Stochastic Life Cycle Cost Modeling Approach for Water Mains

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ABSTRACT

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The ability to regularly deliver safe drinking water is a constant challenge to municipalities. According to the Canadian National Research Council reports, the present estimated cost across Canada for replacement and rehabilitation of water mains is at least $15 billion. Therefore, selecting the best repair and/or rehabilitation scenarios is essential to optimize the quality of the existing water mains and to minimize rehabilitation losses.

Current research identifies several rehabilitation methods for water mains, which are classified into three main categories: (1) repair (i.e. Open trench, sleeves); (2) renovation (i.e. slip lining, cement lining, epoxy lining, CIPP); and (3) replacement (i.e. pipe bursting, micro-tunneling, directional drilling, auger boring, open cut).

Stochastic life cycle cost (SLCC), using Monte Carlo simulation approach, is utilized to compare the current new installation and rehabilitation methods, so that the optimal scenario can be accommodated for different types of water mains (i.e. Cast Iron, Ductile Iron, Concrete, PVC, and Asbestos). Data, related to the cash flow of each scenario, are collected from contractors and municipalities in Canada.

Results showed that using “Open Trench” and “Slip-Lining” are the best methods for “repair” and “renovation” categories, respectively. However, the best method for “replacement” category is pipe bursting for small pipe diameters (<30”) and open cut for large pipe diameters (>30”). Accordingly, a maintenance plan is developed to manage repair, renovation, and replacement decisions.

Current research framework will assist municipality engineers to select the optimum rehabilitation scenario for each type of water main. In addition, it will assist them to properly manage their assets, which guarantee better quality of life for the society.

ACKNOWLEDGMENT

I would like to express my deepest and sincere gratitude to my supervisor Dr. **Zayed, T.** Assistant Professor, Department of Building, Civil, and Environmental Engineering, Concordia University, Montreal, Quebec, without whom the progress of this thesis would not have taken place. His excellent supervision, continuous guidance, kind support and encouragement have greatly helped in progress and completion of this research. His advice, information, patience and guidance shown during all stages of this research made this work possible.

I wish to extend my sincere thanks to my parents for their continuous cooperation and their indulgence and encouragement during this work. I am grateful for their valuable assistance and understanding.

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Montreal, Canada, March 2006

Khaled Shahata

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ABBREVIATIONS

SYMBOL	DESCRIPTIONS
AWWA	American Water Works Association
C/EL	Cement or epoxy lining
CCTV	closed circuit television camera
CFSL	Close-fit Slip-lining
CIPP	Curried in Place Pipe lining
FCM	Federation of Canadian Municipalities
HDD	Horizontal Directional Drilling
LCC	Life Cycle Cost
MT	Microtunneling
NASTT	North American Society for Trenchless Technology
NGSMI	National Guide to Sustainable Municipal Infrastructure
NGSMI	National Guide to Sustainable Municipal Infrastructure
NRC	Canadian National Research Council
OC	Open Cut
OT	Open trench
PB	Pipe Bursting
SL	Slip-lining
SLCC	Stochastic Life-cycle cost
SVS	Sleeves
UKSTT	United Kingdom Society for Trenchless Technology
WSLCC	Web-based Stochastic Life-cycle cost

CHAPTER 1: INTRODUCTION

1.1 Problem statement

Water supply and sewer systems, in Canada, have reached a point where maintenance and renewal is essential. According to a survey conducted by the Canadian National Research Council, rehabilitation of municipal water systems would cost $28 billion from year 1997 to 2012 (NRC 2004). Many municipalities in Canada and the USA lack a comprehensive replacement or rehabilitation plans of their water mains, which results in an unscheduled rehabilitation decision. Some municipalities use a deterministic life cycle cost approach which does not take into consideration the uncertainty in main service life, interest rate, and new construction/rehabilitation costs. This also leads to inaccurate and uninformed decisions. Since it is also unrealistic to replace all water mains simultaneously, there are some repair, renovation and replacement techniques available for rehabilitation of water mains. A selection of the most cost effective method for rehabilitation and/or new installation is crucial in the determination of when to repair, renovate or replace a water main. Moreover, it is required to develop a useful and easy tool to help the decision maker in reaching the optimum rehabilitation or reconstruction decision.

1.2 Research Objectives

The objective of this research is to establish a methodology in order to predict the life cycle cost for water mains, taking into consideration the uncertainty involved in determining its service life, discounted rate, and the cost of new installation or rehabilitation alternatives. In order to fulfill this objective the following sub objectives are identified:

1-Identify the available installation / rehabilitation methods used for water mains.

2- Identify the deterioration of water mains using breakage rate analysis

3- Establish a stochastic life cycle cost (SLCC) model to select the most appropriate new installation and rehabilitation alternatives, using a Monte Carlo simulation.

4- Develop maintenance plan for water main rehabilitation.

5- Implement the SLCC model on the internet platform, and develop web-based SLCC (WSLCC) software that recommends the best new installation/ rehabilitation scenario based on the minimum LCC.

1.3 Methodology

The research methodology achieves the following steps:

1- Review of literature, covering all major disciplines that are necessary to evaluate the life cycle cost (LCC). It consists of problem definition, hydraulic and operating pressures, material specification, location of connections and valves, out of service times and LCC analysis methods.

2- Collect data comprising cost information, deterioration, economic parameters and data pertaining to the available alternatives.

3- Define the SLCC profile, which consists of the main steps required to establish cost profile for each alternative.

4- Use Monte Carlo simulation to address the probability of input data. This section defines the main criteria of Monte Carlo simulation and addresses the "@risk 4.5" software package that is used to perform simulation.

5- Perform sensitivity analysis to examine the effect of variability of main input parameters on the analysis of the overall results. The sensitivity analysis tests the variability of some uncertain input parameters by holding all other parameters constant.

6- Develop the SLCC model; the required SLCC engines are addressed in this section.

7- Generate detailed report for each scenario.

1.4 Thesis organization

1.4.1 Chapter Two

This chapter presents a literature review on various methods used in installation and rehabilitation of water mains. It explains various techniques utilized in new trenchless installation and rehabilitation, and defines the installation process, its advantages and limitations. It illustrates a review of alternatives used in life cycle cost of water mains. It also defines the life cycle cost methods available in the literature, defines the components, and the stages of the life cycle costing process.

1.4.2 Chapter Three

This chapter presents the research methodology, life cycle cost procedure and Monte Carlo simulation technique. It also shows the development of a web based software. In addition, it presents overall modules of the proposed system.

1.4.3 Chapter Four

This chapter presents data collection procedure established in this study. It shows the different methods used in: cost data collection; estimating the service life of mains, and deterioration method used. It also defines the new installation and rehabilitation alternatives used in this study. Finally it illustrates the importance of economic parameters (i.e. discounted rate, service life).

1.4.4 Chapter Five

This chapter describes the results of this research followed by analysis and discussion of these results.

1.4.5 Chapter Six

This chapter presents the conclusion of this research. Principal limitations and the main contributions are highlighted, coupled with the recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter summarizes the literature review of new installation/ rehabilitation for water mains and life cycle cost method. Figure 2.1 illustrates the an organization chart for literature review chapter. The 1^{st} section defines some of the most commonly used technologies for rehabilitation of water mains. The concept of rehabilitation includes repair, renovation, and replacement. Selection of the available technologies is based on several factors (i.e. social, economical, and environmental) which depend on current practices in industry that meet societal needs in Canada. The critical problems facing water distribution systems are: 1) water quality deterioration, 2) hydraulic deterioration and 3) physical deterioration.

In addition, methods of maintenance, selection of the suitable replacement technology, timing of renovation or replacement, and costs attributed to each decision are critically important factors. Biological deterioration, corrosion by-products, disinfection byproducts are examples of water quality deterioration, which is indicated by color, taste, odor, turbidity, and bacteriological failure. Hydraulic deterioration, such as tuberculation from unlined mains and reduction in the level of service of the main, is indicated by poor pressure, flow, and interruption in supply. Corrosion, both internal and external, wear and tear and bedding deterioration are considered physical deterioration.

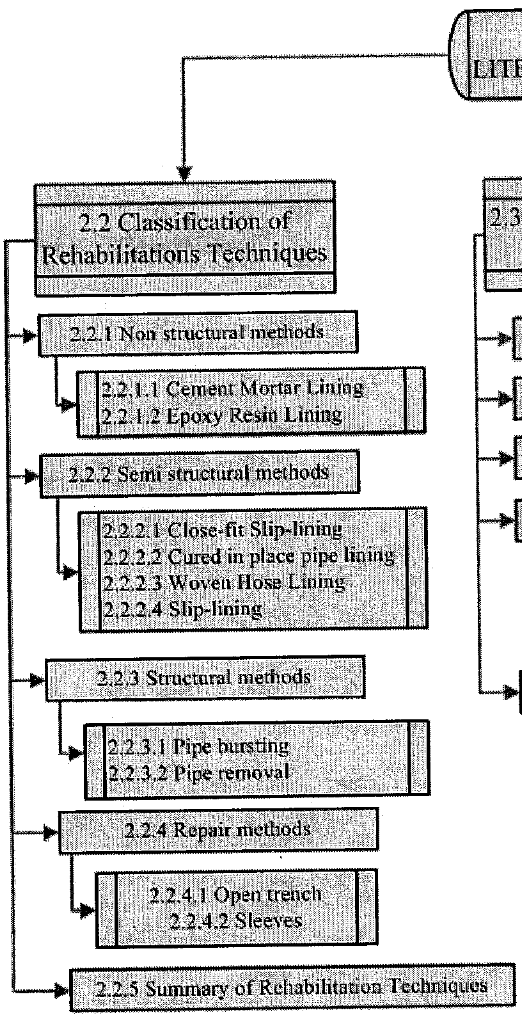


Figure 2.1 Literature review organization chart

2.2 Classification of Rehabilitations Techniques

Federation of Canadian Municipalities (FCM) and National Research Council of Canada (NRC) have joined forces to deliver a National Guide to Sustainable Municipal Infrastructure (NGSMI): *Innovations and Best Practices*. Best practices address the available technologies for rehabilitation of water mains (NGSMI 2003a& b). United Kingdom Society for Trenchless Technology (UKSTT) has a myriad of literature on rehabilitation and installation of water mains and developed computer models to analyze these rehabilitation techniques. In addition, American Water Works Association (AWWA) has evaluated alternative rehabilitation technologies for application on the water utility industry and developed guidelines for those technologies that were used within the industry (AWWA 2001). The following section will discuss the available techniques for water main rehabilitation and new installation as addressed within the literature. North American Society for Trenchless Technology (NASTT) has published some fact sheets for water pipeline rehabilitation methods. These fact sheets cover all major installation procedures for most rehabilitation techniques (NASTT 1999).

Manuals of Water Supply Practices refer to the following classifications based on their effect on the host pipe: 1) Non structural methods, 2) Semi structural methods, and 3) Structural methods (AWWA 2001).

2.2.1 Non structural methods

The main concept of non structural technique is improving hydraulics and capacity of existing pipe by eliminating the build up of tuberculation on interior walls and reducing internal deterioration of water mains (NGSMI, 2003a). They have no effect on structural performance of the host pipe. This technique is used when the problem is internal corrosion and tuberculation and the existing pipe is not leaking and expected to remain in this condition. They can't be used in repairing any disconnection on the host pipe such as joint gaps or corrosion holes. A limitation in nonstructural method is that service connections, valves, bends, and appurtenances will affect productivity and cost of lining projects. Examples of nonstructural techniques include: Cement Mortar Lining, and Epoxy Resin Lining.

2.2.1.1 Cement Mortar Lining

Cement mortar lining is the most common rehabilitation technique in use today for water mains. "*Cement mortar linings were first performed in Australia in 1905 using a hand trowel. In mid-1930s centrifugal sprayers were introduced on large diameters pipes. By 1960s UK were using a remote lining process for small diameter pipes*" fact sheet (NASTT, 1999)"

***Installation Process of Cement mortar lining*:**

Installation process is established using by pass method. First, pipe need to be cleaned carefully and tested for leaks. Lining head spreads the cement lining on the inner walls of the pipe using centrifugal force (NASTT, 1999). Figures (2.2 & 2.3) show two application methods for pipelining Systems, depending on the size of the pipe. They are "*Drag Trowel Method*" and "*Rotary Trowel Method*".

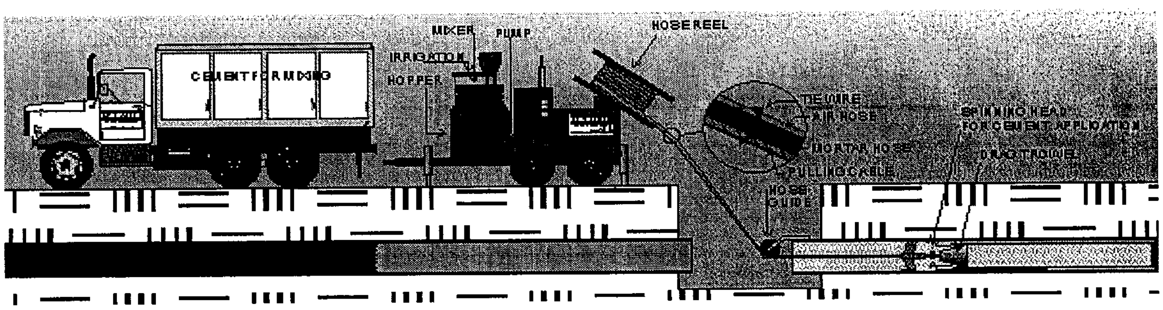


Figure 2.2 Cement lining using "Drag Trowel Method" (DAKOTA Pipelining Systems Inc , 2005)

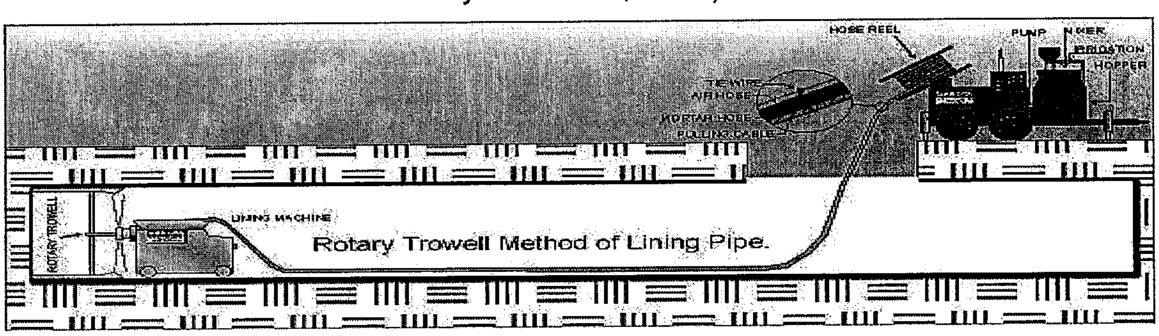


Figure 2.3 Cement lining using "Rotary Trowel Method" (DAKOTA Pipelining Systems Inc , 2005)

2.2.1.2 Epoxy Resin Lining

Epoxy lining is similar to Cement mortar lining as both act to improve the hydraulic characteristic of water mains. *"Epoxy linings were first performed in United Kingdom in 1989. They have been used in North America since early 1990's. Several epoxy-lining materials are currently approved for use in potable (drinkable) water systems in UK but not all of them were approved by North American"* fact sheet (NASTT, 1999)".

Installation Process of Epoxy lining:

At the beginning, the pipe has to be cleaned using rotating scrappers that remove any corrosion and debris. Installation process is established using by pass method (AWWA, 2001). The lining material is a special type of plastic, which protect the pipe from further corrosion. Epoxy is sprayed in liquid form onto the inside of the pipe using a centrifugal method. Figure 2.4 shows the spinning head which is dragged through the pipe line at a constant rate spraying a thin (1 mm) liquid epoxy covering onto the inner wall of the pipe (O'Day, 1992).

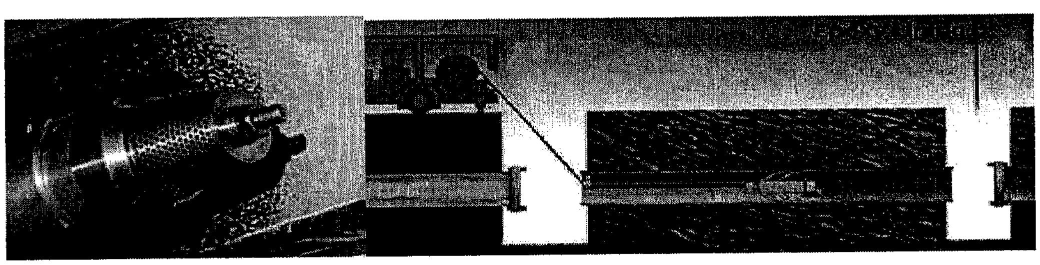


Figure 2.4 The Epoxy spinning head (EPCOR Utilities Inc, 2005)

2.2.2 Semi structural methods

The main concept of Semi-Structural technique is installation of a thin plastics based lining tube that accomplishes a stiff fit to the host pipe wall. All internal pressure loads are transferred to the host pipe. Semi structural technique is suitable for corrosion holes or joint gaps or mains that leaks but doesn't subject to structural failures. It is most used for long transmission mains with few service connections. Limitation of semi structural technique is that it reduces the effective cross-sectional area of the pipe; Also Liners do not turn well through elbows, and it requires excavations at branch connections. Semi structural Liners will not be useful if the pipe faces external corrosion or longitudinal cracks; however, the new liner reduces friction factor as compared to the old. Examples of semi-structural lining techniques include: Close-fit slip lining, Cured in place pipe lining, Woven Hose Lining, and Slip Lining (NGSMI, 2003a).

2.2.2.1 Close-fit Slip-lining (CFSL)

Close fit slip lining involves inserting thin, folded, polyester, polyethylene tube that has been temporarily deformed to allow sufficient clearance for insertion into the host pipe. "*This process was developed for the rehabilitation of water mains in the UK in 1993.*" Fact sheet (NASTT, 1999)"

There are two types of close fit slip lining:

I. <u>Close fit slip lining</u>: Diameter Reduction

These techniques are based on temporary reduction of the pipe diameter to allow satisfactory clearance for insertion in the host pipe. The tube uses a set of static forces for insertion by winching, when the tension force of winch is released, the pipe returns its original shape / dimensions so that it achieves a close fit to the host pipe (NGSMI, 2003a). This technique has been used to renovate oil and gas and mining pipes in North America for small diameter ranges. Waste water pipe renovation used Polyethylene, PVC, and PVC/PE pipes in rehabilitation (NASTT, 1999).

Installation Process of CFSL (Diameter Reduction):

The installation processes is achieved using bypass method. The pipe diameter is reduced immediately before installation. A winch or any pulling device mounted at one end of the pipe then start pulling the close-fit lining into the existing pipeline. After complete installation the new close-fit lining pipe expands to fit perfectly inside the host pipe (NASST, 1999).

II. <u>Close fit slip lining</u>: Factory or Site Folded

These techniques are based on collapsing the tube into a "U" or "C" shape either in the manufacturing plant or on site. The tube is then re-rounded to its original shape and diameter using air and steam to form a close fit in the host pipe (NGSMI, 2003a). Figure 2.5 shows a close fit before and after reversion

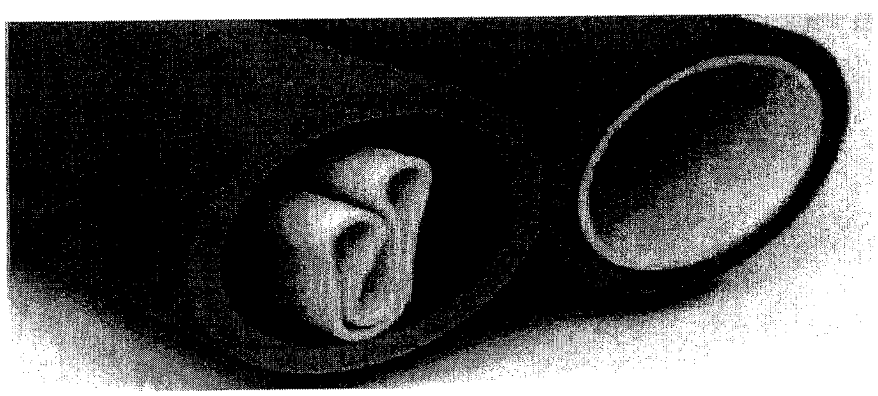


Figure 2.5 Close fit slip lining before and after reversion (Hastak et al. 2001)

Installation Process of CFSL (Factory or Site Folded):

Installation processes is achieved using bypass method. Installation of factory folded close fit slip lining requires an insertion pit and access chamber or a pit at the end to pull the pipe using a winch. Before start installation we reduce the pipe diameter using restrained bands. A winch or any pulling device mounted at one end of the pipe then start pulling the close-fit lining into the host pipeline. Once the liner is installed it is reverted back to its original shape using a combination of heat (typically steam) and water pressure (NGSMI, 2003a).

2.2.2.2 Cured in place pipe lining (CIPP)

Cured in place pipe lining is the most common used technique for semi structural rehabilitation of water mains. Cured in place pipe linings were first performed in United Kingdom in 1971. In mid-1997 an American company got a certification in using this type of lining in North America (NASTT, 1999). Cured in place lining is a semi structural technique used to provide internal corrosion protection and to seal joint gaps and small holes. The process involves the insertion of a fabric tube into the host pipe. Combination of fabric material, with resin can be designed to produce a new pipe that has full structural ability or semi-structural ability (NGSMI, 2003a). Cured in place pipe lining can negotiate multiple bends of up to 90 degrees in pipes. There are two main methods for installation: 1) Inversion in place method, and 2) Winched in place (pulled in place).

***Installation Process of CIPP*:**

There are two main methods for installation:

I. Inversion in place method

In this method the liner is clamped around an inversion ring and then turned inside out (inverted). Water pressure or compressed air are used to simultaneously propel the liner and invert it “inside out” so that resin face is strongly tighten against the pipe wall. After installation, the liner has to be cured according to predetermined time & temperature cycles of circulating heated water or compressed air in the liner (AWWS, 2002).

II. The winched in place (pulled in method)

In this method the liners are pulled into place on protective membrane using a winch. Then the tube is inflated using water pressure or compressed air and allowed to cure.

After installation and cure with either method, the pipe is cooled and drained then inspected using a robot with a close circuit television camera (CCTV). The pipe is then pressure tested and connected to existing line (NASTT, 1999).

2.2.2.3 Woven Hose Lining

Woven Hose Lining is a process for rehabilitation of water mains and it is considered as a semi structural method. Woven Hose Lining involves installation of a thin fabric hose. The liner can only bridge small holes and joint gaps for a long term under normal operating pressures. It was mainly developed for renovation of gas mains in Japan but has also been applied to water mains rehabilitation (NASTT, 1999).

2.2.2.4 Slip-lining (SL)

"Slip-Lining: (1) General term used to describe methods of lining with continuous pipes or lining with discrete pipes. (2) Insertion of a new pipe by pulling or pushing it into the existing pipe and grouting the annular space" (NGSMI, *2003a)*

Slip lining method is used in structural and semi-structural purposes. "Slip lining *was first used in 1940's for renewal of deteriorated pipes* "fact sheet (NASTT, 1999)". Slip lining technique involves the insertion of a new smaller diameter pipe into the existing host pipe and grouting of the annular space. The Slip lining can be divided into two categories:

- ***Continuous Sliplining :***

This method involves the insertion of high density polyethylene pipe or PVC pipe into a continuous pipe line either using pulling or pushing through the existing water main (Najafi, 2005). Figure 2.6 shows a typical continuous slip lining processes

Figure 2.6 Typical continuous slip lining (Hastak et al. 2001)

- ***Segmental Sliplining :***

This method allows shorter lengths of pipe to be inserted from an entry pit. New pipe segments are forced into the host pipe through an entry pit.

Installation Process of Sliplining:

The installation processes is achieved using bypass method. First start inspection and cleaning of the host pipe. Then interest the new pipe Using pulling or pushing from a launch pit to a reception pit (using Continuous or Segmental method). After installing the new pipe start stabilizing the annular space using grout (AWWA, 2001). Then construct the service connections and the laterals.

2.2.3 Structural methods

The main concept of Structural technique is to sustain Maximum Allowable Operating Pressure of the pipe to be renovated on a long-term basis. The new linear should also be capable to survive transient loadings associated with a catastrophic burst failure of the host pipe (NGSMI, 2003a). Fully structural technique can be viewed as a replacement for the original pipe in terms of internal pressure loads although they may not exhibit same capability as the original in terms of external, vacuum or longitudinal loads. Structural method is most suitable when the pipe faces extensive external corrosion or severe longitudinal cracks. The main problem of this method is initial cost associated with it is relatively high. Examples of Structural lining techniques include: Structural Slip Lining, In Line replacement, Open cut replacement.

In-Line Replacement

Main concept of this method is the replacement of the old existing pipe with a new pipe with same or greater diameter. This method can replace all types of pipes and it's most cost effective when the new pipe with greater diameter is required. In line replacement can be categorized into two main categories as shown in figure 2.7. Pipe bursting and Pipe removal (Najafi, 2005).

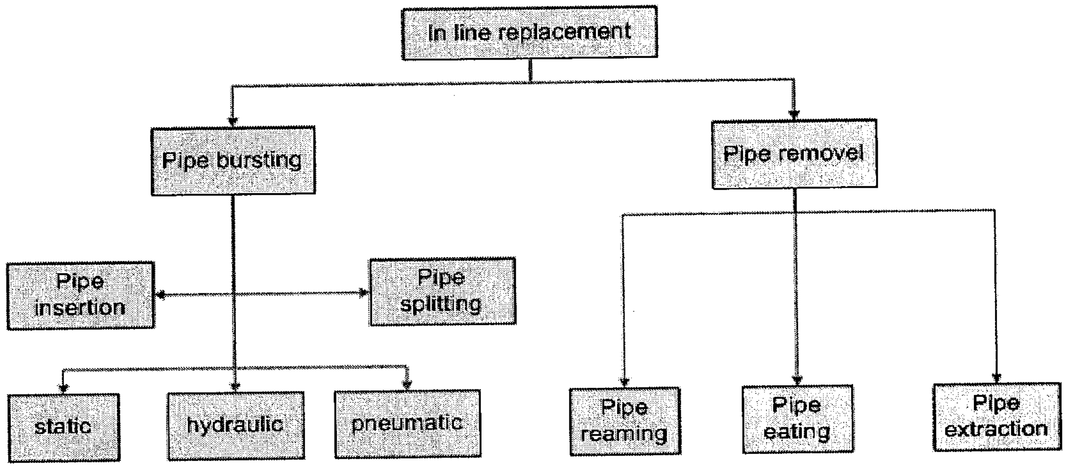


Figure 2.7 Categories of In-Line Replacement Methods (*Najafi, 2005*)

2.2.3.1 Pipe bursting:

Pipe bursting is a technique for breaking out the existing host pipe by using radial forces from inside the pipe. Pipe bursting uses a pneumatic, hydraulic or static head to split and break up the pipe and compress the materials into the surrounding soil (Simicevic and Sterling 2001). The new pipe is pulled or pushed with the bursting head to replace the old existing pipe. Figure 2.8 shows different bursting heads.

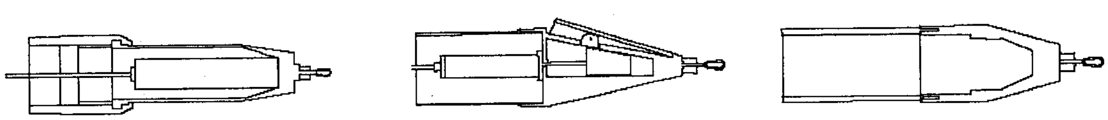


Figure 2.8 Bursting Heads (Simicevic and Sterling 2001)

Pipe splitting

Pipe Splitting is a technique of pipe bursting but it is used on non-fragmental pipes such as Steel, Ductile Iron or Polyethylene. Pipe splitting uses specialist splitting heads designed to cut through the pipe wall. The splitting system consists of three parts Cutting wheels, sail blade, and expander as shown in figure 2.9 (Najafi, 2005). The first two parts act simultaneously to spill the existing old pipe then the expander forces the existing pipe to expand to create a space for the new pipe to be installed in place.

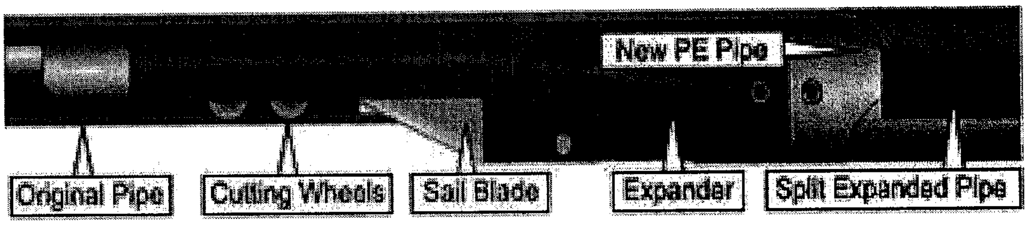


Figure 2.9 Pipe splitting system (UKSTT , 2005)

Pipe insertion

Pipe insertion method is based on pushing or jacking a new pipe into the existing old pipe. This method is illustrated in figure 2.10. It consists of five main parts: *lead, cracker, cone expander, front hydraulic jack, and pipe adapter.* The front steel guide pipe (*lead*) adjusts center of the new pipe to center of existing old pipe. Cracker initially cracks the old pipe. Then cone expander starts to expand existing pipe into the surrounding soil. Front hydraulic jack starts jacking the system to execute the insertion process. And a new pipe is linked to hydraulic front jack using pipe adapter. Lubricant is injected in the space between new pipe and surrounding soil to allow efficient replacement of the old pipe (Najafi, 2005).

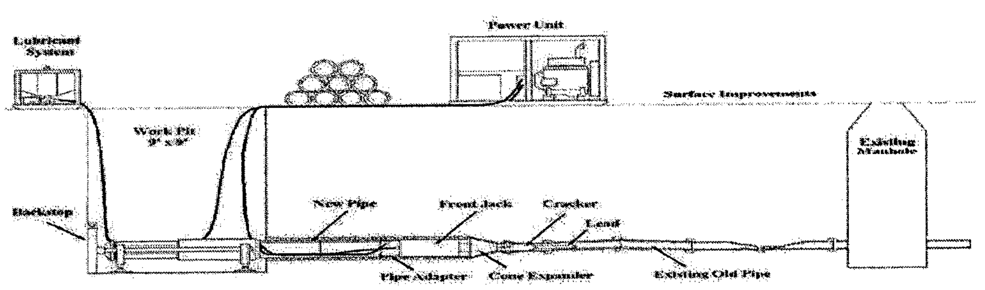


Figure 2.10 Pipe insertion systems (UKSTT, 2005)

Installation Process of Pipe Bursting:

The installation processes is achieved using any method of the described above. Excavate two access pits at both end of the section required to be replaced. Start inspection of host pipe using a closed circuit television camera (CCTV). Then interest a steel pulling rod through the host pipe from a launch pit. Attach the bursting head at the end of pulling rod. Start pulling the new pipe from launch pit to reception pit (NASTT, 1999). When the bursting head reaches the reception pit the new pipe will be installed.

2.2.3.2 Pipe removal:

Pipe removal system is based on the removing of the existing pipe instead of displacing it into the surrounding soil. Pipe removal system is executed by *Horizontal Direction Drilling (HDD) or Micro Tunneling (MT)* so it's similar to new pipe installation systems. Pipe Reaming, Pipe Eating, and Pipe extraction are method used in pipe removal technique.

I. Pipe Reamming Method

Pipe reaming method is a technique of Horizontal Direction Drilling (HDD). Pipe reaming is divided into two main phases; Phase (1) Insertion of pilot drill string, and Pre-reaming. Phase (2) reaming process, and new pipe installation (Najafi, 2005). Figure 2.11 shows Phase (1) the Pre-reaming process. Figure 2.12 illustrates Phase (2) the pipe installation process.

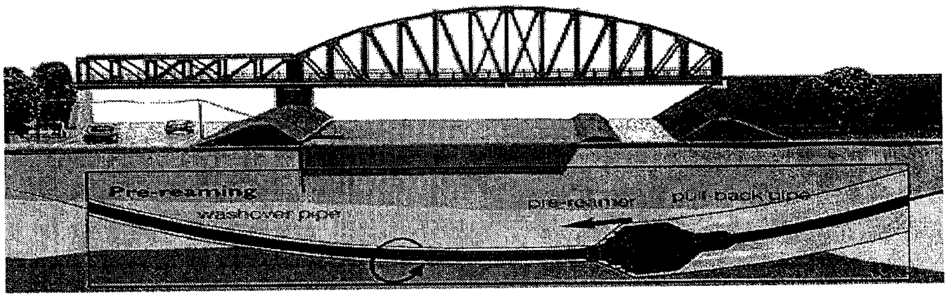


Figure 2.11 Pre-reaming process (LMR Drilling UK Ltd, 2005)

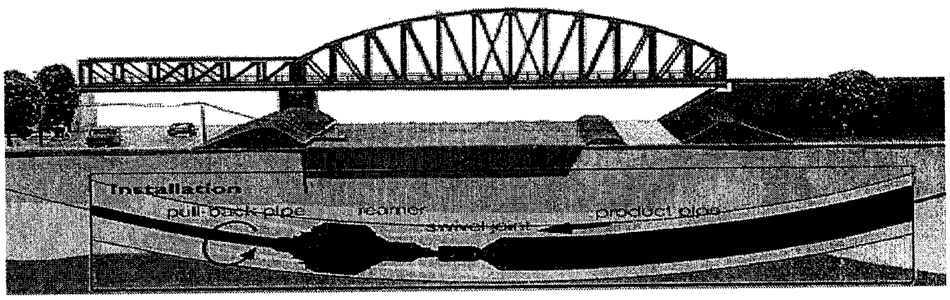


Figure 2.12 Pipe installation process (LMR Drilling UK Ltd, 2005)

II. Pipe eating

Pipe eating is a modified Micro Tunneling (MT) method for pipe replacement. Pipe eating method crushes and removes existing pipe and installs the new replaced pipe using a jacking system behind a micro tunneling machine (Najafi, 2005). New pipe may have a greater diameter than existing pipe. The system has a cutting head and a shield section. Where cutting head is used to cut existing pipe and the shield section is used to carry the cutting head and its hydraulic motor system (Najafi, 2005). Figure 2.13 shows the cutting head and the shield section of the pipe eating system.

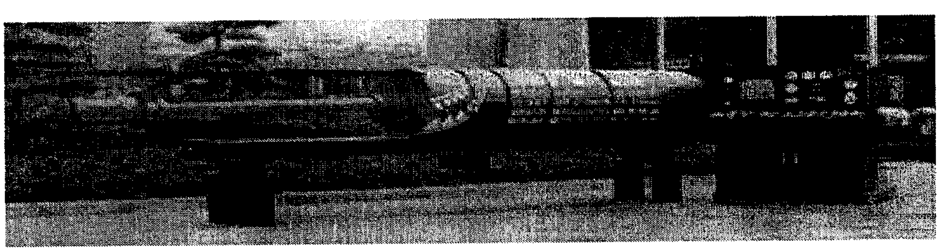


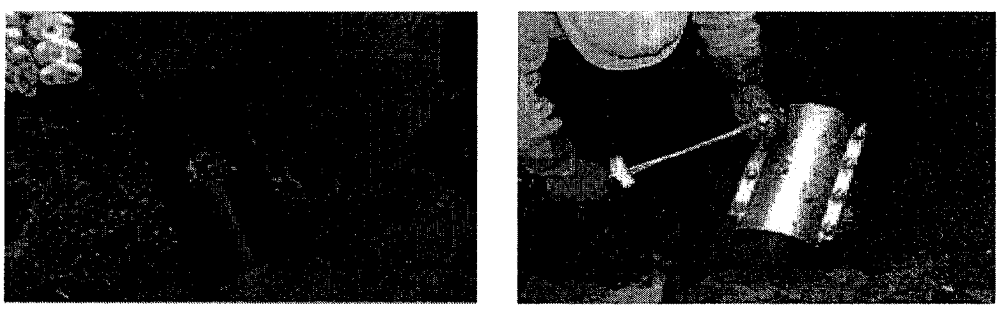
Figure 2.13 Cutting head and the shield section (UKSTT, 2005).

2.2.4 Repair methods

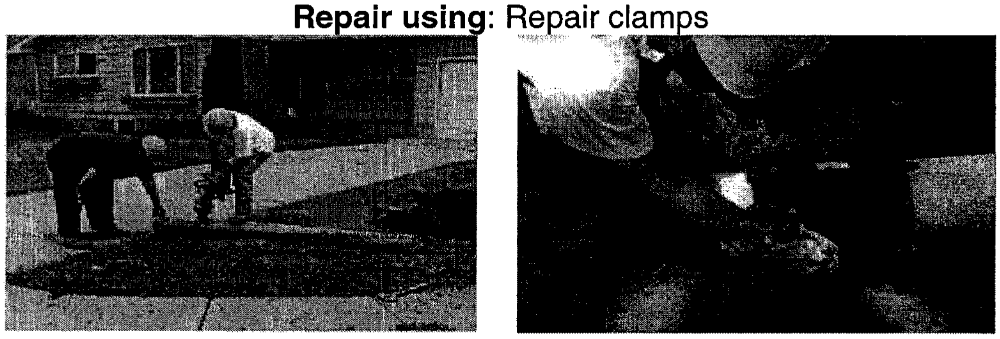
Repairing techniques are used for small pipe segment where it only fixes breaks or any small defective part within the water main. There are two main methods for repairing water mains (e.g. Open trench- Sleeves)

2.2.4.1 Open trench

First step in open trench is to cut the asphalt or concrete with an earth saw (winter), quickie saw (summer), then excavating. Install a submersible pump to suck any excess amount of water. Pipe should be washed in order to inspect condition of pipe and to determine what method and materials will be used to perform repairs. There are two main method used for open trench repairing: 1) Repair clamps and 2) Replacing a section of pipe. Figure 2.14 shows open trench repair methods



Repair using: Repair clamps



Repair using: Replacing a section of pipe

Figure 2.14 shows open trench repair methods (Saskatoon City, 2005)

2.2.4.2 Sleeves

For Repair water mains, the main is taken out of service and pre-inspection carried out using CCTV camera. The pipe needs to be free from any debris, rust and mineral deposits. Thorough cleaning can be accomplished using high-pressure water jets. Then sleeves are installed at the defective section as shown in Figure 2.15.

Before

After

Figure 2.15 shows Sleeves repairing method (Link-Pipe, 2005)

2.2.5 Summary of Rehabilitation Techniques

Table 2.1 shows a summary of the rehabilitation technology for water mains. This summary includes the classification of each rehabilitation method based on AWWA (2001) manuals, and NGSMI Best Practices (2003a&b). For each technique the applicable diameter range and the maximum installation length are highlighted. The water main problems faced in order to use the correspondent technique and the liner material used by each technique are shown.

A summary of the advantages and limitation of each rehabilitation technique are summarized by table 2.2. The information in this table is gathered from AWWA manuals (2001); "Best Practice" by the national guide to sustainable municipal infrastructure (NGSMI, 2003a); North American Society for Trenchless Technology (NASTT 1999) Fact Sheets for rehabilitation of water pipelines; and from companies in North America.

Table 2.1 Summary of Rehabilitation Technology for water mains

rehabilitation technology	classified method	diameter range (inch)	max installation length (feet)	liner material	used to solve
Cement Mortar Lining	Non structural	4" to 170"	1500	Cement mortar	Mild internal corrosion
Epoxy Resin Lining	Non structural	4" to 170"	1500	Epoxy Resin	Tuberculation
Close-fit slip lining	Semi structural				
Diameter reduction		2" to 42"	3000	HDPE - MDPE	Severe internal corrosion
factory or site folded		2" to 8" / 2" to 42"	700 / 3000	HDPE - MDPE	joint failure
Cured in place pipe lining	Semi structural				localized external corrosion
inverted in place		4" to 108"	3000	thermoset resin	Severe internal corrosion
winched in place		4" to 100"	1500	fabric composite	joint failure
Woven Hose Lining	Semi structural	4" to 39"	3000	woven polyester fiber	internal corrosion / joint gaps
Slip lining	Semi structural / Structural				localized external corrosion
Segmental		24" to 160"	1000	PE - PP - PVC - GRP	Severe internal corrosion
Continuous		4" to 63"	1000	PE - PP - PVC - PE/EPDM	joint failure
In line replacement	Structural				
Pipe bursting		4" to 48"	1500	PE - PP - PVC - GRP	Extensive external corrosion
Pipe removal (pipe eating)		up to 36"	300	PE - PP - PVC - GRP	failure of host pipe
Pipe insertion		up to 24"	500	Clay - ductile iron	
Open cut	Structural	unlimited	unlimited	unlimited	failure of host pipe

key

HDPE : high density polyethylene
MDPE : Medium density polyethylene
PE : polyethylene
PP : polypropylene
PVC : Poly-vinyl-chloride
GRP : glass fiber reinforced polyester
PE/EPDM : polyethylene / Ethylene propylene diene monomer

Table 2.2 Advantages and Limitation of Rehabilitation Techniques

Rehabilitation Techniques		Advantages	limitations
Non structural	**Cement Mortar Lining** **Epoxy Resin Lining**	• Minimal excavation is required. • Minimal Pipe diameter reduction is not significant • Most diameters of pipe can be lined, and can negotiate bends. • No need to excavate for service connections. • Improves the hydraulic capacity of pipe. • It reduces yearly maintenance activities (flushing).	• Completely clean and water free main is required. • Butterfly valves or valves that are not full diameter must be removed. • Access to customer homes may be required to isolate every water service line before the lining process begins • Cement lining can temporarily affect the pH values of the water.
Semi structural	**Close-fit slip lining** 1- Diameter Reduction 2- Factory or Site Folded	• Improves the hydraulic capacity of pipe and problems arising from pipe tuberculation. • Fixes leakage from corrosion holes, joint gaps, cracks and failed pipeline joints. • Fast and doesn't cause disturbance to near by utilities. • Powerful method when there are few connections along the host pipe. • Minimal reduction in host pipe diameter • Internal lateral connections are possible	• Has a limited diameter range and length. • Requires large work in preparation for installation. • Not useful when the cross section area of the host pipe changes along the required renovation length. • Need excavation at the location of valves and connections. • The energy required to reduce the pipe diameter increases rapidly with larger pipe sizes and greater wall thicknesses. • There is still uncertainty in the industry regarding the folding and re-rounding process of the liner.

Table 2.2 Continued

Rehabilitation Techniques		Advantages	limitations
Semi structural	**Cured in place pipe lining** 1- Inverted in place 2- Winched in place	• Improves the hydraulic capacity of pipe and problems arising from pipe tuberculation. • has inherent ring stiffness to resist external loads • Most shaped of pipe can be lined, and can negotiate bends. • fixes leakage from corrosion holes, joint gaps, cracks and failed pipeline joints. • fast and requires minimum excavation work, and doesn't cause disturbance to near by utilities. • Minimal reduction in host pipe diameter • CIPP can be used in structural, semi-structural, and non-structural applications. • The thickness of CIPP liner is less than a close-fit liner.	• The difficulty of installation increases with the increase in the diameter of pipe. • As the liner is flexible so it requires support from adjacent material before curing. • cuts at service connections may occur regularly • Partial buckling may occur due to the weight of the liner. • The liner tube must be specially designed for each project.
Semi structural	**Woven Hose Lining**	• Improves the hydraulic capacity of pipe and problems arising from pipe tuberculation. • Most shaped of pipe can be lined, and can negotiate bends. • Fixes leakage from corrosion holes, joint gaps, cracks and failed pipeline joints. • Fast and requires minimum excavation work, and doesn't cause disturbance to near by utilities. • Minimal reduction in host pipe diameter	• Doesn't have inherent ring stiffness to resist external loads; it depends on adhesion to the host pipe. • The difficulty of installation increases with the increase in the diameter of pipe. • As the liner is flexible so it requires support from adjacent material before curing. • Cuts at service connections may occur regularly • Partial buckling may occur due to the weight of the liner.

Table 2.2 Continued

Rehabilitation		Advantages	limitations
Semi structural / Structural	**Slip lining** 1- Segmental 2-Continuous	• Improves the hydraulic capacity of pipe and problems arising from pipe tuberculation. • Live installation with the existing flow is possible. • Used for most types of pipe. • Independent structural integrity and doesn't depend on the host pipe. • Fast and doesn't cause disturbance to near by utilities (when grouted, it is generally slower than other rehabilitation technologies). • Powerful method when there are few connections along the host pipe. • Internal lateral connections are possible.	• Reduction of the pipe diameter. • Need excavation at the location of valves and connections. • Grouting is mostly required • Requires large work in preparation for installation. • Not useful when there is bends in the pipe profile as it doesn't turn well through bend fittings. • The cost of replacing a small section is relatively high
Structural	**In line replacement** 1- Pipe bursting 2- Pipe removal (pipe eating) 3- Pipe insertion	• No need to clean the host pipe. • The new pipe diameter can be increased up to 30% of the host pipe. • Improves the hydraulic and structural capacity of pipe. • Powerful method when there are few connections along the host pipe. • Used for most types of pipe. • Independent structural integrity and doesn't depend on the host pipe. • No need to remove the host pipe as it is left underground.	• Drive and reception shaft is usually required. • Surface or roadway may be susceptible to heaving or slumping. • Affects the near by structures due to the force being transmitted, and the displacement of soil, by the bursting technique. • Pipe bedding and side fill support may be disturbed. • Need excavation at the location of lateral connections. • The cost of replacing a small section is relatively high

Based on data available for various alternatives, a decision tree was established to perform a guide, which can be used to select the best rehabilitation option. This decision tree was developed based upon the American Water Works Association manuals (AWWA, 2001) and National Guide to Sustainable Municipal Infrastructure (NGSMI, 2003b). The reason for designing this new decision tree was that the AWWA manuals have included many details in its flow diagram, which is not suitable for the model presented in this research. The NGSMI decision tree did not give significant details on the type of renovation or replacement method that can be used. It only states that a structural or non-structural method is required for rehabilitation and does not include the repair, or operation and maintenance alternatives in their model. Figure 2.16 shows the introduced rehabilitation decision tree in which it is divided into three main charts: 1) Water quality chart, 2) Hydraulics chart; and 3) Structure chart.

Non compliance with regulatory standards and/or poor drinking water is mainly classified as poor water quality problems. In this situation, the main has to be checked against structural problems such as defects, leakage or internal/ external corrosion. If the main suffers from one or more of these structural problems, the decision tree proceeds to the structural chart. If not the tree continues to the next step. The next step is checking the main against the hydraulic characteristics such as poor flow, poor pressure, poor capacity, or internal corrosion. If the main suffers from one or more of the hydraulic problems, the decision tree proceeds to the hydraulic chart. The next part of the decision tree deals with verifying whether the main suffers from a supply problem.

If the answer is "yes", then fix the supply problem, if no then use an operation and maintenance method (i.e. cleaning and flushing) or use any renovation method.

The hydraulic chart deals with the problems associated with the fluid properties. Water main has to be checked against the structural problems addressed above. If the main suffers from any structural problem, then proceed to the structural chart. If the main does not suffer from any structural problems or excessive leakage, then an operation, maintenance or renovation method (i.e. cleaning and flushing) should be utilized. If it suffers from excessive leakage, then the following issues must be checked: Are there a lot of connections? Is it easy to excavate? Is the disruption low? If the answers to any of these questions are "yes", then proceed with a repair or replacement method. If the answer to all of the previous questions is "no", then proceed with a renovation or repair method.

If the mains suffer from any structural problems, the location of the structural problem must be checked. If these problems occur at a joint only, then use a repair or renovation method. If these problems occur all over the main, then use a replacement method.

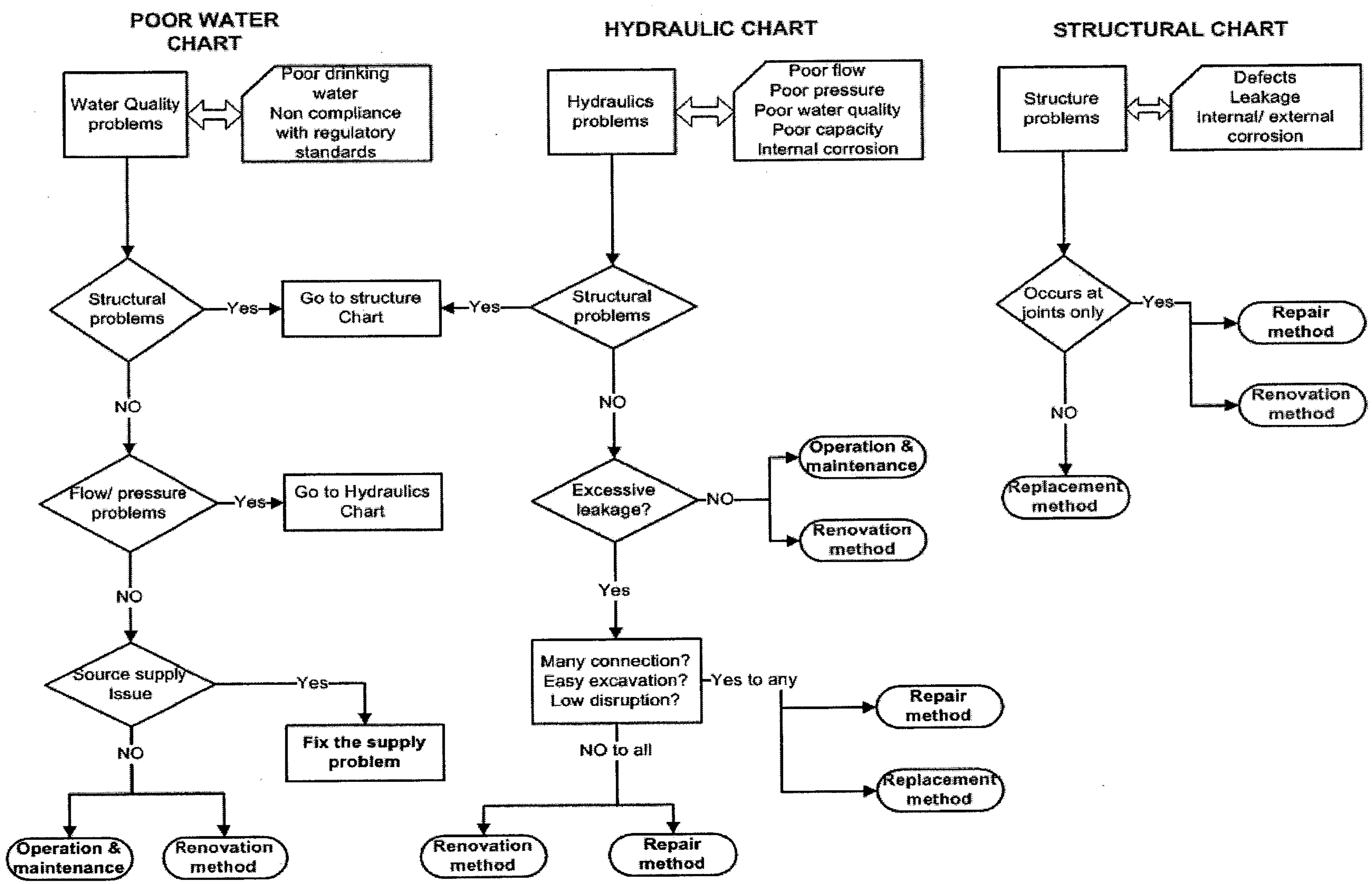


Figure 2.16 decision tree of rehabilitation for water mains

2.3 Life Cycle Costing

2.3.1 Definition of Life Cycle Costing

"A method of comparing costs of equipment or buildings based on original costs plus all operating and maintenance costs over the useful life of the equipment. Future costs are discounted". (Webster, 1997)

The Life cycle cost method takes into account first costs, including capital investment costs, purchase, and installation costs; future costs, including energy costs, operating costs, maintenance costs, capital replacement costs, financing costs; and any resale, salvage, or disposal cost, over the life-time of the project, product, or measure.

2.3.2 Required Data for Life Cycle Costing

Concept of time value of money: It's a reflection of the fact that dollar today does not have equivalent value to a dollar in the future. Present capital money is more valuable than a similar amount of money received in the future, there for time adjustment is necessary. A discount rate is used to convert future values. Inflation rate is also used to express the future value of money where future values can be expressed in constant (real) dollars or current (nominal) dollars Riggs, (1986).

2.3.3 Stages of Life Cycle Costing:

Life cycle cost can be divided into several stages where each stage has its own parameters. Boussabaine and Kirkham (2004) illustrated those stages into six sequential steps and developed a graph emphasizing the expected cost assisted to each steps as shown in Figure 2.17. Those steps are surmised as follows: 1) Justification for investment and client's requirement, 2) Conceptual development, 3) Design stage, 4) Production stage, 5) Operational stage, 6) End of economic life stage.

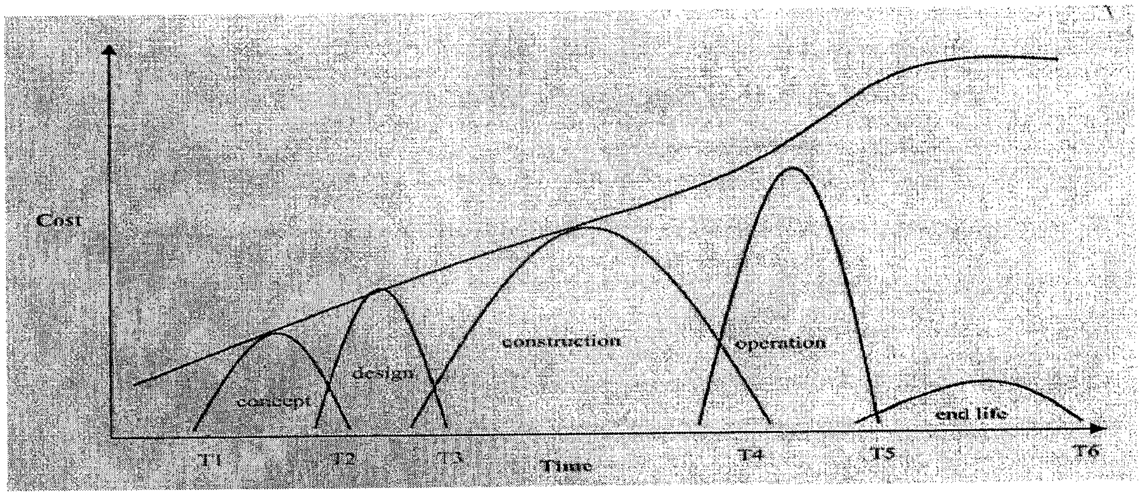


Figure 2.17 Key decisions in the Life Cycle Cost process (Boussabaine and Kirkham, 2004)

2.3.4 Calculation Models of Life Cycle Costing

The concept of life cycle cost can be applied to the whole project or part of the project (Hass, 1997). To enable decision maker to compare between different alternatives and pick up the most feasible and economic solution they should have a tool to achieve that. Modeling of life cycle cost is a tool used for comparing and analyzing of alternatives (G*ransberg et al.,* 2004). On the literatures there were three main methods used in modeling life cycle cost i.e. deterministic, stochastic (probabilistic) and Fuzzy method.

2.3.4.1 Deterministic Method

In the deterministic method a discounted rate is used to compare all cost in the present value. It's assumed that all the cost components of the project to be well defined with a single value. It based on the economic analysis of time value of money. To find the total LCC of a project, sum the present values of each kind of cost and subtract the present values of any positive cash flows such as a resale value (Boussabaine and Kirkham, 2004). Thus, the following formula applies (Riggs, 1986):

$$LCC = C_p + \sum_{t=0}^{n} \frac{C_t}{(1+d)^t} \quad \text{.. (2.1)}$$

Where: **LCC**: the present value of the total life cycle cost; $\mathbf{C_p}$: The capital cost; $\mathbf{C_t}$: sum of the Operation cost, Maintenance and repair, Replacement / Rehabilitation and the Salvage value; **d**: the discounted rate; **n**: The asset service life.

The deterministic method assumes that all the cost is identified by year and with certainty, where there is no probability in the identified values. Limitation of deterministic method that it doesn't address: Statistical Significance, or Variability. Also it's Subject to Manipulation, and there is a Lacks Credibility (G*ransberg et al.,* 2004).

2.3.4.2 Stochastic (Probabilistic) Method

The stochastic method deals with each element in the life cycle cost equation as a probabilistic element which follows a probability distribution function. The stochastic method assumes that the cost center, discounted rate and the service life of asset are randomly distrusted according to different probability distribution functions (*Frangopol et al.*, 2004). This assumption requires that each element to be treated as uncertain element from one year to another. And the output probability of the Life Cycle Cost is defined as risk profile (Boussabaine and Kirkham, 2004). Thus, the following formula applies (Riggs, 1986):

$$f(PV) = f(C_P) + \sum_{t=0}^{n} \frac{f(C_{ti})}{(1+f(d))^t} \quad \text{...} (2.2)$$

Where: ***f(PV)*:** The Present value of the Probability distribution function of the life cycle cost; ***f*(Cp *):*** The probability distribution function of the capital cost; ***f(Cti):*** The probability distribution function of the life cycle cost element (i) in period t; ***f* (d*):*** The probability distribution function of the discounted rate; and **n*:*** The asset service life.

2.3.4.3 Fuzzy Method

Expert judgment plays a major role in defining the cash flow of life cycle cost. As uncertainty adopted by life cycle cost doesn't usually fits the probability distribution functions. So the Fuzzy method was implanted to model the uncertainty with life cycle cost elements. The formulas for the analyses of fuzzy present value, fuzzy equivalent uniform annual value, fuzzy future value, fuzzy benefit–cost ratio, and fuzzy payback period are developed by *Kahraman et al. (2002):*.

$$PV = \left[\begin{array}{l} \sum_{t=0}^{n} \left(\dfrac{\max\left(P_t^{1(y)}, 0\right)}{\prod_{t'=0}^{t}\left(1 + r_{t'}^{r(y)}\right)} + \dfrac{\min\left(P_t^{1(y)}, 0\right)}{\prod_{t'=0}^{t}\left(1 + r_{t'}^{1(y)}\right)} \right), \\ \sum_{t=0}^{n} \left(\dfrac{\max\left(P_t^{r(y)}, 0\right)}{\prod_{t'=0}^{t}\left(1 + r_{t'}^{1(y)}\right)} + \dfrac{\min\left(P_t^{r(y)}, 0\right)}{\prod_{t'=0}^{t}\left(1 + r_{t'}^{r(y)}\right)} \right) \end{array} \right] \quad \text{....} (2.3)$$

The main problem with this model is that the formula is not easy to be applied individually and there is no software available to calculate the life cycle cost using this method.

2.3.5 Limitations of life cycle cost method (Boussabaine and Kirkham, 2004):

- Estimating early in the life of a project when the degree of accuracy has a broad range,
- Assuming that the alternative has a finite life cycle,
- Life Cycle cost is not a method for environmental accounting of the environmental impacts of a specific project.

2.4 Previous works done in life cycle cost and Alternative strategies

This section represents a literature review pertaining to the research performed in life cycle cost of water mains and the new installation/rehabilitation alternatives available in the industry. The National Research Council of Canada (NRC) has developed some models which will be discussed later in this section. The National Guide to Sustainable Municipal Infrastructure has performed some research on trenchless technology involved within installation and rehabilitation of water mains (NGSMI, 2003a). They have also developed flow diagrams to decide when to rehabilitate which will also be discussed in Chapter 4. In addition, the American Water Works Association (AWWA. 2001) has compiled manuals for rehabilitation of water mains which discussions relating to new technologies available for installation and rehabilitation of water mains. The Trenchless technology research in the UK water industry has introduced some guides for water main rehabilitation. This section also highlights the major work done in life cycle cost within the civil infrastructure of North America.

2.4.1 Prior Research in Water Mains

The NRC has published some papers addressing decision-making issues faced by most water utilities regarding their water mains. Rajani *et al.* (2004) explains the difference between failure management of small-diameter mains in distribution systems and failure prevention in large-diameter transmission pipelines. He described the application of fuzzy logic to assess failure risk of large diameter transmission pipelines. Figure 2.18 illustrates the introduced framework for decision making in water mains by Rajani. He also addressed the effect of various cathodic protection measures on life-cycle costs of water mains. Despite the extensive research conducted by Rajani, new installation or rehabilitation methods were not covered.

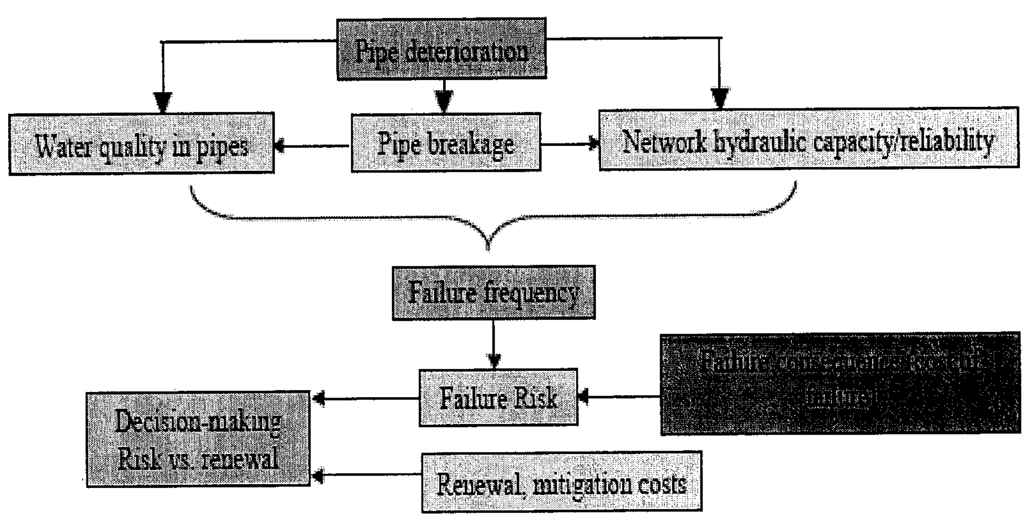


Figure 2.18 Framework for decision making in water mains (Rajani *et al.* 2004)

Kleiner (2001) described a method for selection and scheduling of pipe rehabilitation alternatives that minimizes the life cycle cost over a lifetime horizon based on a dynamic programming approach. He developed for each pipe, the rehabilitation alternatives and its implementation timing that would minimize the total rehabilitation and maintenance cost. The decision variables are: (1) the type of rehabilitation alternative and (2) the implementation timing of the pipe. Two types of deterioration were proposed, namely the deterioration in the hydraulic capacity of pipes (resulting in a reduction of the supply pressure) and the deterioration of the structural integrity (causing increased breakage rates) and a subsequent increase in maintenance cost. The rehabilitation alternatives that Kleiner used were: (1) Relining of the pipe (only improve pipe hydraulic capacity), (2) Replacement with same diameter pipe; (3) Replacement with a pipe one nominal diameter larger, (4) Replacement with a pipe two nominal diameters larger and (5) do nothing. The limitations of Kleiner's research was that he did not address the various methods of new installation or the trenchless technology available for rehabilitation. He also used only five alternatives to for comparison. Kleiner didn't model the uncertainty involved in prediction of the relining or replacement cost.

Najafi *et al.* (2004) presented an investigation of the cost-effectiveness of constructing underground pipelines with trenchless methods versus open-cut methods in urban centers. The study includes a breakdown of the engineering and capital costs of the construction and the social costs for both methods. He also presented an analysis of factors and criteria used for a decision making process. The paper did not include any "real" costs only making reference to the cost as a minor or major cost. He also didn't calculate the life cycle cost of construction projects for any alternative.

The national guide to sustainable municipal infrastructure (NGSMI, 2003 a &b) has performed a series of best practices for potable water. These series have addressed several topics such as the "selection of technologies for the rehabilitation or replacement of sections of a water distribution system" which covers most of the available technologies for rehabilitation of water mains. This best practice provides a flow diagram for determining the technologies available for the rehabilitation or replacement of water mains in their specific situation. However, this flow diagram is very general and it does not specify which technology should be used; it only recommends either a "replacement /structural rehabilitation technique" or a "non structural rehabilitation technique".

The AWWA has printed "Rehabilitation of Water Mains: AWWA Manual M28" and it represents a useful guide that includes different rehabilitation methods. Installation procedures are included for cleaning, lining, and trenchless rehabilitation techniques. The AWWA manuals covers the cleaning and maintenance process; the lining techniques, which are classified into four classes, namely Classes I, II, III, and IV (nonstructural, semi structural and fully structural lining); and the replacement techniques.

Rehabilitation of existing distribution mains with a high density of service line connections presents a problem for the alternative rehabilitation methods by O'Day (1992). Most water main rehabilitation in the United States is provided by main cleaning and cement mortar lining. This technique is suitable for improving the hydraulic condition of a main; however it does not improve the structural condition of a main. British utilities are using a mix of other rehabilitation techniques such as epoxy lining, resin impregnated fabric lining, thermoplastic pipe and slip lining.

Engelhardt *et al.* (2000) mentioned in the literature review, UK perspective that the main rehabilitation strategies are: (1) replacement, (2) relining, (3) cleaning and (4) other techniques: For example, the rate of increase of leakage can be reduced through the application of detection techniques and pressure reduction schemes. External corrosion can be prevented through the installation of sacrificial anodes, and internal corrosion can be inhibited through stabilization of water during the treatment process.

Jones (1992) classified the rehabilitation techniques into structural and non-structural techniques. He also evaluated these techniques based on the range of application, Maximum Length per Application, Unit Cost as a percent of total cost of conventional main laying rates, Potential Benefits of each Technique, Advantages and Disadvantages of each Technique.

Zhi (1993) has stated that the traditional method of life cycle cost analysis cannot meet the needs of dealing with the future uncertainties of a project spanning many years. He introduced a life cycle cost analysis methods that utilized a simulation technique. The impacts of different distributions of the annual discount rates on the net present value of a project life cycle are considered.

2.4.2 Prior Research in Highway

Most studies in civil infrastructure management have focused primarily on highway systems (i.e. pavement and bridge management systems). Pavement management concepts were first developed in the 1970s and matured in the 1980s (Smith and Hall, 1994). This review provides a suitable foundation regarding life cycle cost analysis of civil infrastructure. In this section, several studies which are most relevant to its application to water main systems are summarized

Typical examples of life cycle cost applications can be found in a maintenance program on highway pavement (Salem *et al.* 2003). This paper has introduced the Monte Carlo simulation to the life cycle cost and it modeled the uncertainty involved in predicting the deterioration rate for highway pavement. This study did not include the uncertainty in the alternative costs. Ozbay *et al.* (2003) presented the Monte Carlo simulation as a risk analysis technique in transportation infrastructure with a considerable focus on pavement structures. Gransberg *et al.* (2004) has quantified pavement life cycle cost inflation uncertainty for bridge and highway construction projects using simulations.

Dynamic programming was employed by Feighan *et al.* (1988) for optimization of pavement management systems by minimizing the life cycle cost in conjunction with a Markov chain prediction model. Prediction curves were fitted using Markov chain theory in order to obtain transition probability values that define future performance in terms of states. This technique introduced preventive maintenance options for sections in good to excellent condition, and surface overlays for sections in fair condition.

Smadi and Maze (1994) used a deterministic dynamic program for pavement life cycle cost. This technique provided a procedure for selecting a pavement section treatment or rehabilitation strategy and the time of applying treatment to the section.

Zayed *et al.* (2002) developed economic models that can be used to provide a rational framework for the evaluation of alternatives in the paint maintenance of steel bridges. An economic analysis, which is a deterministic method, and the Markov decision process, which is a stochastic method, were used to carry out the life-cycle cost analysis for steel bridges.

An extensive study of steel bridge maintenance practices was conducted. Based on data and experience from the bridge paint maintenance study, models were formulated and their input data were provided. Since the results of the deterministic and probabilistic methods were quite different, an analysis was conducted to determine the reasons.

Farngopol *et al.* (2001) mentioned that additional research is required to develop better LCC models and tools to quantify the risks, cost and benefits associated with civil infrastructure. The study is intended to provide the necessary background in order to evaluate alternative bridge investment options based on life-cycle cost.

2.4.3 Prior Research in Sewer Systems

Vipulanandan and Pasari (2005) presented a deterministic LCC model for operating and maintaining a wastewater sewer system. The LCC model was based on the population and average household occupancy. The LCC model included treatment, transportation, maintenance and rehabilitation of a wastewater system to control infiltration over the life cycle period.

Wirahadikusumah and Abraham (2003) used probabilistic dynamic programming in conjunction with a Markov chain model to analyze the life cycle cost for wastewater infrastructure. The model was developed to recommend optimal maintenance and rehabilitation methods for each segment in the wastewater network. The model addressed the simulation effect on the variability of the total cost. Sensitivity analyses on discount and inflation rates were tested.

Burgess (1993) described the application of a probabilistic model to simulate the structural condition of wastewater network systems. A Markov chain model was employed to develop the prediction model to minimize the life cycle cost of the system.

Summary and Limitations of Available Literature

This chapter presents a literature review on various methods used in new installation and rehabilitation of water mains. It explains various techniques utilized in trenchless new installation and rehabilitation, as well as defines the installation process, advantage, and limitation of each method. It illustrates a review of alternatives used in the LCC within Civil infrastructure with a focus on water mains. It also defines the LCC methods available in the literature, puts emphasis on defining the components and stages of the LCC process. This chapter also emphasizes on the available LCC models within water mains, highways, and sewer disciplines.

By analyzing prior research done in water mains, the following limitations found:

Despite the extensive research conducted by Rajani (2004) in the life cycle cost of water mains, new installation or rehabilitation methods were not covered in his studies. While Kleiner (2001) didn't model the uncertainty involved in predicting the relining or replacement costs, His study also did not address the various methods of new installation or trenchless technology available for rehabilitation. Najafi (2004) study did not include any "real" costs (i.e. referred to only minor and major costs). It also didn't calculate LCC of rehabilitation projects for any alternative.

While NGSMI (2003a&b), AWWA (2001), Najafi (2005), O'Day (1992), Engelhardt et al. (2000), and Jones (1992) focused their research on defining the available alternatives for rehabilitation of water mains and introducing a renewal plan but without calculating LCC for any alternative.

While studying prior research within highways and sewer systems, it is found that several studies are relevant for implementation to water main systems such as Salem *et al.* (2003), Ozbay *et al.* (2003) and Gransberg *et al.* (2004). These studies have primarily proposed applying the concept of Monte Carlo simulation to LCC prediction. However, Feighan *et al.* (1988), Burgess (1993), Zayed *et al.* (2002) Wirahadikusumah et al. (2003) employed Markov chain model, as stochastic approach, to predict the LCC profile.

CHAPTER 3: METHODOLOGY

3.1 Introduction

As a water pipe ages, the rate of replacement and repair typically increases, and at the same time, as replacement is delayed, the present value of its cost decreases. There is an optimal time for replacement, which can be considered at the end of the economic life of these pipes. For water mains, the best strategy is to reduce the total life-cycle costs.

Many water distribution networks in North America are now considered to be approaching the end of their desirable life. Complete replacement of such pipes would be the ideal option but budget and construction constraints make this unrealistic. In addition, the regulatory requirements with respect to rehabilitation operation should be satisfied. Making decisions on the renewal of a water distribution system is essentially a balancing act between system performance and costs. Rehabilitation of water mains can also extend the operational life of the asset at a reduced cost but we must consider taking a rational approach in the identification of rehabilitation procedures that are justifiable and beneficial.

A component of this research is to establish stochastic life cycle cost (SLCC) package and develop a software model that will enable the extension of planning horizons associated with a whole-life costing approach. The developed model emphasizes the evaluation of aging rates of water mains, determines the SLCC and customizes the strategies of water main replacement. The main elements of such model are illustrated in the chart shown in Figure 3.1. These elements are specifically;

- Literature review
- Data collection
- Life Cycle Cost profile
- Monte Carlo simulation
- System modeling and sensitivity analysis

Each of these building elements within the flow chart will now be introduced in general terms.

3.2 Literature Review

The literature review covers all major disciplines that are necessary in evaluation of SLCC. It consists of the problem definition, hydraulic and operating pressures, material specification, cost estimation models, rehabilitation and replacement alternatives, Life cycle cost methods and Prior research within civil infrastructure. Chapter 2 summarizes the main literature review.

3.3 Data Collection

The data collection covers all major disciplines that are necessary in the evaluation and determination of SLCC. It contains cost data information, deterioration, economic parameters and alternatives data. Chapter 4 summarizes the main data collection method

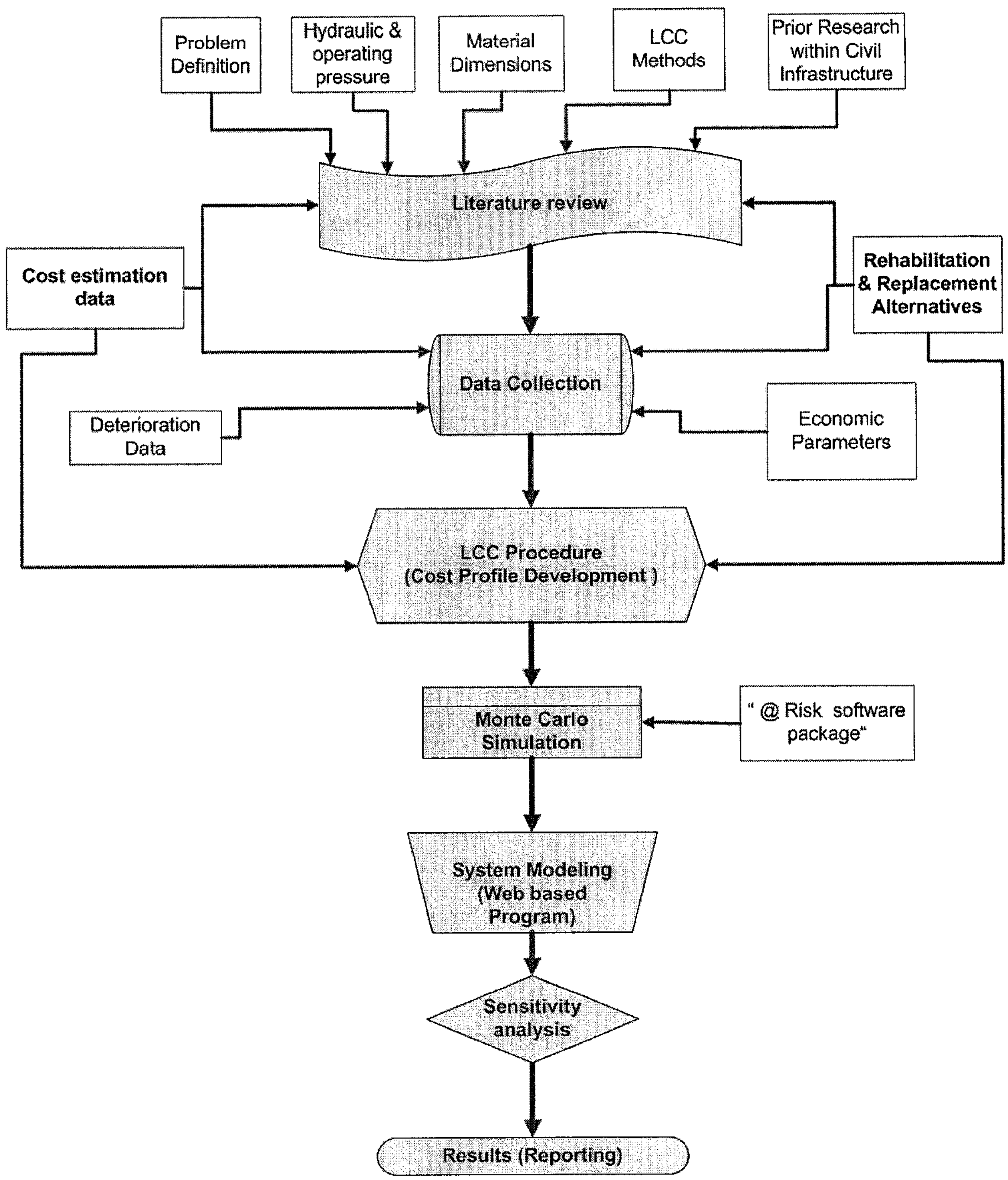


Figure 3.1 Overview of the research methodology

3.4 Stochastic Life Cycle Cost (SLCC) Framework

The prediction of SLCC for water mains needs to be statistically modeled. This chapter and the following ones provide a detailed framework to establish a SLCC model for water mains. Figure (3.2) shows techniques used to build the model together with stages in predicting life cycle cost. The key points of the model are summarized as follows:

- Input parameters
- Simulation
- Sensitivity analysis
- Output.

The input factors affecting the decision-making process of experts which include uncertainty in their values such as: cost of new construction and rehabilitation elements, deterioration parameters (i.e. number of breaks), economic parameters (i.e. interest rate), and new construction and rehabilitation alternatives.

The Simulation Components are expressed in their cyclic action in five main steps:

1) Generate random numbers by the Monte Carlo simulation technique.

2) Sample the predefined probability distribution to generate random values for cost, deterioration and interest rate.

3) Generate random values for cost, deterioration, and interest rate from the cumulative probability distribution.

4) Develop cash flow for the suggested scenarios.

5) Compute the equivalent annual uniform cost (EAUC).

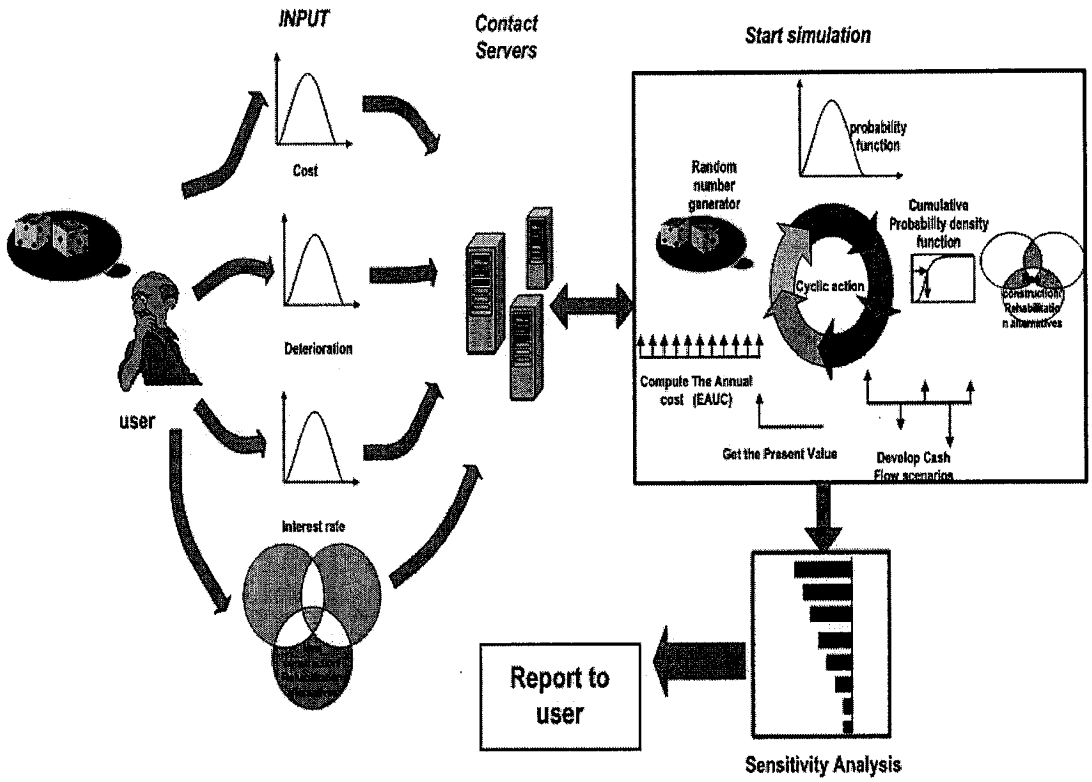


Figure 3.2 Framework for Stochastic Life Cycle Cost (SLCC) model

3.4.1 Stochastic Life Cycle Cost (SLCC) Steps

The major components of SLCC steps are shown in Figure 3.3. It comprises different elements that process the collected data in different ways.

3.4.1.1 Problems Definition

- *Scope and project alternatives definition*:

  It defines the project type whether it is a new construction or rehabilitation. Pipe type and diameter are selected and the water supply system performance is defined.

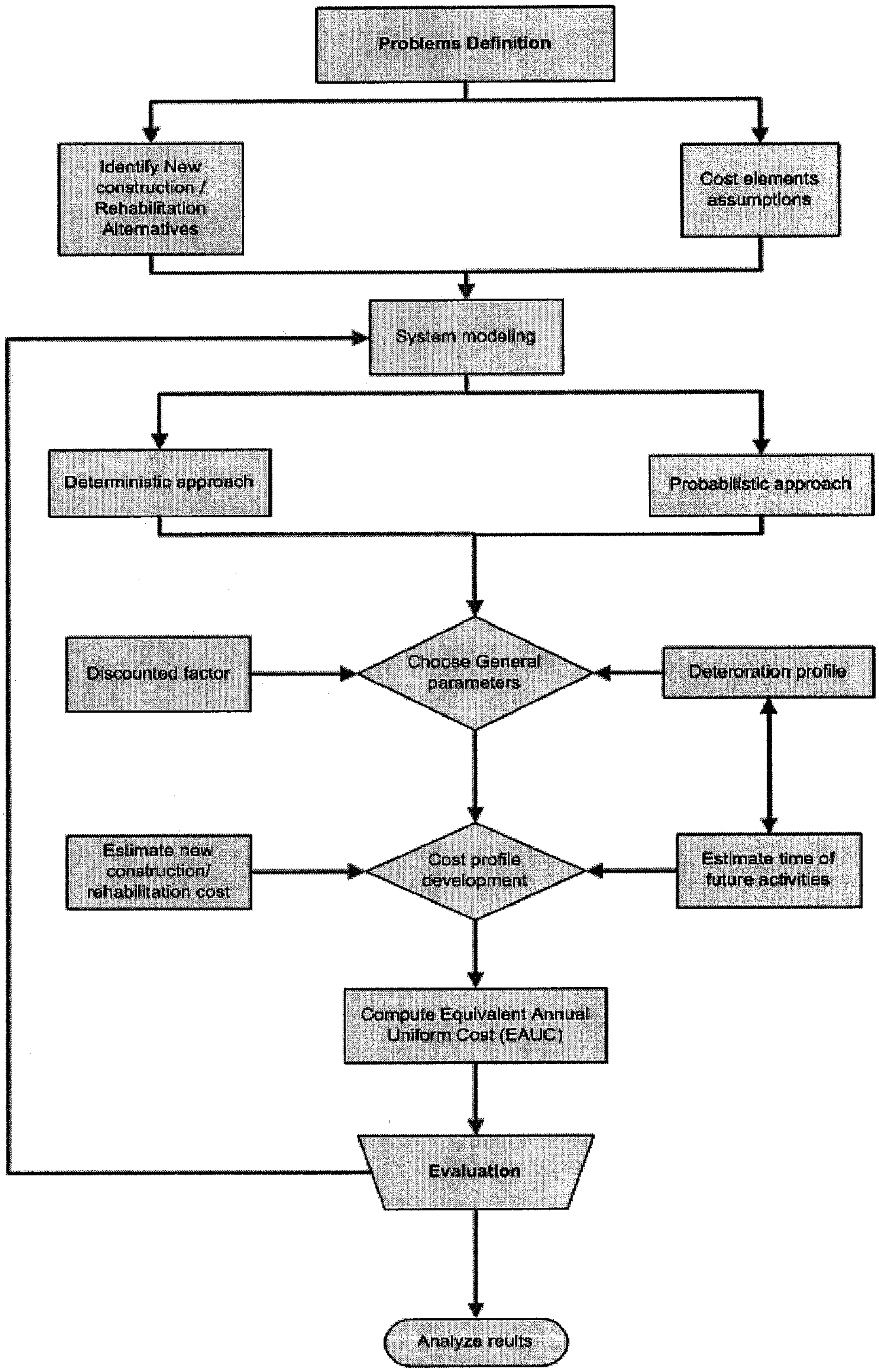


Figure 3.3 Stochastic Life Cycle Cost (SLCC) Steps

- *Evaluation criteria definition (acceptable risk level):*

  Water Quality: The water quality should meet customer satisfaction with respect to taste, odor and color.

  Water Quantity: the water quality should meet the minimum pressure and flow requirement at peak demand.

  Service Reliability: An adequate supply should be provided to the customer and at all times, and also the fire fighters should be supplied.

- *Cost element definition (Cost breakdown structure development):*

  Cost breakdown development is defined according to the method used in either construction or rehabilitation or operation and maintenance. For example, a cost element for new construction project may be open cut, HDD, pipe jacking and/or microtunnelling. Cost elements for rehabilitation are repair (sleeves or open trench); renovation (Slip lining, CIPP or epoxy/ cement lining) and replacement (open cut, pipe bursting ...etc.). Cost elements for operation and maintenance such include chemical cleaning and flushing, changing valves and cathodic protection.

3.4.1.2 System Modeling

- *Decide on the approach: probabilistic vs. deterministic:*

  After defining the project scope and alternatives, a decision should be made to use either a deterministic or probabilistic approach. The choice is usually based on whether the input parameters are deterministic or uncertain. For the deterministic approach, parameters are assumed to have a point value. The probabilistic approach uses a probability distribution function for all uncertain variables and therefore deals with the uncertainty in the model. Since the life cycle cost parameters are usually uncertain, the best method is the probabilistic approach.

3.4.1.3 The probabilistic approach is summarized by the following steps:

- *Identifying the variable or uncertain parameters.*
- *Defining a probability distribution for each predefined parameter that covers all possible values of each parameter.*

  The Probability distributions can be defined by a variety of functions depending on the information and data available. The most common distributions are the normal, lognormal, beta uniform, triangular, and gamma.

  After the probability distribution is defined for all uncertain variables, the Monte Carlo simulation technique is used.

3.4.1.4 Choosing General Parameters

1- *Assign the general economic parameters such as discounted rate and analysis period.*

   Both parameters should be equal for all alternatives. Since the estimated scenarios have unequal service lives, the equivalent annual uniform cost (EAUC) model is typically used to overcome this problem.

2- *Develop the cash flow profile for each alternative:*

   A cost is estimated for each scenario to establish the cash flow profile. In addition, the time of occurrence of each alternative is defined. The present value (PV) for each scenario is calculated using equation (3.1).

$$PV = \frac{FV_n}{(1 + i)^n} \qquad \text{.. (3.1)}$$

Where (FV) is the future value, (n) is the analysis period and (i) is the discount rate.

3- Compute the EAUC for each alternative by substituting PV cost in equation (3.2). As the analysis period is not constant for all scenarios, the EAUC equation was used to compare between alternatives.

$$\text{EAUC} = \left[\sum_{t=0}^{n}\left(PV_{COST_t}\right)\right] \Big/ \left[\sum_{t=1}^{n}\left(\frac{1}{(1+i)^t}\right)\right] \qquad \text{........ .... (3.2)}$$

4- Evaluate the design strategies (Sensitivity analysis, Uncertainty analysis) Having defined the scenarios and calculating the EAUC, a sensitivity analysis is carried out to give a better understanding of the data evaluation. The scenarios that have minimum EAUC or a percent difference of less than 10% of the EAUC for other competitive scenarios are considered similar or equivalent. A sensitivity analysis is introduced to examine the effect of the variability of the main input parameters for the analysis of results. The major parameters that would be tested for sensitivity are:

- The discounted rate.
- The deterioration rate
- Unit cost of all major components.

3.4.1.5 Cost Profile Development

- *Estimate Time of Future Activities:*

In order to estimate timing of future activities the deterioration rate of the existing mains need to be identified. Breakage rate analysis is used to express this deterioration rate. Where, timing of future breaks and pipe condition are analyzed then expressed by a probability distribution function. The breakage rate analysis is covered in chapter (4).

- *Estimate New Installation/Rehabilitation Costs:*

The costs of each new installation/Rehabilitation alternative are collected from municipalities, contractors, and consultants in North America using questionnaire method. Then cost data for each alternative are modeled using a probability distribution function. The cost analysis data are covered in chapter (4).

- *Identify New Installation/Rehabilitation scenarios:*

After defining new installation/rehabilitation alternatives and timing of future activities set of scenarios are suggested. Each suggested scenario is based on combination of repair, renovation, and replacement alternatives. The complete sets of suggested scenarios are covered in chapter (5) and Appendix B.

- *Calculate stochastic life cycle cost*

The present value (PV) for each suggested scenario is then calculated. Since that cost data, service life, and discounted rate are expressed in a stochastic functions, then the PV will be calculated as a probability distribution function. Finally compute EAUC for each scenario also as a probability distribution function, as illustrated in chapter (5)

• *Analyze results:*

After computing the EAUC for each scenario the results of each scenario are analyzed and compared to predict the best new installation/rehabilitation scenario for water main rehabilitation. This section is covered in chapter (5)

3.5 Monte Carlo simulation

3.5.1 Monte Carlo Sampling

Monte Carlo sampling techniques are entirely random so any given sample may fall within the range of the input distribution. Monte Carlo sampling refers to the traditional technique for using random numbers to sample from a probability distribution. The term Monte Carlo was introduced during World War II as a code name for simulation of problems associated with development of the atomic bomb. Today, Monte Carlo techniques are useful to a wide range of complex problems involving random behavior. A wide range of algorithms are available for generating random samples from different types of probability distributions. Monte Carlo sample uses a new random number between 0 and 1. With enough iteration, a problem of clustering, however, arises when a small number of iterations are performed. Monte Carlo technique results in a probability distribution for the EAUC, from which one can obtain meaningful estimates of the median (50-percent confidence level), 95th percentile (95-percent confidence level), and other relevant quantities.

Figure 3.4 shows the Calculation of EAUC using Monte Carlo simulation. This enables decision makers to make informed decisions for new installation/ rehabilitation alternatives and their acceptable level of risk.

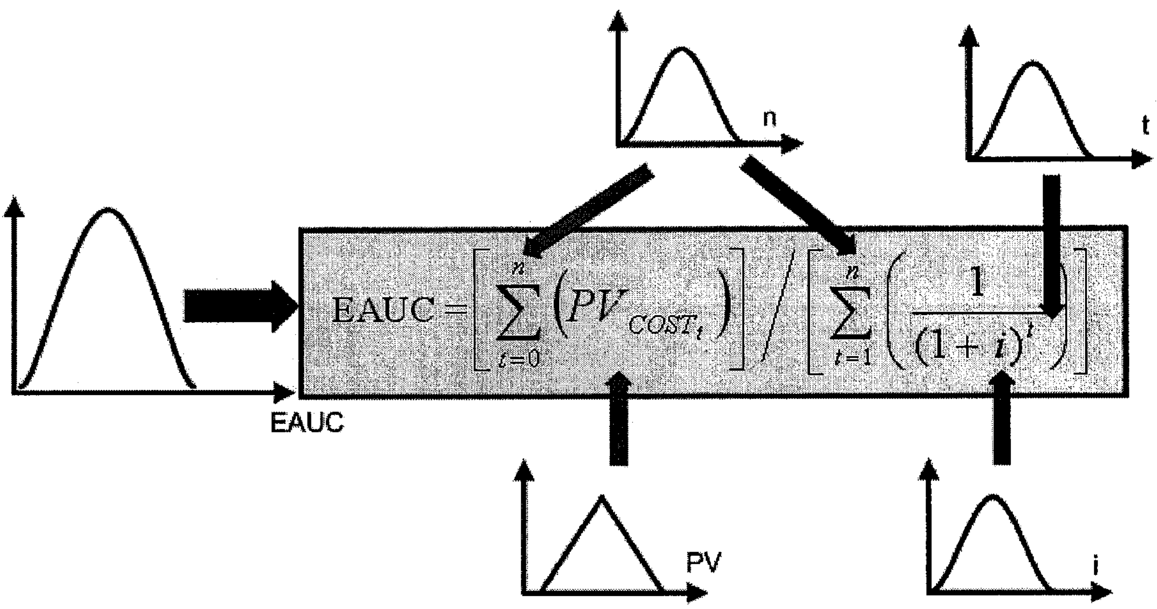


Figure 3.4 Calculating NPV using Monte Carlo Simulation

Where, (EAUC) equivalent annual uniform cost probability distribution function is calculated for each suggested scenario using: (n) service life of new installation/rehabilitation alternative, the service life probability distribution function is established using breakage rate analysis method. (i) Discounted rate is expressed by a normal distribution function based on its pervious values within the last 10 years (1996-2006). ($PVcost_t$) is the sum of present values for new installation/rehabilitation alternative within each scenario. Cost data are expressed using a triangular probability distribution.

The Monte Carlo simulation technique is similar to the "roll of dice play" the following steps describe the major methodology for Monte Carlo simulation

1. A probability distribution function is defined for all uncertain parameters (e.g. service life, discounted rate, new installation/rehabilitation costs).
2. Monte Carlo starts generating random numbers ranges from 0-1.0

3. Random numbers are then used to enter the predefined cumulative probability distribution to get the random values for the uncertain parameters.
4. This process is repeated several times to establish a probability distribution function for the out put life cycle cost elements (e.g. EAUC).

In this study risk based computer software "@risk 4.5" was used to perform the previous steps. An academic version of "@risk 4.5" was used in analysis and developing the web-based stochastic life cycle cost (WSLCC) software program.

3.6 Web-Based Stochastic Life Cycle Cost (WSLCC) Software Package

A typical life cycle cost process usually starts by collecting data about the project requirement and constraints. The WSLCC software is believed to help both new and experienced engineers and experts in the establishment of life cycle cost and benefit from the data stored in the database.

The user is required to enter a set of input data that describes the project and user requirement. The simulation is then executed and based on the input data, the software starts the simulation by calling the "@risk package". A report is generated detailing the scenario analysis and cash flow.

3.6.1 System Modeling Steps

The main system modeling consists of four basic steps as follows:

1. Developing an Excel spreadsheet to calculate the life cycle cost.
2. Developing an @risk model.
3. Modification of "@risk" Student Version to suite the developed model

4. Analyzing the model with simulation.
5. Printing the output results and analysis.

The development of the web based software package was completed after the previous steps. These steps were performed for five pipe types, and three diameter ranges as shown in Appendix B.

Summary of Chapter 3

This chapter presents the research methodology which achieves the following steps: (1) Review of literature, covering all major disciplines that are necessary to evaluate the life cycle cost (LCC). It consists of a problem definition, hydraulic and operating pressures, material specification, location of connections and valves, out of service times and LCC analysis methods, (2) Collection of data comprising cost information, deterioration, economic parameters and data pertaining to the available alternatives. (3) Defining the LCC profile, which consists of the main steps required to establish the cost profile for each alternative, (4) Use of Monte Carlo simulation to address the probability of input data. This section defines the main criteria of the Monte Carlo simulation and addresses the "@risk 4.5" software package used to perform the simulation, (5) Development of the SLCC model; (6) Performance of sensitivity analysis to results; this examines the effect of the variability of the main input parameters for the analysis of the overall results. The sensitivity analysis tests the variability of some uncertain input parameters by holding all other parameters constant, and (7) Generation of detailed report for each scenario.

CHAPTER 4: DATA COLLECTION

4.1 Introduction

The data collection phase was divided into four main branches as shown in Figure 4.1: a) cost data, b) deterioration, c) economic parameters and d) alternatives data. The cost data for the selected new installation & rehabilitation alternatives were collected using both questionnaire and the available cost model equation. The deterioration data were based upon the historical break data collected from Canadian municipalities. The Economic parameters such as interest rate and the inflation rate were collected from the national bank of Canada.

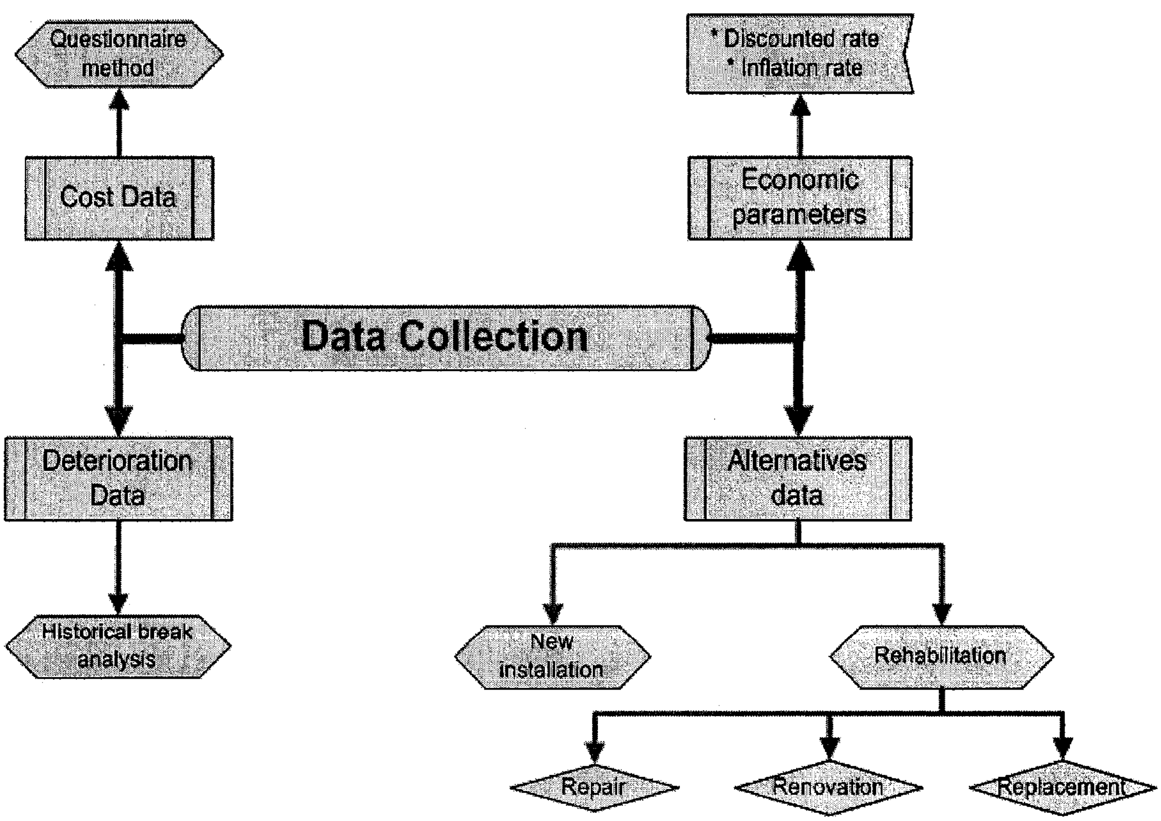


Figure 4.1 Elements of data collection

4.2 New Installation & Rehabilitation Alternatives Data:

Alternatives Data for new installation and/or rehabilitation were collected according to the most commonly used method in the industry. Data collection for this stage was based on the literature review of available new construction and rehabilitation alternatives in the market of water main.

There were several methods for new installation and/or rehabilitation in the literature, however not all of these methods are widely used. According to a survey of most municipalities in Canada and the USA, the most common methods for new installations are Open Cut, Pipe Bursting, Horizontal Directional Drilling and Micro-tunneling for new installation projects. However for rehabilitation, the methods are commonly classified into three categories:

1. Repair using sleeves or open trench.
2. Renovation using cement or epoxy lining, slip lining and curried in place pipe (CIPP).
3. Replacement using pipe bursting, open cut, horizontal directional drilling (HDD) and micro-tunneling (MT).

For all water mains of small and medium diameter, most municipalities commonly use cleaning, chemical flushing and changing damaged valves. For pipes having a large diameter (> 42"), only damaged parts are changed and chemical flushing is not typically used. Cathodic protection methods are sometimes used for cast iron and ductile iron pipes.

4.3 Cost Data

Cost data were divided into cost elements that were collected by questionnaire as shown in Figure 4.2. The questionnaire method was based on previous work done and expert evaluations. The cost elements were divided into three main categories as follows: 1) New installation, 2) Rehabilitation and 3) Operation and maintenance.

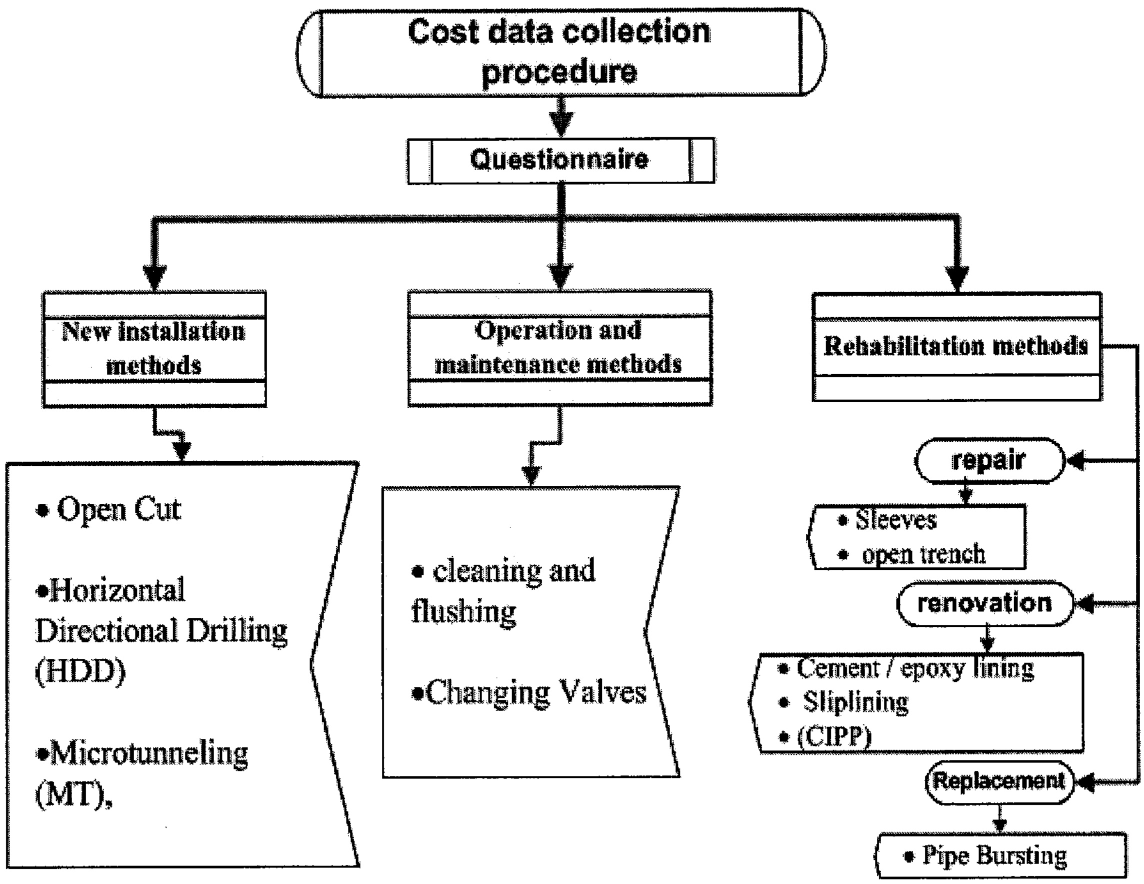


Figure 4.2 Cost data collection procedure

The questionnaire has been carefully designed, as shown in Appendix A so that it would be reliable method of assessment. The questionnaires were developed and distributed to specialized engineers. They asked for information on installation, rehabilitation and operation and maintenance costs. Five pipe materials, and three diameter ranges were assumed in this questionnaire. The selection of these diameter ranges was based on the classification categories found in the literature by O'Day (1992) and also Rajani (2002) as each of these diameter ranges have a similar service life and average cost.

Questionnaires have advantages over other types of surveys in that they are inexpensive, they do not require as much effort from the questioner, and often have standardized answers that make it simple to compile data. However, such standardized answers may frustrate users. Questionnaires are also sharply limited by the fact that respondents must be able to read the questions and respond to them. Thus, for some demographic groups conducting a survey by questionnaire may not be practical. The number of replies to these questionnaires is subject to a sampling error which reflects the effects of chance in the sampling process. The margin of error can be reduced by using a larger sample, which is very difficult in the case of this research, since the number of experience engineers in this area is quite limited. One more problem is the number of non-responsive people, since some people do not answer calls from strangers, or refuse to answer the questionnaires.

Furthermore, the biased answer, the characteristics of those who agree to be interviewed may be markedly different from those who decline. The actual sample is a biased version of the actual answer. In these cases, bias introduces new errors. Error due to bias does not become smaller with larger sample sizes. However, if the people who refuse to answer, or are never reached, have the same characteristics as the people who do answer, the final results will be unbiased.

It is well established that the wording of the questions, the order in which they are asked and the number and form of alternative answers offered can influence the results obtained from questionnaires. One attempt to minimize this effect is to ask the same set of questions over time, in order to track changes in opinion. Due to the inherent uncertainty of questionnaires, another method, cost evaluation by mathematical equations was chosen.

The questionnaire is divided into three main sections as shown in Appendix A. Section one is Company Information, where this section is only required to distinguish between contractor and consultant categories. Also this section is required for records and for any further required.

Section two is related to service life prediction. Service life information is essential to determine project factors that affect pipe service life and enable prediction of life cycle cost cash flows. The required data is available in Canadian municipalities' data bases as shown in APPENDIX A. It's required from the experts to answer eight questions based on historical databases.

The third section is for cost information, where experts have to give an estimate of minimum, most probable and maximum cost for each new installation and rehabilitation activity. The data is required for five pipe material and three diameter ranges as shown in APPENDIX A.

A complete set of information was collected from contractors, consultants, and governmental municipalities in Canada and USA. Contractors were very helpful in delivering the required data and gave a complete set of costs for rehabilitation projects. All costs were converted into Canadian dollars in year 2005 using engineering news record (ENR) cost index 2005. In addition, the city of Montréal and Moncoton provided a complete set of work done in water mains. Results from this questionnaire is compared with the estimated cost equation models presented the next section.

4.4 Deterioration Data

This parameter is one of the highly uncertain and sensitive parameters in the SLCC model. Future activities can be classified as follows:

1. Annual activities: This covers the activities that take place on a cyclical basis, such as annual maintenance and changing valves activities during normal operations. Generally, the timing of these activities corresponds to the time cycles, which is taken as the incremental number of years in SLCC.
2. The second is the future activities that do not recur on a cyclical basis. This covers all rehabilitation and replacement activities.

The main factor that should affect the timing of these activities is the pipe condition. Deterioration models are being developed to predict the pipe condition. The timings of these activities are among the most important yet uncertain parameters in SLCC.

Calculating time of non-recurring future activities in SLCC is based on planning the standard rehabilitation strategies on the basis of past practice within the municipality. Such strategies generally specify the type and timing of rehabilitation that should be performed throughout the lifetime of the pipe. This can be done based on statistical analysis of the information gathered in the municipality management system databases. These databases record the location, type, and timing of every activity. A probability distribution of the rehabilitation intervals is then constructed for each type of pipe and for each type of rehabilitation activity that is generally performed. This method is useful for accounting for the variability of these intervals.

- **Historical Break analysis**:

Most municipalities in Canada do not have a full database of their water main break records. Although some of them have maintained a break record for more than 30 years such as Moncton, New Brunswick and London, Ontario. The historical break analysis established in this research was based on the database of these two municipalities. Table 4.1 summarizes the break history in Moncton sorted by the pipe type for the last 30 years.

Table 4.1 Summary of the Break History in Moncton, New Brunswick *(Dillon and harfan Inc., 2003)*.

Pipe Type	Length (km)	Installation years	Number of breaks	Break/km
Pre War Cast Iron	82.8	1895 - 1950	258	3.1
Post War Cast Iron	94.6	1950 - 1970	1279	13.5
Ductile Iron	139.9	1968 - 2002	234	1.7
Relined Cast Iron	3.8	various	3	0.8
Concrete	30.2	1964 - 1987	0	0
PVC	83.4	1978 - 2002	3	0.04
Asbestos	11.6	1959 - 1970	37	3.2
total	469	--	1903	--

After gathering the break data review and research, an analysis was performed to generate a probability distribution function for each break. The following is an example of the steps done in the analysis section:

As shown in Figure 4.3, the historical break procedure was divided into 5 sections according to the pipe material (cast iron, ductile iron, PVC, concrete or asbestos cement). Each section was divided into 3 subsections for simplicity based on water pipe diameter ranges (6" to 24"), (30" to 42") and (> 42"). The selection of these ranges was based on the classification categories found in literature by O'Day (1992) and also Rajani (2002) as each of these diameter ranges have a similar service life and average cost. The data was sorted out into five stages, based on the number of breaks into: (1) pipes with one break only; (2) pipes with two breaks; (3) pipes with three breaks; (4) pipes with four breaks; (5) pipes with five breaks and above.

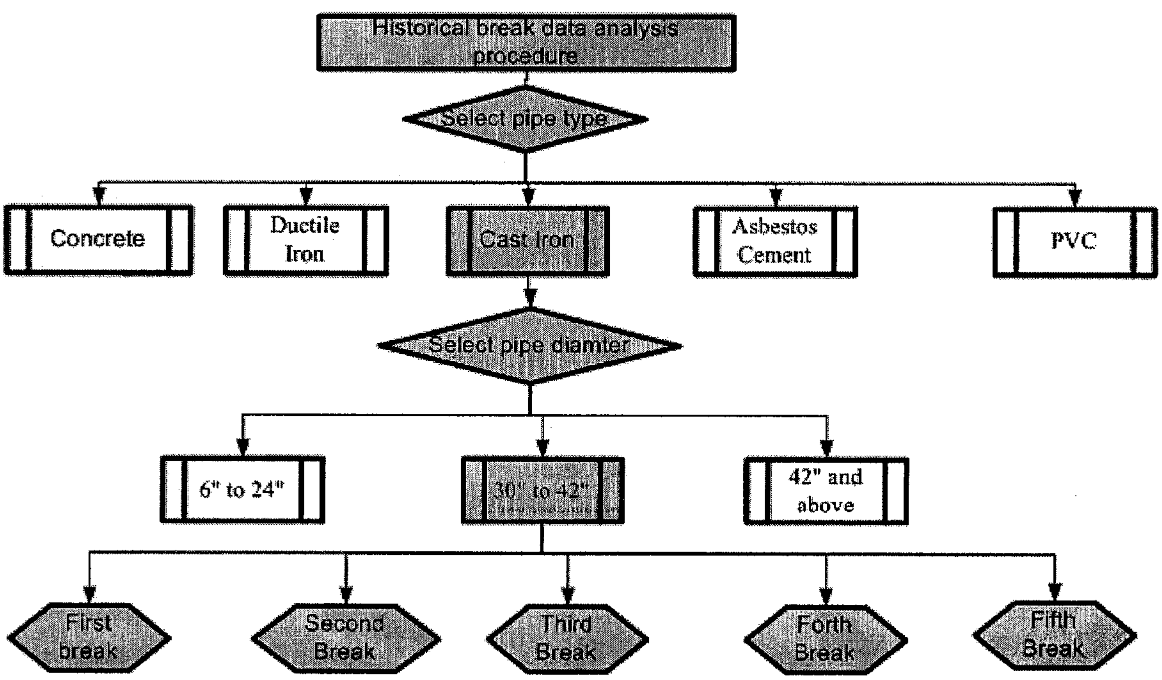


Figure 4.3 Historical break data procedure

A sample of approximately 200 water main pipes was selected and the previous procedure was established for all pipe types. A detailed analysis for the time of occurrence of each break and the number of observations was conducted. The number of observations was used to build a probability distribution function for each break using a software program called "BEST FIT". Figure 4.4 shows the establishment of the probability distribution function for each break. The following criteria were used:

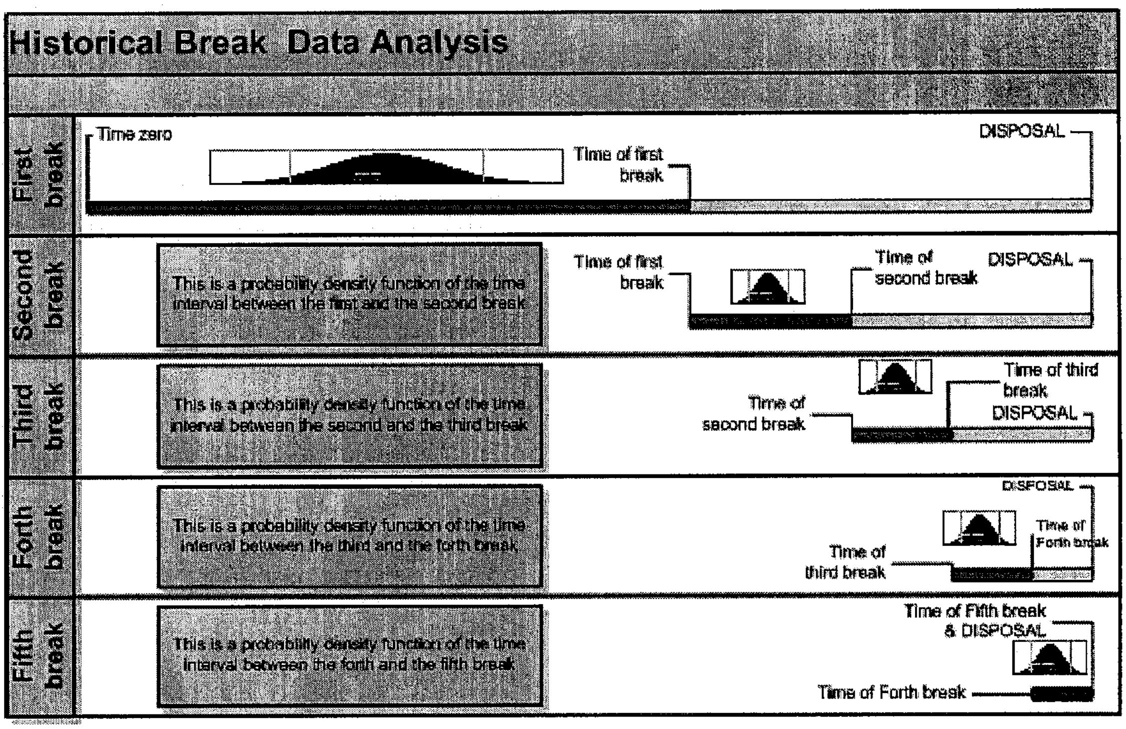


Figure 4.4 Probability distribution functions for each break

1. Occurrence time of 1^{st} break;

Break occurrence interval is calculated by analyzing the first break timing intervals and calculating the range of break occurrence, then building a probability distribution function for this break. The data analyzed showed that a normal probability distribution is common for first break occurrence time.

2. Occurrence time from 1st to 2nd break.

This step analyzes the time interval between first and second break occurrence time. Where water mains having two breaks or more are sorted based on break occurrence time, then a probability distribution function was established. The data analyzed showed that a lognormal probability distribution is common for 1st to 2nd break interval occurrence time.

Similarly data analyzed showed that a lognormal probability distribution is common for each of the following break occurrence times:

3. Occurrence time from 2nd to 3rd break.
4. Occurrence time from 3rd to 4th break.
5. Occurrence time from 4th to 5th break.

4.5 Economic Parameters

Rehabilitation and replacement of water transmission lines is economical if the costs are less than the savings in energy and pumping capacity which occur due to the increased carrying capacity of the pipe. Criteria are developed to determine if it is economical to rehabilitate or reconstruct the pipe for two cases: (1) When the flow is not significantly altered by rehabilitating the pipe; or (2) the system is looped so that the change in carrying capacity significantly changes flow. The decision depends on many factors such as the cost associated in cleaning and relining the pipe, the price of energy, the incremental cost of pumping capacity, the peak and average flow in the pipe, the nominal diameter, the interest rate, the discount rate, the time for each brake and the year in which the rehabilitation or reconstruction will be carried out.

In our model, the economic parameters were divided into the analysis period and the discounted rate. Since the analysis periods vary, the equivalent annual uniform cost (EAUC) was used. The discounted rate was divided into the interest rate and the inflation rate. Data from the Bank of Canada were collected to predict the probability distribution for the interest and inflation rates.

Summary of Chapter 4

This chapter presents the data collection method established in this study. It shows the different methods used in cost data collection. It also defines the methods used in estimating the service life of mains and the deterioration method used. The new installation and rehabilitation alternatives used in this study are also defined. Finally it illustrates the importance of the economic parameters (i.e. the discounted rate, service life)

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Introduction

This section shows an overview of the results for cast iron, ductile iron, PVC, concrete and asbestos cement water mains. A Monte Carlo simulation was used, which allows for the modeling of uncertain quantities in the SLCC model with probabilistic inputs. The simulation procedure randomly samples the inputs and produces outputs that are described by both probability distributions and accumulative curves. The results were first presented according to the material used. The results from all materials were collected and presented for comparison. The developed program allows the user to perform separate simulation runs to compare multiple alternatives, knowing that variations from run to run will be caused by actual input changes. The reproducible results option allows for the selection of numerous routes or scenarios for either rehabilitation or new construction schemes. This facilitates the choice of the most suitable scenario at an optimum cost. The cost probability distribution graphs and tables are provided, showing the percentile values in ascending or descending order.

Figure 5.1 shows the organization of results and discussion chapter. The main results of rehabilitation and new installation project(s) are presented in details for the cast iron pipe material, followed by a summary of results for ductile iron, PVC, concrete, and asbestos cement. Accordingly, a maintenance plan is developed to manage repair, renovation, and replacement decisions.

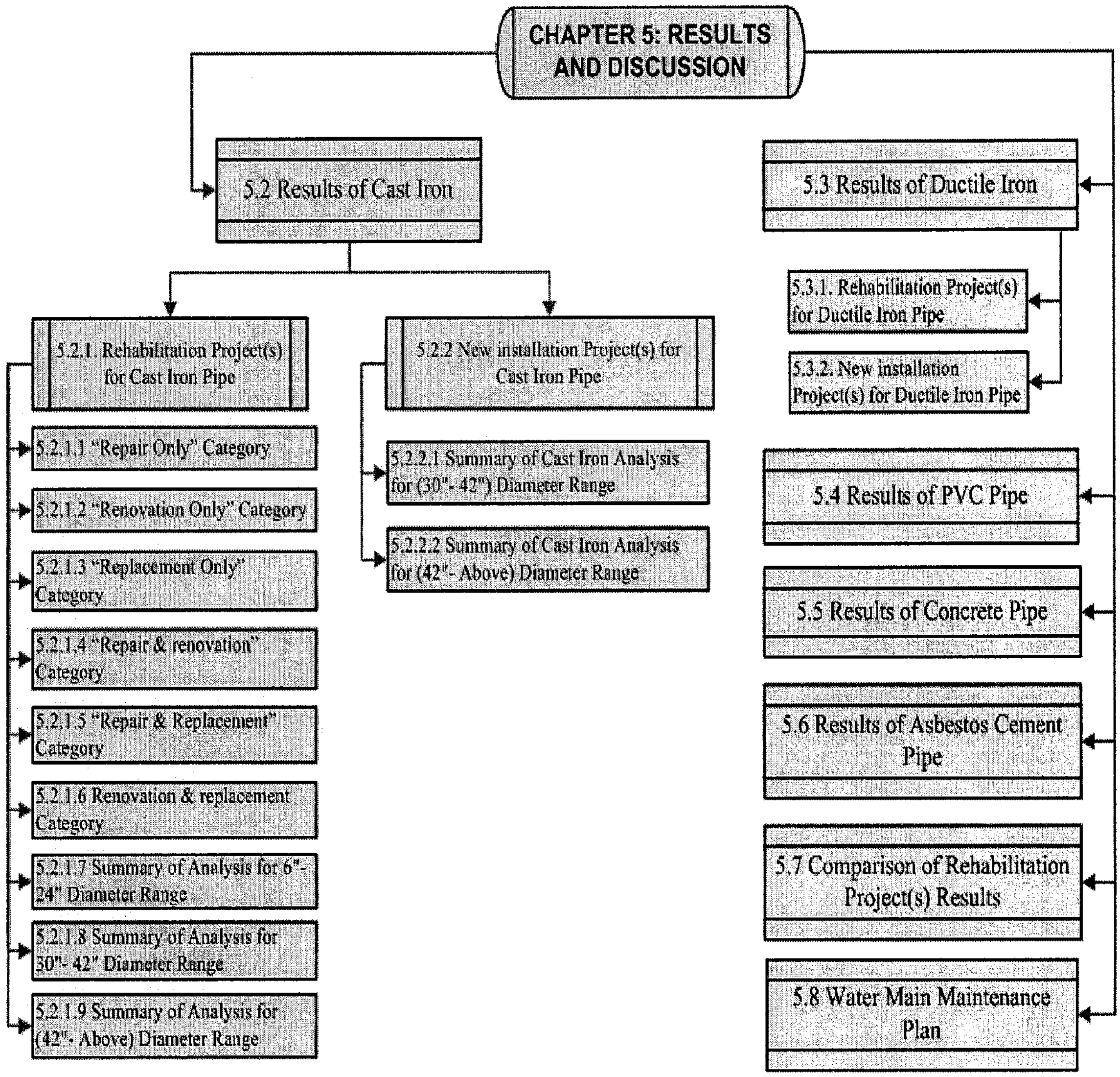


Figure 5.1 Results organization chart

5.2 RESULTS OF CAST IRON

5.2.1. Rehabilitation Project(s) for Cast Iron Pipe

This section compares the rehabilitation costs for a Cast iron pipe with diameters ranging from 6" to 24". The alternatives used for rehabilitation project(s) are shown in Table 5.1. The main scenarios were selected according to the alternative shown in this table. The scenarios were built as follows: when a break occurs, it can be applied up to a maximum of five breaks. The total number of suggested scenarios was predefined to the program as sixty scenarios as shown in Appendix C. The scenarios are developed in 6 main categories as shown in Table 5.2. A selected sample of EUAC and the output statistics are summarized in the following tables and charts. All costs for the EUAC are in ($/km/year).

Table 5.1 Rehabilitation alternatives, diameters from 6" to 24"

	Operation	Description	Symbol
1	Repair	Sleeves	SVS
		Open trench	OT
2	Renovation	Cement or epoxy lining	C/EL
		Slip lining	SL
		Curried in Place Pipe	CIPP
3	Replacement	Pipe Bursting	PB
		Open Cut	OC
		Horizontal Directional Drilling	HDD
		Microtunneling	MT

Table 5.2 Suggested scenarios

Category	Operation	No. of Scenarios
1	Repair only	2
2	Renovation only	3
3	Replacement only	4
4	Repair & renovation	24
5	Repair & replacement	18
6	Renovation & replacement	9
	Total	60

Input Data

The input data are composed of the cost (operation and maintenance cost, rehabilitation alternatives cost), the deterioration rate (the service life of pipe) and the discounted rate. The costs are entered in a triangular probability distribution function with the minimum, most likely, and maximum cost. For both service life and discounted rate, input data are entered using a normal and log normal probability distribution function with the mean (μ), and standard deviation (σ).

These input data were collected based on the methods used in data collection section explained in Chapter 4. Tables 5.3, 5.4 and 5.5 indicate typical input cost data for 6" to 24" diameter pipes. All costs were in $/km length. The program is then executed and sensitivity analyses were carried out.

Table 5.3 Typical input cost data for 6"-24" diameter Cast Iron pipes

Classes	Description	minimum	most likely	max	Unit cost
Operation and maintenance	Cleaning & Flushing	$3,000	$4,500	$4,950	$/km
	changing valves	$1,250	$2,500	$4,000	$/km
Repair	Sleeves	$1,400	$2,000	$4,200	each
	open trench	$800	$1,400	$2,600	each
Renovation	Cement/ epoxy Lining	$120,000	$250,000	$550,000	$/km
	Slip Lining	$190,000	$380,000	$750,000	$/km
	CIPP	$230,000	$450,000	$900,000	$/km
Replacement	Pipe bursting	$260,000	$460,000	$900,000	$/km
	Open CUT	$300,000	$470,000	$850,000	$/km
	HDD	$450,000	$850,000	$1,400,000	$/km
	MT	$700,000	$1,000,000	$2,500,000	$/km

Table 5.4 Probability and number of changed valves for a 6"-24" diameter Cast Iron pipes

Total no. of valves per km	No. of valves changed per year		
	min	most likely	max
5	0	1	2

Table 5.5 Typical input deterioration data for 6"-24" diameter Cast Iron pipes

	Break Number	Time in years				
		Mean (μ)	Standard Deviation (σ)	Truncated Minimum	Truncated Maximum	Function Type
New Pipe	1st	30	10	0	100	Normal
	2nd	3	1.25	0	100	log Normal
	3rd	2.5	1.2	0	100	log Normal
	4th	2	1.3	0	100	log Normal
	5th	1.8	1	0	100	log Normal
Cement lining	1st	10	5	0	100	Normal
	2nd	3	1.25	0	100	log Normal
	3rd	2.5	1.2	0	100	log Normal
	4th	2	1.3	0	100	log Normal
	5th	1.8	1	0	100	log Normal
slip lining	1st	30	10	0	100	Normal
	2nd	3	1.25	0	100	log Normal
	3rd	2.5	1.2	0	100	log Normal
	4th	2	1.3	0	100	log Normal
	5th	1.8	1	0	100	log Normal
CIPP	1st	30	10	0	100	Normal
	2nd	3	1.25	0	100	log Normal
	3rd	2.5	1.2	0	100	log Normal
	4th	2	1.3	0	100	log Normal
	5th	1.8	1	0	100	log Normal
	discounted rate	**4.50%**	**1.30%**	**1%**	**8%**	**Normal**

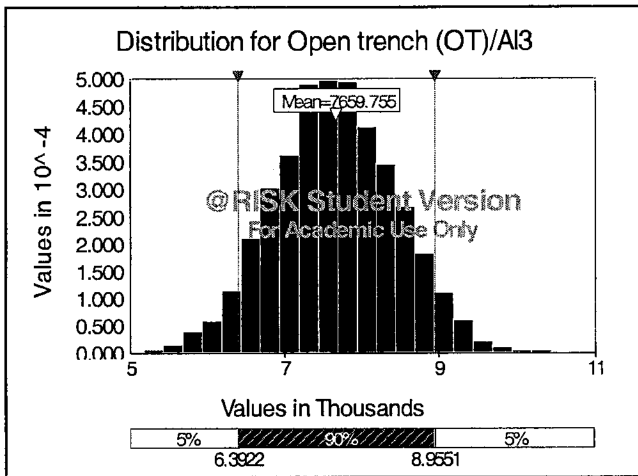
Output Information

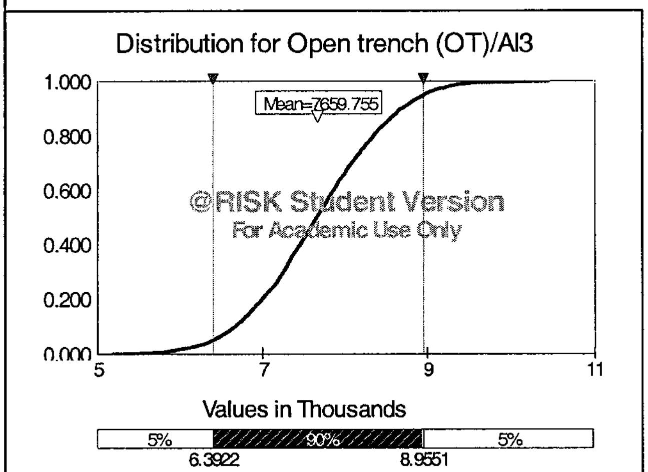
5.2.1.1 "Repair Only" Category:

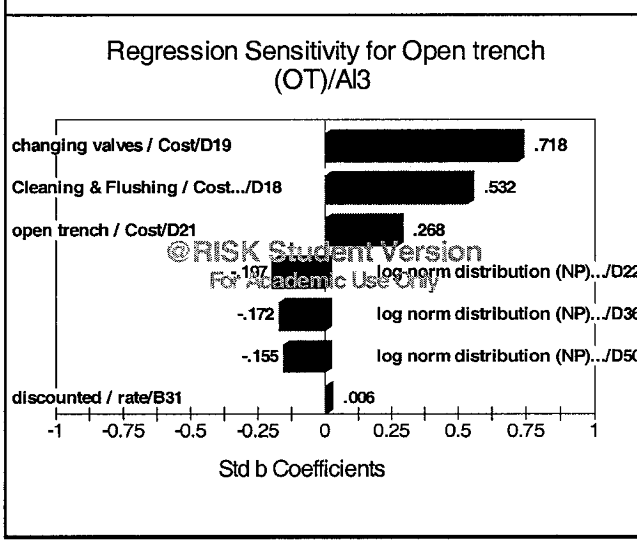
Figure 5.2a shows the results of distribution and regression sensitivity of Repair-Open Trench scenarios. The output distribution worksheets provide a probability distribution, cumulative functions and regression sensitivity graphs. The regression sensitivity graphs describe how inputs affect outputs. For example, the input of changing valves has a positive effect on the output alternative. A correlation coefficient value of 1 would indicate a complete positive correlation between two variables. A value of -1 would indicate a complete inverse correlation between two variables. The value of 0 would indicate that there is no correlation between variables. Results of repair using open trench methodology showed that the mean is slightly below 7660 $/km/yr. The regression sensitivity showed that changing valves, cleaning, flushing and open trench costs have significant positive correlation effects on the EUAC with a range of 0.718 to 0.268.

Other correlation values indicate a partial correlation; the output is affected by changes in the selected input, but may be affected by other variables as well. The summary of information and statistics are further indicated in tables at the right of figure 5.2a. As shown in table, the simulation parameters are set to perform 5000 iteration using Monte Carlo sampling simulation.

Figure 5.2b shows the results of a distribution and regression sensitivity for Repair-Sleeves scenarios. The output distribution worksheets provide probability







Summary Information	
Workbook Name	_rehab_CI_6_24
Number of Simulations	1
Number of Iterations	5000
Number of Inputs	33
Number of Outputs	60
Sampling Type	Monte Carlo
Simulation Start Time	2/3/2006 0:43
Simulation Stop Time	2/3/2006 0:43
Simulation Duration	00:00:27
Random Seed	791582153

Summary Statistics			
Statistic	Value	%tile	Value
Minimum	$5,187	5%	$6,392
Maximum	$10,454	10%	$6,661
Mean	$7,660	15%	$6,836
Std Dev	$781	20%	$6,990
Variance	609981.152	25%	$7,139
Skewness	0.034217879	30%	$7,246
Kurtosis	2.83899975	35%	$7,339
Median	$7,649	40%	$7,447
Mode	$6,840	45%	$7,552
Left X	$6,392	50%	$7,649
Left P	5%	55%	$7,754
Right X	$8,955	60%	$7,850
Right P	95%	65%	$7,953
Diff X	$2,563	70%	$8,068
Diff P	90%	75%	$8,200
#Errors	0	80%	$8,336
Filter Min		85%	$8,493
Filter Max		90%	$8,682
#Filtered	0	95%	$8,955

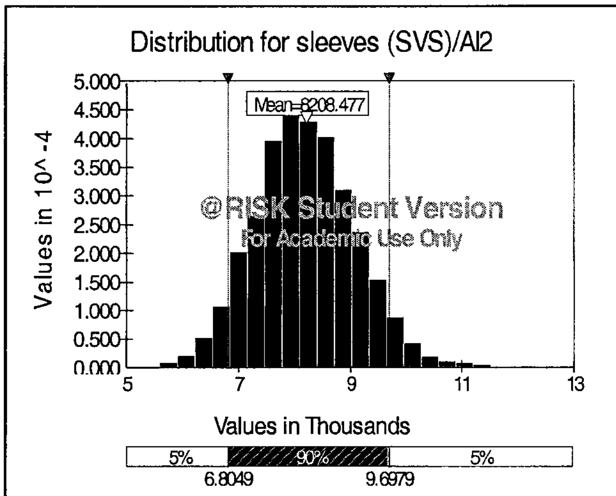
Sensitivity			
Rank	Name	Regr	Corr
#1	changing valves / Cost /	0.718	0.725
#2	Cleaning & Flushing / Co	0.532	0.526
#3	open trench / Cost / D	0.268	0.253
#4	log norm distribution (NP	-0.197	-0.204
#5	log norm distribution (NP	-0.172	-0.149
#6	log norm distribution (NP	-0.155	-0.141
#7	discounted / rate / B3	0.006	-0.008
#8	normal distribution (NP) /	0.000	-0.011
#9	normal distribution (E/CL)	0.000	-0.032
#10	normal distribution (SL) /	0.000	0.015
#11	normal distribution (CIPP)	0.000	0.011
#12	log norm distribution (E/C	0.000	-0.021
#13	log norm distribution (SL)	0.000	-0.019
#14	log norm distribution (CIP	0.000	-0.010
#15	log norm distribution (E/C	0.000	-0.014
#16	log norm distribution (SL)	0.000	0.015

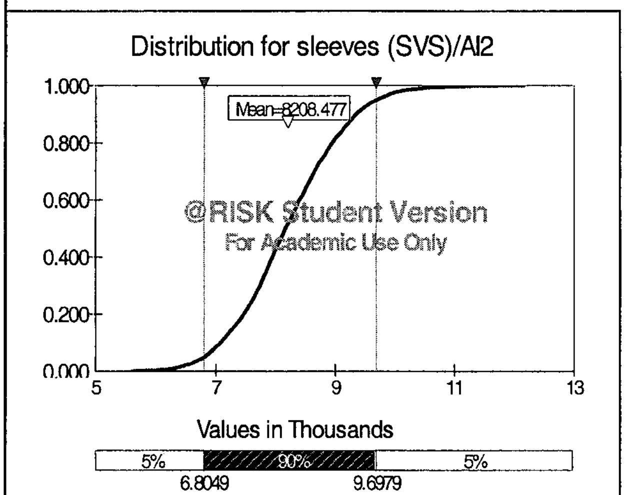
Figure 5.2a EUAC distribution and regression sensitivity for Open Trench scenarios

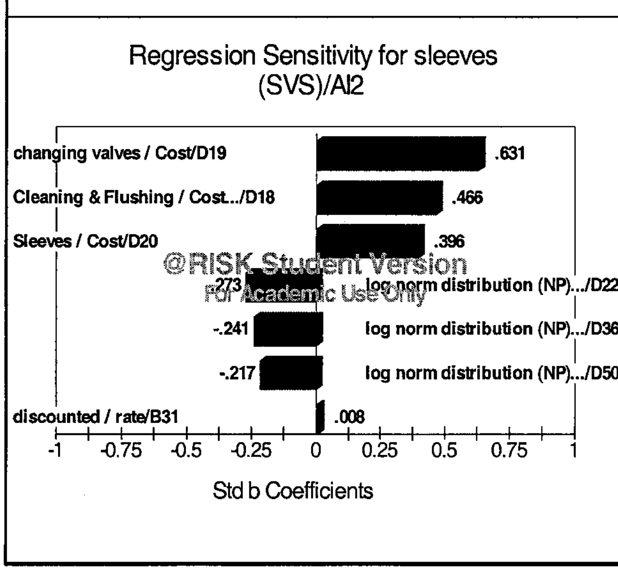
distribution, cumulative functions and regression sensitivity graphs. Results of repair using sleeves showed that a normal distribution is common. The mean is slightly higher at 8208 $/km/yr (7.1% more than the open trench case). The regression sensitivity showed that changing valves, cleaning, flushing and sleeve costs have significant positive correlation coefficient effects on the EUAC with a range of 0.631 to 0.396.

Other correlation values indicate a partial correlation; the output is affected by changes in the selected input, but may be affected by other variables as well. The summary of information and statistics are further indicated in tables at the right of Figure 5.2b. As shown in Table, the simulation parameters are set to perform 5000 iterations using Monte Carlo sampling simulations. Figure 5.3 shows a comparison graph that superimposes the output data and fitted distribution for the "Open Trench" and "Sleeve" scenarios on the same graph, allowing for an immediate comparison. This graph allows the user to determine if the fitted distribution matches the output data in specific areas. For example, it may be important to have a good match around the mean or in the tails. In addition, the Figure shows the Probability-Probability (P-P) graph that plots the distribution of the input data (*Pi*) vs. the distribution of the best fit function result (*F(xi)*). If the fit is "good", the plot will be nearly linear.

Based on the chi-squared fit statistic "BESTFIT" program reports that each of the following probability functions can best fits the output data for "Open Trench" scenario: **Normal** (7641, 806); **Inv Gauss** (45585, 146059935, Shift(-







Summary Information	
Workbook Name	) _rehab_CI_6_24_
Number of Simulations	1
Number of Iterations	5000
Number of Inputs	33
Number of Outputs	60
Sampling Type	Monte Carlo
Simulation Start Time	2/3/2006 0:43
Simulation Stop Time	2/3/2006 0:43
Simulation Duration	00:00:27
Random Seed	791582153

Summary Statistics			
Statistic	Value	%tile	Value
Minimum	$5,607	5%	$6,805
Maximum	$12,156	10%	$7,077
Mean	$8,208	15%	$7,289
Std Dev	$889	20%	$7,468
Variance	789555.1347	25%	$7,616
Skew ness	0.234598544	30%	$7,739
Kurtosis	3.197234383	35%	$7,847
Median	$8,163	40%	$7,945
Mode	$7,439	45%	$8,057
Left X	$6,805	50%	$8,163
Left P	5%	55%	$8,284
Right X	$9,698	60%	$8,400
Right P	95%	65%	$8,525
Diff X	$2,893	70%	$8,652
Diff P	90%	75%	$8,795
#Errors	0	80%	$8,947
Filter Min		85%	$9,139
Filter Max		90%	$9,355
#Filtered	0	95%	$9,698

Sensitivity			
Rank	Name	Regr	Corr
#1	changing valves / Cost / $I	0.631	0.633
#2	Cleaning & Flushing / Cost	0.466	0.471
#3	Sleeves / Cost / D20	0.396	0.367
#4	log norm distribution (NP) /	-0.273	-0.272
#5	log norm distribution (NP) /	-0.241	-0.215
#6	log norm distribution (NP) /	-0.217	-0.206
#7	discounted / rate / B31	0.008	-0.005
#8	normal distribution (NP) / fi	0.000	-0.006
#9	normal distribution (E/CL) /	0.000	-0.031
#10	normal distribution (SL) / fi	0.000	0.013
#11	normal distribution (CIPP) /	0.000	0.017
#12	log norm distribution (E/CL)	0.000	-0.010
#13	log norm distribution (SL) /	0.000	-0.020
#14	log norm distribution (CIPP)	0.000	-0.010
#15	log norm distribution (E/CL)	0.000	-0.011
#16	log norm distribution (SL) /	0.000	0.028

Figure 5.2b EUAC distribution and regression sensitivity for Sleeves scenarios

37944)); **Weibull** (3.4545, 2817, Shift (5105.1)); **Logistic;** (7642.29, 460.32) and **Log-Logistic** (-220711, 228352, 496.07). In addition, the "BESTFIT" program reports that each of the following probability functions can best fit the output data for the "Sleeve" scenario: **Normal** (8184.78, 937.79); **Logistic** (8178.7, 534.55); and **Log Logistic** (-21653, 29825, 55.804); **Lognormal** (26179, 935.95, Shift (-17994)); **Inv Gauss** (26078, 20244276, Shift (-17893)).

A histogram plot of the EAUC against scenarios is shown in Figure 5.4. It shows the ranges of minimum, maximum and mean cost of each scenario. From the relatively large size bars, the variation can be easily seen. Approximately speaking, the histogram plot is the derivative of the cumulative fraction plot. Large histogram values correspond to regions of high slope on the cumulative fraction curve. Table 5.6 shows the same data of figure 5.4 in table form.

Table 5.6 EUAC Statistics for "repair only" scenarios

Output		**EUAC Statistics ($/km/year)**				
category	**Name**	**Minimum**	**Mean**	**Maximum**	**5% percentile**	**95% percentile**
repair only	Open trench (OT)	$5,187	$7,660	$10,454	$6,392	$8,955
	sleeves (SVS)	$5,607	$8,208	$12,156	$6,805	$9,698

"Open trench" Scenario **"Sleeves" Scenario**

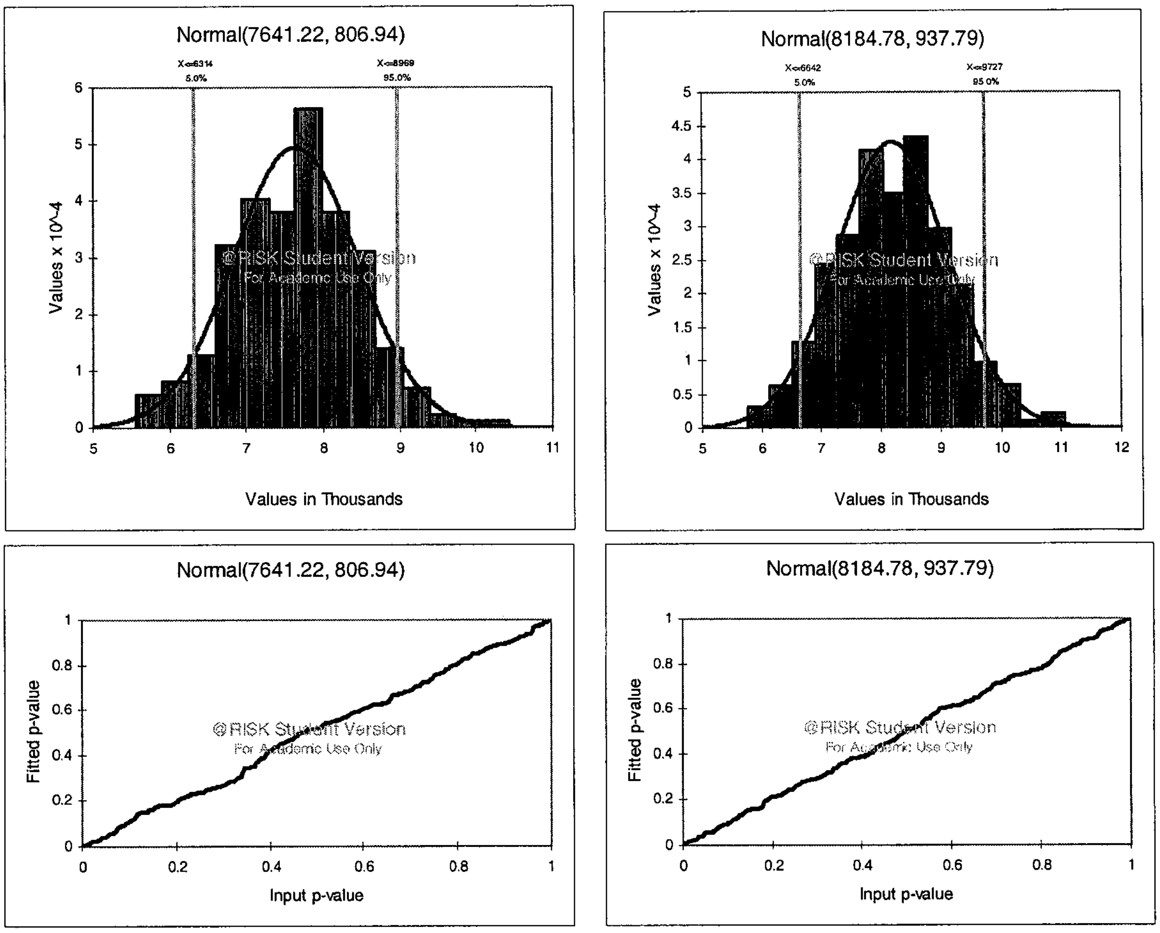


Figure 5.3 Comparison & Probability-Probability (P-P) graph for the repair only scenarios

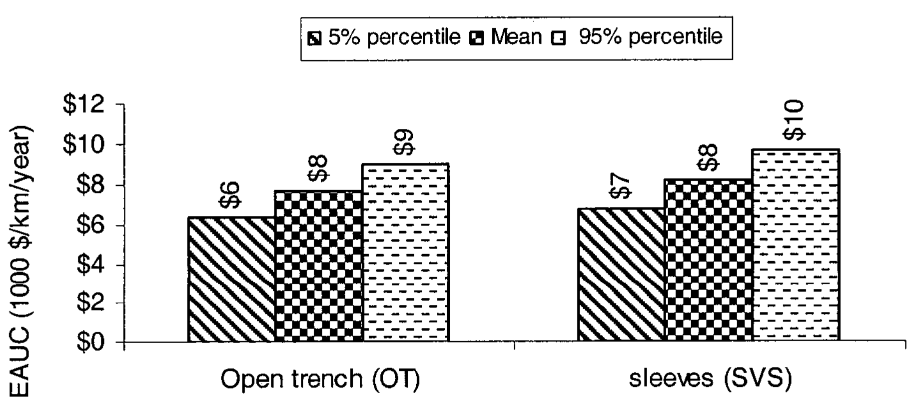


Figure 5.4 EAUC for repair only scenarios.

5.2.1.2 "Renovation Only" Category:

The histogram plot of the EAUC against scenarios is shown in Figure 5.5. The variation can be easily seen, from the relatively large size bars. Results of renovation using Slip lining showed a mean of 37,643 $/km/yr. CIPP, and Cement/ epoxy lining scenarios showed also that the mean is 44,235 $/km/yr (17.5% more than slip lining case), and 83,982$/km/yr (123% more than slip lining case) respectively. Table 5.7 shows the same data of figure 5.5 in tabular format.

The tornado graphs shown in figure 5.6 summarize the regression sensitivity for Slip lining, CIPP, and Cement/ epoxy lining respectively. It showed that the deterioration rate for the first break has the highest effect on the EUAC with a negative correlation coefficient with range of -0.28 to -0.072. The renovation technique costs and the discounted rate have significant positive correlation coefficient effects on the EUAC with range of 0.224 to 0.036. Other correlation values indicate a partial correlation; the output is affected by changes in the selected input, but may be affected by other variables as well. Based on the chi-squared fit statistic, "BESTFIT" program reports that each of the following probability functions can best fits the out put data for "renovation only" category : **Lognormal; Inv Gauss; Log Logistic.**

Table 5.7 EUAC Statistics for "renovation only" scenarios

Output		**EUAC Statistics ($/km/year)**				
category	**Name**	**Minimum**	**Mean**	**Maximum**	**5% percentile**	**95% percentile**
renovation only	slip lining (SL)	$13,056	$37,643	$1,682,250	$21,291	$57,889
	CIPP	$14,528	$44,235	$6,977,700	$24,284	$68,108
	cement/ epoxy (C/EL)	$15,839	$83,982	$82,377,800	$24,811	$130,978

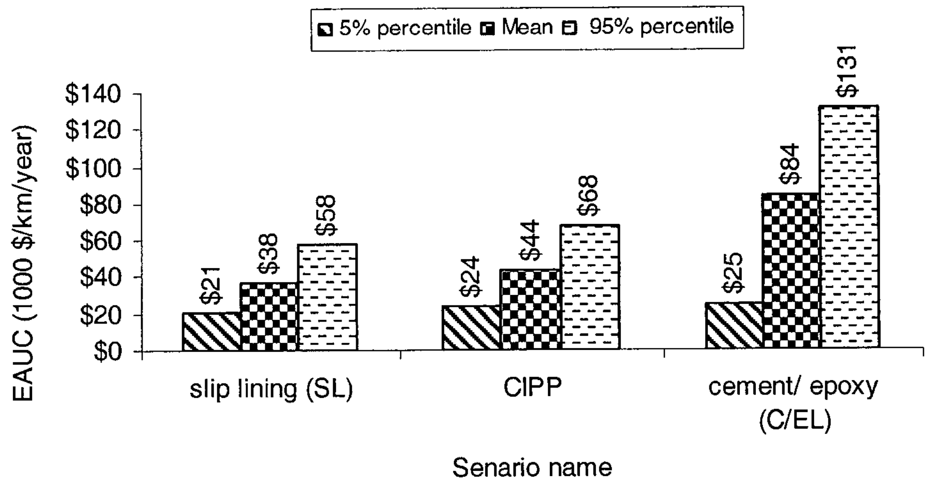


Figure 5.5 EAUC for "renovation only" scenarios.

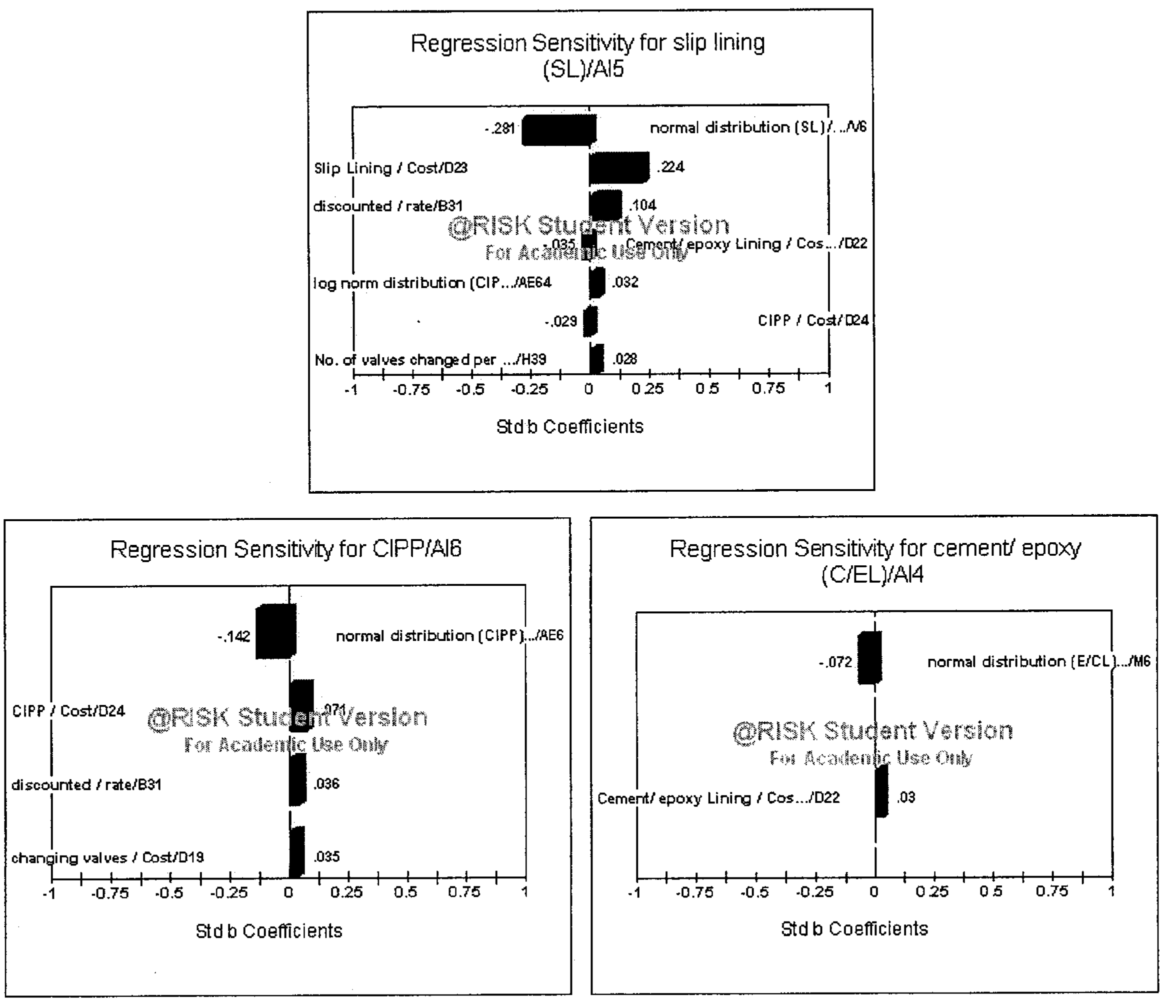


Figure 5.6 Regression Sensitivity for SL, CIPP and C/EL scenarios

5.2.1.3 "Replacement Only" Category:

EAUC of replacement scenarios are shown in Figure 5.7 and Table 5.8 where the values are sorted by mean then by 95% percentile confidence level. Replacement results using Pipe Bursting and Open Cut showed the least EAUC with a mean of 43,313 $/km/yr and 43,541 $/km/yr (0.5% more than Pipe Bursting case) respectively. Results of HDD and Microtuneling (MT) scenarios showed a higher EAUC with a mean of 68,226 $/km/yr (57% more than Pipe Bursting case), and 101,555 $/km/yr (134% more than Pipe Bursting case) respectively.

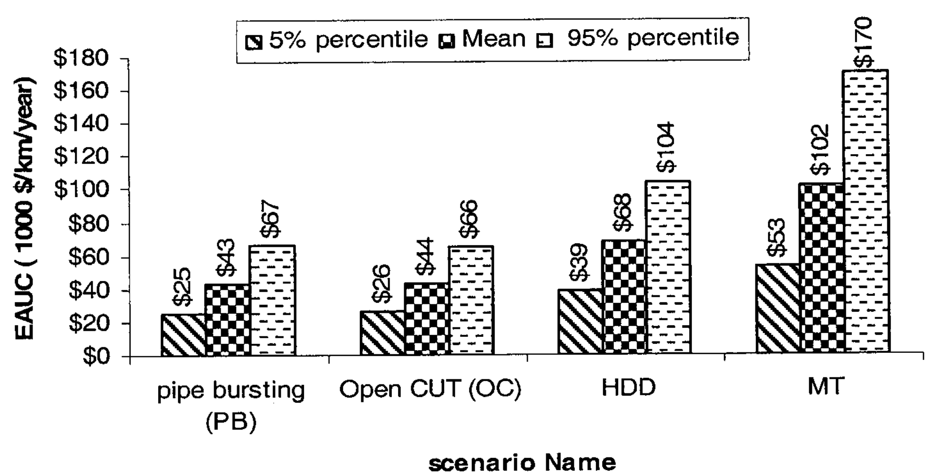


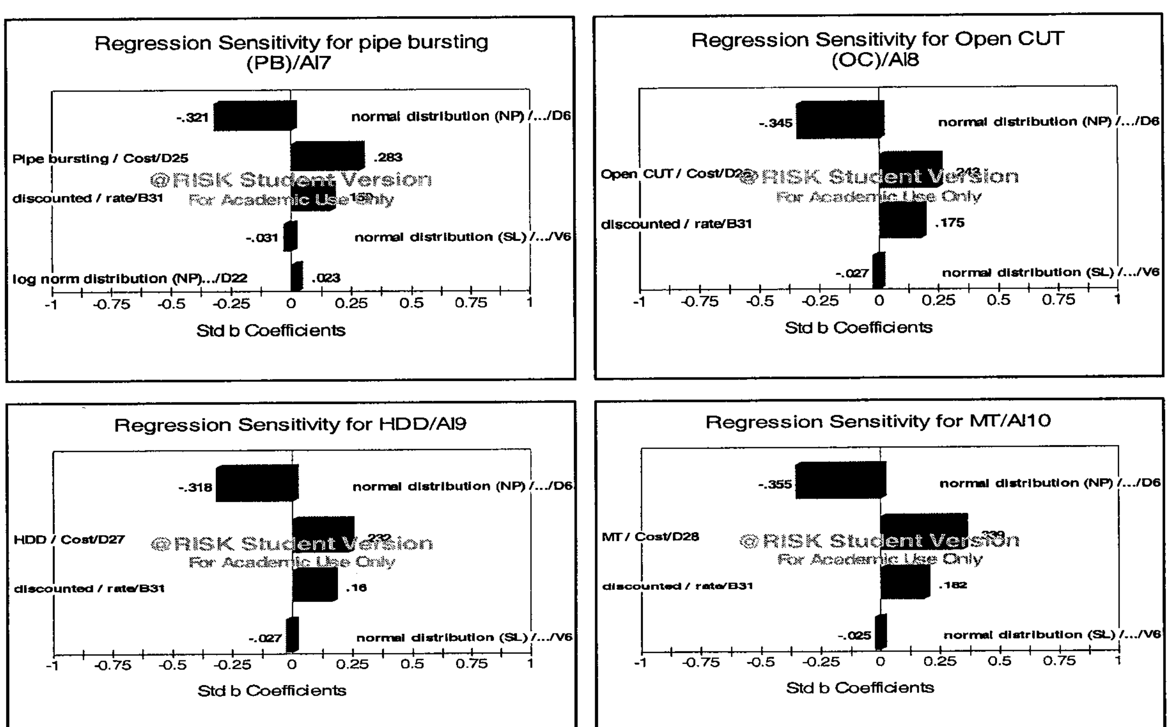
Figure 5.7 EAUC for "replacement only" scenarios.

Table 5.8 EUAC Statistics for "replacement only" scenarios

Output		EUAC Statistics ($/km/year)				
category	Name	Minimum	Mean	Maximum	5% percentile	95% percentile
Replacement only	pipe bursting (PB)	$16,972	$43,313	$1,537,724	$25,140	$66,605
	Open CUT (OC)	$17,089	$43,541	$1,336,039	$26,477	$65,523
	HDD	$24,366	$68,226	$2,659,836	$39,078	$104,343
	MT	$30,588	$101,555	$3,083,984	$53,236	$169,920

The summary of regression sensitivity for "Replacement Only" category is further indicated in figure 5.8. Showing that the deterioration rate for the first break has the highest effect on the EUAC with a negative correlation coefficient having a range of (-0.355 to -0.315). The replacement technique costs and the discounted rate have significant positive correlation coefficient effects on the EUAC with range of 0.339 to 0.159. Other correlation values indicate a partial correlation; the output is affected by changes in the selected input, but may be affected by other variables as well.

Based on the chi-squared fit statistic, "BESTFIT" program reports that each of the following probability functions can best fits the out put data for "replacement only" category: Log Logistic; Lognormal; Inv Gauss; Pearson5.



35 Figure 5.8 Regression Sensitivity for HDD and MT scenarios

5.2.1.4 "Repair & renovation" Category:

The cash flow for the repair with renovation scenarios can be explained as follows: the "OT-OT-OT-OT-C/EL" scenario means, that after the first, second, third, and fourth break there will be a repair with open trench (OT) method. After the fifth break, there will be a renovation with cement or epoxy lining (C/EL). Similarly, the cash flow for the scenario "SVS-SVS-SVS-SVS-SL" means that after the first, second, third, and fourth break there will be a repair using a sleeve (SVS) method. Subsequently after the fifth break there will be a renovation with slip-lining. The cash flow of the scenario "OT-OT-OT-CIPP" describes that after the first, second, and third break there will be a repair using an open trench (OT) method. After the fourth break, there will be a renovation with a curried in place pipe (CIPP).

The results of distribution and regression sensitivity analysis for repair with renovation category indicates that "OT-OT-OT-OT-SL" and "SVS-SVS-SVS-SVS-SL" scenarios have yielded the minimum EAUC. The mean is 23,649 $/km/yr and 23,830 $/km/yr (0.77% more than "OT-OT-OT-OT-SL" case) respectively. The regression sensitivity for theses scenarios showed that slip lining has the highest effect on the EUAC with a positive correlation coefficient in the range of 0.756 to 0.753. Followed by the deterioration rate of slip lining service life, and the timing of the first, second, third, and fourth break have significant negative correlation coefficient effects on the EUAC with a range of -0.379 to -0.191. The discounted rate has significant positive correlation coefficient effects on the EUAC (0.192). Other correlation values indicate a partial correlation; the output is affected by changes in the selected input, but may be affected by other variables as well. The summary of information and statistics are further indicated in Figure 5.9.

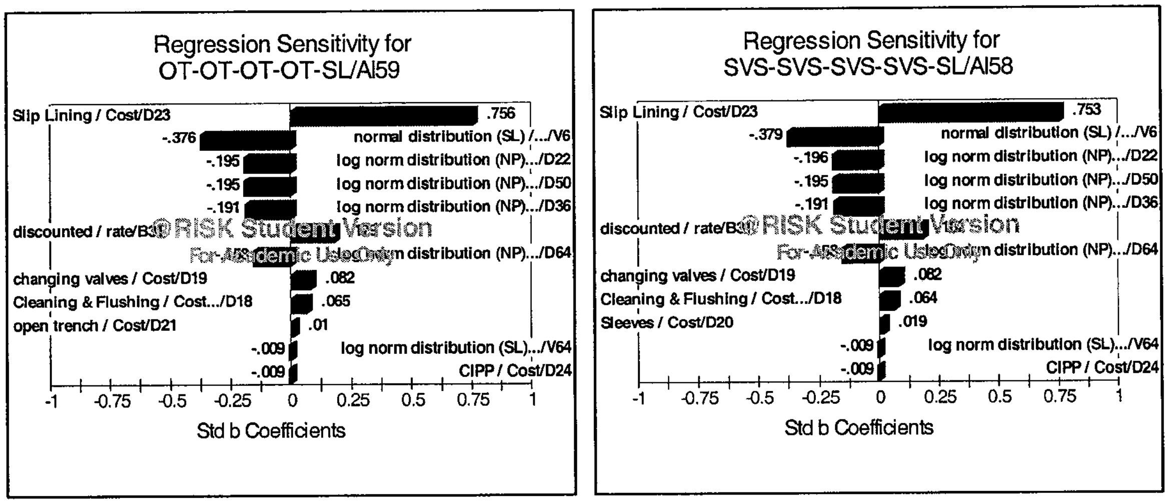


Figure 5.9 Regression Sensitivity of "OT-OT-OT-OT-SL" and "SVS-SVS-SVS-SVS-SL" scenarios

Figure 5-10 shows a comparison graph that superimposes the output data and fitted distribution for "OT-OT-OT-OT-SL" and "OT-OT-OT-OT-C/EL" scenarios on the same graph, allowing for a direct visual comparison. This graph allows you to determine if the fitted distribution matches the output data in specific areas. For example, it may be important to have a good match around the mean or in the tails. In addition, the Figure shows the Probability-Probability (P-P) graph that plots the distribution of the input data (*Pi*) vs. the distribution of the best fit function result (*F(xi)*). If the fit is "good," the plot will be nearly linear.

Based on the chi-squared fit statistic, the BESTFIT program reports that each of the following probability functions best fits the output data for "OT-OT-OT-OT-SL" scenario: **Log-Logistic** (4107.3, 18844, 6.0164); **Inv Gauss** (22870, 375281, Shift(815.44)); **Weibull** (2.2395, 13404, Shift(11815)); and **Beta General** (4.0811, 14.196, 10515, 69502). The probability functions that best fits the output data for the "OT-OT-OT-OT-C/EL" scenario: **Lognormal** (16176, 7585.1, Shift (8105.4)); **Inv Gauss** (16816, 84600, Shift (7470.4)); **Log Logistic** (9311.7, 13364, 3.5726); and **Beta General** (2.1951, 6.8174, 11098, 66476).

"OT-OT-OT-OT-SL" scenario **"OT-OT-OT-OT-C/EL" scenario**

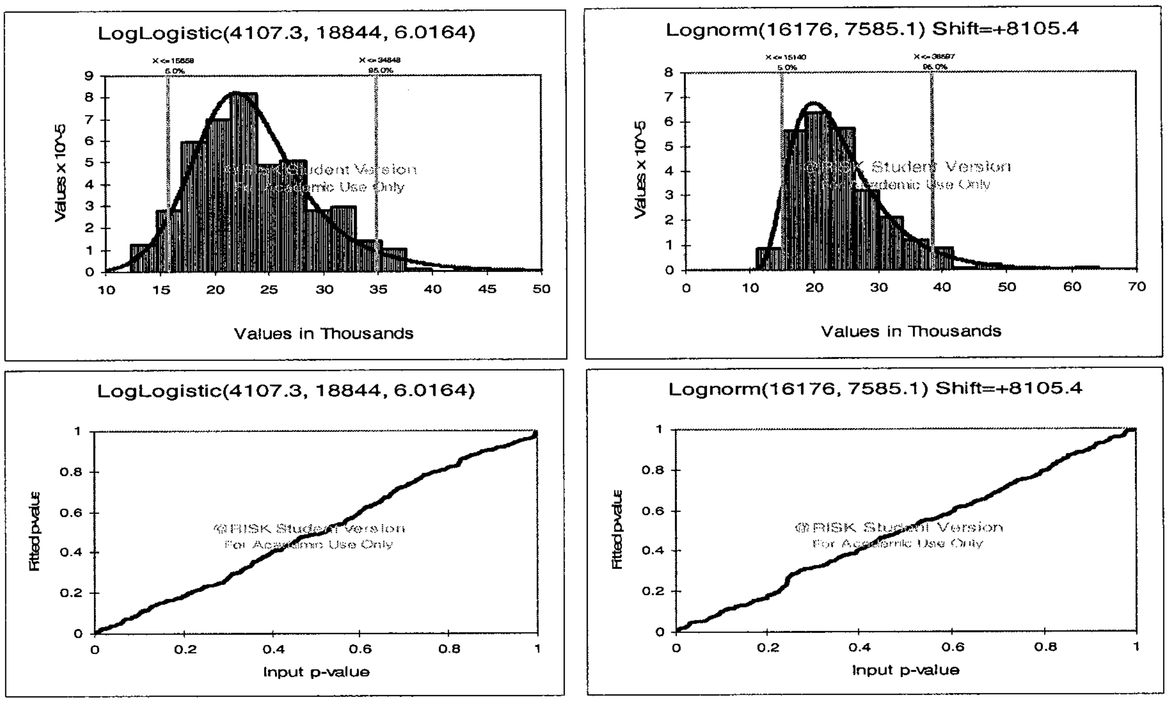


Figure 5.10 Comparison & (P-P) graph for "repair & renovation" category

Table 5.9 shows the EAUC statistics for "repair with renovation" category, where the values are sorted by the mean then by the 95% percentile confidence level. Results showed that scenarios "OT-OT-OT-OT-C/EL" and "OT-OT-OT-SL" has a mean EAUC higher than "OT-OT-OT-OT-SL" scenario by 2.3 % and 7.4 % respectively. While the maximum EAUC was established by "SVS-CIPP" and "SVS-C/EL" scenarios with mean higher than "OT-OT-OT-OT-SL" scenario by a 52 % and 64 % respectively.

BESTFIT program reports that each of the following probability functions can best fit the out put data for repair with renovation category: **Beta General, Log Logistic,** and **Inv Gauss.**

Table 5.9 EUAC Statistics for "repair with renovation" scenarios

Output		EUAC Statistics ($/km/year)				
Cate-gory	**Name**	**Minimum**	**Mean**	**Maximum**	**5% percentile**	**95% percentile**
repair & renovation	OT-OT-OT-OT-SL	$11,140	$23,649	$81,600	$15,873	$33,928
	SVS-SVS-SVS-SVS-SL	$11,313	$23,830	$83,240	$16,019	$34,138
	OT-OT-OT-OT-C/EL	$9,931	$24,184	$80,919	$15,074	$37,134
	SVS-SVS-SVS-SVS-C/EL	$10,051	$24,447	$81,299	$15,265	$37,550
	OT-OT-OT-SL	$11,545	$25,405	$96,583	$16,740	$37,035
	SVS-SVS-SVS-SL	$11,685	$25,551	$98,043	$16,838	$37,228
	OT-OT-OT-C/EL	$10,153	$26,948	$102,448	$16,190	$42,973
	OT-OT-OT-OT-CIPP	$10,488	$26,957	$79,055	$17,613	$39,618
	SVS-SVS-SVS-SVS-CIPP	$10,595	$27,138	$80,075	$17,817	$39,736
	SVS-SVS-SVS-C/EL	$10,261	$27,171	$102,808	$16,358	$43,219
	OT-OT-SL	$11,901	$27,689	$115,913	$17,790	$41,111
	SVS-SVS-SL	$12,005	$27,795	$117,102	$17,901	$41,227
	OT-OT-OT-CIPP	$10,799	$29,055	$107,635	$18,600	$42,784
	SVS-SVS-SVS-CIPP	$10,895	$29,201	$107,685	$18,743	$43,113
	OT-OT-C/EL	$12,219	$30,947	$126,560	$17,859	$51,736
	SVS-SVS-C/EL	$12,305	$31,121	$126,863	$17,990	$52,044
	OT-SL	$12,777	$31,159	$205,233	$19,438	$47,317
	SVS-SL	$12,790	$31,218	$205,666	$19,471	$47,335
	OT-OT-CIPP	$13,751	$31,785	$131,877	$19,911	$47,679
	SVS-SVS-CIPP	$13,764	$31,891	$131,918	$20,006	$47,800
	OT-CIPP	$14,019	$35,920	$175,524	$21,797	$55,394
	SVS-CIPP	$14,026	$35,979	$175,551	$21,844	$55,469
	OT-C/EL	$13,908	$38,691	$280,008	$20,356	$70,195
	SVS-C/EL	$13,963	$38,801	$280,335	$20,426	$70,410

5.2.1.5 "Repair & Replacement" Category:

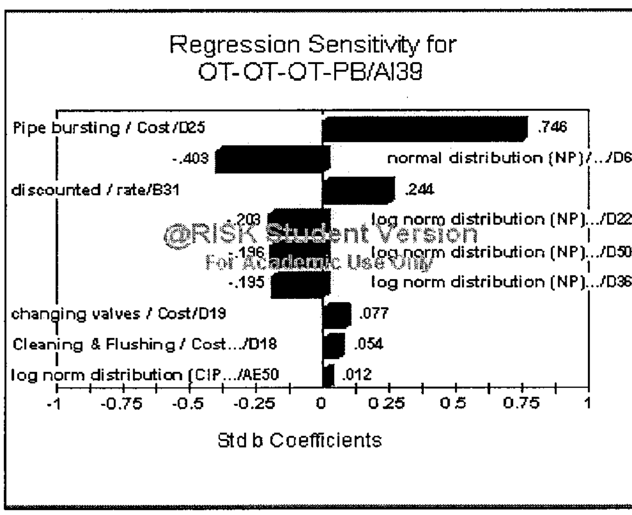
Table 5.10 shows the EAUC statistics data tabular format where the values are sorted by the mean then by the 95% percentile confidence level. "OT-OT-OT-PB" scenario has yielded the minimum EAUC for this category, and "SVS- SVS-SVS-PB" and "OT-OT-OT-OC" scenarios have a higher mean than "OT-OT-OT-PB" by 0.5 % and 0.7 % respectively. So these three scenarios are considered the similar or the same. While "OT-HDD" and "SVS-HDD" has the highest EAUC for this category, having mean higher than "OT-OT-OT-PB" by 92 % and 92.2 % respectively.

Regarding "OT-OT-OT-PB" scenarios regression sensitivity in figure 5.11 showed that the replacement technique costs – pipe bursting has the highest effect on the EUAC with a positive correlation coefficient of 0.746. Followed by the deterioration rate of pipe bursting service life, and the timing of the first, second, and third break have significant negative correlation coefficient effects on the EUAC with range of -0.403 to -0.195. The discounted rate has significant positive correlation coefficient effects on the EUAC of 0.244. Other correlation values indicate a partial correlation; the output is affected by changes in the selected input, but may be affected by other variables as well.

"BESTFIT" program reports that each of the following probability functions can best fit the out put data for repair with replacement category: **Beta General, Weibull, Logistic,** and **Inv Gauss.**

Table 5.10 EUAC Statistics for "repair with replacement" scenarios

Output		EUAC Statistics ($/km/year)				
category	**Name**	**Minimum**	**Mean**	**Maximum**	**5% percentile**	**95% percentile**
Repair & Replacement	OT-OT-OT-PB	$13,335	$29,306	$72,800	$19,355	$42,378
	SVS-SVS-SVS-PB	$13,418	$29,451	$72,779	$19,488	$42,535
	OT-OT-OT-OC	$13,064	$29,505	$108,477	$20,043	$41,946
	SVS-SVS-SVS-OC	$13,159	$29,650	$108,622	$20,190	$42,225
	OT-OT-PB	$15,338	$32,045	$103,223	$20,712	$47,142
	SVS-SVS-PB	$15,385	$32,151	$104,055	$20,791	$47,311
	OT-OT-OC	$15,950	$32,264	$122,032	$21,638	$46,765
	SVS-SVS-OC	$15,927	$32,369	$122,142	$21,711	$46,971
	OT-PB	$16,459	$36,229	$171,638	$22,499	$54,715
	SVS-PB	$16,489	$36,287	$172,131	$22,543	$54,840
	OT-OC	$16,335	$36,473	$191,223	$23,713	$53,729
	SVS-OC	$16,323	$36,532	$191,308	$23,776	$53,792
	OT-OT-OT-HDD	$17,854	$44,551	$128,795	$28,663	$64,872
	SVS-SVS-SVS-HDD	$17,905	$44,696	$129,019	$28,772	$65,031
	OT-OT-HDD	$22,118	$49,208	$142,149	$31,003	$72,346
	SVS-SVS-HDD	$22,257	$49,313	$142,148	$31,084	$72,493
	OT-HDD	$22,997	$56,273	$336,418	$34,519	$85,177
	SVS-HDD	$22,985	$56,331	$336,911	$34,560	$85,229



Sensitivity			
Rank	**Name**	**Regr**	**Corr**
#1	Pipe bursting / Cost / D	0.746	0.783
#2	normal distribution (NP) /	-0.403	-0.351
#3	discounted / rate / B31	0.244	0.242
#4	log norm distribution (NP)	-0.203	-0.218
#5	log norm distribution (NP)	-0.196	-0.181
#6	log norm distribution (NP)	-0.195	-0.158
#7	changing valves / Cost /	0.077	0.094
#8	Cleaning & Flushing / Cos	0.054	0.044
#9	log norm distribution (CIP	0.012	-0.010
#10	normal distribution (E/CL)	0.000	-0.010
#11	normal distribution (SL) /	0.000	-0.002
#12	normal distribution (CIPP)	0.000	0.002
#13	log norm distribution (E/C	0.000	-0.005
#14	log norm distribution (SL)	0.000	-0.009
#15	log norm distribution (CIP	0.000	0.017
#16	log norm distribution (E/C	0.000	-0.025

38 Figure 5.11 Regression sensitivity for "OT-OT-OT-PB" scenarios

5.2.1.6 Renovation & replacement Category:

The EAUC Statistics for renovation with replacement category are summarized in table 5.11 where the values are sorted by the mean then by the 95% percentile confidence level. "SL-PB" scenario has yielded the minimum EAUC for this category. While "SL-OC" and CIPP-PB" scenarios showed a higher mean than "SL-PB" by 0.12 % and 12 % respectively. The following probability functions can best fit the out put data: **Beta General, Weibull, Logistic,** and **Inv Gauss.**

Table 5.11 EUAC Statistics for "renovation with replacement" scenarios

Output		EUAC Statistics ($/km/year)				
category	**Name**	**Minimum**	**Mean**	**Maximum**	**5% percentile**	**95% percentile**
renovation & replacement	SL-PB	$16,881	$36,456	$128,160	$23,760	$53,336
	SL-OC	$16,695	$36,498	$116,569	$24,009	$53,257
	CIPP-PB	$16,323	$40,823	$265,490	$26,119	$59,909
	CIPP-OC	$17,372	$40,922	$292,289	$26,100	$60,294
	SL-HDD	$18,112	$41,816	$154,432	$27,393	$62,011
	C/EL- PB	$20,030	$43,847	$172,347	$28,137	$65,188
	C/EL- OC	$18,086	$43,982	$150,640	$28,857	$65,264
	CIPP-HDD	$19,781	$46,222	$392,903	$29,763	$68,593
	C/EL- HDD	$22,920	$57,313	$278,075	$36,264	$87,015

5.2.1.7 Summary of Cast Iron Analysis for 6"-24" Diameter Range

Top minimum 20 scenarios are summarized in Figure 5.12. They show that the minimum EAUC is for the repair scenarios, followed by repair with renovation and finally by repair with replacement. The top five maximum alternatives summarized in Figure 5.13 showed that the highest EAUC was for the scenario of replacement only. Figures 5.12 and 5.13 compare the cumulative probability distributions for some scenarios from the top twenty. It can be seen that in repair scenarios, the open trench has a lower cost than the sleeve one.

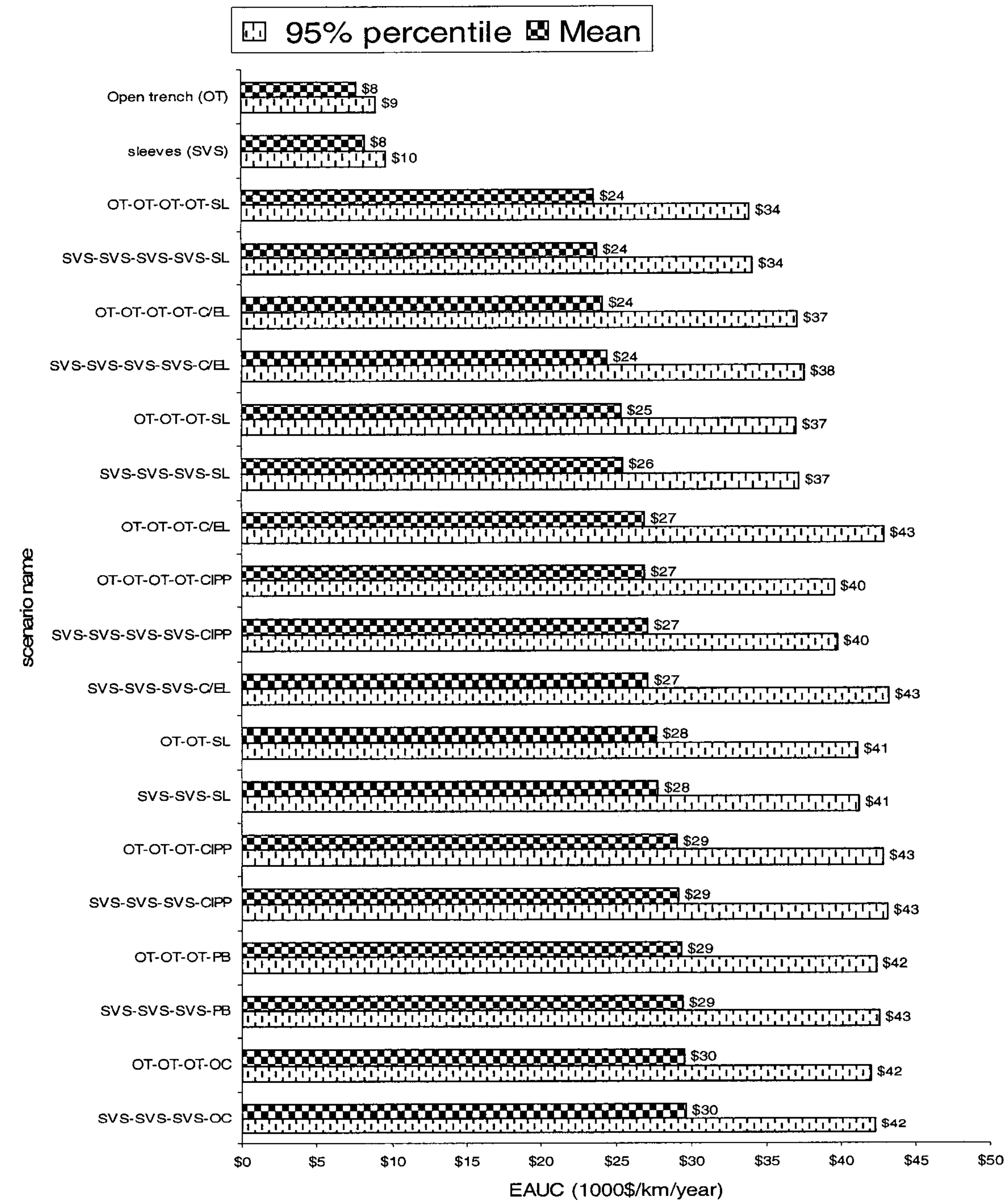


Figure 5.12 Top twenty minimum scenarios for cast iron with diameter range 6"-24"

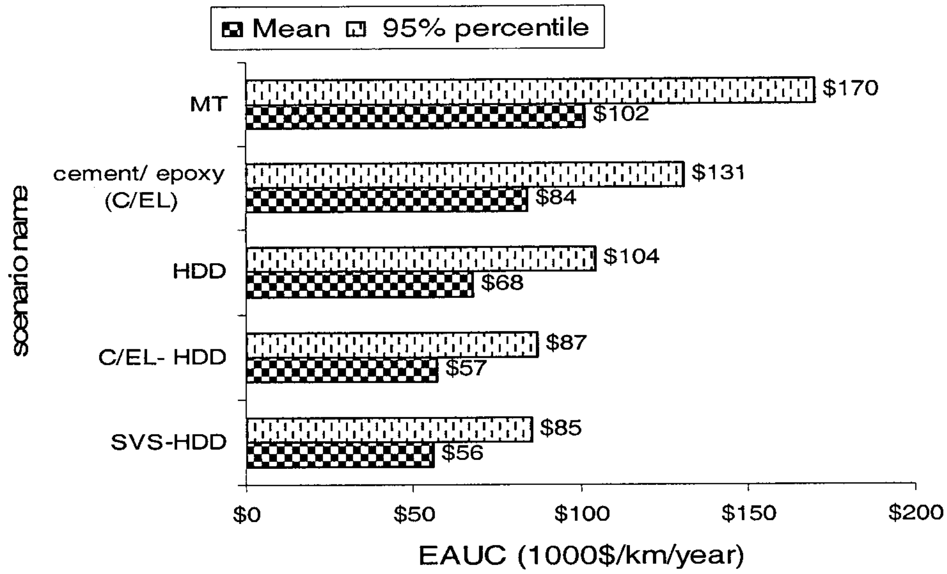


Figure 5.13 Top five maximum scenarios for cast iron with diameter range 6"-24"

The cumulative probability distribution for Open trench (OT) versus Sleeves (SVS) scenarios is shown in figure 5.14. As the super imposed cumulative distribution for both scenarios doesn't intersect then we can easily state that Open trench always encounters a lower EAUC than sleeves,

The cumulative graph as illustrated in Figure 5.15 shows that the probability of "OT-OT-OT-OT- SL" scenario might have higher EAUC values over "OT-OT-OT-OT-E/CL" is 40%. However, OT-OT-OT-OT-SL scenario has a lower EAUC than all other scenarios. The same figure shows that there is a 70.5% probability that the "OT-OT-OT-OC" scenario will have larger EAUC values than scenario "OT-OT-OT-PB".

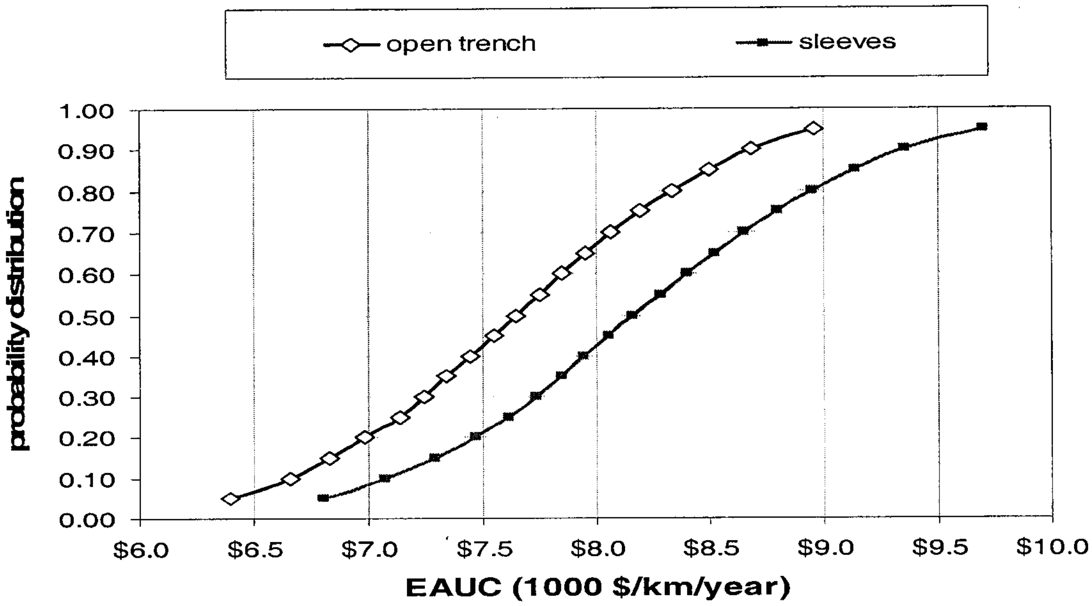
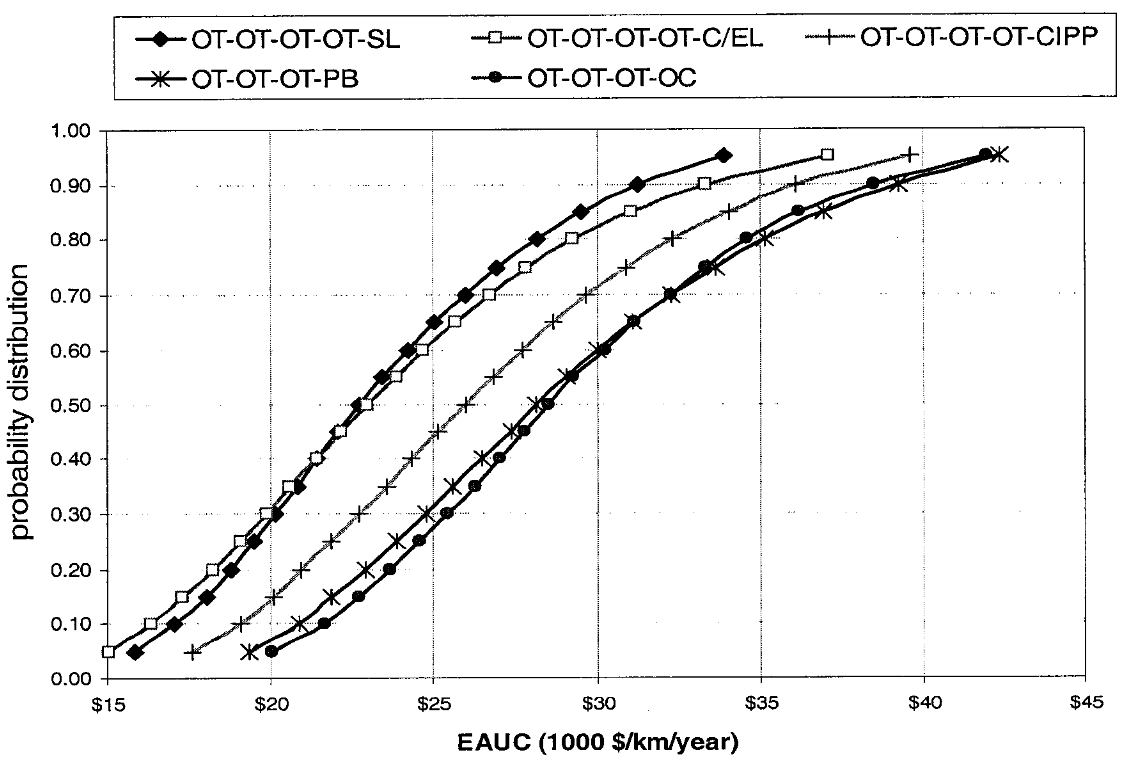


Figure 5.14 Cumulative probability distribution of "OT" and "SVS" scenarios for cast iron 6" -24" diameter



42 Figure 5.15 Cumulative probability distribution for some scenarios of cast iron 6" -24" diameter

5.2.1.8 Summary of Cast Iron Analysis for 30"- 42" Diameter Range

Figure 5.16 illustrates the minimum 20 scenarios of cast iron mains with a diameter range 30"-42". The figure showed a higher EAUC ranging from 30% to 501% higher than the previous diameter range. Also the minimum EAUC was for repair only category. Generally most of the "repair with renovation" scenarios has a lower EAUC than "repair with replacement" ones. On the other hand, the maximum five alternatives are summarized in figure 5.17 showed that the highest EAUC was for "replacement only" scenarios.

Figure 5.18 shows a super imposed cumulative probability graph of "OT-OT-OT-OT- SL", "OT-OT-OT-OT-E/CL", "OT-OT-OT-OT-CIPP", "OT-OT-OT -OC", and "OT-OT-OT-PB" scenarios. The graph shows that the probability of "OT-OT-OT-OT- SL" scenario might have a larger EAUC than Scenario "OT-OT-OT-OT-E/CL" by 8.5 %, and it always yields a lower EAUC than all other scenarios. Also the probability that Scenario "OT-OT-OT-OT- OC" might have a larger EAUC than Scenario "OT-OT-OT-OT-E/CL" by 70 %.

Based on figure 5.18 we can prove that the Slip lining renovation technique is relatively cost effective than other renovation or replacement techniques. By comparing figure 5.18 vs. 5.15, we can conclude that as diameter increase the EAUC of renovation technique increase and the EAUC of Open cut and pipe bursting decrease. Also we can prove that as diameter increase the open cut method yields a lower EAUC over pipe bursting technique.

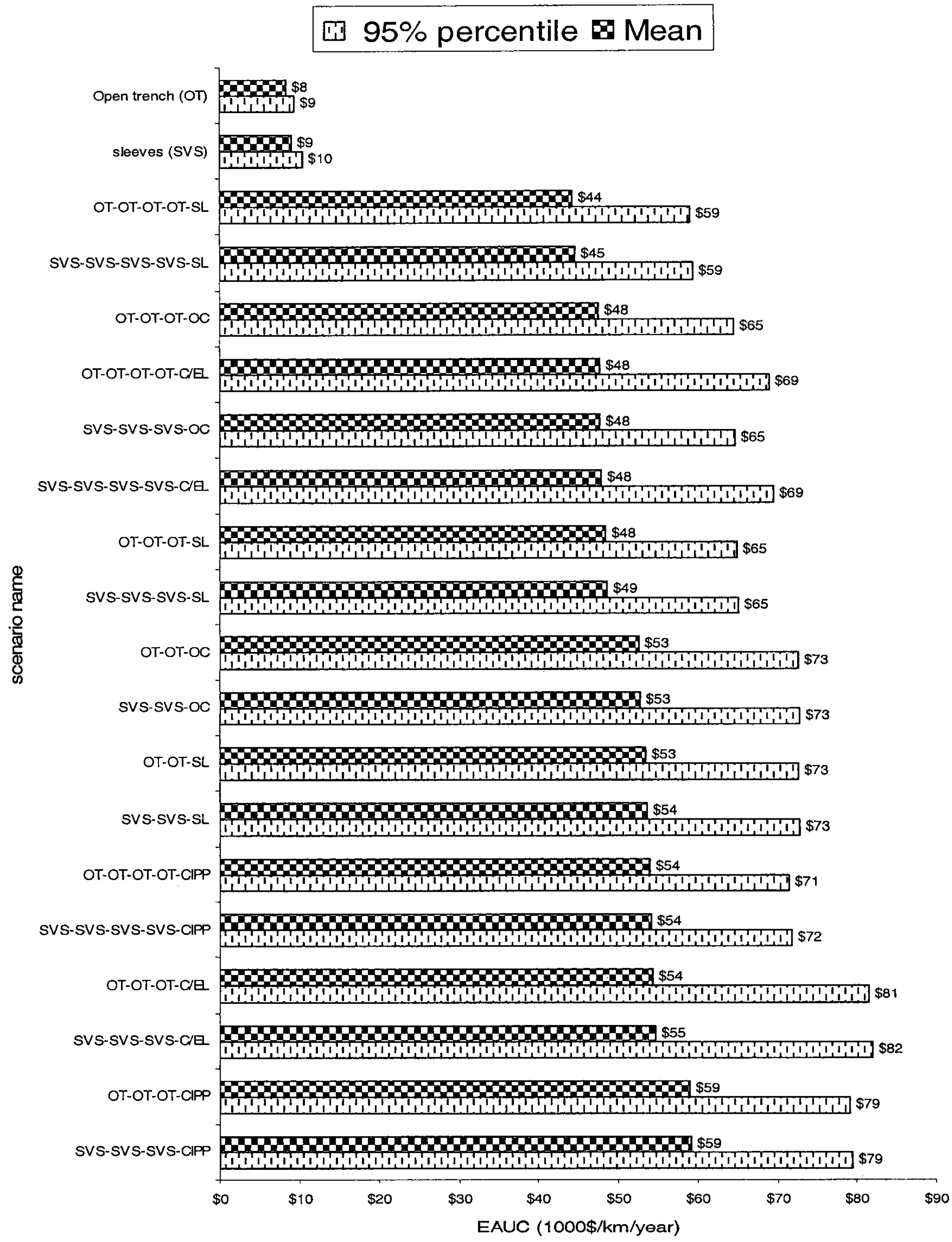


Figure 5.16 Top twenty minimum scenarios for cast iron, diameter range 30"-42"

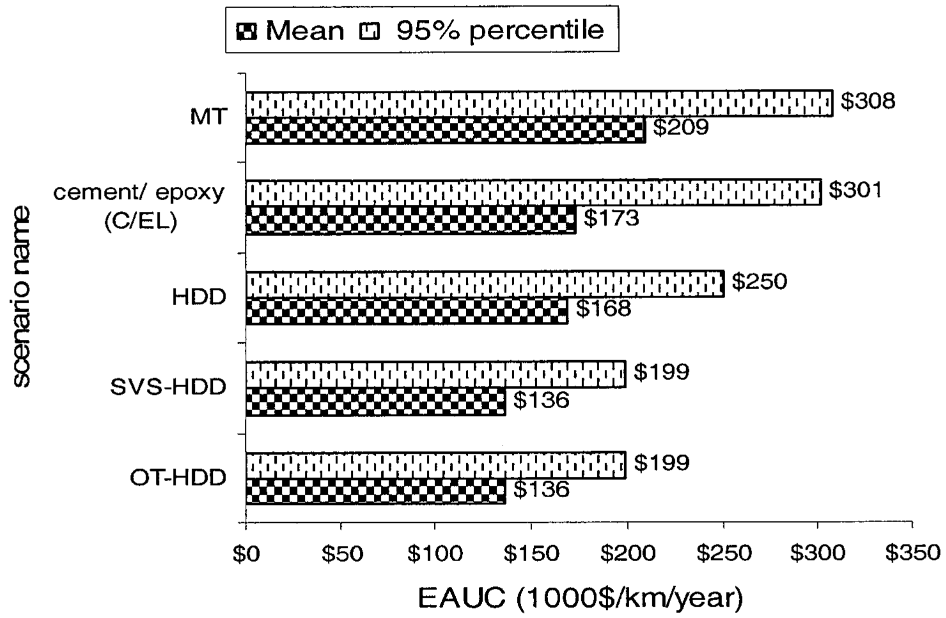


Figure 5.17 Top five maximum scenarios for cast iron, diameter range30”-42”

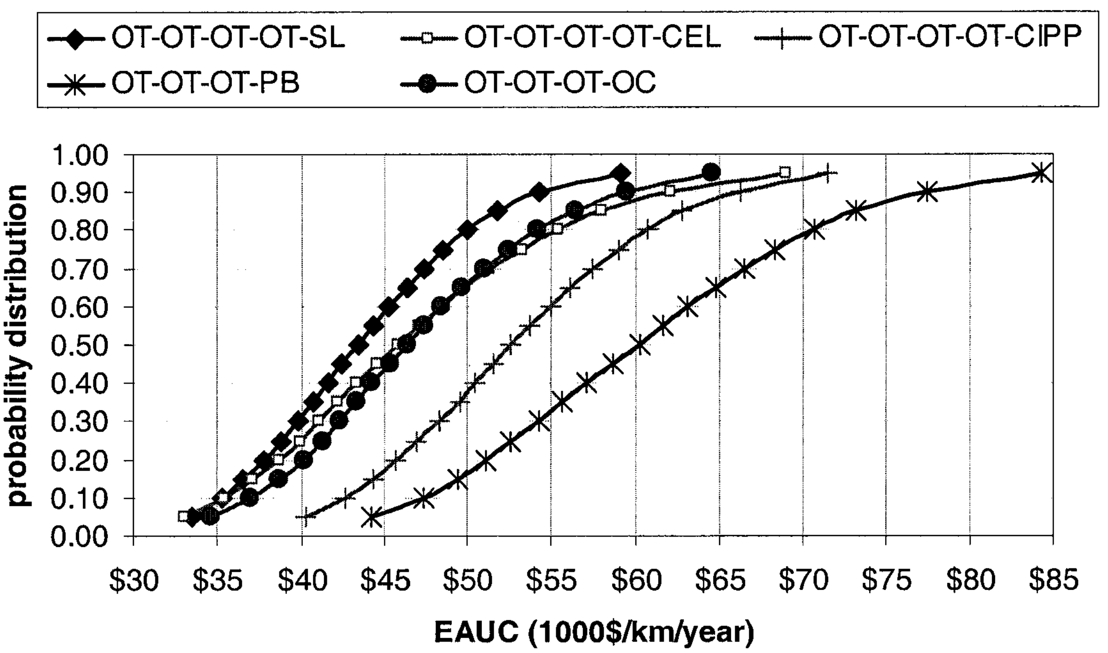


Figure 5.18 Cumulative probability distribution for some scenarios of cast iron 30”-42” diameter

5.2.1.9 Summary of Cast Iron Analysis for (42"- Above) Diameter Range

The top minimum 20 scenarios are summarized in Figure 5.19. They showed that the minimum EAUC was generally for repair scenarios, then followed by some repair with replacement scenario then by repair with renovation one. On the other hand, the top five maximum alternatives summarized in figure 5.20 showed that the highest EAUC was for the scenario of replacement only.

From figure 5.21, the minimum EAUC is for "OT-OT-OT-OC" but the probability of "OT-OT-OT-OC" scenario might have a larger EAUC than Scenario "OT-OT-OT-OT-E/CL" & "OT-OT-OT-OT-SL" is 12.5 %, and it always yields a lower EAUC than all other scenarios. Also the probability that Scenario "OT-OT-OT-OT- SL" might have a larger EAUC than Scenario "OT-OT-OT-OT-E/CL" by 20 %.

Comparing the results of (42" and above) vs. (30"-42") and (6"- 24") diameter ranges, found that as diameter increase the EAUC increase ranging from 20% to 40% Over (30"-42") range and ranging from 50% to 67% over (6"- 24") range. Also the open cut technique proved to be the most cost efficient technique for large diameter pipes. On the other hand Pipe bursting technique yields a higher EAUC for large diameter than small ones.

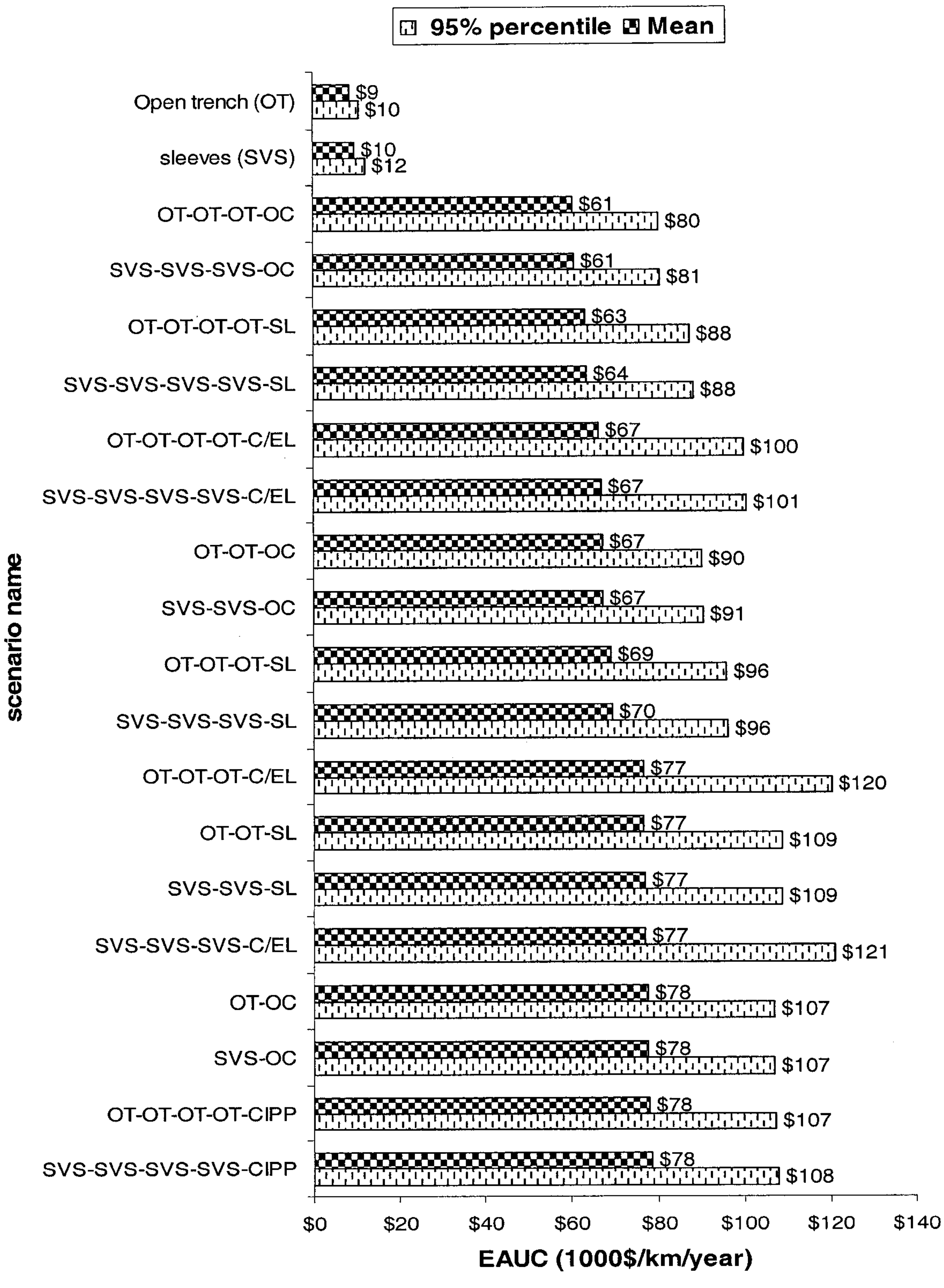


Figure 5.19 Top twenty minimum scenarios for cast iron with diameter range 42"& above

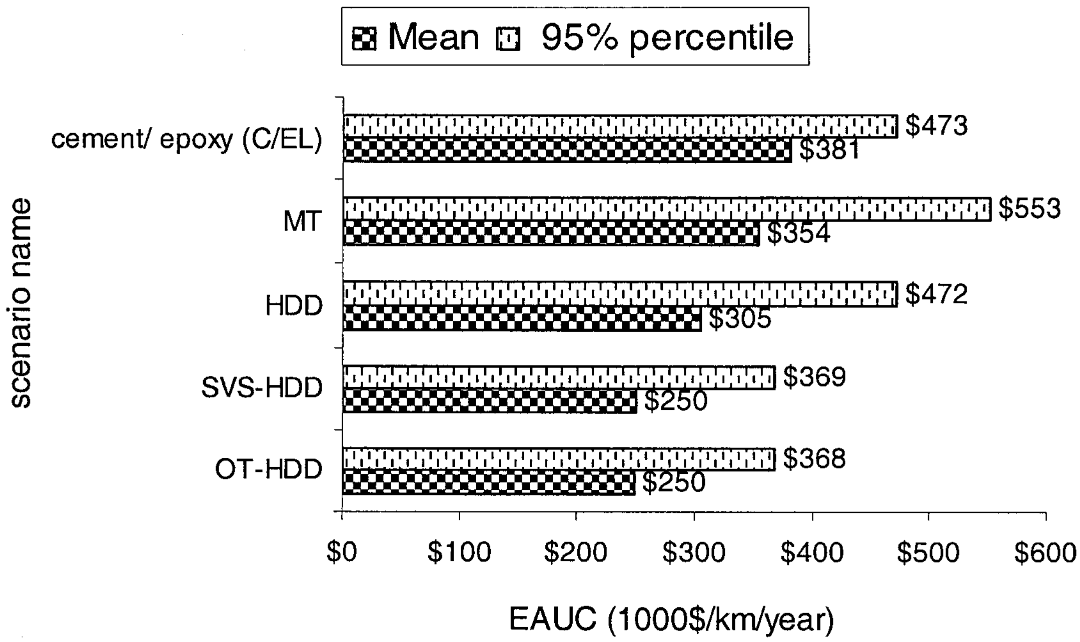


Figure 5.20 Top five maximum scenarios for cast iron with diameter range (42"& above)

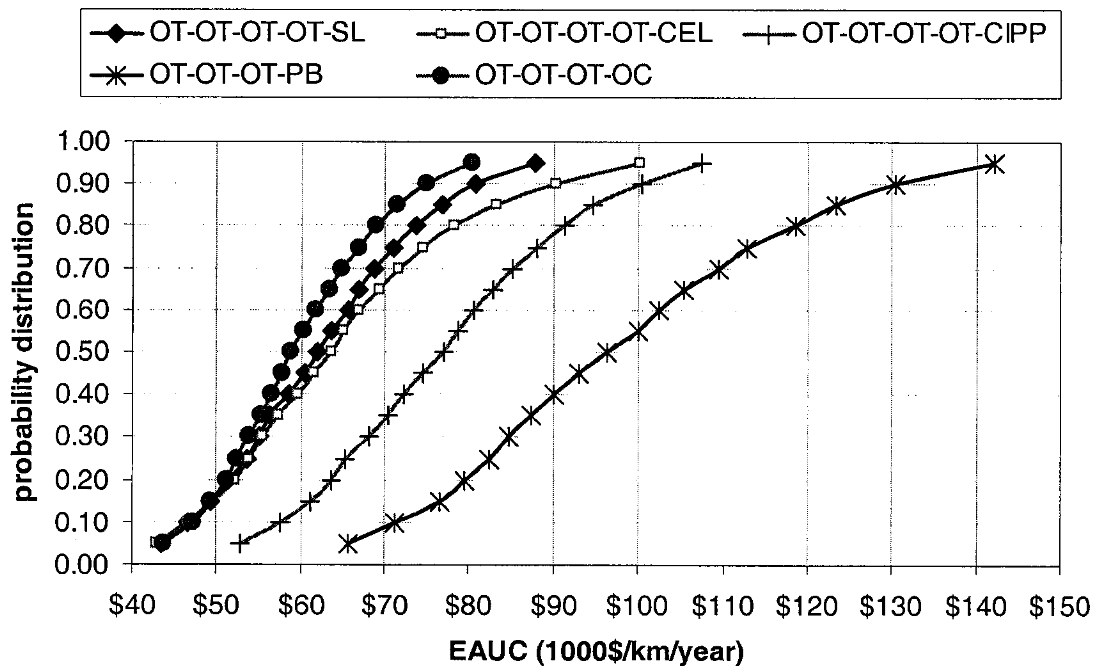


Figure 5.21 Cumulative probability distribution for some scenarios of cast iron (42"& above) diameter range

5.2.2 New installation Project(s) for Cast Iron Pipe

This section deals with a comparison of new installation costs for a cast iron pipe with diameter ranging from 6" to 24". The alternatives used for new installation project(s) are Pipe Bursting, Open Cut, Horizontal Directional Drilling, and Microtunneling. The main scenarios were selected according to the alternative shown in this table. The number of suggested scenarios was predefined to the program as eight scenarios as shown in Appendix C. The scenarios are developed in two main categories using normal pipe or initial cemented pipe. A selected sample of EUAC and the output statistics are summarized in the following tables and charts. All costs for the EUAC are in ($/km/year).

Input Data

The input data are composed of the costs (operation and maintenance cost, new installation alternatives cost), the deterioration rate (the service life of pipe) and the discounted rate. The costs are entered in a triangular probability distribution function with the minimum, most likely, and maximum cost. For both service life and discounted rate, input data are entered using a normal and log normal probability distribution function with the mean (μ), and standard deviation (σ). The input data were collected based on the methods used in data collection section explained in chapter 3. Tables 5.12, 5.13 and 5.14 indicate typical input cost data for 6" to 24" diameter pipes. All costs were in $/km length. The program is then executed and sensitivity analyses are carried out.

Table 5.12 Typical input cost data for 6”-24” diameter Cast Iron pipes.

Classes	Description	minimum	most likely	maximum	Unit cost
Operation & maintenance	Cleaning & Flushing	$3,000	$4,500	$4,950	$/km
	changing valves	$1,250	$2,500	$4,000	$/km
Replacement	Pipe bursting	$260,000	$460,000	$900,000	$/km
	Open CUT	$300,000	$470,000	$850,000	$/km
	HDD	$450,000	$850,000	$1,400,000	$/km
	MT	$700,000	$1,000,000	$2,500,000	$/km
	Initial cement lining	$100,000	$200,000	$400,000	$/km

Table 5.13 Probability and number of changed valves for a 6”-24” diameter Cast Iron pipes

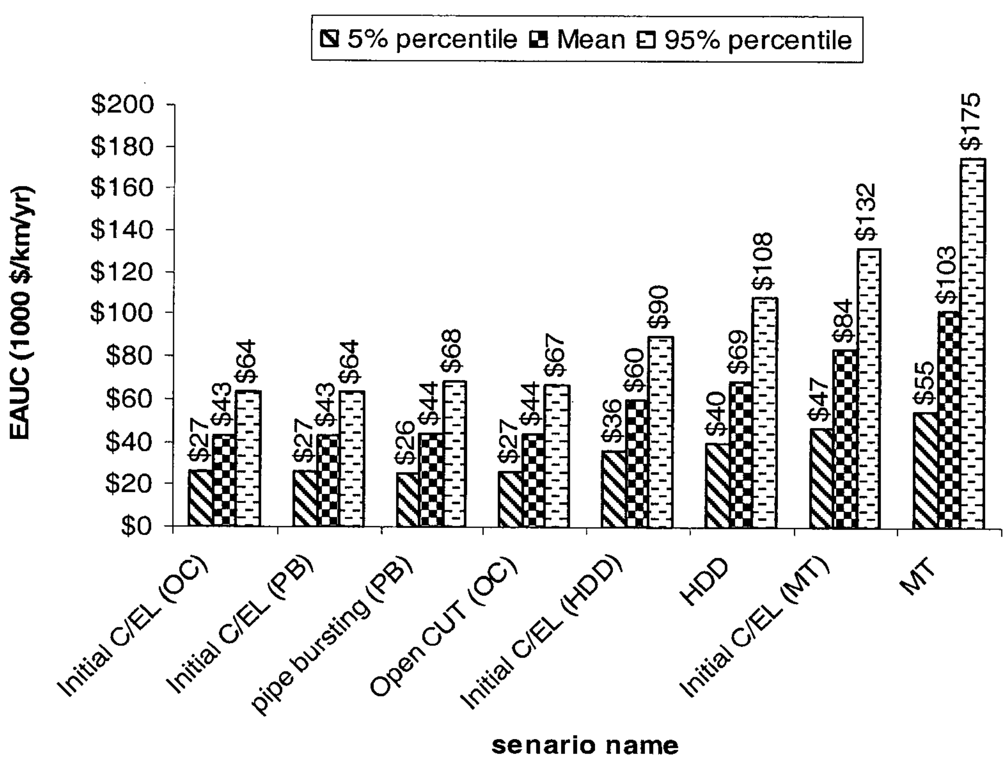
Total no. of valves per km	No. of valves changed per year		
	min	most likely	max
5	0	1	2

Table 5.14 Typical input deterioration data for a 6”-24” diameter Cast Iron pipes

	Time In Years				
Service life	Mean (μ)	standard deviation (σ)	Truncated Minimum	Truncated maximum	Function type
New Pipe	30	10	0	100	Normal
Initial cement lined pipe	60	15	0	150	Normal
discounted rate	4.50%	1.30%	1%	8%	Normal

OUTPUT INFORMATION

After defining the input variables, the simulation parameters are set to perform 5000 iterations using a Monte Carlo sampling simulation. The total numbers of the suggested scenarios were predefined to the program as eight scenarios. A histogram plot of the EAUC versus scenario type is shown in Figure 5.22. It showed that the Initial C/EL (OC) and Initial C/EL (PB) has the minimum EAUC among all scenarios. This is followed by the pipe bursting method then the open cut method. The Microtunneling technique yielded the maximum EAUC among all new installation scenarios. Table 5.15 shows the same data as in Figure 5.22 in tabular form.



49

Figure 5.22 EAUC for the new installation scenarios 6" to 24"

Table 5.15 EUAC Statistics new installation scenarios

Output	EAUC Statistics ($/km/yr)				
Name	Minimum	Mean	Maximum	5% percentile	95% percentile
Initial C/EL (OC)	$16,249	$43,135	$92,357	$26,803	$63,621
Initial C/EL (PB)	$14,729	$43,142	$99,242	$26,612	$63,864
pipe bursting (PB)	$16,430	$43,758	$765,288	$25,587	$68,312
Open CUT (OC)	$15,939	$43,790	$809,819	$26,640	$67,062
Initial C/EL (HDD)	$21,212	$60,175	$133,547	$36,251	$89,767
HDD	$23,727	$68,503	$1,255,333	$39,505	$108,267
Initial C/EL (MT)	$25,916	$83,545	$201,317	$46,747	$131,927
MT	$30,833	$102,562	$1,855,286	$54,526	$175,109

The results of a distribution and regression sensitivity for new installation - Initial C/EL (OC) and Initial C/EI (PB) scenarios are shown in Figure 5.23. The output distribution worksheets provide probability distribution, cumulative functions and regression sensitivity graphs. The regression sensitivity graphs describe how input affects output. For example, the input changing valves has a positive effect on the output alternative. A correlation coefficient value of 1 would indicate a complete positive correlation between two variables. A value of -1 would indicate a complete inverse correlation between two variables. The value of 0 would indicate that there is no correlation between variables.

The output results of new installation using Initial C/EL (OC) and Initial C/EL (PB) showed that the mean is slightly below 43,135 $/km/yr and 43,142 $/km/yr. The regression sensitivity showed that the new installation technique cost, the initial cement lining cost and the discounted rate have significant positive correlation coefficient effects on the EUAC with a range of 0.793 to 0.264. Other correlation values indicate a partial correlation; the output is affected by changes in the selected input, but may be affected by other variables as well.

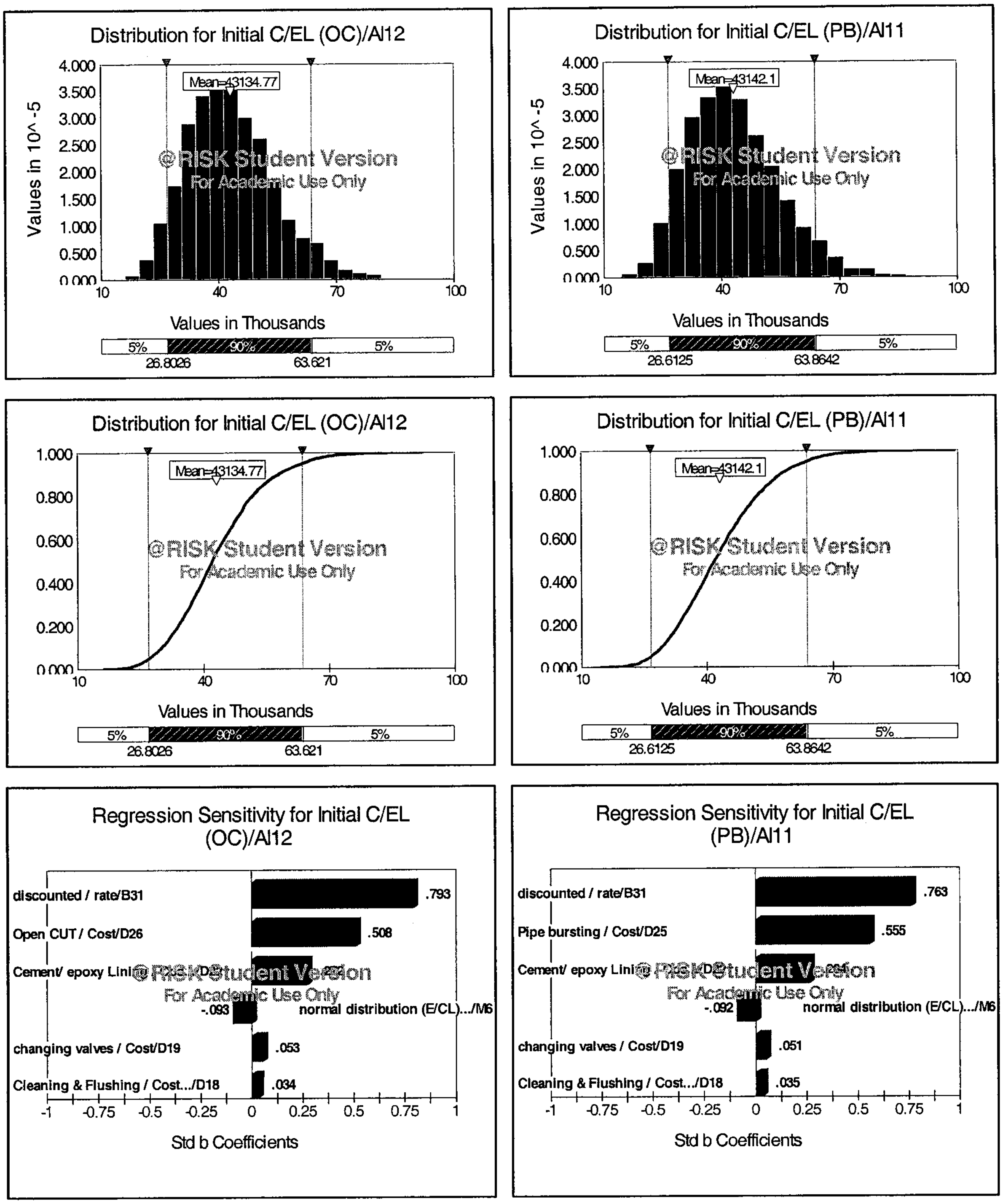
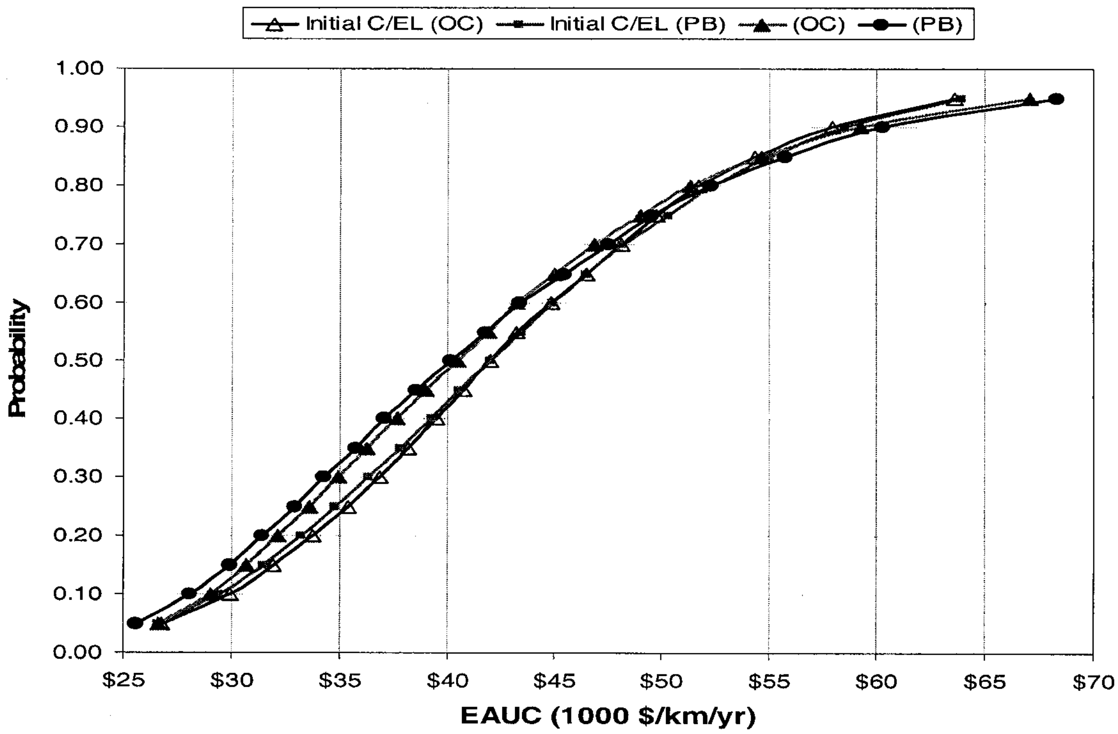


Figure 5.23 EUAC distribution and regression sensitivity for “Initial C/EL (OC)” and “Initial C/EL (PB)” scenarios

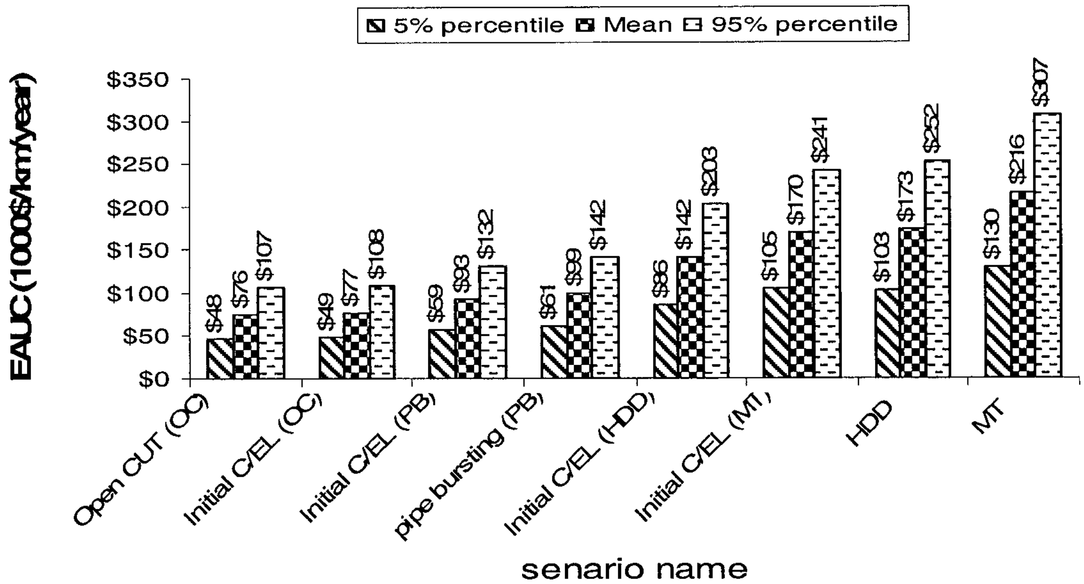
Figure 5.24 shows the cumulative probability distribution for "initial C/EL (OC)", "initial C/EL (PB)", "OC", and "PB". The Figure shows that "initial C/EL (OC)" has the minimum cumulative cost over all scenarios. It is apparent that all scenarios are close and the difference between their respective means is less than 2%, and are therefore considered similar or the same.



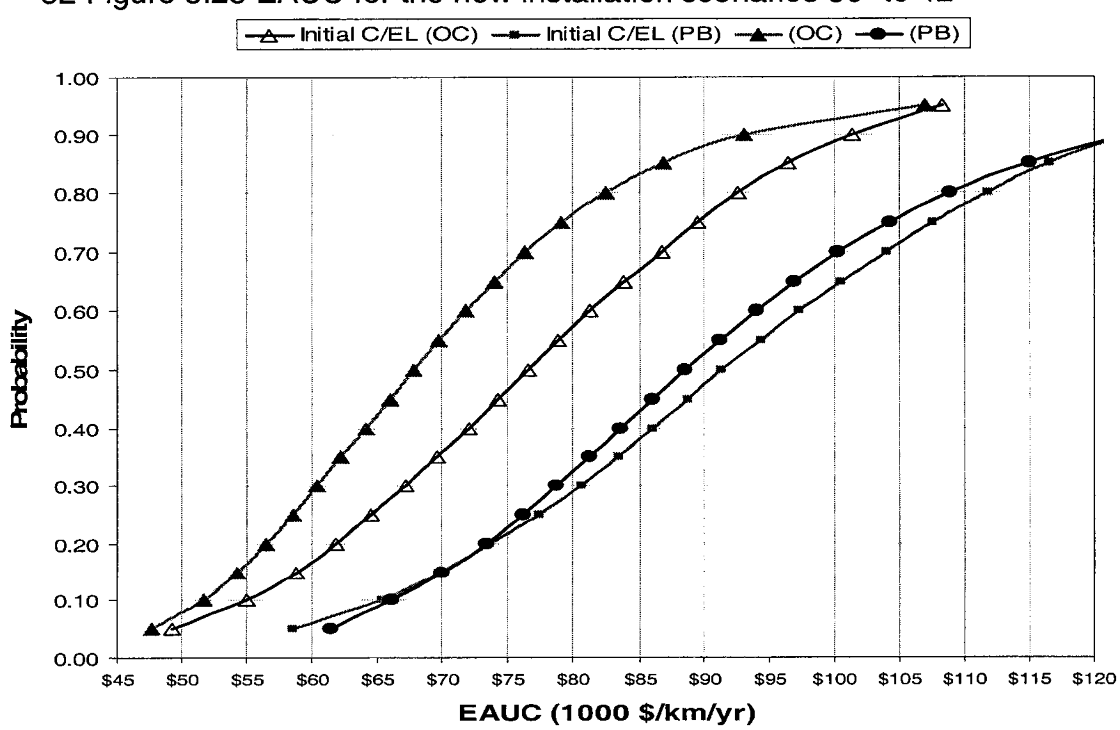
51 Figure 5.24 Cumulative probability distribution for some new installation scenarios diameter range 6" -24"

5.2.2.1 Summary of Cast Iron Analysis for (30"- 42") Diameter Range

The new installation scenarios are summarized in Figure 5.25. They showed that minimum EAUC was for the open cut scenarios, and then followed by Initial C/EL (OC) scenario then Initial C/EL (PB) scenario. On the other hand, the highest EAUC was for the scenario of MT scenario. Figure 5.26 shows the cumulative probability distribution for initial C/EL (OC)", "initial C/EL (PB)", "OC", and “PB”. The figure shows that the “OC” scenario always yields a lower EAUC than all other scenarios. Also show that the probability that Scenario “Initial C/EL (PB)” might have a lower EAUC than Scenario “PB” by 20 %



52 Figure 5.25 EAUC for the new installation scenarios 30” to 42”



53 Figure 5.26 Cumulative probability distribution for some new installation scenarios diameter range 30” -42”

5.2.2.2 Summary of Cast Iron Analysis for (42"- Above) Diameter Range

The new installation scenarios are summarized in Figure 5.27. They showed that the minimum EAUC was for the open cut scenarios, and then followed by Initial C/EL (OC) scenario then (PB) scenario. On the other hand, the highest EAUC was for the scenario of MT scenario. Figure 5.28 shows the cumulative probability distribution for initial C/EL (OC)", "initial C/EL (PB)", "OC", and "PB". The figure shows that the "OC" scenario always yields a lower EAUC than all other scenarios.

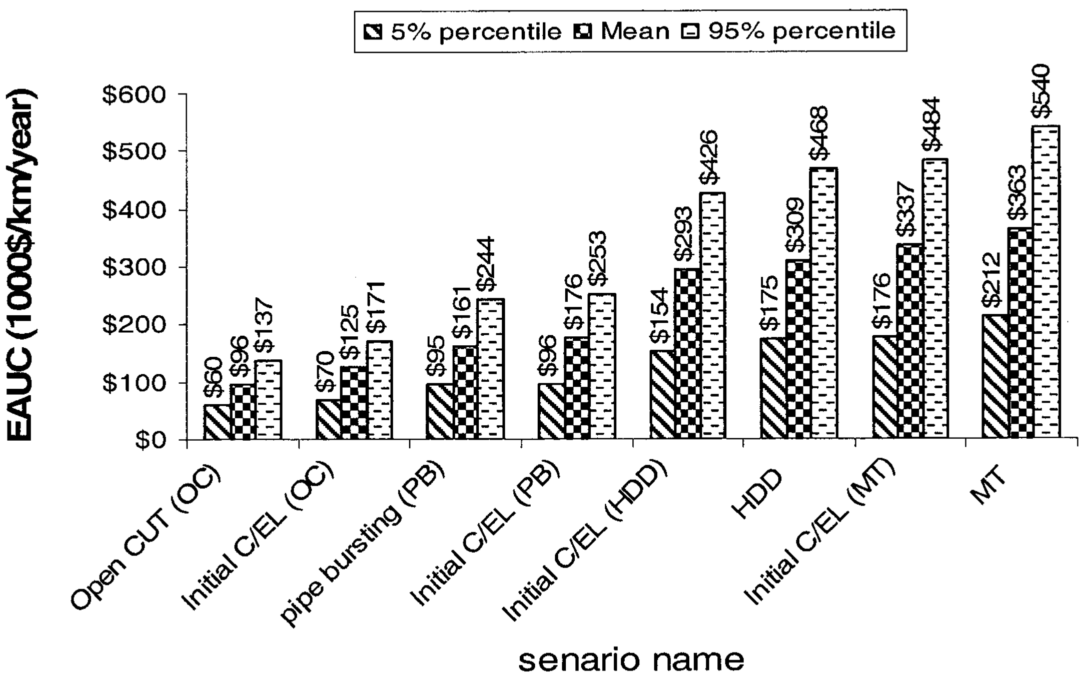


Figure 5.27 EAUC for the new installation scenarios 42"and above

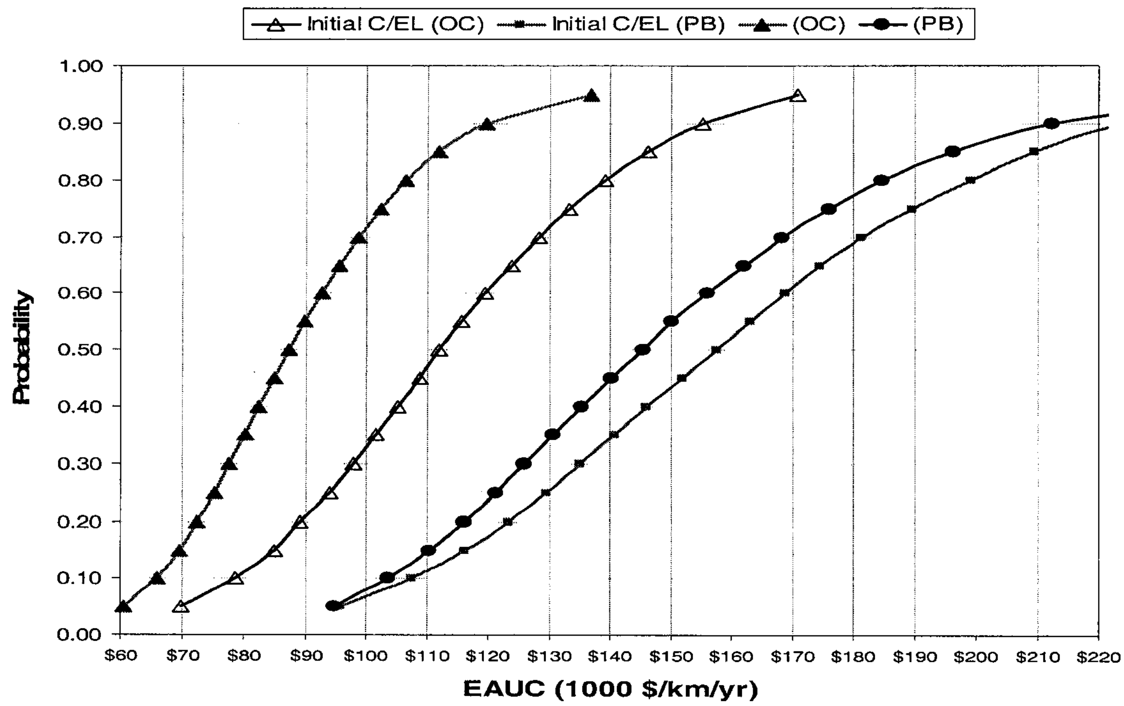


Figure 5.28 Cumulative probability distribution for some new installation scenarios diameter range 42" and above

5.3 Results of Ductile Iron

5.3.1. Rehabilitation Project(s) for Ductile Iron Pipe

Table 5.16 summarizes the top twenty minimum EAUC scenarios among a total of 60 scenarios executed for rehabilitation projects for ductile iron water mains. The table shows the results of ductile iron mains with diameter ranging from 6" to 24", 30" to 42" and 42" and above. The scenarios for each diameter range are sorted based on their mean. As shown below the minimum EAUC for all diameter ranges is the repair only category scenarios. This indicates that the first option to study when executing a life cycle cost analysis for water mains is the repair scenario. Since that the repair only option is not always feasible as shown in alternative data section in chapter (3). Therefore the summary of all other scenarios has to be studied as well in order to select the best feasible scenario among the rest.

The results for 6" to 24" diameter pipes have shown that the best scenario after the repair-only scenarios was "OT-OT-OT-OT-SL"; using a reparation method consisting of either open trench followed by sleeves at the end of service life of pipe – (i.e. until the timing of the fourth break or until the number of breaks reach 0.5 break per kilometer per year, which ever occurs first). At this point in time it is recommended that the pipe should be renovated with slip lining or cement/epoxy lining. These scenarios are cost more effective than using "OT-OT-OT-OC" or "OT-OT-O0T-PB" by about 18% and 24% respectively. These results indicate that the "OT-OT-OT-SL" scenario has a 7% lower EAUC than the "OT-OT-OT-OT-CIPP" scenario. This means that using a repair technique three times followed by a renovation with slip lining, is more cost effective than using a repair technique four times, followed by the utilization of cured in place piping (CIPP).

The results for 30" to 42" diameter pipes have shown that the best scenario after the repair only scenarios was "OT-OT-OT-OT-SL". This range has also recommended using a repairing method either open trench or sleeves until the end of service life of pipe, followed by renovation with slip lining or cement/epoxy lining. These scenarios are more cost effective than using "OT-OT-OT-OC" or "OT-OT-OT-PB" by 16% and 29% respectively. The "OT-OT-OT-OT-CIPP" scenario has established a higher EAUC than "OT-OT-OT-OT-SL", "OT-OT-OT-SL", and "OT-OT-SL" by approximately 21%, 12%, and 1% respectively. This means that using a repair technique four, three, or two times followed by renovation via slip lining is more cost effective than using a repair technique four times followed by cured in place piping (CIPP).

The results for pipe diameters of greater than 42" have shown that the best scenario after the repair only scenarios was "OT-OT-OT-OC". A repair method is recommended, followed by open trenches or sleeves until the end of the service life of the pipe. Once the service life of the pipe has elapsed, the simulation recommends then replacement via open cut techniques. These scenarios are more cost effective than using "OT-OT-OT-OT-SL" or "OT-OT-OT-OT-C/EL" by approximately 3% and 7.5% respectively. The "OT-OT-OT-OT-CIPP" scenario has established a higher EAUC than "OT-OT-OT-OC", "OT-OT-OC", and "OT-OC" by approximately 21%, 12%, and 1% respectively. It should be noted that the "OT-OT-OT-PB" or any other replacement scenario didn't appear among the top 20 minimum EAUC scenarios.

The top twenty minimum EAUC scenarios for all diameter ranges have shown that the "repair only" category is the best category with the least minimum EAUC. This is followed by a few "repair with renovation" and "repair with replacement" scenarios.

Table 5.16 Top twenty minimum EAUC scenarios of Ductile Iron pipes for rehabilitation project(s)

6" to 24" diameter		30" to 42" diameter		42" & above diameter	
scenario Name	Mean $/Km/yr	scenario Name	Mean $/Km/yr	scenario Name	Mean $/Km/yr
Open trench (OT)	$7,680	Open trench (OT)	$8,532	Open trench (OT)	$8,516
sleeves (SVS)	$8,232	sleeves (SVS)	$8,984	sleeves (SVS)	$9,672
OT-OT-OT-OT-SL	$23,539	OT-OT-OT-OT-SL	$44,360	OT-OT-OT-OC	$61,753
SVS-SVS-SVS-SVS-SL	$23,718	SVS-SVS-SVS-SVS-SL	$44,510	SVS-SVS-SVS-OC	$62,030
OT-OT-OT-OT-C/EL	$24,281	OT-OT-OT-OT-C/EL	$47,661	OT-OT-OT-OT-SL	$63,792
SVS-SVS-SVS-SVS-C/EL	$24,545	SVS-SVS-SVS-SVS-C/EL	$47,877	SVS-SVS-SVS-SVS-SL	$64,173
OT-OT-OT-SL	$25,275	OT-OT-OT-SL	$48,282	OT-OT-OT-OT-C/EL	$66,542
SVS-SVS-SVS-SL	$25,419	SVS-SVS-SVS-SL	$48,403	SVS-SVS-SVS-SVS-C/EL	$67,095
OT-OT-OT-OT-CIPP	$27,044	OT-OT-OT-OC	$51,729	OT-OT-OC	$67,620
OT-OT-OT-C/EL	$27,093	SVS-SVS-SVS-OC	$51,838	SVS-SVS-OC	$67,819
SVS-SVS-SVS-SVS-CIPP	$27,223	OT-OT-SL	$53,343	OT-OT-OT-SL	$69,803
SVS-SVS-SVS-C/EL	$27,317	SVS-SVS-SL	$53,430	SVS-SVS-SVS-SL	$70,111
OT-OT-SL	$27,480	OT-OT-OT-OT-CIPP	$53,867	OT-OT-OT-C/EL	$76,178
SVS-SVS-SL	$27,585	SVS-SVS-SVS-SVS-CIPP	$54,016	OT-OC	$76,290
OT-OT-OT-OC	$27,860	OT-OT-OT-C/EL	$54,247	SVS-OC	$76,399
SVS-SVS-SVS-OC	$27,991	SVS-SVS-SVS-C/EL	$54,431	SVS-SVS-SVS-C/EL	$76,647
OT-OT-OT-PB	$29,304	OT-OT-OC	$56,622	OT-OT-SL	$77,592
OT-OT-OT-CIPP	$29,362	SVS-SVS-OC	$56,700	SVS-SVS-SL	$77,816
SVS-SVS-SVS-PB	$29,435	OT-OT-OT-PB	$57,382	OT-OT-OT-OT-CIPP	$78,112
SVS-SVS-SVS-CIPP	$29,508	SVS-SVS-SVS-PB	$57,491	SVS-SVS-SVS-SVS-CIPP	$78,494

5.3.2. New installation Project(s) for Ductile Iron Pipe

Table 5.17 summarizes the new installation scenarios for ductile iron water mains. The table shows the results of ductile iron mains with diameter ranges of 6" to 24", 30" to 42" and 42" and above. The scenarios for each diameter range are sorted based on their mean. As shown, the minimum EAUC for all diameter ranges was open cut and pipe bursting scenarios. This indicates that the first option to study when executing a life cycle cost analysis for water mains is the open cut scenario. Since the open cut option is not always feasible due to any social interference. Therefore the summary of all other scenarios has to be studied as well in order to select the best scenario among the remaining trenchless technologies.

The results for 6" to 24" pipe diameters have shown that the best scenario was "PB". Then "OC" scenario yielded an EAUC with a difference of about 1.4% from pipe bursting scenario. "Initial C/EL (OC)" and "Initial C/EL (PB)" has established a higher EAUC than "PB", 12.7% and 11.6%, respectively. The "MT" scenario yielded the maximum EAUC among the remaining scenarios, approximately 116% higher than the "PB" scenario.

The results for the 30" to 42" pipe diameter range have shown that the best scenario was "OC". The "PB" scenario yielded an EAUC with a percent difference of 11.4% when compared to the open cut scenario. "Initial C/EL (OC)" and "Initial C/EL (PB)" had a higher EAUC than "PB", approximately 18.5%, and 28% respectively. On The "MT" scenario yielded the highest EAUC among the remaining scenarios; 124% higher than the "OC" scenario.

The results for pipe diameters of 42" and above have shown that the best scenario was "OC". The "PB" scenario yielded an EAUC with a difference of about 60% when compared to the open cut scenario. "Initial C/EL (OC)" and "Initial C/EL (PB)" established an EAUC higher than "PB" by approximately 62%, and 120% respectively. The "MT" scenario yielded the highest EAUC among the remaining scenarios; 290% higher than the "OC" scenario.

The scenarios for the 6" to 24" diameter range have shown that the pipe bursting scenario is the best with the least minimum EAUC for ductile iron pipes having small diameters, followed by the open cut scenario. After subsequent breakages, the model suggest movement toward the initial cement lining scenarios using pipe bursting and open cut installation methods. Both 30" to 42" and 42" and above diameter ranges have shown that the best scenario is the open cut followed by pipe bursting. In addition, they have shown that as the pipe diameter increases, the difference in the EAUC between open cut and pipe bursting increases from 11% to 60%. All diameter ranges have shown that the microtunneling scenario has the highest EAUC.

Table 5.17 EAUC Statistics of ductile iron pipe for new installation project(s)

EAUC ($/km/yr) 6" to 24" diameter			
scenario Name	5% percentile	Mean	95% percentile
pipe bursting (PB)	$27,306	$42,402	$42,402
Open CUT (OC)	$28,357	$42,983	$42,983
Initial C/EL (PB)	$29,228	$47,343	$47,343
Initial C/EL (OC)	$29,919	$47,802	$47,802
HDD	$40,157	$63,851	$63,851
Initial C/EL (HDD)	$39,728	$65,001	$65,001
Initial C/EL (MT)	$50,363	$88,315	$88,315
MT	$52,413	$91,859	$91,859
EAUC ($/km/yr) 30" to 42" diameter			
Open CUT (OC)	$49,601	$73,884	$101,257
pipe bursting (PB)	$55,562	$82,312	$113,026
Initial C/EL (OC)	$54,555	$87,580	$123,066
Initial C/EL (PB)	$59,166	$94,583	$132,130
HDD	$95,750	$144,476	$203,160
Initial C/EL (HDD)	$90,072	$146,216	$208,339
Initial C/EL (MT)	$100,303	$163,984	$232,308
MT	$109,925	$165,914	$231,803
EAUC ($/km/yr) 42" & above diameter			
Open CUT (OC)	$59,869	$89,113	$122,693
pipe bursting (PB)	$90,985	$142,987	$208,496
Initial C/EL (OC)	$80,967	$144,323	$204,573
Initial C/EL (PB)	$106,333	$196,220	$286,258
HDD	$159,087	$258,670	$375,746
MT	$192,133	$303,210	$440,128
Initial C/EL (HDD)	$161,329	$307,686	$456,164
Initial C/EL (MT)	$187,477	$349,675	$515,164

5.4 Results of PVC Pipe

Table 5.18 summarizes the new installation scenarios for PVC water main. While Table 5.19 summarizes the top twenty minimum EAUC scenarios among a total of 60 scenarios executed for rehabilitation projects for PVC water main. The tables shows the results of (6" to 24"), (30" to 42"), and (42" & above) diameters.

Table 5.18 EAUC Statistics of PVC pipe for new installation project(s)

EAUC ($/km/yr) 6" to 24" diameter			
scenario Name	5% percentile	Mean	95% percentile
Open CUT (OC)	$19,811	$31,161	$46,189
Initial C/EL (OC)	$23,113	$36,524	$52,616
pipe bursting (PB)	$24,753	$40,691	$61,472
Initial C/EL (PB)	$26,993	$43,897	$64,272
Initial C/EL (HDD)	$37,860	$62,797	$92,014
HDD	$40,439	$65,142	$96,524
Initial C/EL (MT)	$48,254	$86,133	$135,673
MT	$53,098	$95,486	$153,217
EAUC ($/km/yr) 30" to 42" diameter			
Open CUT (OC)	$40,649	$59,173	$82,154
Initial C/EL (OC)	$45,813	$72,397	$101,422
pipe bursting (PB)	$62,890	$91,402	$125,185
Initial C/EL (PB)	$61,456	$97,416	$136,036
Initial C/EL (HDD)	$81,583	$133,190	$189,818
HDD	$90,103	$137,520	$194,829
Initial C/EL (MT)	$98,699	$160,054	$227,832
MT	$113,819	$172,199	$243,935
EAUC ($/km/yr) 42" & above diameter			
Open CUT (OC)	$52,408	$78,632	$109,045
Initial C/EL (OC)	$65,299	$118,556	$165,349
pipe bursting (PB)	$83,454	$135,999	$202,181
Initial C/EL (PB)	$90,470	$169,713	$247,751
HDD	$159,152	$267,011	$400,115
Initial C/EL (HDD)	$150,303	$286,102	$415,823
MT	$192,888	$312,534	$457,310
Initial C/EL (MT)	$174,463	$326,782	$471,310

Table 5.19 Top twenty minimum EAUC scenarios of PVC pipes for rehabilitation project(s)

6" to 24" diameter		30" to 42" diameter		42" & above diameter	
scenario Name	Mean $/Km/yr	scenario Name	Mean $/Km/yr	scenario Name	Mean $/Km/yr
Open trench (OT)	$7,670	Open trench (OT)	$8,537	Open trench (OT)	$8,516
sleeves (SVS)	$8,203	sleeves (SVS)	$8,995	sleeves (SVS)	$9,668
OT-OT-OT-OC	$22,633	OT-OT-OT-OC	$41,437	OT-OT-OT-OC	$53,344
SVS-SVS-SVS-OC	$22,769	SVS-SVS-SVS-OC	$41,553	SVS-SVS-SVS-OC	$53,634
OT-OT-OT-OT-SL	$23,665	OT-OT-OT-OT-SL	$44,663	OT-OT-OC	$58,620
SVS-SVS-SVS-SVS-SL	$23,843	SVS-SVS-SVS-SVS-SL	$44,815	SVS-SVS-OC	$58,830
OT-OT-OT-OT-C/EL	$24,335	OT-OT-OC	$45,285	OT-OT-OT-OT-SL	$64,006
OT-OT-OC	$24,426	SVS-SVS-OC	$45,368	SVS-SVS-SVS-SVS-SL	$64,388
SVS-SVS-OC	$24,525	OT-OT-OT-OT-C/EL	$47,698	OT-OT-OT-OT-C/EL	$66,417
SVS-SVS-SVS-SVS-C/EL	$24,594	SVS-SVS-SVS-SVS-C/EL	$47,917	OT-OC	$66,604
OT-OT-OT-SL	$25,420	OT-OT-OT-SL	$48,664	SVS-OC	$66,720
SVS-SVS-SVS-SL	$25,564	SVS-SVS-SVS-SL	$48,786	SVS-SVS-SVS-SVS-C/EL	$66,968
OT-OT-OT-OT-CIPP	$26,790	OT-OC	$51,077	OT-OT-OT-SL	$70,146
SVS-SVS-SVS-SVS-CIPP	$26,968	SVS-OC	$51,123	SVS-SVS-SVS-SL	$70,455
OT-OC	$27,090	OT-OT-SL	$53,754	OT-OT-OT-C/EL	$76,174
SVS-OC	$27,145	SVS-SVS-SL	$53,843	SVS-SVS-SVS-C/EL	$76,642
OT-OT-OT-C/EL	$27,176	OT-OT-OT-OT-CIPP	$54,159	OT-OT-SL	$77,841
SVS-SVS-SVS-C/EL	$27,396	OT-OT-OT-C/EL	$54,296	SVS-SVS-SL	$78,065
OT-OT-OT-PB	$28,850	SVS-SVS-SVS-SVS-CIPP	$54,311	OT-OT-OT-OT-CIPP	$78,391
OT-OT-OT-CIPP	$28,951	SVS-SVS-SVS-C/EL	$54,483	SVS-SVS-SVS-SVS-CIPP	$78,773

5.5 Results of Concrete Pipe

Table 5.20 summarizes the new installation scenarios for concrete water main. While Table 5.21 summarizes the top twenty minimum EAUC scenarios among a total of 60 scenarios executed for rehabilitation projects for concrete water main. The tables shows the results of (6" to 24"), (30" to 42"), and (42" & above) diameters ranges.

Table 5.20 EAUC Statistics of Concrete pipe for new installation project(s)

scenario Name	5% percentile	Mean	95% percentile
EAUC ($/km/yr) 6" to 24" diameter			
Open CUT (OC)	$21,672	$32,028	$44,857
Initial C/EL (OC)	$25,698	$40,568	$58,353
pipe bursting (PB)	$28,275	$44,679	$63,689
Initial C/EL (PB)	$31,950	$52,045	$75,580
HDD	$37,827	$58,809	$85,988
Initial C/EL (HDD)	$39,125	$64,843	$95,296
MT	$51,782	$89,619	$141,130
Initial C/EL (MT)	$51,779	$92,755	$144,830
EAUC ($/km/yr) 30" to 42" diameter			
Open CUT (OC)	$35,249	$50,762	$68,253
Initial C/EL (OC)	$48,126	$70,610	$95,750
pipe bursting (PB)	$45,792	$71,961	$101,046
Initial C/EL (PB)	$56,330	$90,011	$126,742
HDD	$77,536	$117,330	$162,483
Initial C/EL (HDD)	$81,945	$132,494	$189,202
MT	$91,107	$136,366	$188,647
Initial C/EL (MT)	$92,475	$149,803	$213,283
EAUC ($/km/yr) 42" & above diameter			
Open CUT (OC)	$39,116	$57,117	$77,074
Initial C/EL (OC)	$69,850	$105,745	$145,932
pipe bursting (PB)	$60,651	$112,075	$152,918
Initial C/EL (PB)	$87,913	$165,276	$226,954
HDD	$126,785	$213,708	$316,125
MT	$159,317	$255,947	$371,944
Initial C/EL (HDD)	$140,594	$282,254	$407,674
Initial C/EL (MT)	$168,040	$332,222	$473,496

Table 5.21 Top twenty minimum EAUC scenarios of concrete pipes for rehabilitation project(s)

6" to 24" diameter		30" to 42" diameter		42" & above diameter	
scenario Name	Mean $/Km/yr	scenario Name	Mean $/Km/yr	scenario Name	Mean $/Km/yr
Open trench (OT)	$7,658	Open trench (OT)	$8,543	Open trench (OT)	$8,516
sleeves (SVS)	$8,210	sleeves (SVS)	$9,001	sleeves (SVS)	$9,681
OT-OT-OT-OT-SL	$23,853	OT-OT-OT-OC	$37,317	OT-OT-OT-OC	$41,332
SVS-SVS-SVS-SVS-SL	$24,035	SVS-SVS-SVS-OC	$37,420	SVS-SVS-SVS-OC	$41,595
OT-OT-OT-OT-C/EL	$24,139	OT-OT-OC	$40,305	OT-OT-OC	$44,785
OT-OT-OT-OC	$24,157	SVS-SVS-OC	$40,378	SVS-SVS-OC	$44,973
SVS-SVS-SVS-OC	$24,281	OT-OT-OT-OT-SL	$44,405	OT-OC	$49,793
SVS-SVS-SVS-SVS-C/EL	$24,403	SVS-SVS-SVS-SVS-SL	$44,555	SVS-OC	$49,894
OT-OT-OT-SL	$25,597	OT-OC	$44,674	Open CUT (OC)	$56,893
SVS-SVS-SVS-SL	$25,743	SVS-OC	$44,714	OT-OT-OT-OT-SL	$63,784
OT-OT-OC	$25,885	OT-OT-OT-OT-C/EL	$47,971	SVS-SVS-SVS-SVS-SL	$64,168
SVS-SVS-OC	$25,974	SVS-SVS-SVS-SVS-C/EL	$48,190	OT-OT-OT-OT-C/EL	$66,815
OT-OT-OT-C/EL	$26,852	OT-OT-OT-SL	$48,370	SVS-SVS-SVS-SVS-C/EL	$67,372
SVS-SVS-SVS-C/EL	$27,076	SVS-SVS-SVS-SL	$48,491	OT-OT-OT-SL	$69,844
OT-OT-OT-OT-CIPP	$27,084	Open CUT (OC)	$50,829	SVS-SVS-SVS-SL	$70,153
SVS-SVS-SVS-SVS-CIPP	$27,265	OT-OT-SL	$53,335	OT-OT-OT-C/EL	$76,557
OT-OT-SL	$27,848	SVS-SVS-SL	$53,423	SVS-SVS-SVS-C/EL	$77,029
SVS-SVS-SL	$27,954	OT-OT-OT-OT-CIPP	$53,854	OT-OT-SL	$77,657
OT-OC	$28,360	SVS-SVS-SVS-SVS-CIPP	$54,004	SVS-SVS-SL	$77,882
SVS-OC	$28,408	OT-OT-OT-C/EL	$54,728	OT-OT-OT-OT-CIPP	$77,972

5.6 Results of Asbestos Cement Pipe

Table 5.22 summarizes the new installation scenarios for Asbestos cement water main. While Table 5.23 summarizes the top twenty minimum EAUC scenarios among a total of 60 scenarios executed for rehabilitation projects for Asbestos cement water main. The tables shows the results of (6" to 24"), (30" to 42"), and (42" & above) diameter ranges.

Table 5.22 EAUC Statistics for Asbestos cement pipe of new installation project(s)

scenario Name	5% percentile	Mean	95% percentile
EAUC ($/km/yr) 6" to 24" diameter			
Open CUT (OC)	$22,949	$35,896	$52,193
Initial C/EL (OC)	$25,880	$42,182	$61,816
pipe bursting (PB)	$30,862	$48,495	$70,404
Initial C/EL (PB)	$31,990	$52,690	$76,570
HDD	$37,390	$59,149	$87,671
Initial C/EL (HDD)	$37,470	$61,543	$91,339
Initial C/EL (MT)	$50,368	$90,405	$143,089
MT	$53,492	$93,711	$149,095
EAUC ($/km/yr) 30" to 42" diameter			
Open CUT (OC)	$46,692	$70,548	$100,604
Initial C/EL (OC)	$53,072	$85,045	$121,392
pipe bursting (PB)	$57,958	$85,479	$116,810
Initial C/EL (PB)	$60,669	$97,455	$136,723
HDD	$95,873	$145,238	$202,077
Initial C/EL (HDD)	$90,144	$147,107	$206,521
Initial C/EL (MT)	$103,505	$169,513	$240,845
MT	$114,355	$172,221	$238,903
EAUC ($/km/yr) 42" & above diameter			
Open CUT (OC)	$60,648	$89,289	$120,535
Initial C/EL (OC)	$90,377	$142,799	$206,173
pipe bursting (PB)	$75,389	$167,343	$191,745
Initial C/EL (PB)	$99,995	$234,067	$273,908
HDD	$158,179	$258,242	$372,575
MT	$191,703	$301,504	$433,288
Initial C/EL (HDD)	$156,090	$370,254	$438,295
Initial C/EL (MT)	$179,792	$421,298	$506,586

Table 5.23 Top twenty minimum EAUC scenarios for Asbestos cement pipes for rehabilitation project(s)

6" to 24" diameter		30" to 42" diameter		42" & above diameter	
scenario Name	Mean $/Km/yr	scenario Name	Mean $/Km/yr	scenario Name	Mean $/Km/yr
Open trench (OT)	$7,668	Open trench (OT)	$8,520	Open trench (OT)	$8,516
sleeves (SVS)	$8,218	sleeves (SVS)	$8,977	sleeves (SVS)	$9,670
OT-OT-OT-OT-SL	$23,697	OT-OT-OT-OT-SL	$43,672	OT-OT-OT-OC	$61,525
SVS-SVS-SVS-SVS-SL	$23,879	SVS-SVS-SVS-SVS-SL	$43,822	SVS-SVS-SVS-OC	$61,801
OT-OT-OT-OT-C/EL	$24,113	OT-OT-OT-OT-C/EL	$47,527	OT-OT-OT-OT-SL	$63,343
SVS-SVS-SVS-SVS-C/EL	$24,376	OT-OT-OT-SL	$47,569	SVS-SVS-SVS-SVS-SL	$63,722
OT-OT-OT-SL	$25,446	SVS-SVS-SVS-SL	$47,690	OT-OT-OT-OT-C/EL	$67,056
SVS-SVS-SVS-SL	$25,592	SVS-SVS-SVS-SVS-C/EL	$47,745	OT-OT-OC	$67,479
OT-OT-OT-OC	$26,341	OT-OT-OT-OC	$49,429	SVS-SVS-SVS-SVS-C/EL	$67,612
SVS-SVS-SVS-OC	$26,473	SVS-SVS-SVS-OC	$49,539	SVS-SVS-OC	$67,677
OT-OT-OT-C/EL	$26,841	OT-OT-SL	$52,489	OT-OT-OT-SL	$69,356
OT-OT-OT-OT-CIPP	$26,919	SVS-SVS-SL	$52,577	SVS-SVS-SVS-SL	$69,662
SVS-SVS-SVS-C/EL	$27,065	OT-OT-OT-OT-CIPP	$53,750	OT-OC	$76,077
SVS-SVS-SVS-SVS-CIPP	$27,100	SVS-SVS-SVS-SVS-CIPP	$53,900	SVS-OC	$76,185
OT-OT-SL	$27,657	OT-OT-OC	$53,994	OT-OT-OT-C/EL	$76,977
SVS-SVS-SL	$27,763	SVS-SVS-OC	$54,073	OT-OT-SL	$77,046
OT-OT-OC	$28,401	OT-OT-OT-C/EL	$54,176	SVS-SVS-SL	$77,268
SVS-SVS-OC	$28,496	SVS-SVS-SVS-C/EL	$54,362	SVS-SVS-SVS-C/EL	$77,449
OT-OT-OT-CIPP	$29,019	OT-OT-OT-CIPP	$58,755	OT-OT-OT-OT-CIPP	$77,942
SVS-SVS-SVS-CIPP	$29,165	SVS-SVS-SVS-CIPP	$58,877	SVS-SVS-SVS-SVS-CIPP	$78,320

5.7 Comparison of Rehabilitation Project(s) Results

This section highlights the major rehabilitations scenarios and compare between the output results for the above mentioned pipe types. Table 5.24 shows a comparison matrix for rehabilitation project(s) results. This table compares the mean EAUC result of each pipe material for “OT-OT-OT-OT-SL”, “OT-OT-OT-OT-C/EL”, “OT-OT-OT-OT-CIPP”, “OT-OT-OT-OC”, “OT-OT-OT-PB”, “OT-OT-OT-HDD” Scenarios. The reference cell is “OT-OT-OT-OT-SL” scenario for cast iron pipe with (6”-24”) diameter range, having a mean EAUC of 23,649 $/km/yr. all other values in the table are expressed as a percent of this reference scenario.

Table 5.24 Comparison matrixes for rehabilitation project(s) results

scenario name	*Cast iron*	*Ductile Iron*	*PVC*	*Concrete*	*Asbestos Cement*
	(6" - 24") diameter				
OT-OT-OT-OT-SL	100.00%	99.53%	100.07%	100.86%	100.20%
OT-OT-OT-OT-C/EL	102.26%	102.67%	102.90%	102.07%	101.96%
OT-OT-OT-OT-CIPP	113.99%	114.35%	113.28%	114.52%	113.83%
OT-OT-OT-OC	124.76%	117.81%	95.70%	102.15%	111.38%
OT-OT-OT-PB	123.92%	123.91%	121.99%	138.89%	146.45%
OT-OT-OT-HDD	188.38%	193.87%	193.87%	180.18%	176.08%
scenario name	**(30" - 42") diameter**				
OT-OT-OT-OT-SL	188.03%	187.58%	188.86%	187.77%	184.67%
OT-OT-OT-OT-C/EL	201.86%	201.53%	201.69%	202.85%	200.97%
OT-OT-OT-OT-CIPP	228.06%	227.78%	229.01%	227.72%	227.28%
OT-OT-OT-OC	201.81%	218.74%	175.22%	157.80%	209.01%
OT-OT-OT-PB	261.00%	242.64%	264.87%	215.19%	250.07%
OT-OT-OT-HDD	444.75%	417.08%	417.08%	350.73%	416.85%
scenario name	**(42" - above) diameter**				
OT-OT-OT-OT-SL	267.20%	269.74%	270.65%	269.71%	267.85%
OT-OT-OT-OT-C/EL	281.45%	281.38%	280.85%	282.53%	283.55%
OT-OT-OT-OT-CIPP	330.09%	330.30%	331.48%	329.71%	329.58%
OT-OT-OT-OC	256.09%	261.12%	225.57%	174.77%	260.16%
OT-OT-OT-PB	421.43%	412.80%	381.76%	314.34%	412.23%
OT-OT-OT-HDD	805.80%	737.14%	737.14%	623.77%	734.55%

5.8 Water Main Maintenance Plan

A maintenance plan is a set of rehabilitation procedure steps that satisfy the minimum rehabilitation cost. A stochastic life-cycle cost (SLCC) analysis was performed for different rehabilitation techniques in order to determine the best scenario of rehabilitation for the maintenance plan.

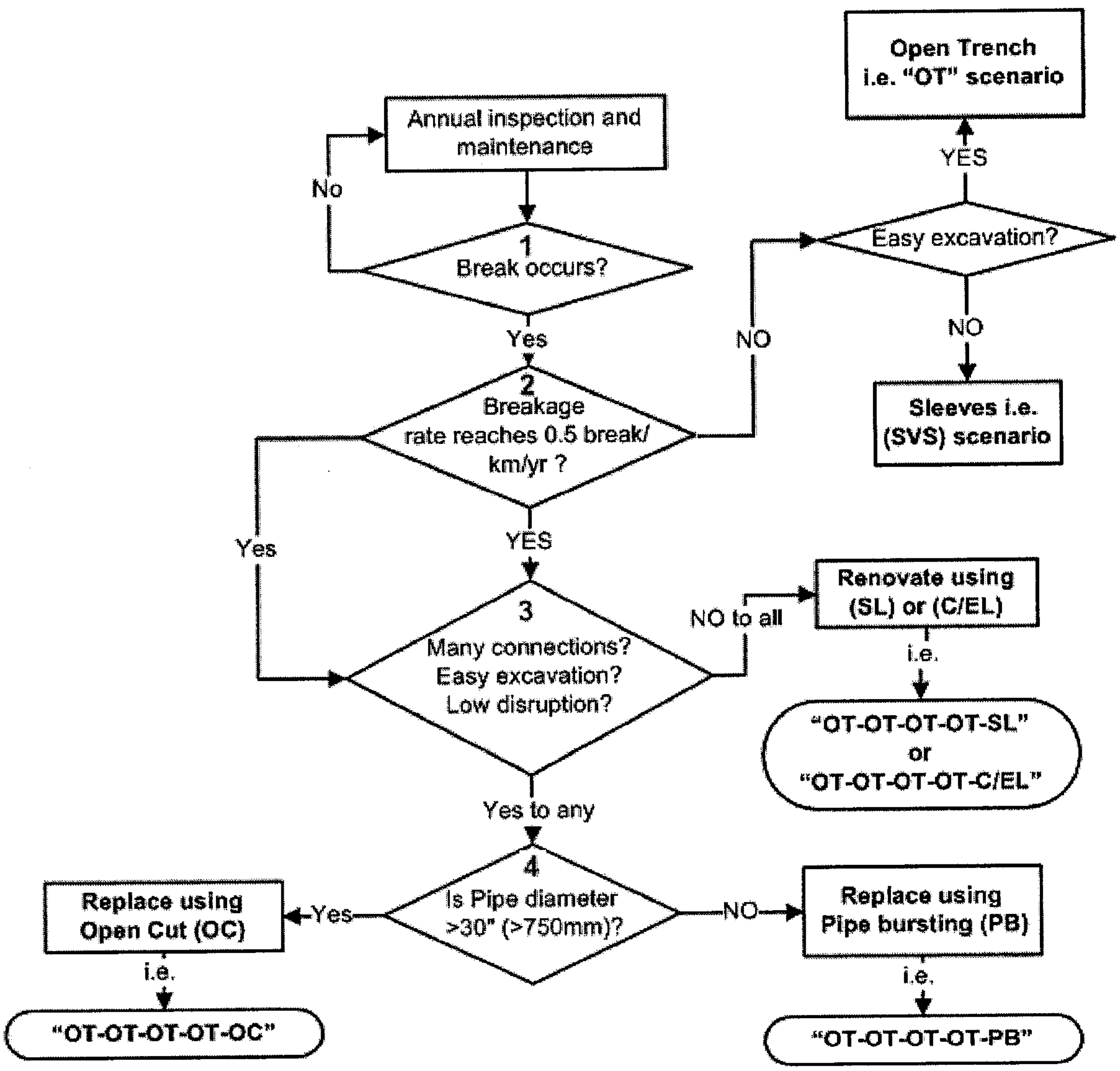


Figure 5.29 Maintenance plan procedure flowchart

Based on the SLCC analysis, and the best rehabilitation scenario, a proposed maintenance plan and its procedural steps are summarized in Figure 5.29. Water main should be inspected and maintained annually (i.e. annual flushing). The proposed maintenance plain includes 4 mains steps or 4 major questions should be asked to the inspector as follows:

Step 1: does a break occurs?

Step 2: is the breakage rate greater than *0.5 break/km/yr? (Dillon and harfan Inc., 2003).*

Step 3: does any of the following condition exist "does the water main contains many connections, is it easy to excavate, is it going to have a low disruption".

Step 4: is the pipe diameter is greater than 30" (750mm)?

If a break occurs, the question to the inspector is, "Is the breakage rate greater than *0.5 break/km/yr?*" If the answer is affirmative, the inspector should directly go to step 3 as there may be no point in repairing the water main because it should be renovated or replaced. If the breakage rate is less than 0.5 break/km/yr, a repair method should be automatically done. The open trench method is the cost effective method for repairing, but if the excavation was not easy, then the second solution would be sleeves method.

If number of breaks reaches 0.5 break/km/yr, either a renovation or replacement method should be automatically done. To decide which method to be used, questions in step 3 should be answered.

The inspector should ask (Step 3), "Does the main contain many connections, is it easy to excavate, is it going to have a low disruption". If the answer is no to all, then best cost effective solution is to renovate using Slip lining method.

If the answer is affirmative to any question in step 3, then a replacement method should be used. The pipe bursting method is the cost effective method for pipe diameters less than 30" (750 mm). If the pipe diameter is greater than 30" then the open cut method would be cost effective compared to all other replacement methods.

CHAPTER 6: CONCLUSIONS, CONTRIBUTIONS AND RECOMMENDATIONS

6.1 Conclusions

In this research work, a stochastic life cycle cost (SLCC) procedure and statistical analysis of service life (breakage rate analysis) of water mains were conducted. A stochastic model has been developed to perform life cycle cost for several water main materials. The model has been tested for several scenarios. A combination of repair, renovation and replacement techniques are integrated in the model to develop different scenarios for rehabilitation of water mains. The minimum equivalent annual uniform costs (EAUC) for rehabilitation of water mains were evaluated. The model was implemented on the internet platform through a web-based stochastic life cycle cost (WSLCC). The following conclusions were found based on the SLCC model:

- Life cycle costs can be stochastically analyzed based on cost and deterioration (service life) probabilities.
- A combination of repair, renovation, and replacement techniques are integrated to develop different scenarios of water main rehabilitation.
- The minimum equivalent annual uniform costs (EAUC) for rehabilitation of water mains were found based on 60 selected scenarios as follows:
  - Open Trench (OT) method has established the minimum EAUC for all selected diameter ranges in the "repair only" category.

- Among "renovation only" category, Slip-Lining (SL) method for all selected diameter ranges has the least EAUC.
- The "replacement only" category shows that small diameter water mains (i.e. 6" to 24") yield a minimum EAUC using pipe bursting (PB) method.
- The open cut (OC) method has the least EAUC for large diameter ranges (i.e. >30").
- Using "OT-OT-OT-OT-SL" scenario is the best scenario within "repair & renovation" category for all selected diameter ranges.
- Both "OT-OT-OT-PB" and "OT-OT-OT-OC" has relatively similar EAUC for small diameter ranges within "repair & replacement" category.
- Horizontal directional drilling (HDD) has higher EAUC than (PB) and (OC).
- Microtunneling (MT) method has the maximum EAUC among other replacement methods for "replacement only" category.
- As water main diameter increases, "OT-OT-OT-OC" scenario yields a lower EAUC than "OT-OT-OT-OT-SL" scenario.
- Using "OT-SL", "OT-OT-SL", or "OT-OT-OT-SL" provides a higher EAUC than "OT-OT-OT-OT-SL" for all diameter ranges.
- Open cut scenarios have shown variance in EAUC values among different pipe materials. (i.e. "OT-OT-OT-OC" scenario, for PVC mains has a lower EAUC than that of other pipe materials).

- The EAUC of sliplining shows relatively similar EAUC values within the different pipe materials.

6.2 Contributions

The contributions of this research can be summarized as:

1. Develop a new methodology and model to perform stochastic life cycle costs (SLCC) for new installation or rehabilitation alternatives of water mains using simulation approach.
2. Breakage rate analysis was successfully developed in order to predict the rehabilitation intervals of various alternatives.
3. Develop a maintenance plan for water mains rehabilitation alternatives based on SLCC model.
4. Modify the @risk student version software package to suite the developed SLCC model.
5. Develop web-based SLCC (WSLCC) software to determine the SLCC of water mains. The web-based software saves significant time and money in performing the cost analysis of water mains. The system will help municipal engineers to predict the suitable new installation and/or rehabilitation programs as well as their corresponding costs, thereby to avoid any unpleasant surprises.

6.3 Limitations

The developed system and model are limited to water mains. A set of specific itemized limitations of life cycle cost, input data, and WSLCC software, are as follows:

6.3.1 Life cycle cost

- Estimating early in the life of a project when the degree of accuracy has a broad range,
- Assuming that the alternative has a finite life cycle,
- Life cycle cost is not a method that account for environmental impacts on a specific project.

6.3.2 Input data

- The cost data are embedded into the model as a triangular probability distribution only.
- The system is limited to the predefined rehabilitation or new installation methods.
- The deterioration rate has to be input in the form of the breakage rate interval form.

6.3.3 WSLCC Software

- Limitations of the @risk student version:

  1- Run at most 1000 iterations of unattended simulations.

  2- Data sets are limited to maximum of 100 @RISK input functions in the developed model

- User cannot have access to change or develop new scenarios.

- User has to wait until the total simulation report is generated for all scenarios in order to view the detailed report for any scenario.

6.4 Recommendations

6.4.1 Research Enhancements

In this model, the randomness of the Monte Carlo simulation process is introduced through probability distributions representing break times, cost of various alternatives, and discounted rate. An enhancement of this model is required in the following areas:

- Add benefits (revenues) as stochastic variables; consider cost data into the model using other probability distribution functions (i.e. normal, beta, gamma, etc.....); and include other maintenance techniques (i.e. cathodic protection) to the developed model in order to account for the uncertainty involved in the prediction of the various input parameters.
- Incorporate deterioration models in order to account for other physical, environmental, and operational factors to the model. This can help decision-makers to define the service life of the water mains and predict the new installation/ rehabilitation costs, which reduce the uncertainty in their behavior.

6.4.2 Research Extensions

An extension of this research work can be summarized in the following areas:

- Develop standardized data collection system and format that help in designing a precise SLCC.

- Develop a fuzzy life cycle cost model that considers fuzzy variables in life cycle cost analysis of water mains.
- Develop budget allocation model, based upon SLCC, to plan municipal rehabilitation and maintenance budget.
- Adapt the developed SLCC model to analyze LCC of other civil infrastructures such as sewer, bridges, tunnels, buildings, and roads.

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Appendices

APPENDIX A : Questionnaire

QUESTIONNAIRE FOR LIFE CYCLE COST INFORMATION

I. COMPANY INFORMATION:

This information provided in this questionnaire is confidential and not for public use. It is required to distinguish only between contractor and consultant categories.

I.1 Your Company's name:

I.2 Check your company's classification:

a. Contractor. ___

b. Consultant. ________

I.3 Your information:

Name:	
Position:	
Email:	
Phone:	
Fax:	

II. SERVICE LIFE INFORMATION

This information is essential to determine the project overview factors that affect the pipe service life. Please select project(s) and answer the following questions. You could add any other suitable information in blank areas of the questionnaire:

1) What is the project Name?
2) Define the total number of break occurred to this pipe?
3) What is the date of occurrence of each break?
4) What was the age of the pipe when the break occurred?
5) What is the pipe type (material)?
6) What is the pipe diameter?
7) What is the total length of the pipe?
8) What is the depth of cover over the pipe?

Project Name	Break Number	Date	Pipe Age	Pipe Type	Pipe Diameter	Break reason	Pipe length	Cover

III. COST INFORMATION

This type of information is needed in order to build the life cycle cost for the water mains. Therefore, please try to estimate the minimum, most probable and maximum cost of each activity. Please complete the following tables for the following materials and diameter ranges:

1-Cast Iron 2-Ductile Iron

3-Concrete 4-Asbestos Cement

5-Steel

Diameter ranges:

1- from 6" to 24"
2- from 30" to 42"
3- from 42" and above

Installation of new pipe

Description		Cost $			unit	Pipe Diameter	Pipe Material
		Minimum	Most likely	Maximum			
1	Open CUT				$/m		
2	Micro Tunneling				$/m		
3	Horizontal directional drilling				$/m		
4	Pipe bursting				$/m		

Rehabilitation

Description		Cost $			unit	Pipe Diameter	Pipe Material
		Minimum	Most likely	Maximum			
5	Sleeves				each		
6	open trench				each		
7	Cement/ epoxy Lining				$/m		
8	Slip Lining				$/m		
9	CIPP				$/m		

Operation and maintenance

Description		Cost $			unit	Pipe Diameter	Pipe Material
		Minimum	Most likely	Maximum			
10	Cleaning & Flushing				$/m/year		
11	changing valves				each		

APPENDIX B: WEB-BASED STOCHASTIC LIFE CYCLE COST (WSLCC)

Appendix B

WEB-BASED STOCHASTIC LIFE CYCLE COST (WSLCC)

B.1 System Requirements

Operating Systems:

- Windows 95, Windows 98, or Windows NT 4.0 or higher. The software will not run on OS/2, Macintosh, or UNIX platforms.

Online access to reports only:

- Microsoft requires Internet Explorer 4.0 or the latest version of Internet Explorer, which is available free of charge from Microsoft at www.microsoft.com
- Adobe Acrobat Reader 4.0 or higher. Adobe Acrobat Reader is available without charge from www.adobe.com

Systems required for running the server

- @ Risk version 4.5 or higher. @ Risk 4.5 is available for a fee from www.palisade.com
- Active PDF server side printer driver for the generation of PDF documents. This is available with a charge from www.activepdf.com
- A copy of Microsoft Excel and Microsoft Access version 97 (8.0) or higher.
- Microsoft office Visio version 2000 or higher.

It is recommended having a minimum of 32 MB RAM to run @RISK 4.5. Using 64 MB or more is preferred. The user must have 50MB of free hard disk space for the installation of @RISK. Since @RISK runs simulations which can generate a large amount of temporary data, it is recommend to have an additional 50MB free hard disk space for temporary files.

B.2 Web-Based Stochastic Life Cycle Cost (WSLCC) Software Package

A typical life cycle cost process usually starts by collecting data about the project requirement and constraints. This part describes the development of the web-based software to estimate the life cycle cost for water mains, followed by a the selection of the minimum life cycle cost. The software is believed to help both new and experienced engineers and experts in the establishment of life cycle cost and benefit from the data stored in the database.

The user is required to enter a set of input data that describes the project and user requirement. The simulation is then executed and based on the input data, the software starts the simulation by calling the "@risk package". A report is generated detailing the scenario analysis and cash flow.

B.2.1 System Modeling Steps

The main system modeling consists of four basic steps as follows:

1. Developing an Excel spreadsheet to calculate the life cycle cost.
2. Developing an @risk model.
3. Analyzing the model with simulation.
4. Printing the output results and analysis.

The development of the web based software package was completed after the previous steps. These steps were performed for five pipe types, and three diameter ranges.

B.2.1.1 Developing an Excel spread sheet

This comprises a series of facts used in modeling to calculate the life cycle cost. The Excel spreadsheet file was divided into two sections; new installation and rehabilitation projects. Five Excel files were designed; one file for each pipe material. Each file was divided into three Excel spreadsheets, namely for input data, for various scenarios and for output results.

The input data spreadsheets do not contain any calculations but only contain input data from the user regarding cost of rehabilitation methods, new installation, and operation and maintenance methods. It also includes the deterioration input data, interest rate, and inflation rate. The scenario spreadsheet includes all possible scenarios using each of the entered new installation or rehabilitation alternatives. In this sheet all possible combinations between alternatives and the deterioration data are entered. There are links to the input spreadsheet that allows for updating the cost for each scenario based on the entered data. Formulas are applied to establish the present value and the equivalent annual uniform cost for each scenario. The output spreadsheet includes a summary for all EAUC of each scenario.

B.2.1.2 developing an @risk model

The @ risk model is developed by identifying uncertainty in the input variables and specifying their possible values with probability distributions. The uncertain output results are then identified in the output spreadsheet. The cost input variables are defined by a triangular probability distribution by entering the minimum, most likely and maximum values. Each of the deterioration data were defined by six probability distribution functions (normal, general beta, lognormal, gamma, triangular and uniform probability distribution) and the user has to choose one of these distributions and enter its variable parameters.

The interest rate and the inflation rate were also defined with a triangular probability distribution. The @RISK analysis generates results and stores them in output spreadsheet. Each @risk package includes a program called "Best Fit" which is used to fit the historical break data to the best probability distribution function that best describes these data. The best fit program was also used to fit the output distributions of each scenario.

B.2.1.3 Analyzing the Model Via Simulation

The @RISK uses a Monte Carlo simulation to perform a risk analysis. Simulation in this sense refers to a method whereby the distribution of possible outcomes is generated by allowing a computer to recalculate the worksheet in an repetitive fashion, each time using different randomly selected sets of values for the probability distributions in the input cells and formulas. In effect, the computer is trying all valid combinations of the values of input variables to simulate all possible outcomes.

B.2.1.4 Printing the output results and analysis

The @risk software package generates sets of output reports for each scenario. Each report includes the probability distribution range and likelihood of its occurrence, the cumulative probability distribution, tornado graphs which explain the effect of the input parameters on the output results. The @RISK model window enables fitting probability distributions to input data.

The probability distribution range and likelihood of occurrence are directly related to the level of risk associated with a particular event. Using this distribution helps the user to make a decision based on the level of risk they are willing to take. Figure B.1 shows that the probability distribution of scenario B has greater risk than scenario A. This is due to the fact that the range and the probability of occurrence are more spread for scenario B than that of scenario A.

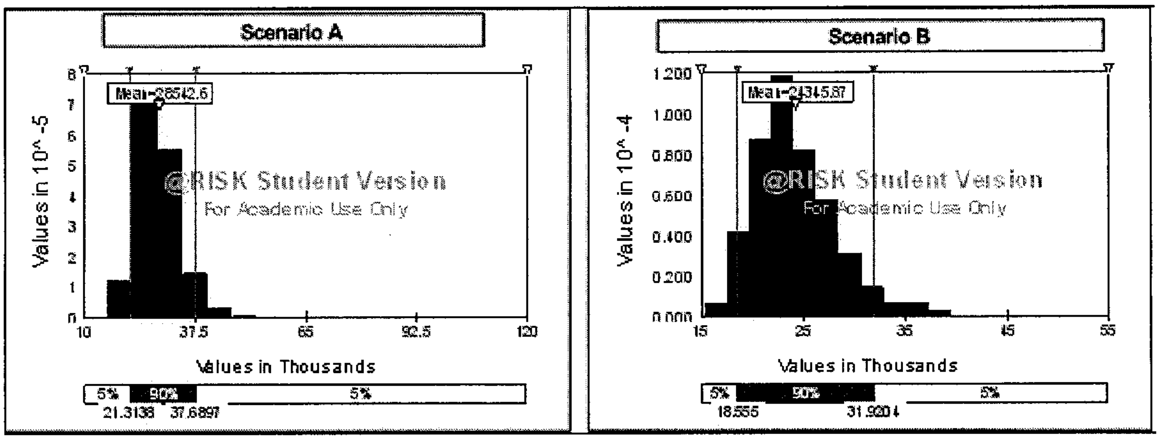


Figure B.1 Probability distribution of scenario A and B

Figure B.2 shows the Probability distribution scenario D represents greater risk than scenario C because the probability of occurrence is uniform across the wide range for scenario D whereas it is concentrated around 24 thousand for scenario C.

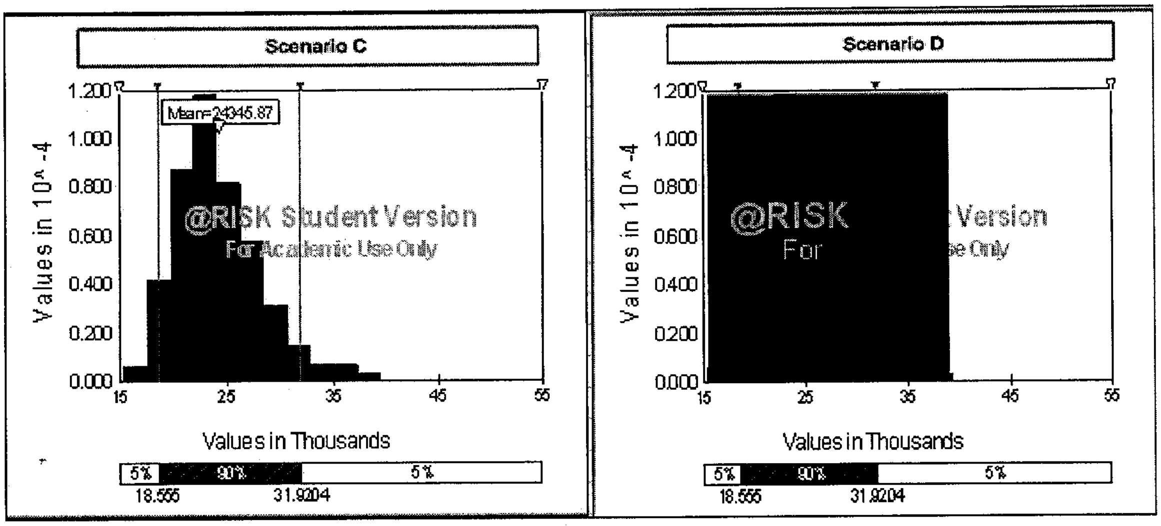


Figure B.2 Probability distribution of scenario C and D

B.2.2 Flow chart of data processing

Figure B.3 shows the flow diagram of data processing required to develop web based software. The model was established using visual basic (VB6). During the modeling process, problems arose which required a modification of the model and the introduction of new steps. The problems encountered faced in the modeling are summarized in the next section.

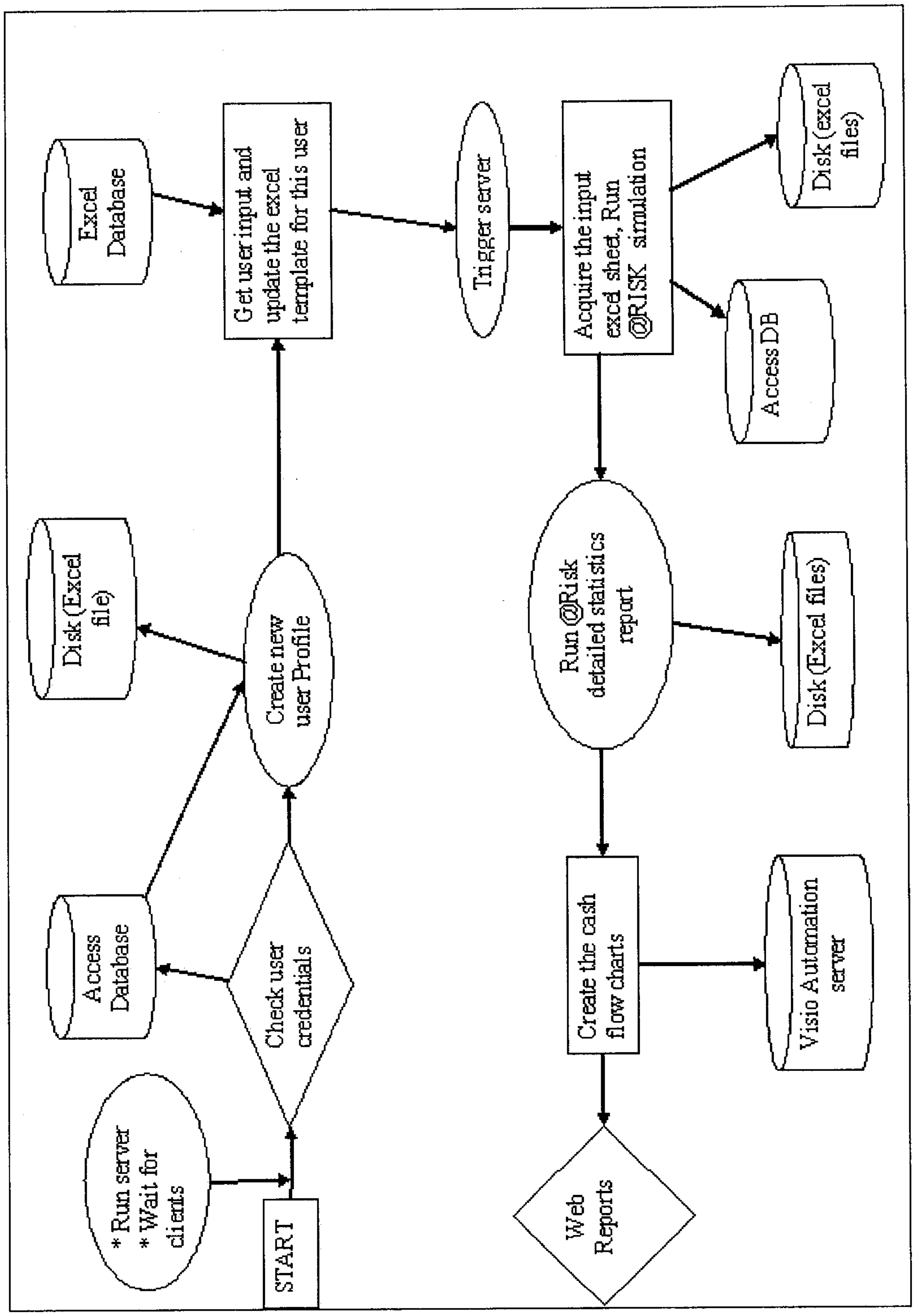


Figure B.3 Data processing for the web based software

As shown in the above flow chart the first step is to start the software package by running the server and waiting for the client to access the web address. As soon as the user registers in the model, the database file in Microsoft Access is updated and creates a new user profile. The program starts by copying typical Excel template files into the new folder for the new user. As soon as the user logs in, the program starts to take the input entered by the user and then update the Excel template file for this user from the Excel database. The server is subsequently triggered and then simulation is carried out.

The simulation is divided into two steps. Firstly, the simulation begins the execution of the @risk module and generates a quick summary report, which includes the output scenario name and the output statistics. After generation of this quick summary report, the program starts generating the detailed statistics report while the user is reading the first quick report. The reason for dividing the simulation reporting into two steps is to reduce the user's idle time. These reports are generated by accessing both Excel template file and Access database. When the simulation ends and during the report generation detailed statistics, the program starts drawing the cash flow of each scenario using Visio automation server. As soon as the detailed statistics report is generated, all links will be active for the user to analyze the output. The program is used to enhance the analysis process by allowing the user to sort data with a minimum, mean or maximum cost and helps the user to select the minimum cost scenario.

B.2.3 Problems Faced During Modeling

There are some problems faced during development of our model. Some of these problems are summarized as follows:

- Selecting suitable software:

1. Monte Carlo. This software has the following limitations; it requires a complete set of modeling through Microsoft Excel, the number of iterations is limited to 1000, it doesn't generate any reports, and it has a limited set of probability distribution functions.
2. Monte Carlo simulation "Crystal Ball" is available on www.palisade.com. This software has the following limitations; it is very slow, includes only 20 probability distribution functions and the license of this software is limited to a 7 day trial period. We were unable to obtain a student version for this software.
3. Monte Carlo simulation "@risk student version". An academic version of this software was obtained. It was satisfactory for our purpose, however, it has the following limitations:
   - @RISK student version models are limited to 4 worksheets, each with 300 rows by 100 columns in a single Excel workbook.
   - The maximum number of @RISK input functions in our model is 100.
   - In the integrated "BestFit" program, data sets are limited to 250 points only.
   - At most 1000 iterations of unattended simulations can be run.

B.2.4 Modification of Monte Carlo Simulation ("@risk" Student Version)

The aforementioned limitations have great influences on this research. The main problem is to choose from 6 probability distribution functions for each break time in the deterioration input data. This required at least 200 @RISK input functions in order to predefine these functions for all breaks and for all pipe types. But the user can only have about 20 @RISK input functions to run the simulation. Therefore, an Excel macro was introduced to solve this problem by developing a series of If-Then scenarios.

The second problem was that the student version may run at most 1000 iterations of unattended simulations. Furthermore, we were unable to run a simulation using VBA directly. Therefore, an Excel macro was employed to run the simulation. This problem is associated only while using the @ risk student version. It is recommended to use the professional version instead of the academic version.

The third problem time required for generating a report, as the program needs approximately 10-15 seconds to generate a detailed report for each scenario. A total of 200 scenarios are required for both new installation and rehabilitation projects. Therefore, as least 60 minutes are required to develop this report. This is a relatively long time for both the server and user. To overcome this problem, the model was divided into two main sections; new installation and rehabilitation. Using this division, the total number of scenarios was reduced approximately in half. In addition, the repeated scenarios and non reasonable scenarios were disregarded. Using these modifications, the simulation was reduced to 68 scenarios. These scenarios were organized into sub-sections where the user can only select the required category so the program doesn't have to generate a detailed report for all scenarios. The report generation time was reduced to a maximum of 10 minutes instead of 60 minutes.

In summary, the user has an option to choose either a new installation project or rehabilitation categories to get a detailed report. The installation project contains only 8 scenarios and the rehabilitation project(s) contains three main sub categories: repair, renovation, and replacement. The user can choose to obtain a report for one or more sub-category which saves time.

B.3 Overview of the main input and output

This section provides an overview of the final web-based software developed and a guide to the user detailing the required input data and output information. As shown in Figure B.4, the required input data are as follows:

Input data

1. Pipe material
2. Pipe diameter range
3. The project type (new installation or rehabilitation)
4. Interest rate
5. Inflation rate
6. Operation & maintenance cost
7. Deterioration data for the main pipe
8. Rehabilitation method

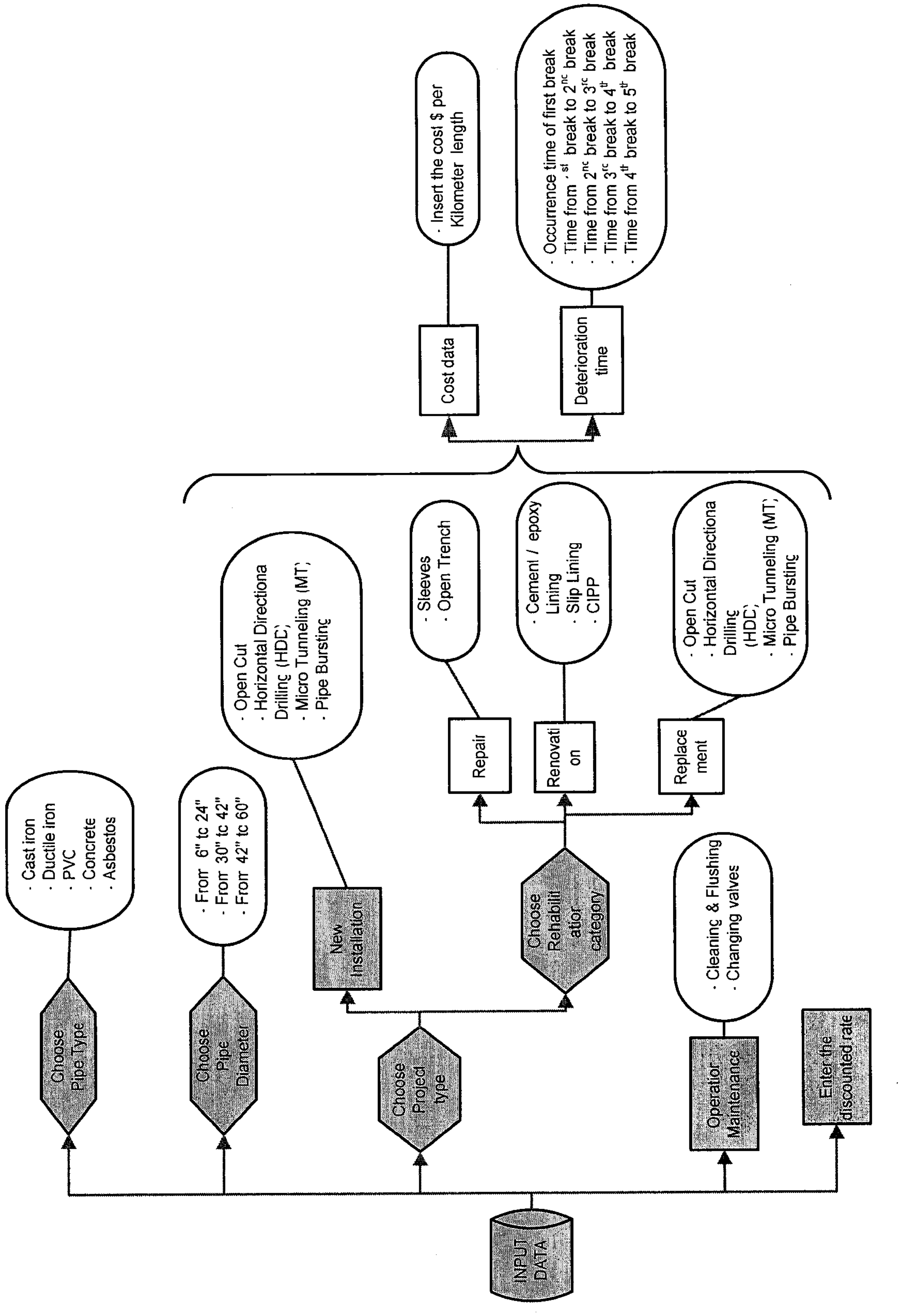


Figure B.4 Input data

B.4 Rehabilitation Project(s)

A typical start screen, as shown in Figure B.5, appears when the user starts the WSLCC software. The user is asked to register and enter a user name, password, full name, and email address as shown. The program will create a new folder for the user and copy all necessary files to this folder. The user is directed to the login page, where a user name and password is required to have access to old files.

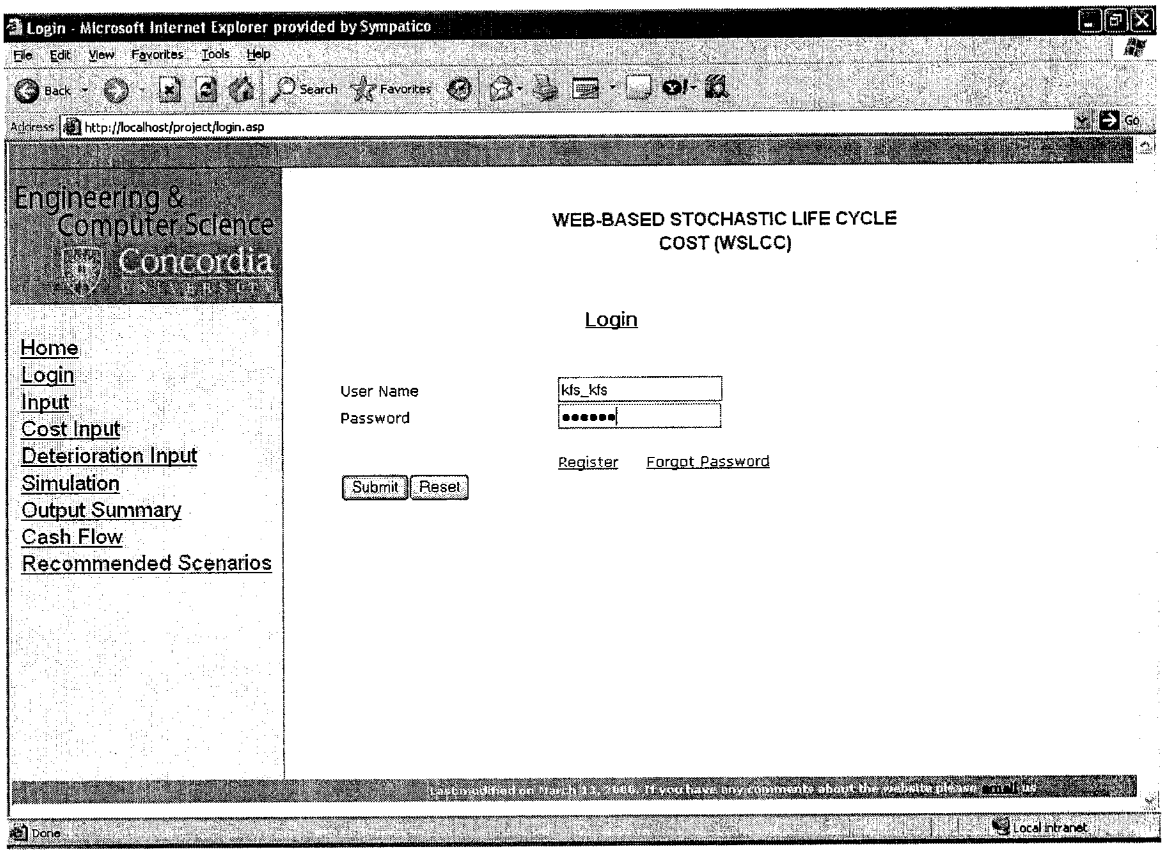


Figure B.5 Login page

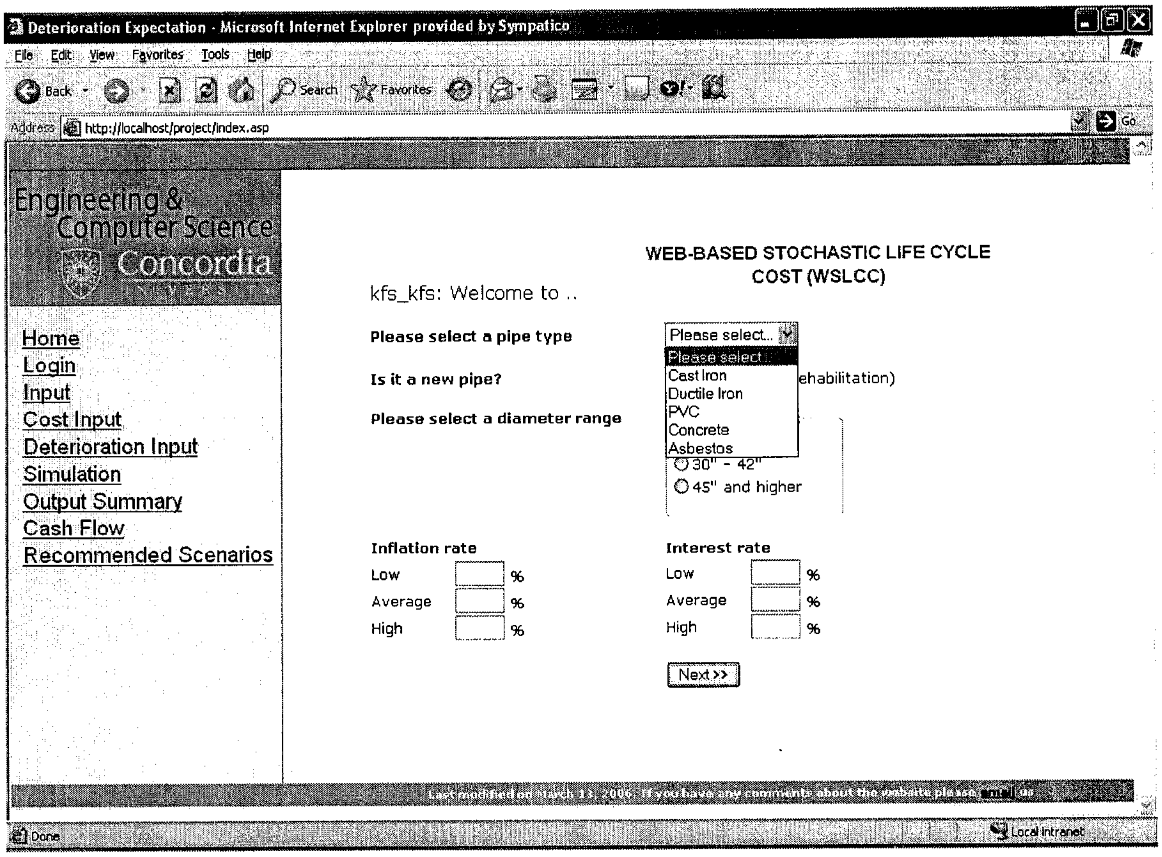


Figure B.6 Main screen page

The user is then directed to the main page shown in Figure B.6. In this screen, the required data are arranged to be easily selected or introduced. The user has to select the project type (new installation or rehabilitation). The material type (Cast Iron, Ductile Iron, PVC, Concrete, and Asbestos Cement), pipe diameter range, interest rate values (minimum, maximum, and average) and inflation rate are also selected.

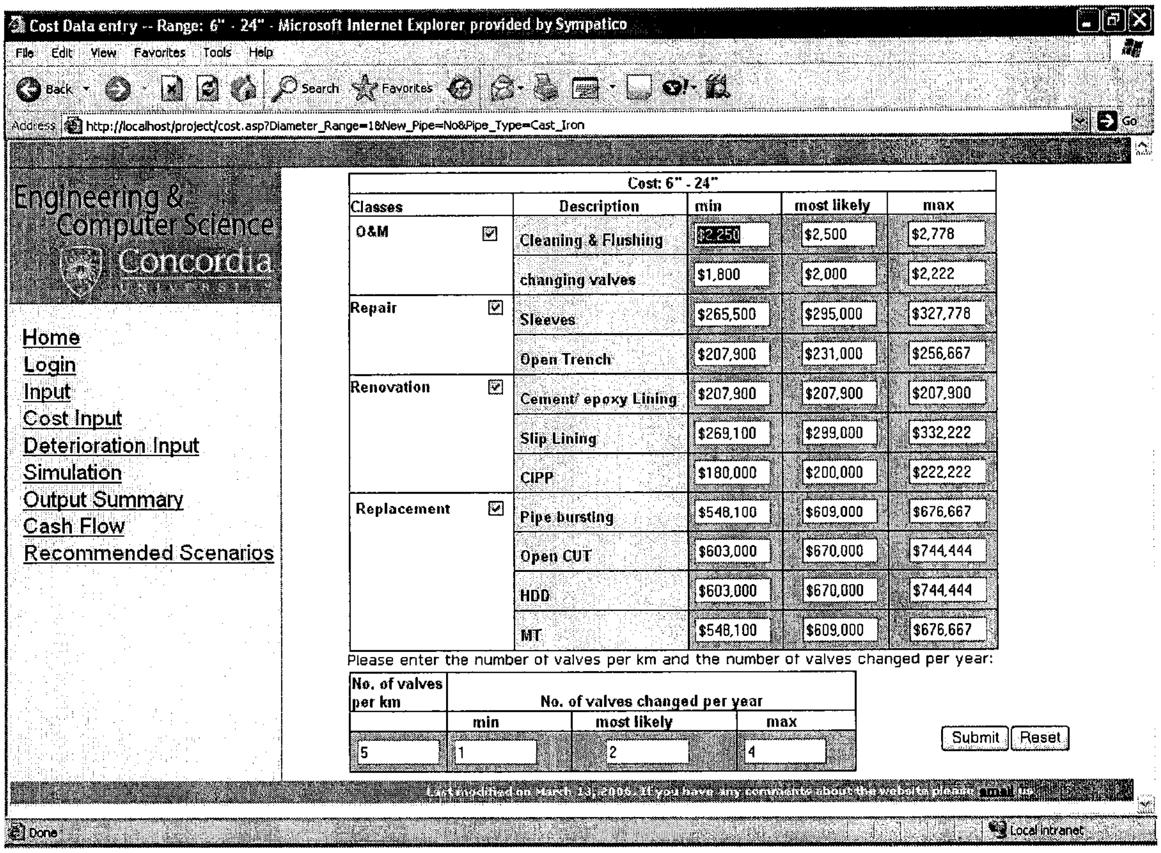


Figure B.7 Cost data screen

The user defines the values for the triangular probability distribution, for the cost data of the selected class or category as indicated in Figure B.7. The user can also select more than one category to collect the life cycle cost for them. In this example, Renovation and Operation & Maintenance categories were selected. All cost data units should be entered in $/km. Number of valves changed per year for each km of pipe length. The total number of valves per km length of the pipe and their triangular probability distribution of the estimated number of valves changed per year are entered (B.7).

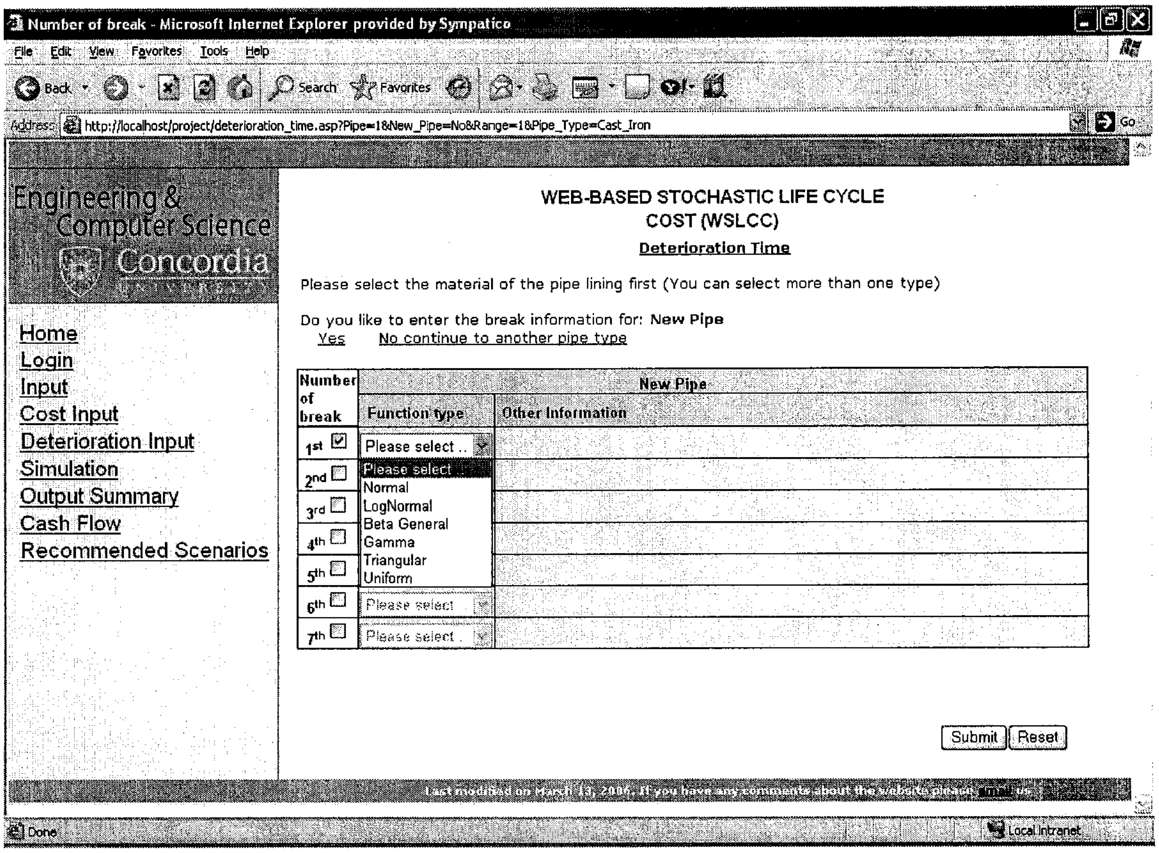


Figure B.8 Deterioration data screen

The user may enter the deterioration data for the new pipe (or the existing pipe), by selecting the break number and the probability distribution estimated for this break. The user can choose from 6 probability distribution functions such as Normal, Log Normal, Gamma, General Beta, triangular, and uniform. For example, the user can enter a normal probability distribution function for the first break timing by entering the mean, standard deviation, and the truncated minimum (TR min.) and maximum (TR max.) values. The truncated minimum and maximum values are important because they prevent the chance of obtaining negative values for the normal probability distribution or an unrealistic value for the maximum break time. It should be noted that the user can choose not to enter any new data and use the stored data in the program. The program will automatically get the incomplete data from the stored database.

The previous steps will be repeated for all liner materials available in the rehabilitation methods. Figure B.8 to Figure B.11 show the deterioration screens for Epoxy/Cement lining, Slip Lining, and Cured-in-Place pipe (CIPP) rehabilitation methods respectively.

After entering the above input data, the program will be directed to the simulation page where the program can be executed (Figure B.12).

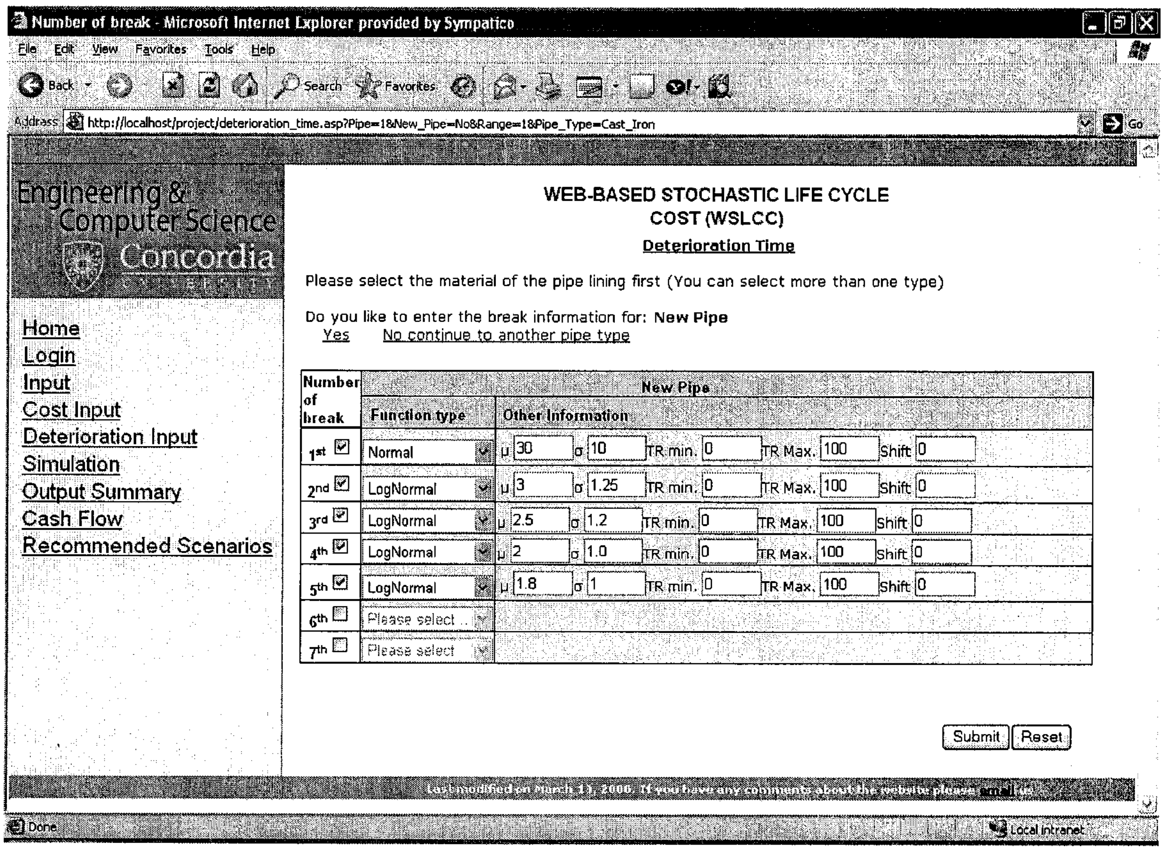


Figure B.9 Deterioration screen for new pipe rehabilitation method.

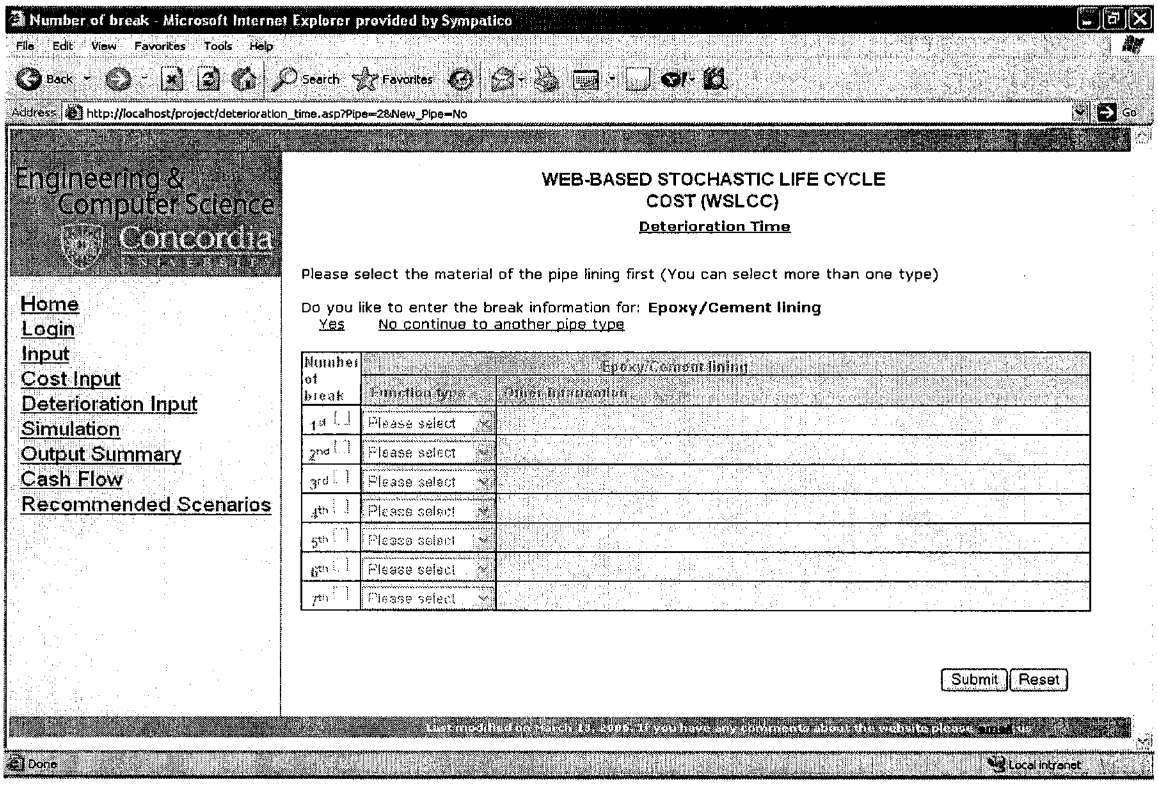


Figure B.10 Deterioration for epoxy/ cement lining rehabilitation method.

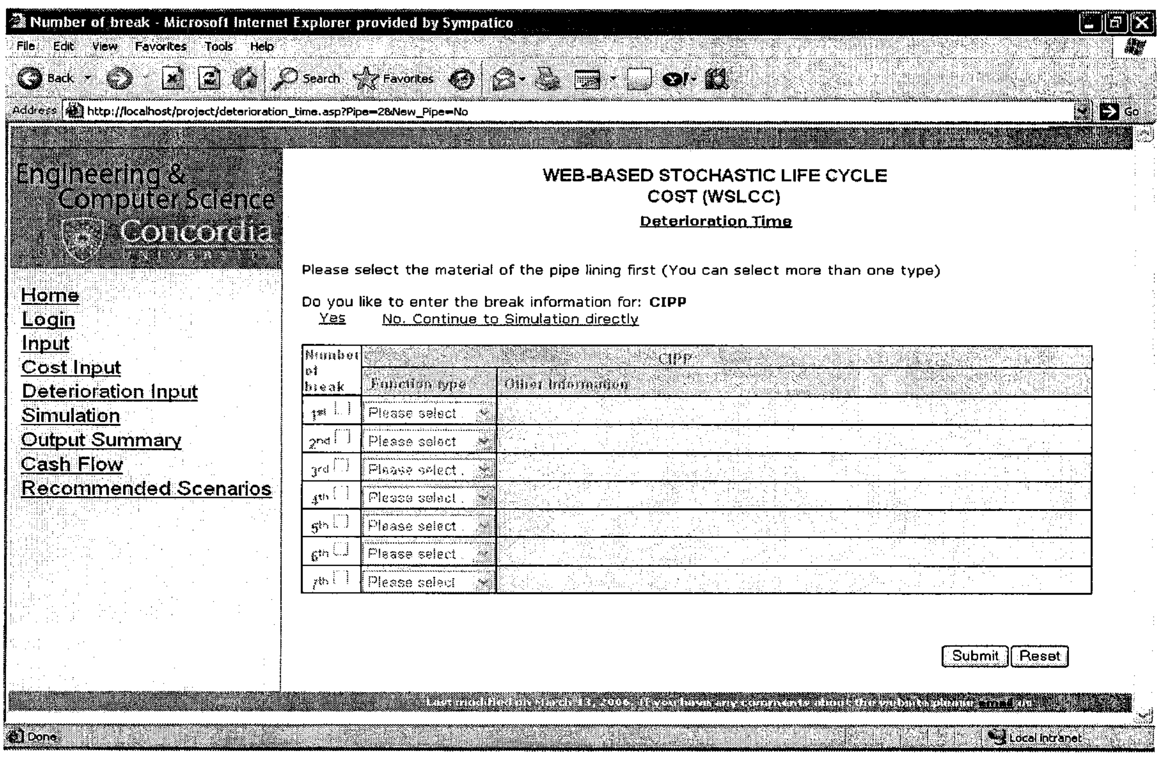


Figure B.11 Deterioration screen for cured in place pipe (CIPP) rehabilitation methods

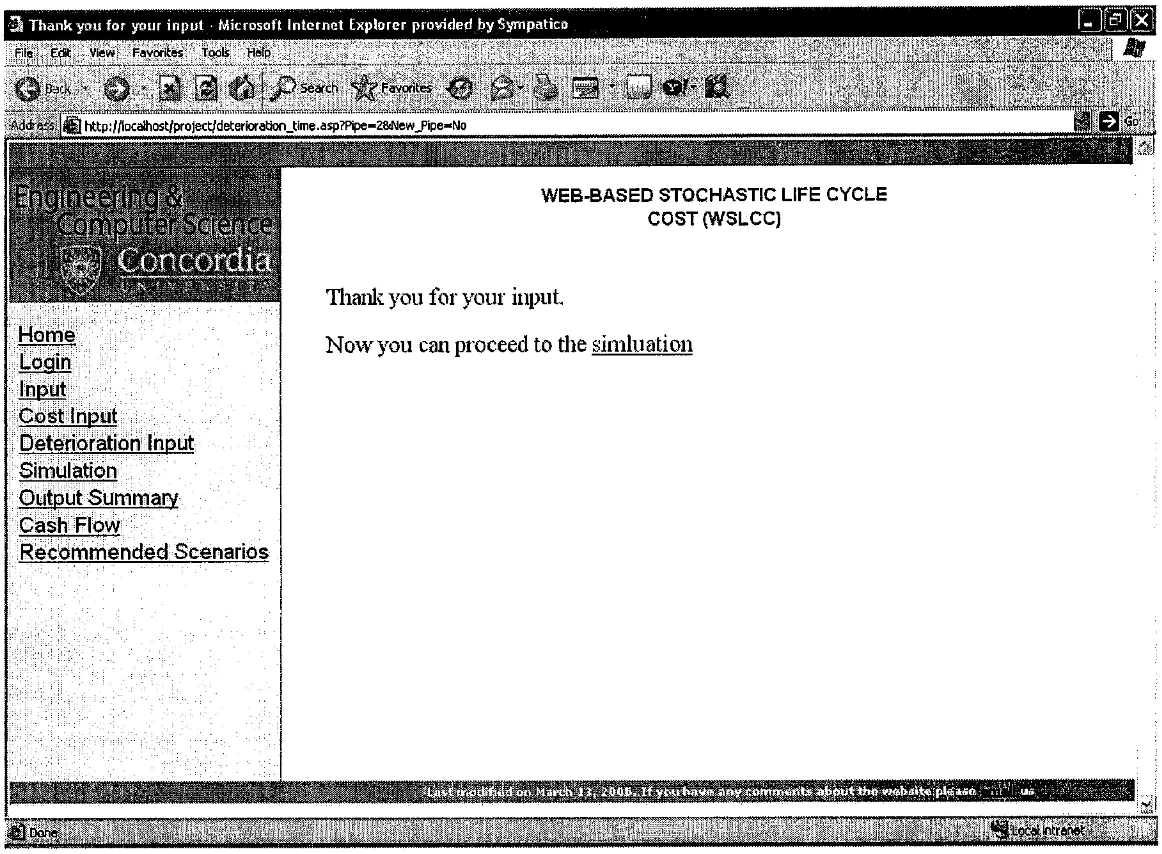


Figure B.12 Start screen for simulation.

Figure B.13 shows the results of a simulation analysis in which the top 5 scenarios are displayed. It includes a quick statistical summary of all scenarios including the minimum, mean, and maximum equivalent annual uniform cost (EAUC) values. The user can sort the scenarios based on minimum, mean, or maximum EAUC. The program also provides the values at 5% and 95% percentile confidence levels. The simulation summary screen contains links for different items. For example, a link to view the input data list, the cash flow and a detailed report for each scenario can be viewed in PDF format by clicking on item required.

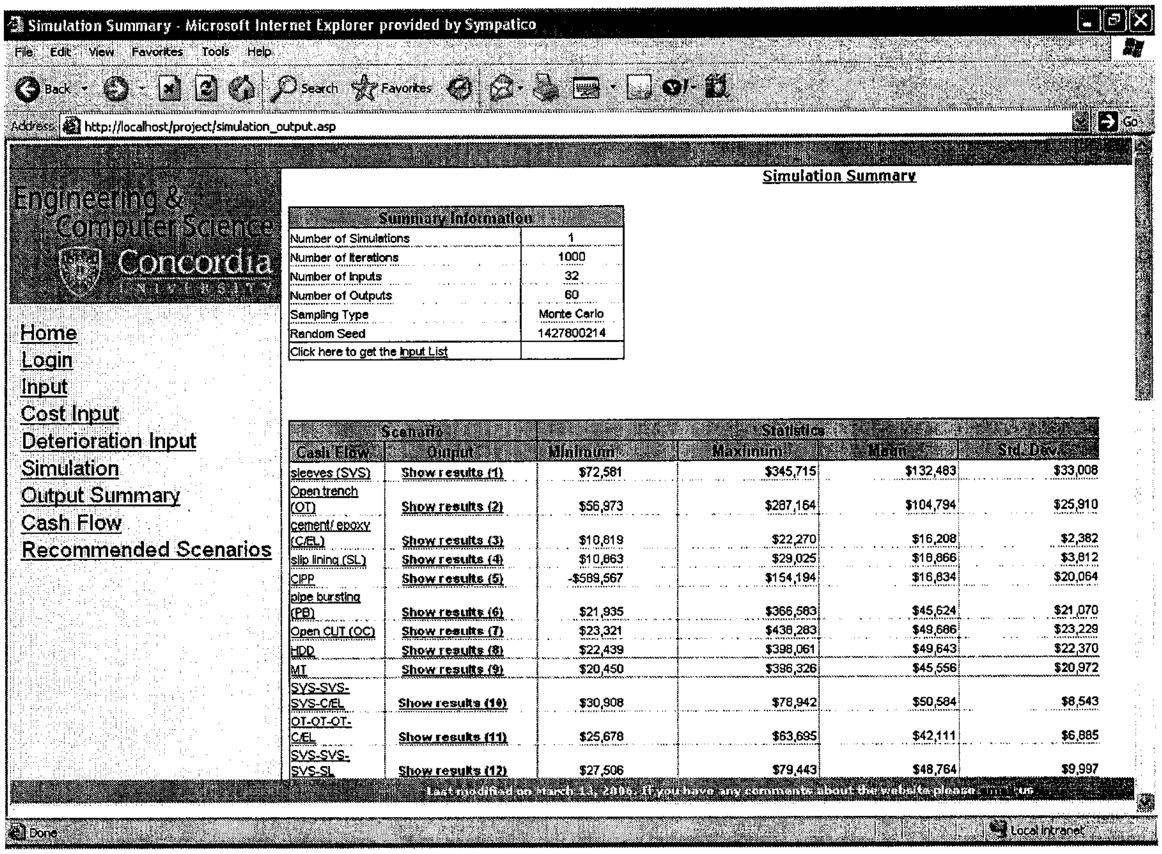


Figure B.13 Results of simulation analysis

The program can use Microsoft Visio in order to generate a cash flow diagram for each scenario, as shown in Figure B.3. The user can access this page from the simulation summary (Figure B.14) of the main page by clicking on the "show cash" flow link. The cash flow appears as an image in PDF format.

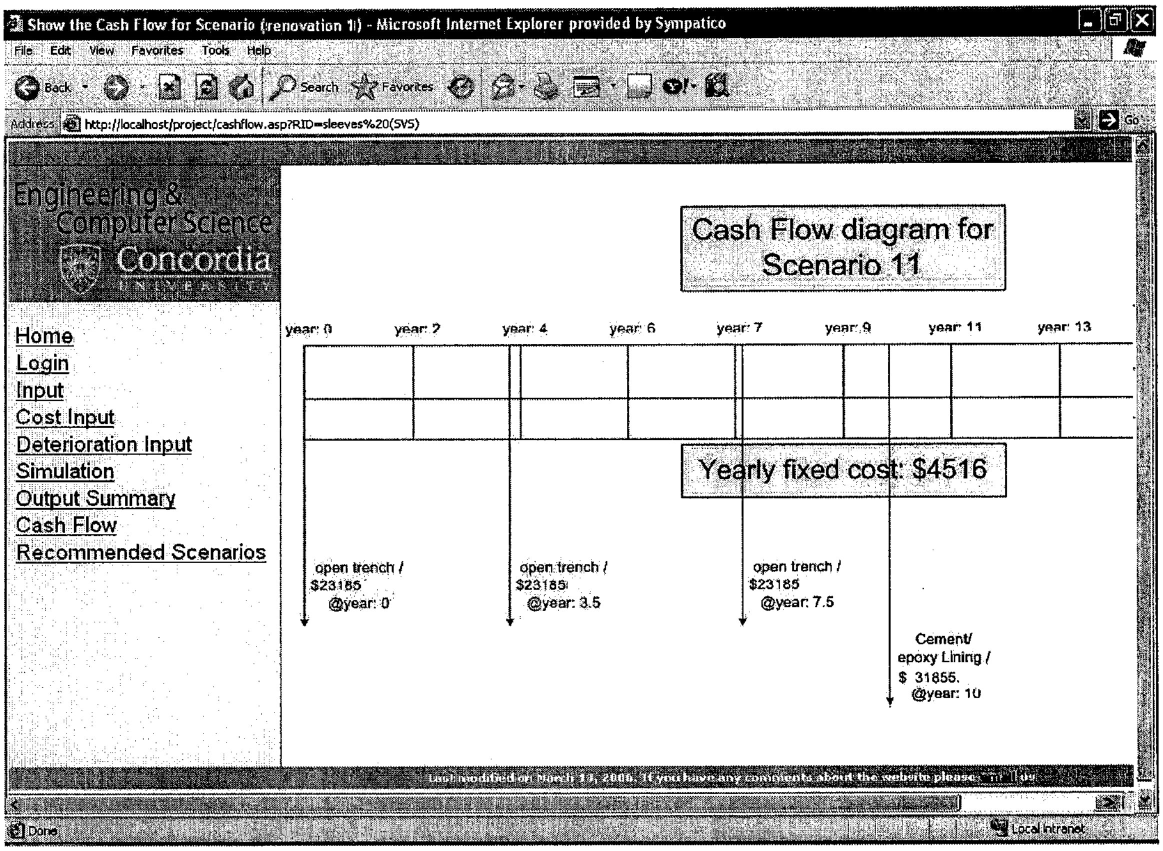


Figure B.14 Cash flow diagram

The detailed report can be accessed by clicking on "show report "in the simulation summary located on the main page. As shown in Figure B.15, the report shows the distribution of the scenario, a cumulative probability distribution, and a tornado graph. The latter summarizes the sensitivity analysis for that scenario and defines the sensitive input parameters that may affect the total output results.

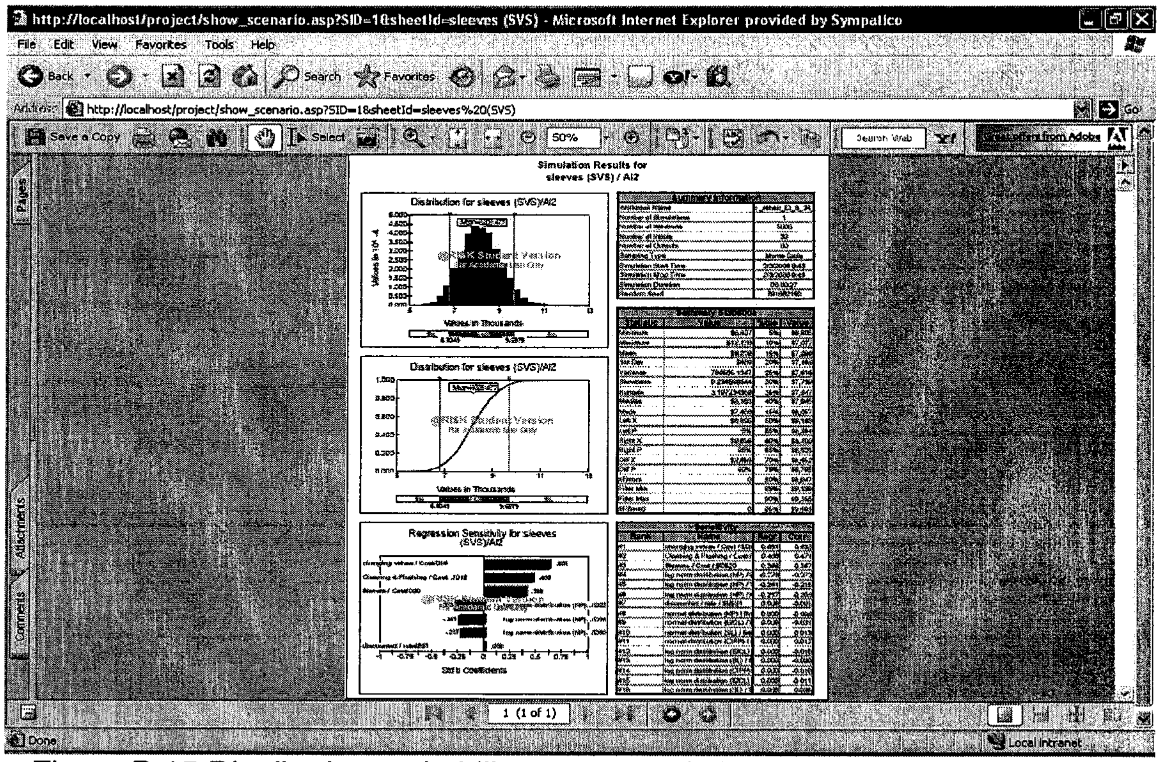
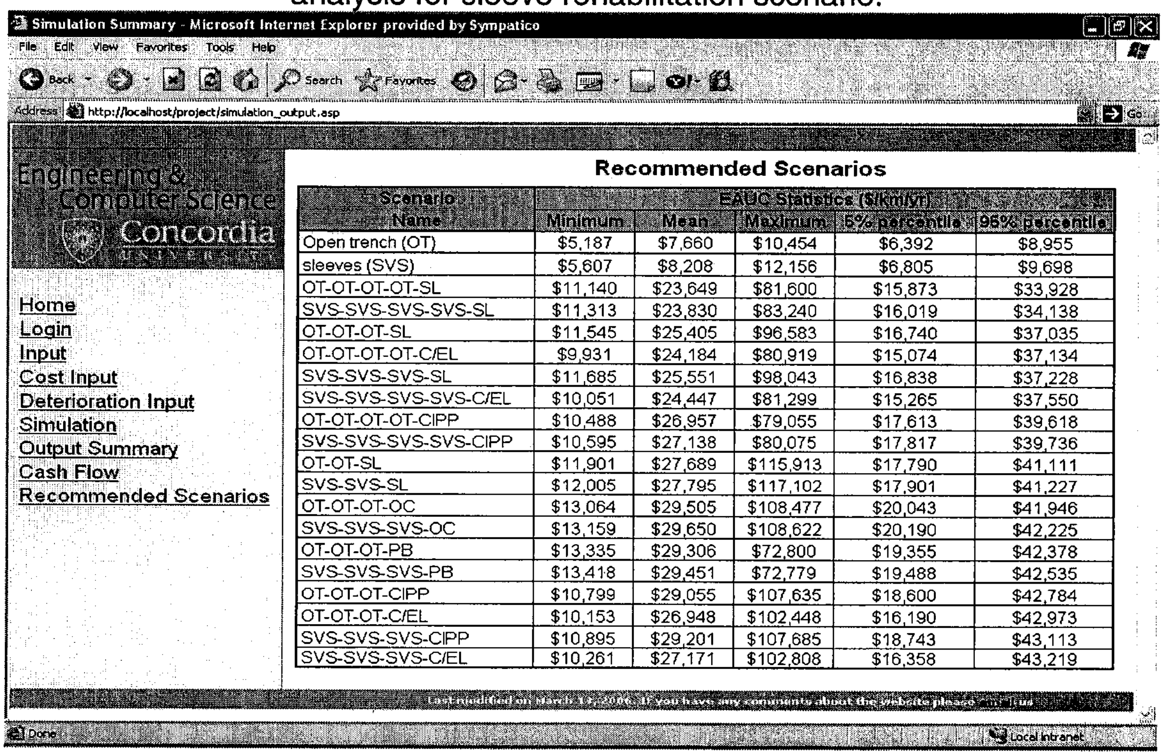


Figure B.15 Distribution probability, cost cumulative and regression sensitivity analysis for sleeve rehabilitation scenario.



Recommended Scenarios

Scenario Name	EAUC Statistics ($/km/yr)				
	Minimum	Mean	Maximum	5% percentile	95% percentile
Open trench (OT)	$5,187	$7,660	$10,454	$6,392	$8,955
sleeves (SVS)	$5,607	$8,208	$12,156	$6,805	$9,698
OT-OT-OT-OT-SL	$11,140	$23,649	$81,600	$15,873	$33,928
SVS-SVS-SVS-SVS-SL	$11,313	$23,830	$83,240	$16,019	$34,138
OT-OT-OT-SL	$11,545	$25,405	$96,583	$16,740	$37,035
OT-OT-OT-OT-C/EL	$9,931	$24,184	$80,919	$15,074	$37,134
SVS-SVS-SVS-SL	$11,685	$25,551	$98,043	$16,838	$37,228
SVS-SVS-SVS-SVS-C/EL	$10,051	$24,447	$81,299	$15,265	$37,550
OT-OT-OT-OT-CIPP	$10,488	$26,957	$79,055	$17,613	$39,618
SVS-SVS-SVS-SVS-CIPP	$10,595	$27,138	$80,075	$17,817	$39,736
OT-OT-SL	$11,901	$27,689	$115,913	$17,790	$41,111
SVS-SVS-SL	$12,005	$27,795	$117,102	$17,901	$41,227
OT-OT-OT-OC	$13,064	$29,505	$108,477	$20,043	$41,946
SVS-SVS-SVS-OC	$13,159	$29,650	$108,622	$20,190	$42,225
OT-OT-OT-PB	$13,335	$29,306	$72,800	$19,355	$42,378
SVS-SVS-SVS-PB	$13,418	$29,451	$72,779	$19,488	$42,535
OT-OT-OT-CIPP	$10,799	$29,055	$107,635	$18,600	$42,784
OT-OT-OT-C/EL	$10,153	$26,948	$102,448	$16,190	$42,973
SVS-SVS-SVS-CIPP	$10,895	$29,201	$107,685	$18,743	$43,113
SVS-SVS-SVS-C/EL	$10,261	$27,171	$102,808	$16,358	$43,219

Figure B.16 Finally the program can recommend the best minimum life cycle cost scenarios

B.5 New Installation Project(s)

For inputting date associated with new installation projects, the user is directed to the main page shown in Figure B.17. On this screen, the user must select the project type (new installation or rehabilitation). Pipe material type (Cast Iron, Ductile Iron, PVC, Concrete, and Asbestos Cement), pipe diameter range, interest rate values (minimum, maximum, and average) and inflation rate are also selected. In this example, new installation project was selected. All cost data units should be in $/km. The procedure is similar to the one employed in the rehabilitation projects. The data and output are presented in Figure B.21.

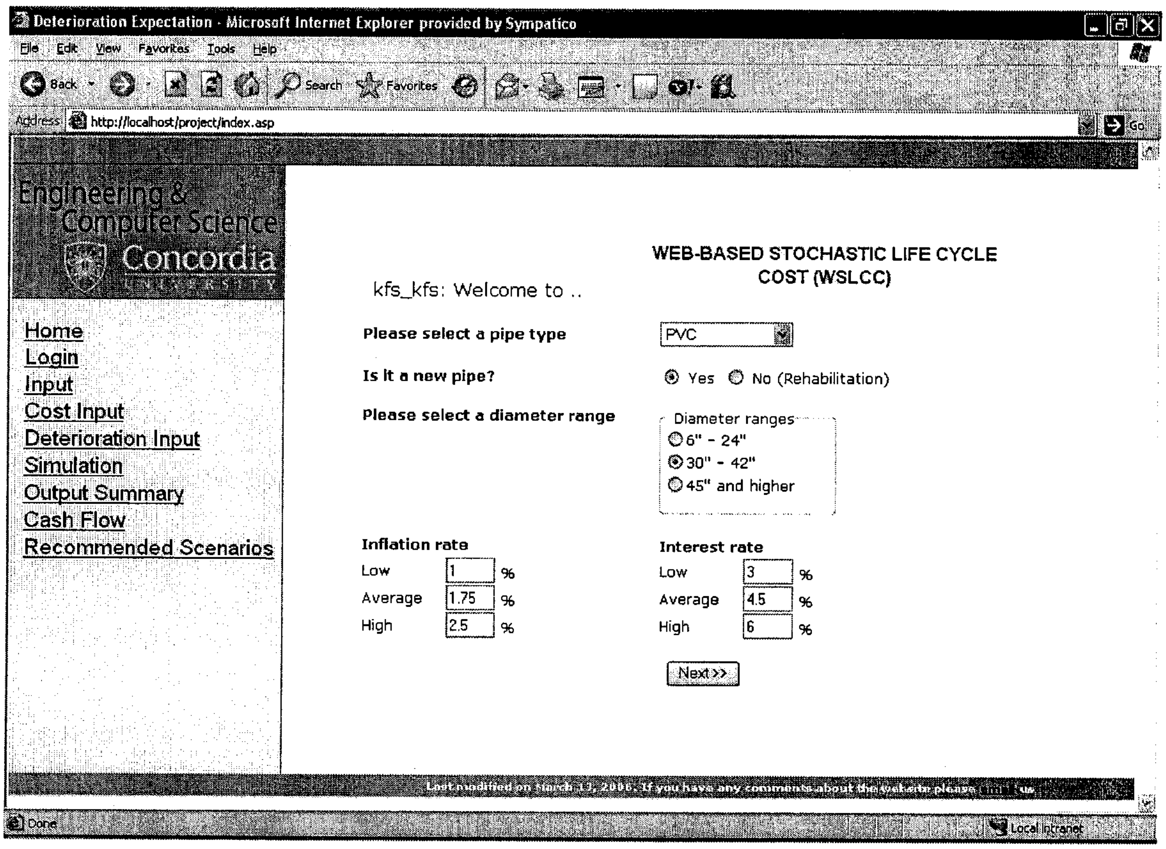


Figure B.17 Main screen page for PVC Construction pipes

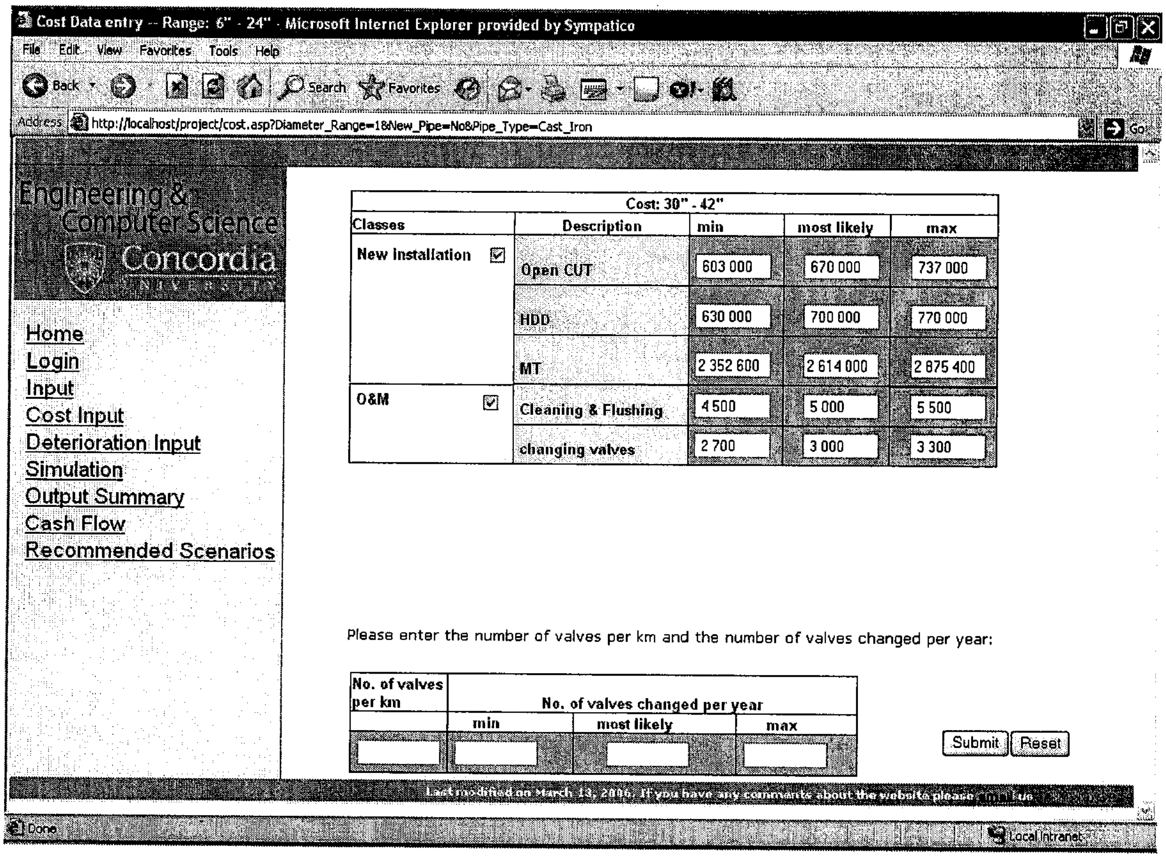


Figure B.18 The cost data screen

The user is then directed to the cost information page (Figure B.18) and asked to enter the triangular distribution values for each new installation method. The operation & maintenance cost data is selected. Finally, the total number of valves per km length of pipe and the probability distribution of the total number of replaced valves per year are introduced.

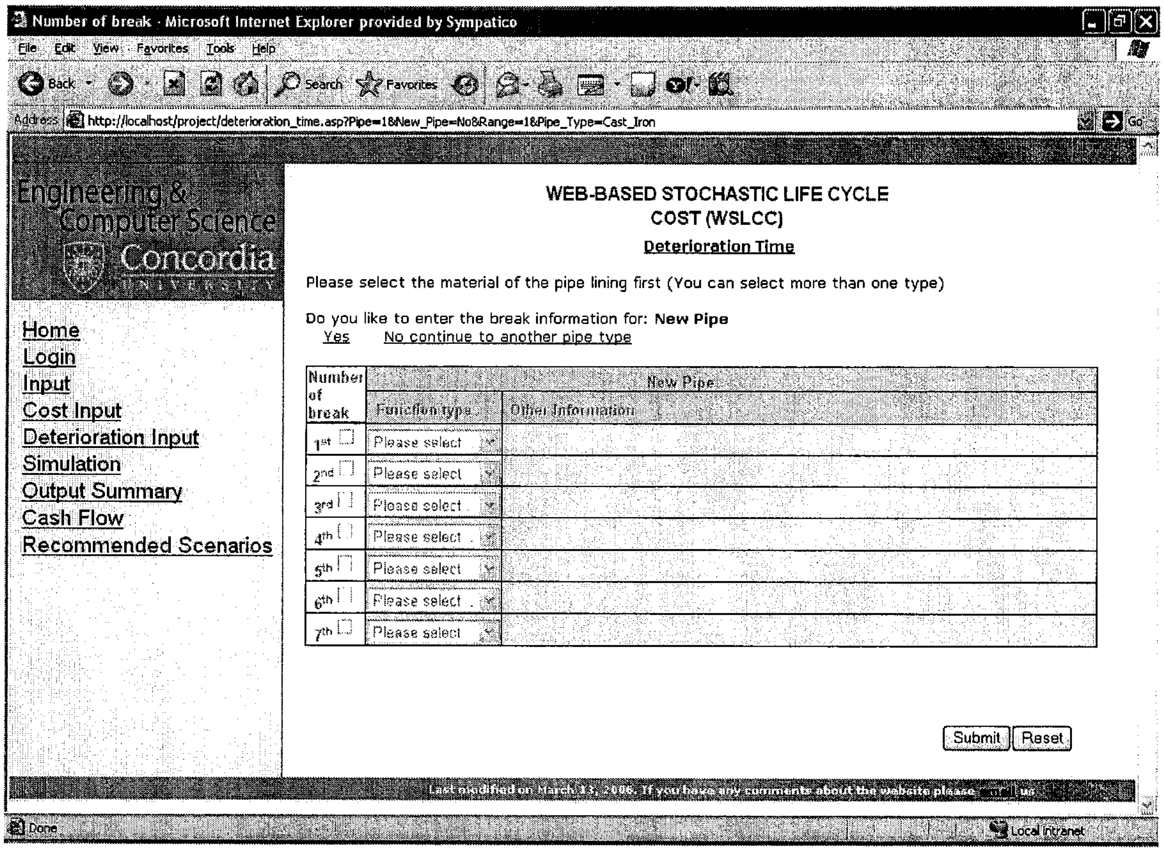


Figure B.19 Deterioration screen for new pipe installation

After entering the above input data, the program will be directed to the simulation page for the new installed pipe and the initial cement lining (Figure B.20).

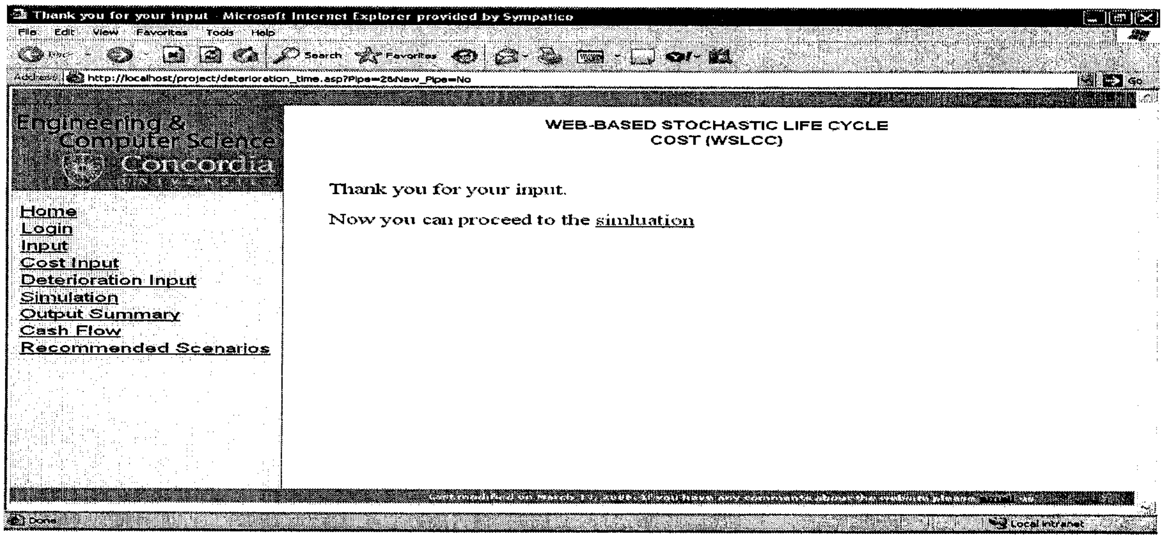


Figure B.20 Start screen for simulation

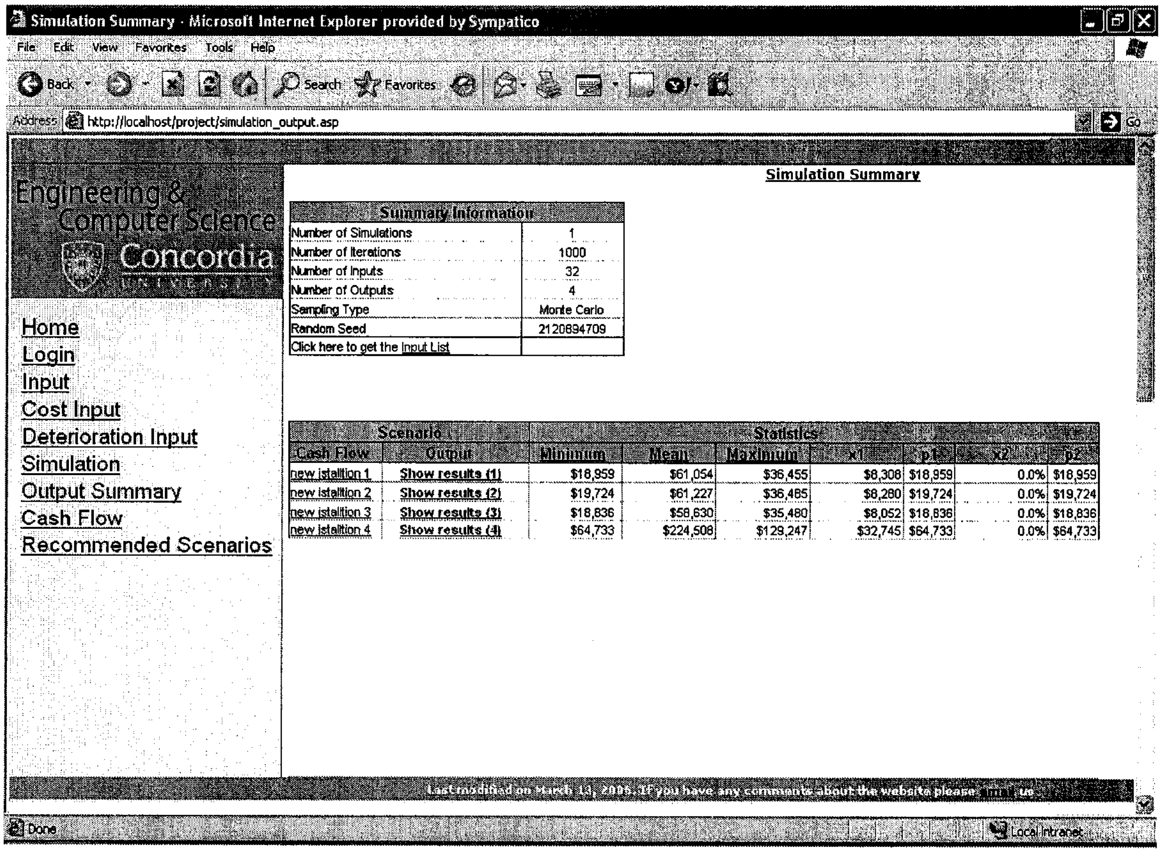


Figure B.21 Results of simulation analysis

Similar to the rehabilitation project, a simulation summary page will appear after ending the simulation. The user will have access to a detailed report for each scenario, including cash flow and a simulation input summary.

Limitations of the developed software:

1- Limitations of the @risk student version

2- User cannot have access to change or develop new scenarios.

3- User has to wait until the total simulation report is generated for all scenarios in order to view the detailed report for any scenario.

APPENDIX C: Rehabilitation and New Installation Scenarios

REHABILITATION SCENARIOS

	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 1	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	Sleeves	$296,093	0.727	$215,404
	10.00	Sleeves	$296,093	0.654	$193,730
	10.00	Disposal			
	annual cost	Cleaning & Flushing	$2,509	7.978	$20,019
	annual cost	changing valves	$2,007	7.978	$16,015
		TOTAL PV			$996,499
		EAUC			$124,907
scenario 2	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	open trench	$231,856	0.727	$168,673
	10.00	open trench	$231,856	0.654	$151,700
	10.00	Disposal			
	annual cost	Cleaning & Flushing	$2,509	7.978	$20,019
	annual cost	changing valves	$2,007	7.978	$16,015
		TOTAL PV			$788,127
		EAUC			$98,788
scenario 3	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Cement/ epoxy Lining	$231,856	1.000	$231,856
	8.45	Disposal			
	annual cost	Cleaning & Flushing	$2,509	6.951	$17,442
	annual cost	changing valves	$2,007	6.951	$13,953
		TOTAL PV			$263,250
		EAUC			$37,873
scenario 4	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Slip Lining	$300,107	1.000	$300,107
	61.38	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.369	$53,620
	annual cost	changing valves	$2,007	21.369	$42,896
		TOTAL PV			$396,624
		EAUC			$18,561
scenario 5	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	CIPP	$200,741	1.000	$200,741
	31.50	Disposal			
	annual cost	Cleaning & Flushing	$2,509	17.012	$42,687
	annual cost	changing valves	$2,007	17.012	$34,149
		TOTAL PV			$277,577
		EAUC			$16,317
scenario 6	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Pipe bursting	$672,481	1.000	$672,481
	61.25	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.360	$53,598
	annual cost	changing valves	$2,007	21.360	$42,878
		TOTAL PV			$768,957
		EAUC			$36,000

	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 7	0.00	Open CUT	$672,481	1.000	$672,481
	61.25	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.360	$53,598
	annual cost	changing valves	$2,007	21.360	$42,878
	TOTAL PV				$768,957
	EAUC				$36,000
scenario8	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	HDD	$652,407	1.000	$652,407
	61.25	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.360	$53,598
	annual cost	changing valves	$2,007	21.360	$42,878
	TOTAL PV				$748,883
	EAUC				$35,060
scenario9	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	MT	$2,623,681	1.000	$2,623,681
	61.25	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.360	$53,598
	annual cost	changing valves	$2,007	21.360	$42,878
	TOTAL PV				$2,720,157
	EAUC				$127,348
scenario 10	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	Sleeves	$296,093	0.727	$215,404
	10.00	Cement/ epoxy Lining	$231,856	0.654	$151,700
	18.45	Disposal			
	annual cost	Cleaning & Flushing	$2,509	12.526	$31,431
	annual cost	changing valves	$2,007	12.526	$25,144
	TOTAL PV				$423,680
	EAUC				$33,824
scenario 11	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	open trench	$231,856	0.727	$168,673
	10.00	Cement/ epoxy Lining	$231,856	0.654	$151,700
	18.45	Disposal			
	annual cost	Cleaning & Flushing	$2,509	12.526	$31,431
	annual cost	changing valves	$2,007	12.526	$25,144
	TOTAL PV				$808,669
	EAUC				$64,560
scenario12	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	Sleeves	$296,093	0.727	$215,404
	10.00	Slip Lining	$300,107	0.654	$196,357
	71.38	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.959	$55,102
	annual cost	changing valves	$2,007	21.959	$44,082
	TOTAL PV				$1,062,276
	EAUC				$48,374

	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 13	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	open trench	$231,856	0.727	$168,673
	10.00	Slip Lining	$300,107	0.654	$196,357
	71.38	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.959	$55,102
	annual cost	changing valves	$2,007	21.959	$44,082
	TOTAL PV				$895,933
	EAUC				$40,799
scenario 14	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	Sleeves	$296,093	0.727	$215,404
	10.00	CIPP	$200,741	0.654	$131,342
	41.50	Disposal			
	annual cost	Cleaning & Flushing	$2,509	19.108	$47,948
	annual cost	changing valves	$2,007	19.108	$38,359
	TOTAL PV				$984,385
	EAUC				$51,516
scenario 15	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	open trench	$231,856	0.727	$168,673
	10.00	CIPP	$200,741	0.654	$131,342
	41.50	Disposal			
	annual cost	Cleaning & Flushing	$2,509	19.108	$47,948
	annual cost	changing valves	$2,007	19.108	$38,359
	TOTAL PV				$818,042
	EAUC				$42,810
scenario 16	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	Cement/ epoxy Lining	$231,856	0.727	$168,673
	15.95	Disposal			
	annual cost	Cleaning & Flushing	$2,509	11.345	$28,469
	annual cost	changing valves	$2,007	11.345	$22,775
	TOTAL PV				$771,247
	EAUC				$67,979
scenario 17	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	Cement/ epoxy Lining	$231,856	0.727	$168,673
	15.95	Disposal			
	annual cost	Cleaning & Flushing	$2,509	11.345	$28,469
	annual cost	changing valves	$2,007	11.345	$22,775
	TOTAL PV				$651,637
	EAUC				$57,436
scenario 18	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	Slip Lining	$300,107	0.727	$218,325
	68.88	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.834	$54,788
	annual cost	changing valves	$2,007	21.834	$43,831
	TOTAL PV				$868,275
	EAUC				$39,766

Scenario	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 19	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	Slip Lining	$300,107	0.727	$218,325
	68.88	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.834	$54,788
	annual cost	changing valves	$2,007	21.834	$43,831
		TOTAL PV			$748,665
		EAUC			$34,288
scenario 20	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	CIPP	$200,741	0.727	$146,037
	39.00	Disposal			
	annual cost	Cleaning & Flushing	$2,509	18.664	$46,834
	annual cost	changing valves	$2,007	18.664	$37,467
		TOTAL PV			$781,670
		EAUC			$41,880
scenario 21	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	CIPP	$200,741	0.727	$146,037
	39.00	Disposal			
	annual cost	Cleaning & Flushing	$2,509	18.664	$46,834
	annual cost	changing valves	$2,007	18.664	$37,467
		TOTAL PV			$662,059
		EAUC			$35,472
scenario 22	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Cement/ epoxy Lining	$231,856	0.862	$199,865
	11.95	Disposal			
	annual cost	Cleaning & Flushing	$2,509	9.176	$23,025
	annual cost	changing valves	$2,007	9.176	$18,420
		TOTAL PV			$537,402
		EAUC			$58,567
scenario 23	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	Cement/ epoxy Lining	$231,856	0.862	$199,865
	11.95	Disposal			
	annual cost	Cleaning & Flushing	$2,509	9.176	$23,025
	annual cost	changing valves	$2,007	9.176	$18,420
		TOTAL PV			$473,165
		EAUC			$51,566
scenario 24	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Slip Lining	$300,107	0.862	$258,700
	64.88	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.605	$54,212
	annual cost	changing valves	$2,007	21.605	$43,369
	TOTAL PV				$652,373
	EAUC				$30,196

Scenario	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 25	0.00	open trench	$231,856	1.000	$231,856
	3.50	Slip Lining	$300,107	0.862	$258,700
	64.88	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.605	$54,212
	annual cost	changing valves	$2,007	21.605	$43,369
	TOTAL PV				$588,136
	EAUC				$27,223
scenario 26	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	CIPP	$200,741	0.862	$173,043
	35.00	Disposal			
	annual cost	Cleaning & Flushing	$2,509	17.849	$44,787
	annual cost	changing valves	$2,007	17.849	$35,829
	TOTAL PV				$549,752
	EAUC				$30,801
scenario 27	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	CIPP	$200,741	0.862	$173,043
	35.00	Disposal			
	annual cost	Cleaning & Flushing	$2,509	17.849	$44,787
	annual cost	changing valves	$2,007	17.849	$35,829
	TOTAL PV				$485,515
	EAUC				$27,202
scenario 28	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Cement/ epoxy Lining	$231,856	1.000	$231,856
	8.45	Pipe bursting	$672,481	0.699	$469,926
	69.70	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.877	$54,895
	annual cost	changing valves	$2,007	21.877	$43,916
	TOTAL PV				$800,593
	EAUC				$36,595
scenario 29	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Slip Lining	$300,107	1.000	$300,107
	61.38	Pipe bursting	$672,481	0.074	$49,770
	122.63	Disposal			
	annual cost	Cleaning & Flushing	$2,509	22.950	$57,587
	annual cost	changing valves	$2,007	22.950	$46,070
	TOTAL PV				$453,534
	EAUC				$19,762
scenario 30	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Cement/ epoxy Lining	$231,856	1.000	$231,856
	8.45	Open CUT	$672,481	0.699	$469,926
	69.70	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.877	$54,895
	annual cost	changing valves	$2,007	21.877	$43,916
	TOTAL PV				$800,593
	EAUC				$36,595
scenario 31	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Slip Lining	$300,107	1.000	$300,107
	61.38	Open CUT	$672,481	0.074	$49,770
	122.63	Disposal			
	annual cost	Cleaning & Flushing	$2,509	22.950	$57,587
	annual cost	changing valves	$2,007	22.950	$46,070
	TOTAL PV				$453,534
	EAUC				$19,762

Scenario	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 32	0.00	Cement/ epoxy Lining	$231,856	1.000	$231,856
	8.45	HDD	$652,407	0.699	$455,899
	69.70	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.877	$54,895
	annual cost	changing valves	$2,007	21.877	$43,916
		TOTAL PV			$786,566
		EAUC			$35,954
scenario 33	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Slip Lining	$300,107	1.000	$300,107
	61.38	HDD	$652,407	0.074	$48,284
	122.63	Disposal			
	annual cost	Cleaning & Flushing	$2,509	22.950	$57,587
	annual cost	changing valves	$2,007	22.950	$46,070
		TOTAL PV			$452,048
		EAUC			$19,697
scenario 34	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	CIPP	$200,741	1.000	$200,741
	31.50	Pipe bursting	$672,481	0.263	$176,747
	92.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	22.626	$56,774
	annual cost	changing valves	$2,007	22.626	$45,419
		TOTAL PV			$479,681
		EAUC			$21,201
scenario 35	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	CIPP	$200,741	1.000	$200,741
	31.50	Open CUT	$672,481	0.263	$176,747
	92.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	22.626	$56,774
	annual cost	changing valves	$2,007	22.626	$45,419
		TOTAL PV			$479,681
		EAUC			$21,201
scenario 36	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	CIPP	$200,741	1.000	$200,741
	31.50	HDD	$652,407	0.263	$171,471
	92.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	22.626	$56,774
	annual cost	changing valves	$2,007	22.626	$45,419
		TOTAL PV			$474,405
		EAUC			$20,968
scenario 37	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	Sleeves	$296,093	0.727	$215,404
	10.00	Pipe bursting	$672,481	0.654	$439,997
	71.25	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.954	$55,087
	annual cost	changing valves	$2,007	21.954	$44,070
		TOTAL PV			$1,305,889
		EAUC			$59,484
scenario 38	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	open trench	$231,856	0.727	$168,673
	10.00	Pipe bursting	$672,481	0.654	$439,997
	71.25	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.954	$55,087
	annual cost	changing valves	$2,007	21.954	$44,070
		TOTAL PV			$1,139,547
		EAUC			$51,907

Scenario	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 39	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	Sleeves	$296,093	0.727	$215,404
	10.00	Open CUT	$672,481	0.654	$439,997
	71.25	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.954	$55,087
	annual cost	changing valves	$2,007	21.954	$44,070
		TOTAL PV			$1,305,889
		EAUC			$59,484
scenario 40	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	open trench	$231,856	0.727	$168,673
	10.00	Open CUT	$672,481	0.654	$439,997
	71.25	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.954	$55,087
	annual cost	changing valves	$2,007	21.954	$44,070
		TOTAL PV			$1,139,547
		EAUC			$51,907
scenario 41	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	Sleeves	$296,093	0.727	$215,404
	10.00	HDD	$652,407	0.654	$426,863
	71.25	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.954	$55,087
	annual cost	changing valves	$2,007	21.954	$44,070
	TOTAL PV				$1,292,755
	EAUC				$58,886
scenario 42	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	open trench	$231,856	0.727	$168,673
	10.00	HDD	$652,407	0.654	$426,863
	71.25	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.954	$55,087
	annual cost	changing valves	$2,007	21.954	$44,070
		TOTAL PV			$1,126,412
		EAUC			$51,309
scenario 43	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	Pipe bursting	$672,481	0.727	$489,223
	68.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.828	$54,772
	annual cost	changing valves	$2,007	21.828	$43,817
		TOTAL NPV			$1,139,144
		ANW			$52,188
scenario 44	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	Pipe bursting	$672,481	0.727	$489,223
	68.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.828	$54,772
	annual cost	changing valves	$2,007	21.828	$43,817
		TOTAL PV			$1,019,533
		EAUC			$46,708

Scenario	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 45	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	Open CUT	$672,481	0.727	$489,223
	68.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.828	$54,772
	annual cost	changing valves	$2,007	21.828	$43,817
	TOTAL PV				$1,139,144
	EAUC				$52,188
scenario 46	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	Open CUT	$672,481	0.727	$489,223
	68.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.828	$54,772
	annual cost	changing valves	$2,007	21.828	$43,817
	TOTAL PV				$1,019,533
	EAUC				$46,708
scenario 47	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Sleeves	$296,093	0.862	$255,239
	7.50	HDD	$652,407	0.727	$474,620
	68.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.828	$54,772
	annual cost	changing valves	$2,007	21.828	$43,817
	TOTAL PV				$1,124,540
	EAUC				$51,519
scenario 48	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	open trench	$231,856	0.862	$199,865
	7.50	HDD	$652,407	0.727	$474,620
	68.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.828	$54,772
	annual cost	changing valves	$2,007	21.828	$43,817
	TOTAL PV				$1,004,929
	EAUC				$46,089
scenario 49	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Pipe bursting	$672,481	0.862	$579,695
	64.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.597	$54,192
	annual cost	changing valves	$2,007	21.597	$43,354
	TOTAL PV				$973,333
	EAUC				$45,068
scenario 50	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	Pipe bursting	$672,481	0.862	$579,695
	64.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.597	$54,192
	annual cost	changing valves	$2,007	21.597	$43,354
	TOTAL PV				$909,096
	EAUC				$42,094
scenario 51	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	Open CUT	$672,481	0.862	$579,695
	64.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.597	$54,192
	annual cost	changing valves	$2,007	21.597	$43,354
	TOTAL PV				$973,333
	EAUC				$45,068

Scenario	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 52	0.00	open trench	$231,856	1.000	$231,856
	3.50	Open CUT	$672,481	0.862	$579,695
	64.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.597	$54,192
	annual cost	changing valves	$2,007	21.597	$43,354
		TOTAL PV			$909,096
		EAUC			$42,094
scenario 53	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$296,093	1.000	$296,093
	3.50	HDD	$652,407	0.862	$562,391
	64.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.597	$54,192
	annual cost	changing valves	$2,007	21.597	$43,354
		TOTAL PV			$956,029
		EAUC			$44,267
scenario 55	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$231,856	1.000	$231,856
	3.50	HDD	$652,407	0.862	$562,391
	64.75	Disposal			
	annual cost	Cleaning & Flushing	$2,509	21.597	$54,192
	annual cost	changing valves	$2,007	21.597	$43,354
		TOTAL PV			$891,792
		EAUC			$41,293
scenario 56	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$2,000	1.000	$2,000
	3.00	Sleeves	$2,000	0.876	$1,753
	5.50	Sleeves	$2,000	0.78498327	$1,570
	7.49	Sleeves	$2,000	0.719	$1,438
	9.29	Cement/ epoxy Lining	$204,333	0.664	$135,754
	19.56	Disposal			
	annual cost	Cleaning & Flushing	$4,150	12.828	$53,237
	annual cost	changing valves	$2,500	12.828	$32,071
		TOTAL PV			$227,822
		EAUC			$17,759
scenario 57	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$1,400	1.000	$1,400
	3.00	open trench	$1,400	0.876	$1,227
	5.50	open trench	$1,400	0.78498327	$1,099
	7.49	open trench	$1,400	0.719	$1,007
	9.29	Cement/ epoxy Lining	$204,333	0.664	$135,754
	19.56	Disposal			
	annual cost	Cleaning & Flushing	$4,150	12.828	$53,237
	annual cost	changing valves	$2,500	12.828	$32,071
		TOTAL PV			$225,794
		EAUC			$17,601
scenario 58	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$2,000	1.000	$2,000
	3.00	Sleeves	$2,000	0.876	$1,753
	5.50	Sleeves	$2,000	0.78498327	$1,570
	7.49	Sleeves	$2,000	0.719	$1,438
	9.29	Slip Lining	$367,333	0.664	$244,047
	39.33	Disposal			
	annual cost	Cleaning & Flushing	$4,150	18.287	$75,891
	annual cost	changing valves	$2,500	18.287	$45,718
	TOTAL PV				$372,417
	EAUC				$20,365

	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 58	0.00	open trench	$1,400	1.000	$1,400
	3.00	open trench	$1,400	0.876	$1,227
	5.50	open trench	$1,400	0.78498327	$1,099
	7.49	open trench	$1,400	0.719	$1,007
	9.29	Slip Lining	$367,333	0.664	$244,047
	39.33	Disposal			
	annual cost	Cleaning & Flushing	$4,150	18.287	$75,891
	annual cost	changing valves	$2,500	18.287	$45,718
	TOTAL PV				$370,388
	EAUC				$20,254
scenario 59	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Sleeves	$2,000	1.000	$2,000
	3.00	Sleeves	$2,000	0.876	$1,753
	5.50	Sleeves	$2,000	0.78498327	$1,570
	7.49	Sleeves	$2,000	0.719	$1,438
	9.29	CIPP	$467,333	0.664	$310,484
	39.33	Disposal			
	annual cost	Cleaning & Flushing	$4,150	18.287	$75,891
	annual cost	changing valves	$2,500	18.287	$45,718
	TOTAL PV				$438,854
	EAUC				$23,998
scenario 60	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	open trench	$1,400	1.000	$1,400
	3.00	open trench	$1,400	0.876	$1,227
	5.50	open trench	$1,400	0.78498327	$1,099
	7.49	open trench	$1,400	0.719	$1,007
	9.29	CIPP	$467,333	0.664	$310,484
	39.33	Disposal			
	annual cost	Cleaning & Flushing	$4,150	18.287	$75,891
	annual cost	changing valves	$2,500	18.287	$45,718
	TOTAL PV				$436,826
	EAUC				$23,887

New installation scenarios

	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 1	0.00	Pipe bursting	$540,000	1.000	$540,000
	30.04	Disposal			
	annual cost	Cleaning & Flushing	$4,150	16.2991593	$67,642
	annual cost	changing valves	$2,583	16.299	$42,106
	TOTAL PV				$649,748
	EAUC				$39,864
scenario 2	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	HDD	$900,000	1.000	$900,000
	30.04	Disposal			
	annual cost	Cleaning & Flushing	$4,150	16.2991593	$67,642
	annual cost	changing valves	$2,583	16.299	$42,106
	TOTAL PV				$1,009,748
	EAUC				$61,951
scenario 3	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Open CUT	$540,000	1.000	$540,000
	30.04	Disposal			
	annual cost	Cleaning & Flushing	$4,150	16.2991593	$67,642
	annual cost	changing valves	$2,583	16.299	$42,106
	TOTAL PV				$649,748
	EAUC				$39,864
scenario 4	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	MT	$1,400,000	1.000	$1,400,000
	30.04	Disposal			
	annual cost	Cleaning & Flushing	$4,150	16.2991593	$67,642
	annual cost	changing valves	$2,583	16.299	$42,106
	TOTAL PV				$1,509,748
	EAUC				$92,627

	year	Activates	Cost $/m	Dis Factor	Dis Cost
scenario 5	0.00	Pipe bursting	$540,000	1.000	$540,000
	80.00	Cement/ epoxy Lining	$233,333	1.000	$233,333
	80.00	Disposal			
	annual cost	Cleaning & Flushing	$4,150	21.565343	$89,496
	annual cost	changing valves	$2,583	21.565	$55,710
	TOTAL PV				$918,540
	EAUC				$42,593
scenario 6	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	Open CUT	$540,000	1.000	$540,000
	80.00	Cement/ epoxy Lining	$233,333	1.000	$233,333
	80.00	Disposal			
	annual cost	Cleaning & Flushing	$4,150	21.565343	$89,496
	annual cost	changing valves	$2,583	21.565	$55,710
	TOTAL PV				$918,540
	EAUC				$42,593
scenario 7	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	HDD	$900,000	1.000	$900,000
	80.00	Cement/ epoxy Lining	$233,333	1.000	$233,333
	80.00	Disposal			
	annual cost	Cleaning & Flushing	$4,150	21.565343	$89,496
	annual cost	changing valves	$2,583	21.565	$55,710
	TOTAL PV				$1,278,540
	EAUC				$59,287
scenario 8	year	Activates	Cost $/m	Dis Factor	Dis Cost
	0.00	MT	$1,400,000	1.000	$1,400,000
	80.00	Cement/ epoxy Lining	$233,333	1.000	$233,333
	80.00	Disposal			
	annual cost	Cleaning & Flushing	$4,150	21.565343	$89,496
	annual cost	changing valves	$2,583	21.565	$55,710
	TOTAL PV				$1,778,540
	EAUC				$82,472