in the water main located at Blvd. Notre-Dame is shown in Table 4.2. It should be noted that the productivity was calculated based on the data collected on site during the lining process.

Table 4.2 Productivity of "Phoenix" Eversion Lining System (Notre Dame 2003)

Street Name	Length (m)	Time for Lining Pipe Segment*	Productivity (meters covered during expansion/hr)
Dover Drive-92	70	45 mins	93.33
Harvard- 92	85	55 mins	92.72
Harvard- Elisabeth	85	55 mins	92.72
Elisabeth- Pt 1(A)	108	1 hr 5 mins	99.69
Pt 1(A)- Pt 2 (A)	105	1 hr 5 mins	96.92
Pt 2(A)- Pt 3 (A)	140	1 hr 25 mins	98.82
Pt 3(A)- 100 Av.	135	1 hr 20 mins	101.25
100 Av.- Pt1 (B)	65	40 mins	97.5
Pt 1 (B)- 101 Av.	70	45 mins	93.33
Total Length Lined =	**875 m**	**Average Productivity =**	**96.26 m /hr**

* Assuming that the pipe segments have negligible curvature and negligible degree of bends.

As indicated in Table 4.2, the "Phoenix" eversion, which is also known as inversion, lining machine covers an average of 96.25 linear meters per hour using air at a temperature of 24 °C and a pressure of 2.5 bars.

4.2.5 Difficulties Encountered During Rehabilitation Work

The following difficulties were observed on site during the installation process:

- Directing the lining from one pipe segment to another during eversion and expansion process.
- Air bubble formation between grey cast iron (host) pipe and lining.

- Creation of longitudinal folding and wrinkling of the lining due to the usage of a liner with an outer diameter exactly equal to the grey cast iron (host) main inner diameter and incomplete eversion process.
- Creation of folds and wrinkles due to the presence of bends and curvature.
- Possibility of service line blockage due to the propagation of epoxy resin.

4.3 Method Utilized

The City engineers have decided to rehabilitate the city's deteriorated water main network using a new structural cured-in-place pipe product called Tubetex L-1 lining, also referred to as rigid liner. Cured-in-place pipes (CIPP), one of the mostly utilized trenchless rehabilitation methods, involve the insertion of a hose or a polymer fiber tube impregnated with a thermosetting resin system into the host pipe. After curing the resin, the lining becomes a semi-rigid or rigid "pipe within pipe" depending on the structure of the lining (AWWA 2001). The rehabilitation process is usually carried out with minimal environmental disturbance and pipe closure, thus reducing the social costs associated with rehabilitation works. It has been reported that the CIPP rehabilitation cost are 50% to 80% less than the cost of open cut pipe replacement method (NordiTUBE Tech. AB 2003).

The main function of the cured-in-place lining is to restore the host pipe to its original condition or even better. Moreover, the lining will:

- Improve the weak mechanical resistance of the grey cast iron pipe.
- Eliminate incrustations, tuberculations, and bacterial proliferations found in potable water pipes.

- Improve the Hazen-William coefficient of the host pipe i.e. improving the hydraulic capacity of the pipe.
- Stop internal corrosion.
- Stop infiltration and ex-filtration.
- Seal leaking joints, cracks, corrosion pits, and interval between pipes.
- Reduce the number of water main breaks and insure the water tightness of the network

4.4 Onsite Operations

Below is a description of the sequential activities performed in the preparation and lining procedure, used in the rehabilitation of water mains located at Blvd. Notre-Dame, Laval.

- Excavation and site preparation: A square or a rectangular entry pit is excavated above any water main valve. Any connection, along the water main, between the water valve and the main must be cut and removed. All valves in inspection chambers must be dismantled.
- Cleaning and inspection of host pipe: The host pipe must be cleaned and inspected before lining, to ensure maximum bondage between the epoxy resin, thus the lining, and the host pipe. The CCTV inspection assists in determining the location of lateral service connections. It also examines and records the condition of the host pipe with the type and location of any debris, corrosion, or fracture.
- Lining of host pipe: Using high air pressure, the "Phoenix" eversion machine everts the lining inside out exposing the impregnated resin.

- Curing the lined pipe: High pressure steam is used to cure the epoxy resin (red viscous liquid) after the lining has been completely everted and installed. A controlled exhaust air opening is installed at the end of the lining to allow the steam to propagate from one end of the pipe to the other. Thus achieving better steam circulation, and therefore better curing process.
- CCTV Inspection of lined pipe: CCTV inspection is used to inspect the lined pipe to make sure that the resin is fully cured and bonded to the host pipe without any collapse of lining or formation of water or air bubble.
- Lateral service line reconnection: After being lined, cured, and inspected by the CCTV, the technician uses a remotely controlled rotor cutter to cut the lining and reconnect the residential water lines.
- Commissioning of host pipe: After connecting the lateral service lines, all water valves are installed onto the rehabilitated pipe. The lined pipe is then flushed using high jet water to remove all debris and residues. After flushing, the rehabilitated pipe is chlorinated to sanitize the lining.
- Backfilling of excavated pits: During backfilling, soil is filled and slowly compacted around the pipe. No vibratory compactors were used over the pipe, to avoid damage of the brittle host pipe.

4.5 Experimental Tests

Laboratory tests were performed, before utilizing the lining material, to evaluate the Tubetex L-1 lining's structural properties in order to meet the requirements set by the City of Laval. It was observed that there were no standardized tests for this new technology. Therefore the lab tests were based on tests performed by European researchers on similar cured-in-place pipe technology.

The preparation of the tests was carried out by Aqua-Rehab Inc. (the contractor), under the supervision of DESSAU-SOPRIN (the consultant) and the tests were conducted at the Laboratory of Control and Research of the City of Montreal. Samples of cast iron pipes were taken from an existing in-service 300 mm diameter pipe located at Blvd. Notre-Dame. These samples were cleaned prior to testing to simulate the actual rehabilitation process. Other samples were obtained from new poly-vinyl chloride (PVC) DR. I. 8, 300 mm diameter pipe.

After some discussion with the engineers of City of Laval, it was decided to perform five tests to ensure the performance of the Tubetex L-1 lining. The objectives of each test along with their respective results are summarized in Table 4.3. The data was extracted from the consultant's report.

Table 4.3 List and Summary of Experimental Tests

Test	Objective of Test	Description of Test	Desired Test Result	Test Results
180° Peeling Test	Evaluates the adherence of the lining and resin to the walls of the existing pipe.	Consists of peeling the lining from lined samples at 180 degrees.	The average adhesion force should range from 5 N/cm to 15 N/cm.	The average adhesion force for the cast iron samples was found to be 31.3 N/cm.
Three Points Flexure Test	Observes the behavior of the lining when the host pipe is subjected to a rupture, thus evaluates if such a rupture will cause a failure in the lining.	Consists of loading the host pipe at its center being supported at its ends, which represents the most critical load situation.	A lined pipe sample, of length equal to five times its internal diameter, subjected to a three point flexure loads has to stay without failure under internal water pressure varying from 320 KPa to 350 KPa and until the displacement of the sensor equal to 20% of its internal diameter.	The samples did not present any failure or leakage after 60mm sensor displacement from the center line under a water pressure of 350KPa.
Shear Test	Presents the level of adhesion of the lining to the walls of the existing pipe in the case of a circular fracture in the host pipe.	A lined pipe sample is subjected to a shear test with 5mm spacing between the two elements.	The lining should stay without leakage under internal water pressure varying from 320 KPa to 350 KPa after breaking of the cast iron and until a displacement equal to 20% of its internal diameter.	The samples did not present any failure or leakage under a water pressure of 350KPa and a displacement of 60 mm.
Internal Water Pressure Test	Measures the (popping) breakage pressure of the lining as a function of the spacing between two pipes.	A lined pipe sample with a 900 mm center space is subjected to a 1200 KPa.	The minimum breakage pressure should be 1200 KPa (175 psi) for a spacing equivalent to three times the internal diameter of the pipe.	After a pressure of 1200 KPa and a delay time of 8 min. and 30 sec., the popping or breakage of lining occurred.
Vacuum Pressure Test	Observes the behavior of the lining under the application of a negative pressure (vacuum) into a pipe with pre-pierced holes.	Consists of creating a vacuum (emptiness) in one lined pipe.	The vacuum pressure was to represent worse case conditions such as in the case of a fire, that is to say negative pressure of 150 KPa (22 psi).	With a negative pressure of 150 KPa, no detachment was observed.

4.6 Analysis and Findings of the Study

Site observations, data analysis, and study of this pilot project revealed considerable benefits and a number of drawbacks. They are summarized in Table 4.4 below.

Table 4.4 Summary of Benefits and Drawbacks (Notre Dame 2003)

Benefits	Drawbacks
Little ground surface disruption, therefore reduced social costs	In the case of an air or water bubble formation between the lining and the host pipe, the whole defected segment of pipe must be replaced by a lined cast iron pipe using open cut replacement method. The replacement process will greatly increase the capital and social costs associated with the rehabilitation process
Environmentally friendly	Possibility of the epoxy resin blocking the service lines. In Blvd. Notre-Dame, on a total of 104 services lines, 20 of them had to be excavated near the main pipe because the epoxy resin blocked them. This has been apparently corrected now by the installation of a plug before the liner is put in place
Flexible liner	Scientific follow up is difficult since pipe service has to be interrupted
Imperceptible thickness	
Improvement of flow rate due to the increase in the Hazen-William coefficient	
No perceptible influence on the discharge of the pipe	
Lines different types of pipes such as: steel, cast iron and PVC pipes	
Can easily over come bends and pipe divers	
Requires no water to evert the lining therefore less time consuming and more environmentally friendly since no contaminated water will be discharged into the sewer system	
Does not require an inversion tower	
Rehabilitation costs were 40% less than replacement	

CHAPTER 5

Proposed Automated Selection System

5.1 Introduction

Automated computer systems are used in the construction industry to assist engineers in planning and controlling projects and in quality, safety, and in productivity quantification (Moselhi et al. 1992). Although automated construction systems are widely needed, not many were developed due to the misunderstanding of automated systems and the fear of job losses (Navon et al. 1992). However, researchers have found that automated systems improve working conditions, labour wages, security, and the quality of work.

Automated systems have been developed to manage and control water distribution infrastructure to achieve its most efficient status. However the literature indicates that none have been developed to assist engineers in the selection of the most efficient and suitable rehabilitation method(s) for water mains. Thus the selection process is still manually performed. Hence it is heavily dependent on human experience and knowledge (Shehab Eldeen 2001). Most of the rehabilitation processes performed since the mid 1990's use one of the types of trenchless technology (Ariaratnam et al. 1999). A survey conducted by Allouche (2002) has indicated that the utilization of different types of trenchless technology by Canadian municipalities is on the rise, with 82% of municipalities using one or more lining techniques in year 2000, as compared to 66% in 1996 and 32% in 1991. The selection of the most appropriate trenchless method is a demanding task since the choice involves many factors and relies especially on the engineer's knowledge and experience. This process may overlook other efficient and modern methods and new products due to lack of experience and knowledge (Shehab Eldeen 2001).

This chapter describes the process of developing an automated system named "WaterRehab Select". The system has been developed to assist municipalities in the water main rehabilitation process by selecting the most suitable trenchless technology. In addition, it will assist senior and junior engineers to gain experience in the water main rehabilitation field. The automated system consists of three modules: interactive flowcharts, Data Files and Query System (DFQS), and a Decision Support System (DSS). The interactive flowcharts, query system, and DSS were developed using Visual Basic 6.0 programming language. The data files were developed using Microsoft Access.

The interactive flowcharts selects the method(s) that can rehabilitate the water main based on the type of defect(s) the pipe is suffering from. Based on the selected rehabilitation method(s), the system automatically directs the user to input a set of information regarding the project characteristics and user requirements. When the information is entered, the system utilizes the Data Files and Query System to choose technically feasible, contractually acceptable, and cost attractive trenchless technology rehabilitation/replacement product(s). If more than one rehabilitation or replacement product is proposed by DFQS, the system automatically utilizes a Decision Support System, which is based on Multi-Attribute Utility Theory (MAUT) (Keeney and Raiffa 1976) and Analytical Hierarchy Process (AHP) (Saaty 1982), to rank the products in decreasing order of suitability. The DSS ranks the products according to the user's requirements and the technical, contractual and cost effectiveness requirements of the project. Figure 5.1 illustrates the schematic diagram of the system and the input of data in the system.

The last section of this chapter presents an application example to test and validate the developed system. The application example will demonstrate the capabilities of the developed system. The findings of the case study are used to validate the developed system.

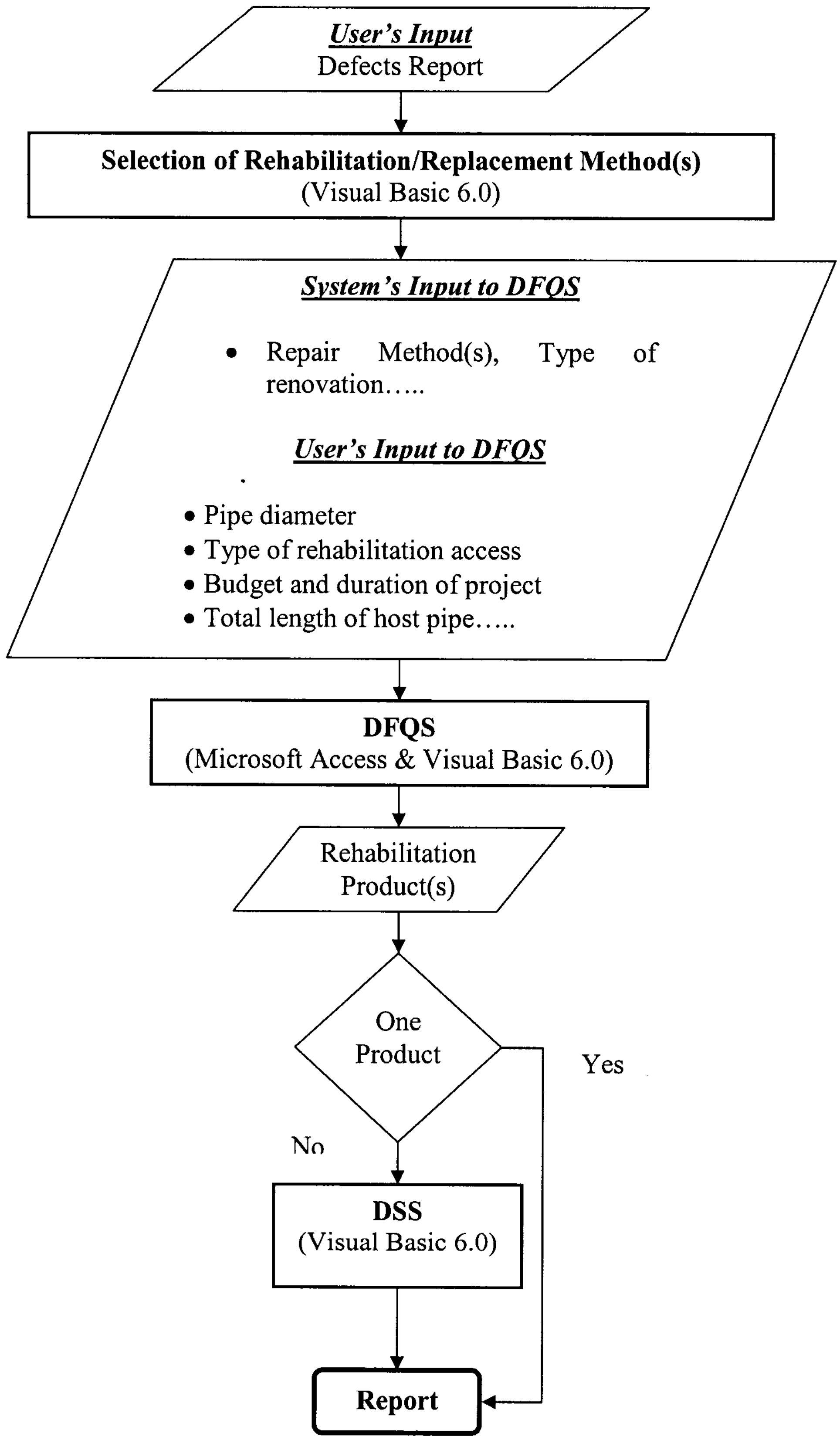


Figure 5.1 WaterRehab Select System Schematic Diagram

5.2 Selection Factors

The selection of an appropriate trenchless method for a certain project depends on elements that can be categorized according to three main factors, which are technical, contractual, and cost effectiveness (Moselhi and Shehab Eldeen 2001). Each of the above-mentioned factors can be subdivided into attributes that assist in the selection process. Based on review of the literature, a number of attributes were selected (Duggan et al. 1995, Moselhi and Sigurdardottir 1998, and Najafi et al. 1997). The following is a description of each factor and its associated attributes (Moselhi and Shehab Eldeen 2001):

Technical requirements determine the feasibility of the rehabilitation method for the project under consideration, in which the technical factors are considered independent of any user or contractual requirements. The attributes of the technical requirements are as follows:

1. Type of Repair: Different methods have different rehabilitation capabilities. Some can be used only for structural rehabilitation; others can only be used for semi-structural or non-structural rehabilitation.
2. Diameter and Type of Pipe: Products can be applied to a certain range of diameters and to certain types of pipes.
3. Degree of Bends: Each method can overcome a specific degree of bend. Some products can not overcome any degree of bends and others can overcome 90^{o} bends. The methods that can accommodate a high degree of bends are more flexible than the methods that can accommodate only a low degree of bends;

therefore they are more applicable to different projects. This attribute should be carefully checked with the manufacturer and the supplier of the rehabilitation product.

4. Hydraulic Characteristics: Some methods can reduce the cross-sectional area of the rehabilitated pipe, thereby reducing its hydraulic characteristics and the water flow rate. However, rehabilitating the water main increases its Hazen-William coefficient (Hauser 1991) thus improving the flow rate and thereby compensating for the cross-sectional area reduction. In spite of the Hazen-William coefficient improvement, the engineer should project for any future losses in the Hazen-William coefficient due to service defects, thereby aiding the reduced cross-sectional area in reducing the hydraulic capacity of the pipe.
5. Differential Settlements and Thermal Allowance: Some products are unable to withstand soil differential settlements due to improper bedding structure and external forces. In addition, some products have low thermal allowance, making them inappropriate for certain regions and areas, especially in low temperature areas.
6. By-passing and Cleaning Requirements: Water mains are pressure supporting pipes, therefore by-passing is obligatory for all rehabilitation works. Different methods have different cleaning requirements. Cleaning increases the rehabilitation cost and the project duration.
7. Length of Pipe: Different products allow a single-shot insertion of different lengths of lining without any human or machine intervention. The shorter the single shot lining length range, the higher the costs due to labour and other

factors. Also it should be recognized that shorter single shot lining length range may require a larger number of excavated access pits thus increasing the cost of rehabilitation.

8. Type of Access Pits: Some products can be installed into the host pipe through inspection chambers. Others require excavated access pits, which may have a severe impact on above-ground services and traffic. Most municipalities prefer to use trenchless products that can be installed through inspection chambers, especially in urban areas to reduce the social disruption and the social costs associated with excavated pits.
9. Lateral Service Connections: Connecting the lateral service lines to the main line may have a great impact on the selection of the trenchless technology. Some methods require only robotic cutters to reopen the connections. Others require full-line excavation and manual reconnection to the main line.
10. Reactivity of Liner: The supplier has to make sure that the lining product does not react with potable water, specifically with chlorine used to antisepticise the water pipe. The quality of water may vary from region to region. Care should therefore be taken to meet regional requirements.

Contractual requirements ensure the compliance of the trenchless product(s) and the method(s) of installation with the terms and conditions of the contract of the project under consideration. The attributes of contractual requirements are as follows:

1. Duration of Project: Different products require different installation periods. Therefore the engineer should make sure that the method chosen is consistent with the project schedule.
2. Years in Business: This attribute assists the municipalities in the choice of new types of technology by increasing or decreasing confidence in the product. The manufacturer or supplier should provide the municipalities with the number of years the product has been in use and the total length of installed linear meters or the number of installed products.
3. Availability of Supplier and Size of Contract (Locality): This factor is of concern to municipalities that prefer to use local suppliers. Dealing with a local contractor may be mandatory for economic and political reasons. In addition, local suppliers are more available and easier to reach, in case of emergencies, than national or international suppliers. Furthermore, the size of the project should be considered in choosing the supplier location because it might be costly to use national or international suppliers for projects with low budgets.
4. Life Expectancy: Each product has a certain design-life expectancy that should be used to meet the requirements of the stakeholders.
5. Degree of Innovations: Some suppliers and manufacturers are able to accommodate different client's requirements that are not part of the production standards of the manufacturers. This attribute is used to show the ability of the supplier to accommodate non-standard conditions.

Cost Effectiveness, clearly, ensures that the cost of the trenchless product(s) that will be installed is within the budgetary limits of the project under consideration. The attributes of cost requirements are as follows:

1. Total Capital (Direct and Indirect) Cost: The direct and indirect costs of the product chosen should be under or equal to the project budget.
2. Life Cycle Cost: The chosen method should fulfill the above-mentioned attributes and be the most cost effective method on the basis of life-cycle cost. The analysis of life cycle costs should consider socio-economic costs and the rehabilitation costs.

In order to collect information about different trenchless technology products, English and French questionnaire survey forms, listed in Appendix A, were sent to American and Canadian manufacturers and suppliers of trenchless technology products.

5.3 WaterRehab Select System Interactive Flowcharts

The "WaterRehab Select" system flowcharts were developed by integrating the three flowcharts shown in Appendix B, developed by the Canadian National Guide to Sustainable Municipal Infrastructure and the American Water Works Association. These flowcharts include the:

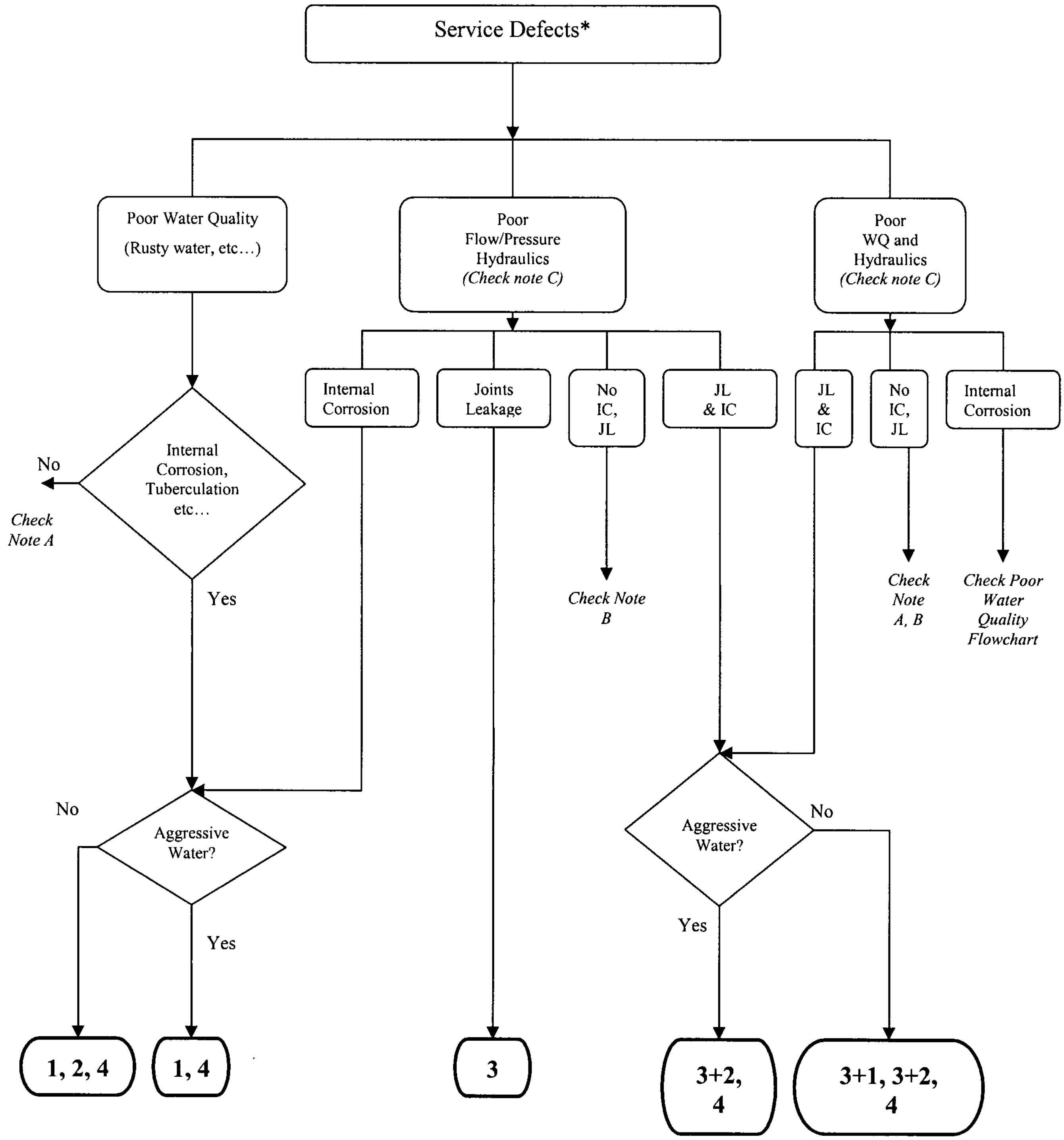
1. Flowchart for Selecting the Rehabilitation or Replacement Technology; Selection of Technologies for the Rehabilitation or Replacement of Sections of a Water Distribution System, A Best Practice by the National Guide to Sustainable Municipal Infrastructure (March 2003),

2. Selection of Rehabilitation Techniques to Resolve Structural Problems; Water Quality Problems; Flow, Pressure, and Leakage Problems Rehabilitation of Water Mains; Manual of Water Supply Practices, American Water Works Association (2001), and
3. Selection of Alternative Water Main Renewal Technologies; American Water Works Association RF, (2002a).

The above-mentioned flowcharts were developed using the knowledge and experience of senior in-house American and Canadian municipality engineers. In all three flowcharts, the selection of water main rehabilitation method(s) was mainly based on the type of defect found in the water pipe and on the cause and the problem(s) associated with that defect. The flowcharts that were developed by the American Water Works Association include some selection factors such as the aggressitivity of the potable water, the social disruption associated with the rehabilitation process, etc. While the selection of the most suitable trenchless technology on the basis of the defect(s) and problem(s) encountered is one of the main requirements, it does not cover all aspects and issues involved in the selection process. As stated earlier, other critical factors, such as contractual and cost requirements, must be taken into consideration in the selection process. Figure 5.2 depicts the general aspect of the selection methodologies used in the developed "WaterRehab Select" system for rehabilitation of water mains. Figures 5.3 and 5.4 illustrate the flowchart diagrams for the rehabilitation of service and structural defects respectively.

Type of Defect	Problems	Causes	Selection Factors	Rehabilitation Technology
• **Service Defects**	• Poor Water Quality (WQ) • Poor Hydraulics/Flow • Poor WQ and Hydraulics	• Internal Corrosion (IC), other... • IC and/or Joint Leakage (JL), other... • Not IC and/or JL, other...	• Aggressive Water?	• **Spray Lining** • **Internal Joint Sealing** • **Pipe Lining**
• **Structural Defects**	• Poor Structural Integrity (SI) • Poor SI and WQ • Poor SI and Hydraulics • Poor SI, WQ, Hydraulics	• IC, External Corrosion (EC) • Material Failure • Pit Corrosion • Material Defects	• Condition of Host Pipe • Upsizing Requirements • Reduction of Host Pipe Diameter/Flow • Level of Social Disruption Allowed? • No. of Lateral Connections/ Close-by Utilities	• **Pipe Lining,** • **Pipe Bursting**

Figure 5.2 WaterRehab Select System General Flowchart



Service Defects*
Poor Water Quality
(Rusty water, etc…)
Poor
Flow/Pressure
Hydraulics
(Check note C)
Poor
WQ and
Hydraulics
(Check note C)
Internal
Corrosion,
Tuberculation
etc…
No
Check
Note A
Yes
Internal
Corrosion
Joints
Leakage
No
IC,
JL
JL
& IC
JL
&
IC
No
IC,
JL
Internal
Corrosion
Check Note
B
Check
Note
A, B
Check Poor
Water
Quality
Flowchart
No
Aggressive
Water?
Yes
Aggressive
Water?
No
Yes
1, 2, 4
1, 4
3
3+2,
4
3+1, 3+2,
4

Notes

*Pipe is structurally sound and no pipe upsizing is required

A. If not an internal corrosion issue, it is either the water source supply issue or water stagnation issue and should be addressed by a Water Quality professional
B. This is either a poor water pressure supply issue or a piping configuration and sizing issue
C. The following flowchart procedure assumes that renovated pipe provides adequate hydraulic performance; if not pipe bursting or open cut replacement will resolve the hydraulic deficiency

JL: Leakage at joints
IC: Internal corrosion, tuberculation, and encrustations

1, 2, 4: Methods 1 or 2 or 4
3+2: Methods 2 and 3 combined
3+1, 3+2, 4: Methods 1 or 2 with method 3 combined or method 4 alone

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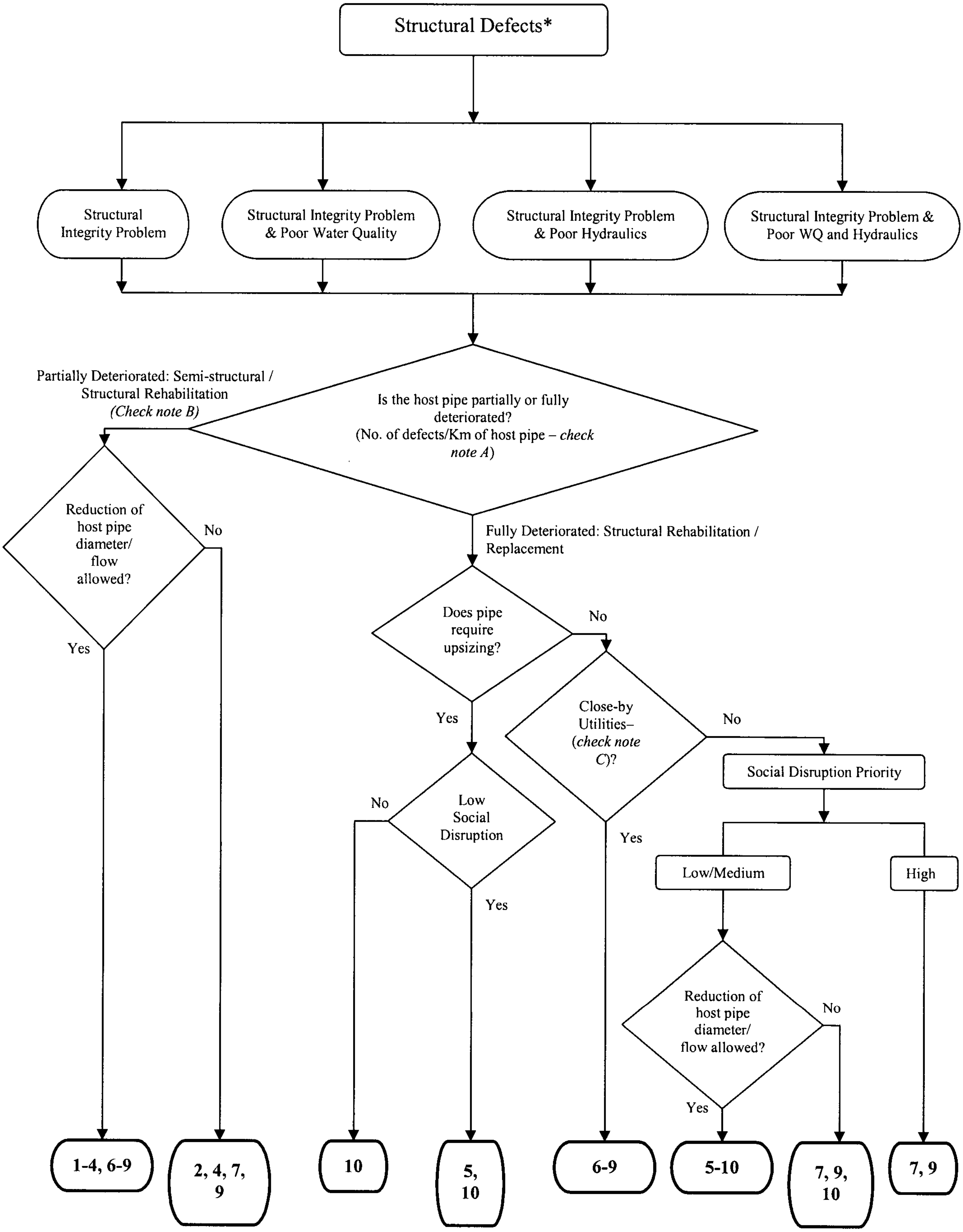
Non-structural Rehabilitation Options:

1. Epoxy Lining
2. Cement Lining
3. Internal Joint Sealing

Non-structural or Semi-structural Rehabilitation Options:

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

Figure 5.3 WaterRehab Select System Service Defects Flowchart


Structural Defects*
Structural Integrity Problem
Structural Integrity Problem & Poor Water Quality
Structural Integrity Problem & Poor Hydraulics
Structural Integrity Problem & Poor WQ and Hydraulics
Partially Deteriorated: Semi-structural / Structural Rehabilitation (Check note B)
Is the host pipe partially or fully deteriorated? (No. of defects/Km of host pipe – check note A)
Reduction of host pipe diameter/ flow allowed?
No
Yes
Fully Deteriorated: Structural Rehabilitation / Replacement
Does pipe require upsizing?
No
Yes
Close-by Utilities– (check note C)?
No
Yes
Low Social Disruption
No
Yes
Social Disruption Priority
Low/Medium
High
Reduction of host pipe diameter/ flow allowed?
No
Yes
1-4, 6-9
2, 4, 7, 9
10
5, 10
6-9
5-10
7, 9, 10
7, 9

Notes

*Can have service defect

A. Partial deterioration of host pipe: Number of defects <= 1 break/ Km of host pipe length
Full deterioration of host pipe: Number of defects > 1 break/ Km of host pipe length

B. Engineers have to check whether semi-structural rehabilitation is adequate to restore the structural integrity of the host pipe

C. Are there any close-by utilities that might be damaged due to the rehabilitation/replacement process?

2, 3, 4: Methods 2 or 3 or 4
5-10: Methods 5 or 6 or 7 or 8 or 9 or 10

Semi-structural Rehabilitation Options:

1. Swaged Lining (Reduced Diameter)
2. Fold and Formed Lining
3. Slip Lining
4. Cured-In Place Lining (CIPP)

Structural Rehabilitation Options:

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

Figure 5.4 WaterRehab Select System Structural Defects Flowchart

The service and structural defects flowcharts were automated using Visual Basic 6.0 programming language thereby creating interactive flowcharts. The first user-interface screen, shown in Figure 5.5, prompt the user to select the type of defect(s) the water pipe is suffering from.

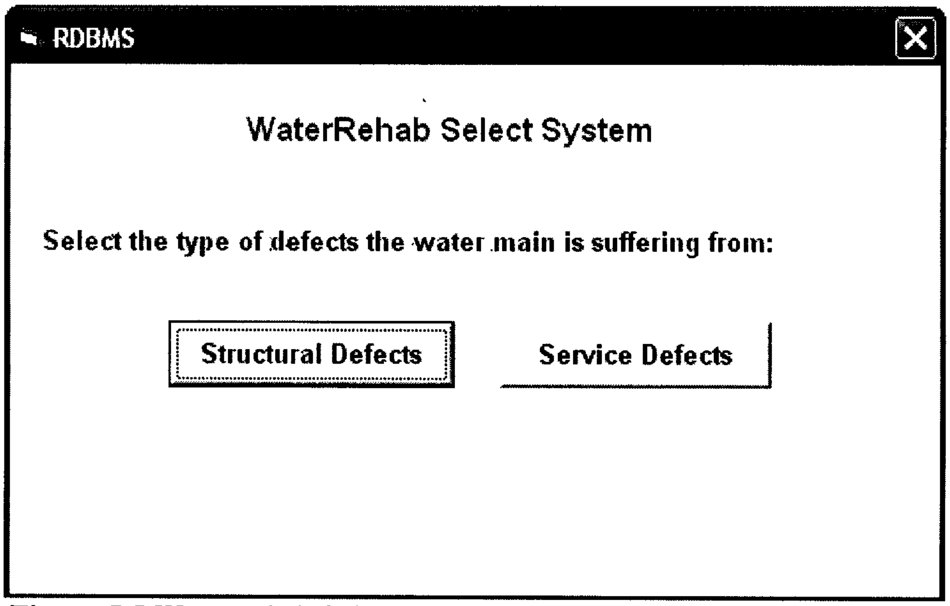


Figure 5.5 WaterRehab Select System Interactive Flowchart Start Screen

After the type of defect is identified, the interactive flowchart prompts the user to state the problem(s) caused by the defect(s), as shown in Figures 5.6A and 5.6B for service and structural defects, respectively.

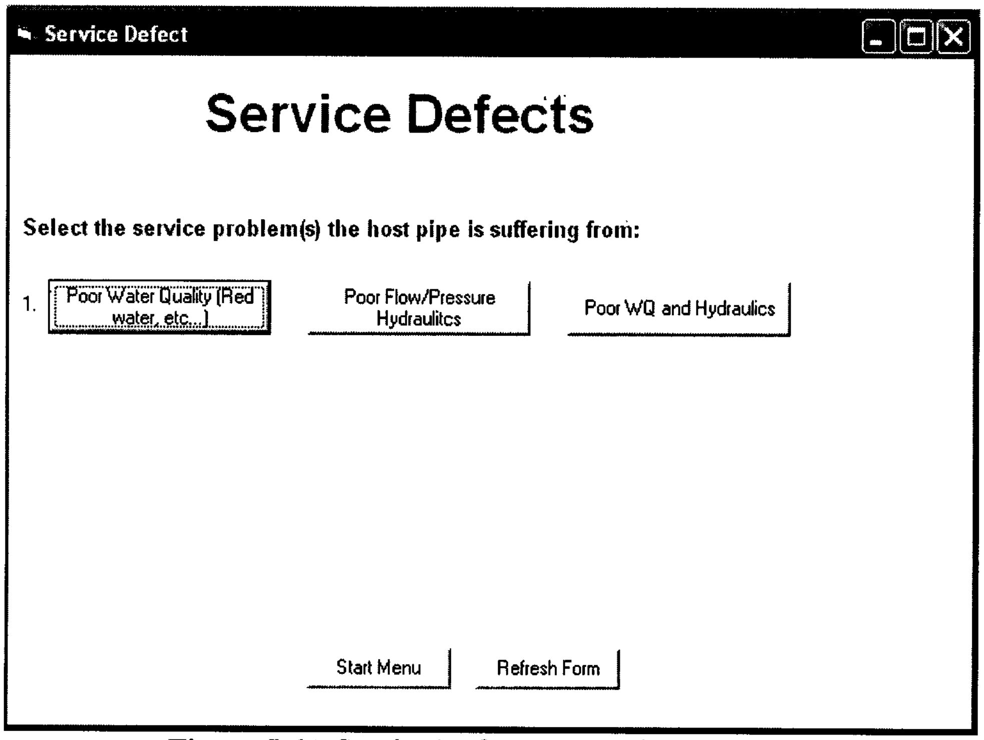


Figure 5.6A Service Defects Interactive Flowchart

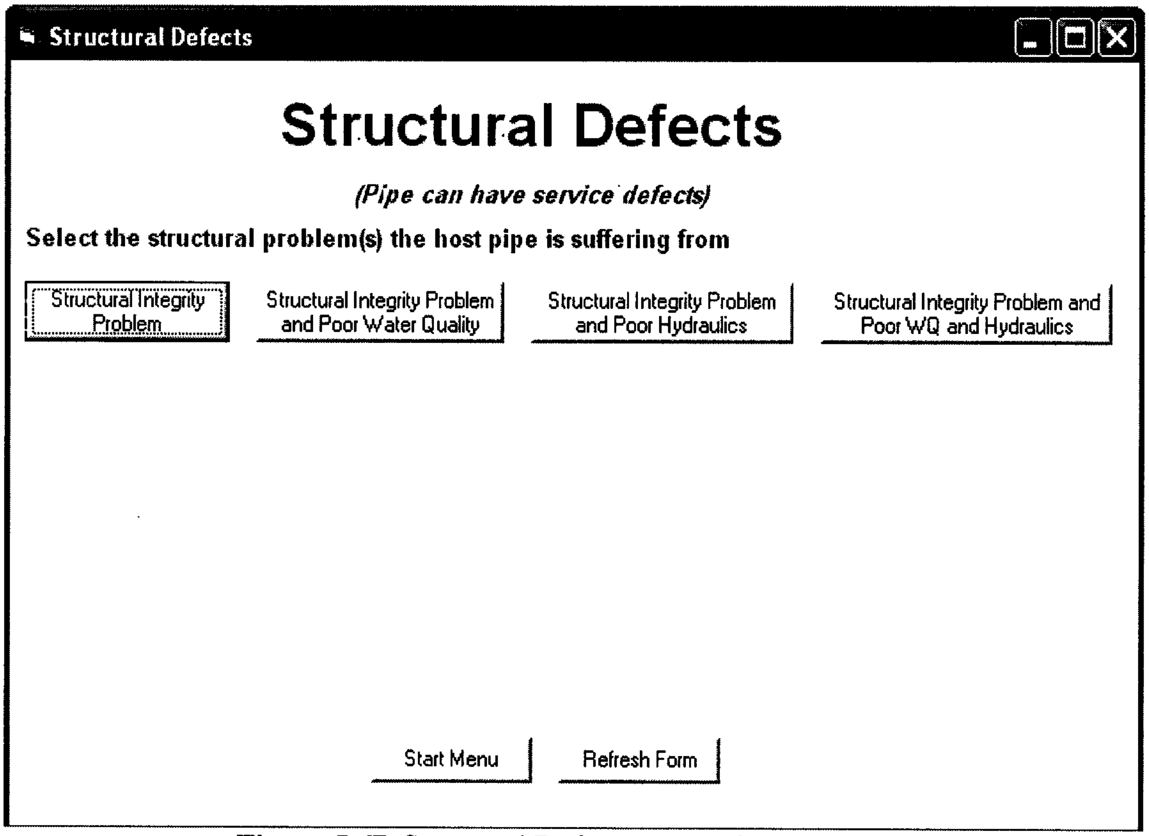


Figure 5.6B Structural Defects Interactive Flowchart

Subsequently, the interactive flowchart asks the user to input the cause of the problem and to respond questions related to the selection factors as shown in Figures 5.3 and 5.4.

After all the questions in the interactive flowchart have been responded to, the system automatically directs the user to a user-interface screen that lists the suitable rehabilitation method(s) indicated by the interactive flowchart. If more than one method has been identified and listed by the system, as shown in Figure 5.7, the system prompts the user to select the method of his/her choice. The interactive flowcharts may identify more than one method because these methods fulfill the repair requirements of the defects and other factors as indicated in Figures 5.3 and 5.4, respectively. The system provides the user with the option of selecting the rehabilitation method of his/her defined criteria, taking into account his/her knowledge about the benefits and drawbacks of each method.

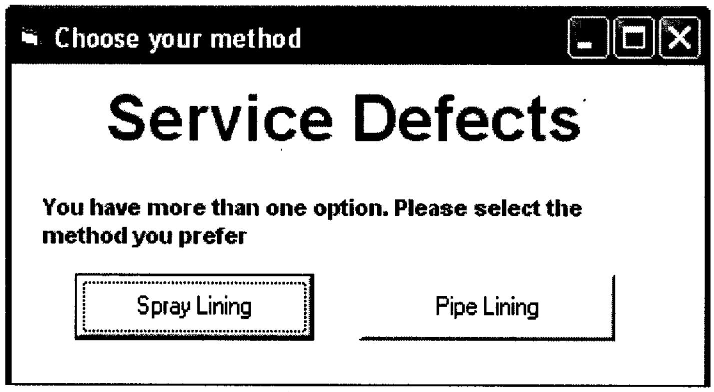


Figure 5.7 Selection of Rehabilitation Method

Although the automated system is founded on the basis of the three flowcharts shown in Appendix B, there are major differences between them. The automated system takes into consideration technical, cost, and contractual factors in the selection process, thus covering a wide spectrum of issues and aspects that need to be considered in the rehabilitation/replacement process. Furthermore, the system specifies and ranks the rehabilitation/replacement products to be utilized according to the user's selection criteria and project characteristics. On the other hand, the three flowcharts shown in Appendix B just identify the type of rehabilitation that must be utilized for a certain problem without recommending the most suitable product(s).

5.4 Data Files and Query System (DFQS)

Data files are created to store information and data in an organized manner for quick access and specific purposes. It is estimated that 35% of Canadian municipalities utilize computerized data files systems because of efficiency and speed in data retrieval

(Allouche et al. 2002). Developing these data files, using Microsoft Access, involves the definition of entities, attributes, and tables (Elmasri and Navathe 1994 and Shehab Eldeen 2001). Since data files are used to store large amounts of information, a query should be developed to facilitate data retrieval. The query is used to extract specific information stored in one or many tables based on a selective criterion. And as such, the query acts as a search engine. The "WaterRehab Select" system data files consist of four tables, each of which stores the information of a certain type of rehabilitation method. The four data files tables are:

1. Spray Lining
2. Joint Sealing
3. Pipe Lining
4. Pipe Bursting

Table 5.1 presents the attributes associated with the four data files tables. Some attributes are not applicable to a particular method of rehabilitation; they are not used in all of the four tables. Defining the tables consists of specifying the type of data that is stored with its associated description. Identifying the data type, i.e. text, number, date/time, etc., specifies the format in which the data is stored. In addition, the data file developer can alter the way the data is shown in the table or can, by utilizing the field properties (Elmasri and Navathe 1994), place certain restrictions on the type of the data that is entered. After the entity tables with their associated attributes are developed, each attribute must be assigned a type, i.e. text, number, date/time, etc., with the description of each attribute. Furthermore, a field property can be altered to place certain restrictions on the format of the attribute (Elmasri and Navathe 1994).

Table 5.1 Table's Attributes, Type, and Description

Attribute Name	Attribute Type	Attribute Description	Joint Sealing Table	Spray Lining Table	Pipe Lining Table	Pipe Bursting Table
Product ID	Auto-number	Products automated identification number	X	X	X	X
Repair Method	Memo	Repair method commercial name	X	X	X	X
Type of Defect	Text	Type of defect	X	X	X	X
Type of Repair	Text	Classification of repair	X	X	X	X
Type of Pipe	Text	Type of host pipe	X	X	X	X
Diameter – L	Number	Product's lower bound diameter (mm)	X	X	X	X
Diameter – H	Number	Product's higher bound diameter (mm)	X	X	X	X
Host Pipe Material	Text	Type of pipe: Grey Cast Iron, Ductile Iron, Steel, CPP, etc…		X	X	X
Lining Material	Text	Type of lining or pipe installed in the rehabilitation process		X	X	X
Hazen-William coefficient	Number	Hydraulic characteristics of installed lining or new pipe		X	X	X
Reduction of Host Diameter	Number	The percentage of minor reduction of the host pipe's inner diameter i.e. flow rate		X	X	
Max. Lining Distance / Shot	Number	Max. lining or installation distance in a single shot without any human or machine intervention		X	X	X
Max. Degree of Bends	Number	Max. degree of bends the lining or replacement machine can overcome		X	X	X
Access Type	Text	Type of access to host pipe		X	X	X
Lateral Service Re-connection	Text	Type of lateral service reconnection: either through excavating lines or by rotary robotic cutters		X	X	X
Cleaning and Dewatering	Yes/No	Indicates whether the rehabilitation method requires cleaning and dewatering of host pipe before rehabilitation	X	X	X	X

Table 5.1-Cont'd Table's Attributes, Type, and Description

Attribute Name	Attribute Type	Attribute Description	Joint Sealing Table	Spray Lining Table	Pipe Lining Table	Pipe Bursting Table
Thermal Settlement	Yes/No	Indicates whether the rehabilitation method can withstand thermal strains			X	
Differential Settlement	Yes/No	Indicates whether the rehabilitation method can withstand differential strains due to improper bedding			X	
Joint Gap Width	Number	Standard up to 127mm (5") Extra Wide 203mm (8")	X			
Type of Joint Seal	Text	Indicated the type of joint seal installed	X			
Type of Joint Expander	Text	Indicates the type of ring expander utilized in the rehabilitation process	X			
Upsizing Ability	Number	Indicates the upsizing ability of host pipe				X
Distance to Close-by Utilities	Number	Indicates the min. required distance to close-by utilities during the rehabilitation process				X
Average Capital Cost	Number	Cost of installed product ($ /cm Diameter / Linear Meter)	X	X	X	X
Average Duration	Number	Average duration to install a straight 500 m or 1 joint seal	X	X	X	X
Life Expectancy	Number	Design life expectancy of product (Years)	X	X	X	X
Life Cycle Cost	Number	Life-cycle cost including socio-economic costs	X	X	X	X
Business Years	Number	Number of years supplier or manufacturer in business	X	X	X	X
Products Installed	Number	Total length (m) or number of products installed by supplier or manufacturer	X	X	X	X
Innovations	Number	Supplier or manufacturer innovation	X	X	X	X

Table 5.1-Cont'd Table's Attributes, Type, and Description

Attribute Name	**Attribute Type**	**Attribute Description**	**Joint Sealing Table**	**Spray Lining Table**	**Pipe Lining Table**	**Pipe Bursting Table**
Locality	Text	National availability of the supplier or manufacturer	X	X	X	X
Supplier's Coordinates	Text	Supplier or manufacturer address	X	X	X	X
Supplier's Phone Number	Text	Supplier or manufacturer number	X	X	X	X
Supplier's Phone Website	Text	Supplier or manufacturer website	X	X	X	X

X: Applicable

Figure 5.8 shows the Pipe Lining Table as an example of developing the data files tables as they appear in Microsoft Access table design view.

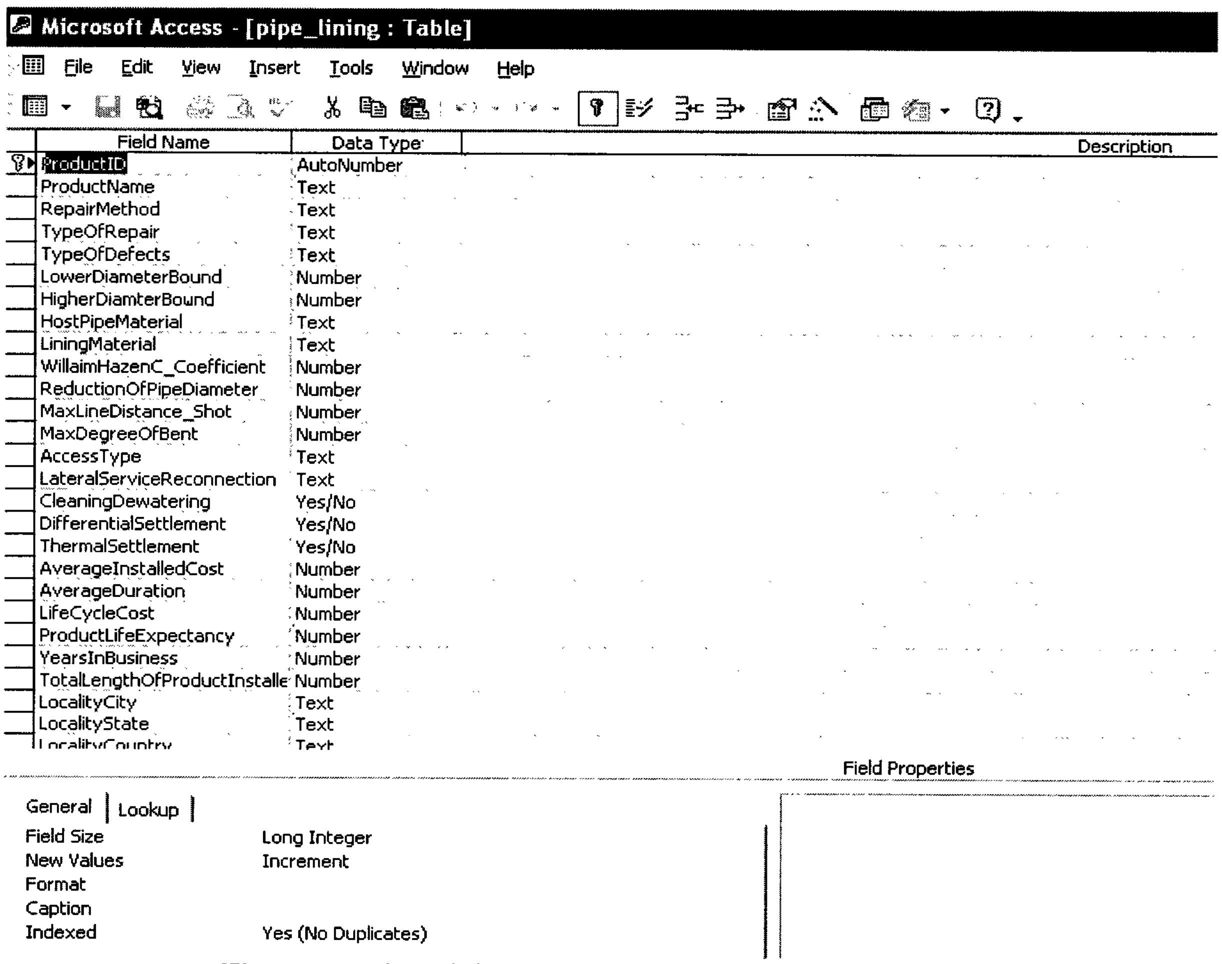


Figure 5.8 Pipe Lining Data File Table in Design View

To transform the data files from a conceptual design to physical one, user-interface forms and a query system were developed (Elmasri and Navathe 1994). Due to the complexity of the search coding, a query was designed using Visual Basic programming language. The query was designed to search the data files for matches entered by the user in the user-interface screens. Therefore, the query was designed to check for two diameter bounds and to compare the value entered by user with the diameter boundaries of a certain product. Furthermore, the query checks for numeric attributes, such as the maximum installation distance, the maximum degree of bends, the total capital cost, the number of years of experience, the product life expectancy, and the project duration; matches such that the value entered by user is less than or equal to the value in the data files tables.

The four technical requirements query screens, one for each rehabilitation method, are shown in Figures 5.9 to 5.12. Each screen will automatically be linked to its corresponding data file table.

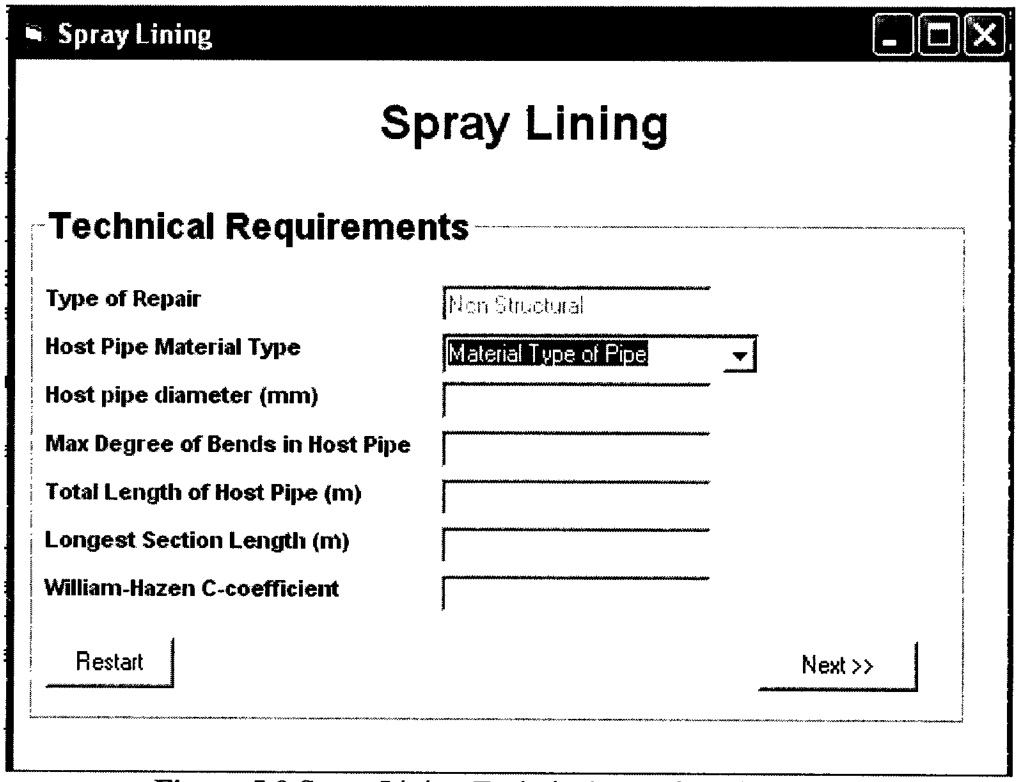


Figure 5.9 Spray Lining Technical User-interface Form

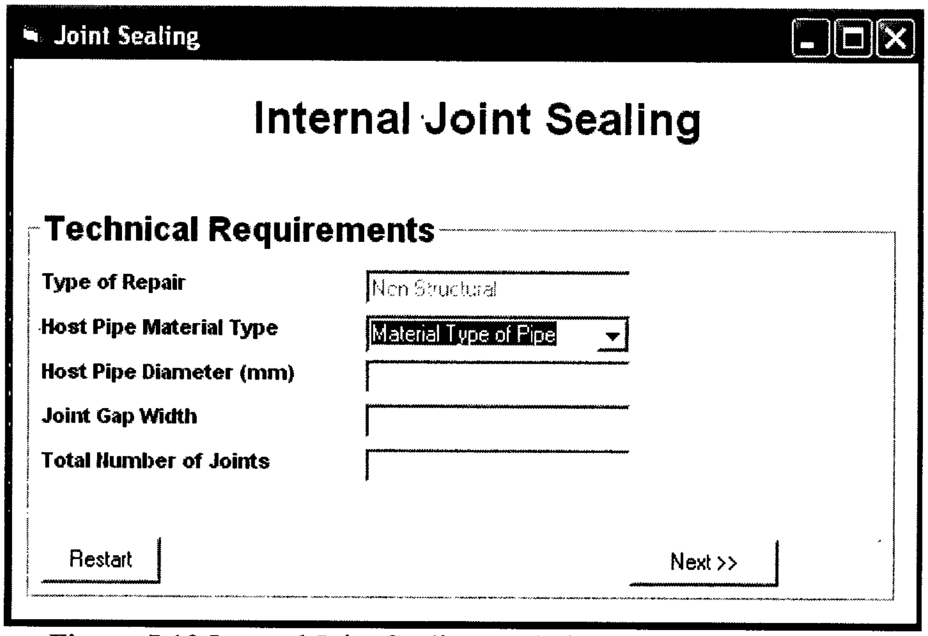


Figure 5.10 Internal Joint Sealing Technical User-interface Form

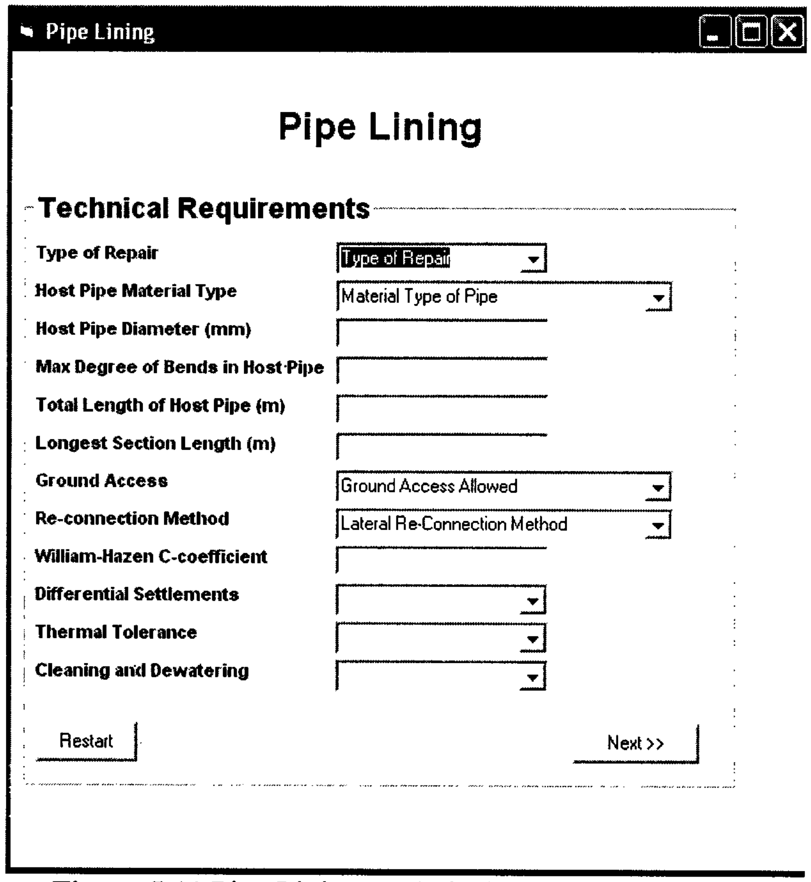


Figure 5.11 Pipe Lining Technical User-interface Form

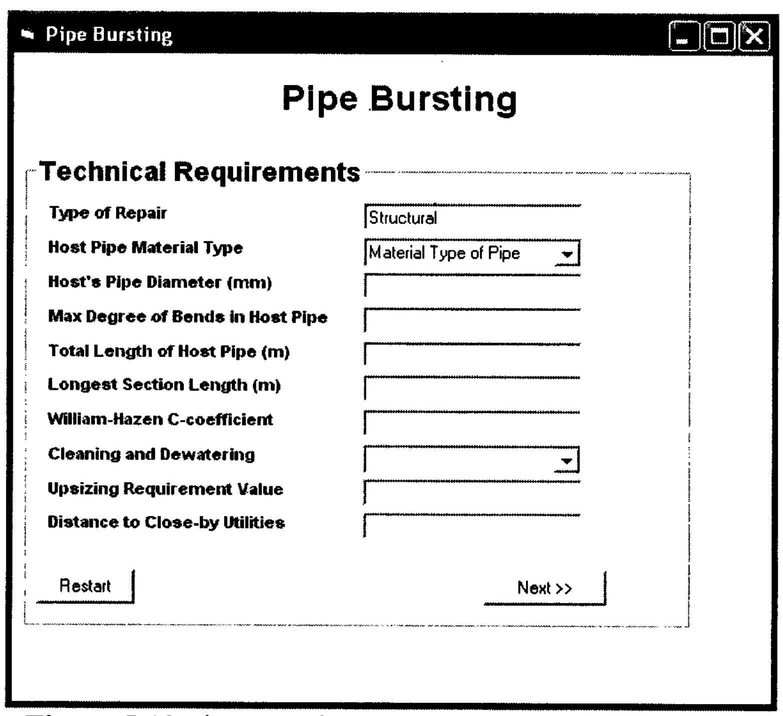


Figure 5.12 Pipe Bursting Technical User-interface Form

After completing the technical requirements screens, the user is prompted to complete the contractual and cost effectiveness requirements. Figure 5.13 shows the contractual requirements and cost effectiveness query screen for the pipe lining method.

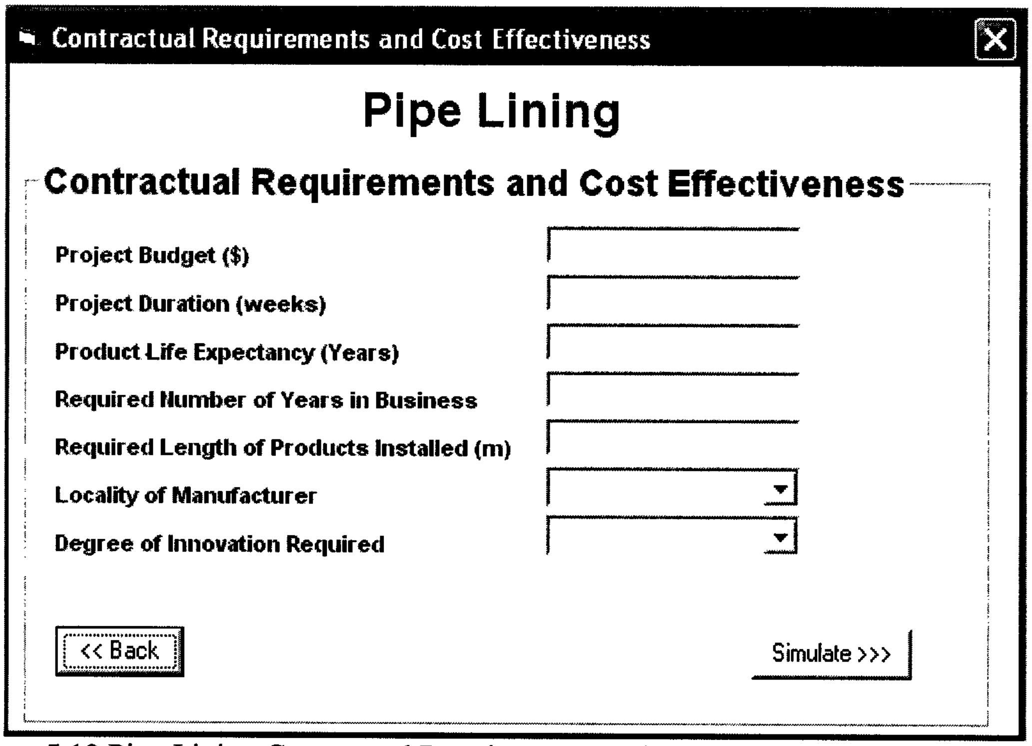


Figure 5.13 Pipe Lining Contractual Requirements and Cost Effectiveness User-interface Form

Upon completing the technical, contractual and cost effectiveness forms, the automated system lists the product(s) that have met the requirements. If more than one product has been suggested, developed system links the user to the Decision Support System to rank the products according to the user's selection criteria. The development of the DSS is explained in the following section.

5.5 Decision Support System (DSS)

The decision support system is activated only if more than one rehabilitation product is suggested by the Data Files and Query System. The methodologies utilized for the evaluation of competing methods of rehabilitation/replacement technology may be classified using two general categories: algorithmic procedures (utility theory, rate of return, analytical hierarchy process, constraint satisfaction technique) and reasoning by deduction (expert systems) (Allouche et al. 2002). A comparison of the features of nine models proposed in the literature in recent years for selection of replacement/rehabilitation methods for buried pipes and conduits is listed in Table 5.2.

Table 5.2 Comparison of Various Evaluation Models (Allouche et al. 2002)

Model	Method	Flexibility	Handle Multiple Methods	Tangible & Intangible Attributes	Trade-off Among Attributes	Accounts for Risk
Hastak 98	AHP	High	X	●	X	X
AbouRizk et al. 94 b	AHP	High	X	●	X	●
Iseley et al. 97	------	Low	●	X	X	X
Moselhi and Siguardardottir 98	Utility	High	●	●	X	X
Stein 94	Expert	Medium	●	●	X	X
Russell et al. 97	Expert	Medium	●	●	X	X
Mckim 97	AHP	Low	●	X	X	X
Ueki et al. 99	Expert	Low	X	●	X	X
Allouche 2000	Utility/ CST	High	●	●	●	●

●: Capable; X: Incapable
AHP: Analytical Hierarchy Process
CST: Constraint Satisfaction Technique

In its analysis the DSS of the developed system utilizes a hybrid methodology consisting of the Multi-Attribute Utility Theory (MAUT) and the Analytical Hierarchy Process (AHP). The multi-attribute system has proven its effectiveness in comparing alternatives in a multi-attribute decision environment (Moselhi and Sigurdardottir 1998).

A similar methodology was developed by Moselhi and Marzouk (2003) to estimate the construction bidding markup and select the most suitable bid. The methodology combines the advantages of both MAUT and AHP, thus providing the users with the flexibility of selecting the utility function of each attribute and capturing the user's attitude toward risk. Also a similar methodology was developed by Moselhi and Shehab-Eldeen (2001) to rank different types of trenchless technology used in the rehabilitation of sewer pipes. The advantages of using a hybrid MAUT and AHP methodology in "WaterRehab Select" system are as follows (Moselhi and Marzouk 2003):

1. Expresses the user's degree of satisfaction (utility value) for each attribute in the decision hierarchy as the attributes take on utility values between the most and least acceptable.
2. Establishes the weights of each attribute in an orderly manner.
3. Allows the user to check the consistency of the relative importance or ranking among the attributes used in the decision hierarchy and to re-do such ranking to satisfy the consistency condition.

Using the template for evaluation of models suggested by Allouche (2002) in Table 5.2, a comparison of the hybrid MAUT and AHP methodologies and the other nine models is shown in Table 5.3.

Table 5.3 Re-comparison of Evaluation Models

Model	Method	Flexibility	Handle Multiple Methods	Tangible & Intangible Attributes	Trade-off Among Attributes	Accounts for Risk
Moselhi and Marzouk 2003	Utility/ AHP	High	•	•	X	•
Moselhi and Shehab Eldeen 2002	Utility/ AHP	High	•	•	X	X
Hybrid Methodology used in Developed System	Utility/ AHP	High	•	•	X	X
Hastak 98	AHP	High	X	•	X	X
AbouRizk et al. 94 b	AHP	High	X	•	X	•
Iseley et al. 97	------	Low	•	X	X	X
Moselhi and Siguardardottir 98	Utility	High	•	•	X	X
Stein 94	Expert	Medium	•	•	X	X
Russell et al. 97	Expert	Medium	•	•	X	X
Mckim 97	AHP	Low	•	X	X	X
Ueki et al. 99	Expert	Low	X	•	X	X
Allouche 2000	Utility/ CST	High	•	•	•	•

•: Capable; X: Incapable

Assuming that all attributes are mutually independent, MAUT defines a utility value for each attribute. By assigning a relative weight for each attribute, the overall utility value for each product is calculated using the following expression (Keeney and Raiffa 1976):

$$U_i = \sum_{j=1}^{n} W_j U_{ij} \tag{5-1}$$

Where W_j is the relative weight assigned to the j^{th} attribute

U_{ij} is the utility value (calculated using its utility function) of the j^{th} attribute associated with the i^{th} alternative method of rehabilitation

U_i is the overall utility value of each alternative method of rehabilitation

As depicted in Equation 5-1, the two basic parameters used in determining the overall utility value for each alternative are the relative weight associated with each attribute (i.e., its priority or relative importance among all considered attributes (Shehab Eldeen 2001)) and the utility value of each attribute. The calculation of the relative weight is based on a pair-wise comparison of all attributes in the same hierarchy level (Saaty 1982). The pair-wise comparison is performed based on a scale of 1 to 9 (Table 5.3) developed by Saaty (1982).

Table 5.4 Pair-wise Comparison Scale (Saaty 1982)

Importance Intensity	**Definition**	**Explanation**
1	Equal importance of both attributes	Two attributes contribute equally to the requirements
3	Weak importance of one attribute over another	Experience and judgment slightly favor one attribute over another
5	Essential importance of one attribute over another	Experience and judgment strongly favor one attribute over another
7	Demonstrated importance of one attribute over another	Demonstrated dominance and strong favor of one attribute over another
9	Absolute importance of one attribute over another	Highest possible order of affirmation of favoring of one attribute over the another
2,4,6,8	Intermediate values between two adjacent judgments	Compromise is needed between two judgments

The decision hierarchy of the developed DSS consists of three levels as shown in Figure 5.14. The first level, which is the focus of the analysis, is the selection of the most suitable rehabilitation method. In the following level, level 2, the focus is branched into the project requirements, which are technical, contractual, and cost effectiveness. At the last level, level 3, the requirements are branched into factors affecting and controlling the project's requirements, which are similarly prioritized.

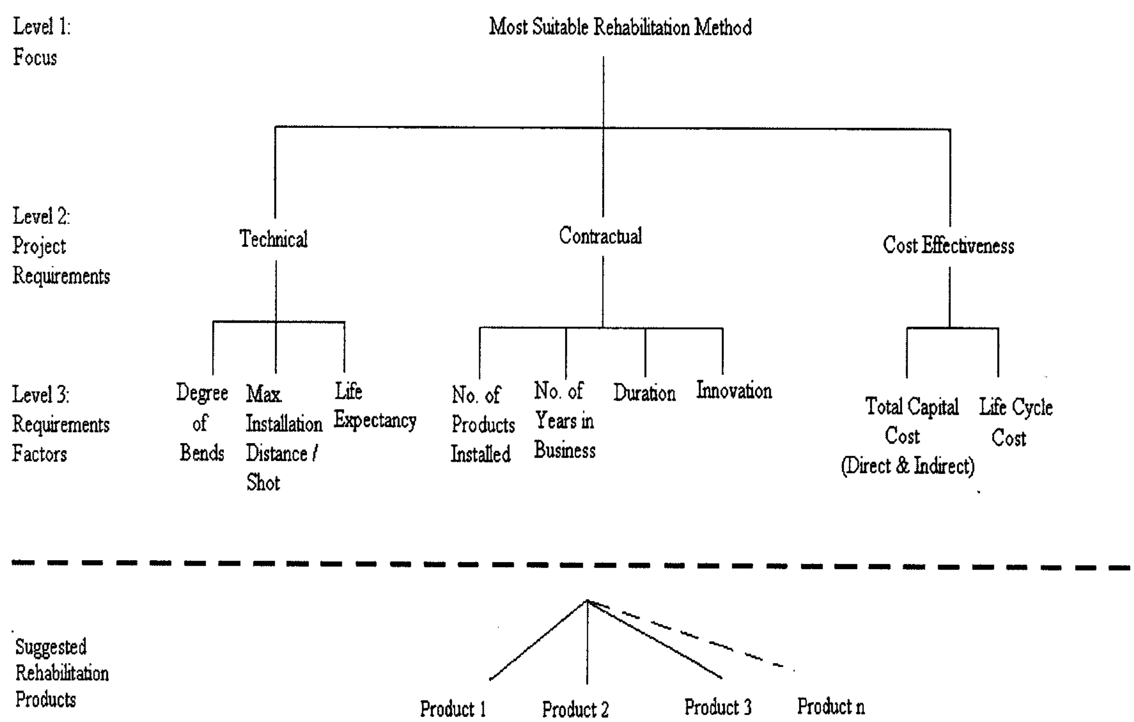


Figure 5.14 Decision Hierarchy for Selecting the Most Suitable Rehabilitation Method

In a multi-attributed decision-making environment, it is important to check the consistency of the pair-wise comparison scale numbers expressed by the decision-makers to establish the relative weights of the decision attributes. Decisions with low consistency are based on random judgments and inexperienced arbitrary decisions. On the other hand, perfect consistency is hard to live up to (Saaty 1982). In most pair-wise comparison matrices, judgments are made to force consistency between alternatives, in other words, to reduce random decisions. The analytical hierarchy process measures the overall consistency of judgments by means of a consistency ratio (Saaty 1982). The consistency ratio (CR) should have a value of 10 percent or less to provide reasonable relative weights among the decision hierarchy attributes. If the CR value is more than 10 percent, the decision is somewhat arbitrary, and the defined attribute relative weights are inconsistent. The consistency ratio is calculated according to the following expression (Saaty 1982):

Consistency Ratio (CR) = Consistency Index (CI) / Random Consistency (5-2)

Consistency Index (CI) = $\lambda_{max} - n / (n-1)$

λ_{max} = Maximum eigenvalue of the matrix containing weights associated with attributes

n = Number of attributes

Random consistency: For a random number that is a function of the size of the matrix, i.e. number of attributes, check Table 5.5 (Saaty 1982)

Table 5.5 Random Consistency Number

Size of Matrix	**Random Consistency**
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

It should be noted that if the values of CR are greater than 10 percent, the user will be prompted to revise the pair-wise comparison entries.

The developed decision support system was designed in a manner to accommodate the user's selection criteria in specifying the attributes for comparison for each project being considered. The decision is based on a maximum of nine attributes: three account for technical requirements, four for contractual requirements, and the remaining two for the cost effectiveness requirement. These attributes are, respectively, degree of bends, maximum access distance, life expectancy, number of products installed, number of years in business, duration, innovation, total capital cost (direct and indirect), and life cycle cost as shown in Figure 5.14. It should be noted that all methods of rehabilitation should meet the project's technical characteristics. The user can select certain attributes or a maximum of nine attributes, as shown in Figure 5.15, to evaluate the various rehabilitation products suggested by the DFQS. In this way, the system can better accommodate the user's selection criteria in the selection of the most suitable rehabilitation product.

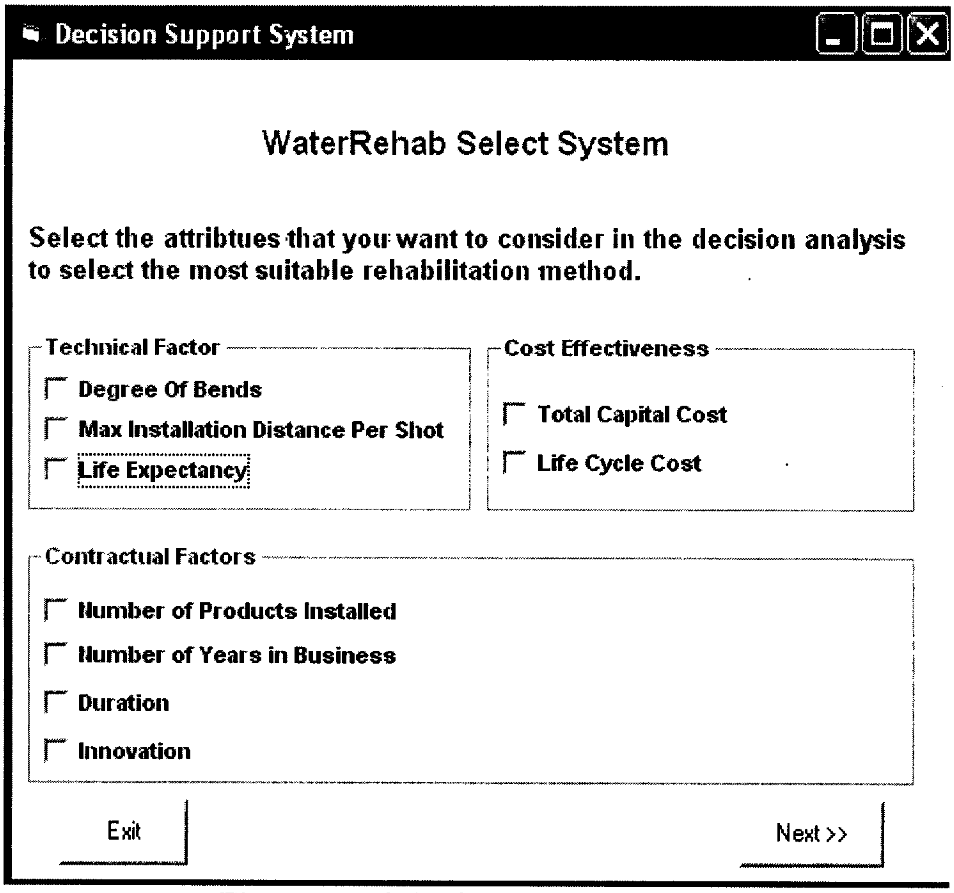


Figure 5.15 Selection of DSS Attributes

After selecting the attributes for comparison, the system prompts the user through an interactive dialogue consisting of a set of questions. The questions are designed to elicit the user's input with respect to the most and least value each attribute can have as shown in Figure 5.16. In doing so, the most and least attribute values are assigned utility values of 1.0 and 0.0, respectively. The attributes of the suggested products are assigned an intermediate utility value between the two extremes to express the user's degree of satisfaction.

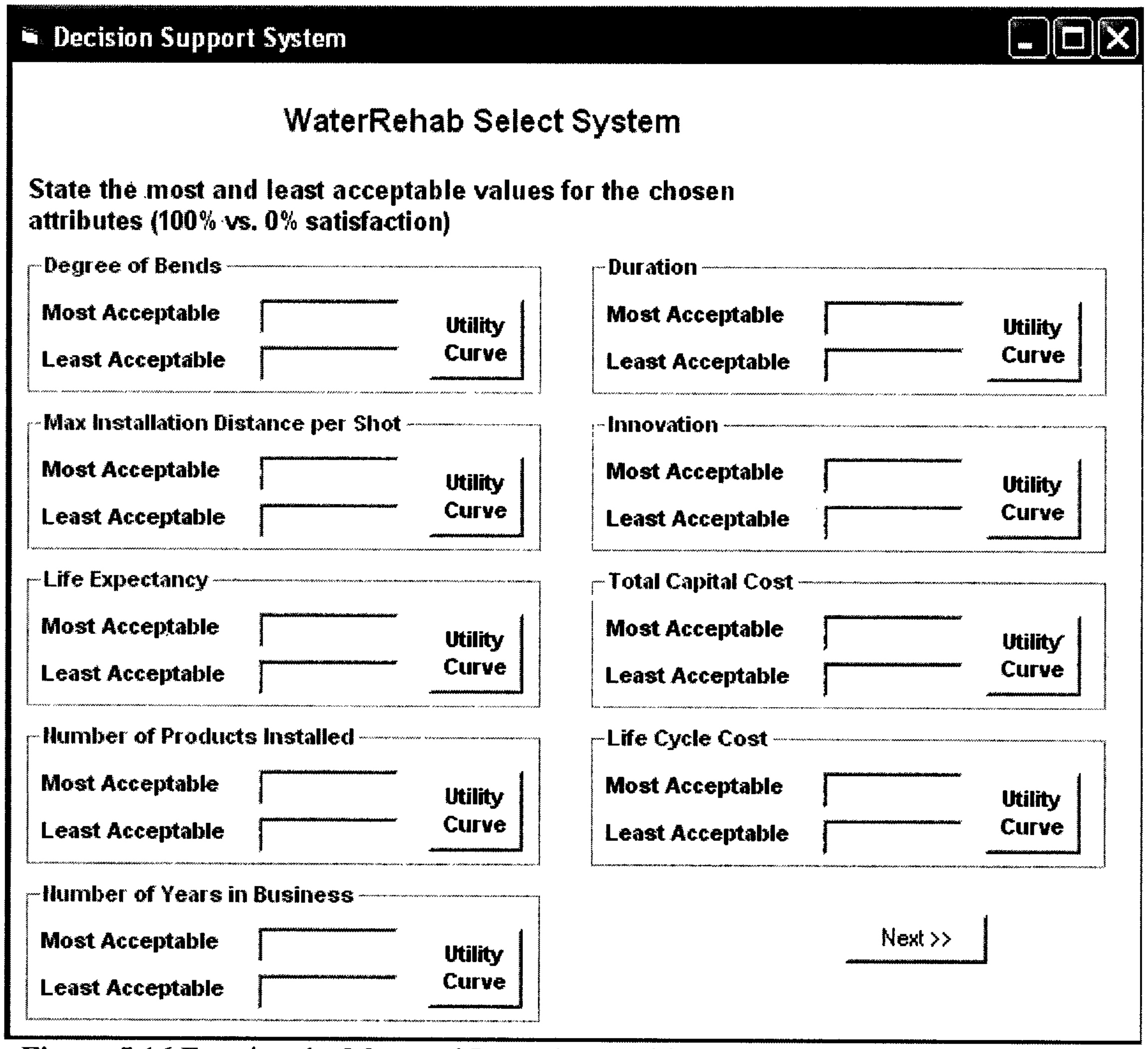


Figure 5.16 Entering the Most and Least Acceptable Values for the Selected Attributes

After the user's defined criteria is expressed as each attribute takes on values between its least and most bounds, the system generates the utility function that best describes the decision-maker's attitude towards risk for each attribute. Four functions are incorporated in the developed DSS to facilitate the generation of the system's utility function. They are linear, logarithmic, exponential, and 2nd degree polynomial, and can be expressed as follows (Keeney and Raiffa 1976) (Ang and Tang 1984):

- Linear: $u(x) = a + bx$ (5-3)

- Logarithmic: $u(x) = a \ln(x + \beta) + b$ (5-4)
- Exponential: $u(x) = a + be^{-\gamma x}$ (5-5)
- 2nd Degree Polynomial: $u(x) = a(x - \frac{1}{2}\alpha x^2) + b$ (5-6)

where

a & b are normalization constants

γ, β, and α are parameters related to the degree of risk-aversion.

Clicking on the Utility Curve button, shown in Figure 5.16, directs the user to the window screen shown in Figure 5.17, to select the utility function that best describes his/her attitude toward risk.

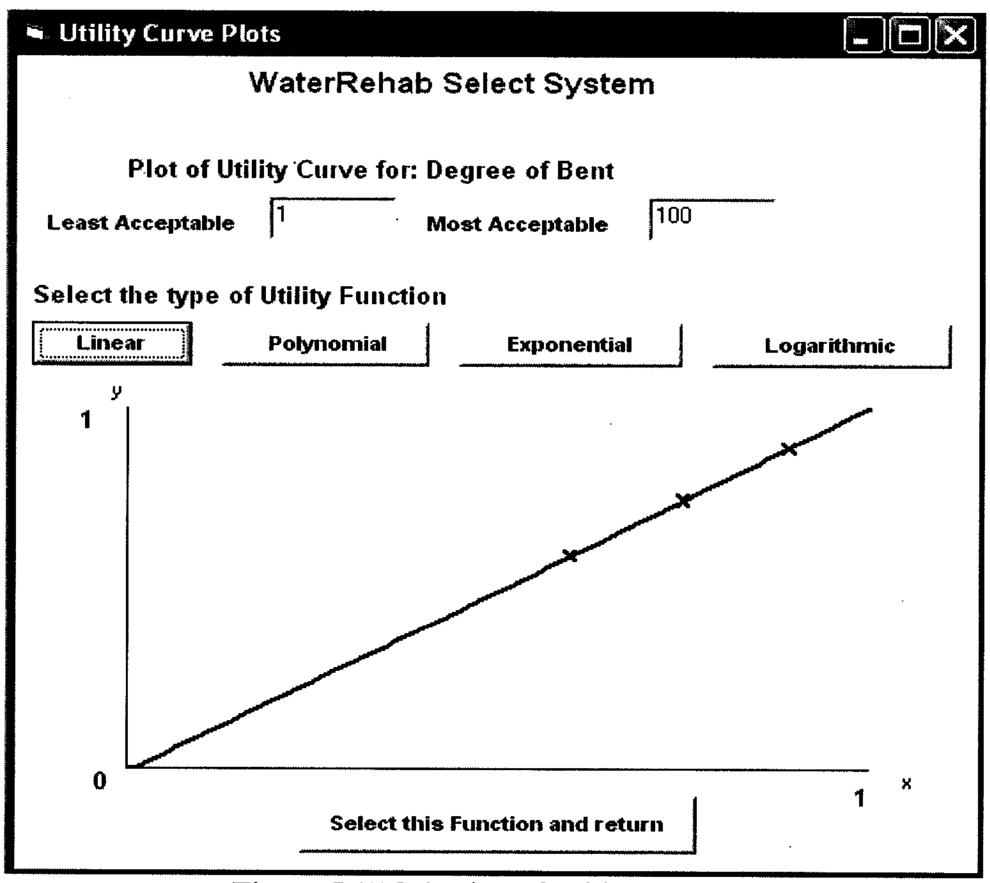


Figure 5.17 Selection of Utility Function

After defining the utility values for the suggested product's attribute, the system prompts the user to establish the relative weights of decision hierarchy attributes using the analytical hierarchy process as described above. The system provides the user with two options. The first option consists of simply entering his/her defined criteria of relative weights or of using predefined relative weights of previous profiles as shown in Figure 5.18.

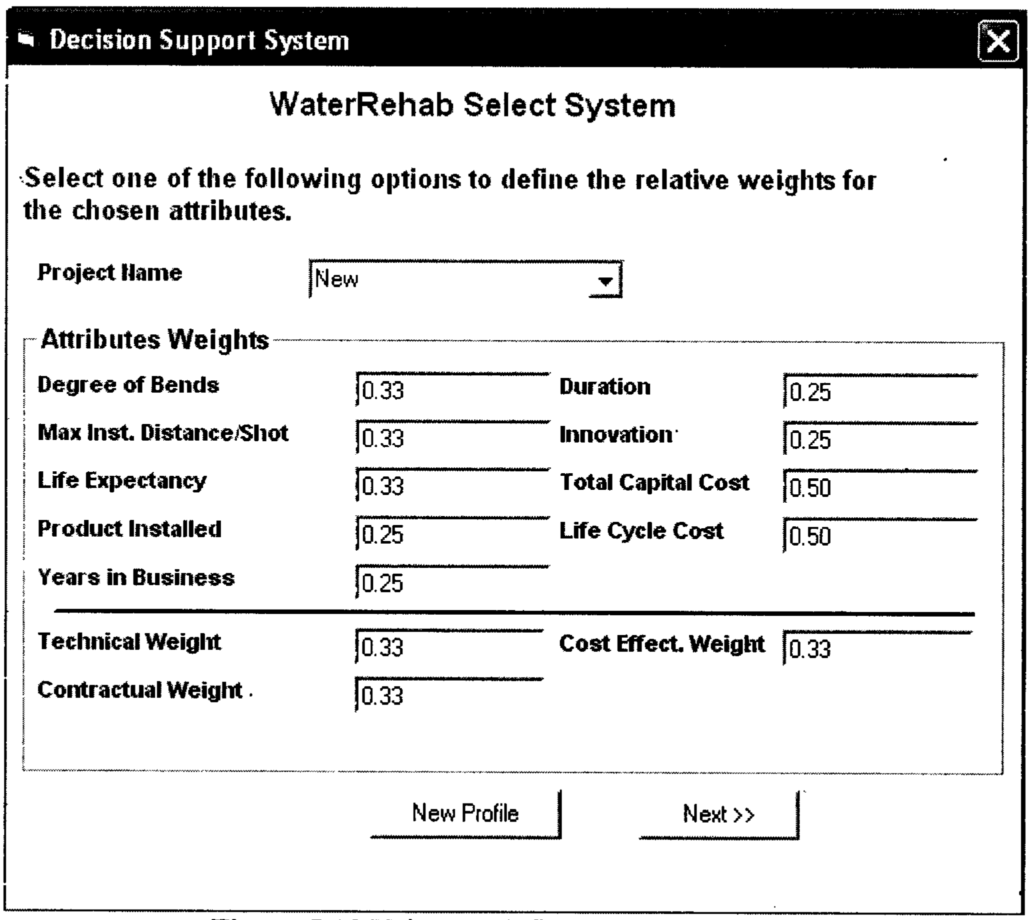


Figure 5.18 Using Predefined Relative Weights

The second option lets the DSS system calculate the relative weights of attributes automatically after the user has finished stating the relative importance factors in the pair-wise comparison matrix using a scale of 1 to 9. Since the pair-wise comparison is performed in a matrix, the user is required to fill in the triangle above the diagonal, because the system automatically fills in the triangle below the diagonal by reciprocating the values in the higher triangle. This facilitates the relative importance factors entry. The window screen for the project requirement matrix is shown in Figure 5.19.

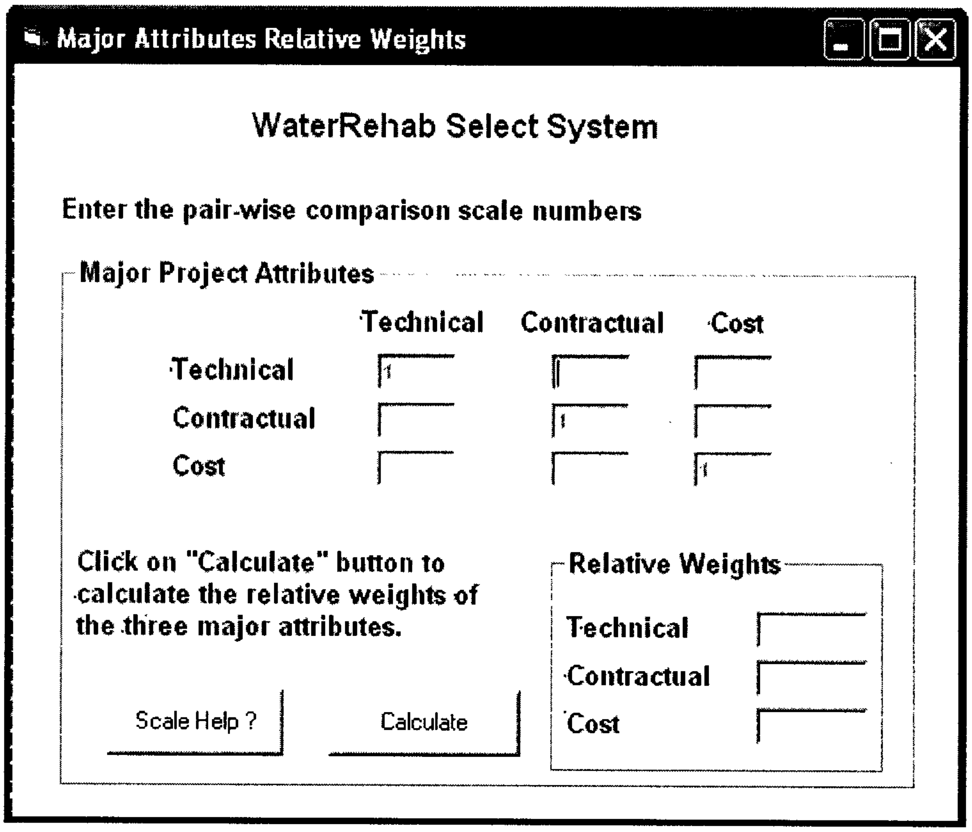
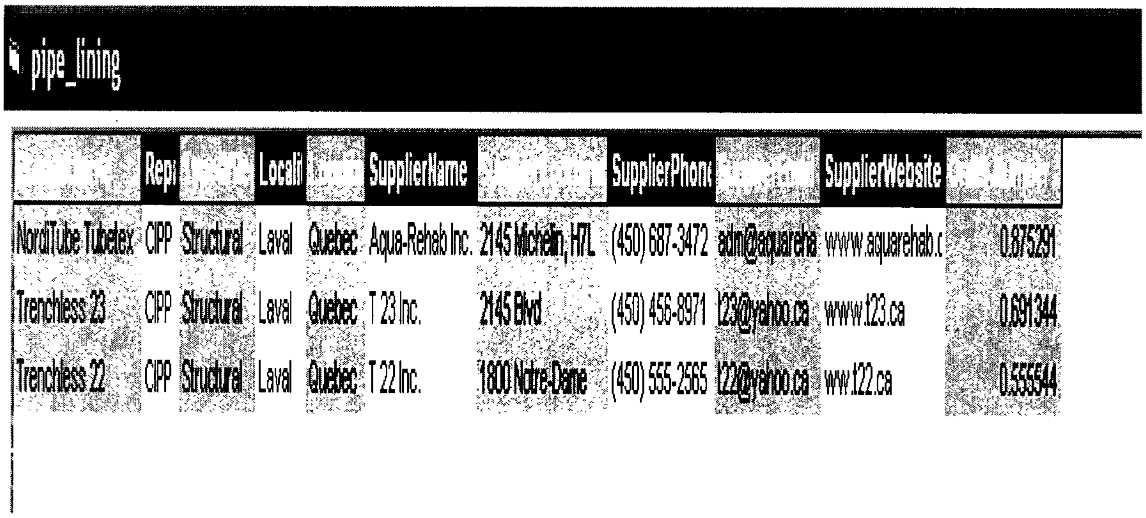


Figure 5.19 Project Requirements Matrix

After calculating the relative weights of each attribute chosen, the system automatically calculates the consistency ratio. If the CR is less than or equal to 10%, the system prompts the user to the final screen, shown in Figure 5.20, which shows the overall utility value of each product. The product with the highest overall utility value will be the most suitable method. In addition, Figure 5.20 shows the DSS ranking of products from decreasing order of suitability. If the CR is greater than 10 percent, the system prompts the user to revise the importance factors data entered in the pair-wise comparison matrix and to repeat the process.



pipe_lining

	Repi		Localit		SupplierName		SupplierPhon		SupplierWebsite	
NordiTube Tubetex	CIPP	Structural	Laval	Quebec	Aqua-Rehab Inc.	2145 Michelin, H7L	(450) 687-3472	adm@aquareha	www.aquarehab.c	0.875291
Trenchless 23	CIPP	Structural	Laval	Quebec	T 23 Inc.	2145 Blvd	(450) 456-8971	t23@yahoo.ca	www.t23.ca	0.691344
Trenchless 22	CIPP	Structural	Laval	Quebec	T 22 Inc.	1800 Notre-Dame	(450) 555-2565	t22@yahoo.ca	ww.t22.ca	0.555544

Figure 5.20 DSS Ranked Products

5.6 Limitations of Developed System

The following are the limitations of the "WaterRehab Select" system:

- The system can be utilized only when a defect report has been issued and a decision has been taken to rehabilitate/ replace the water main.
- The Decision Support System assumes that the attributes in the analysis are mutually independent, i.e. altering one attribute will not affect other attributes. This assumption does not show the relationship between the attributes.
- The hybrid methodology utilized in the system uses a neutral risk attitude and does not account for averse or pro-risk attitudes.

- The system does not suggest any trenchless method utilized in the construction of new water main such as Horizontal Directional Drilling (HDD) and Micro-tunnelling.
- The system requires the periodical update of data stored in the data files
- The information stored in the data files was collected from trenchless product manufacturers and suppliers and has not been checked by end users such as contractors, consultants, and municipalities.

5.7 Application of Automated System

As presented in the case study mentioned above, the water main located at Blvd. Notre-Dame required immediate rehabilitation. It is required to select the most suitable trenchless rehabilitation method for this water main considering technical, contractual, and cost effectiveness requirements, shown in Table 5.6.

Table 5.6 Blvd. Notre-Dame Project Information

Blvd. Notre-Dame	
• Type of Defect	Structural Defect
Problem Encountered	Poor Structural Integrity, Water Quality and Hydraulics (Full deterioration)
Any close-by utilities that might be damaged during rehabilitation process	No
Importance of Reducing Social Disruption	High
• Type of Repair Required	Structural Rehabilitation
Host Pipe Material Type	Grey Cast Iron
Host Pipe Diameter	300 mm
Max. Degree of Bends in Host Pipe	22.5^{o}
Total Length of Pipe	875m
Longest Section Length	140m
Allowable Ground Access	Inspection Chambers and Excavated Pits
Reconnection of Lateral Service Lines	Robotic Cutters
Required Hazen-William coefficient	140
Accommodate Differential Settlements	Yes
Accommodate Thermal Strains	Yes
Cleaning and Dewatering	Yes
Planned Project Budget	$ 295,000 (CND)
Planned Project Duration	7 Weeks
Required Product Life Expectancy	25 Years
Required No. of Years In Business	10 Years
Required Length of Product Installed	5000 m
Locality of Manufacturer	Canada
Required Degree of Innovation (1-5)	3

The diameter of the water main does not require any upsizing to meet the population requirements. On the other hand, no reduction of the cross-sectional area of the pipe, i.e., the flow rate, is allowed. Checking the underground water main plans revealed that there are no close-by infrastructure systems. However, the water main lies beneath a main boulevard, i.e., there are high traffic concentrations. Therefore, the social activities and traffic disruption should be taken into careful consideration. The following Figures 5.21 to 5.40 show the window screens retrieved after utilizing the developed system.

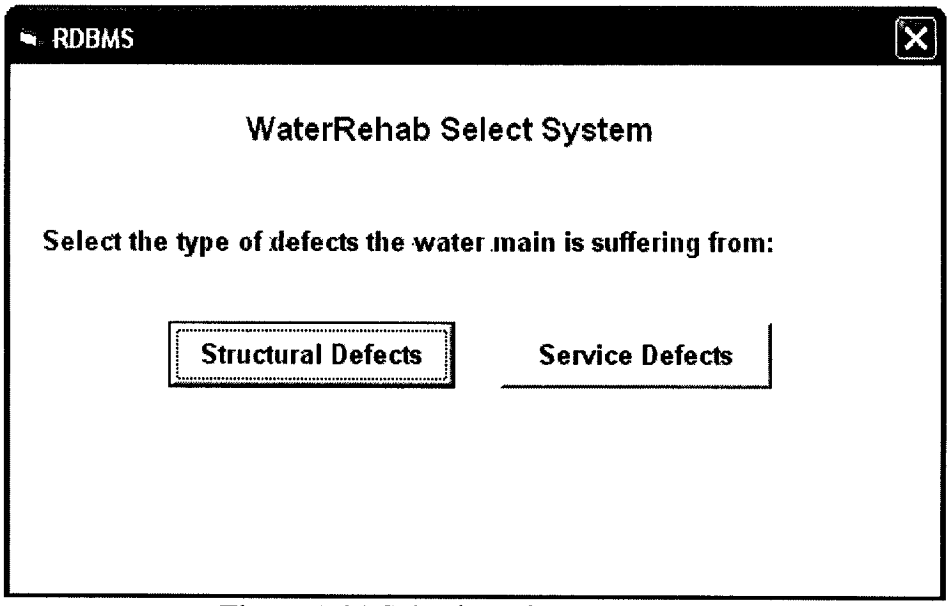


Figure 5.21 Selection of Type of Defect

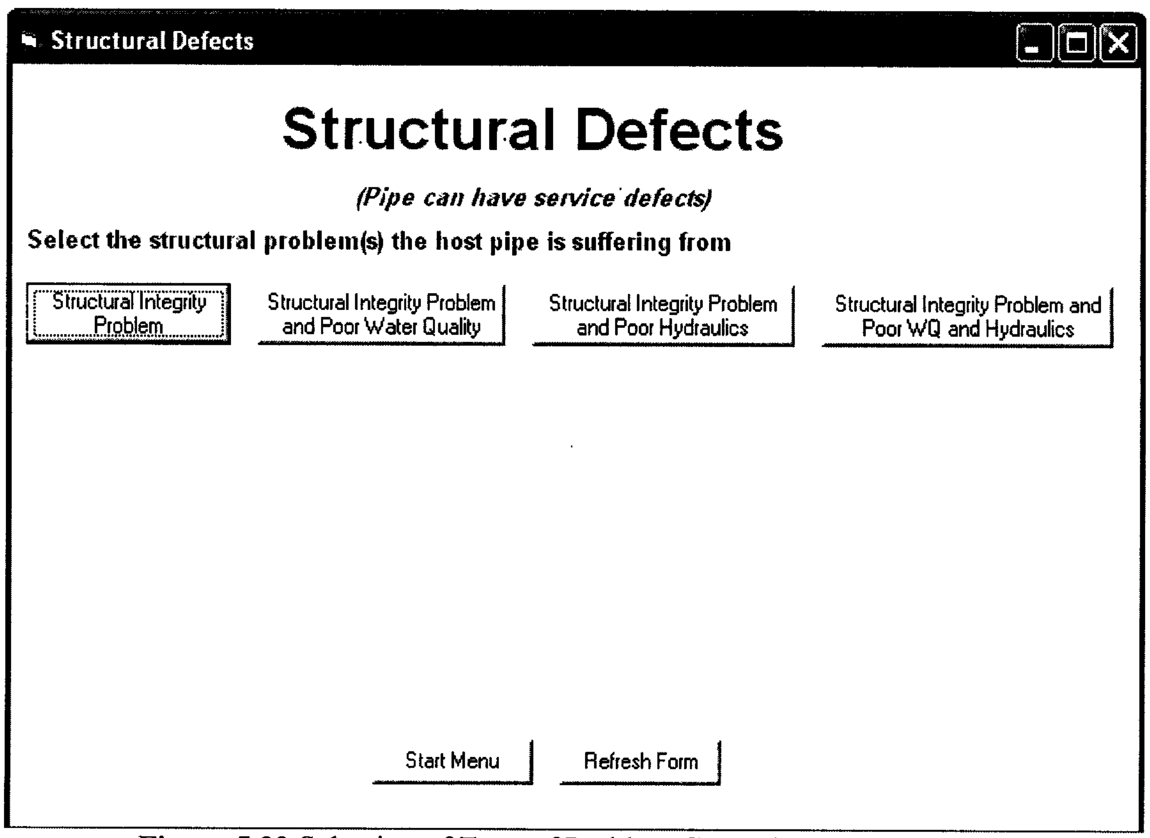


Figure 5.22 Selection of Type of Problem Created Due to the Defect

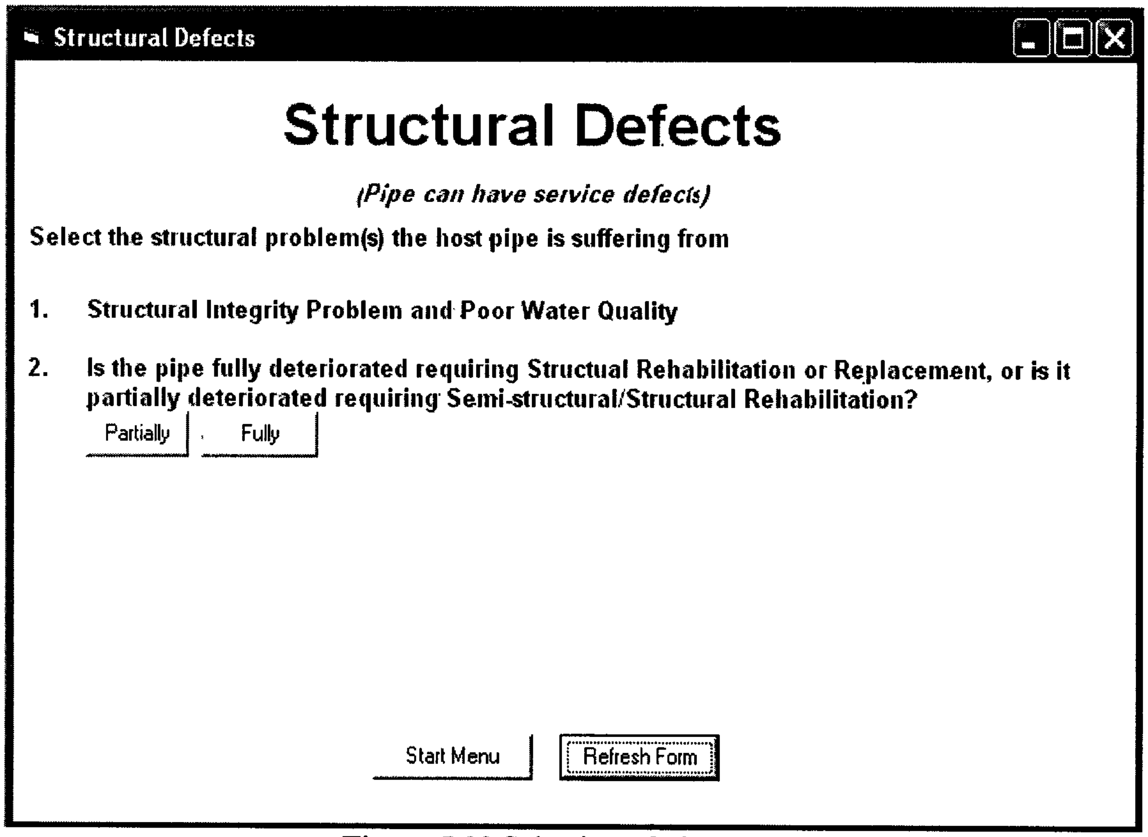


Figure 5.23 Selection of Pipe Status

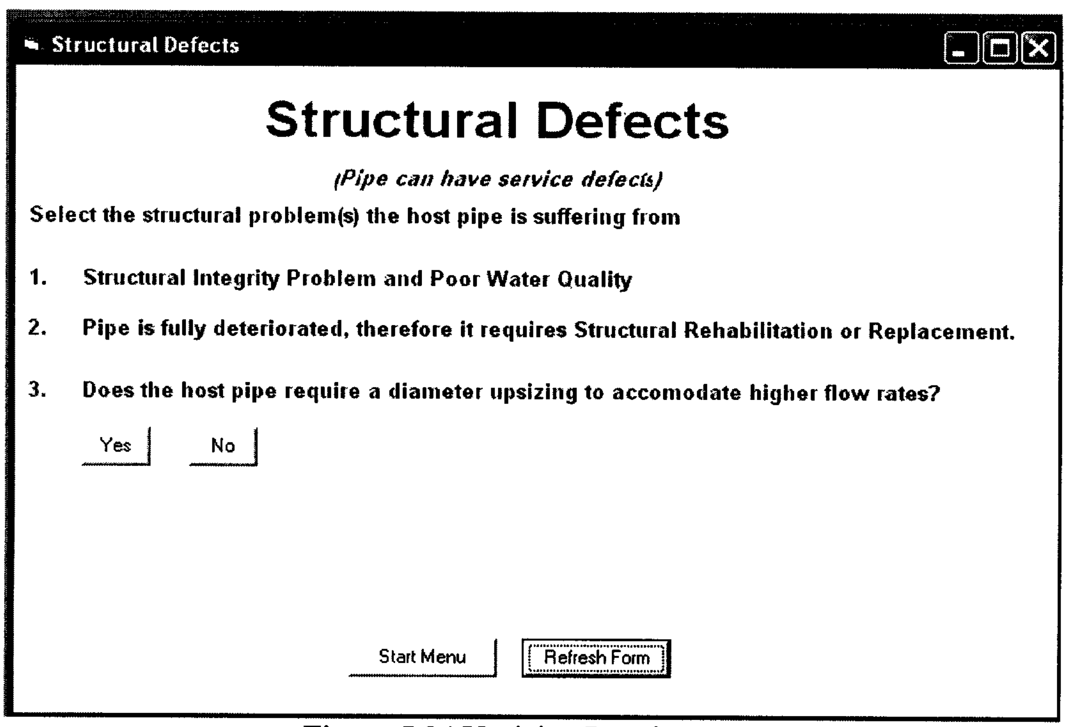


Figure 5.24 Upsizing Requirements

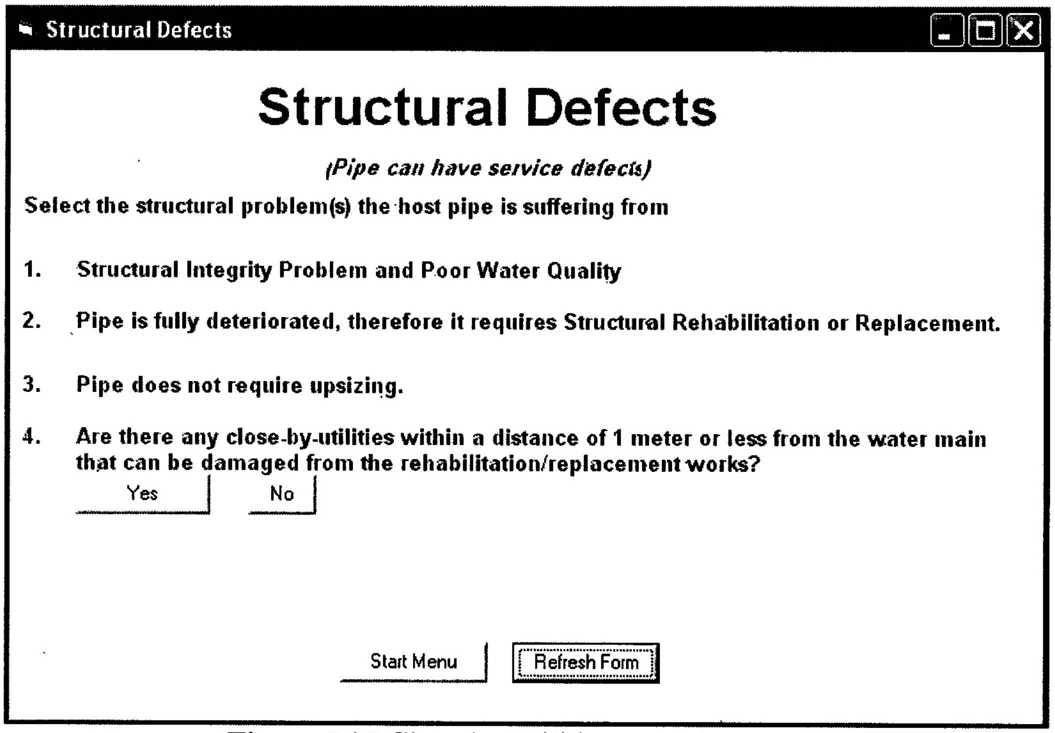


Figure 5.25 Close-by Utilities Selection Factor

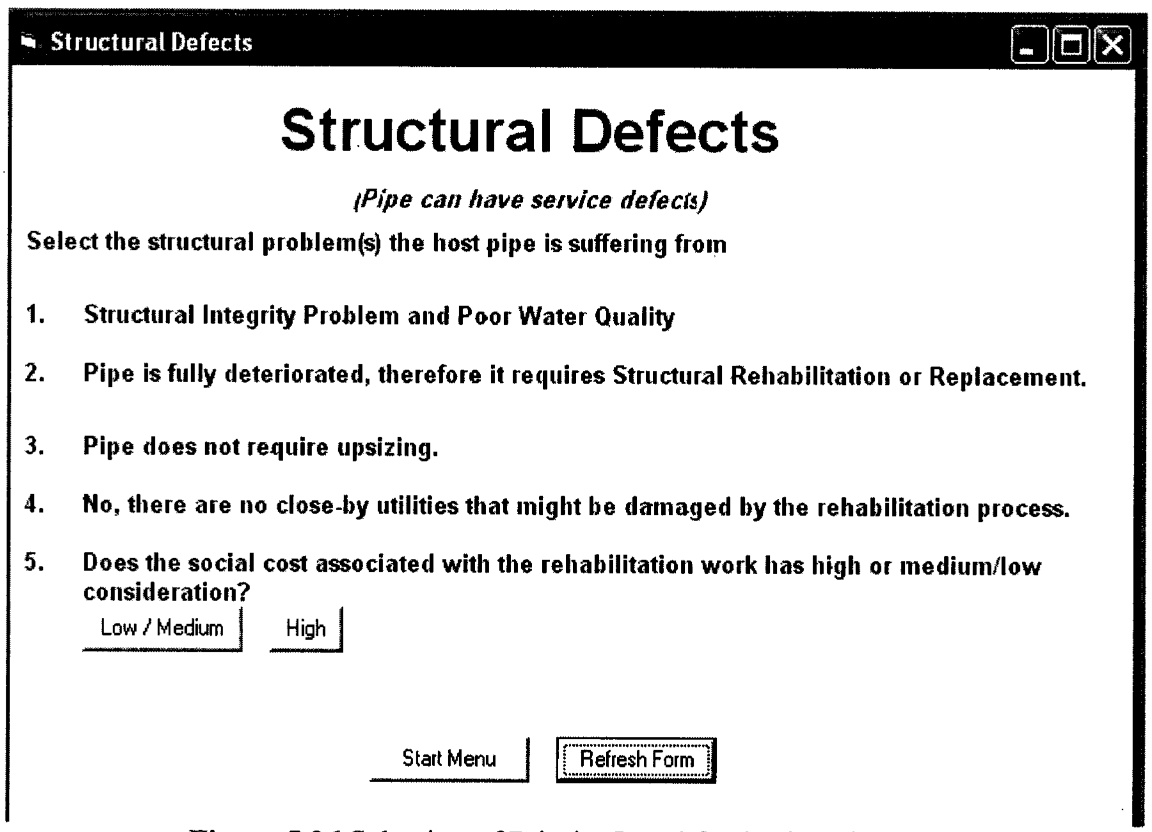


Figure 5.26 Selection of Priority Level for Social Disruption

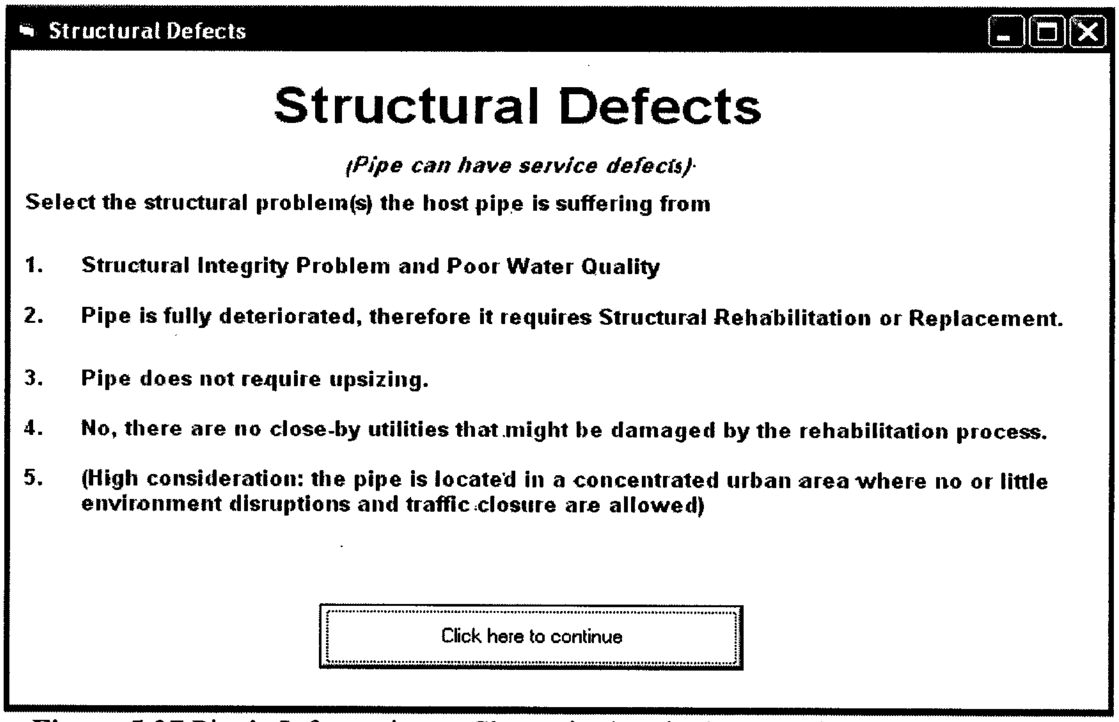


Figure 5.27 Pipe's Information as Shown in the Final Interactive Flowchart Screen

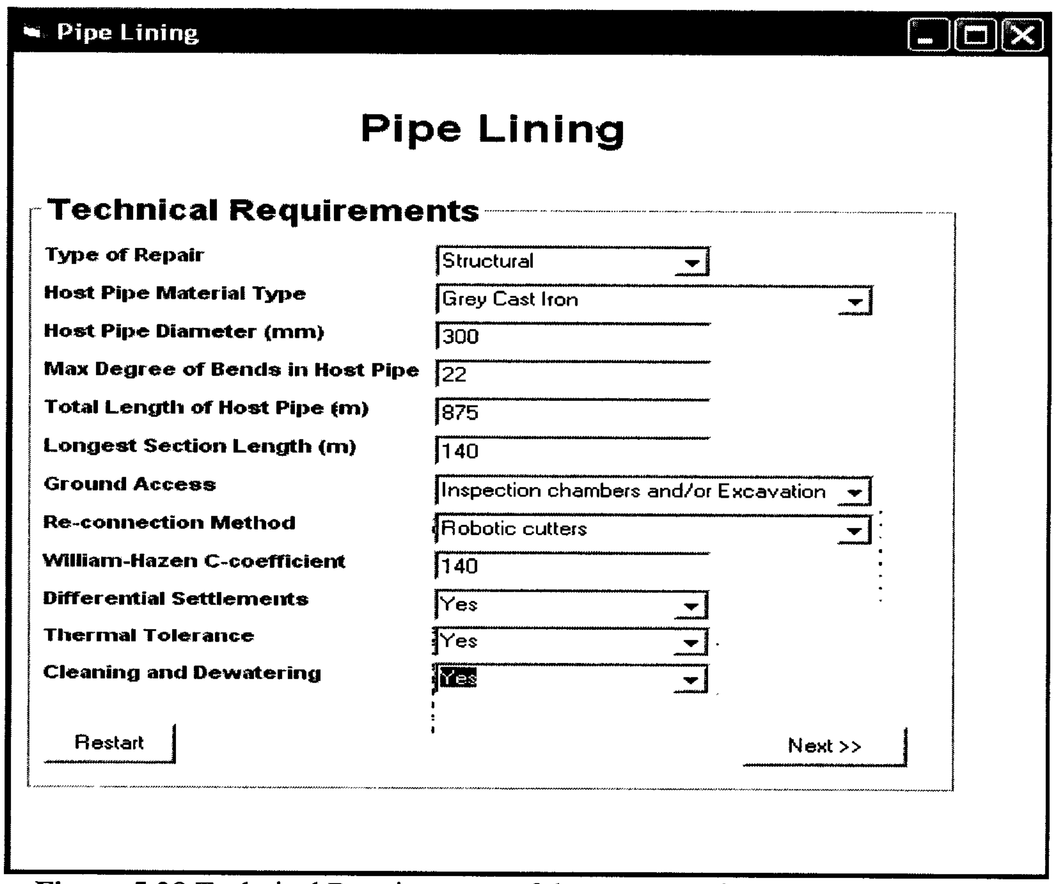


Figure 5.28 Technical Requirements of the Water Main at Blvd. Notre-Dame

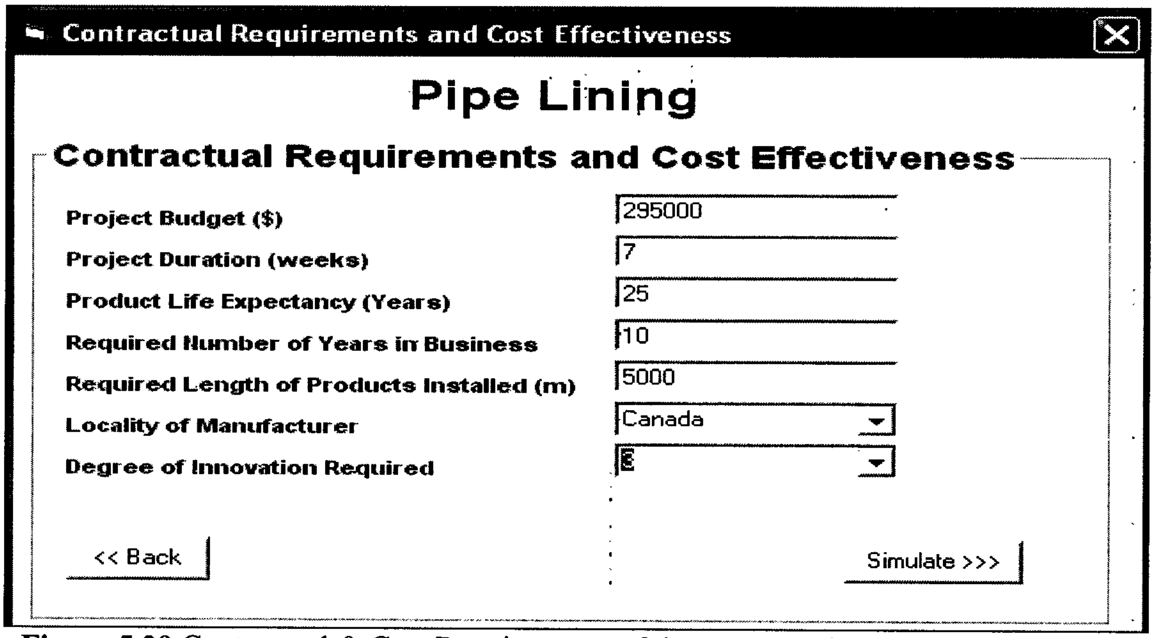


Figure 5.29 Contractual & Cost Requirements of the Water Main at Blvd. Notre-Dame

The stated project budget shown in Figure 5.29 is compared to the total capital cost of the products which is the product of the total length of the host pipe, the diameter of the host pipe, and the cost of installed product per cm diameter per linear meter. Activating the DFQS yields the following pipe lining products:

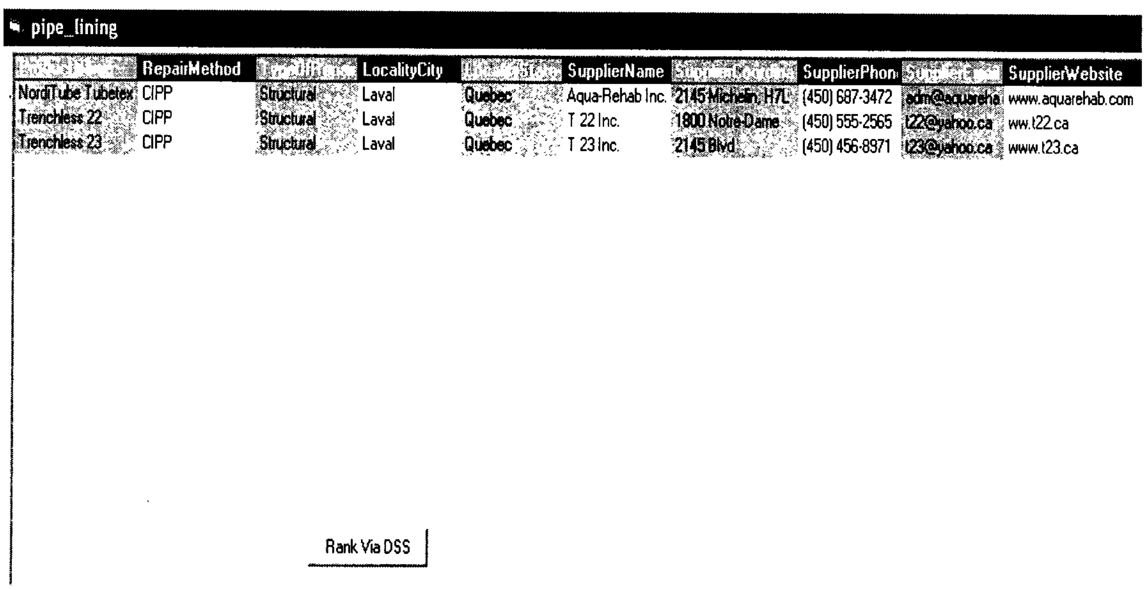


Figure 5.30 DFQS Output

Since more than one product has been suggested by the Data Files and the Query System, as shown in Figure 5.30, the Decision Support System has been activated to rank the products according to the user's selection criteria. The user has decided, as shown in Figure 5.31, to use the maximum degree of bends, service life expectancy, and maximum lining distance per shot in his decision analysis.

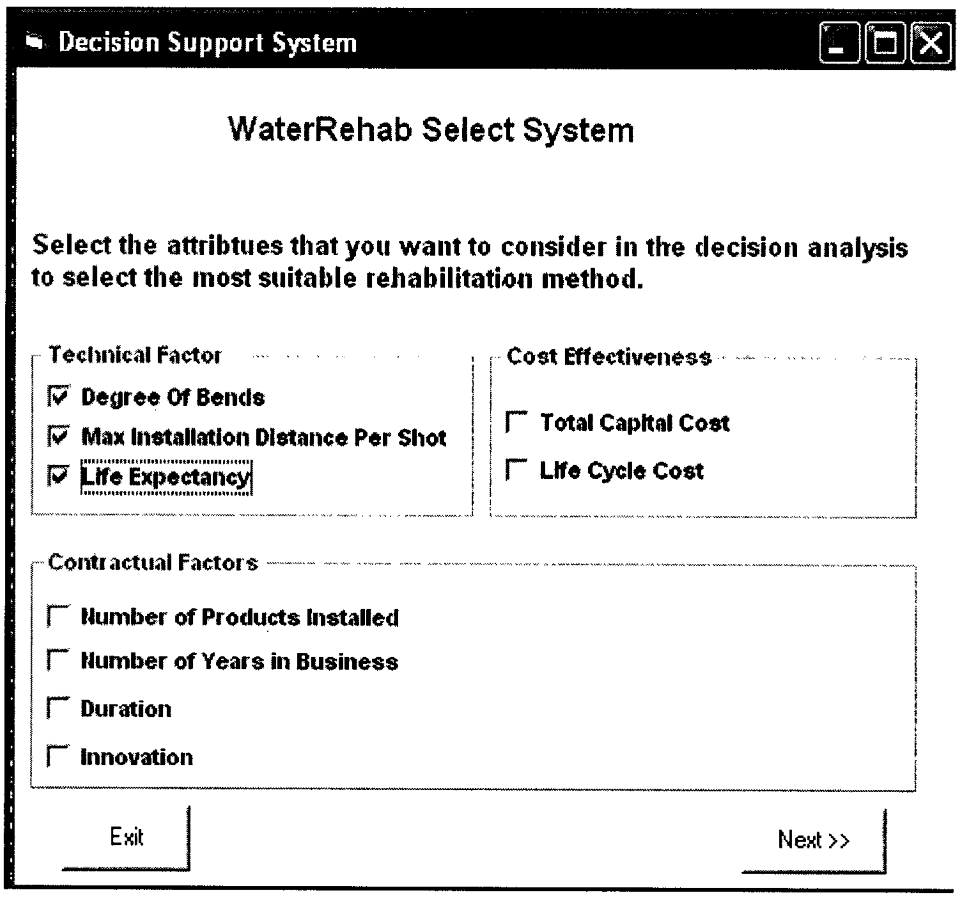


Figure 5.31 Selection of Decision Attributes

After selecting the attributes that will be used in the decision support system, the user has to enter the most and least acceptable value of each attribute according to his/her defined criteria, as shown in Figure 5.32. Figures 5.33 through 5.35 indicate the utility function chosen for each attribute. The chosen function will be utilized by the system to calculate the utility value of attribute for each product.

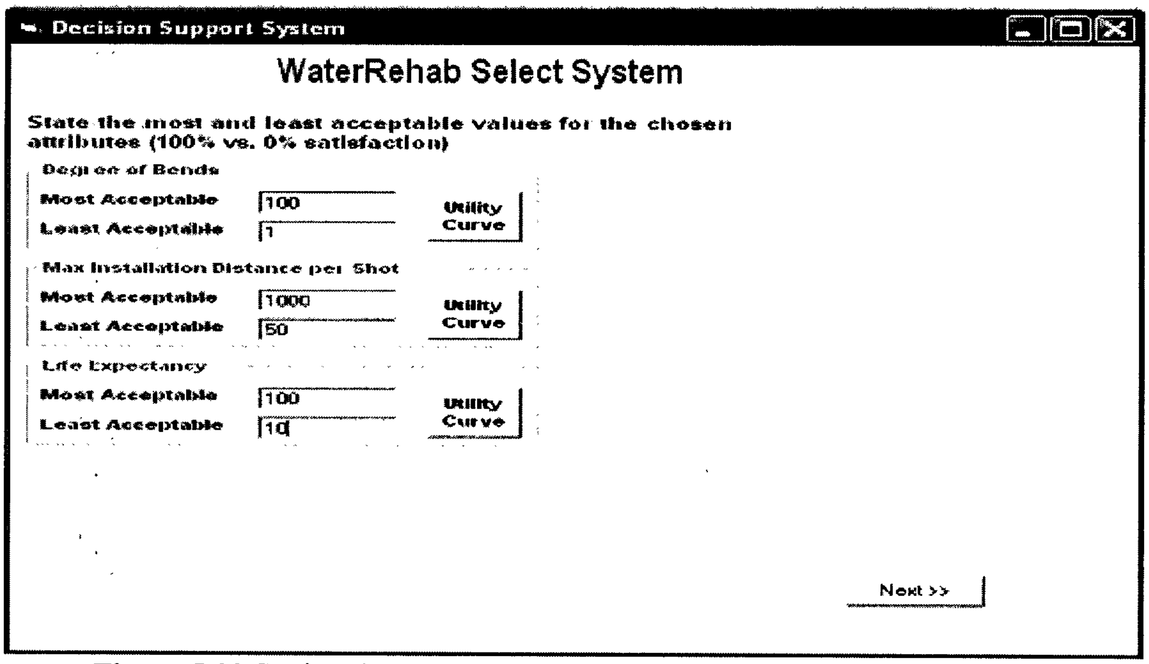


Figure 5.32 Stating the Least and Most Acceptable Values of the Attributes

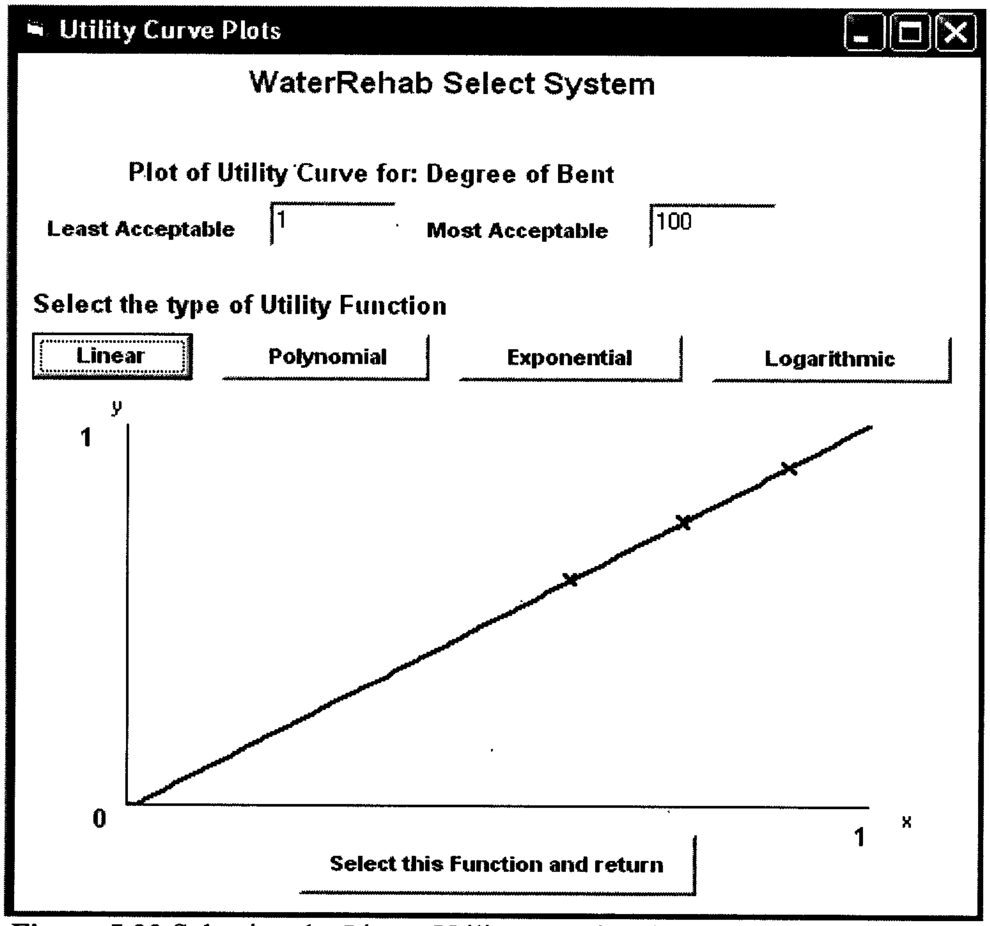


Figure 5.33 Selecting the Linear Utility Function for Max. Degree of Bends

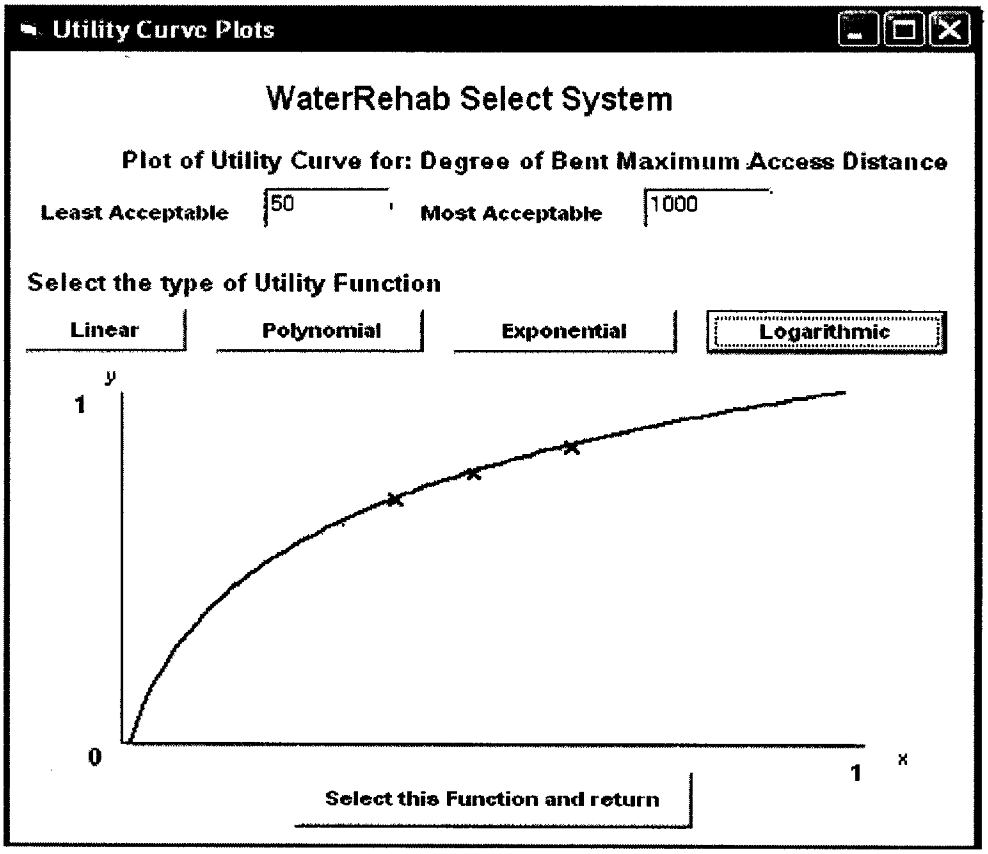


Figure 5.34 Selecting the Logarithmic Utility Function for Max. Installation Distance per Shot

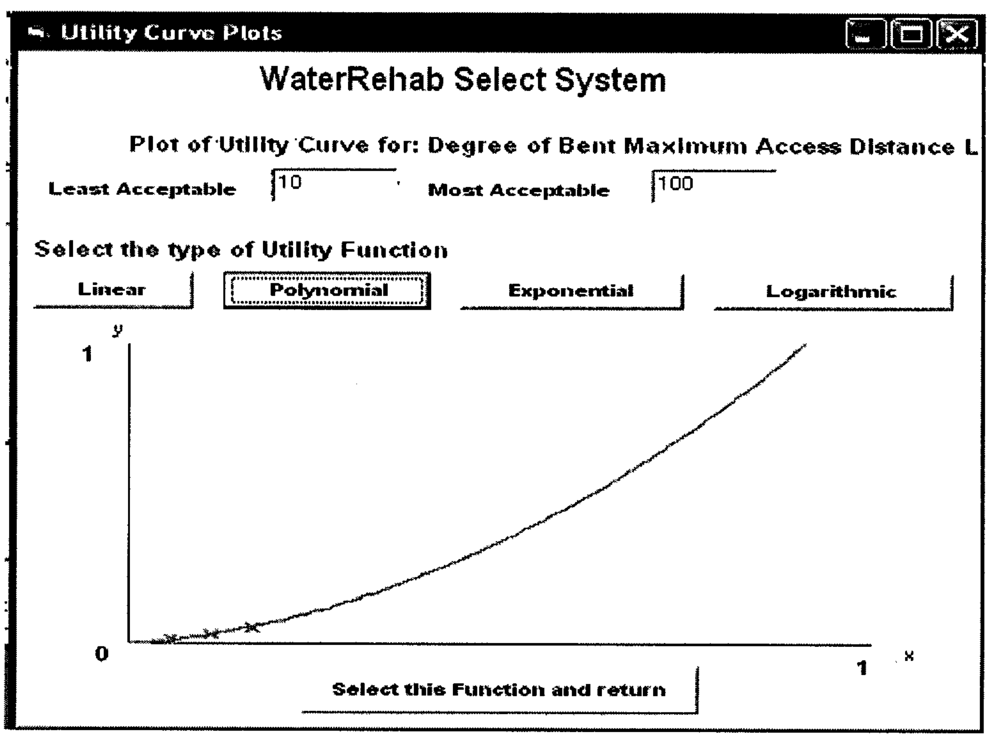


Figure 5.35 Selecting the Polynomial Utility Function for Life Expectancy

The user then has to enter his/her defined criteria of relative weights or let the developed system calculate the relative weights. The user has decided to let the developed system calculate the relative weights as shown in Figure 5.36.

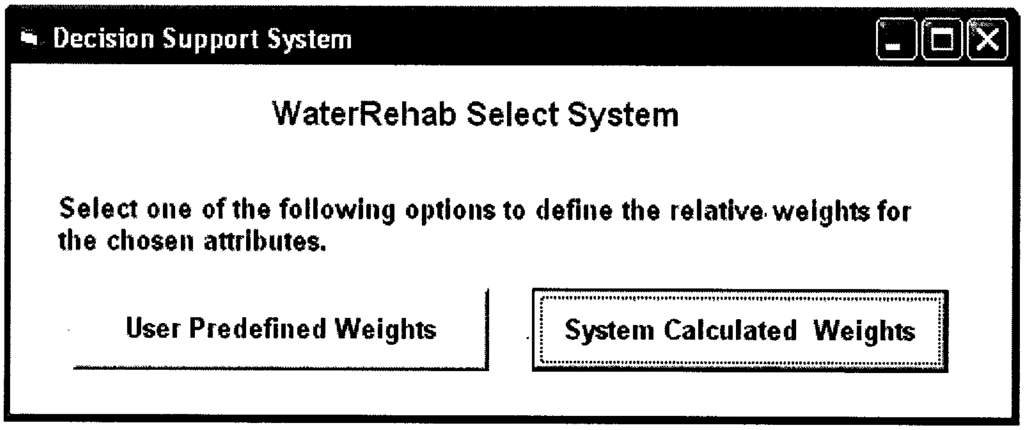


Figure 5.36 Calculating Relative Weights Using the System

The developed system has asked the user to enter the 1 to 9 pair-wise comparison scale numbers for all project attributes, as shown in Figures 5.37 and 5.38.

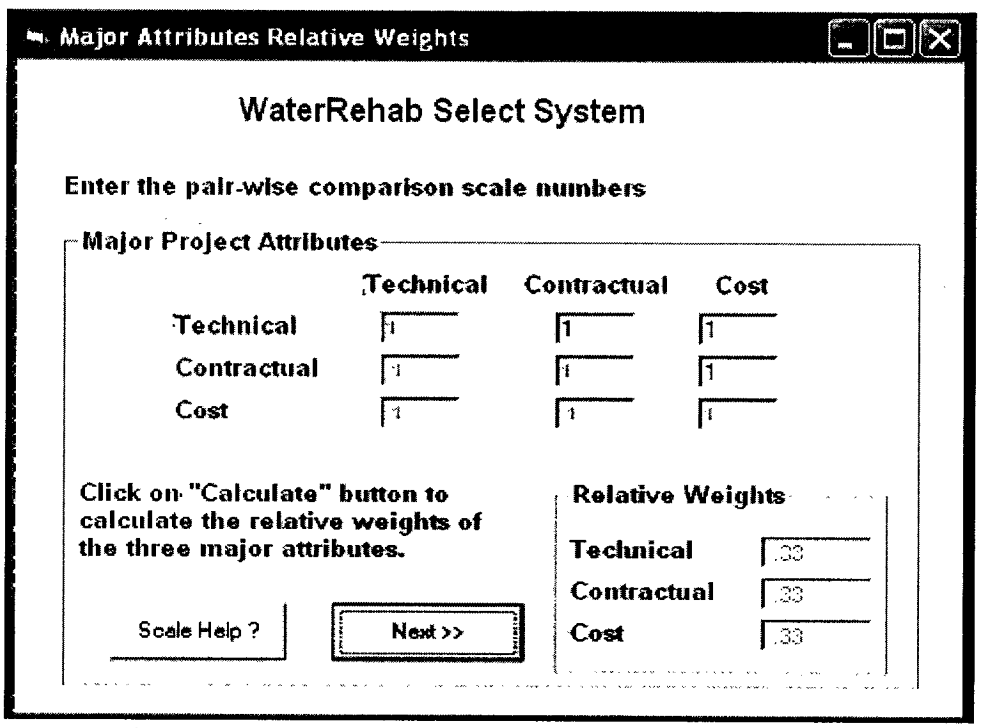


Figure 5.37 Calculating Major Attributes Relative Weights

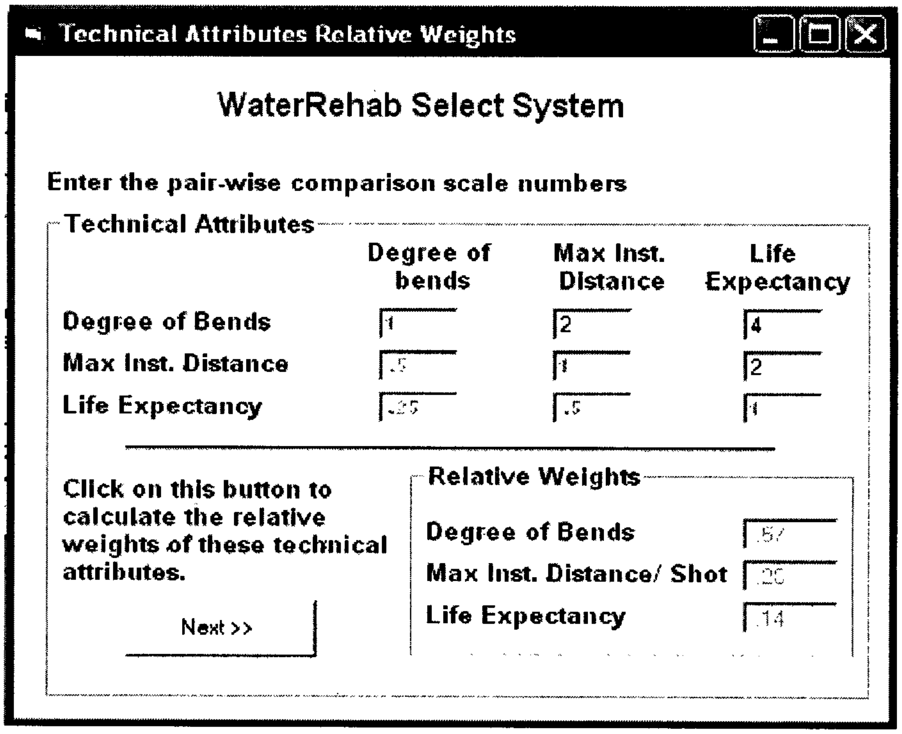


Figure 5.38 Calculating Technical Attributes Relative Weights

The system calculated relative weights for the technical attributes are shown in Figure 5.38. The contractual and cost attributes has been assigned equal relative weights respectively as shown in Figure 5.39.

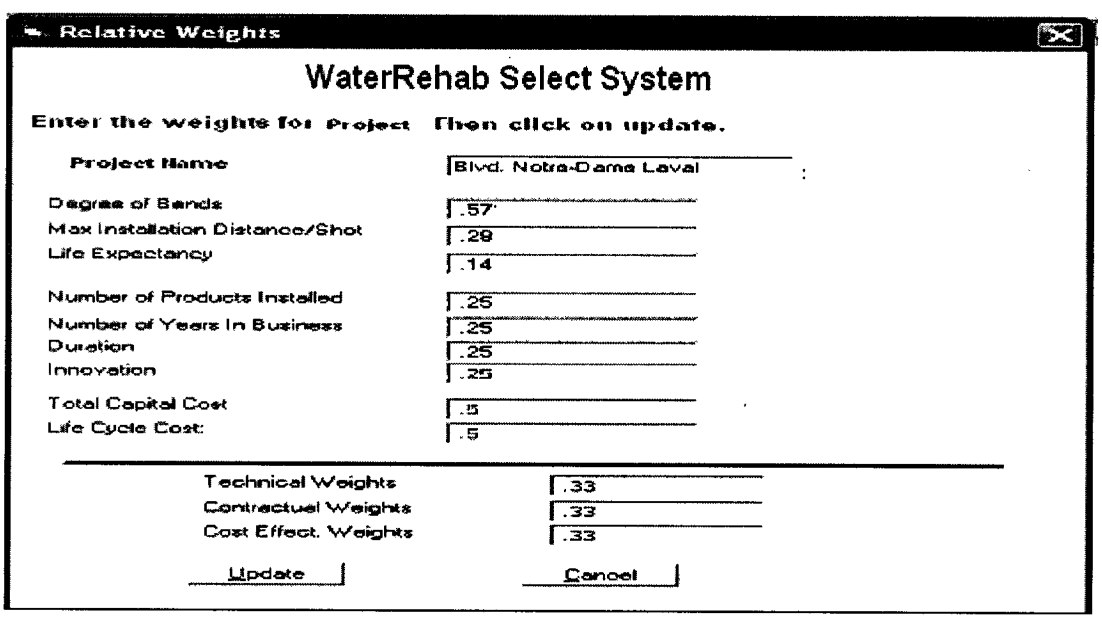
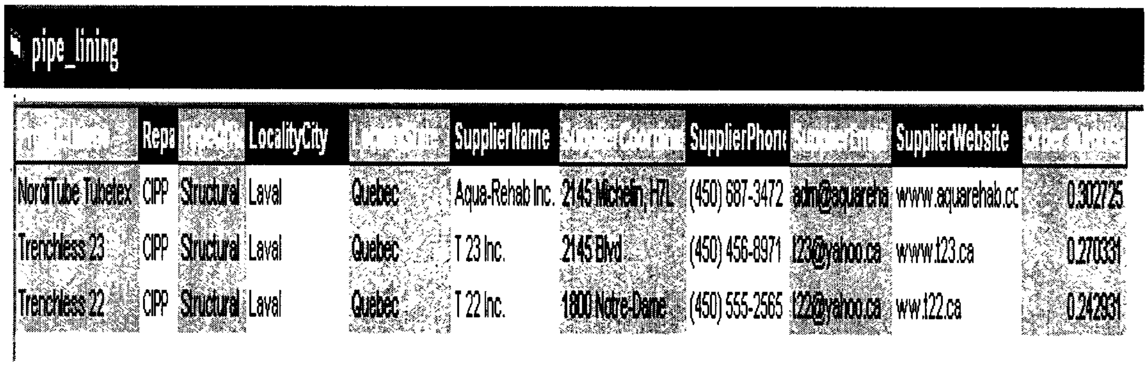


Figure 5.39 System Calculated Attributes Relative Weights

The developed system will then calculate the overall utility values according to Equation 5-1. The products are ranked in an order according to their respective descending overall utility values.



pipe_lining

[illegible]	Repa	[illegible]	LocalityCity	[illegible]	SupplierName	[illegible]	SupplierPhon	[illegible]	SupplierWebsite	[illegible]
NordiTube Tubetex	CIPP	Structural	Laval	Quebec	Aqua-Rehab Inc.	2145 Michelin, H7L	(450) 687-3472	adm@aquareha	www.aquarehab.cc	0.302725
Trenchless 23	CIPP	Structural	Laval	Quebec	T 23 Inc.	2145 Blvd	(450) 456-8971	t23@yahoo.ca	www.t23.ca	0.270331
Trenchless 22	CIPP	Structural	Laval	Quebec	T 22 Inc.	1800 Notre-Dame	(450) 555-2565	t22@yahoo.ca	ww.t22.ca	0.242931

Figure 5.40 DSS Ranked Products

The following is the rank and the overall utility value of each product as shown in Figure 5.40:

1. NordiTube Tubetex lining with an overall utility value of 0.30
2. Trenchless 23 lining with overall utility value of 0.27
3. Trenchless 22 lining with overall utility value of 0.24

The municipal engineers, of Laval, decision for using Tubetex L-1 lining for the rehabilitation of the water main located at Blvd. Notre-Dame can be validated by the developed system. Tubetex L-1 lining had the highest overall utility value therefore it is the most suitable trenchless product according to the project requirements and user's selection criteria.

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APPENDICES

APPENDIX A

Dear Sir/ Madame,

My name is Ahmad Al-Aghbar, Master's of Applied Science student in the area of Construction Engineering and Management at Concordia University, Montreal, Canada. I am currently conducting a research on the rehabilitation of water mains using available trenchless technologies.

I would like to seek your assistance in my research as I am currently trying to gather information about available trenchless technology products 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 "Automated Selection of Trenchless Technology for Rehabilitation of Water Mains." 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.

Please click on this link to fill out the form:
http://brightvision.net/asttrwm/q_english.html

Best regards,

Ahmad Al-Aghbar

Graduate Student
Master's of Applied Science- Construction Engineering and Management
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Questionnaire Form

All responses will remain **STRICTLY CONFIDENTIAL** and will be used for educational and research purposes only. Please respond by putting a cross mark (X) next to your selection(s).

PART 1: COMPANY'S PROFILE

COMPANY'S NAME: ____________________

TITLE OR POSITION OF RESPONDENT: ____________________

ADDRESS:

TELEPHONE / FAX / WEBSITE / E-MAIL:

---

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

☐ < =10 Years ________ ☐ 10-20 ________ ☐ 20-30 ________

☐ > 30 ________

2. **What percentage of your rehabilitation works uses trenchless technology; please specify?**

☐ < 50 % ________ ☐ 50% - < 70% ________

☐ 70 - < 90 % ________ ☐ > 90% ________

3. **Has the demand for the use of trenchless technology *increased/decreased/same* during the past 5 years; please specify the percentage (%) it has increased/decreased?**

☐ Increased________% ☐ Decreased________%

☐ Same

4. **Do you have offices in different locations in Canada; if Yes please specify in which provinces and cities?**

☐ YES ☐ NO

____

____

____

5. **Can you accommodate new client requirements that are not part of your design or production standard? If Yes, please rank your ability to accommodate on a scale of 1 to 5 for 1 (lowest) & 5 (highest).**

☐ YES: (Rank) 1 2 3 4 5 ☐ NO

6. **Would you like to be acknowledged in my research thesis?**

☐ YES ☐ NO

PART 2: PRODUCT'S PROFILE

Please duplicate this part (i.e. Part 2) for each different product.

PRODUCT'S COMMERCIAL NAME: ______________________________

1. **Under which trenchless method is this product categorized?**

☐ Cured-In Place Pipes ☐ Slip Lining ☐ Swaged Lining ☐ Spray Lining

☐ Fold & Formed Lining ☐ Pipe Reaming ☐ Pipe Bursting ☐ Pipe Eating

☐ Horizontal Directional Drilling ☐ Micro-tunneling ☐ Impact Moling

☐ Others: (Specify) ____________

2. **Indicate the type of repair this product is suitable for:**

☐ Non-Structural ☐ Semi-Structural ☐ Structural

3. **What type of defects this product can repair?**

☐ Structural Defects (Cracks, etc.) ☐ Service Defects (Tuberculation, etc.)

4. **What type(s) (materials) of host pipe is this product suitable for?**

☐ PVC ☐ Grey Cast Iron ☐ Ductile Iron ☐ Concrete Pressure Pipes

☐ Polyethylene (PE & HDPE) ☐ Steel ☐ Others: (Specify)__________

5. **What is the product's range of diameters (mm)?**

☐ 50 - 600 mm ☐ 100 – 1000 ☐ 100-1500 ☐ 100-3000

☐ 100-4500 ☐ Others: (Specify) ________________

6. **What is the maximum allowable degree of bend this product can accommodate:**

☐ 0° ☐ 45° ☐ 90° ☐ Others: (Specify) ____________

7. **Does this product *improves/degrades/no effect* on the original hydraulic characteristics (William Hazen "C" coefficient) of the host pipe? Please provide the reason(s) for your answer.**

☐ Improves (Increases C) ☐ Degrades (Decreases x-sectional area)

☐ No Effect (No change) ☐ Others: (Specify) ____________

*Reason:*____

____

____

8. **How many straight horizontal meters of this product can be installed in a single shot without any human or machine intervention (i.e. maximum distance between access points in meters)**

☐ Less than 100 meters ☐ 100 m ☐ 300 ☐ 500

☐ 600 ☐ Others: (Specify) ____________________

9. **Does this product accommodate differential settlements; if Yes please specify the allowable value of settlement in (mm of settlement / meter length of pipe)?**

☐ YES (Specify) _____________ ☐ NO

10. **Does this product tolerate thermal expansions and contractions of the host pipe please provide reason(s) for your answer?**

☐ YES ☐ NO

*Reason:*____

____

11. **What type of ground access does this product require?**

☐ Inspection Chambers ☐ Excavated Pits

☐ Other: (Specify) ______________

12. **What type of host pipe preparation(s) does this product require?**

☐ Cleaning ☐ Dewatering ☐ Others: (Specify) ____________

13. **How do you re-connect the service lines after rehabilitation?**

☐ Remote Controlled Robotic Cutters ☐ Excavate Service Lines

☐ Others: (Specify) ______________

14. **What is the average time and size of labor crew (i.e. number of crewmen) required to install a straight 500m of this product?**

☐ 1 week; _______ crewmen ☐ 2 weeks; ________ ☐ 3 weeks; ________

☐ 4 weeks; ______ ☐ Others: (Specify) ____________

15. **What is the installed cost per centimeter of diameter per linear meter of this product ($/ cm Dia. / LM)? Please estimate the percentage of cost used for labor and material.**

($ / cm Diameter of Product / Linear Meter of Product)

Labor: ______________% & Material: ______________%

16. **How many meters or chamber to chamber lengths of this product have you installed?**

☐ Meters _______________ ☐ Chamber to Chamber ________________

17. **What is the product's design life; please specify?**

☐ <10 Years ___________ ☐ 10 - < 30 ____________

☐ 30- < 50________________ ☐ > = 50 _____________

Thanking you for your assistance,
A. Al-Aghbar

Cher Monsieur / Madame,

Mon nom est Ahmad Al-Aghbar, un étudiant en maîtrise de Science Appliquée en Ingénierie et Gestion de la Construction à l'Université de Concordia, à Montréal, au Canada. Mon sujet de recherche porte sur la réhabilitation des réseaux d'aqueducs avec des méthodes et technologies sans tranchée.

Je suis entrain d'essayer d'établir une base de données sur les diverses techniques sans-tranchées qui sont disponibles. Ainsi, je voudrai demander votre aide sur ce sujet, en vous demandant de compléter le questionnaire qui est attaché ci-après.

Les informations amassées à partir du questionnaire seront utilisées dans la base de données d'un système informatique appelé "Système Automatisé pour la Sélection des Technologies de réhabilitation sans-tranchée des Aqueducs" (Automated Selection of Trenchless Technology for Rehabilitation of Water Mains). Vous pouvez être assuré que toutes les informations partagées seront strictement confidentielles et utilisées seulement pour des buts universitaires. N'hésitez pas de me contacter si vous avez besoin de clarifications ou d'informations complémentaires. Votre temps et aide seront grandement appréciées.

Cliquez s'il vous plaît sur cette liaison pour remplir la forme :
http://brightvision.net/asttrwm/q_french.html

Sincères salutations,

Ahmad Al-Aghbar
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Questionnaire

Toutes les réponses resteront STRICTEMENT CONFIDENTIELLES et seront seulement utilisées pour des buts éducatifs et de recherche. S'il vous plaît répondez en mettant une marque mutuelle (X) à côté de votre sélection(s).

LA PARTIE 1: LE PROFIL DE LA SOCIÉTÉ

LE NOM DE LA SOCIÉTÉ: ______________________________

TITRE OU POSITION DU RÉPONDANT: ______________________________

ADRESSE:

TÉLÉPHONE / FAX / SITE-WEB / Courrier Électronique:

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1. **La société a combien d'années d'expérience dans le domaine de la réhabilitation des infrastructures souterraines.**

   ☐ < =10 ANS ________ ☐ 10-20 ________ ☐ 20-30 ______

   ☐ > 30 __________

2. **Quel pourcentage de vos travaux de réhabilitation souterraine sont entrepris avec des techniques sans-tranchées ?**

   ☐ < 50 % __________ ☐ 50% - < 70% __________

   ☐ 70 - < 90 % __________ ☐ > 90% __________

3. **Pendant les cinq dernières années est-ce que la demande pour l'utilisation des technologies sans-tranchées a *augmenté / diminué / resté au même niveau*; SVP spécifiez le % dont elle a augmenté/diminué?**

   ☐ Augmenté __________ ☐ Diminué __________

   ☐ Resté au même niveau

4. Avez-vous des bureaux dans d'autres villes au Canada; Si oui, s'il vous plaît spécifiez dans quelle province/ville?

☐ OUI ☐ NON

____

____

5. Pouvez-vous accommoder les nouvelles exigences des clients qui ne font pas partie de votre conception ou production de norme? Si oui, s'il vous plaît classez votre capacité d'accommoder ces nouvelles exigences sur une échelle de 1 à 5 avec 1 (étant le plus bas) et 5 (étant le plus haut)

☐ OUI: (Rang) 1 2 3 4 5 ☐ NON

6. Voudriez-vous être mentionné / nommé dans ma thèse de recherche?

☐ OUI ☐ NON

LA PARTIE 2: INFORMATIONS SUR LE PRODUIT

S'il vous plaît complétez la partie 2 pour chaque produit différent qui est utilisé par votre entreprise.

LE NOM COMMERCIAL DU PRODUIT : ______________________________

1. **Le produit est catégorisé sous quelle catégorie des méthodes de réhabilitation sans-tranchée?**

☐ Chemisage (Cured-In Place Pipes) ☐ Insertion (Slip Lining)

☐ Gainage Ajusté (Swaged Lining) ☐ Projection (Spray Lining)

☐ Gaine déformée-reformée (Fold & Formed Lining) ☐ Alésage (Pipe Reaming)

☐ Eclatage (Pipe Bursting) ☐ Pipe Eating

☐ Microtunnelage (Micro-tunneling)

☐ Forage Dirigé(Horizontal Directional Drilling)

☐ Forage à la torpille (Impact Moling)

☐ Autres:(Spécifiez)__________

2. **Indiquer la catégorie de réhabilitation/réparation pour laquelle ce produit est approprié:**

☐ Non-structural ☐ Semi-structural ☐ Structural

3. **Ce produit peut-être utilisé pour réparer quel type de défauts?**

☐ Défauts Structuraux (Fissures, etc.)

☐ Défauts de Service/fonctionnels (Tuberculation, etc)

4. **Quel type de conduite d'accueil (matériaux) peut-être réhabilitée avec ce produit?**

☐ PVC ☐ Fonte grise ☐ Fonte Ductile ☐ Béton armé

☐ Polyéthylène (PE & HDPE) ☐ Acier ☐ Autres:(Spécifiez)__________

5. Quelle est la gamme de diamètres de ce produit (en millimètres)?

☐ 50 - 600 ☐ 100 – 1000 ☐ 100-1500 ☐ 100-3000

☐ 100-4500 ☐ Autres:(Spécifiez)________________

6. Quelle est l'angle de courbure maximal permis qui peut être accommodé par ce produit?

☐ 0^{o} ☐ 45^{o} ☐ 90^{o} ☐ Autre:(Spécifiez)____________

7. Est-ce que ce produit *augmente/diminue/n'a pas d'effet* sur les caractéristiques hydrauliques de la conduite d'accueil (Coefficient Hazen-Williams)? Fournissez s'il vous plaît la raison/s pour votre réponse.

☐ *Augmente* (augmente C) ☐ Dégrade (Diminue l'aire de section)

☐ N'a pas d'effet (Aucun changement)

Raison:____

____

____

8. Combien de mètres linéaires de ce produit peuvent être installés dans une seule intervention (sans intervention d'hommes ou de machines), c'est-à-dire la distance maximale entre deux points d'accès (en mètres) ?

☐ Moins de 100 ☐ 100 ☐ 300 ☐ 500

☐ 600 ☐ Autres:(Spécifiez)____________________

9. **Est-ce que ce produit peut accommoder des tassements différentiels ? Si oui s'il vous plaît spécifiez la valeur de tassement permise (en millimètres de tassement / la longueur de mètre de conduite).**

☐ OUI :(Spécifiez)____________ ☐ NON

10. **Ce produit tolère-t-il les dilatations et** <u>rétrécissements</u> **thermiques de la conduite d'accueil; fournissez s'il vous plaît la raison/s pour votre réponse?**

☐ OUI ☐ NON

*Raison:*____

____

11. **Quel type d'accès est requis pour ce produit?**

☐ Puits d'inspections ☐ Puits d'excavation

12. **Quelle type de préparation sur la conduite d'accueil est requise avant l'installation de ce produit?**

☐ Nettoyage ☐ Évacuation d'eau

☐ Autres: (Spécifiez)______________

13. **Comment est-ce que vous re-connectez les lignes de service après la réhabilitation ?**

☐ Coupeurs Robotisés ☐ Excavation des lignes de service

☐ Autres: (Spécifiez)______________

14. Quel est le temps moyen et la grandeur d'équipe de travail (nombre d'ouvriers) exigé pour installer une longueur (linéaire) de 500m de ce produit?

☐ 1 semaine,________ Ouvriers ☐ 2 semaines,________ ☐ 3 semaines,_____

☐ 4 semaines,________ ☐ Autres:(Spécifiez)____________________

15. Quel est le coût d'installation de ce produit en centimètres de diamètre par mètre linéaire($ /cm Dia. / LM)? S'il vous plaît indiquez le pourcentage de coût associé à l'installation/main-d'oeuvre et aux matériaux.

($ / cm Diamètre de Produit / Mètre Linéaire de Produit)

Installation/main d'œuvre : _______________ % et Matériaux : _______________ %

16. Combien de mètres ou de longueur "chamber-to-chamber (puit d'inspection)" avez-vous installé ?

☐ Mètre _________________ ☐ Chamber-to-Chamber _________________

17. Quelle est la durée de vie de conception de ce produit ? spécifiez s'il vous plaît.

☐ <10 ANS _____________ ☐ 10 - < 30 _____________

☐ 30- < 50__________________ ☐ > = 50 _______________

Vous remerciant pour votre aide,
A. Al-Aghbar

APPENDIX B

Figure B.1: *Flowchart for Selecting the Rehabilitation or Replacement Technology*
Selection of Technologies for the Rehabilitation or Replacement of Sections of a Water Distribution System, A Best Practice by the National Guide to Sustainable Municipal Infrastructure, March 2003

Figure B.2 to B.4: *Selection of Rehabilitation Techniques to Resolve Structural Problem; Water Quality Problems; Flow, Pressure, and Leakage Problems*
Rehabilitation of Water Mains, Manual of Water Supply Practices, American Water Works Association, 2001

Figure B.5: *Selection of Alternative Water Main Renewal Technologies*
Adapted from American Water Works Association RF, 2002a

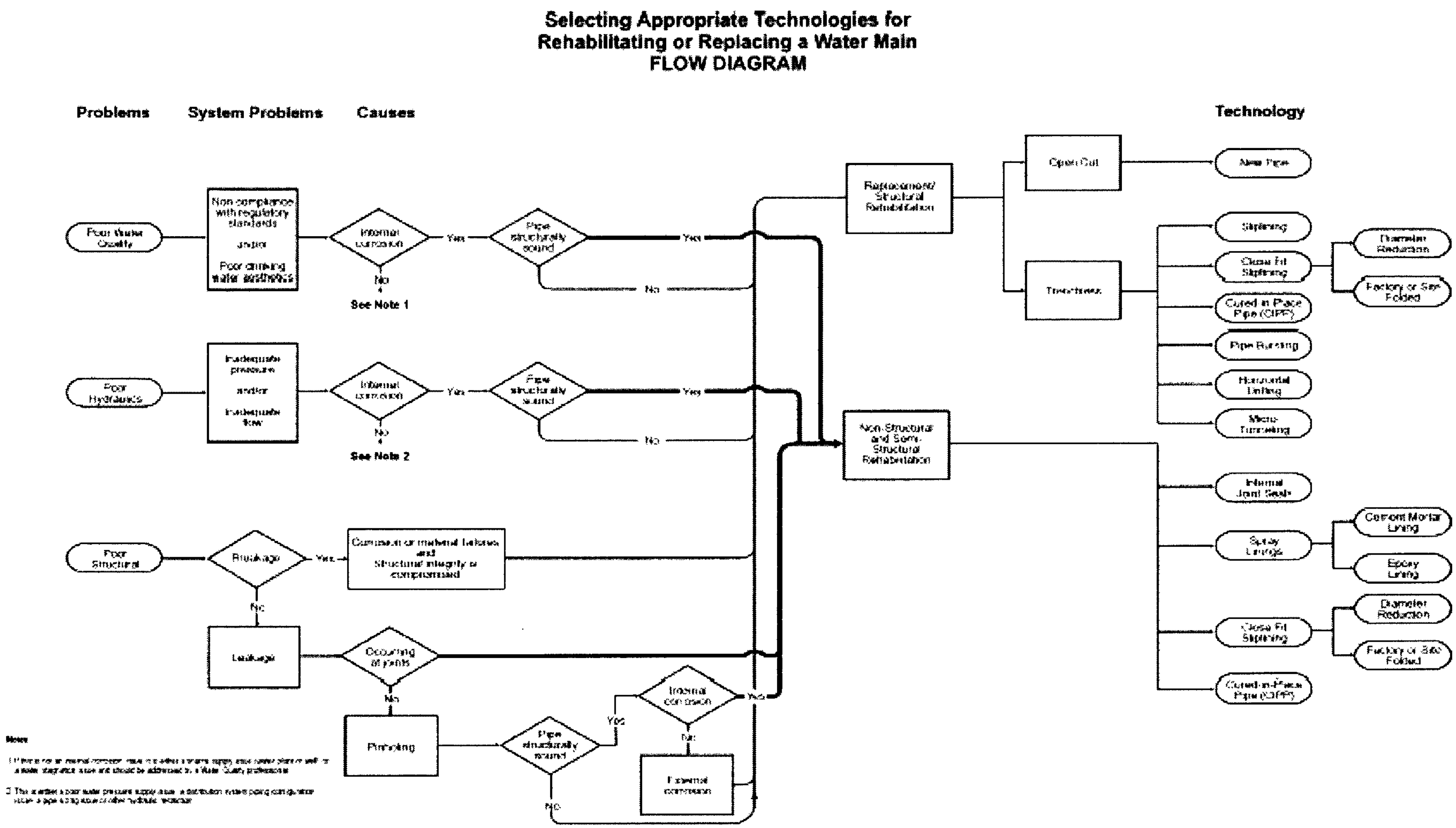


Figure B.1 Selecting Appropriate Technologies for Rehabilitating or Replacing a Water Main Flow Diagram

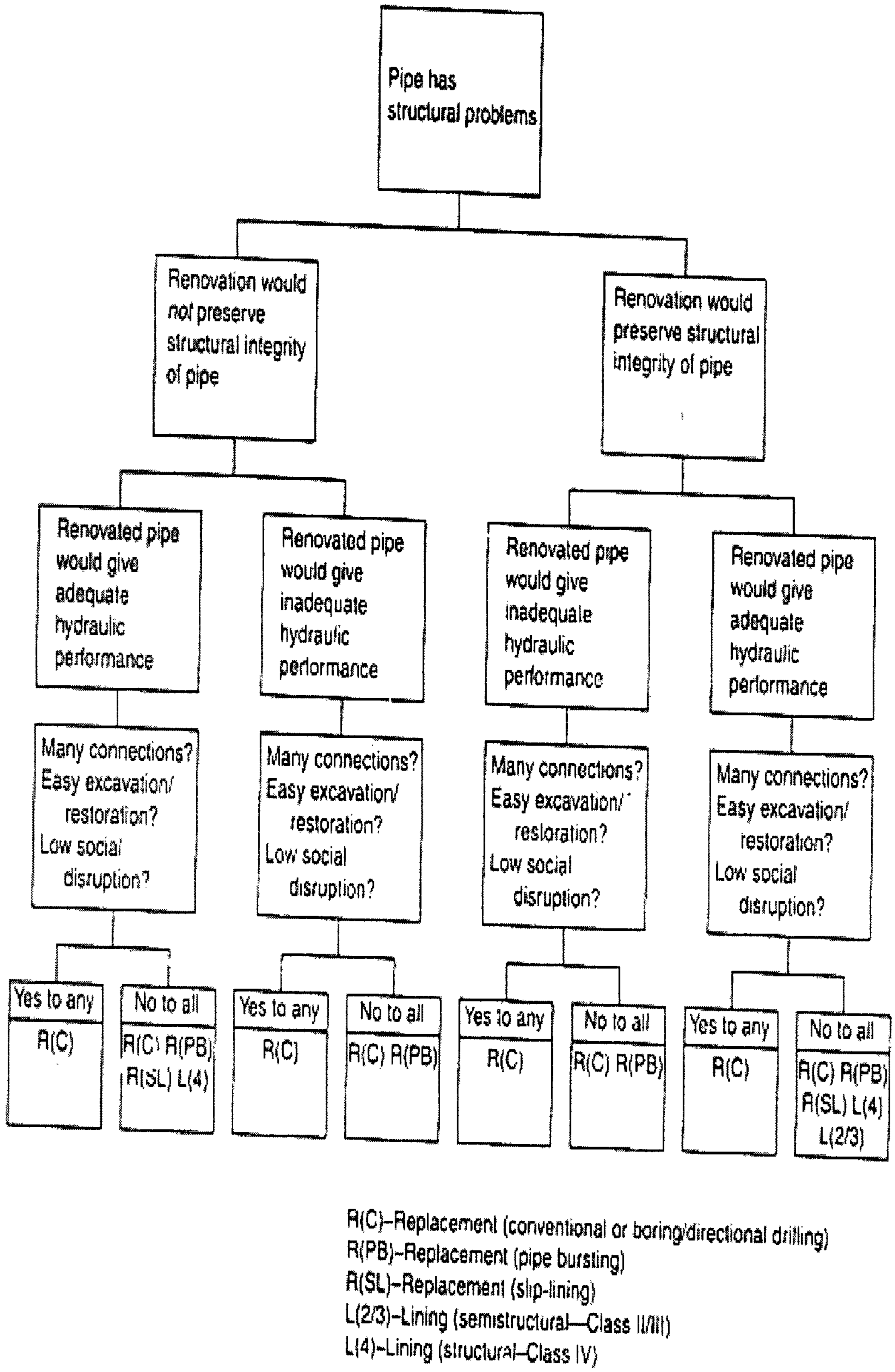


Figure B.2 Selection of Rehabilitation Techniques to Resolve Structural Problem

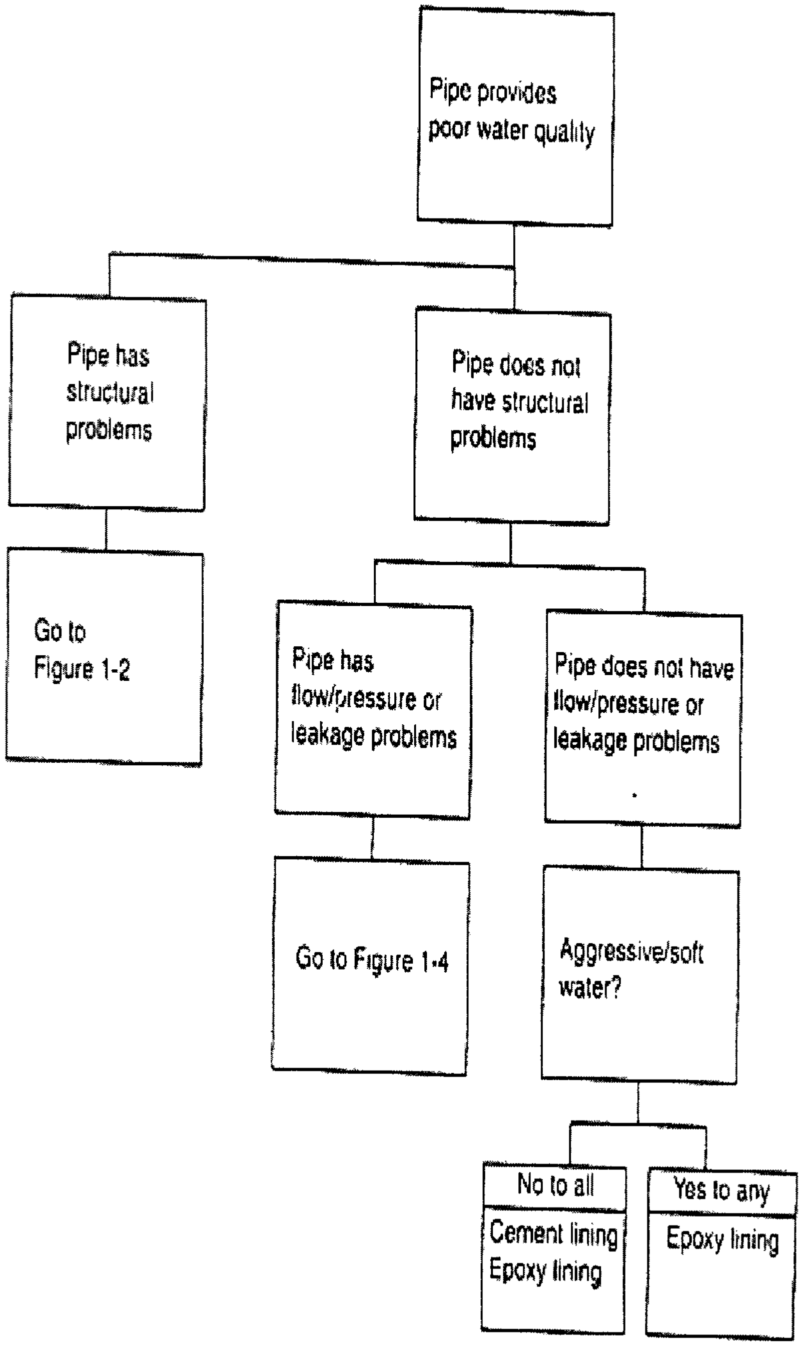
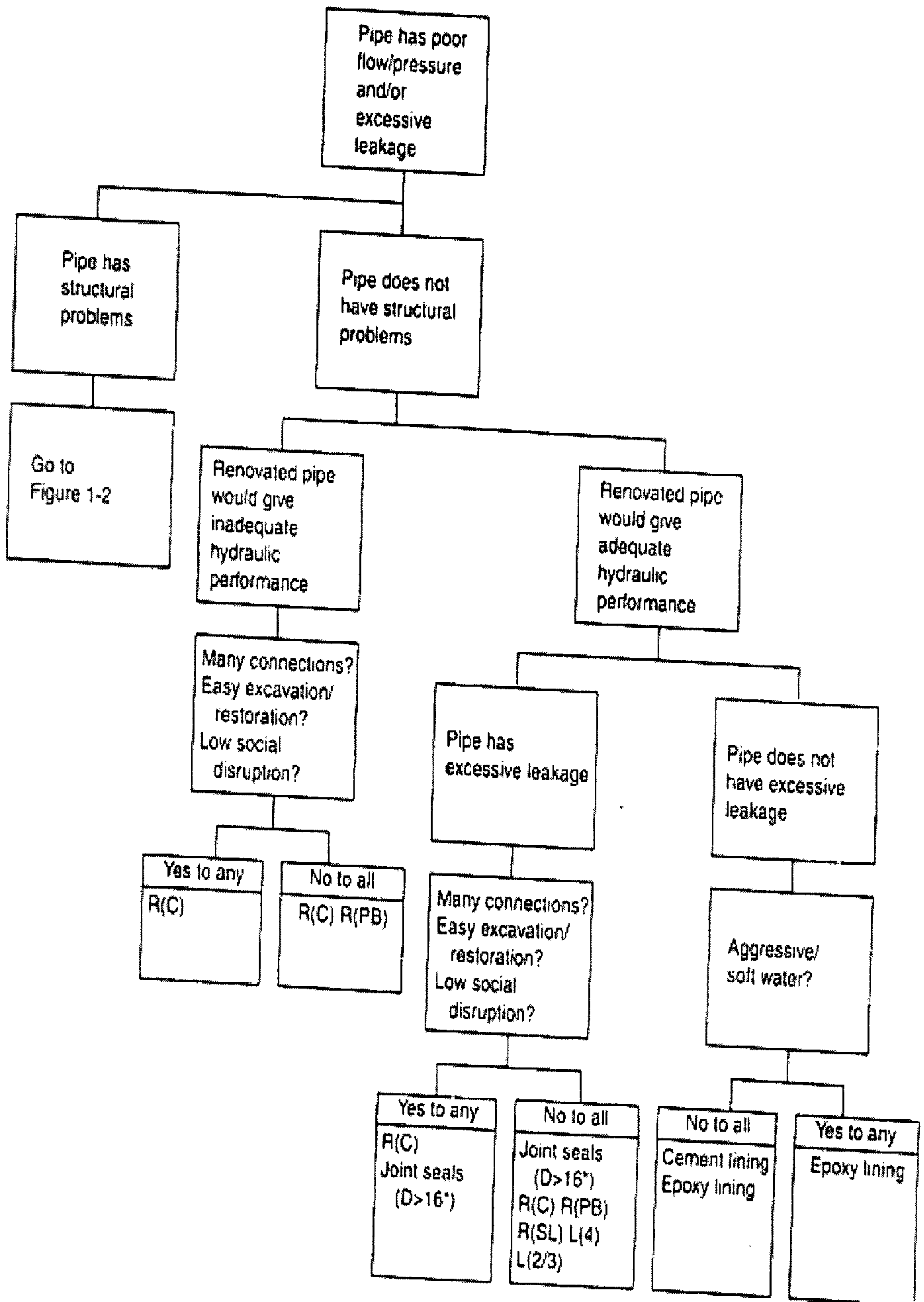


Figure B.3 Selection of Rehabilitation Techniques to Resolve Water Quality Problems



R(C)–Replacement (conventional or boring/directional drilling)
R(PB)–Replacement (pipe bursting)
R(SL)–Replacement (slip-lining)
L(2/3)–Lining (semistructural—Class II/III)
L(4)–Lining (structural—Class IV)

Figure B.4 Selection of Rehabilitation Techniques to Resolve Flow, Pressure, and Leakage Problems

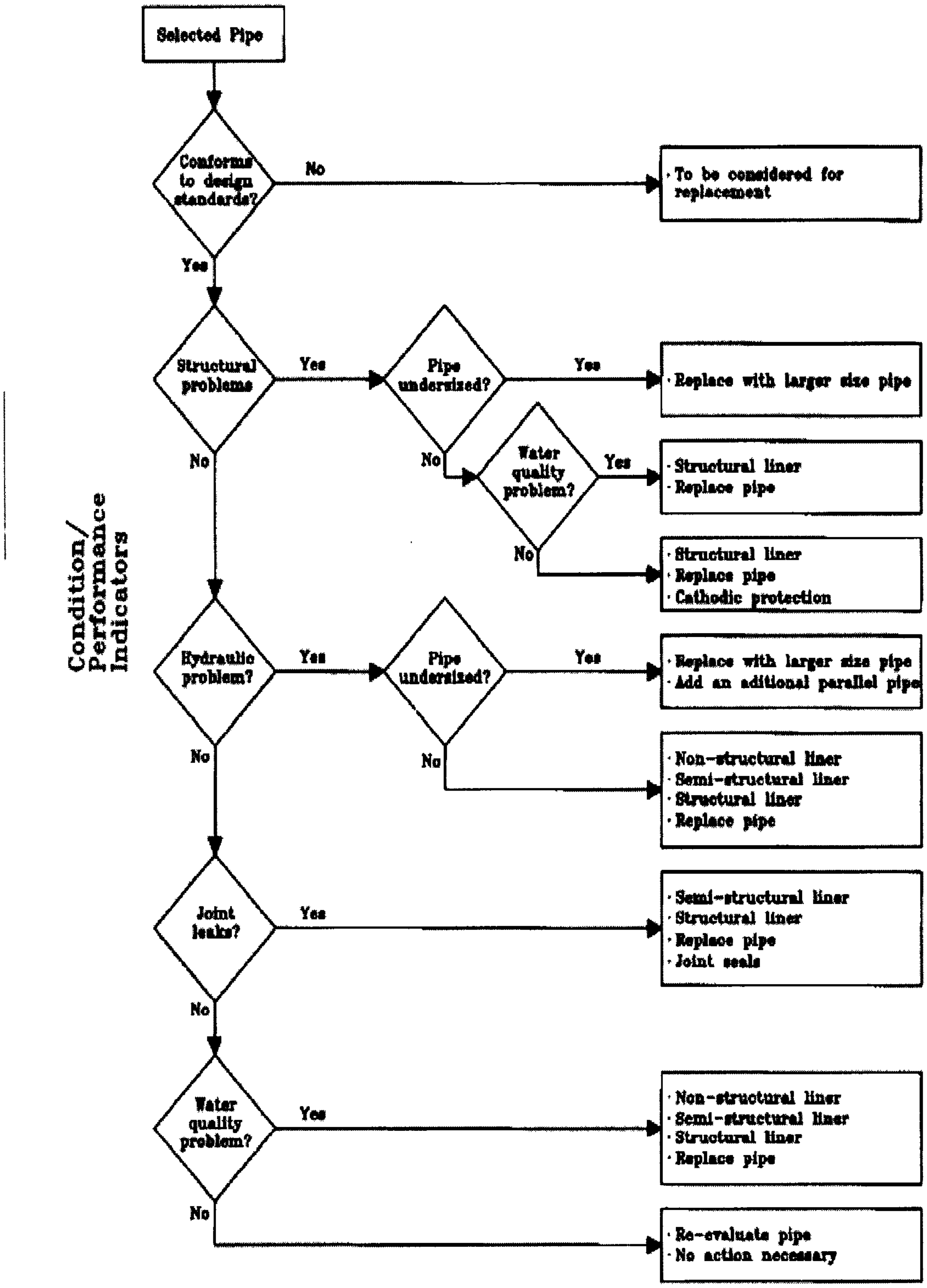


Figure B.5 Selection of Alternative Water Main Renewal Technologies