A Water Main Life Cycle Analysis Framework for the Economic Evaluation of OM&R (Operation, Maintenance, and Renovation) Strategies

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada, 2018

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Municipal water systems deliver potable water to residents, businesses, and industries. The potable water infrastructure was mostly laid in 1880-1970`s in North America. Being a buried asset i.e. an out of sight network, it did not capture the attention of the public at the time and once inside the ground, was forgotten about. Until recently, the pipes that were installed well over 80-100 years ago have started to leak and break with a frequency that increases with every passing year.

Municipalities are facing ever-increasing challenges in maintaining their buried infrastructure due to increasing backlogs (aging infrastructure assets), constantly rising OM&R (Operation, Maintenance, and Renovation) requirements to sustain the assets and maintaining the current levels of services towards the consumers, businesses, and environment. All these problems of water distributions systems can be traced back to a lack of fiscal and technical resources by the municipalities.

This thesis identifies the gaps causing uncertainties in the decision-making process and prioritizing the maintenance operations. An OM&R and replacement strategy has been proposed that explains and clearly establishes the variables that need to be defined to come up with a viable asset management plan that can reduce the life cycle costs while still being able to maintain the assets over an extended period of time. The strategy is then further built upon to come up with an extensive framework consisting of a number of modules that cover the existing conventional rehabilitation and maintenance approaches such as fix upon break approach, total replacement, lining approach and/or a combination of them. A proposed strategy module is added to the framework both in its basic as well as an advanced version that comes up with a cost-optimized OM&R and replacement strategy covering a planning horizon of 100 years which is the same as the life cycle of a typical water distribution system.

The proposed framework based on a number of input variables generates a cross-comparison of all the conventional approaches as well as the proposed strategy by distributing the pipe network into different age bins, assigning them priority based on age, and analyzing the future OM&R and replacement costs for that very age bin. The age bins are individually analyzed continuously until the whole network is analyzed and a cumulative life cycle cost is generated for all the conventional approach modules as well as the proposed strategy. Based on the analysis, plots are generated which gives a clear cost comparison analysis as well as different cut-offs among the policies at certain points in time which helps in decision making regarding the optimal time to adapt a certain policy.

The framework is then validated using the SDLC V-Model (software development life cycle validation and verification model).

A software that is designed around the framework presented in this research to make it accessible to the asset managers, contractors as well as other stakeholders so they can have an overview of the estimated cumulative future OM&R costs of the utility concerned. The software is again tested and verified using the SDLC V-Model. A sensitivity analysis is also carried out for the framework using a case study in the designated software. All the concerned variables are tested and their sensitivity is reported in this research.

Results indicate that applying the proposed strategy modules of the framework to case studies consistently resulted in considerable cost savings over the life cycle of the network. Results also highlighted that the more historical (analysis ready) information a utility has about its buried infrastructure, the more is the potential of realizing OM&R cost savings over the network`s life cycle.

Statement of Contribution

Chapter 2 of this thesis consists of a paper that will be submitted for publication. The paper is co-authored by myself, Dr. Mark Knight and Mr. Ahmed Abdel-aal. Dr. Mark Knight supervised the research and refined the research idea, I developed the parameters and framework for the idea and Mr. Ahmed Abdel-aal implemented the idea using excel spreadsheets.

Chapter 3 of this thesis consists of another paper that is set to be submitted for publication. The paper is co-authored by myself, Dr. Mark Knight and Mr. Ahmed Abdel-aal. An extensive methodology was proposed to be implemented as part of the framework developed in Chapter 2. I carried out the simulation, documented and drafted the results, while Mr Ahmed Abdel-aal assisted with writing and implementing the code for it.

Chapter 4 of this thesis consists of verification and sensitivity analysis of the model that is developed in Chapter 3. The paper is co-authored by myself, Dr. Mark Knight and Mr. Ahmed Abdel-aal.

Acknowledgments

I would like to take this opportunity to sincerely express my gratitude to Dr. Mark Knight, my MASc. supervisor, for his continuous guidance and untiring support throughout my graduate studies at the University of Waterloo. Working with Dr. Knight has been a remarkable experience. Without his knowledge and support, my research would not have been possible.

I would also like to thank Dr. Rizwan Younis for helping me throughout my graduate studies and for constantly guiding me for the last 3 years. His critical review of my work made it possible for me to conduct quality research work.

I would like to extend my gratitude to Dr. Rashid Rehan, for inspiring and encouraging me to pursue graduate studies and for connecting me with Prof. Mark Knight.

I would like to thank Mr. Ahmed Abdel-aal from the core of my heart for helping me throughout the journey. He has been an integral part of my research and his ability to program and execute on the ideas I used to present to him is a core reason of my successful degree completion.

I am grateful to Alice Seviora, who has become a good friend over time and helped solved all the administrative issues I faced during the course of studies.

Dr. Faizul Mohee, who shared graduate office space with me during the course of my studies, has been a constant mentor to me throughout the whole process. I would like to extend my sincere thanks to him as his critical review of my work made it possible for it to be technically sound and bring about perfection in it.

I would like to thank my friends and family who were and still are a constant source of motivation for me and keep my spirits high.

Dedication

To my parents, grandparents, siblings, and friends for their support and encouragement every step of the way. I would never be able to thank them enough. I wish nothing but the best for them in this world and beyond.

Table of Contents

Chapter 3 Proposal and Validation of an Extensive Water Main Life cycle Analysis Framework for Future Cost Estimations of Different OM&R and CW Strategies 27

Chapter 4 Verification and Sensitivity Analysis of a Water Distribution Asset LCE (Life cycle Cost Estimation) Tool Using SDLC V-Model 47

List of Figures

List of Tables

Chapter 1

General Introduction

1.1 Background and Motivation

A well maintained buried water distribution network (WDN) is an integral part of a well-functioning society. Water distribution systems are a combination of interconnected series of pipes, valves, storage facilities, pumping stations, hydrants for fire protection, filtering facilities like treatment systems and treatment plants (McNeill and Tate 1991). All of these components operate in a systematic way for the successful delivery of water from aqueducts, reservoirs, and tanks all the way to a consumer`s tap with an acceptable level of service (LOS). To ensure the required LOS, financial management of WDN of potable water is the most important factor of all (Grigg 1986).

Canada and the United States (US) have a growing problem of the aging water distribution system with little to no replacement or renovation. The Canadian Infrastructure Report Card (Canadian Society of Civil Engineers 2016) reported that 29% of potable water infrastructure is in very poor, poor or fair state.

Due to limitations of OM&R (Operation, Maintenance, and Renovation) funds, the municipalities are not readily able to cope with the problem at the rate needed causing a buildup of backlogs due to deferred maintenance, renovation, and replacement of the potable water network (Canadian Society of Civil Engineers 2016).

The US Environmental Protection Agency (EPA) estimates an annual replacement rate of 4000-5000 miles (6000-8000 kilometers) of water-mains for all municipalities in US and further predicts the hike in replacement rate due to many pipes in the US reportedly nearing the end of their useful service life (EPA 2013). The projected cost to replace those pipes for the next two and a half decades will be over 1 trillion USD to ensure the maintenance of current levels of service to the consumer (Syachrani et al. 2013). With the ever-increasing backlogs and constantly increasing population justifying the need to expand the current water distribution infrastructure, governments are being put under increased financial stress which can potentially render water services unaffordable and the levels of service unsustainable at current prices (MOE 2007).

To achieve the long-term goal of financial sustainability of potable water systems, a framework is needed that understands future financial requirements and can estimate future construction, expansion, replacement, operation and maintenance costs. As per Akintoye and Skitmore (1994), better cost estimations are essential for future cost estimations which can assist with future budgeting. Failure to address the budgeting issue for renewal and maintenance of aging infrastructure can result in deterioration of levels of service and public health.

To be able to budget the future OM&R and replacement needs of a certain municipality, an understanding of the conventional and non-conventional maintenance, rehabilitation and replacement approach is important. Currently, the predominant method to deal with old infrastructure is a continuous open-cut replacement with temporary bypass of the water main to continue the supply of water to consumers.

In contrast to open cut approaches, a fairly recent construction methodology, namely trenchless technology, eliminates the need to dig trenches and traffic disruptions and in most cases services can be restored to normal within 24-48 hours. Lining, a trenchless technology, is essentially building a pipe inside of an existing pipe. Liners are predominantly of three types: non-structural (spray on coating), semi-structural or fully structural (Olukayode 2017). They provide corrosion resistance and depending on the type of liner can add structural integrity of varying degrees.

Where open cut policies cause environmental, traffic and business disruption in the area of operation; putting an economic burden on the local service recipient, trenchless technologies have a demonstrated positive effect socially and environmentally as it offers advantages in both installing new utilities and rehabilitating the existing infrastructure by using “green” principles reducing the impacts caused by open-cut construction i.e. reduced surface nuisance (Ariaratnam 2012). According to Knight and Rehan (2008), the use of trenchless construction methods as for pipeline installations can result in 80% to 98% of greenhouse gas savings when compared to an open cut replacement.

1.2 Problem Definition

Sustainability of a technology is based on three main categories i.e. social, environmental and economic sustainability (Ariaratnam 2012). Trenchless technology has a demonstrated edge over the open-cut approaches when it comes to social and environmental sustainability such as decreased noise and traffic disruption and superlative safety.

Regarding the economic sustainability of various open-cut and trenchless policies, estimates of construction costs can be a challenging task in the construction industry (Hwang 2011), given the existence of a high number of uncertainties which is exactly the case with WDNs.

WDNs face a series of problems which include lack of cost effective management strategies i.e. a comprehensive framework which is essential for an effective asset management plan (Pressman et al. 2017).

Another problem is the lack of funds reported by municipalities to perform the operation, maintenance and renovation of old or broken pipes, as well as, expand the current networks due to increasing population densities (Folkman 2018). Absence of a software modelled after a comprehensive economic OM&R framework for water utilities that is applicable, accessible and user-friendly to water utilities is another problem that the municipalities face rendering them unable to make economically informed decisions.

The three problems discussed above form the core of the issues that needs to be addressed and a viable solution needs to be proposed to make future decision-making regarding water distribution network economically sustainable. The next section proposes solutions to the problems defined in this section.

1.3 Research Objectives and Scope

The main goal of this thesis is the development of an economic framework for water utilities to assist in the sustainable financial management of potable water systems by predicting future cost for conventional and non-conventional operational, rehabilitation, maintenance and renovation practices.

The specific objectives of this research are as follows:

- Develop a strategy that enables better decision making in regards to adopting the most economical potable water network rehabilitation approach to be used over the life cycle of the water distribution network (50-100 years).
- Design a framework that employs and simulates the developed strategy and simulate the current conventional operation, maintenance, rehabilitation and renovation policies and provides future life cycle cost estimate for each policy.
- Develop an interface to compare the results of cost simulations of all approaches and the proposed (developed) strategy.
- Develop a user-friendly tool for the framework wherein the asset managers or other water utility stakeholders can enter the input parameters to easily visualize the cost estimations of different approaches for the same utility to maintain the current levels of service for the life cycle of the network.

It is anticipated that by achieving the objectives of this research, an economic framework will be developed that can readily be used to strategize the OM&R and operations over the life cycle of the network. The framework will essentially enable the municipalities to make informed decisions and come up with better financial budgeting ability.

1.4 Thesis Organization

This thesis has been written in a “manuscript-based” style, organized into five chapters, starting with a general introduction followed by the main body from Chapter 2 to Chapter 4 organized in an integrated article format. The last Chapter presents the overall conclusions of the research study.

Chapter 1: General Introduction – This chapter introduces the purpose of the study by providing a background related to the research. Current trends in the industry are highlighted along with their drawbacks. The problems that are faced by the industry and intended to be solved in this research are highlighted. Research objectives are defined in this chapter which is addressed in the next articles of the thesis in detail.

Chapter 2: Manuscript 1 – The title of the first technical paper is “Establishing the need for adopting smart strategies to maintain current levels of service of water distribution network over an extended period of time”. This paper sheds light on the current condition of buried water infrastructure for US and Canada and explains where it is headed in terms of condition and financial needs of future. Conventional OM&R approaches are explained and then compared against a proposed strategy to come up with an economically informed decision. The proposed strategy and conventional OM&R approaches are put together in a framework for ease of analysis. A case study is performed which uses the framework to establish the usefulness of the strategy and establish a premise to further develop the strategy.

Chapter 3: Manuscript 2 – The title of the second technical paper is “Proposal and validation of an extensive water main life cycle analysis framework for future cost estimations of different OM&R strategies”. This paper is an extension of paper 1 and proposes an advanced strategy by incorporating variables that asset managers have to deal with. This paper presents extensive modules of all the conventional approaches and the proposed strategy both in their basic and advanced forms. All the modules are then put into a single framework which simulates them together to come up with future economic forecasting for any given municipality.

Chapter 4: Manuscript 3 – The title of the third technical paper is “Verification and sensitivity analysis of a water distribution asset management software using SDLC V-Model”. A methodology is used to verify the software that has been designed over the framework proposed and validated in Chapter 2. Additionally, sensitivity analysis is carried out using a case study to highlight the importance of certain variables in the OM&R cost estimation.

Chapter 5: Conclusions and Future Work Recommendations - The findings of the research are presented in this Chapter along with the recommendations to further develop the framework.

Chapter 2

Establishing the Need for Adopting Smart Strategies to Maintain Current Levels of Service of Water Distribution Network over an Extended Period of Time

2.1 Overview

This chapter establishes the need for an extensive economic forecasting framework and preferably a software designed around the framework to apply it to municipalities that present high number of variabilities.

North American potable water infrastructure is experiencing an ever-increasing number of old pipes that have surpassed their design life but are still in service. These old pipes experience a high number of breaks annually and have created huge backlogs. This makes it inevitable for the municipalities to adopt smarter infrastructure maintenance strategies that can efficiently deal with the backlogs and are able to maintain the infrastructure economically for at least the next 100 years. Due to a consistent increase in backlogs, current operation, maintenance and renovation (OM&R) strategies employed by Canadian municipalities for water main network will become economically infeasible in the near future.

A framework that includes current and newly proposed OM&R and replacement strategies is proposed in this chapter. The framework is developed to be applicable to the North American municipalities and serves to optimize the costs needed to maintain the current levels of service of water mains for the next 50-100 years.

The proposed OM&R strategy is put to test using a simple hypothesized water main network and considerable cost savings are consistently realized against the least cost OM&R approach when analyzed for the next 100 years.

2.2 Introduction

Water mains are pressurized buried systems. Their job alongside firefighting is the transmission of potable water from storage tanks and distribute it to consumers and businesses. Canadian and American water systems were primarily installed in 1970`s or earlier and has served the communities well since then. Much of this buried infrastructure is now approaching the end of its useful life (AWWA 2001).

Given their importance, all the water mains in general and the critical water mains (CWMs) in particular are required to be maintained in an efficient and cost effective manner to ensure acceptable water main condition (Li et al. 2005).

In defiance of the criticality, North America's potable water infrastructure is in a state of constant decline, a major reason being aged infrastructure which has led to infrastructure backlogs (Rehan et al. 2015). In addition, water utilities have limited condition data which causes a lack of prioritization in maintenance and rehabilitation operations (Rehan et al. 2015). Both of these problems are directly linked to the lack of sufficient funds, as the user fees and water rates are set to cover operation costs only.

Most of the North American water infrastructure using Cast Iron (CI) was built in the 1880-1970's which according to Rajani and Kleiner (2004) was the predominant pipe construction material.

Most of the cast-iron pipes that were installed pre-1970 are still in service. According to a survey by Knight (2016), as can be seen in Figure 2-1, 85% of the Watermain network is over 30 years old with 10% being older than 70 years, 14% is older than 50 years and only 15% is less than 30 years old which is considered as a relatively new condition. This leads to infrastructure backlogs where a lot of pipes are starting to experience failure at the same time. According to Bernstein and Laquidara-Carr (2013), nearly 75% of the respondents of a 2012 North America`s water and wastewater infrastructure sector singled out aging infrastructure as a vital factor leading to the adoption of asset management practices. Since most of the network is still in service, it has either reached or is reaching the end of its useful service life, that is around 75 years (Rehan et al. 2015).

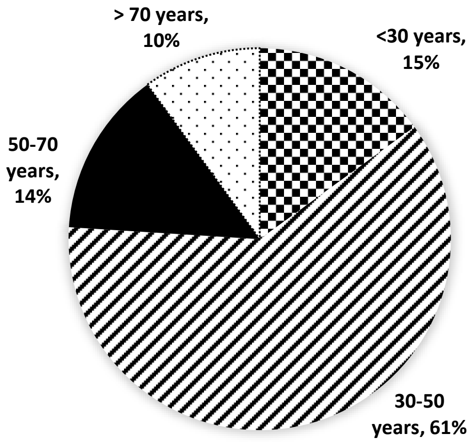


Figure 2-1: Age distribution of water main pipe network in Canada (Knight 2016)

According to a more recent survey by Folkman (2018) of Utah State University, a water main network age distribution survey in both USA and Canada was carried out. The network distribution by age is shown in Figure 2-2 wherein 28% of the network is over 50 years old and only 28% of the surveyed network was found to be 20 years of age or below. This further strengthens the argument of old infrastructure being still in-service causing backlogs.

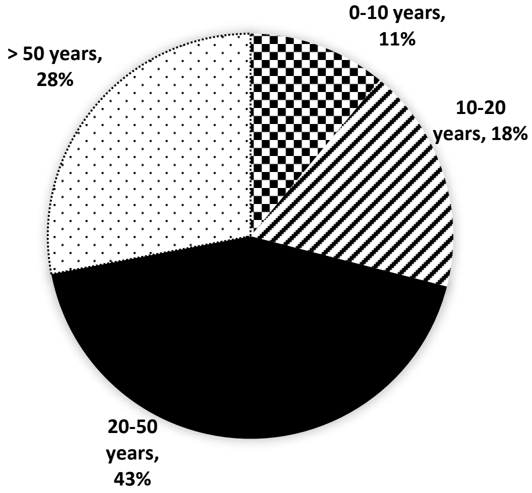


Figure 2-2: Water main age distribution for all Material Types From The Detailed Survey for both US and Canada (Folkman 2018)

With backlogs, come the frequent loss of water service which is a management nuisance, given the fact that it jeopardizes social, economic and public health (Underground 2014). The widespread concern among water utilities about their aging infrastructure has incited a rapid adoption of advanced management practices to minimize risk to an acceptable level while ensuring established levels of service.

Another issue facing Canada’s potable water infrastructure and other industrialized countries is that standard analytical procedures for water infrastructure`s planning and maintenance activities have not been developed by water utility industry to assess distribution system conditions extensively (O’Day D.K, Weiss R, Chiavri S 1989). A lack of routine maintenance has contributed to its deterioration and much of this infrastructure is now nearing the end of its useful life. Factors such as inadequate funding and lack of quality control measures are also aggravating the situation resulting in poor water quality, ever-increasing leakages, and break frequency. Figure 2-3 shows that 50% of small municipalities, 26% of medium size municipalities and 16% of large municipalities report having insufficient funds to maintain their current infrastructure (Knight 2016).

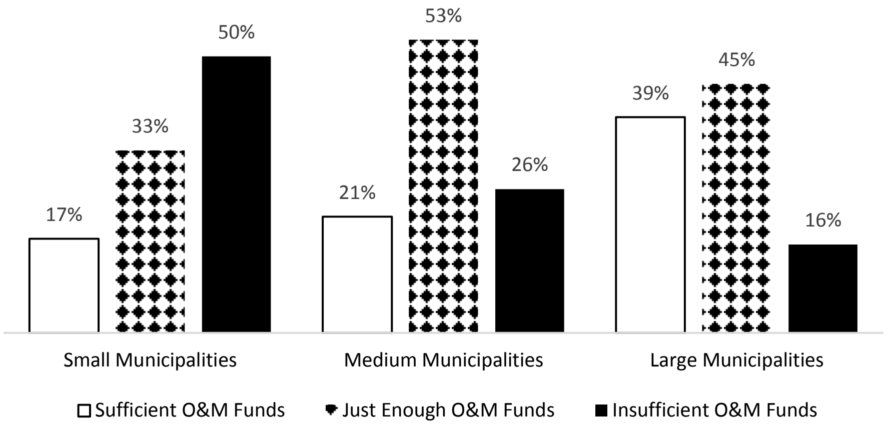


Figure 2-3: Current operation and maintenance funding situation for municipalities (Knight 2016)

Finally, yet important, is the lack of condition data and its inaccuracy. According to the Canadian Infrastructure Report Card (2016), 50% of responding municipalities had no condition assessment data.

All of these problems can be traced back to less informed decisions on prioritization and characterization of buried infrastructure which in turn causes uncertainty in coming up with an optimal renovation practice and/or replacement of the infrastructure that is economically feasible for the decades to come.

Thus, the purpose of this study is to present an alternative framework to current Operation, Maintenance & Renovation (OM&R) and capital works (CW) practices that can potentially save municipalities upwards of 10% of OM&R and CW costs over the network`s life cycle.

2.3 Traditional Operation and Maintenance (O&M) and Capital Works Operations

Asset management practices aim to minimize infrastructure replacement costs, extend the life of present assets and work towards sustainable growth and maintenance over time for a municipality (Harvey 2015).

Water mains are typically less than 300 mm in diameter. In addition, they are pressurized systems always flowing full. The combination of small size and being pressurized creates unique challenges to rehabilitate or replace these pipes. Annual budgets for water utilities are typically divided into OM&R and capital works operations.

2.3.1 Operating and Maintenance (O&M)

Operating and maintenance budgets include all short-term costs to run the system. This includes staffing, supplies and cost to clean, fix water main breaks and leaks etc.

Water main breaks result in flooding and damages which are a hazard to the public and must be dealt with immediately. Breaks are required to be repaired at the earliest possible opportunity depending on the severity of leak, water loss, immediate and potential damage to roads or other public property ("Public Works Operations & Maintenance Performance Standards" 2017). Water mains have a design life of about 75 (cast iron) to 100 (PVC) years depending on the pipe material (Rehan et al. 2015). As the pipe networks age, the break frequency increases exponentially (Shamir and Howard 1979). With increasing annual break frequency due to network aging, the operating budget allocation needs to be increased accordingly.

Apart from regular break and leak fixes, periodic cleaning of water mains is also covered under the operating and maintenance budget. Cleaning the watermain can be achieved by a multitude of methods such as, flushing, metal scraping, air scouring, ball cleaning, power boring or using other mechanical cleaning techniques (AWWA 2001). Regardless of the method used, a well-planned and well executed pipe cleaning is undertaken by water utilities on a regular basis as it provides many benefits such as increasing efficiency of pipe, reducing health hazards and risk of water discoloration, taste and odor problems.

Flushing is the most widely adopted cleaning technique as it is the least expensive cleaning method (Ellison and Duranceau 2003). According to a study funded by American Water Works Association Research Foundation (AWWARF) undertaken by (Wiedemann et al. (2001), a flushing program should encompass each of the following strategies i.e. spot flushing (reactive), stagnant area flushing (short-term preventive) and scheduled system-wide flushing (long-term preventive).

Regardless of the flushing strategy, Unidirectional Flushing (UDF) is the most widespread technique used to achieve the purpose in both reactive and system-wide flushing. According to AWWA Research foundation`s report on water distribution systems guidance and management, UDF is more effective than traditional flushing techniques in regards to cleaning and longevity of results, therefore the flushing frequency can be reduced making UDF an economically effective technique as well. This can also help reduce the operating costs.

2.3.2 Capital Works (CW) Operation

Capital work expenses include large investments such as building a new treatment plant, replacement of pipes, or completion of a watermain renovation project. Capital projects are typically tendered annually or in multiyear programs.

The Capital works operation in North America to maintain and extend pipe service life is sketched out in Figure 2-4.

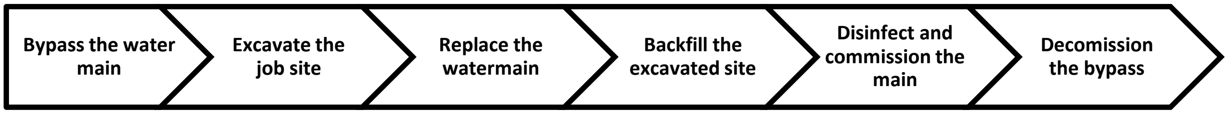


Figure 2-4: Current capital works practice In North America

Water mains in North America cannot be decommissioned without the continuous provision of water to the customers which can amount to of 20-30% of project cost. This is accomplished by construction of an on surface temporary water main bypass piping network. Therefore, a disinfected bypass is first installed to supply water to the residents and businesses.

Once the bypass is installed, the roads are cordoned off and watermain is replaced. Replacement is followed by backfilling the job site and repaving any road section that was milled during the excavation.

The next step is to disinfect the pipe by chlorination where three clean water samples are taken over a span of three days from the water main to test for infectants. When the pipe is declared as disinfected, the service is restored and the bypass is removed.

The current capital work operations incur high costs due to public`s expectation of a bypass service which constitutes a significant portion of the total cost. In United Kingdom, there is no bypass and supply trucks are provided during these procedures. The question in North America is, whether or not it is possible to eliminate the usage of a bypass, and along with that what would constitute an acceptable out of service time?

Certain companies are entering the new trenchless cleaning, inspection and lining marketplace and are offering services that reduce the time and hence cost. One such company is Envirologics and came up with a technology called Tomahawk™ that offers cleaning, inspection, lining (optional), shock chlorination (to control bacterial contamination), drying and return to service within 48 to 72 hours. The cleaning is performed with abrasives and no water is used, which eliminates the time needed for the pipe to dry before liner application.

Figure 2-5 shows the capital work operations that involve cleaning, inspecting and lining the watermain instead of open cut replacement. The practice has recently been adopted by City of Toronto for the rehabilitation of the city`s watermains with high break frequencies.

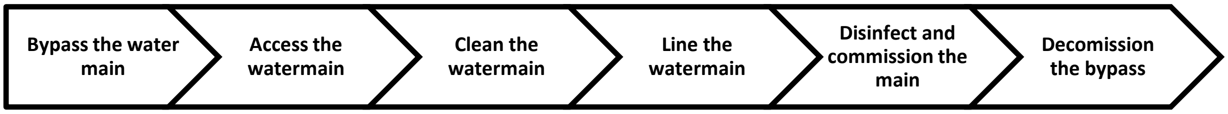


Figure 2-5: New Capital works operation coming into practice

Typically, once the bypass is in place, the pipe is isolated, taken out of service, opened and cleaned. The objective of pipe cleaning is to rid the pipes of deposits and sediments by scouring/abrasion. The pipe is then left to dry before application of liner. Once the desirable level of dryness is achieved, the liner is then applied and left to cure. Upon curing the pipe is disinfected by chlorination. Three clean water samples are then taken over a span of three days from the water main to test for infectants. When the pipe is declared as disinfected, the service is restored and the bypass, removed.

2.4 Conventional Maintenance & Rehabilitation Approaches

Apart from the mandatory inspection and cleaning operation of water mains, there are several distinct policies directed towards rehabilitation and maintenance of the water distribution mains to cater to structural issues of pipes:

- Fix upon break (O&M)
- Replacement (CW)
- Lining (CW)
- Combination approach

2.4.1 Fix Upon Break

Fixing the pipe breaks and leaks is an operational expenditure and is covered under operating and maintenance budget. It is by and large the most adopted approach by water utilities to maintain their buried infrastructure. Whenever a water main breaks or a leak is detected, an emergency repair operation is warranted. This is a relatively low-cost approach in the short-term and offers a quick contemporary fix.

Shamir and Howard (1979) proposed a break model (see Figure 2-6) where the number of breaks (break frequency) increases exponentially with increasing pipe age. Equation 2.1 is modeled after exponential break trend.

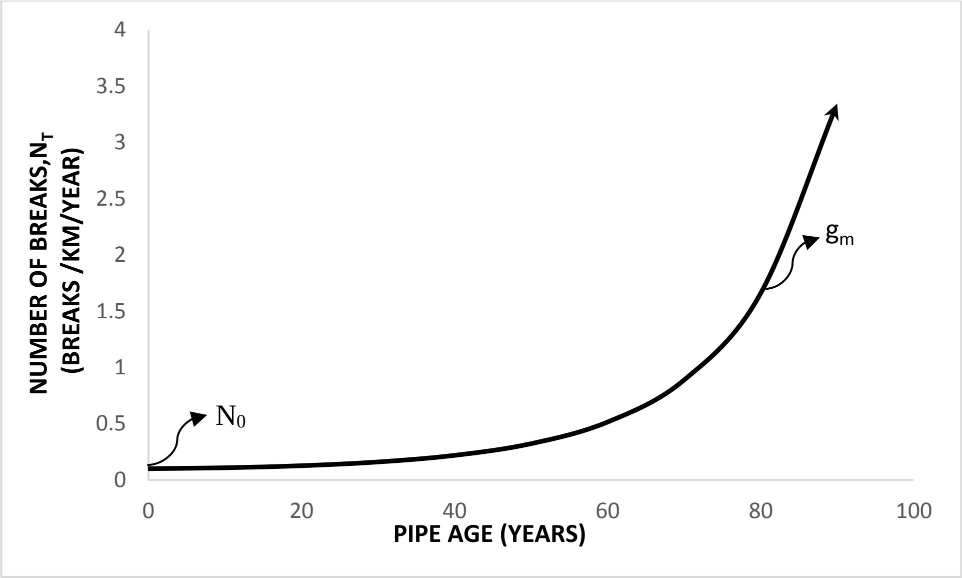


Figure 2-6: Shamir and Howard`s Exponential break trend (Shamir and Howard 1979)

$$\boldsymbol{N_T = N_0 e^{g_m * T}} \quad \textbf{(2.1)}$$

where:

N_T: Number of breaks at time t (breaks/km/year)

N_0: Initial number of breaks (unitless)

g_m: Break growth rate

T: Pipe age (years)

Fix upon break is a reactive approach, and is employed as an emergency. According to Clancy and Gustafson (1999), it costs the province of Saskatchewan around $5770 to repair a single water main break, while Collicott et al. (2012) reports the price of single break repair to be $10,000.

2.4.2 Replacement

The continuous open-cut approach consists of ground excavation, removal of the old water main and replacing it with a new pipe section, followed by back filling the site and reconstruction of the road. Open-cut replacement operation incurs social and environmental costs and being open-cut, it leaves a carbon footprint i.e. 90% increased greenhouse gas emissions when compared to trenchless operations (Knight and Rehan, 2008). Open cut replacement costs range anywhere between $600-$1000 per meter replacement (Collicott et al. 2012).

As more and more pipes are reaching their end of useful service life, the need to adopt an economical rehabilitation program has increased, this need has been demonstrated by Zayed et al. (2011), as according to them around 59% of water systems are in need of rehabilitation.

The current replacement rate is very low i.e. less than 1% per year (Folkman 2018) which in no way is able to cope with the annually increasing failure frequency. An article in (AWWA 2011) “Buried no Longer” states that in America more than a million miles (1.6 million kilometers) of pipes are nearing the end of useful service life and in need of replacement. The costs incurred on replacing these pipes along with project expansion costs will surpass $1 trillion over the next two decades.

Open-cut replacement often create traffic delays, detours need to be provided which generates social costs in the form of business losses and public nuisance (Collicott et al. 2012) lasting anywhere from a few weeks to certain months depending on the magnitude of the capital works program. In addition, open-cut programs in relation to trenchless techniques can cause an increase in greenhouse gas emissions of up to 90% (Knight and Rehan 2008).

2.4.3 Lining

According to the ISTT (International Society for Trenchless Technology), rehabilitation is any measure that restores or upgrades the performance of existing utility system including renovation, replacement or repair to overcome problems that hamper the performance of the system. Renovation is a type of rehabilitation that serves to improve the performance of the pipe. Renovation can either be structutal or non-structural depending whether or not the host pipe wall is required to contribute to the ring stiffness to satisfy the integrity of utility.

Lining is a trenchless alternative to open cut replacement. It is a non-invasive trenchless technique that may either be a non-structural spray on polymer lining (Polyurea materials) to coat the interior surface of the pipe, an intermediate liner or a fully structural one that can withstand design loads on its own e.g. Cured in Place Pipe (CIPP) or Sprayed in Place Pipe (SIPP) lining. A pipe that is deteriorated but still has remaining useful life is a potential lining candidate, the level of deterioration determines the type of liner to be used. Pipes are first cleaned, inspected and then cleared for lining.

Liner classification adopted from proceedings of AWWA (2014) and class of liners in practice is provided in Table 2-1.

Table 2-1: Structural classification and class of liners. (AWWA 2014)

Liner Characteristics	Non-Structural	Semi-Structural		Fully Structural
	Class I	Class II	Class III	Class IV
Internal corrosion barrier	Yes	Yes	Yes	Yes
Bridges holes/gaps at pipe operating pressure	No	Yes	Yes	Yes
Inherent ring stiffness	No (Depends on adhesion)	No (Depends on adhesion)	Yes	Yes
Long-term independent pressure rating ≥ pipe operating pressure	No	No	No	Yes
Survives "burst" failure of host pipe?	No	No	No	Yes

Lining is gaining widespread acceptance in the municipalities as a rehabilitation technique due to low construction cost and less disruption to the public, businesses and has fast construction time compared to open cut replacement.

Knight and Rehan (2008) report that trenchless construction methods for pipeline installations can result in 80% to 98% of greenhouse gas savings when compared with open cut replacement.

2.4.4 Combination Approach

Currently, municipalities follow a strategy consisting of a mix of the above-mentioned approaches, where fix upon break approach is used through most of the service life of pipe and when a certain pipe segment surpasses the threshold break frequency standardized by the municipality, which is usually towards the end of the pipe`s useful life, then the pipe is replaced or lined.

The question is, which approach is most economical and whether a strategy exists that is a combination of the three that makes the most sense economically over the long term i.e. the planning horizon. This chapter addresses this question by proposing a strategy that covers the different aspects of the problem and proposes an optimal solution.

2.5 Proposed Strategy

A strategy has been developed to optimize and confidently prioritize among different maintenance and rehabilitation policies. The strategy aims at maximizing the cost savings over the planning horizon while retaining the acceptable levels of service.

A summary of the proposed strategy is outlined below which is followed by a detailed framework to put the strategy into practice and compare with conventional policies:

- Clean and inspect the old pipes (typically 75+ years of age) of a network.
- Breakdown the inspected water mains into three categories based on conditions:
    - Pipes to be left alone i.e. acceptable condition
    - Pipes to be replaced
    - Pipes to be lined
- Pipes that are designated as not old (typically less than 75 years of age) are fixed upon break.

2.5.1 Practical Framework

A framework has been developed to put the proposed strategy into practice and achieve the goal of cost optimization over the next 50-100 years using network inspection results. The framework consists of completion of the following tasks for a water distribution network:

1. Classify water main segments into different age groups (bins) under the assumption that every successive age bin will have increased break frequency.

2. Complete a cost estimate for each policy by performing a desktop cost analysis on the last age bin (say bin X) by applying fix upon break, open-cut replacement, lining policy and the proposed strategy on the network individually and come up with costs that a municipality would incur by going with the conventional policies as well as the proposed strategy.

3. All the other bins are subjected to the fix upon break policy and their cost is estimated separately.

4. Step 2 and 3 are repeated in a cyclic manner, such that bin (X-1) will now be subjected to step 2 and the rest of the bins to step 3.

5. Once done, the pipe group in bin (X-2) are then subjected to step 2 and the rest to step 3. In a similar manner, all the bins (pipe age groups) are analyzed for future cost estimation using different conventional policies and the proposed strategy.

6. Once the desktop cost analysis is performed for all network, a cumulative economic forecast for all policies is generated over the planning horizon. The total costs incurred on all the pipe age bins are summed up to come up with the final predicted cost, i.e. the network`s economic forecast.
7. All the economic forecasts are plotted on a single chart to examine the predicted life cycle costs for the different policies, compare them to the proposed strategy and come up with an optimized plan to maintain the infrastructure over the next 100 years life cycle.

Figure 2-7 shows a block diagram depicting the framework.

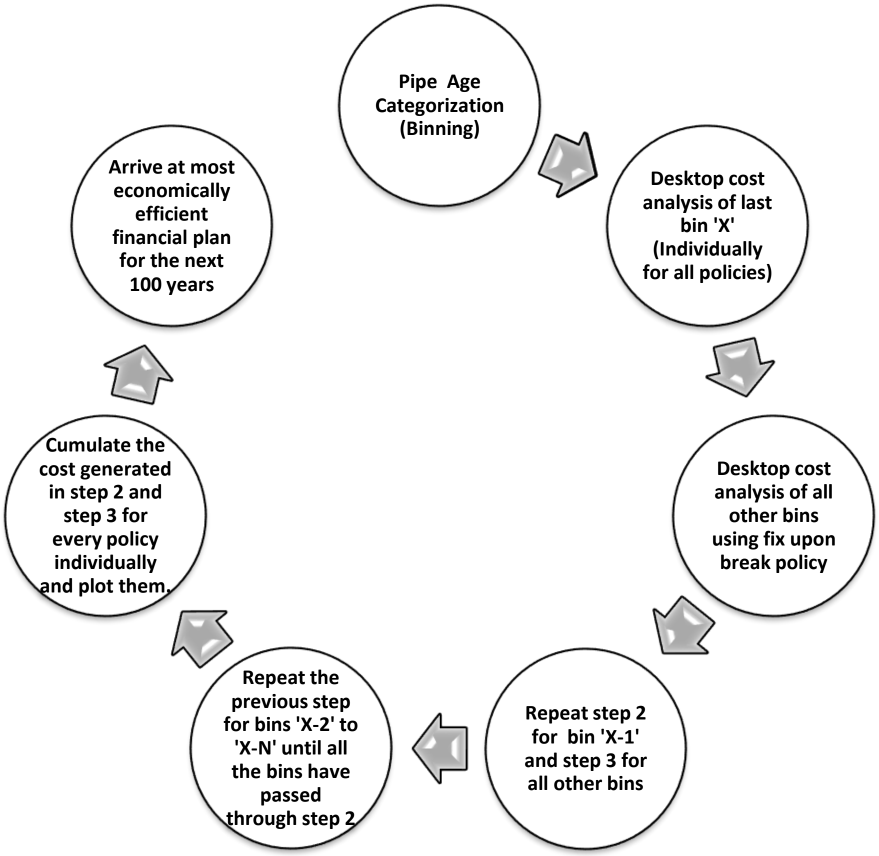


Figure 2-7: Practical Framework

In order to practically employ this framework to a water utility, equations need to be developed to simulate the conventional policies, proposed strategy, and ultimately the economic forecasts (cumulative cost) against each policy. Equations have been developed and a demonstration case study is performed using those equations in section 2.6.

2.6 Demonstration Case Study

To come up with useful insights about the water utility`s long-term financial situation, it is imperative to simulate the network over a similar planning horizon. This case study will demonstrate the accumulation of expenses using the conventional policies and how they compare against each other versus their comparison with the proposed methodology.

For this case study, a hypothetical potable water utility constituting of 400 km of water mains has been used and data synthesized from it to perform the financial forecast. The water mains are assumed to be all cast iron pipes. The age distribution is uniform i.e. there are 5 age bins (see Table 2-2).

Table 2-2: Hypothetical water utility`s pipe age binning

Bin Number	Pipe Age Range (Years)	Length of Pipe (KM)
1	0-20	80
2	20-40	80
3	40-60	80
4	60-80	80
5	80-100	80

The pipe length represents a typical city with a midsize population of about 200,000. For ease of analysis, it is assumed that the population served and hence network length will remain constant for the duration covered by the analysis i.e. next 100 years.

2.6.1 Parametrization of Model Variables

This section explains the estimation process and methodology required to parametrize and perform the cost estimation analysis by using equations from the literature to make the framework model. As is previously mentioned, the pipe segment lengths have been kept constant to simplify the study and maintain the focus on the long-term economic behavior of the network.

The cost parameter used in this study is the unit cost of pipe maintenance ($/meter/year). Pipe maintenance cost has two main components i.e. fixed component and a variable component. That is why the annual water distribution cost can be divided into a fixed annual cost and variable maintenance cost (Rehan et al. 2015). This study, however, does not take into account the fixed annual cost and shows costs in terms of variable maintenance costs only as they serve the purpose to highlight the fluctuation in costs when a policy change is exercised, which is the purpose of this case study. Thus, the complexity of calculations is reduced by limiting the analysis to variable maintenance costs in different policies.

The equation presented by Shamir and Howard (1979) is used to model pipe break pattern (see Equation 2.1) wherein 'N_T' (number of breaks at a given time 't') are calculated using 'g_m' (Break growth rate) and 'N_0' (Initial break growth rate).

Cost per break repair in the case study is $5770 for each individual break which is the average break repair cost in Saskatchewan.

Equation 2.2 is used to model the fix upon break cost estimation equation is as follows:

$$\boldsymbol{F_T = \sum_t Fs * N_T} \tag{2.2}$$

where:

F_S: Cost of fixing single break

N_T: Number of breaks at time t

F_T: Cumulative Repair cost

Clancy and Gustafson (1999)`s replacement cost model shown in Equation 2.3 is used for replacement cost estimations, which is as follows:

$$\boldsymbol{R = Y * Ls + X} \tag{2.3}$$

where:

R = Replacement Cost

Y =Average per meter replacement cost

L_s = Length of water main being replaced

X = Miscellaneous cost per site

A similar model shown in Equation 2.4 is used to perform lining cost estimations:

$$\boldsymbol{L = B * L_L + A} \tag{2.4}$$

where:

L = Lining cost

B =Average per meter lining cost

L_L = Length of water main being lined
A = Miscellaneous cost per site

A model for both replacement and lining (Equation 2.5) given the miscellaneous costs are included within the average cost would be:

$$\boldsymbol{C = S * L'} \qquad (2.5)$$

where:
C = Total replacement / lining cost
S = Average replacement / lining cost
L' = Length of water main being replaced / lined

Equation 2.5 (simplified equation) can be used when actual site information is not available regarding miscellaneous cost. As the water utility being considered in this case study is hypothetical, the simplified equation has been used to calculate lining and replacement costs.

For the case study, the replacement cost is assumed to be $800/meter, structural lining cost at $600/meter and non-structural lining cost is considered at $200/meter. The values that are to be used in the demonstration case study economic analysis are shown in Table 2-3.

Table 2-3: Assumed variable values

Variables	Assumed Values
Minimum Break Frequency	0.01 breaks / km /year
Break growth rate (g_m)	7.4% / year
Cost of fixing single break (Ft)	$5770
Overall Cost of replacement	$800 / m
Overall cost of structural liner	$600 / m
Overall cost of non-structural liner	$200 / m

2.7 Model Simulation and Results

Water mains on average have a service life of 75-100 years (Rehan et al. 2015). That is why they need to be simulated for service over a similar planning horizon to come up with substantive conclusions about the water utility`s financial sustainability in regards to maintaining an acceptable level of service.

The following four approaches have been adopted for the hypothetical city`s case study demonstration and the long-term financial forecasts. The approaches are as follows:

1. ‘Do nothing’ i.e. fix upon break for the next hundred years.
2. Replacement of all the pipe segments that are in the oldest age bin and keep fixing the pipes upon breaking that fall in the younger age bins.
3. Structurally lining all the pipe segments that are in oldest age bin and keep fixing the pipe segments upon breaking that fall in the younger age bins.
4. Inspecting all the pipes in the last age bin and categorizing them as per the proposed strategy`s inspection breakdown.

2.7.1 Model Simulation for Conventional Policies

The first three approaches are the conventional O&M and CW policies adopted by the cities to maintain their buried water infrastructure. Simulation results for the conventional policies life cycle cost estimation are presented in Figure 2-8. The figure illustrates economic forecast for the same water utility by simulating the costs accumulated up to 100 years (see Figure A3-A6 in Appendix A for details).

Equation 2.1 gives the number of breaks for the hypothetical water network. Using the number of breaks generated, Equations 2.2 – 2.5 are used to generate the fix upon break, replacement, lining costs.

Pipe age binning and break number prediction using Equation 2.1 has been shown in detail in Appendix A (Figure A1 – A2).

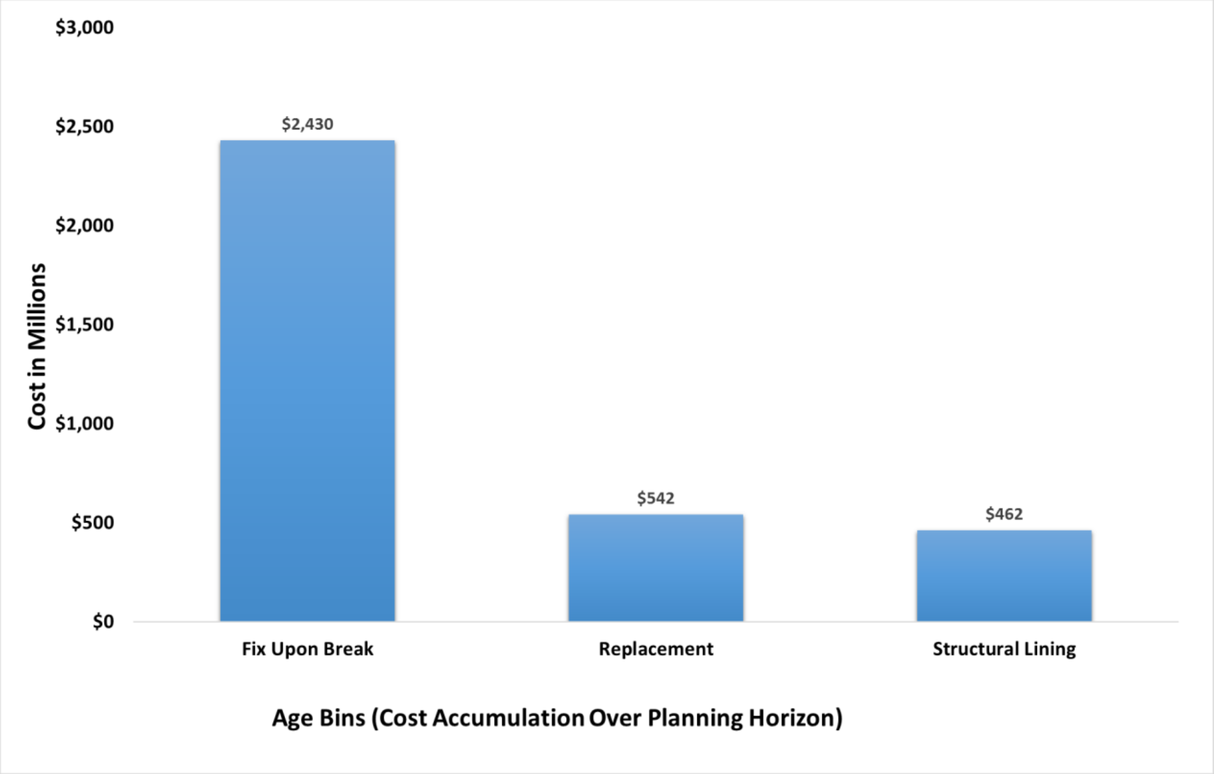


Figure 2-8: Cumulative comparative cost analysis of different rehabilitation & maintenance approaches over a planning horizon of 100 years

As is evident in Figure 2-8, fix upon break policy will incur $2,430 million if the municipality decides to adopt this policy for the next 100 years, followed by replacement which costs around 4.5 times less then fix upon break policy, details can be seen in Appendix A (Figure A3-A4). Structural lining further reduces the life cycle costs and in comparison, to fix upon break policy, it costs five times less than the fix upon break policy and almost $80 million less than the replacement policy (see Appendix A Figure A5).

2.7.2 Model Simulation for Proposed Strategy

To illustrate the usefulness of the proposed strategy, three scenarios (based on inspections) are presented in addition to the conventional policies which are then cross compared. The three additional inspection-based scenarios are aimed at highlighting the usefulness of inspecting old age pipes and its effect on long-term financial forecast using the proposed strategy. The three scenarios are shown in Table 2-4.

Table 2-4: Hypothetical scenarios based on the proposed strategy

	Leave Alone (L_A)	**Structural Lining (L_S)**	**Non-structural lining (L_{NS})**
Scenario 1	20%	60%	20%
Scenario 2	30%	20%	50%
Scenario 3	50%	20%	30%

The scenarios considered are very conservative as according to Pure Technologies™, after inspecting thousands of kilometers of water main, they deduced that only about 3.4% of the pipes that are inspected turns out to be damaged (Higgins et.al. 2012). This means we can put a higher percentage in the leave alone category.

The costs for the scenarios are a combination of fix upon break and lining equations as is evident from Table 2-4 where the policy breakdown for the scenarios have been described.

Figure 2-9 illustrates the life cycle cost comparisons of the three trenchless scenarios described in Table 2-4. It is observed that breaking down the results of inspection (scenario 1, 2 and 3) based on network water main conditions can have a huge impact i.e. in millions of dollars, depending on how we classify our pipe condition. This helps further reduce our rehabilitation and maintenance cost.

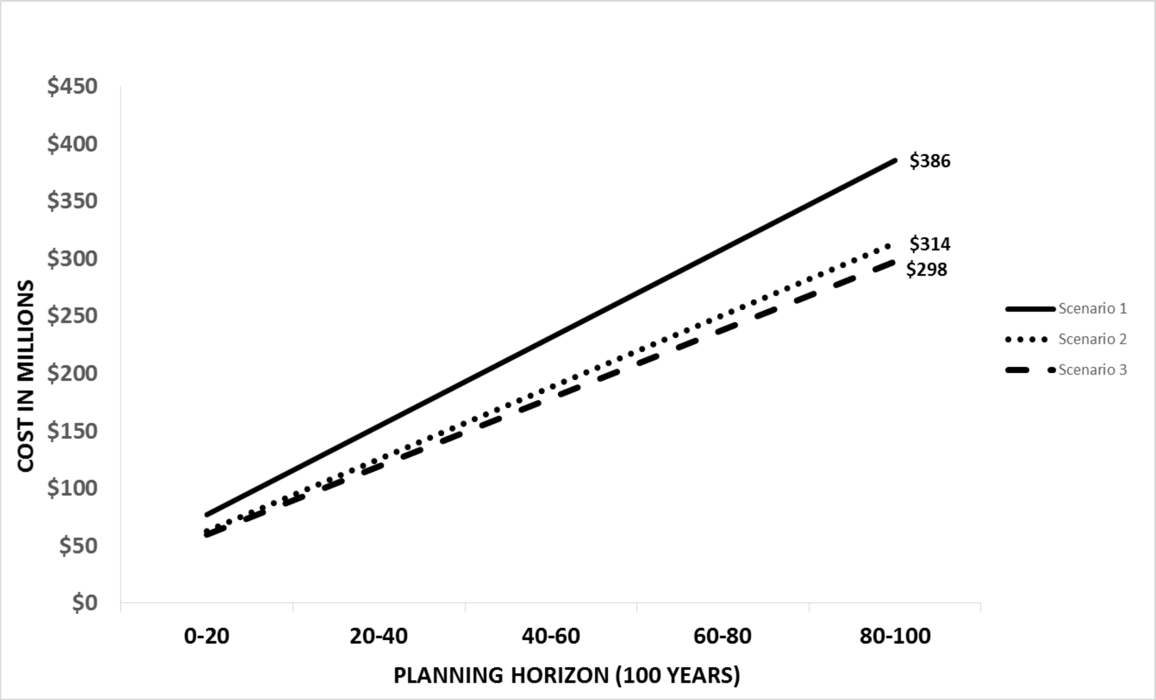


Figure 2-9: Cost comparison of assumed scenarios for proposed strategy over the planning horizon

Scenario 1 with highest structural lining percentage i.e. 60% has a life cycle cost of $386 million followed by scenario 2 with the highest non-structural lining percentage i.e. 50% incurs life cycle costs of $314 million. Scenario 3 where 50% of the watermains are maintained using fix upon break policy has a life cycle cost of $298 million (see Appendix Figures A6-A8 for details).

2.8 Discussion

As is evident from Figure 2-8, fix upon break although being fast and quick fix to pipe breaks and leaks, is comparatively not a financially smart solution in regards to sustainability over the life cycle of the network. The cost of fix upon break according to the simulation is over 4.5 times more expensive to the next most expensive approach of replacement towards the end of the planning horizon. The reason being that fix upon break only provides a temporary fix and does not in any way has a positive effect on the aging of pipe. Since the network keeps aging, this leads to higher break frequency, hence higher maintenance costs.

Lining and replacement, on the other hand, extends the life of pipe and hence hinders the aging process. Replacement replaces the aged pipes with new ones while lining stop corrosion build-up and depending on the liner type may take up design load fully, partially or not at all. The liner costs simulated in the section 2.7.1 are for structural liner. In this analysis, it`s assumed that the pipes that were deteriorated enough to be structurally lined.

For the utility under consideration, structural lining costs are $462 million over the network life cycle which is 81% cheaper than the conventional fix upon break life cycle cost. When structural lining is employed instead of total replacement, a cost saving of $80 million is realized which amounts to 14.8% of savings over a period of 100 years.

The simulated scenarios based on the approach that is proposed in this paper are to demonstrate impact of decisions on cost-effectiveness in the long term, i.e. life cycle of network. Details of the cost-effectiveness of all approaches are given in Table 2-5. Non-structural liner has also been considered in the hypothetical scenarios for partially deteriorated pipes as non-structural liner serves to improve the flow as well as extends life of a partially deteriorated pipe (Peterborough utilities 2013).

Table 2-5: Percentage savings of every rehabilitation & maintenance approach agast the rest to analyze the cost-effectiveness of each

Cost Savings Over 100-year period	**Fix Upon Break**	**Replacement**	**Structural Lining**	**Scenario 1**	**Scenario 2**
Replacement	77.7%	N / A	M / E	M / E	M / E
Structural Lining	81.0%	14.6%	N / A	M / E	M / E
Scenario 1	84.1%	28.9%	16.5%	N / A	M / E
Scenario 2	87.1%	42.1%	32.1%	18.7%	N / A
Scenario 3	87.8%	45.1%	35.6%	22.8%	M / E

In Table 2-5, every network maintenance approach in the first column is compared against all the other approaches to see if any cost savings are realized based on the simulation results. It is clear from the Table 2-5 that following the framework for proposed strategy and going for inspection (scenario 2 & 3) before performing rehabilitation operations can result in huge savings which are based on the fact that not all old pipes are bad. Based on the assumed network conditions, the maximum cost savings we realized when scenario 1, 2 and 3 (details in Table 2-4) are compared against fix upon break approach are 87.8% ($2132 million), 45.1% ($244 million) against replacement and 35.6% ($164 million) life cycle cost savings against structural lining.

2.9 Conclusions

1. Fixing the pipe upon break detection is not an economically smart strategy in the long run as the breaks tend to increase in frequency as the pipes age, warranting more fixes which can lead to operating budget deficit for municipalities resulting in backlogs.
2. Using the simplified model for the hypothetical network, the proposed strategy enabled the municipality to realize maximum cost savings of 87.8% against fix upon break approach, 45.1% against replacement and 35.1% against structural lining. The minimum savings that were realized were 84% against fix upon break approach, 29% against replacement and 16.5% against structural lining. The cost savings are subjective and may vary depending upon the actual network condition.
3. Additional reduction in costs can be realized by carefully inspecting the old pipes in a network and assigning them condition grade. The three hypothetical scenarios demonstrate this argument.
4. An extensive model applicable to water utilities across North America needs to be designed around the framework that is presented here.
5. All the parameters that are a function of data recorded by municipalities need to be defined clearly. This will help in robust analysis and will enhance long term decision making by increasing confidence in the life cycle cost estimations of the framework.

Chapter 3

Proposal and Validation of an Extensive Water Main Life cycle Analysis Framework for Future Cost Estimations of Different OM&R and CW Strategies

3.1 Overview

In this chapter an extensive framework for watermain life cycle cost analysis is presented that covers all the conventional and proposed OM&R approaches in search for the most economic approach to maintain the current infrastructure for the next 100 years. Further, the framework has been validated using a hypothetical average size water utility for a Canadian municipality.

The conventional OM&R (Operation, Maintenance, and Rehabilitation) approaches have resulted in large backlogs due to the expenses incurred on these approaches which the municipalities, by and large, cannot cope with, given their current revenues. Development, as well as rapid adoption of smarter water distribution network maintenance strategies supplying the utilities with enough information regarding the right time for a renewal or rehabilitation investment is now needed more than ever.

The framework has divided the approaches in to basic and advanced versions. Models have been designed for each approach and equations developed to come up with life cycle cost estimations.

The framework is then applied to a hypothetical water utility and the proposed strategy is analyzed and compared to the conventional OM&R approaches. Considerable cost savings were realized by employing the proposed strategy over the life cycle of water distribution network (WDN).

A software around the framework needs to be designed and verified to make the complex analyses easy for water utilities to perform.

3.2 Introduction

As was established in Chapter 2, when a municipality`s buried water infrastructure ages, it starts deteriorating i.e. leakage issues and structural failures start appearing at an increasing rate. These failures have direct consequences in terms of increased maintenance costs, lowering of water quality, service interruptions and consumer dissatisfaction.

Municipalities are constantly evolving and are striving to adopt a practical method to assess different Operation and Maintenance (O&M) and Capital Works (CW) policies. Currently, there are three prevalent approaches (policies) towards rehabilitation and maintenance of the water distribution mains:

1- ‘Fix upon break’ policy termed by (Li et al. 2005) as a reactive or emergency approach. It is the fixing of the pipe when breaks occur (O&M).

2- Age based or based on annually incurred breaks per unit length, the open-cut replacement (CW) is second most prevalent policy.

3- Recently lining is gaining widespread acceptance in the market; Non-structural lining of an old water main with some structural integrity and structural lining of water mains which are in a bad enough condition to warrant replacement are the two major liner types.

These approaches as discussed in Chapter 2 will have huge cost implications in the next five to ten decades if the municipalities are to maintain the current levels of service to the consumers and businesses. The conceptual framework (combination of proposed and traditional approaches) to estimate these costs for the next 100 years was also discussed in Chapter 2, the results of which are shown here in Figure 3-1 to get an idea of the potential cost savings when proposed strategy (inspection based approach) is compared to the traditional fix upon break, replacement and lining approaches. The analysis was performed on a 400 km hypothetical city.

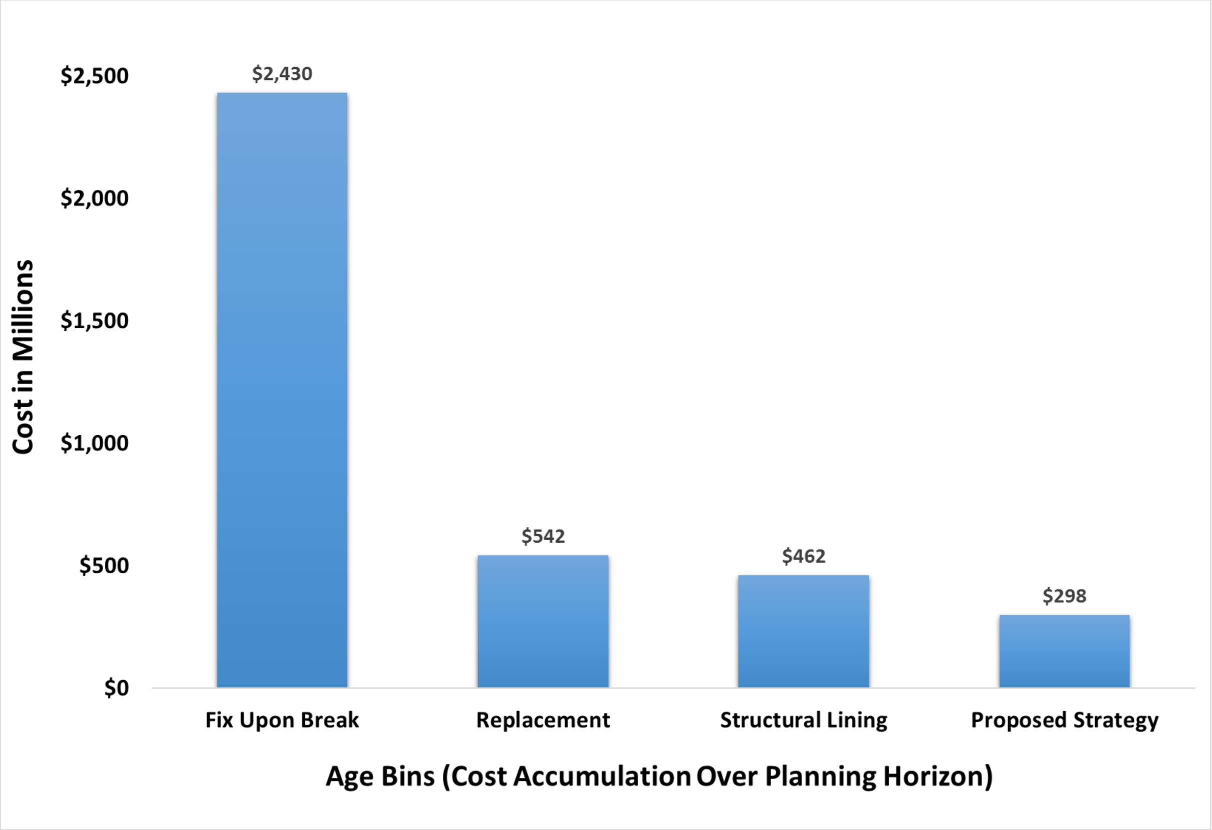


Figure 3-1: Cumulative comparative cost analysis of traditional policies and conceptual framework

The conceptual framework presented in Chapter 2 does not cover in detail all the variables that play a role in the actual cost analysis. Therefore, an extensive framework which accounts for all the cost variables that come into play in the traditional rehabilitation policies as well as the proposed strategy`s cost estimation needs to developed. Further, it should be developed in such a manner that all the policies are embedded into the framework and life cycle cost estimations for different policies can be examined and cross-compared.

To achieve this, cost models have to be developed for the all the different types of traditional approaches in practice and for the proposed approach that is based on inspection results. Thus, variables have been defined and equations developed for fix upon break, open-cut replacement, lining and the proposed strategy. Further, the equations developed have been categorized as basic and advanced. This categorization depends on the information available at hand to perform the cost analysis, any costs that are not accounted for are included as cost overruns and added to the final arrived life cycle costs.

3.3 Parametrization of Framework`s Model Variables

This section defines all the variables and the governing equations that are used to model the prevalent life cycle cost models i.e. fix upon break, replacement and lining in both basic and advanced form.

3.3.1 Fix Upon Break Cost Model

Shamir and Howard (1979) in their exponential pipe break model show that Pipes tend to break with a continuously increasing break frequency (Figure 3-2).

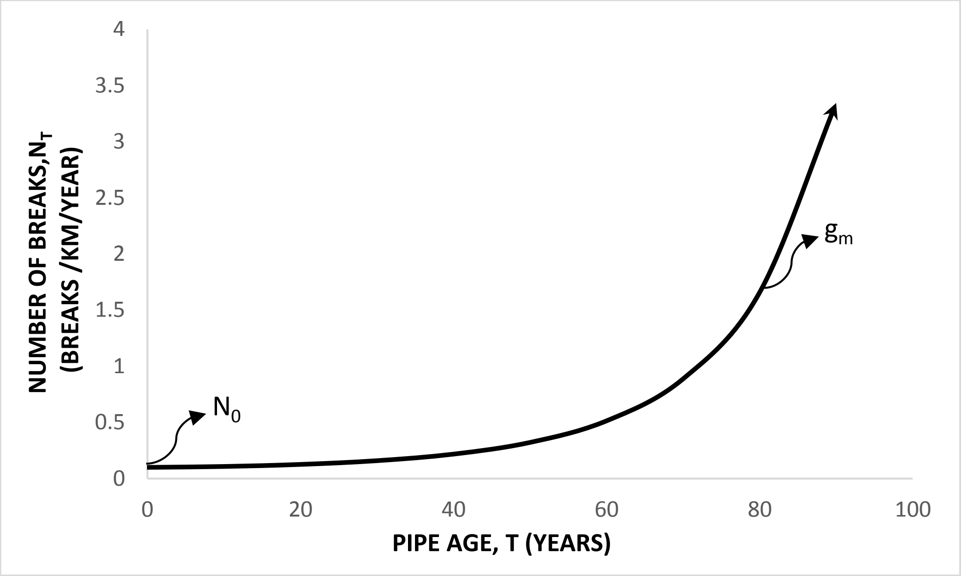


Figure 3-2: Shamir and Howard`s Exponential break trend (Shamir and Howard, 1999)

In Figure 3-2, 'N_T' is the total number of breaks at time T (years), 'N_0' is the initial number of breaks while 'g_m' is the break growth rate on an annual basis per unit length. Equation 3.1 by (Shamir and Howard (1979) is used to model a pipe`s break growth rate.

$$N_T = N_0 e^{g_m * T} \tag{3.1}$$

where:

N_T: Number of breaks at time T (years)
N_0: Initial number of breaks (-)
g_m: Break growth rate (per year)
T: Time (years)

The break growth rate 'g_m' and the initial number of breaks 'N_0' for the network under consideration are selected by an experienced Asset Manager of the relevant municipality.

As the network ages, the break rate will increase and hence the cumulative repair cost increase with it. Figure 3-3 shows the variables that go into the calculation of fix upon break approach.

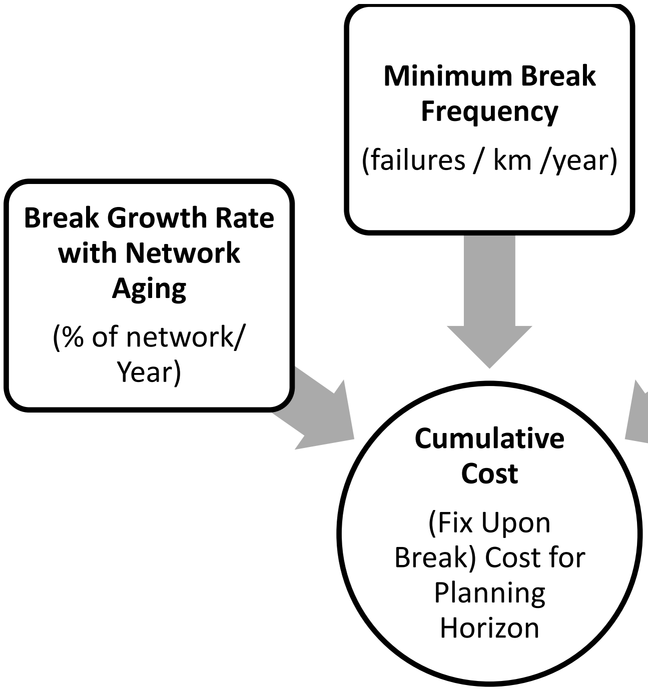


Figure 3-3: Fix upon break cost model

Equation 3.2 is used to calculate the costs incurred for the maintenance of the water distribution system of a municipality using fix upon break approach.

$$\boldsymbol{F_T = \sum_t F_S * N_T} \tag{3.2}$$

where:

F_T: Cumulative Fix upon Break Cost ($)

F_S: Cost of fixing a single break ($ / break)

N_T: Number of breaks at time T (# of breaks)

An average cost associated with a typical repair is used which according to Clancy and Gustafson (1999) is $5770 in the Province of Saskatchewan.

3.3.2 Open-Cut Replacement Model

The open-cut replacement cost model is designed with two different sets of variables essentially creating two models, one of which is used at a time. First one is called the Basic Replacement cost model while the second one is an Advanced Replacement cost model.

Basic Replacement cost model (Figure 3-4) uses an overall price per meter that includes the cost of bypass, pits and other miscellaneous costs for a replacement. Old pipes of the network that have surpassed their service design life or are in a bad condition rendering them unserviceable are selected for replacement. The rest of the network is maintained using the previously explained fix upon break model.

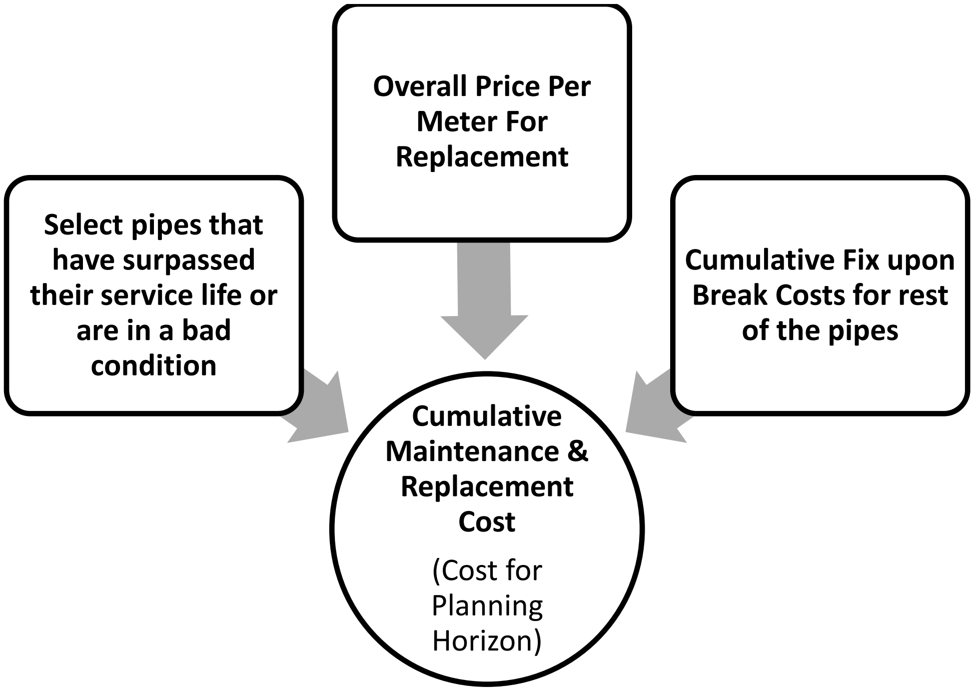


Figure 3-4: Basic Replacement cost model

Equation 3.3 is used to determine the cumulative costs for the basic replacement cost model is as follows:

$$\boldsymbol{CMR = Po * L_R + F_T} \qquad \textbf{(3.3)}$$

where:

CMR: Cumulative Maintenance & Replacement Cost (\$)

Po: Overall Price per Meter for Replacement (\$ / m)

L_R: Length of water main being replaced (m)

F_T: Cumulative Fix upon Break Cost (Equation 3.2)

Advanced Replacement cost model takes (Figure 3-5) into account all the individual costs that are incurred the open cut replacement job making the cost estimation analysis more accurate. Rather than an overall price per meter to replace the pipe, a combination of price per meter to replace the pipe and cost per site size are used in conjunction to come up with an estimation.

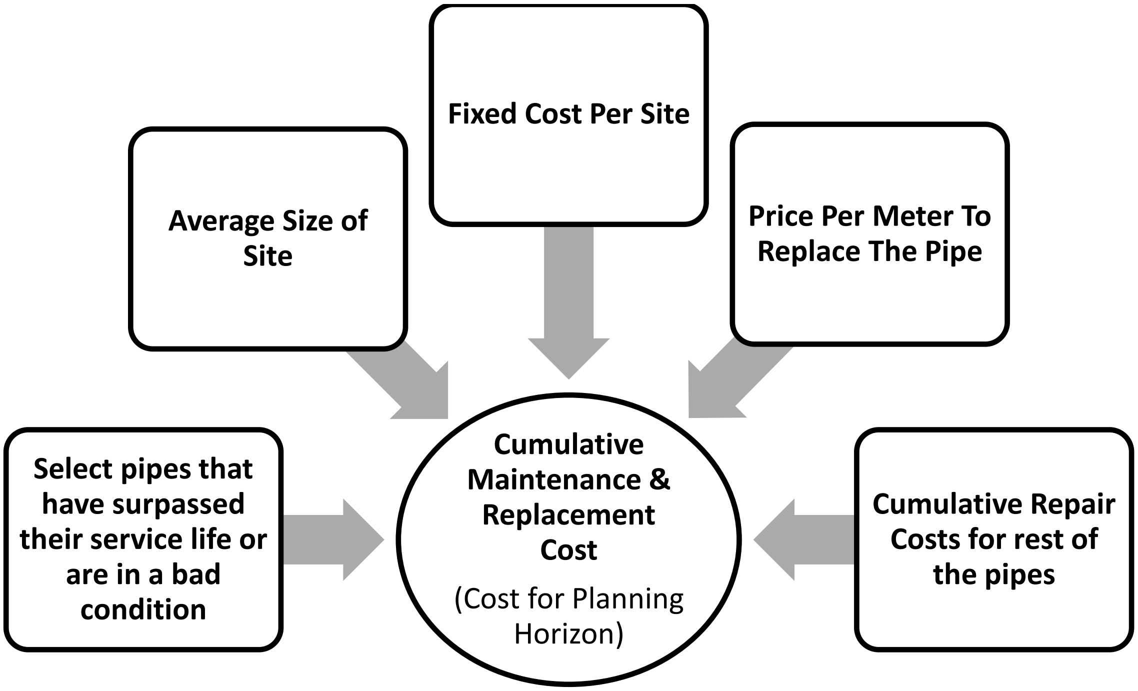


Figure 3-5 Advanced Replacement cost model

The Advanced Replacement cost model Equation 3.4 is as follows:

$$\boldsymbol{CMR = (P_R * L_R) + (F_s * N_s) + F_T} \tag{3.4}$$

where:

CMR: Cumulative Maintenance & Replacement Cost ($)

P_R: Price per Meter for Replacement ($ / m)

F_S: Fixed cost per site ($10,000 is the average for the province of Saskatchewan)

L_R = Length of water main being Replaced (m)

N_S: Number of sites to be dealt with in the program where $Ns = \frac{SS}{L_R}$

SS: Size of site (m)

F_T: Cumulative Fix upon Break Cost (Equation 3.2)

3.3.3 Lining Model

Figure 3-6 shows a basic lining cost model. Similar to that of replacement cost model, in lining cost model, pipes that are old or are in bad condition are selected as per the municipality's needs and budget limitations. In case of non-structural lining, water mains that are declared extremely bad and whose life cannot be extended with application of simple coating, are set aside for replacement. The rest of the network pipes are maintained using fix upon break cost model.

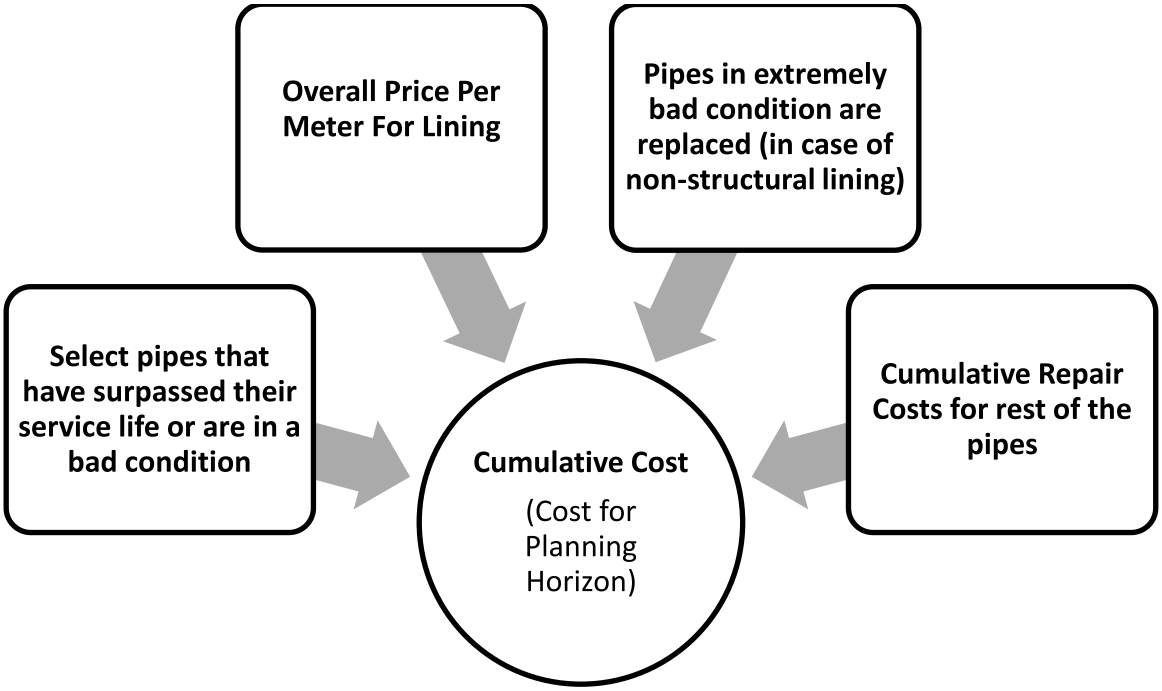


Figure 3-6: Basic Lining cost model

Cumulative costs for the Basic Lining cost model is determined using Equation 3.5.

$$CC = (P_L * L_L) + (P_R * L_R) + F_T \tag{3.5}$$

where:

CC = Cumulative Cost ($)

P_L = Overall price per meter for lining ($ / m)

L_L = Length Of water main being lined (m)

P_R = Overall price per meter for replacement ($ / m)

L_R = Length of water main being replaced (m)

F_T: Cumulative Fix upon Break Cost (Equation 3.2)

The Advanced Lining cost model takes into account the costs incurred at the site (length of pipeline rehabilitated or replaced in a single day) and separates it from the liner price per meter.

Figure 3-7 shows all the variables that go into advanced cost estimation when using lining as the primary rehabilitation approach.

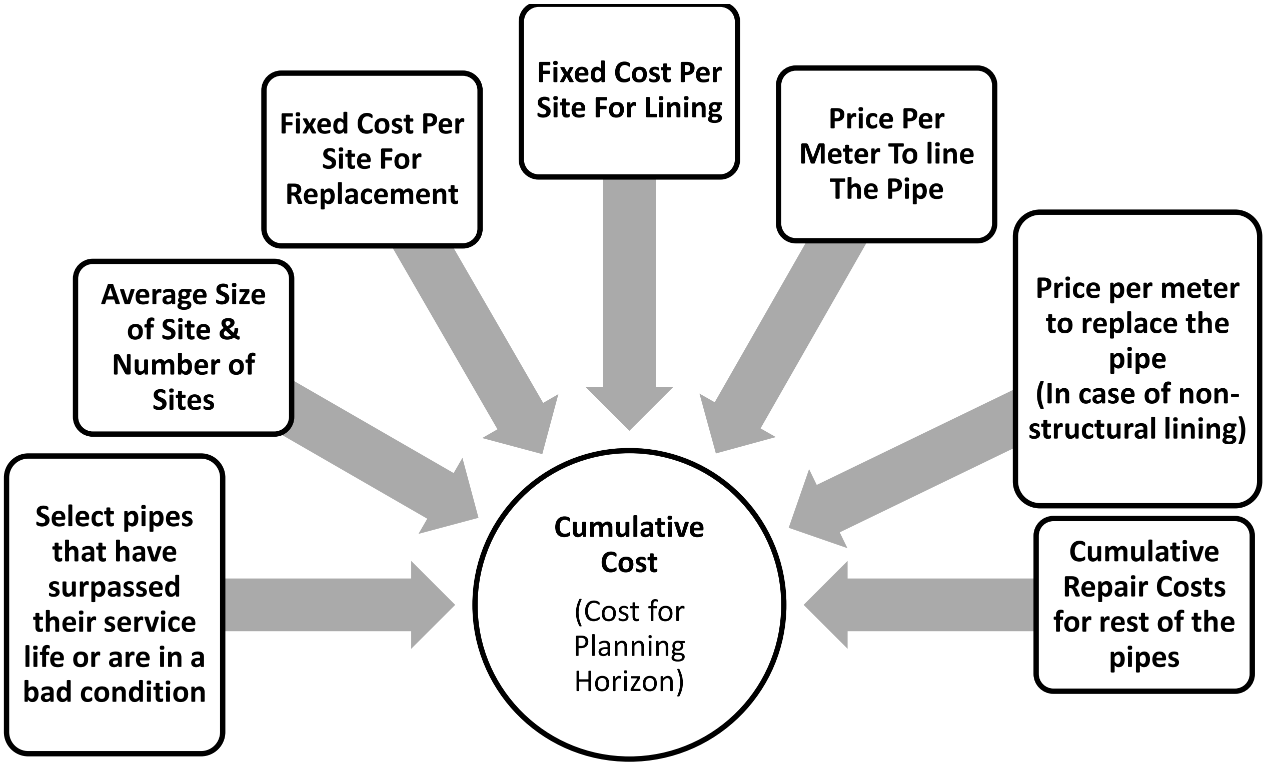


Figure 3-7: Advanced Lining cost model

Equation 3.6 is used to calculate the cumulative costs for the Advanced Lining cost model.

$$\boldsymbol{CC = (P_L * L_L) + (P_R * L_R) + (Fs_L * Ns_L) + (Fs_R * Ns_R) + F_T} \tag{3.6}$$

where:

CC: Cumulative Cost ($)

P_L: Price per meter for lining ($ / m)

L_L: Length of water main being lined (m)

P_R: Overall price per meter for replacement ($ / m)

L_R: Length of water main being replaced (m)

Fs_L: Fixed cost per site for lining ($)

SS_L: Size of site (length of water main replaced per day)

Ns_L: Number of lining sites where $\mathrm{Ns_L} = \frac{L_L}{SS_L}$

Fs_R: Fixed cost per site for replacement ($)

$\mathrm{Ns_R}$: Number of replacement sites where $\mathrm{Ns_R} = \frac{L_R}{SS_R}$

$\mathrm{SS_R}$: Size of site (length of water main lined per day)

F_T: Cumulative Fix upon Break Cost (Equation 3.2)

3.4 Framework`s Proposed Strategy

To optimize the Water Distribution Network (WDN) OM&R costs over a planning horizon of 100 years, a strategy that combines all the conventional approaches which are covered in the previous cost model has been designed that follows a stepwise process towards making certain decisions based on economic viability and network condition. The process loops through the network life cycle that is depicted in the decision flowchart in Figure 3-8. The loop repeats until an economic forecast for the required planning horizon is achieved and an optimal strategy to maintain and rehabilitate the network is envisioned.

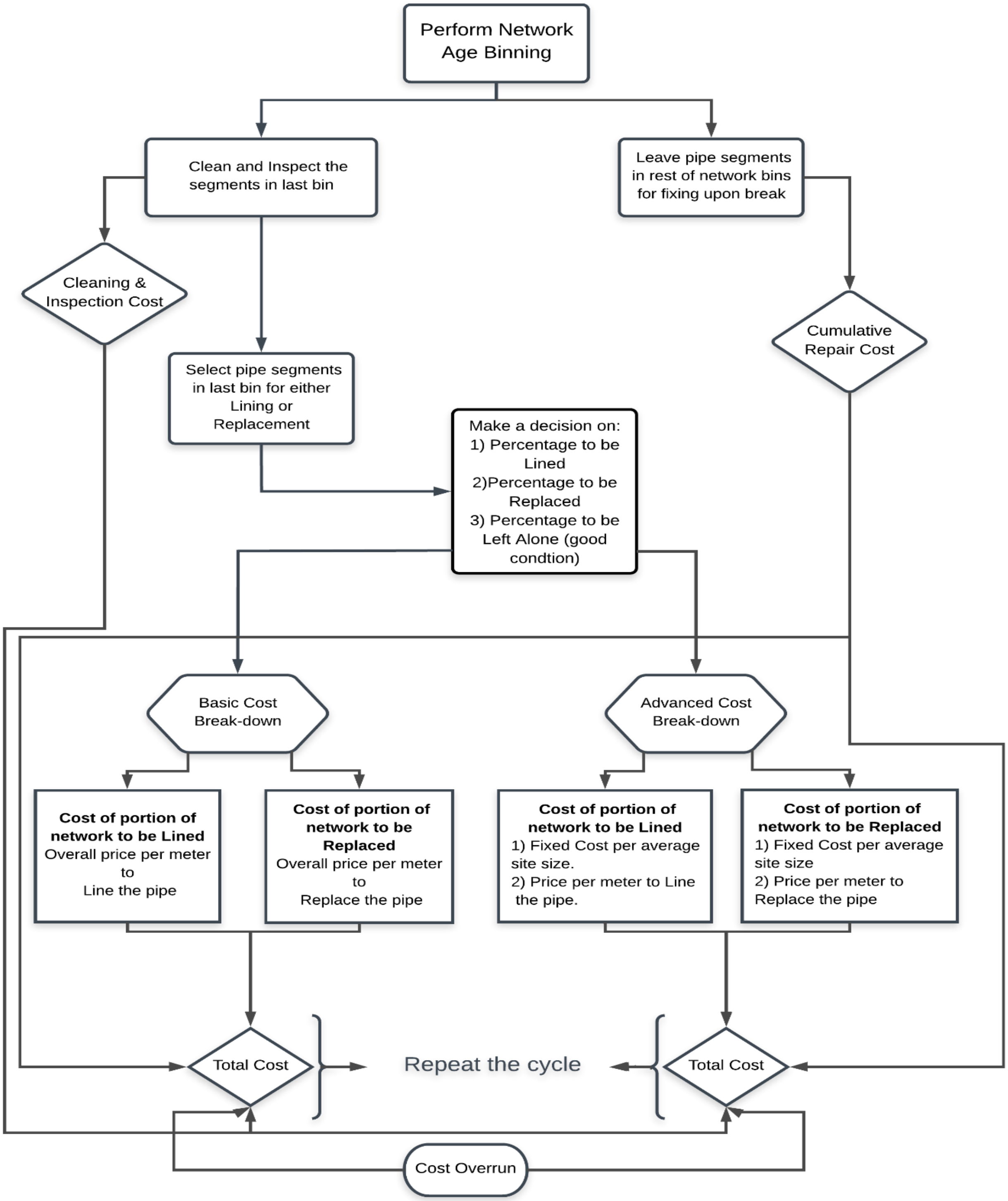


Figure 3-8: Proposed strategy`s decision flow chart

Initially, the WDN is classified into different age groups which will be referred to as binning. The size of bin or age group depends on the decision of the asset manager as it will have an impact on the concerned utility`s OM&R and capital works budget.

Upon network binning, where pipe segments are assigned different age groups and are clustered together, the oldest bin pipes are prioritized for cleaning and inspection. The rest of the network which lies in other bins is left to be maintained in the conventional fix upon break manner and the cost for that is estimated using the fix upon break cost model.

Cleaning and inspection costs are calculated on a per meter basis as is proposed by Clancy and Gustafson (1999). Once the pipes are cleaned and inspected using any of the available inspection technique, they can essentially be distinguished into three different categories i.e. pipes that can be restored with liner, pipes that needs immediate replacement and pipes that are in good condition. Based on the inspection results, the asset manager along with the contractor and other stakeholders need to arrive at the following decisions:

1. Percentage of the inspected water mains that need to be lined (non-structural) to extend their service life.
2. Percentage of the water mains that needs replacement or structural lining.
3. Percentage of water mains that are left alone (water mains that are old but still in good serviceable condition).

Based on the above decisions, the cost to perform the necessary OM&R and capital works operations are estimated based on the level of information available to the asset manager and contractor. Depending on the level of available information the cost estimation can either be basic or advanced.

Basic cost breakdown requires:

- Length of water mains to be lined.
- Length of water mains to be replaced.
- Overall price per meter to line the water mains.
- Overall price per meter to replace the water mains.
- Cumulative cost for fix upon break of all other water mains.

Once the lengths and prices are acquired, Equation 3.7 is then used to get the cost estimation using the basic method. Cumulative fix upon break cost is calculated using Equation 3.2, the outcome of which is then put into Equation 3.7.

$$\boldsymbol{BMRR = (P_{OR} * L_R) + (P_{OL} * L_L) + F_T} \tag{3.7}$$

where:

BMRR: Basic Maintenance, Rehabilitation, and Replacement cost

P_{OR}: Overall price per meter to replace the water main

L_R: Length of water main to be replaced

P_{OL}: Overall price per meter to line the water main

L_L: Length of water main to be lined

F_T: Cumulative Fix upon Break Cost (Equation 3.2)

For the advanced method the cost model requirements will be as follows:

- Price per meter to replace the water mains.
- Price per meter to line the water mains.
- Length of water main to be replaced.
- Length of water main to be lined.
- Cumulative cost for fix upon break of all other water mains.
- Size (length of water main) of work site covered per day.
- Total number of sites in the program.
- Fixed cost per average site size.

Pertinent to the availability of the required information, Equation 3.8 is used to get an advanced maintenance, rehabilitation, and replacement cost estimation. Similar to that of BMRR calculation, cumulative fix upon break cost is calculated using Equation 3.2 which is then put into Equation 3.8.

$$\boldsymbol{AMRR = (P_{ER} * L_R) + (P_{EL} * L_L) + (Fs_L * Ns_L) + (Fs_R * Ns_R) + F_T} \tag{3.8}$$

where:

AMRR: Advanced Maintenance, Rehabilitation, and Replacement cost ($)

P_{ER}: Price per meter (exclusive) to replace the water main ($ / m)

L_R: Length of water main to be replaced (m)

P_{EL}: Price per meter (exclusive) to line the water main ($ / m)

$\mathrm{L_L}$: Length of water main to be lined (m)
$\mathrm{Fs_L}$: Fixed cost per site for lining ($)
$\mathrm{Ns_L}$: Number of lining sites where $\mathrm{Ns_L} = \frac{\mathrm{L_L}}{\mathrm{SS_L}}$
$\mathrm{SS_L}$: Size of site (length of water main replaced per day)
$\mathrm{Fs_R}$: Fixed cost per site for replacement ($)
$\mathrm{Ns_R}$: Number of replacement sites where $\mathrm{Ns_R} = \frac{\mathrm{L_R}}{\mathrm{SS_R}}$
$\mathrm{SS_R}$: Size of site (length of water main lined per day)
F_T : Cumulative Fix upon Break Cost (Equation 3.2)

Once we have either of BMRR or AMRR, the cost of cleaning, inspection and cost overruns are added to it. The final total cost for the planning horizon is arrived at by summing all these costs, as is shown in Equation 3.9 and Equation 3.10 for basic and advanced life cycle cost estimation, respectively.

$$\textbf{Basic Total OM\&R Cost} = \textbf{BMRR} + \textbf{Cleaning} \,\&\, \textbf{Inspection} + \textbf{Cost Overrun} \tag{3.9}$$

$$\textbf{Advanced Total OM\&R Cost} = \textbf{AMRR} + \textbf{Cleaning} \,\&\, \textbf{Inspection} + \textbf{Cost Overrun} \tag{3.10}$$

The costs calculated here are for a specific number of years which are equal to the network age bin size. To calculate the costs for a full life cycle of around 100 years (typical design life of water network), the decision loop has to be repeated a number of times till the costs for full life cycle are obtained.

The total life cycle cost is the cumulative basic or cumulative advanced OM&R or capital works cost, the equations for which are as follows:

$$\sum_{\mathbf{N}} \textbf{Life Cycle Basic OM\&R Cost} = \sum_{\mathbf{N}} (\textbf{BMRR} + \textbf{Cleaning} \,\&\, \textbf{Inspection} + \textbf{Cost Overrun}) \tag{3.11}$$

$$\sum_{\mathbf{N}} \textbf{Life Cycle Advanced OM\&R Cost} = \sum_{\mathbf{N}} (\textbf{AMRR} + \textbf{Cleaning} \,\&\, \textbf{Inspection} + \textbf{Cost Overrun}) \tag{3.12}$$

where N is the number of cycles the loop has to be repeated to calculate the total life-cycle costs.

3.5 Framework Demonstration Case Study

To demonstrate the effectiveness of the proposed strategy, framework is applied to a hypothetical water utility as was done in Chapter 2. The purpose is to compare the proposed strategy against the conventional OM&R approaches, as well as, arrive at useful insights about the utility`s long-term financial situation.

As the average service life of water mains ranges from 75 to 100 (Rehan et al. 2015) years depending on the material used, the framework will be applied to the water utility for 100 years.

As is mentioned in Chapter 2, a hypothetical water utility of 400 km of water distribution mains are used in the case study. Pipe ages have been distributed with an increment of 20 years per bin. 2000 mains are considered in total, each 200m in length. There are five age bins of each spanning over 20 years (see Table 3-1).

Table 3-1: Hypothetical water utility`s pipe age distribution

Bin Number	Pipe Age Bins (years)	Total Length In Each Bin (Kilometers)
1	0-20	60
2	20-40	80
3	40-60	120
4	60-80	80
5	80-100	60

Population served and network length is assumed to remain constant for the duration of the analysis i.e. 100 years.

The case study analyzes five cost models of the framework that cover the conventional approaches and the proposed strategy i.e.

- Fix upon break cost model
- Basic Replacement cost model
- Advanced Replacement cost model
- Basic Lining cost model
- Advanced Lining cost model
- Basic Proposed cost model
- Advanced Proposed cost model

In the Proposed strategy, a decision needs to be taken regarding the portion of the network in the last age bin to be either lined, replaced or left alone. Table 3-2 presents three different scenarios that will be analyzed using the framework to highlight the long-term financial effect of the decisions on the proposed strategy.

Table 3-2: Hypothetical scenarios analyzed

	Leave Alone	Structural lining	Non-structural lining
Scenario 1	20%	60%	20%
Scenario 2	30%	20%	50%
Scenario 3	50%	20%	30%

Table 3-3 shows the different variables and the default values assigned to them that are used in computing the costs. The default values are taken in part from (Clancy and Gustafson (1999) and in part from industry experts.

Table 3-3: Variables values assumed throughout the analysis

Variables	Assumed Values
Minimum Break Frequency	0.01 breaks / km /year
Break growth rate (g_m)	7.4% / year
Cost of fixing a single break (Fs)	$5770
The Overall Cost of replacement(Basic)	$800 / m
The overall cost of non-structural liner (Basic)	$200 / m
The overall cost of structural liner (Basic)	$600 / m
Size of Site (In terms of water main length)	200 m
Fixed Cost per site (replacement)	$4000
Number of sites (replacement)	10
Replacement price (Advanced)	$400 / m
Lining price (Advanced)	$100 / m
Size of Site	200 m
Fixed Cost per site (lining)	$2000

3.6 Results and Discussion

Table 3-4 presents a summary of the costs incurred using the conventional OM&R and CW policies as well as the proposed strategy both under basic and advanced cost models of the proposed framework.

Table 3-4: Accumulated costs over a 100-year period for different OM&R approaches

Cost model	Basic model costs	Advanced model costs
Fix Upon Break	$2 Billion	$2 Billion
Replacement	$436 million	$284 million
Structural Lining	$356 million	$244 million
Scenario 1	$329 million	$229 million
Scenario 2	$224 million	$175 million
Scenario 3	$208 million	$166 million

Table 3-5 and Table 3-6 in the subsequent sections show the percentage difference in life cycle costs the utilities will incur depending on what approach they follow. The cells with "N/A" entry means cost savings are not applicable while cells with "M/E" entry means more expensive. Table 3-5 and Table 3-6 clearly demonstrate that different approaches will have major effects on cost over the life cycle of the network.

3.6.1 Framework`s Basic Cost Models Simulation Results

In following the proposed strategy`s basic cost model which have been implemented in the scenario 1, 2 and 3 (see Table 3-5), the maximum cost saving that is realized against conventional fix upon break approach is 89.6% when compared against proposed strategy`s third scenario.

Table 3-5: Percentage savings of all OM&R approaches against each other to realize cost-effectiveness of each using basic cost models

Cost Savings (Basic cost *models)*	Fix Upon Break	Replacement	Structural Lining	Scenario 1	Scenario 2
Replacement	78.2%	N / A	M / E	M / E	M / E
Structural Lining	82.2%	18.3%	N / A	M / E	M / E
Scenario 1	83.5%	24.6%	7.7%	N / A	M / E
Scenario 2	88.8%	48.6%	37.1%	31.9%	N / A
Scenario 3	89.6%	52.3%	41.6%	36.7%	7.1%

3.6.2 Framework`s Advanced Cost Models Simulation Results

Table 3-6 demonstrates the cost comparisons of different approaches when the analysis for the framework was carried out using advanced cost models. The maximum cost saving that is realized against conventional fix upon break approach is 91.7% when compared to advanced cost model of proposed strategy in third scenario. Although the percentage savings compared to basic cost models are low in certain comparisons, the actual monetary savings are greater as using advanced cost models reduces the conventional approach`s costs as well in the first place. This means that the proposed strategy scenarios are compared to a lower cost in the first place. This is explained more in Figure 3-9, where cost savings in the magnitude of millions are realized consistently when advanced cost model analyses are compared to basic cost model analyses.

Table 3-6: Percentage savings of all OM&R approaches against each other to realize cost-effectiveness of each using advanced cost models

Cost Savings (Advanced* cost *models)	**Fix Upon Break**	**Replacement**	**Structural Lining**	**Scenario 1**	**Scenario 2**
Replacement	85.8%	N / A	M / E	M / E	M / E
Structural Lining	90.1%	14.1%	N / A	M / E	M / E
Scenario 1	88.5%	19.3%	6.1%	N / A	M / E
Scenario 2	91.2%	38.3%	28.2%	23.6%	N / A
Scenario 3	91.7%	41.4%	31.8%	27.4%	5.0%

3.6.3 Comparative Analysis of Basic and Advanced Framework Models

As is evident in Figure 3-9, it is clear that following the proposed strategy as has been applied to the three scenarios in the case study economizes the life cycle budget of network`s OM&R and realize multifold cost savings in millions. Figure 3-9 also illustrates the fact that having past records and access to information regarding the municipality`s buried infrastructure is always beneficial in terms of cost savings as having more information allows for the usage of advanced cost models which takes into account a lot more variables and increases the accuracy of cost estimations over the life cycle of the network.

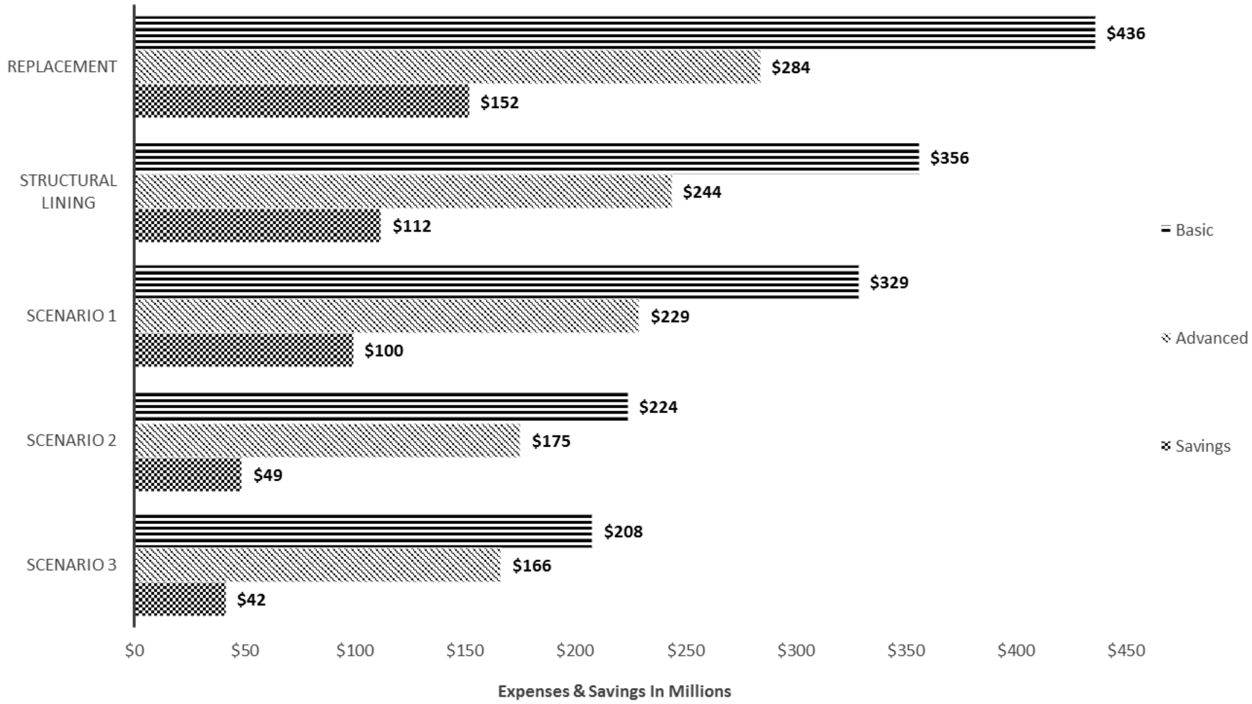


Figure 3-9: Comparative Life cycle Cost Estimations of Traditional and Proposed Cost models

Figure 3-9 infers from the analysis of framework that advanced cost models realized cost savings of $152 million, $112 million, $100 million, $49 million and $42 million against basic cost models of open-cut replacement, structural lining, scenario1, 2 and 3 respectively. Fix upon break approach has not been discussed here as it does not have a basic and advanced version.

3.7 Conclusions

- Introducing smart asset planning strategies for the subsurface utilities particularly water distribution network is important for their maintenance over an extended period of time i.e. life cycle of the network.
- There is an exponential increase in deterioration of buried water distribution infrastructure.
- The proposed strategy in the paper results in savings of millions of dollars over the network life cycle compared to conventional OM&R policies.
- The proposition of inspecting pipes in the old age bin saves utilities of unnecessary inspection costs and helps further reduce the cost by identifying pipes that are old but still in good working condition i.e. they don`t require any major maintenance.
- The more the information available about the water main network, the better the OM&R strategy and more cost savings can be realized.
- ‘Do nothing’ or fix upon break strategy is extremely expensive, i.e. more than three times more expensive than the next most expensive approach i.e. replacement.
- The proposed strategy in the framework enabled the hypothetical municipality to realize minimum cost savings of $1.7 billion (83.5%) against fix upon break approach, $55 million (24.6%) against replacement and $27 million (7.7%) against structural lining using the basic cost model.
- By using advanced cost model, the minimum savings that were realized were $1.8 billion (88.5%) against fix upon break approach, $59 million (19.3%) against replacement and $15 million (6.1%) against structural lining. The cost savings are subjective and may vary depending upon the actual network condition.
- Although the figures are lower than basic cost models savings, due to the fact that advanced cost models have already lowered the conventional policies costs due to the availability of information. That is why cost savings in advanced cost models are additional to that of the basic cost model savings for the particular approach, i.e. the more the information available about the network, more will be the realized savings.
- A verified life cycle cost estimation tool (software) needs to be designed around the framework for ease of access to the municipalities.

Chapter 4

Verification and Sensitivity Analysis of a Water Distribution Asset LCE (Life Cycle Cost Estimation) Tool Using SDLC V-Model

4.1 Overview

In this chapter, an extensive tool has been designed and verified using the SDLC V-Model (software development life cycle validation and verification). A sensitivity analysis has been performed to highlight the important and sensitive variables in the cost estimation and decision-making process.

Water utilities are in a state of growing uncertainty about their OM&R (Operation, Maintenance, and Renovation) strategies due to a consistent increase in backlogs in the Canadian and the American water distribution industry. These backlogs are constantly on the rise due to limited funding and deferred maintenance, renewal, and replacement of aging water infrastructure (O’Day D.K, Weiss R, Chiavri S 1989, AWWA 2011).

Chapter 2 addressed the defined gap and as an answer Chapter 3 presented an extensive framework with a number of models covering all the OM&R as well as replacement approaches and cross compared them to be able to obtain a holistic view of life cycle costs to maintain the old water conveyance infrastructure. In essence, Chapter 3 comes up with an optimized life cycle cost strategy for a water utility covering a planning horizon of up to 100 years.

A tool has been developed to automate the framework presented in Chapter 3 i.e. simulating all models presented within the framework and facilitating the process of life cycle cost estimation using the established OM&R, replacement and proposed water utility policies. In this Chapter, a full-fledged integrated system verification for the tool is performed using data from a case study and the analysis results are compared against the MS Excel arrived at results using the model equations from the framework developed in Chapter 3.

A sensitivity analysis has been performed to examine variable`s long term effect on the life cycle costs. The results of the sensitivity analysis show that the variable ‘break growth rate’ is the most sensitive of all variables in the framework wherein 1% change leads to a 7% change in the life cycle costs.

4.2 Introduction

Municipal water systems provide potable water to consumers that include residents, businesses, and industries. Water systems being buried infrastructure and often out of the sight of public loses its immediate importance and value unless a watermain leak, break or contaminant occurrence is detected. Water mains with a service life of 75-100 years (Rehan 2011) typically start developing breaks at a high frequency towards the end of their useful service lives. In North America, many municipalities are faced with the challenge of limited financial and personnel resources to maintain the infrastructure nearing the end of its useful service life (Rehan et al. 2015).

Vanier (2004) states about the need to improve the operational efficiency and effectiveness of managing infrastructure assets by enhancing the capabilities of the decision support systems. According to Newton (2005), the vast majority of existing asset management systems focus on the day to day operational and management activities, essentially giving little to no support for long-term maintenance and renewal planning.

Newton (2006) states that management strategies and decision support tools for buried water and wastewater infrastructure are basically non-existent, except for a few proprietary tools. According to Grigg (2003), when compared to software systems developed for other sectors, the softwares developed for the asset management industry are limited in their scope, very less in number and not mature enough to handle all the variabilities. Grigg (2003) further enforces the idea of water asset management systems being limited to integrating activities like data registration, assessment, and grading of infrastructure condition, analysis of data to predict remaining service life etc.

An extensive framework applicable to water utilities that takes into account all the variables affecting the OM&R (Operation, maintenance and renovation) and CW (Capital Works) costs, and perform life cycle cost analysis by prioritization of rehabilitation activities to ensure maximum benefits at minimum costs has been presented in Chapter 3. This chapter presents a tool that has been developed around that very framework which tries to cover the identified gaps.

The tool`s verification and sensitivity analysis have been performed in this chapter to highlight the important and sensitive variables in the cost estimation and decision-making process.

4.3 Overview of the Developed Life cycle Cost Estimation Tool Interface

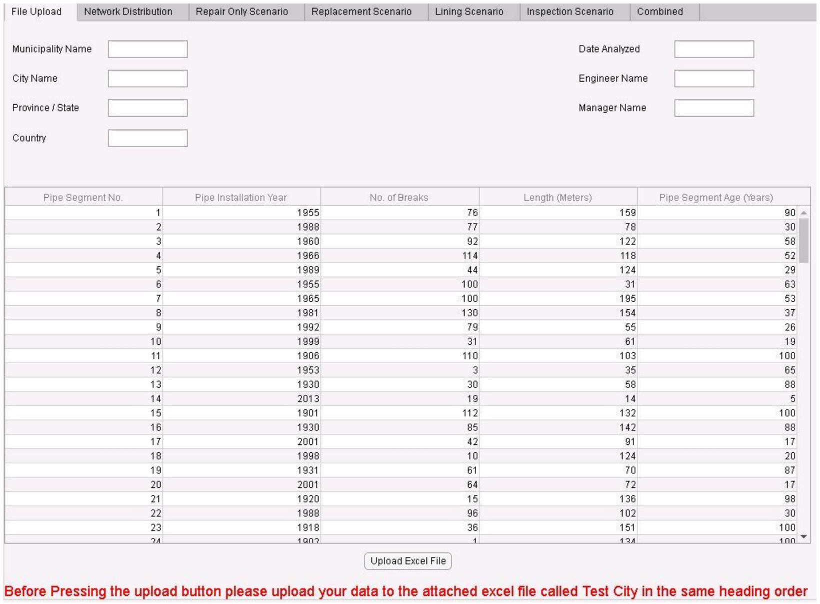
This section introduces the front-end interfaces the LCE (Life Cycle Cost Estimation) tool returns when different tabs are accessed within it. There are three different pop-up windows and eight different tabs the LCE tool returns as and when requested by the user.

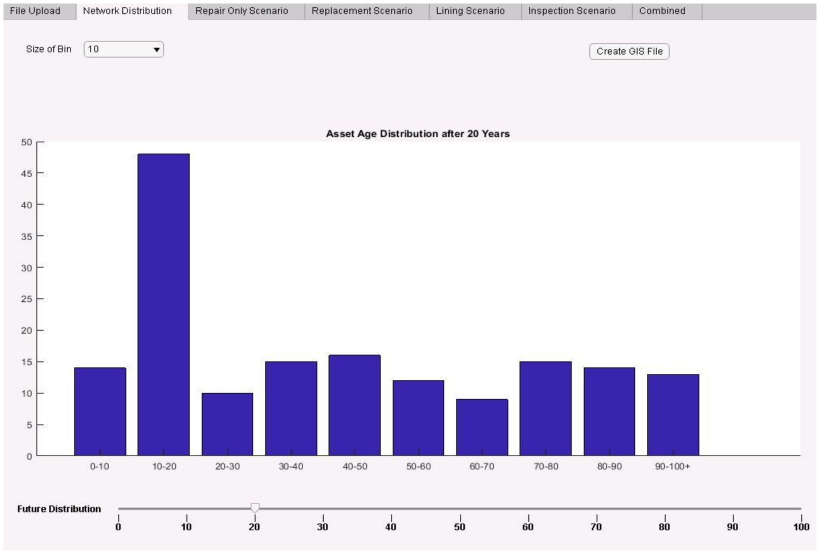
The three pop-up windows the LCE tool open up are the following:

1. Excel sheet upload window.
2. Break growth rate simulation window.
3. Creating a separate GIS readable file.

The screenshots for the pop-up windows are provided in Appendix B-1, C2 and C3.

The eight different main screens the LCE tool returns after analysis along with their brief descriptions are shown in Figure 4-1:

<table>
<tr><th>Main screen</th><th>Description</th></tr>
<tr><td>


<table>
<tr><th>Pipe Segment No.</th><th>Pipe Installation Year</th><th>No. of Breaks</th><th>Length (Meters)</th><th>Pipe Segment Age (Years)</th></tr>
<tr><td>1</td><td>1955</td><td>76</td><td>159</td><td>90</td></tr>
<tr><td>2</td><td>1988</td><td>77</td><td>78</td><td>30</td></tr>
<tr><td>3</td><td>1960</td><td>92</td><td>122</td><td>58</td></tr>
<tr><td>4</td><td>1966</td><td>114</td><td>118</td><td>52</td></tr>
<tr><td>5</td><td>1989</td><td>44</td><td>124</td><td>29</td></tr>
<tr><td>6</td><td>1955</td><td>100</td><td>31</td><td>63</td></tr>
<tr><td>7</td><td>1965</td><td>100</td><td>195</td><td>53</td></tr>
<tr><td>8</td><td>1981</td><td>130</td><td>154</td><td>37</td></tr>
<tr><td>9</td><td>1992</td><td>79</td><td>55</td><td>26</td></tr>
<tr><td>10</td><td>1999</td><td>31</td><td>61</td><td>19</td></tr>
<tr><td>11</td><td>1906</td><td>110</td><td>103</td><td>100</td></tr>
<tr><td>12</td><td>1953</td><td>3</td><td>35</td><td>65</td></tr>
<tr><td>13</td><td>1930</td><td>30</td><td>58</td><td>88</td></tr>
<tr><td>14</td><td>2013</td><td>19</td><td>14</td><td>5</td></tr>
<tr><td>15</td><td>1901</td><td>112</td><td>132</td><td>100</td></tr>
<tr><td>16</td><td>1930</td><td>85</td><td>142</td><td>88</td></tr>
<tr><td>17</td><td>2001</td><td>42</td><td>91</td><td>17</td></tr>
<tr><td>18</td><td>1998</td><td>10</td><td>124</td><td>20</td></tr>
<tr><td>19</td><td>1931</td><td>61</td><td>70</td><td>87</td></tr>
<tr><td>20</td><td>2001</td><td>64</td><td>72</td><td>17</td></tr>
<tr><td>21</td><td>1920</td><td>15</td><td>136</td><td>98</td></tr>
<tr><td>22</td><td>1988</td><td>96</td><td>102</td><td>30</td></tr>
<tr><td>23</td><td>1918</td><td>36</td><td>151</td><td>100</td></tr>
</table>
Before Pressing the upload button please upload your data to the attached excel file called Test City in the same heading order
</td><td>
- Front Page
- Uploads Data from Excel.
- Sorts the data into four columns i.e,
1) Pipe segment number
2) Pipe Installation Year
3) Number of breaks since installation.
4) Length of each segment
5) Pipe Age
- Collects information for report making purposes
</td></tr>
<tr><td>


</td><td>
- Pictorial age group (Bin) representation of the watermain network being analyzed.
- Ability to show future age distribution of the network.
- Creates GIS readable file.
- Selectable Bin size from dropdown.
</td></tr>
</table>

Figure 4-1: Main screens of ‘File Upload’ and ‘Network Distribution’ tabs along with description

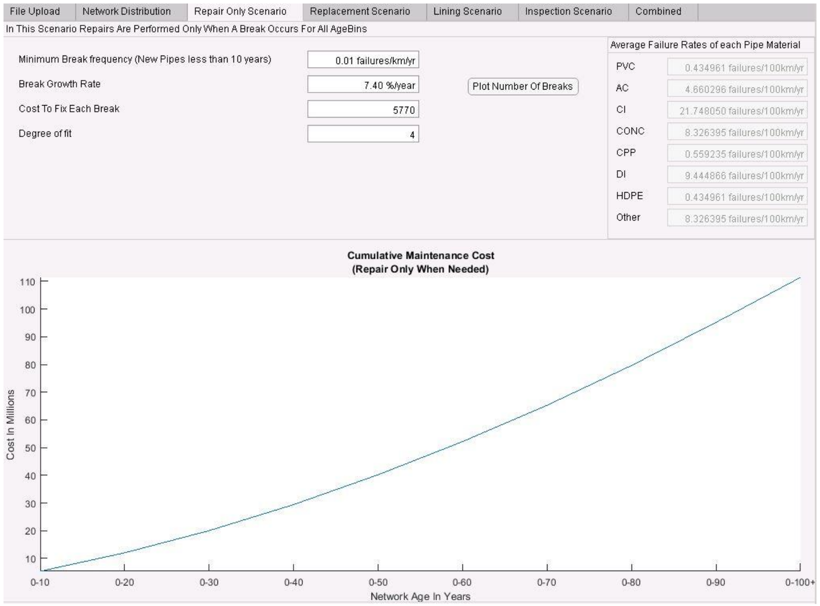
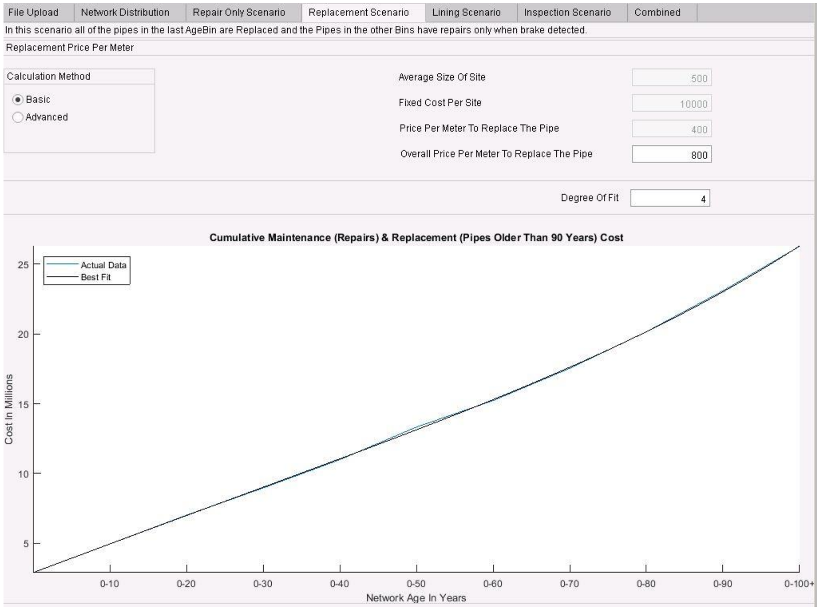
Main screen	Description
 In This Scenario Repairs Are Performed Only When A Break Occurs For All AgeBins Minimum Break frequency (New Pipes less than 10 years): 0.01 failures/km/yr Break Growth Rate: 7.40 %/year Cost To Fix Each Break: 5770 Degree of fit: 4 Average Failure Rates of each Pipe Material PVC: 0.434961 failures/100km/yr AC: 4.660296 failures/100km/yr CI: 21.748050 failures/100km/yr CONC: 8.326395 failures/100km/yr CPP: 0.559235 failures/100km/yr DI: 9.444866 failures/100km/yr HDPE: 0.434961 failures/100km/yr Other: 8.326395 failures/100km/yr	• Pictorial life cycle cost representation for the Fix upon break scenario. • Adjustable break growth rate based on the pipe material. • Adjustable cost to repair each break.
 In this scenario all of the pipes in the last AgeBin are Replaced and the Pipes in the other Bins have repairs only when brake detected. Replacement Price Per Meter Calculation Method ● Basic ○ Advanced Average Size Of Site: 500 Fixed Cost Per Site: 10000 Price Per Meter To Replace The Pipe: 400 Overall Price Per Meter To Replace The Pipe: 800 Degree Of Fit: 4	• Pictorial life cycle cost representation for the Replacement scenario. • Selectable calculation method i.e Basic and Advanced.

Figure 4-2: Main screens of ‘Break Repair only’ and ‘Replacement only’ tabs along with description

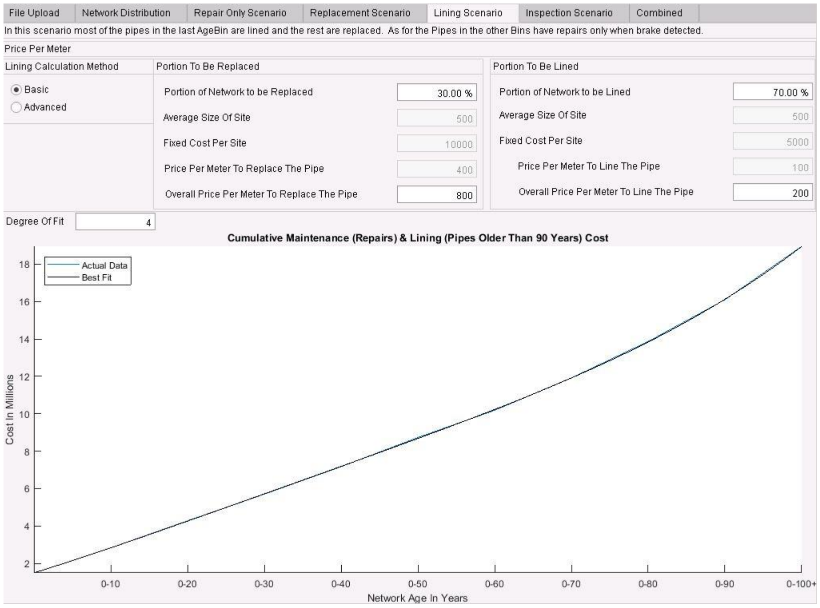
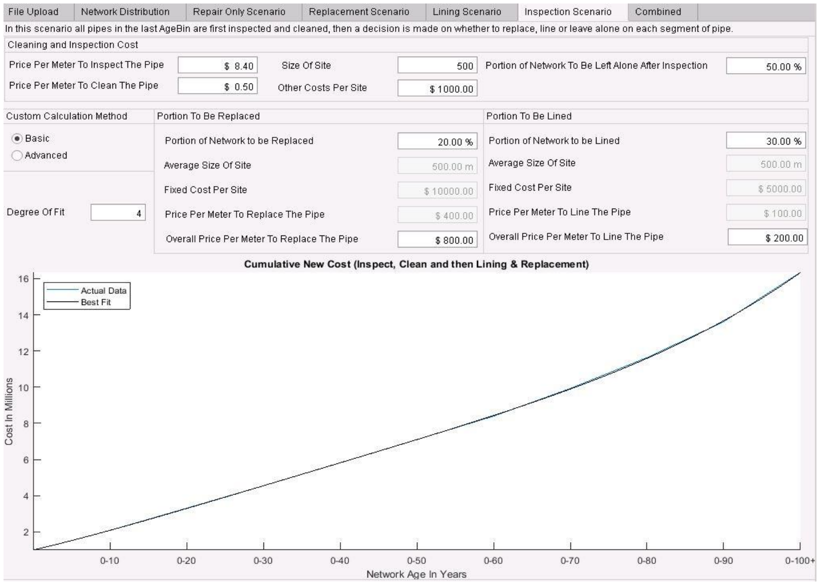
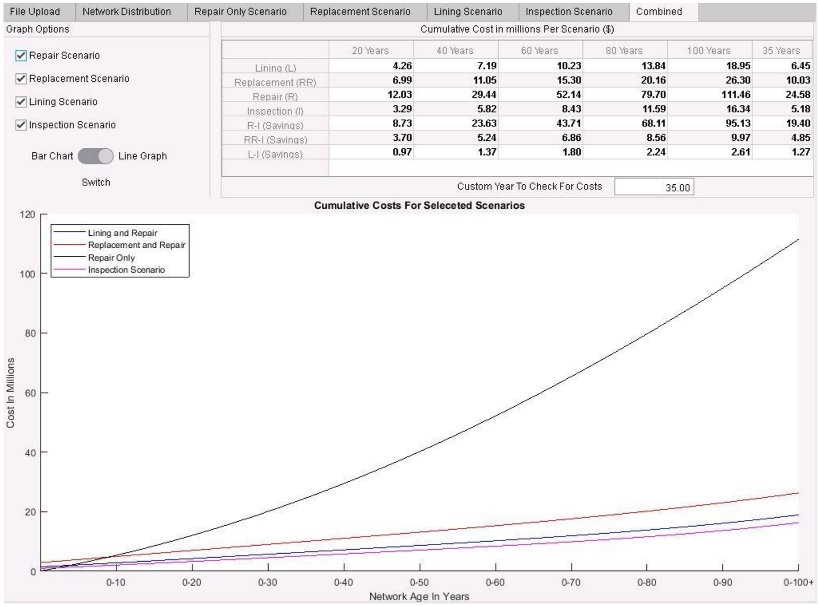
Main screen	Description
 In this scenario most of the pipes in the last AgeBin are lined and the rest are replaced. As for the Pipes in the other Bins have repairs only when brake detected. Price Per Meter Lining Calculation Method ● Basic ○ Advanced Portion To Be Replaced Portion of Network to be Replaced: 30.00 % Average Size Of Site: 500 Fixed Cost Per Site: 10000 Price Per Meter To Replace The Pipe: 400 Overall Price Per Meter To Replace The Pipe: 800 Portion To Be Lined Portion of Network to be Lined: 70.00 % Average Size Of Site: 500 Fixed Cost Per Site: 5000 Price Per Meter To Line The Pipe: 100 Overall Price Per Meter To Line The Pipe: 200 Degree Of Fit: 4 	- Pictorial life cycle cost representation for the Lining scenario. - Selectable calculation method i.e Basic and Advanced.
 In this scenario all pipes in the last AgeBin are first inspected and cleaned, then a decision is made on whether to replace, line or leave alone on each segment of pipe. Cleaning and Inspection Cost Price Per Meter To Inspect The Pipe: $ 8.40 Price Per Meter To Clean The Pipe: $ 0.50 Size Of Site: 500 Other Costs Per Site: $ 1000.00 Portion of Network To Be Left Alone After Inspection: 50.00 % Custom Calculation Method ● Basic ○ Advanced Degree Of Fit: 4 Portion To Be Replaced Portion of Network to be Replaced: 20.00 % Average Size Of Site: 500.00 m Fixed Cost Per Site: $ 10000.00 Price Per Meter To Replace The Pipe: $ 400.00 Overall Price Per Meter To Replace The Pipe: $ 800.00 Portion To Be Lined Portion of Network to be Lined: 30.00 % Average Size Of Site: 500.00 m Fixed Cost Per Site: $ 5000.00 Price Per Meter To Line The Pipe: $ 100.00 Overall Price Per Meter To Line The Pipe: $ 200.00 	- Pictorial life cycle cost representation for the Inspection scenario (Proposed strategy). - Selectable calculation method i.e Basic and Advanced.

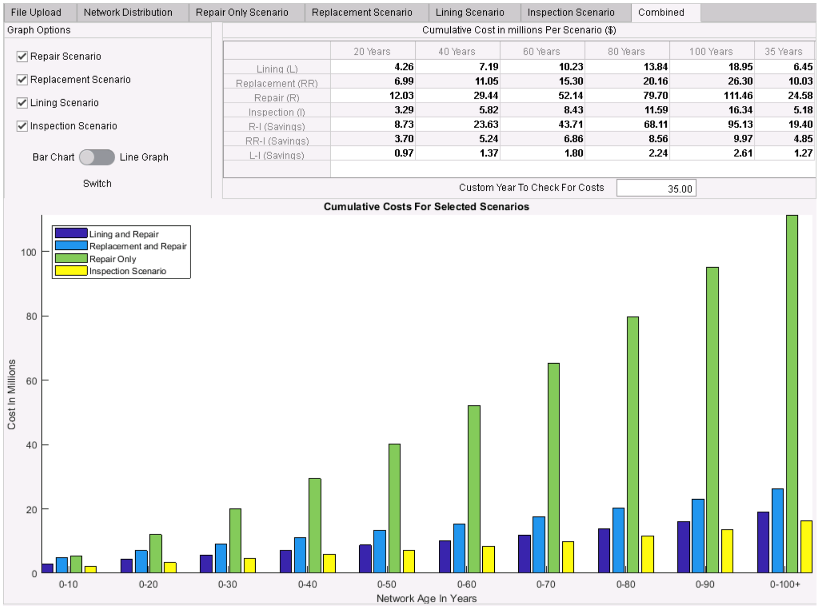
Figure 4-3: Main screens of ‘Lining Scenario’ and ‘Inspection Scenario’ tabs along with description

<table>
<tr><th>Main screen</th><th>Description</th></tr>
<tr><td>


☑ Repair Scenario
☑ Replacement Scenario
☑ Lining Scenario
☑ Inspection Scenario

Cumulative Cost in millions Per Scenario ($)
<table>
<tr><th></th><th>20 Years</th><th>40 Years</th><th>60 Years</th><th>80 Years</th><th>100 Years</th><th>35 Years</th></tr>
<tr><td>Lining (L)</td><td>4.26</td><td>7.19</td><td>10.23</td><td>13.84</td><td>18.95</td><td>6.45</td></tr>
<tr><td>Replacement (RR)</td><td>6.99</td><td>11.05</td><td>15.30</td><td>20.16</td><td>26.30</td><td>10.03</td></tr>
<tr><td>Repair (R)</td><td>12.03</td><td>29.44</td><td>52.14</td><td>79.70</td><td>111.46</td><td>24.58</td></tr>
<tr><td>Inspection (I)</td><td>3.29</td><td>5.82</td><td>8.43</td><td>11.59</td><td>16.34</td><td>5.18</td></tr>
<tr><td>R-I (Savings)</td><td>8.73</td><td>23.63</td><td>43.71</td><td>68.11</td><td>95.13</td><td>19.40</td></tr>
<tr><td>RR-I (Savings)</td><td>3.70</td><td>5.24</td><td>6.86</td><td>8.56</td><td>9.97</td><td>4.85</td></tr>
<tr><td>L-I (Savings)</td><td>0.97</td><td>1.37</td><td>1.80</td><td>2.24</td><td>2.61</td><td>1.27</td></tr>
</table>
Custom Year To Check For Costs: 35.00
Cumulative Costs For Seleceted Scenarios
</td><td>

Linear pictorial life cycle cost comparison for analyzed scenarios.
Returns cost per scenario at any choosen year during the life cycle.

</td></tr>
<tr><td>


☑ Repair Scenario
☑ Replacement Scenario
☑ Lining Scenario
☑ Inspection Scenario

Cumulative Cost in millions Per Scenario ($)
<table>
<tr><th></th><th>20 Years</th><th>40 Years</th><th>60 Years</th><th>80 Years</th><th>100 Years</th><th>35 Years</th></tr>
<tr><td>Lining (L)</td><td>4.26</td><td>7.19</td><td>10.23</td><td>13.84</td><td>18.95</td><td>6.45</td></tr>
<tr><td>Replacement (RR)</td><td>6.99</td><td>11.05</td><td>15.30</td><td>20.16</td><td>26.30</td><td>10.03</td></tr>
<tr><td>Repair (R)</td><td>12.03</td><td>29.44</td><td>52.14</td><td>79.70</td><td>111.46</td><td>24.58</td></tr>
<tr><td>Inspection (I)</td><td>3.29</td><td>5.82</td><td>8.43</td><td>11.59</td><td>16.34</td><td>5.18</td></tr>
<tr><td>R-I (Savings)</td><td>8.73</td><td>23.63</td><td>43.71</td><td>68.11</td><td>95.13</td><td>19.40</td></tr>
<tr><td>RR-I (Savings)</td><td>3.70</td><td>5.24</td><td>6.86</td><td>8.56</td><td>9.97</td><td>4.85</td></tr>
<tr><td>L-I (Savings)</td><td>0.97</td><td>1.37</td><td>1.80</td><td>2.24</td><td>2.61</td><td>1.27</td></tr>
</table>
Custom Year To Check For Costs: 35.00
Cumulative Costs For Selected Scenarios
</td><td>

Bar chart pictorial life cycle cost comparison for analyzed scenarios.
Returns cost per scenario at any choosen year during the life cycle.

</td></tr>
</table>

Figure 4-4: Main screens of ‘Combined Scenario’ tabs along with description

4.4 LCE Tool Verification

This study takes a hypothetical water distribution network`s inputs and applies them to the LCE tool to generate outputs in terms of cost estimations. The same inputs are then used in the framework equations proposed in Chapter 3 and the outputs generated are then used as a reference to judge the accuracy of the LCE tool.

Verification of the LCE tool is completed using the SDLC V-model (software development life cycle validation and verification) shown in Figure 4-5below:

The left wing of the V-model was discussed in Chapter 3 which covered validation. This chapter (right wing) covers the coding, model testing, integrated system testing, performing sensitivity analysis and then reporting the validation and verification of the LCE tool.

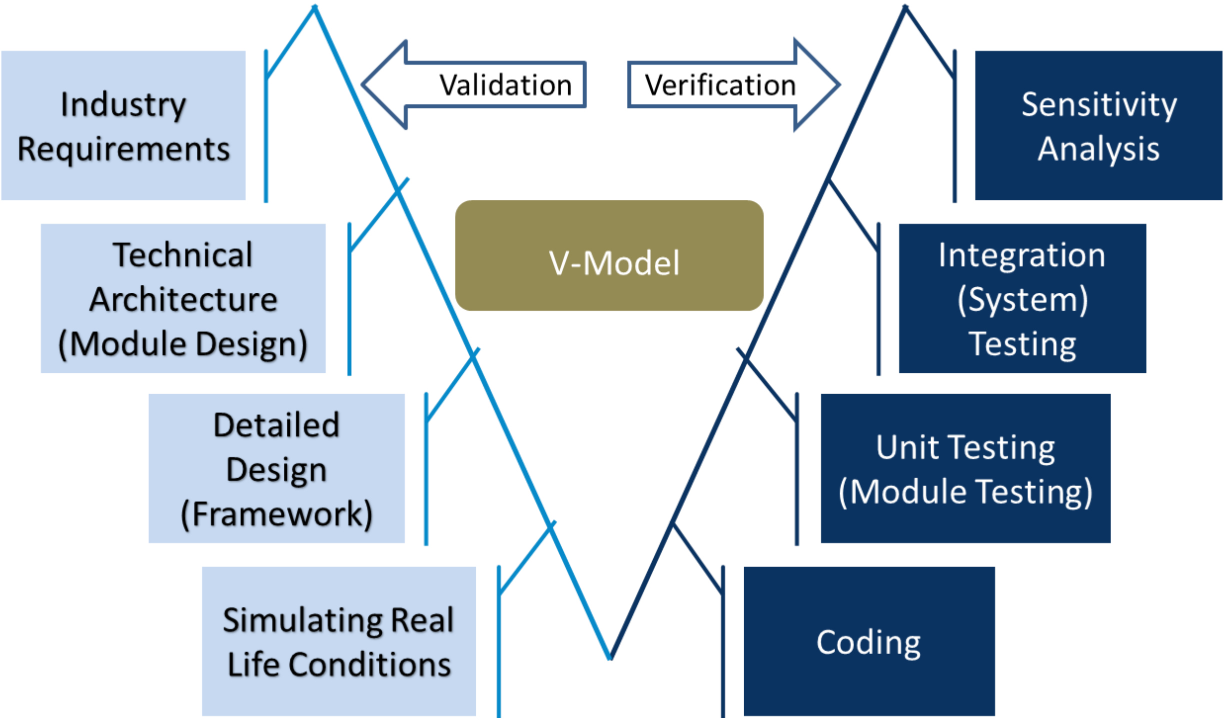


Figure 4-5 SDLC V-Model used for LCE tool verification

To verify the LCE tool, a case study has been performed on a hypothetical water utility and unit testing, integration testing and sensitivity analysis has been performed for the hypothetical water utility using the LCE tool and verified against MS Excel calculations.

4.5 Demonstration of Model Simulations

This section presents a case study on a hypothetical water utility on which module testing has been performed. Every module has been referred to as a model and has been tested to verify the results.

4.5.1 Initial Conditions and Assumptions

A hypothetical water utility of 10,000 m of water mains is used as a case study. The hypothetical utility is assumed to have pipes ranging in age from 0-100 years. It is further assumed that the age is uniformly distributed such that 2000 m of pipe is in each age bin where an age bin covers a 20 year span i.e. there are five age bins in total each with 2000 m of water main. Table 4-1 below shows the hypothetical utility`s age distribution. Appendix C-1 shows the network distribution as done in the LCE tool.

Table 4-1: Hypothetical water utility`s age distribution

Bin Number	Pipe Age Bins (years)	Total Length In Each Bin (meters)
1	0-20	2000
2	20-40	2000
3	40-60	2000
4	60-80	2000
5	80-100	2000

As was described in Chapter 3, there are five models for conventional approaches and a sixth model of a proposed strategy all of which collectively form the framework that has been proposed and validated in Chapter 3.

Each model representing a conventional approach is referred to as a cost model preceded by the name of the approach used i.e.

1. Fix upon break (Repair)
2. Basic replacement
3. Advanced replacement
4. Basic Lining
5. Advanced Lining

The sixth model which is the proposed strategy has two models, basic and advanced model.

4.5.2 Model Testing (Individual Model Verification)

4.5.2.1 Fix Upon Break (Repair) Cost Model

First and foremost, comes the fix upon break cost model, which estimates the costs of maintaining the network over its planning horizon (assumed 100 years here) by essentially doing nothing i.e. fixing the breaks when they occur.

Figure 4-6 represents the Fix upon Break cost model which was designed and validated in Chapter 3, shows the input parameters required to arrive at the cumulative costs.

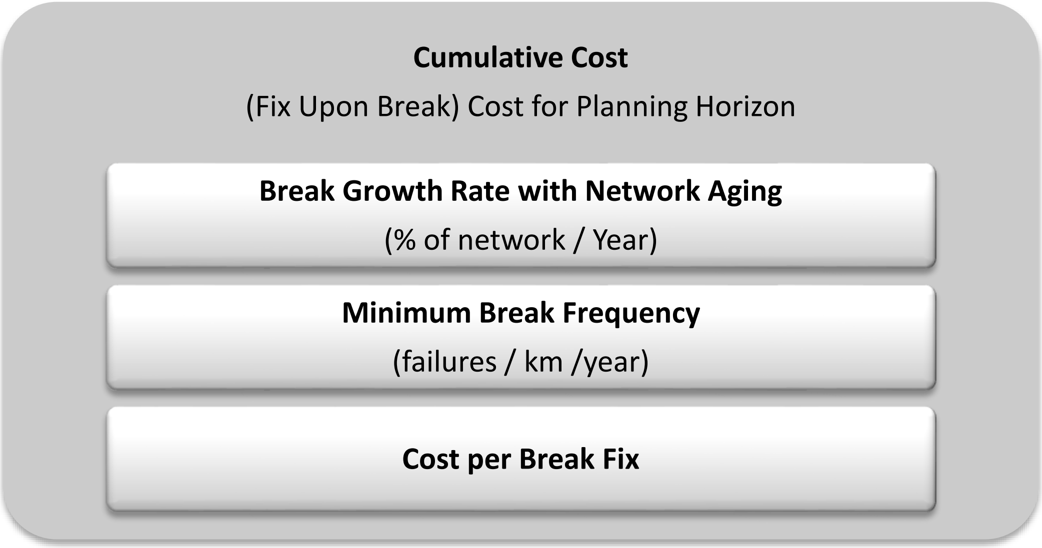


Figure 4-6: Fix upon break cost model

$$F_T = \sum_t Fs * N_T \tag{4.1}$$

Equation 4.1 is used to calculate the costs incurred for the maintenance of the water distribution system of a municipality using fix upon break policy.

where:

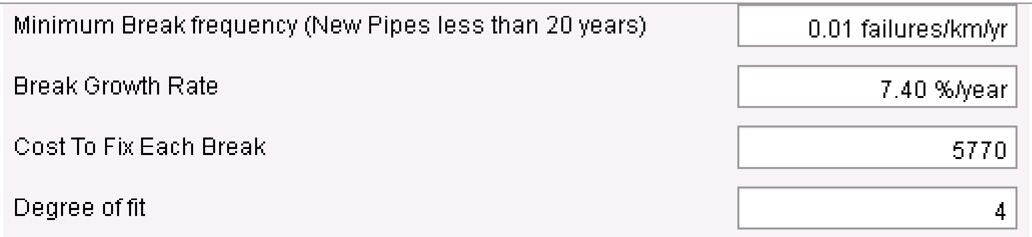
F_T: Cumulative Fix Upon Break (Repair) Cost ($)

Fs: Cost of fixing single break ($ / break)

N_T: Number of breaks at time T

The input variables obtained from (Clancy and Gustafson 1999, Rehan 2011) are provided in Table 4-2 which also shows a screenshot of the LCE tool with the Fix upon Break policy inputs.

Table 4-2 Assumed input variable values

Input Variable	Assumed Value
Minimum Break Frequency	0.01 failures/km/year
Break Growth Rate	7.4%/year
Cost Per Break	$5770 / break
Input variables as seen in LCE tool	
	

Minimum Break frequency (New Pipes less than 20 years) 0.01 failures/km/yr

Break Growth Rate 7.40 %/year

Cost To Fix Each Break 5770

Degree of fit 4

The LCE tool cost was compared with Excel spreadsheet results to verify the programming. The LCE tool and MS Excel results are provided in Table 4-3. This table shows both methods agreed.

Table 4-3 Results comparison of LCE tool and framework (Fix upon Break cost model)

Network Age Bins (Years)	Framework (Excel) Estimated Cost ($ Millions)	LCE tool Estimated Cost ($ Millions)	Agreement of Results (Yes /No)
0-20	4.88	4.89	YES
20-40	13.53	13.54	YES
40-60	25.91	25.92	YES
60-80	41.88	41.88	YES
80-100	60.76	60.76	YES

Appendix C-2 shows the programming code that was used to code the Fix upon Break cost model. Appendix C-3 shows the 2-D plot generated by the code for the Fix upon Break cost model.

4.5.2.2 Basic Replacement Cost Model

The second model is the basic replacement cost model which estimates the costs of maintaining the network over its planning horizon (assumed 100 years here) by replacing the pipes that are in the last age bin i.e. 80-100 years old and keeps fixing pipe breaks for the remaining age bins. Figure 4-7 represents the Basic Replacement cost model.

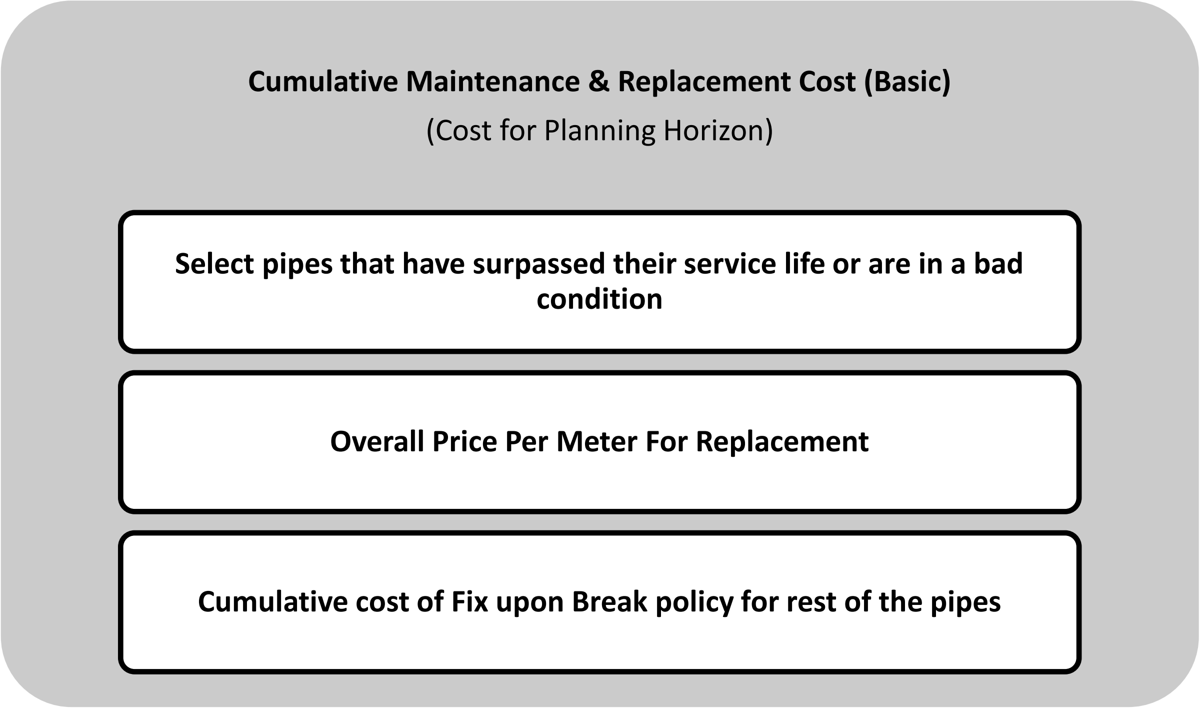


Figure 4-7: Basic Replacement cost model

Equation 4.2 is used to calculate the cumulative costs for the basic replacement cost model.

$$CMR = Po * L_R + F_T \tag{4.2}$$

where:

CMR: Cumulative Maintenance & Replacement Cost ($)

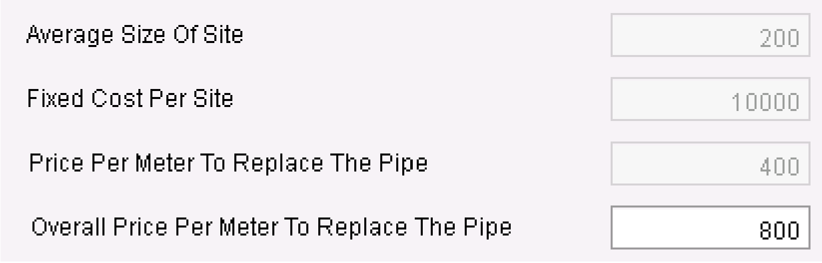
Po: Overall Price per Meter for Replacement ($ / m)

L_R: Length of water main being replaced (m)

F_T: Cumulative Fix upon Break Cost (Equation 4.1)

The Basic Replacement cost model takes into account the Fix upon Break cost model costs for all the other age bins except the last age bin, for this reason all the input variables provided in Table 4-4 are to be considered as input variables here and the rest of the models as well. Table 4-4 also shows a screenshot of the LCE tool with the Basic Replacement policy inputs.

Table 4-4 Additional input variables for Basic Replacement cost model

Input Variable	Assumed Value
Overall Price Per Meter to Replace the Pipe	$800 / m
Input variables as seen in LCE tool	
	

Average Size Of Site 200
Fixed Cost Per Site 10000
Price Per Meter To Replace The Pipe 400
Overall Price Per Meter To Replace The Pipe 800

The LCE tool and MS Excel results are provided in Table 4-5. This table shows both methods agreed.

Table 4-5: Results comparison of tool and framework (Basic Replacement cost model)

Network Age Bins (Years)	Framework (Excel) Estimated Cost ($ Millions)	LCE Tool Estimated Cost ($ Millions)	Agreement of Results (Yes /No)
0-20	2.71	2.71	YES
20-40	5.42	5.42	YES
40-60	8.13	8.13	YES
60-80	10.84	10.84	YES
80-100	13.55	13.55	YES

Appendix C-4 shows the programming code that was used to code the Replacement cost model. Appendix C-5 shows the 2-D plot generated by the code for the Basic Replacement cost model.

4.5.2.3 Advanced Replacement Cost Model

The third model called Advanced Replacement cost model is a more extensive version of the previous model i.e. the Basic Replacement cost model. This model comes up with more sophisticated replacement costs calculations for the planning horizon given the increased number of inputs it requires to perform its cost estimation calculations.

Figure 4-8 shows the input parameters required to arrive at the cumulative costs for the Advanced Replacement cost model.

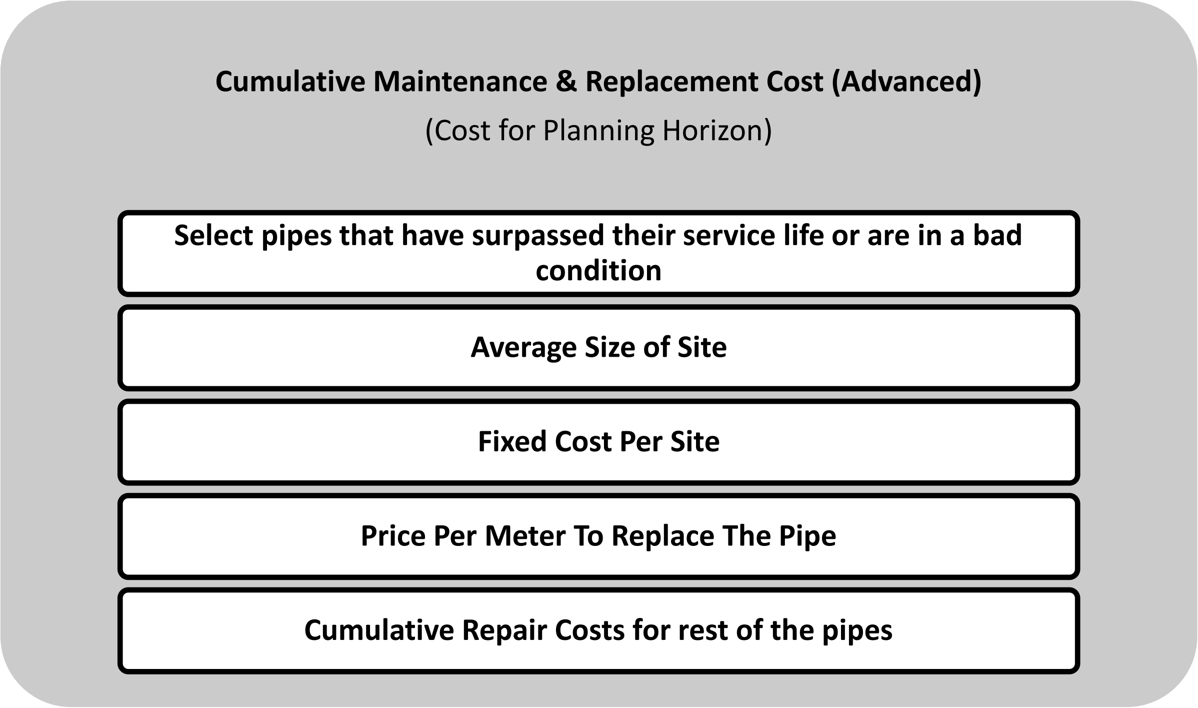


Figure 4-8: Advanced Replacement cost model

Equation 4.3 is used to calculate the cumulative cost using the Advanced Replacement cost model:

$$\boldsymbol{CMR = (P_R * L_R) + (Fs * Ns) + F_T} \tag{4.3}$$

where:

CMR: Cumulative Maintenance & Replacement Cost ($)

P_R: Price per Meter for Replacement (exclusive) ($ / m)

Fs: Fixed cost per site ($10,000 is the average for the province of Saskatchewan)

Ns: Number of sites to be dealt with in the program where $\mathrm{Ns} = \frac{SS}{L_R}$

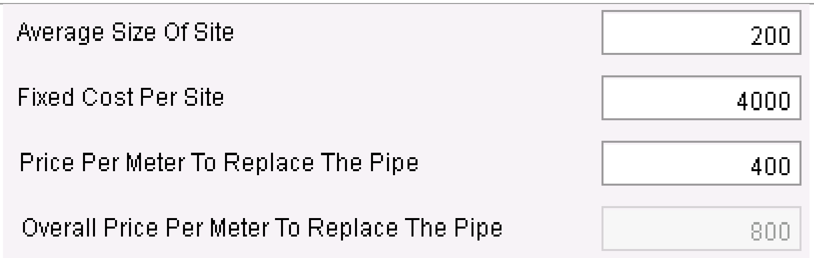
SS: Size of site (in units of length)

L_R = Length of water main being Replaced (m)

F_T: Cumulative Fix upon Break Cost (Equation 4.2)

The input values shown in Table 4-6 are taken from Clancy and Gustafson (1999) which are the average values for the province of Saskatchewan, the values have been scaled to represent a 200 m site length. Table 4-6 also shows a screenshot of the LCE tool with the Basic Replacement policy inputs.

Table 4-6 Additional input variables for Advanced Replacement cost model

Input Variable	Assumed Value
Price Per Meter to Replace the Pipe	$400 / m
Fixed Cost Per Site	$4000
Average Size Of Site	200 m
Input variables as seen in LCE tool	
 Average Size Of Site 200 Fixed Cost Per Site 4000 Price Per Meter To Replace The Pipe 400 Overall Price Per Meter To Replace The Pipe 800	

The LCE tool generated costs were compared with Excel spreadsheet results to verify the programming. The LCE tool and MS Excel results are provided in Table 4-7. This table shows that both methods agreed.

Table 4-7: Results comparison of tool and framework (Advanced Replacement cost model)

Network Age Bins (Years)	Framework (Excel) Estimated Cost ($ Millions)	LCE Tool Estimated Cost ($ Millions)	Agreement of Results (Yes /No)
0-20	1.95	1.95	YES
20-40	3.90	3.90	YES
40-60	5.85	5.85	YES
60-80	7.80	7.80	YES
80-100	9.75	9.75	YES

Appendix C-4 shows the programming code that was used to code the Replacement cost model. Appendix C-6 shows the 2-D plot generated by the code for the Advancement Replacement cost model.

4.5.2.4 Basic Lining Cost Model

The fourth model is the Basic Lining model estimating the cost of maintaining the network over a planning horizon of 100 years which is the assumed life cycle span of the buried infrastructure in the hypothetical utility. In this model, the pipes in the oldest age bin are rehabilitated using lining as the rehabilitation approach.

Figure 4-9 represents the Basic Lining cost model input parameters which required to arrive at the cumulative life cycle costs.

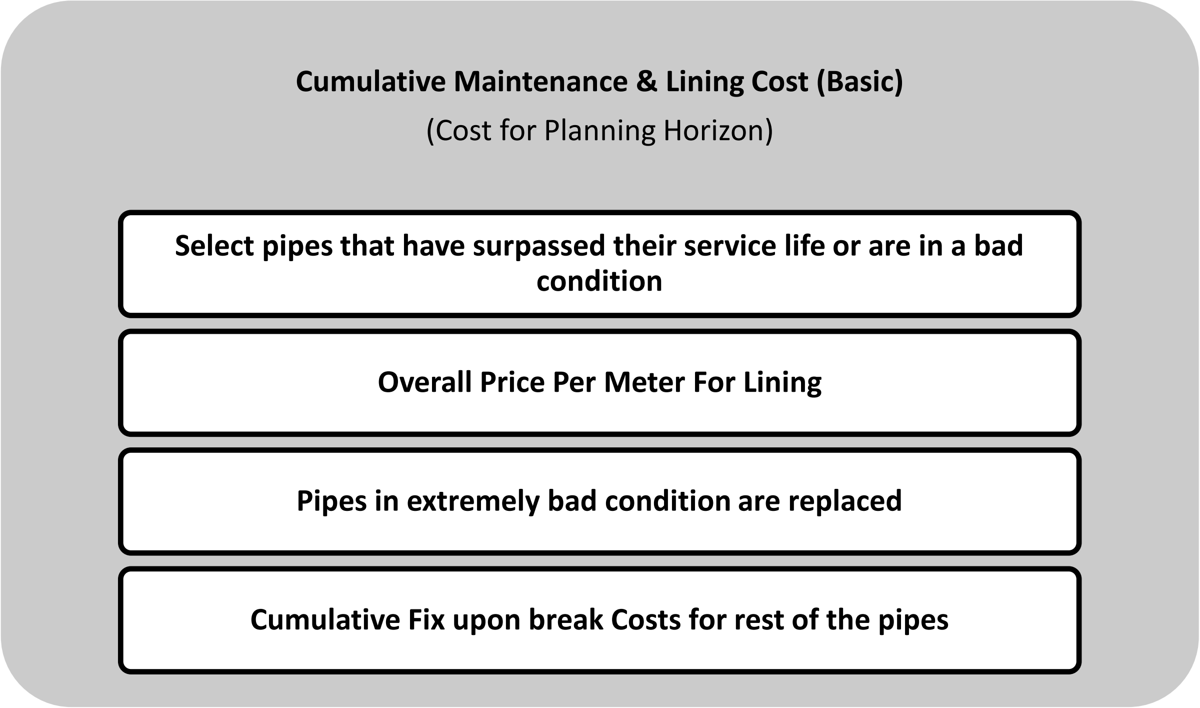


Figure 4-9 Basic Lining cost model

Equation 4.4 is used to calculate the cumulative costs for the Basic Lining cost model is as follows:

$$\boldsymbol{CC} = (\boldsymbol{P_L} * \boldsymbol{L_L}) + (\boldsymbol{P_R} * \boldsymbol{L_R}) + \mathbf{F_T} \tag{4.4}$$

where:

CC = Cumulative Cost ($)

P_L = Overall Price per Meter for Lining ($ / m)

L_L = Length of water main being Lined (m)

P_R = Overall Price per Meter for Replacement ($ / m)

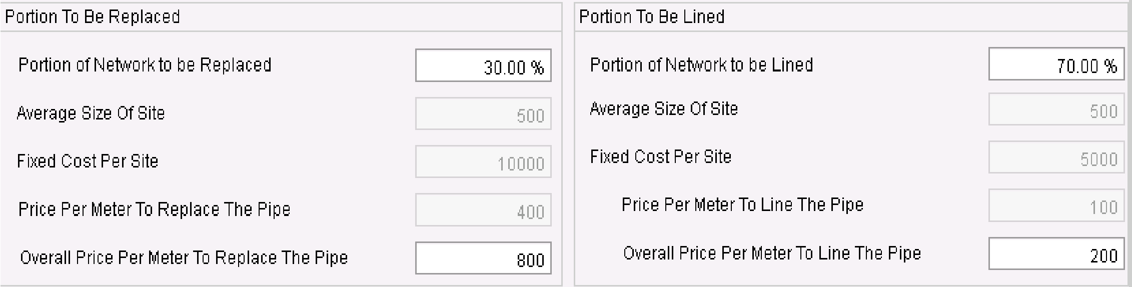
L_R = Length of water main being Replaced (m)

F_T: Cumulative Fix upon break Cost (Equation 4.2)

Table 4-8 represents the input variables that go into calculation of the Basic Lining cost model calculations for the last age bin. For the previous age bins, input values of Table 4-2 are taken by default. Table 4-8 also shows a screenshot of the LCE tool with the Basic Lining policy inputs.

Table 4-8: Additional input variables for Basic Lining cost model

Input Variable	Assumed Value
Lining price per meter	\$200 / m
Replacement price per meter	\$800 / m
Portion of Network to be Replaced	30%
Portion of Network to be Lined	70%
Input variables as seen in LCE tool	



Portion To Be Replaced

Portion of Network to be Replaced	30.00 %
Average Size Of Site	500
Fixed Cost Per Site	10000
Price Per Meter To Replace The Pipe	400
Overall Price Per Meter To Replace The Pipe	800

Portion To Be Lined

Portion of Network to be Lined	70.00 %
Average Size Of Site	500
Fixed Cost Per Site	5000
Price Per Meter To Line The Pipe	100
Overall Price Per Meter To Line The Pipe	200

The LCE tool and MS Excel results are provided in Table 4-9. This table shows both methods produce similar results.

Table 4-9: Results comparison of tool and framework (Basic Lining cost model)

Framework (Excel) Estimated Cost (\$ Millions)	LCE Tool Estimated Cost (\$ Millions)	Framework (Excel) Estimated Cost (\$ Millions)	Agreement of Results (Yes /No)
0-20	1.89	1.89	YES
20-40	3.74	3.74	YES
40-60	5.61	5.61	YES
60-80	7.48	7.48	YES
80-100	9.35	9.35	YES

Appendix C-7 shows the programming code that was used to code the Lining cost model. Appendix C-8 shows the 2-D plot generated by the code for the Basic Lining cost model.

4.5.2.5 Advanced Lining Cost Model

The fifth model i.e. Advanced Lining cost model is an extensive version of the previous model i.e. the Basic Lining cost model. This model comes up with more sophisticated calculations for replacement costs over the planning horizon given the increased number of inputs it requires to perform its cost estimation calculations.

Figure 4-10 represents the Advanced Lining cost model input parameters which required to arrive at the cumulative life cycle costs.

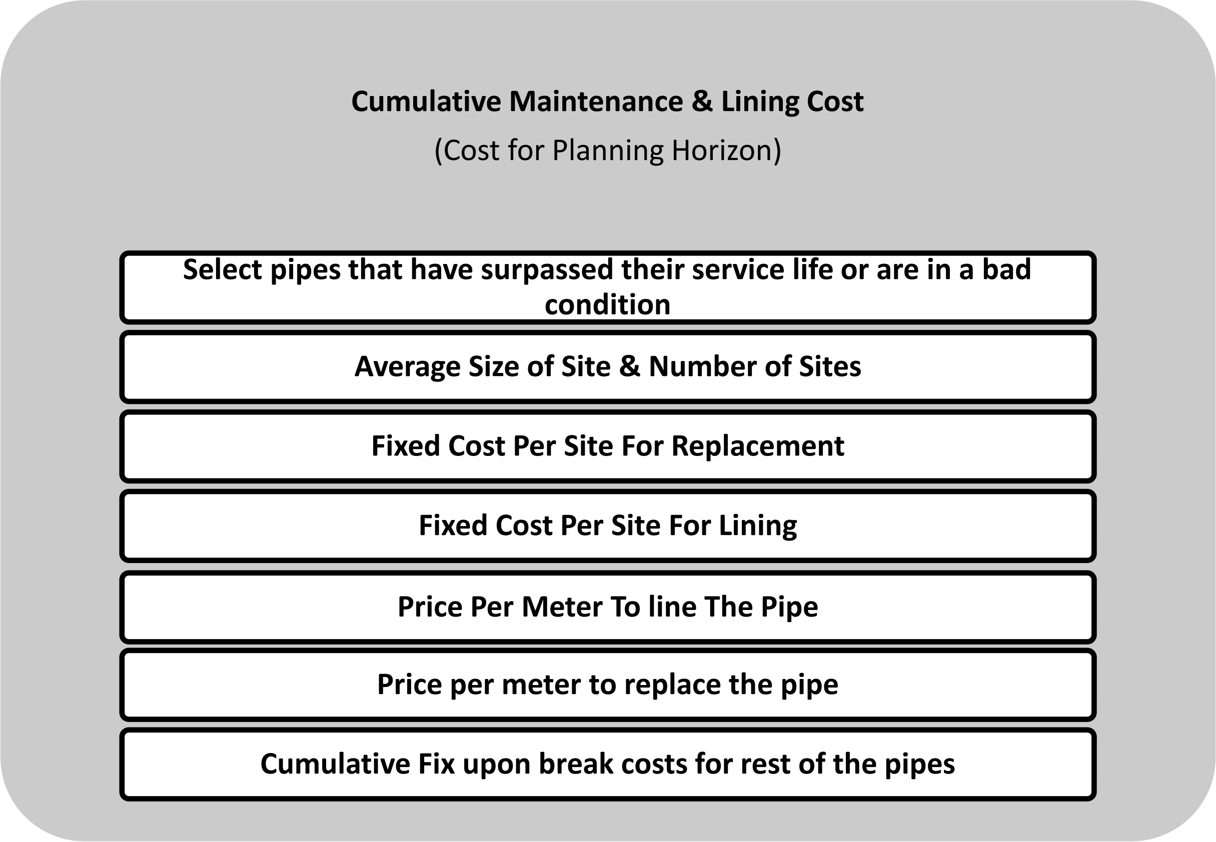


Figure 4-10: Advanced Lining Cost model

Equation 4.5 is used to calculate the cumulative costs for the Advanced Lining cost model is as follows:

$$\boldsymbol{CC = (P_L * L_L) + (P_R * L_R) + (Fs_L * Ns_L) + (Fs_R * Ns_R) + F_T} \tag{4.5}$$

where:

CC: Cumulative Cost ($)

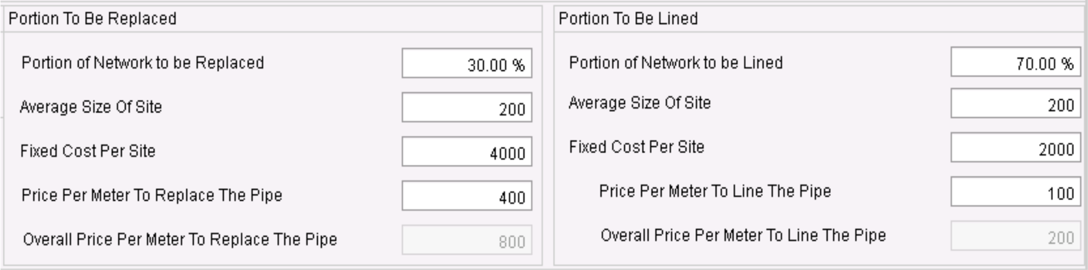
P_L: Price per Meter for Lining (exclusive) ($ / m)

LL: Length of water main being Lined (m)
PR: Overall Price per Meter for Replacement (exclusive) ($ / m)
LR: Length of water main being Replaced (m)
Fs_L: Fixed cost per site for lining ($)
Fs_R: Fixed cost per site for replacement ($)
NSR: Number of replacement sites where $\mathrm{Ns_R} = \frac{L_R}{SS_R}$
NSL: Number of lining sites where $\mathrm{Ns_L} = \frac{L_L}{SS_L}$
SSR: Size of site (length of water main lined per day)
SSL: Size of site (length of water main replaced per day)
FT: Cumulative Fix upon break Cost (Equation 4.2)

Table 4-10 shows the additional input values needed by the Advanced Lining cost model to calculate costs for the oldest pipe age bin over the planning horizon of 100 years, the rest of the bins as previously explained are maintained using the fix upon break approach and the input values are taken from Table 4-2.

Table 4-10 also shows a screenshot of the LCE tool with the Basic Replacement policy inputs.

Table 4-10: Additional input variables for Advanced Lining cost model

Input Variable	Assumed Value
Size of Site	200 m
Fixed Cost per site for replacement	$4000
Fixed Cost per site for lining	$2000
Replacement price per meter	$400 / m
Lining price per meter	$100 / m
Number of sites	10
Input variables as seen in LCE tool	
	

Portion To Be Replaced
Portion of Network to be Replaced: 30.00 %
Average Size Of Site: 200
Fixed Cost Per Site: 4000
Price Per Meter To Replace The Pipe: 400
Overall Price Per Meter To Replace The Pipe: 800

Portion To Be Lined
Portion of Network to be Lined: 70.00 %
Average Size Of Site: 200
Fixed Cost Per Site: 2000
Price Per Meter To Line The Pipe: 100
Overall Price Per Meter To Line The Pipe: 200

The LCE tool and MS Excel results are provided in Table 4-11. This table shows both methods produced same results.

Table 4-11: Results comparison of tool and framework (Advanced Lining cost model)

Network Age Bins (Years)	Framework (Excel) Estimated Cost ($ Millions)	LCE Tool Estimated Cost ($ Millions)	Agreement of Results (Yes /No)
0-20	1.52	1.52	YES
20-40	3.03	3.03	YES
40-60	4.55	4.55	YES
60-80	6.06	6.06	YES
80-100	7.58	7.58	YES

Appendix C-7 shows the programming code that was used to code the Lining cost model. Appendix C-9 shows the 2-D plot generated by the code for the Advanced Lining cost model.

4.5.3 Proposed Strategy Model

The sixth model known as the proposed strategy model as is seen in the Figure 4-7 covers both basic and advanced versions of the proposed strategy. Equation 4.7 shows the basic cost estimation for the proposed strategy while Equation 4.8 shows the advanced cost estimation for the proposed strategy.

$$\boldsymbol{BMRR = (P_{OR} * L_R) + (P_{OL} * L_L) + F_T} \tag{4.7}$$

where:

BMRR: Basic Maintenance, Rehabilitation, and Replacement cost ($)

P_{OR}: Overall price per meter to Replace the water main ($ / m)

L_R: Length of water main to be replaced (m)

P_{OL}: Overall price per meter to Line the water main ($ / m)

L_L: Length of water main to be lined (m)

F_T: Cumulative Fix upon break Cost (Equation 4.2)

Equation 4.8 is used to calculate the advanced cost estimation using the advanced form of the proposed strategy.

$$\boldsymbol{AMRR = (P_{ER} * L_R) + (P_{EL} * L_L) + (Fs_L * Ns_L) + (Fs_R * Ns_R) + F_T} \tag{4.8}$$

where:

AMRR: Advanced Maintenance, Rehabilitation, and Replacement cost ($)

P_{ER}: Price per meter (exclusive) to Replace the water main ($ / m)

PEL: Price per meter (exclusive) to Line the water main ($ / m)
LR: Length of water main to be replaced (m)
LL: Length of water main to be lined (m)
Fs_L: Fixed cost per site for lining ($)
Fs_R: Fixed cost per site for replacement ($)
NSR: Number of replacement sites where $\mathrm{Ns_R} = \frac{L_R}{SS_R}$
NSL: Number of lining sites where $\mathrm{Ns_L} = \frac{L_L}{SS_L}$
SSR: Size of site (length of water main lined per day)
SSL: Size of site (length of water main replaced per day)
FT: Cumulative Fix upon break Cost (Equation 4..2)

To come up with the total cost as per the requirement of the proposed strategy, Equation 4.11 and Equation 4.12 are used to calculate the total basic and advanced cost estimations respectively using the proposed strategy.

$$\sum_{\boldsymbol{N}} \boldsymbol{Life\ Cycle\ Basic\ OM\&R\ Cost} = \sum_{\boldsymbol{N}} (\boldsymbol{BMRR} + \boldsymbol{Cleaning}\ \&\ \boldsymbol{Inspection} + \boldsymbol{Cost\ Overrun}) \tag{4.11}$$

$$\sum_{\boldsymbol{N}} \boldsymbol{Life\ Cycle\ Advanced\ OM\&R\ Cost} = \sum_{\boldsymbol{N}} (\boldsymbol{AMRR} + \boldsymbol{Cleaning}\ \&\ \boldsymbol{Inspection} + \boldsymbol{Cost\ Overrun}) \tag{4.12}$$

where N is the number of cycles the loop has to be repeated to calculate the total life-cycle costs.

Figure 4-11 shows all the individual costs that go into the proposed strategy to come up with the cumulative life cycle costs of maintaining the water infrastructure.

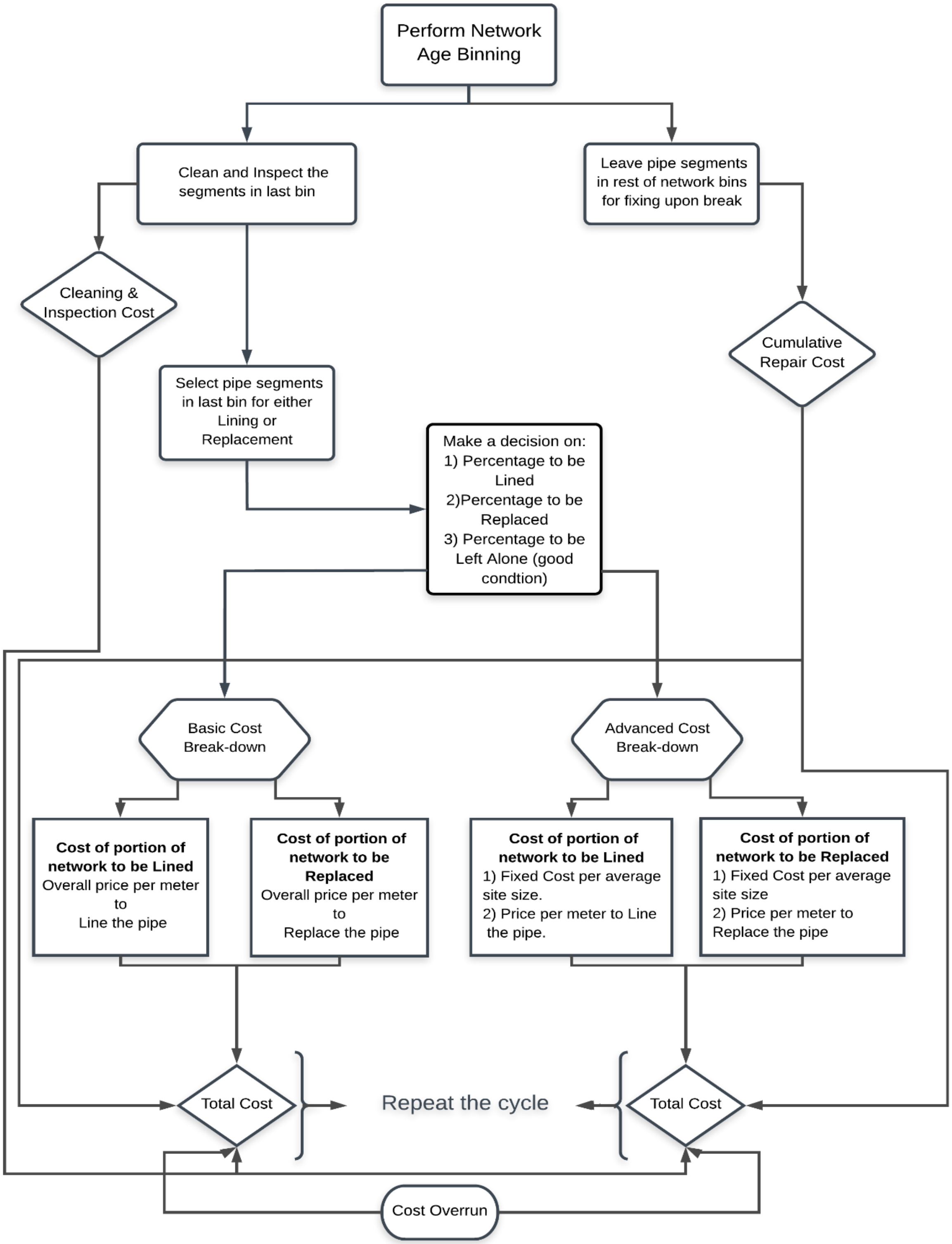
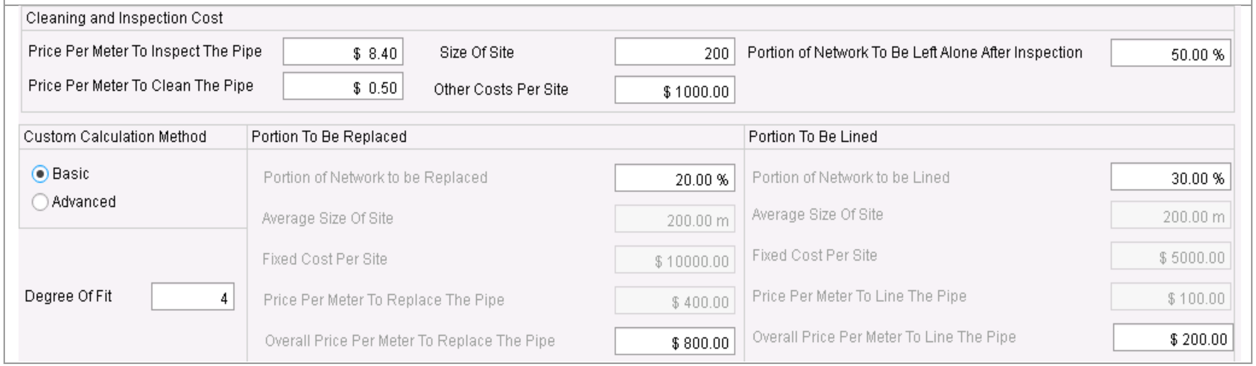


Figure 4-11: Flow chart for the proposed strategy

As in the previous cases, a number of inputs are needed for the basic and advanced proposed strategy models which are shown in Table 4-12 and Table 4-13. These tables also show screenshots of the LCE tool with the Basic and Advanced proposed strategy inputs.

Table 4-12: Input variables for Basic cost model of proposed strategy

Input Variable	Assumed Value
Lining price per meter	\$200 / m
Replacement price per meter	\$800 / m
Price Per Meter To Inspect The Pipe	\$8.4 / m
Price Per Meter To Clean The Pipe	\$0.5 / m
Other Costs Per Site	\$1000
Size Of Site	200 m
Portion of Network To Be Left Alone After Inspection	50%
Portion of Network to be Replaced	20%
Portion of Network to be Lined	30%
Input variables as seen in LCE tool	
	

Cleaning and Inspection Cost

Price Per Meter To Inspect The Pipe: $ 8.40
Price Per Meter To Clean The Pipe: $ 0.50
Size Of Site: 200
Other Costs Per Site: $ 1000.00
Portion of Network To Be Left Alone After Inspection: 50.00 %

Custom Calculation Method

● Basic
○ Advanced

Degree Of Fit: 4

Portion To Be Replaced

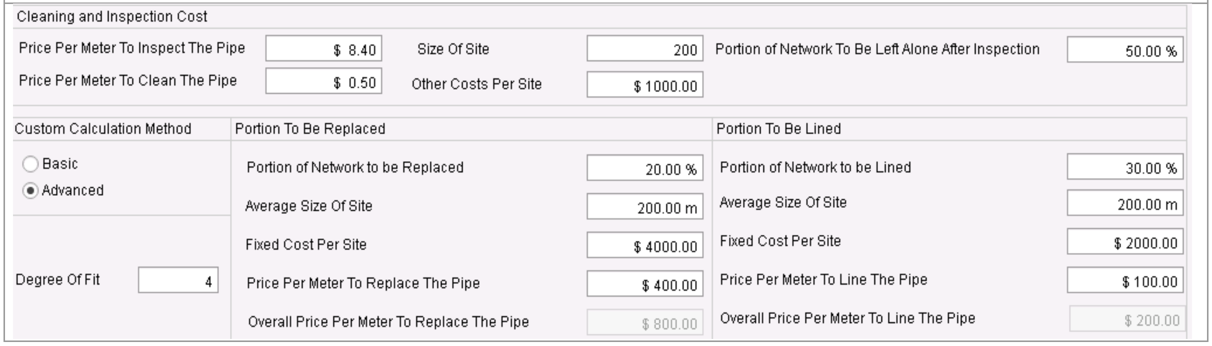
Portion of Network to be Replaced: 20.00 %
Average Size Of Site: 200.00 m
Fixed Cost Per Site: $ 10000.00
Price Per Meter To Replace The Pipe: $ 400.00
Overall Price Per Meter To Replace The Pipe: $ 800.00

Portion To Be Lined

Portion of Network to be Lined: 30.00 %
Average Size Of Site: 200.00 m
Fixed Cost Per Site: $ 5000.00
Price Per Meter To Line The Pipe: $ 100.00
Overall Price Per Meter To Line The Pipe: $ 200.00

Table 4-13: Input variables for Advanced cost model of proposed strategy

Input Variable	Assumed Value
Fixed Cost per site for replacement	$4000
Fixed Cost per site for lining	$2000
Replacement price per meter	$400 / m
Lining price per meter	$100 / m
Price Per Meter To Inspect The Pipe	$8.4 / m
Price Per Meter To Clean The Pipe	$0.5 / m
Other Costs Per Site	$1000
Size Of Site	200 m
Portion of Network To Be Left Alone After Inspection	50%
Portion of Network to be Replaced	20%
Portion of Network to be Lined	30%
Input variables as seen in LCE tool	



Cleaning and Inspection Cost

Price Per Meter To Inspect The Pipe: $ 8.40

Price Per Meter To Clean The Pipe: $ 0.50

Size Of Site: 200

Other Costs Per Site: $ 1000.00

Portion of Network To Be Left Alone After Inspection: 50.00 %

Custom Calculation Method

○ Basic

● Advanced

Degree Of Fit: 4

Portion To Be Replaced

Portion of Network to be Replaced: 20.00 %

Average Size Of Site: 200.00 m

Fixed Cost Per Site: $ 4000.00

Price Per Meter To Replace The Pipe: $ 400.00

Overall Price Per Meter To Replace The Pipe: $ 800.00

Portion To Be Lined

Portion of Network to be Lined: 30.00 %

Average Size Of Site: 200.00 m

Fixed Cost Per Site: $ 2000.00

Price Per Meter To Line The Pipe: $ 100.00

Overall Price Per Meter To Line The Pipe: $ 200.00

As is the case with all the conventional models, the tool results are in high agreement with the MS Excel framework calculations for the proposed strategy.

As is seen in Table 4-14, the estimated costs for both basic and advanced proposed strategy are nearly identical with advanced estimations returning relatively less life cycle costs due to availability of more information.

Table 4-14: Tool results comparison with MS Excel calculations

Network Age Bins (Years)	Framework (Excel) Estimated Cost ($ Millions)	LCE Tool Estimated Cost ($ Millions)	Framework (Excel) Estimated Cost ($ Millions)	LCE Tool Estimated Cost ($ Millions)	Agreement of Results (Yes /No)
0-20	1.57	1.57	1.37	1.37	YES
20-40	3.155	3.14	2.74	2.73	YES
40-60	4.73	4.71	4.11	4.10	YES
60-80	6.31	6.29	5.48	5.46	YES
80-100	7.88	7.86	6.85	6.83	YES

The agreement of the framework (MS Excel calculations) and the tool estimated cumulative calculations verify the accuracy of the code for Proposed Strategy cost model.

4.5.4 Integrated System Testing

Testing the final cost estimations for both basic and advanced frameworks show high agreement between MS Excel as well as LCE tool simulation generated results.

The life cycle cost estimation charts for all cost model calculated by the MS Excel framework calculations using excel as well as the LCE tool are shown in Figure 4-12 and Figure 4-13. The results can be seen to be identical. The proposed strategy is worded as ‘Inspection based scenario’ in Figure 4-12 and Figure 4-14 in this section.

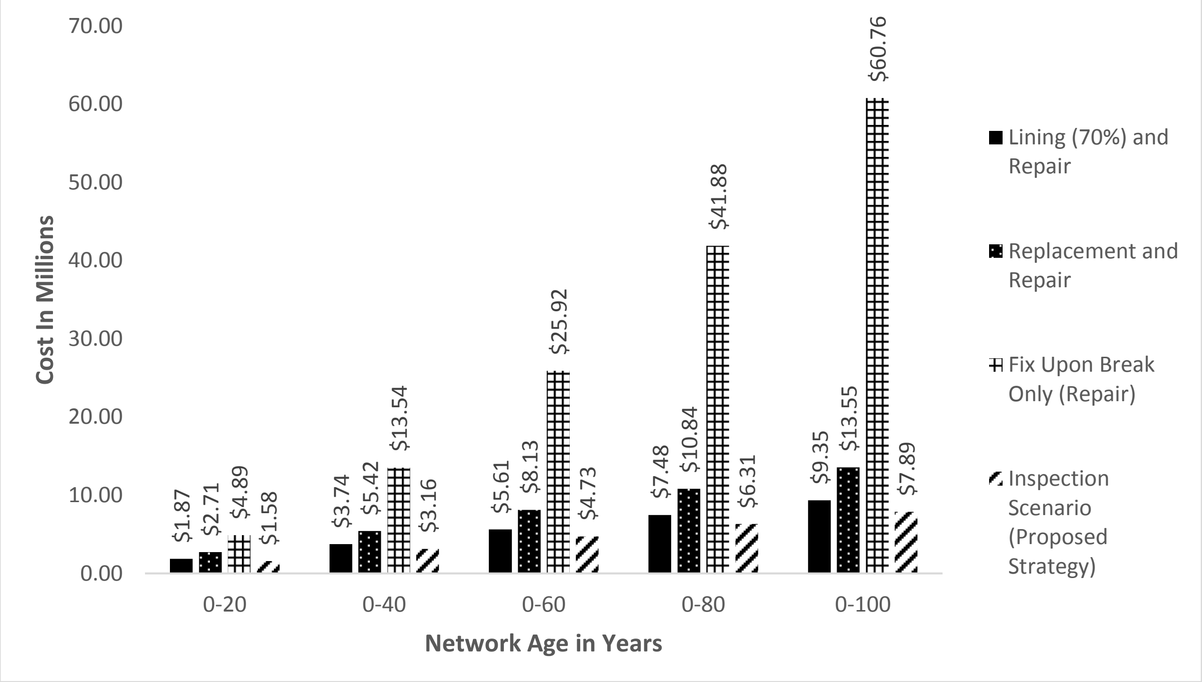
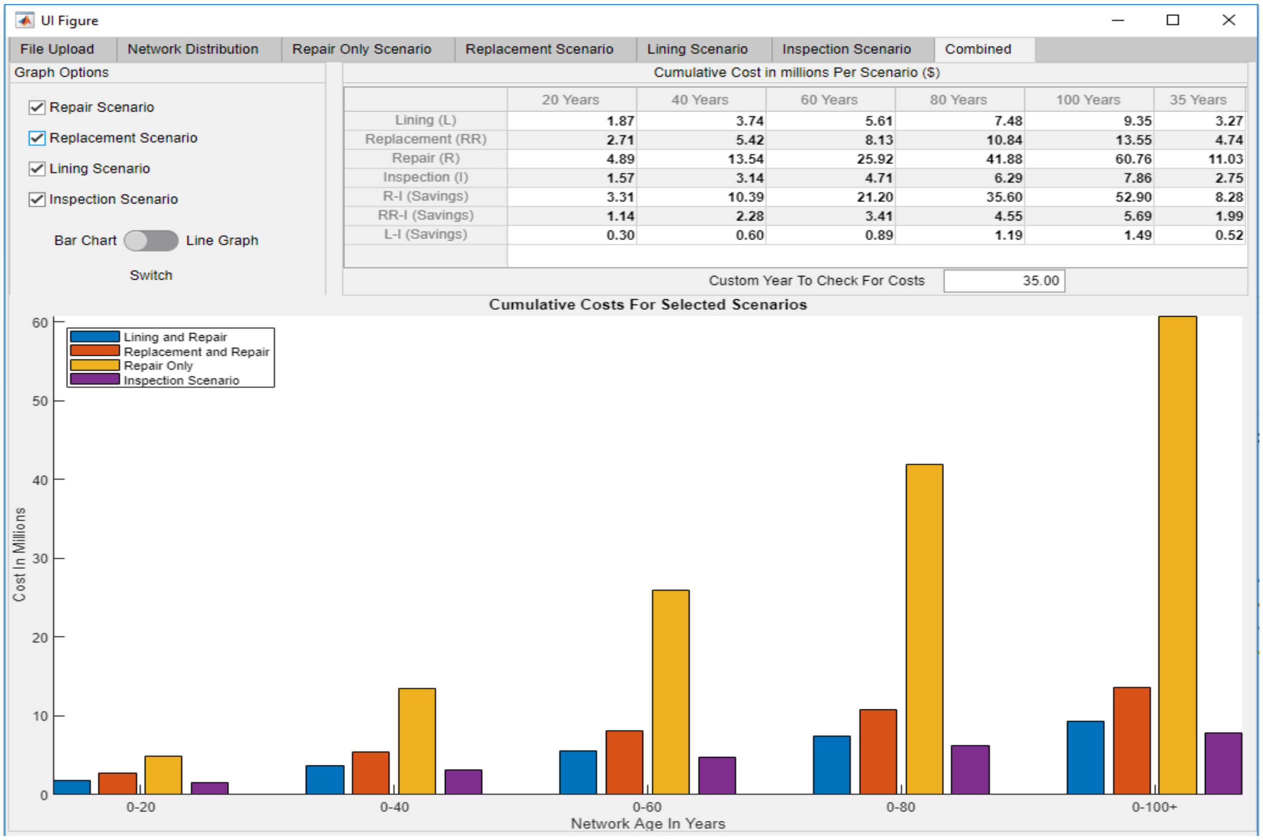


Figure 4-12: Basic cumulative framework costs calculated via MS Excel



☑ Repair Scenario
☑ Replacement Scenario
☑ Lining Scenario
☑ Inspection Scenario

Cumulative Cost in millions Per Scenario ($)

	20 Years	40 Years	60 Years	80 Years	100 Years	35 Years
Lining (L)	1.87	3.74	5.61	7.48	9.35	3.27
Replacement (RR)	2.71	5.42	8.13	10.84	13.55	4.74
Repair (R)	4.89	13.54	25.92	41.88	60.76	11.03
Inspection (I)	1.57	3.14	4.71	6.29	7.86	2.75
R-I (Savings)	3.31	10.39	21.20	35.60	52.90	8.28
RR-I (Savings)	1.14	2.28	3.41	4.55	5.69	1.99
L-I (Savings)	0.30	0.60	0.89	1.19	1.49	0.52

Custom Year To Check For Costs: 35.00

Figure 4-13: Basic cumulative costs from LCE tool

The advanced life cycle cost estimations for all cost models and proposed strategy in the framework calculated both via MS Excel and by the tool are presented below in Figure 4-14 and Figure 4-15 respectively.

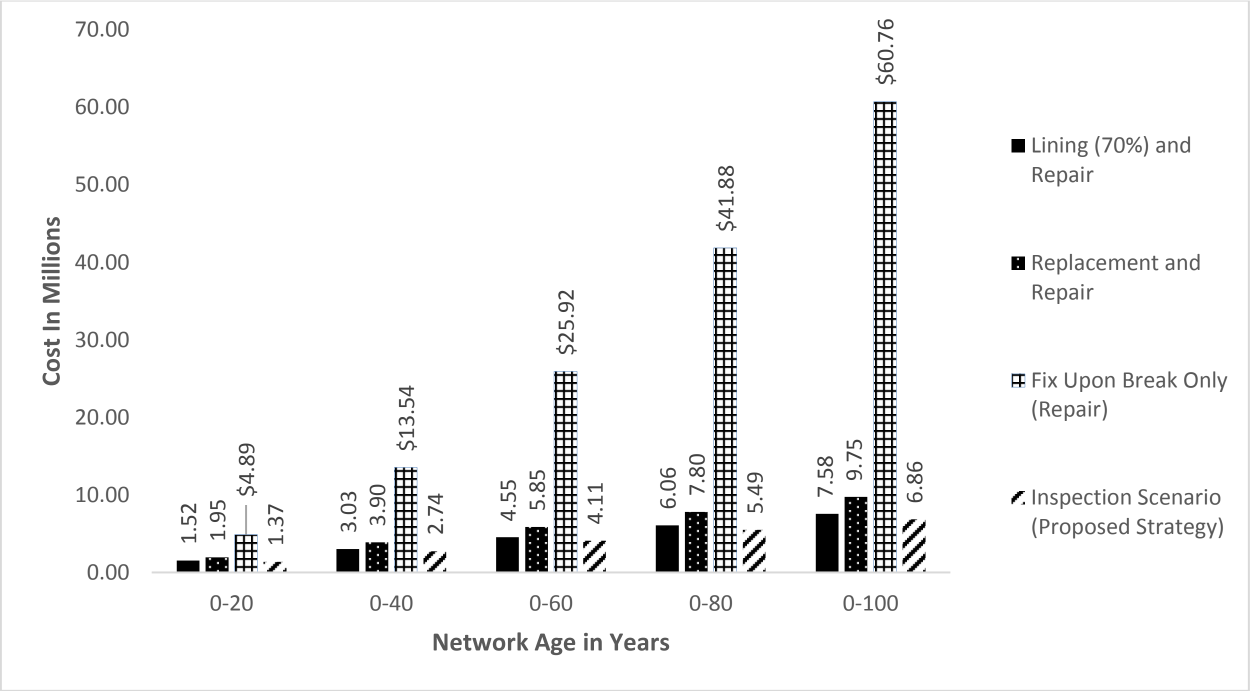
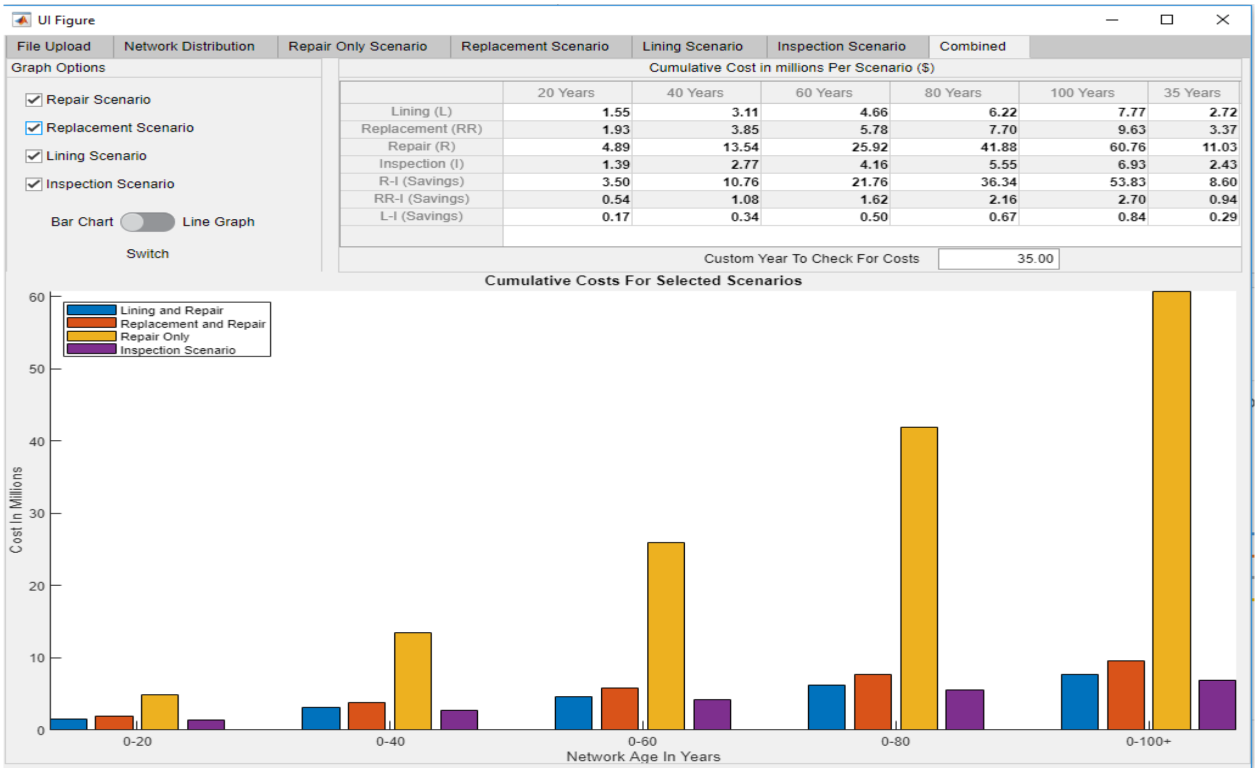


Figure 4-14: Advanced cumulative framework costs calculated via MS Excel



☑ Repair Scenario
☑ Replacement Scenario
☑ Lining Scenario
☑ Inspection Scenario

Cumulative Cost in millions Per Scenario ($)

	20 Years	40 Years	60 Years	80 Years	100 Years	35 Years
Lining (L)	1.55	3.11	4.66	6.22	7.77	2.72
Replacement (RR)	1.93	3.85	5.78	7.70	9.63	3.37
Repair (R)	4.89	13.54	25.92	41.88	60.76	11.03
Inspection (I)	1.39	2.77	4.16	5.55	6.93	2.43
R-I (Savings)	3.50	10.76	21.76	36.34	53.83	8.60
RR-I (Savings)	0.54	1.08	1.62	2.16	2.70	0.94
L-I (Savings)	0.17	0.34	0.50	0.67	0.84	0.29

Custom Year To Check For Costs: 35.00

Figure 4-15: Advanced cumulative costs from LCE tool

Figure 4-14 and Figure 4-15 shows agreement between LCE tool calculations as well as the manual (MS Excel) calculations. The agreement between the two to the nearest thousand dollars (basic framework calculations) show the precision of the tool programming code which verifies the combined cumulative cost estimations model of the tool. The slight changes in the results for advanced framework calculations is due to inclusion of multiple variables into the cost estimation algorithm which makes it the simulations rather complex due to continuously updating variables leading to slight changes between the MS Excel generated results and the LCE tool calculated results.

4.6 Sensitivity Analysis

There is a multitude of variables involved in the framework, a sensitivity analysis is carried out to examine the impact of the change in the variables on the final life cycle cost. Table 4-15 to Table 4-21 show the different variables linked to different models and their impact on life cycle cost estimations.

Table 4-15: Sensitivity analysis results for fix upon break cost model

Input Variable	Original Value	Percent Change of Value	New Value	Original Cost after 100 years (Million $)	New Cost (Million $)	Percent change of Cost
Fix upon Break Cost model						
Minimum Break Frequency	0.01 failures / km / year	+10%	0.011	60.76	66.84	+10%
		-10%	0.009		54.69	-10%
		+100%	0.02		121.52	+100%
		-90%	0.001		6.08	-90%
Break Growth Rate	7.4% / year	+10%	8.14%	60.76	125.97	+107%
		-10%	6.66%		29.38	-51.6%
		+1%	7.474%		65.35	+7.6%
		-1%	7.326%		56.50	-7%
Cost Per Break	$5770 / break	+10%	$6347	60.76	66.84	+10%
		-10%	$5193		54.69	-10%
		+100%	$11540		121.52	+100%
		-90%	$577		6.08	-90%

Table 4-16: Sensitivity analysis results for basic replacement cost model

Input Variable	Original Value	Percent Change of Value	New Value	Original Cost after 100 years (Million $)	New Cost (Million $)	Percent change of Cost
Basic Replacement Cost model						
Overall Price Per Meter to Replace the Pipe	$800 / m	+10%	880	13.55	14.35	+5.9%
		-10%	720		12.75	-5.9%
		+100%	1600		21.55	+59%
		-90%	80		6.35	-53%

Table 4-17: Sensitivity analysis results for advanced replacement cost model

Input Variable	Original Value	Percent Change of Value	New Value	Original Cost after 100 years (Million $)	New Cost (Million $)	Percent change of Cost
Advanced Replacement Cost model						
Price Per Meter to Replace the Pipe	$400 / m	+10%	440	9.75	10.15	4.1%
		-10%	360		9.35	-4.1%
		+100%	800		13.75	41.0%
		-90%	40		6.15	-36.9%
Fixed Cost Per Site	$4000	+10%	4400	9.75	9.77	0.2%
		-10%	3600		9.73	-0.2%
		+100%	8000		9.95	2.1%
		-90%	400		9.57	-1.8%
Average Size Of Site	200m	+10%	220	9.75	9.73	-0.2%
		-10%	180		9.77	0.2%
		+100%	400		9.65	-1.0%
		-90%	20		11.55	18.5%

Table 4-18: Sensitivity analysis results for Basic Lining cost model

Input Variable	Original Value	Percent Change of Value	New Value	Original Cost after 100 years (Million $)	New Cost (Million $)	Percent change of Cost
Basic Lining Cost model						
Lining price per meter	$200 / m	+10%	220	9.35	9.49	1.5%
		-10%	180		9.21	-1.5%
		+100%	400		10.75	15.0%
		-90%	20		8.09	-13.5%
Replacement price per meter	$800 / m	+10%	880	9.35	9.59	2.6%
		-10%	720		9.11	-2.6%
		+100%	1600		11.75	25.7%
		-90%	80		7.19	-23.1%
Portion of Network to be Lined	70%	+10%	77%	9.35	8.93	-4.5%
		-10%	63%		9.77	4.5%
		+43%	100%		7.55	-19.3%
		-43%	40%		11.75	25.7%

Table 4-19: Sensitivity analysis results for Advanced Lining cost model

Input Variable	Original Value	Percent Change of Value	New Value	Original Cost after 100 years (Million $)	New Cost (Million $)	Percent change of Cost
Advanced Lining Cost model						
Portion of Network to be Lined	70%	+10%	77%	7.77	7.55	-2.8%
		-10%	63%		8.00	3.0%
		+43%	100%		6.80	-12.5%
		-43%	40%		8.75	12.6%
Average Size Of Lining Site	200 m	+10%	220	7.77	7.76	-0.1%
		-10%	180		7.79	0.3%
		+100%	400		7.69	-1.0%
		-90%	20		9.35	20.3%
Fixed Cost per site for lining	$5000 **/ m**	+10%	5500	7.77	7.79	0.3%
		-10%	4500		7.76	-0.1%
		+100%	10000		7.95	2.3%
		-90%	500		7.62	-1.9%
Lining price per meter	**$** 100 **/ m**	+10%	110	7.77	7.84	0.9%
		-10%	90		7.70	-0.9%
		+100%	200		8.47	9.0%
		-90%	10		7.14	-8.1%
Average Size Of Replacement Site	200 **m**	+10%	220	7.77	7.76	-0.1%
		-10%	180		7.79	0.3%
		+100%	400		7.70	-0.9%
		-90%	20		9.12	17.4%
Fixed Cost per site for Replacement	$10000	+10%	11000	7.77	7.79	0.3%
		-10%	9000		7.76	-0.1%
		+100%	20000		7.92	1.9%
		-90%	1000		7.64	-1.7%
Replacement price per meter	$400 / m	+10%	440	7.77	7.89	0.9%
		-10%	360		7.65	-0.9%
		+100%	800		8.97	9.0%
		-90%	40		6.69	-8.1%

Table 4-20: Sensitivity analysis results for basic proposed strategy cost model

Input Variable	Original Value	Percent Change of Value	New Value	Original Cost after 100 years (Million $)	New Cost (Million $)	Percent change of Cost
Basic Proposed Strategy Cost model						
Portion of Network to be left alone*	50%	+10%	55%	7.89	7.79	-1.3%
		-10%	45%		7.99	1.3%
		+100%	100%		5.69	-27.9%
		-90%	5%		8.79	11.4%
Portion of Network to be replaced**	20%	+10%	22%	7.89	8.05	2.0%
		-10%	18%		7.73	-2.0%
		+100%	40%		9.49	20.3%
		-90%	2%		6.45	-18.3%
Portion of Network to be lined***	30%	+10%	33%	7.89	7.95	0.8%
		-10%	27%		7.83	-0.8%
		+100%	60%		8.49	7.6%
		-90%	3%		7.35	-6.8%
Price Per Meter To Inspect The Pipe	$8.4 / m	10%	9.24	7.89	7.9	0.1%
		-10%	7.56		7.88	-0.1%
		100%	16.80		7.97	1.0%
		-90%	0.84		7.81	-1.0%
Price Per Meter To Clean The Pipe	$0.5 / m	10%	0.55	7.89	7.891	0.0%
		-10%	0.45		7.889	0.0%
		100%	1.00		7.894	0.1%
		-90%	0.05		7.88	-0.1%
Average Size Of Inspection Site	200 m	10%	220.00	7.89	7.88	-0.1%
		-10%	180.00		7.9	0.1%
		100%	400.00		7.86	-0.4%
		-90%	20.00		8.34	5.7%
Other Costs Per Inspection Site	$1000 / m	10%	1100.00	7.89	7.894	0.1%
		-10%	900.00		7.88	-0.1%
		100%	2000.00		7.94	0.6%
		-90%	100.00		7.84	-0.6%
Lining price per meter	$200 / m	10%	220	7.89	7.95	0.8%
		-10%	180		7.83	-0.8%
		100%	400		8.49	7.6%
		-90%	20		7.35	-6.8%
Replacement price per meter	$800 / m	10%	880	7.89	8.05	2.0%
		-10%	720		7.73	-2.0%
		100%	1600		9.49	20.3%
		-90%	80		6.45	-18.3%
* When Portion to be left alone was changed the corresponding change was applied to portion to be lined.						

** When Portion to be replaced was changed the corresponding change was applied to portion to be left alone.
*** When Portion to be lined was changed the corresponding change was applied to portion to be left alone.

Table 4-21: Sensitivity analysis results for advanced proposed strategy cost model

Input Variable	Original Value	Percent Change of Value	New Value	Original Cost after 100 years (Million $)	New Cost (Million $)	Percent change of Cost
Advanced Proposed Strategy Cost model						
Portion of Network to be left alone*	50%	+10%	55%	6.96	6.89	-1.0%
		-10%	45%		7.03	1.0%
		+100%	100%		5.69	-18.2%
		-90%	5%		7.53	8.2%
Portion of Network to be replaced**	20%	+10%	22%	6.96	7.05	1.3%
		-10%	18%		6.87	-1.3%
		+100%	40%		7.86	12.9%
		-90%	2%		6.15	-11.6%
Portion of Network to be lined***	30%	+10%	33%	6.96	7	0.6%
		-10%	27%		6.93	-0.4%
		+100%	60%		7.34	5.5%
		-90%	3%		6.63	-4.7%
Price Per Meter To Inspect The Pipe	$8.4 / m	10%	9.24	6.96	6.97	0.1%
		-10%	7.56		6.95	-0.1%
		100%	16.80		7.05	1.3%
		-90%	0.84		6.89	-1.0%
Price Per Meter To Clean The Pipe	$0.5 / m	10%	0.55	6.96	6.964	0.1%
		-10%	0.45		6.956	-0.1%
		100%	1.00		6.97	0.1%
		-90%	0.05		6.956	-0.1%
Average Size Of Inspection Site	200 m	10%	220.00	6.96	6.956	-0.1%
		-10%	180.00		6.97	0.1%
		100%	400.00		6.94	-0.3%
		-90%	20.00		7.41	6.5%
Other Costs Per Inspection Site	$1000	10%	1100.00	6.96	6.97	0.1%
		-10%	900.00		6.954	-0.1%
		100%	2000.00		7.01	0.7%
		-90%	100.00		6.92	-0.6%
Average Size Of Lining Site	200 m	+10%	220	6.96	6.956	-0.1%
		-10%	180		6.97	0.1%
		+100%	400		6.93	-0.4%
		-90%	20		7.64	9.8%
Fixed Cost per site for lining	$5000	+10%	5500	6.96	6.97	0.1%
		-10%	4500		6.956	-0.1%
		+100%	10000		7.04	1.1%
		-90%	500		6.9	-0.9%
Lining price per meter	$100 / m	+10%	110	6.96	6.99	0.4%
		-10%	90		6.93	-0.4%
		+100%	200		7.26	4.3%

		-90%	10		6.69	-3.9%
Average Size Of Replacement Site	$200 / m	+10%	220	6.96	6.95	-0.1%
		-10%	180		6.97	0.1%
		+100%	400		6.91	-0.7%
		-90%	20		7.86	12.9%
Fixed Cost per site for Replacement	$10000	+10%	11000	6.96	6.97	0.1%
		-10%	9000		6.95	-0.1%
		+100%	20000		7.06	1.4%
		-90%	1000		6.87	-1.3%
Replacement price per meter	$400 / m	+10%	440	6.96	7.04	1.1%
		-10%	360		6.88	-1.1%
		+100%	800		7.76	11.5%
		-90%	40		6.24	-10.3%
* When Portion to be left alone was changed the corresponding change was applied to portion to be lined. ** When Portion to be replaced was changed the corresponding change was applied to portion to be left alone. *** When Portion to be lined was changed the corresponding change was applied to portion to be left alone.						

4.7 SDLC V-Model Verification Process and Sensitivity Results

This section is divided in to two main subsections. The first one discusses the verification process while the second subsection highlights the main findings of the sensitivity analysis and discusses the probable solutions to deal with them.

4.7.1 LCE tool Verification

The SDLC V-Model used to verify the pre-validated life cycle cost estimation framework for different strategies for a water utility has verified the framework satisfactorily. The cross comparison of every single model used in the framework showed the same results which were produced by MS Excel calculations. The calculations when performed for the integrated system were accurate well into the thousands ($), which is a very high degree of accuracy given the cost estimations are in range of tens of millions ($) for the case study presented in this Chapter.

4.7.2 Variable Sensitivity & Long-Term Economic Problems It Poses

The sensitivity analysis results indicated that out of all the variables that were involved in the life cycle cost estimation, the ‘break growth rate’ turned out to be the most sensitive in terms of life cycle cost of a given utility, as increasing the ‘break growth rate’ by 1% increased the total life cycle cost of the Fix upon Break model by 7.6%. In addition, as the ‘break growth rate’ grows in an exponential manner, the increase in rate of break growth will cause exponential increase in the life cycle estimated costs. For an increase of 10% in ‘break growth rate’, an increase of 107% in life cycle costs of fix upon break model was recorded showing the sensitivity of the aforementioned variable.

The variable ‘break growth rate’ affects not only the Fix upon Break model to which it serves as a direct input but affect the rest of models as well because every other model uses Fix upon Break policy for the pipes which have still not reached their maximum service/design life (that are not in the oldest age bin). The fact that the variable ‘break growth rate’ affects every single model (demonstrated in chapter 3) and hence affects the future O&M and capital works cost estimations holistically by a large margin with only a small increase or decrease in its value establishes a need to cater the cost accumulations by either inhibiting the break growth rate, reducing the repair cost or adopting the other policies which can tackle the pipe break problem with a reduced economic consequence.

4.7.3 Discussion

The findings in this study regarding the sensitivity of ‘break growth rate’ and its economic implications using the LCE tool are also supported by recent research which focus on reducing the break growth rate.

(Folkman 2018) from Utah State University did a comprehensive study on water main break rates in USA and Canada and his study supports the argument of water-main failure rate increasing at an exponential rate which was first suggested by Kleiner (2002) and used in modelling of break growth rate in the framework proposed in this chapter. These studies are in parallel with the industry knowledge and short-term fixes which can hinder the 'break growth rate' are suggested in these studies mainly for iron pipes. These fixes are primarily corrosion prevention techniques as corrosion is the primary driver of 'break growth rate' in iron pipes. They include Polywrap, Cathodic protection, V-bio polywrap, Impressed current and Dielectric current.

Water utilities often do not know the cause of corrosion in the water mains externally, and these preventative measures may not work effectively (Folkman 2018). Besides, other non-corrodible materials like plastic and HDPE (highly ductile polyethylene) pipes have captured a huge market in the water industry and corrosion is not an issue in these pipes as they age.

Consequently, long term solutions need to be sought which can cover a larger spectrum of pipe design materials and are economically viable in the long run such as structural/nonstructural lining or replacement of the pipes with high break frequency. These approaches can effectively slow down the 'break growth rate'. These rehabilitation and capital work programs need to be vetted for their economic efficacy against the status quo policies and long-term cost savings.

The tool presented in this chapter can successfully achieve the target of vetting all the different maintenance, rehabilitation and replacement policies wherein it can simulate the all the possible approaches and a decision can be made on the most economic approach based on their long term economic efficacy for the next 100 years to come.

4.8 Conclusions

- The SDLC V-Model successfully verifies the pre-validated life cycle OM&R and capital work strategies framework presented in Chapter 3.
- 'Break Growth Rate' is an extremely sensitive variable which can greatly alter the life cycle costs by slight variation i.e. 1% increase or decrease can alter the cumulative life cycle costs by 7%.
- Increasing the size of the site to be operated per day can reduce the life cycle costs. By doubling the size of the site for a 24 hours work, the life cycle costs can be reduced anywhere from 0.4% - 1% depending on the approach that is being used.

- The tool developed for the framework makes it easier for the asset managers, contractors as well as other stakeholders to look into different variables and optimize their life cycle costs for maintaining their water utility`s current infrastructure.

Chapter 5

Conclusions and Recommendations for Future Work

5.1 Conclusions

The research presented herein provides a comprehensive study of the problems faced by utilities regarding their water distribution systems. The absence of a sophisticated methodology that can deal with the backlogs and OM&R life cycle costs have been addressed here and an extensive framework, as well as a tool that can simulate the framework, has been created. Case studies were carried out to test the framework and the tool. Based on this research study, the following conclusions are made:

1. Utilities are in a dire need of smart strategies and extensive framework for their water distribution systems that can deal with the increasing magnitude of backlogs, OM&R and capital works costs.
2. There is an exponential increase in deterioration of buried water infrastructure, hence exponentially increasing backlogs.
3. An extensive framework was developed which consistently resulted in life cycle cost savings of upwards of 10% when the hypothetical municipality was subjected to it.
4. The SDLC V-Model successfully validates and verifies the proposed framework and the tool designed around it.
5. The more the historical information available to the municipality about their infrastructure, the more is the realization of potential cost savings.
6. By applying the cost models to the hypothetical water distribution system, the fix upon break approach (conventionally adopted maintenance approach) is six times expensive then the next most expensive approach i.e. replacement.
7. Sensitivity analysis showed that ‘rate of break growth’ is a very sensitive variable in the framework when it was applied to a case study using a tool. 1% change in the break growth rate resulted in 7% increase in life cycle OM&R costs.
8. Using advanced cost models in the framework, given enough utility information is available, increased cost savings can be realized as compared to the basic cost models of the tool.

5.2 Recommendations for Future Work

A new and innovate framework has been proposed in this research to deal with the infrastructure backlog and increasing OM&R costs. The research has successfully achieved these objectives. However, there are some limitations that need to be addressed to further improve the accuracy of the proposed framework.

1. The cost estimation does not take into account the inflation rate, this needs to be inculcated in the framework to increase the accuracy of cumulative life cycle OM&R cost predictions.
2. Population growth as well as the growing infrastructure associated with it is not included in the work and is recommended for future works to increase the accuracy.
3. The tool should be integrated with GIS so that it can extract data and present the outputs on a GIS interface.

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Appendix A

Minimum break frequency	0.01	Growth Rate	0.074	
Pipe Segment No.	**Pipe Installation Year**	**Length In meters**	**Age Of Pipe**	**Binning**
1	1918	8000	100	Bin5
2	1918	8000	100	Bin5
3	1918	8000	100	Bin5
4	1918	8000	100	Bin5
5	1918	8000	100	Bin5
6	1918	8000	100	Bin5
7	1918	8000	100	Bin5
8	1918	8000	100	Bin5
9	1918	8000	100	Bin5
10	1918	8000	100	Bin5
11	1938	8000	80	Bin4
12	1938	8000	80	Bin4
13	1938	8000	80	Bin4
14	1938	8000	80	Bin4
15	1938	8000	80	Bin4
16	1938	8000	80	Bin4
17	1938	8000	80	Bin4
18	1938	8000	80	Bin4
19	1938	8000	80	Bin4
20	1938	8000	80	Bin4
21	1958	8000	60	Bin3
22	1958	8000	60	Bin3
23	1958	8000	60	Bin3
24	1958	8000	60	Bin3
25	1958	8000	60	Bin3
26	1958	8000	60	Bin3
27	1958	8000	60	Bin3
28	1958	8000	60	Bin3
29	1958	8000	60	Bin3
30	1958	8000	60	Bin3
31	1978	8000	40	Bin2
32	1978	8000	40	Bin2
33	1978	8000	40	Bin2
34	1978	8000	40	Bin2
35	1978	8000	40	Bin2
36	1978	8000	40	Bin2
37	1978	8000	40	Bin2
38	1978	8000	40	Bin2
39	1978	8000	40	Bin2
40	1978	8000	40	Bin2
41	1998	8000	20	Bin1
42	1998	8000	20	Bin1
43	1998	8000	20	Bin1
44	1998	8000	20	Bin1
45	1998	8000	20	Bin1
46	1998	8000	20	Bin1
47	1998	8000	20	Bin1
48	1998	8000	20	Bin1
49	1998	8000	20	Bin1
50	1998	8000	20	Bin1

Figure A1: Hypothetical water network binning

Number of Breaks (nothing done) per km					
Age of Pipe Segment	Currently	Next 20 years	Next 40 years	Next 60 years	Next 80 years
100	16.36	16.36	16.36	16.36	16.36
100	16.36	16.36	16.36	16.36	16.36
100	16.36	16.36	16.36	16.36	16.36
100	16.36	16.36	16.36	16.36	16.36
100	16.36	16.36	16.36	16.36	16.36
100	16.36	16.36	16.36	16.36	16.36
100	16.36	16.36	16.36	16.36	16.36
100	16.36	16.36	16.36	16.36	16.36
100	16.36	16.36	16.36	16.36	16.36
100	16.36	16.36	16.36	16.36	16.36
80	3.72	16.36	16.36	16.36	16.36
80	3.72	16.36	16.36	16.36	16.36
80	3.72	16.36	16.36	16.36	16.36
80	3.72	16.36	16.36	16.36	16.36
80	3.72	16.36	16.36	16.36	16.36
80	3.72	16.36	16.36	16.36	16.36
80	3.72	16.36	16.36	16.36	16.36
80	3.72	16.36	16.36	16.36	16.36
80	3.72	16.36	16.36	16.36	16.36
80	3.72	16.36	16.36	16.36	16.36
60	0.85	3.72	16.36	16.36	16.36
60	0.85	3.72	16.36	16.36	16.36
60	0.85	3.72	16.36	16.36	16.36
60	0.85	3.72	16.36	16.36	16.36
60	0.85	3.72	16.36	16.36	16.36
60	0.85	3.72	16.36	16.36	16.36
60	0.85	3.72	16.36	16.36	16.36
60	0.85	3.72	16.36	16.36	16.36
60	0.85	3.72	16.36	16.36	16.36
60	0.85	3.72	16.36	16.36	16.36
40	0.19	0.85	3.72	16.36	16.36
40	0.19	0.85	3.72	16.36	16.36
40	0.19	0.85	3.72	16.36	16.36
40	0.19	0.85	3.72	16.36	16.36
40	0.19	0.85	3.72	16.36	16.36
40	0.19	0.85	3.72	16.36	16.36
40	0.19	0.85	3.72	16.36	16.36
40	0.19	0.85	3.72	16.36	16.36
40	0.19	0.85	3.72	16.36	16.36
40	0.19	0.85	3.72	16.36	16.36
20	0.04	0.19	0.85	3.72	16.36
20	0.04	0.19	0.85	3.72	16.36
20	0.04	0.19	0.85	3.72	16.36
20	0.04	0.19	0.85	3.72	16.36
20	0.04	0.19	0.85	3.72	16.36
20	0.04	0.19	0.85	3.72	16.36
20	0.04	0.19	0.85	3.72	16.36
20	0.04	0.19	0.85	3.72	16.36
20	0.04	0.19	0.85	3.72	16.36
20	0.04	0.19	0.85	3.72	16.36

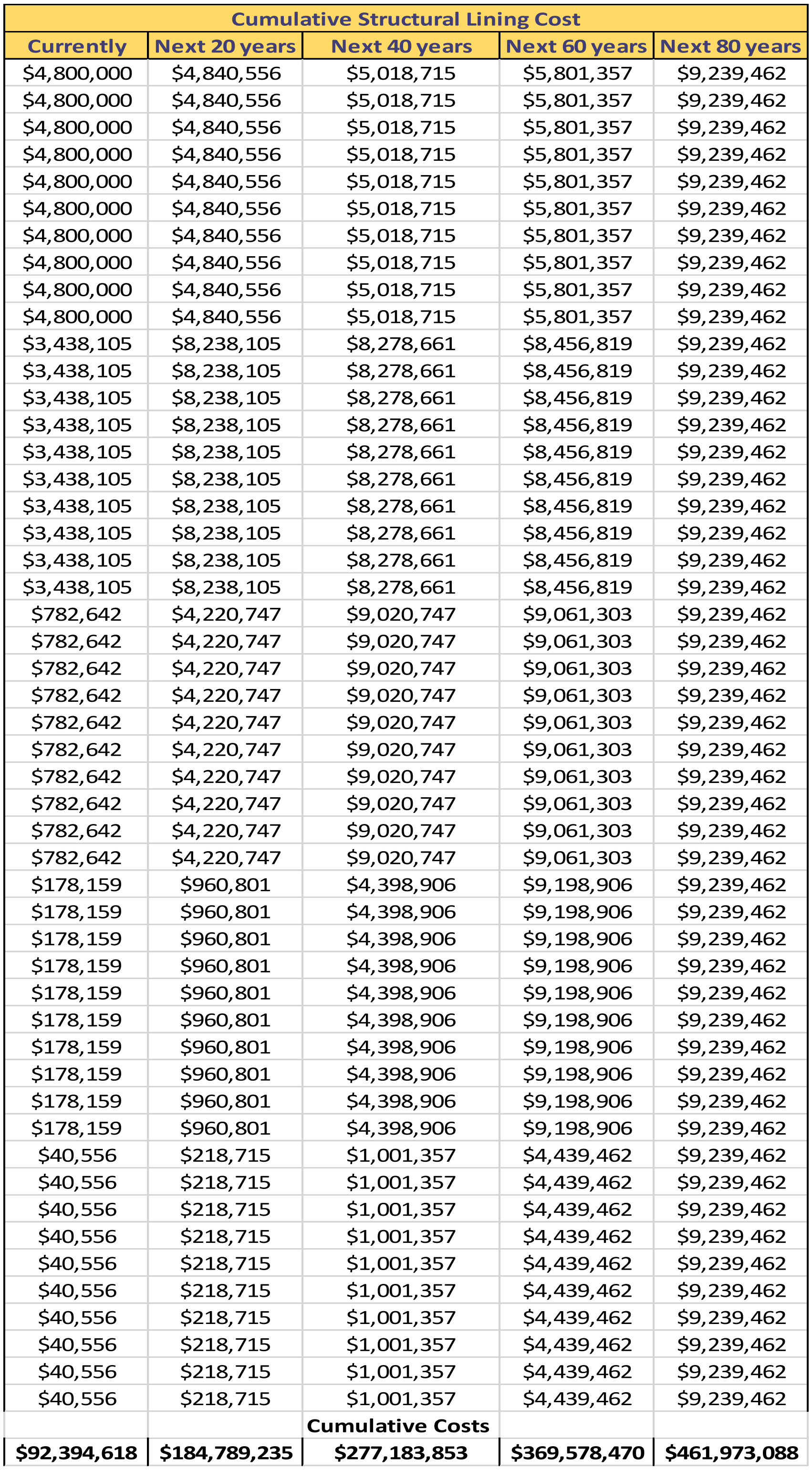
Figure A2: Pipe break frequency over a life cycle of 100 years

Fix Upon Break Cumulative Costs				
Currently	Next 20 years	Next 40 years	Next 60 years	Next 80 years
$15,103,408	$30,206,817	$45,310,225	$60,413,633	$75,517,041
$15,103,408	$30,206,817	$45,310,225	$60,413,633	$75,517,041
$15,103,408	$30,206,817	$45,310,225	$60,413,633	$75,517,041
$15,103,408	$30,206,817	$45,310,225	$60,413,633	$75,517,041
$15,103,408	$30,206,817	$45,310,225	$60,413,633	$75,517,041
$15,103,408	$30,206,817	$45,310,225	$60,413,633	$75,517,041
$15,103,408	$30,206,817	$45,310,225	$60,413,633	$75,517,041
$15,103,408	$30,206,817	$45,310,225	$60,413,633	$75,517,041
$15,103,408	$30,206,817	$45,310,225	$60,413,633	$75,517,041
$15,103,408	$30,206,817	$45,310,225	$60,413,633	$75,517,041
$3,438,105	$18,541,513	$33,644,921	$48,748,330	$63,851,738
$3,438,105	$18,541,513	$33,644,921	$48,748,330	$63,851,738
$3,438,105	$18,541,513	$33,644,921	$48,748,330	$63,851,738
$3,438,105	$18,541,513	$33,644,921	$48,748,330	$63,851,738
$3,438,105	$18,541,513	$33,644,921	$48,748,330	$63,851,738
$3,438,105	$18,541,513	$33,644,921	$48,748,330	$63,851,738
$3,438,105	$18,541,513	$33,644,921	$48,748,330	$63,851,738
$3,438,105	$18,541,513	$33,644,921	$48,748,330	$63,851,738
$3,438,105	$18,541,513	$33,644,921	$48,748,330	$63,851,738
$3,438,105	$18,541,513	$33,644,921	$48,748,330	$63,851,738
$782,642	$4,220,747	$19,324,155	$34,427,564	$49,530,972
$782,642	$4,220,747	$19,324,155	$34,427,564	$49,530,972
$782,642	$4,220,747	$19,324,155	$34,427,564	$49,530,972
$782,642	$4,220,747	$19,324,155	$34,427,564	$49,530,972
$782,642	$4,220,747	$19,324,155	$34,427,564	$49,530,972
$782,642	$4,220,747	$19,324,155	$34,427,564	$49,530,972
$782,642	$4,220,747	$19,324,155	$34,427,564	$49,530,972
$782,642	$4,220,747	$19,324,155	$34,427,564	$49,530,972
$782,642	$4,220,747	$19,324,155	$34,427,564	$49,530,972
$782,642	$4,220,747	$19,324,155	$34,427,564	$49,530,972
$178,159	$960,801	$4,398,906	$19,502,314	$34,605,723
$178,159	$960,801	$4,398,906	$19,502,314	$34,605,723
$178,159	$960,801	$4,398,906	$19,502,314	$34,605,723
$178,159	$960,801	$4,398,906	$19,502,314	$34,605,723
$178,159	$960,801	$4,398,906	$19,502,314	$34,605,723
$178,159	$960,801	$4,398,906	$19,502,314	$34,605,723
$178,159	$960,801	$4,398,906	$19,502,314	$34,605,723
$178,159	$960,801	$4,398,906	$19,502,314	$34,605,723
$178,159	$960,801	$4,398,906	$19,502,314	$34,605,723
$178,159	$960,801	$4,398,906	$19,502,314	$34,605,723
$40,556	$218,715	$1,001,357	$4,439,462	$19,542,870
$40,556	$218,715	$1,001,357	$4,439,462	$19,542,870
$40,556	$218,715	$1,001,357	$4,439,462	$19,542,870
$40,556	$218,715	$1,001,357	$4,439,462	$19,542,870
$40,556	$218,715	$1,001,357	$4,439,462	$19,542,870
$40,556	$218,715	$1,001,357	$4,439,462	$19,542,870
$40,556	$218,715	$1,001,357	$4,439,462	$19,542,870
$40,556	$218,715	$1,001,357	$4,439,462	$19,542,870
$40,556	$218,715	$1,001,357	$4,439,462	$19,542,870
$40,556	$218,715	$1,001,357	$4,439,462	$19,542,870
		Cumulative Cost		
$195,428,700	**$541,485,926**	**$1,036,795,646**	**$1,675,313,026**	**$2,430,483,438**

Figure A3: Fix Upon Break Cumulative Costs

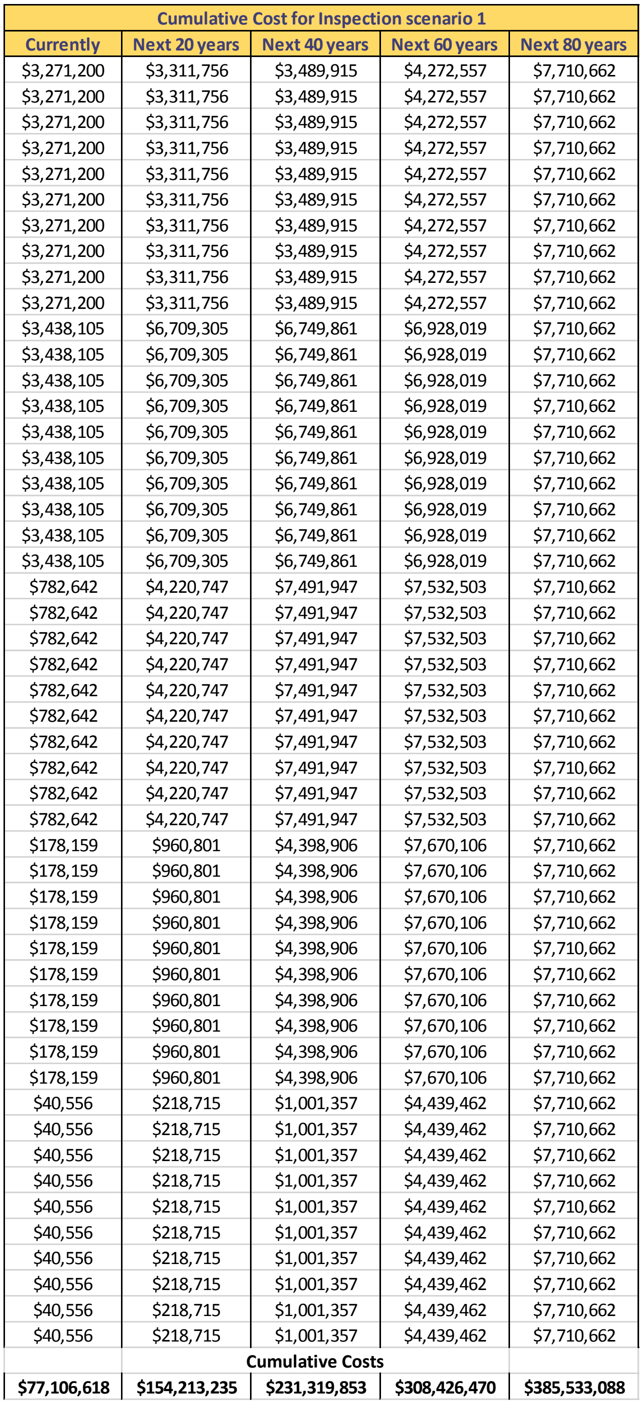
Cumulative Cost for 100% replacement scenario				
Currently	Next 20 years	Next 40 years	Next 60 years	Next 80 years
$6,400,000	$6,440,556	$6,618,715	$7,401,357	$10,839,462
$6,400,000	$6,440,556	$6,618,715	$7,401,357	$10,839,462
$6,400,000	$6,440,556	$6,618,715	$7,401,357	$10,839,462
$6,400,000	$6,440,556	$6,618,715	$7,401,357	$10,839,462
$6,400,000	$6,440,556	$6,618,715	$7,401,357	$10,839,462
$6,400,000	$6,440,556	$6,618,715	$7,401,357	$10,839,462
$6,400,000	$6,440,556	$6,618,715	$7,401,357	$10,839,462
$6,400,000	$6,440,556	$6,618,715	$7,401,357	$10,839,462
$6,400,000	$6,440,556	$6,618,715	$7,401,357	$10,839,462
$6,400,000	$6,440,556	$6,618,715	$7,401,357	$10,839,462
$3,438,105	$9,838,105	$9,878,661	$10,056,819	$10,839,462
$3,438,105	$9,838,105	$9,878,661	$10,056,819	$10,839,462
$3,438,105	$9,838,105	$9,878,661	$10,056,819	$10,839,462
$3,438,105	$9,838,105	$9,878,661	$10,056,819	$10,839,462
$3,438,105	$9,838,105	$9,878,661	$10,056,819	$10,839,462
$3,438,105	$9,838,105	$9,878,661	$10,056,819	$10,839,462
$3,438,105	$9,838,105	$9,878,661	$10,056,819	$10,839,462
$3,438,105	$9,838,105	$9,878,661	$10,056,819	$10,839,462
$3,438,105	$9,838,105	$9,878,661	$10,056,819	$10,839,462
$3,438,105	$9,838,105	$9,878,661	$10,056,819	$10,839,462
$782,642	$4,220,747	$10,620,747	$10,661,303	$10,839,462
$782,642	$4,220,747	$10,620,747	$10,661,303	$10,839,462
$782,642	$4,220,747	$10,620,747	$10,661,303	$10,839,462
$782,642	$4,220,747	$10,620,747	$10,661,303	$10,839,462
$782,642	$4,220,747	$10,620,747	$10,661,303	$10,839,462
$782,642	$4,220,747	$10,620,747	$10,661,303	$10,839,462
$782,642	$4,220,747	$10,620,747	$10,661,303	$10,839,462
$782,642	$4,220,747	$10,620,747	$10,661,303	$10,839,462
$782,642	$4,220,747	$10,620,747	$10,661,303	$10,839,462
$782,642	$4,220,747	$10,620,747	$10,661,303	$10,839,462
$178,159	$960,801	$4,398,906	$10,798,906	$10,839,462
$178,159	$960,801	$4,398,906	$10,798,906	$10,839,462
$178,159	$960,801	$4,398,906	$10,798,906	$10,839,462
$178,159	$960,801	$4,398,906	$10,798,906	$10,839,462
$178,159	$960,801	$4,398,906	$10,798,906	$10,839,462
$178,159	$960,801	$4,398,906	$10,798,906	$10,839,462
$178,159	$960,801	$4,398,906	$10,798,906	$10,839,462
$178,159	$960,801	$4,398,906	$10,798,906	$10,839,462
$178,159	$960,801	$4,398,906	$10,798,906	$10,839,462
$178,159	$960,801	$4,398,906	$10,798,906	$10,839,462
$40,556	$218,715	$1,001,357	$4,439,462	$10,839,462
$40,556	$218,715	$1,001,357	$4,439,462	$10,839,462
$40,556	$218,715	$1,001,357	$4,439,462	$10,839,462
$40,556	$218,715	$1,001,357	$4,439,462	$10,839,462
$40,556	$218,715	$1,001,357	$4,439,462	$10,839,462
$40,556	$218,715	$1,001,357	$4,439,462	$10,839,462
$40,556	$218,715	$1,001,357	$4,439,462	$10,839,462
$40,556	$218,715	$1,001,357	$4,439,462	$10,839,462
$40,556	$218,715	$1,001,357	$4,439,462	$10,839,462
$40,556	$218,715	$1,001,357	$4,439,462	$10,839,462
		Cumulative Costs		
$108,394,618	**$216,789,235**	**$325,183,853**	**$433,578,470**	**$541,973,088**

Figure A4: Replacement Cumulative Costs



Cumulative Structural Lining Cost				
Currently	**Next 20 years**	**Next 40 years**	**Next 60 years**	**Next 80 years**
$4,800,000	$4,840,556	$5,018,715	$5,801,357	$9,239,462
$4,800,000	$4,840,556	$5,018,715	$5,801,357	$9,239,462
$4,800,000	$4,840,556	$5,018,715	$5,801,357	$9,239,462
$4,800,000	$4,840,556	$5,018,715	$5,801,357	$9,239,462
$4,800,000	$4,840,556	$5,018,715	$5,801,357	$9,239,462
$4,800,000	$4,840,556	$5,018,715	$5,801,357	$9,239,462
$4,800,000	$4,840,556	$5,018,715	$5,801,357	$9,239,462
$4,800,000	$4,840,556	$5,018,715	$5,801,357	$9,239,462
$4,800,000	$4,840,556	$5,018,715	$5,801,357	$9,239,462
$4,800,000	$4,840,556	$5,018,715	$5,801,357	$9,239,462
$3,438,105	$8,238,105	$8,278,661	$8,456,819	$9,239,462
$3,438,105	$8,238,105	$8,278,661	$8,456,819	$9,239,462
$3,438,105	$8,238,105	$8,278,661	$8,456,819	$9,239,462
$3,438,105	$8,238,105	$8,278,661	$8,456,819	$9,239,462
$3,438,105	$8,238,105	$8,278,661	$8,456,819	$9,239,462
$3,438,105	$8,238,105	$8,278,661	$8,456,819	$9,239,462
$3,438,105	$8,238,105	$8,278,661	$8,456,819	$9,239,462
$3,438,105	$8,238,105	$8,278,661	$8,456,819	$9,239,462
$3,438,105	$8,238,105	$8,278,661	$8,456,819	$9,239,462
$3,438,105	$8,238,105	$8,278,661	$8,456,819	$9,239,462
$782,642	$4,220,747	$9,020,747	$9,061,303	$9,239,462
$782,642	$4,220,747	$9,020,747	$9,061,303	$9,239,462
$782,642	$4,220,747	$9,020,747	$9,061,303	$9,239,462
$782,642	$4,220,747	$9,020,747	$9,061,303	$9,239,462
$782,642	$4,220,747	$9,020,747	$9,061,303	$9,239,462
$782,642	$4,220,747	$9,020,747	$9,061,303	$9,239,462
$782,642	$4,220,747	$9,020,747	$9,061,303	$9,239,462
$782,642	$4,220,747	$9,020,747	$9,061,303	$9,239,462
$782,642	$4,220,747	$9,020,747	$9,061,303	$9,239,462
$782,642	$4,220,747	$9,020,747	$9,061,303	$9,239,462
$178,159	$960,801	$4,398,906	$9,198,906	$9,239,462
$178,159	$960,801	$4,398,906	$9,198,906	$9,239,462
$178,159	$960,801	$4,398,906	$9,198,906	$9,239,462
$178,159	$960,801	$4,398,906	$9,198,906	$9,239,462
$178,159	$960,801	$4,398,906	$9,198,906	$9,239,462
$178,159	$960,801	$4,398,906	$9,198,906	$9,239,462
$178,159	$960,801	$4,398,906	$9,198,906	$9,239,462
$178,159	$960,801	$4,398,906	$9,198,906	$9,239,462
$178,159	$960,801	$4,398,906	$9,198,906	$9,239,462
$178,159	$960,801	$4,398,906	$9,198,906	$9,239,462
$40,556	$218,715	$1,001,357	$4,439,462	$9,239,462
$40,556	$218,715	$1,001,357	$4,439,462	$9,239,462
$40,556	$218,715	$1,001,357	$4,439,462	$9,239,462
$40,556	$218,715	$1,001,357	$4,439,462	$9,239,462
$40,556	$218,715	$1,001,357	$4,439,462	$9,239,462
$40,556	$218,715	$1,001,357	$4,439,462	$9,239,462
$40,556	$218,715	$1,001,357	$4,439,462	$9,239,462
$40,556	$218,715	$1,001,357	$4,439,462	$9,239,462
$40,556	$218,715	$1,001,357	$4,439,462	$9,239,462
$40,556	$218,715	$1,001,357	$4,439,462	$9,239,462
		Cumulative Costs		
$92,394,618	**$184,789,235**	**$277,183,853**	**$369,578,470**	**$461,973,088**

Figure A5: Cumulative Structural Lining Cost

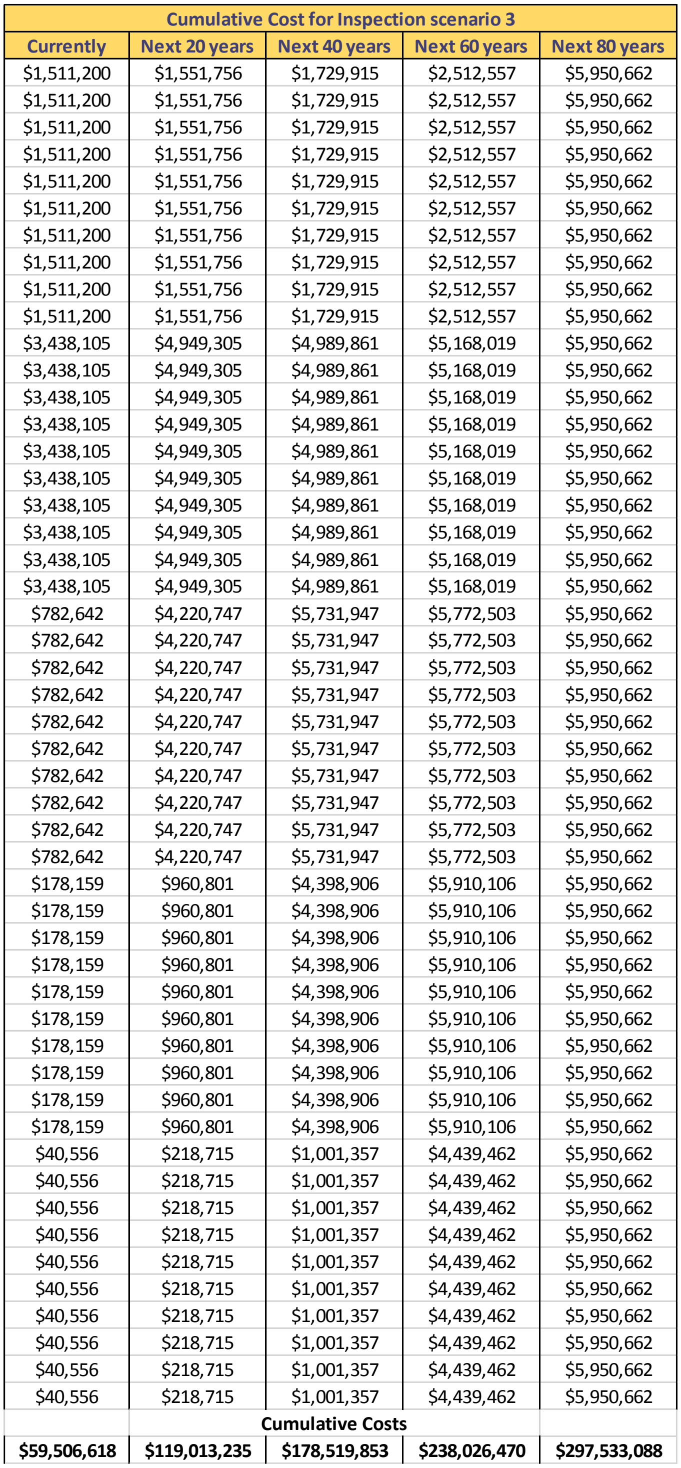


Cumulative Cost for Inspection scenario 1				
Currently	Next 20 years	Next 40 years	Next 60 years	Next 80 years
$3,271,200	$3,311,756	$3,489,915	$4,272,557	$7,710,662
$3,271,200	$3,311,756	$3,489,915	$4,272,557	$7,710,662
$3,271,200	$3,311,756	$3,489,915	$4,272,557	$7,710,662
$3,271,200	$3,311,756	$3,489,915	$4,272,557	$7,710,662
$3,271,200	$3,311,756	$3,489,915	$4,272,557	$7,710,662
$3,271,200	$3,311,756	$3,489,915	$4,272,557	$7,710,662
$3,271,200	$3,311,756	$3,489,915	$4,272,557	$7,710,662
$3,271,200	$3,311,756	$3,489,915	$4,272,557	$7,710,662
$3,271,200	$3,311,756	$3,489,915	$4,272,557	$7,710,662
$3,271,200	$3,311,756	$3,489,915	$4,272,557	$7,710,662
$3,438,105	$6,709,305	$6,749,861	$6,928,019	$7,710,662
$3,438,105	$6,709,305	$6,749,861	$6,928,019	$7,710,662
$3,438,105	$6,709,305	$6,749,861	$6,928,019	$7,710,662
$3,438,105	$6,709,305	$6,749,861	$6,928,019	$7,710,662
$3,438,105	$6,709,305	$6,749,861	$6,928,019	$7,710,662
$3,438,105	$6,709,305	$6,749,861	$6,928,019	$7,710,662
$3,438,105	$6,709,305	$6,749,861	$6,928,019	$7,710,662
$3,438,105	$6,709,305	$6,749,861	$6,928,019	$7,710,662
$3,438,105	$6,709,305	$6,749,861	$6,928,019	$7,710,662
$3,438,105	$6,709,305	$6,749,861	$6,928,019	$7,710,662
$782,642	$4,220,747	$7,491,947	$7,532,503	$7,710,662
$782,642	$4,220,747	$7,491,947	$7,532,503	$7,710,662
$782,642	$4,220,747	$7,491,947	$7,532,503	$7,710,662
$782,642	$4,220,747	$7,491,947	$7,532,503	$7,710,662
$782,642	$4,220,747	$7,491,947	$7,532,503	$7,710,662
$782,642	$4,220,747	$7,491,947	$7,532,503	$7,710,662
$782,642	$4,220,747	$7,491,947	$7,532,503	$7,710,662
$782,642	$4,220,747	$7,491,947	$7,532,503	$7,710,662
$782,642	$4,220,747	$7,491,947	$7,532,503	$7,710,662
$782,642	$4,220,747	$7,491,947	$7,532,503	$7,710,662
$178,159	$960,801	$4,398,906	$7,670,106	$7,710,662
$178,159	$960,801	$4,398,906	$7,670,106	$7,710,662
$178,159	$960,801	$4,398,906	$7,670,106	$7,710,662
$178,159	$960,801	$4,398,906	$7,670,106	$7,710,662
$178,159	$960,801	$4,398,906	$7,670,106	$7,710,662
$178,159	$960,801	$4,398,906	$7,670,106	$7,710,662
$178,159	$960,801	$4,398,906	$7,670,106	$7,710,662
$178,159	$960,801	$4,398,906	$7,670,106	$7,710,662
$178,159	$960,801	$4,398,906	$7,670,106	$7,710,662
$178,159	$960,801	$4,398,906	$7,670,106	$7,710,662
$40,556	$218,715	$1,001,357	$4,439,462	$7,710,662
$40,556	$218,715	$1,001,357	$4,439,462	$7,710,662
$40,556	$218,715	$1,001,357	$4,439,462	$7,710,662
$40,556	$218,715	$1,001,357	$4,439,462	$7,710,662
$40,556	$218,715	$1,001,357	$4,439,462	$7,710,662
$40,556	$218,715	$1,001,357	$4,439,462	$7,710,662
$40,556	$218,715	$1,001,357	$4,439,462	$7,710,662
$40,556	$218,715	$1,001,357	$4,439,462	$7,710,662
$40,556	$218,715	$1,001,357	$4,439,462	$7,710,662
$40,556	$218,715	$1,001,357	$4,439,462	$7,710,662
		Cumulative Costs		
$77,106,618	**$154,213,235**	**$231,319,853**	**$308,426,470**	**$385,533,088**

Figure A6: Cumulative Costs for Inspection Scenario 1

Cumulative Cost for Inspection scenario 2				
Currently	**Next 20 years**	**Next 40 years**	**Next 60 years**	**Next 80 years**
$1,831,200	$1,871,756	$2,049,915	$2,832,557	$6,270,662
$1,831,200	$1,871,756	$2,049,915	$2,832,557	$6,270,662
$1,831,200	$1,871,756	$2,049,915	$2,832,557	$6,270,662
$1,831,200	$1,871,756	$2,049,915	$2,832,557	$6,270,662
$1,831,200	$1,871,756	$2,049,915	$2,832,557	$6,270,662
$1,831,200	$1,871,756	$2,049,915	$2,832,557	$6,270,662
$1,831,200	$1,871,756	$2,049,915	$2,832,557	$6,270,662
$1,831,200	$1,871,756	$2,049,915	$2,832,557	$6,270,662
$1,831,200	$1,871,756	$2,049,915	$2,832,557	$6,270,662
$1,831,200	$1,871,756	$2,049,915	$2,832,557	$6,270,662
$3,438,105	$5,269,305	$5,309,861	$5,488,019	$6,270,662
$3,438,105	$5,269,305	$5,309,861	$5,488,019	$6,270,662
$3,438,105	$5,269,305	$5,309,861	$5,488,019	$6,270,662
$3,438,105	$5,269,305	$5,309,861	$5,488,019	$6,270,662
$3,438,105	$5,269,305	$5,309,861	$5,488,019	$6,270,662
$3,438,105	$5,269,305	$5,309,861	$5,488,019	$6,270,662
$3,438,105	$5,269,305	$5,309,861	$5,488,019	$6,270,662
$3,438,105	$5,269,305	$5,309,861	$5,488,019	$6,270,662
$3,438,105	$5,269,305	$5,309,861	$5,488,019	$6,270,662
$3,438,105	$5,269,305	$5,309,861	$5,488,019	$6,270,662
$782,642	$4,220,747	$6,051,947	$6,092,503	$6,270,662
$782,642	$4,220,747	$6,051,947	$6,092,503	$6,270,662
$782,642	$4,220,747	$6,051,947	$6,092,503	$6,270,662
$782,642	$4,220,747	$6,051,947	$6,092,503	$6,270,662
$782,642	$4,220,747	$6,051,947	$6,092,503	$6,270,662
$782,642	$4,220,747	$6,051,947	$6,092,503	$6,270,662
$782,642	$4,220,747	$6,051,947	$6,092,503	$6,270,662
$782,642	$4,220,747	$6,051,947	$6,092,503	$6,270,662
$782,642	$4,220,747	$6,051,947	$6,092,503	$6,270,662
$782,642	$4,220,747	$6,051,947	$6,092,503	$6,270,662
$178,159	$960,801	$4,398,906	$6,230,106	$6,270,662
$178,159	$960,801	$4,398,906	$6,230,106	$6,270,662
$178,159	$960,801	$4,398,906	$6,230,106	$6,270,662
$178,159	$960,801	$4,398,906	$6,230,106	$6,270,662
$178,159	$960,801	$4,398,906	$6,230,106	$6,270,662
$178,159	$960,801	$4,398,906	$6,230,106	$6,270,662
$178,159	$960,801	$4,398,906	$6,230,106	$6,270,662
$178,159	$960,801	$4,398,906	$6,230,106	$6,270,662
$178,159	$960,801	$4,398,906	$6,230,106	$6,270,662
$178,159	$960,801	$4,398,906	$6,230,106	$6,270,662
$40,556	$218,715	$1,001,357	$4,439,462	$6,270,662
$40,556	$218,715	$1,001,357	$4,439,462	$6,270,662
$40,556	$218,715	$1,001,357	$4,439,462	$6,270,662
$40,556	$218,715	$1,001,357	$4,439,462	$6,270,662
$40,556	$218,715	$1,001,357	$4,439,462	$6,270,662
$40,556	$218,715	$1,001,357	$4,439,462	$6,270,662
$40,556	$218,715	$1,001,357	$4,439,462	$6,270,662
$40,556	$218,715	$1,001,357	$4,439,462	$6,270,662
$40,556	$218,715	$1,001,357	$4,439,462	$6,270,662
$40,556	$218,715	$1,001,357	$4,439,462	$6,270,662
	Cumulative Costs			
$62,706,618	**$125,413,235**	**$188,119,853**	**$250,826,470**	**$313,533,088**

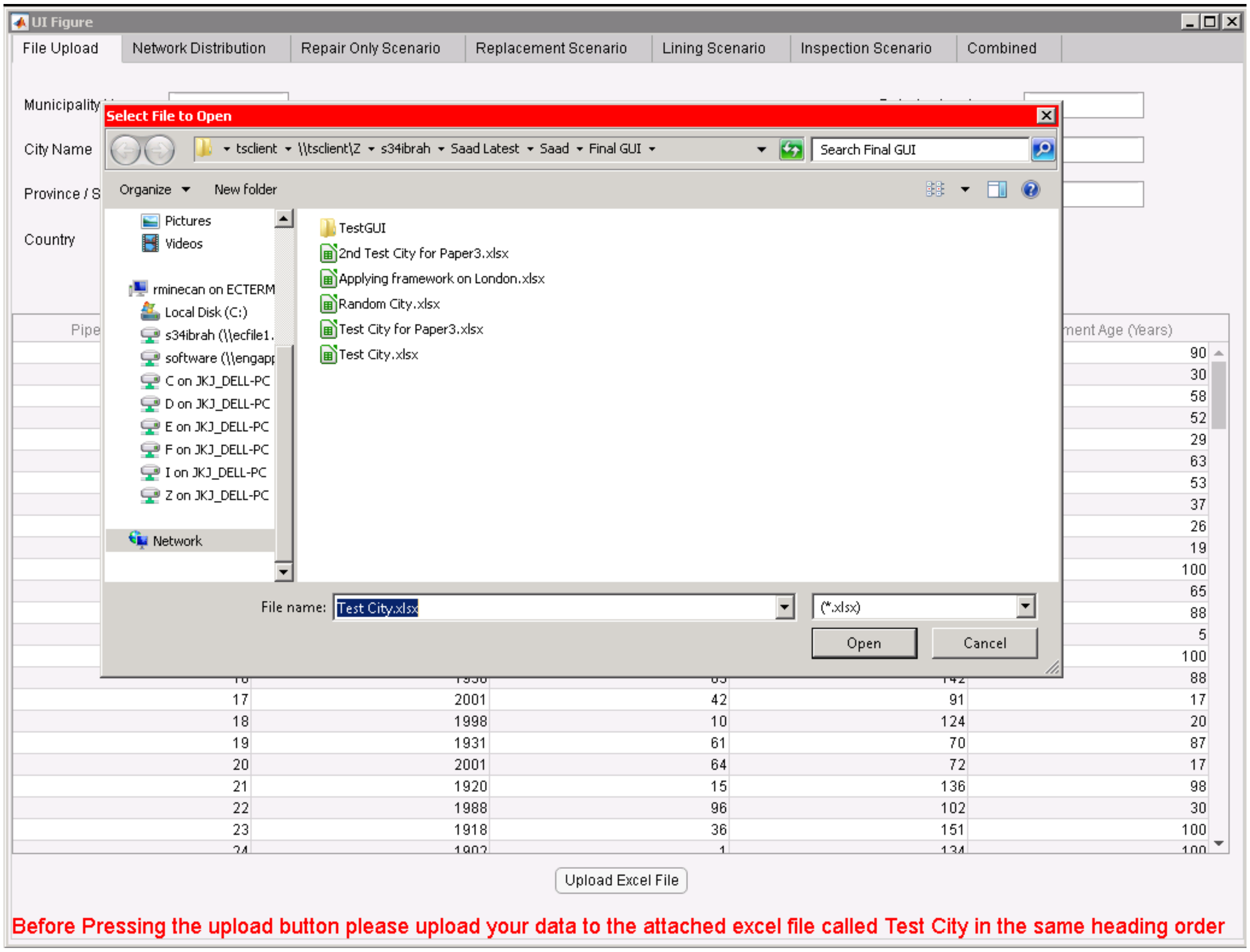
Figure A7: Cumulative Costs for scenario 2



Cumulative Cost for Inspection scenario 3				
Currently	**Next 20 years**	**Next 40 years**	**Next 60 years**	**Next 80 years**
$1,511,200	$1,551,756	$1,729,915	$2,512,557	$5,950,662
$1,511,200	$1,551,756	$1,729,915	$2,512,557	$5,950,662
$1,511,200	$1,551,756	$1,729,915	$2,512,557	$5,950,662
$1,511,200	$1,551,756	$1,729,915	$2,512,557	$5,950,662
$1,511,200	$1,551,756	$1,729,915	$2,512,557	$5,950,662
$1,511,200	$1,551,756	$1,729,915	$2,512,557	$5,950,662
$1,511,200	$1,551,756	$1,729,915	$2,512,557	$5,950,662
$1,511,200	$1,551,756	$1,729,915	$2,512,557	$5,950,662
$1,511,200	$1,551,756	$1,729,915	$2,512,557	$5,950,662
$1,511,200	$1,551,756	$1,729,915	$2,512,557	$5,950,662
$3,438,105	$4,949,305	$4,989,861	$5,168,019	$5,950,662
$3,438,105	$4,949,305	$4,989,861	$5,168,019	$5,950,662
$3,438,105	$4,949,305	$4,989,861	$5,168,019	$5,950,662
$3,438,105	$4,949,305	$4,989,861	$5,168,019	$5,950,662
$3,438,105	$4,949,305	$4,989,861	$5,168,019	$5,950,662
$3,438,105	$4,949,305	$4,989,861	$5,168,019	$5,950,662
$3,438,105	$4,949,305	$4,989,861	$5,168,019	$5,950,662
$3,438,105	$4,949,305	$4,989,861	$5,168,019	$5,950,662
$3,438,105	$4,949,305	$4,989,861	$5,168,019	$5,950,662
$3,438,105	$4,949,305	$4,989,861	$5,168,019	$5,950,662
$782,642	$4,220,747	$5,731,947	$5,772,503	$5,950,662
$782,642	$4,220,747	$5,731,947	$5,772,503	$5,950,662
$782,642	$4,220,747	$5,731,947	$5,772,503	$5,950,662
$782,642	$4,220,747	$5,731,947	$5,772,503	$5,950,662
$782,642	$4,220,747	$5,731,947	$5,772,503	$5,950,662
$782,642	$4,220,747	$5,731,947	$5,772,503	$5,950,662
$782,642	$4,220,747	$5,731,947	$5,772,503	$5,950,662
$782,642	$4,220,747	$5,731,947	$5,772,503	$5,950,662
$782,642	$4,220,747	$5,731,947	$5,772,503	$5,950,662
$782,642	$4,220,747	$5,731,947	$5,772,503	$5,950,662
$178,159	$960,801	$4,398,906	$5,910,106	$5,950,662
$178,159	$960,801	$4,398,906	$5,910,106	$5,950,662
$178,159	$960,801	$4,398,906	$5,910,106	$5,950,662
$178,159	$960,801	$4,398,906	$5,910,106	$5,950,662
$178,159	$960,801	$4,398,906	$5,910,106	$5,950,662
$178,159	$960,801	$4,398,906	$5,910,106	$5,950,662
$178,159	$960,801	$4,398,906	$5,910,106	$5,950,662
$178,159	$960,801	$4,398,906	$5,910,106	$5,950,662
$178,159	$960,801	$4,398,906	$5,910,106	$5,950,662
$178,159	$960,801	$4,398,906	$5,910,106	$5,950,662
$40,556	$218,715	$1,001,357	$4,439,462	$5,950,662
$40,556	$218,715	$1,001,357	$4,439,462	$5,950,662
$40,556	$218,715	$1,001,357	$4,439,462	$5,950,662
$40,556	$218,715	$1,001,357	$4,439,462	$5,950,662
$40,556	$218,715	$1,001,357	$4,439,462	$5,950,662
$40,556	$218,715	$1,001,357	$4,439,462	$5,950,662
$40,556	$218,715	$1,001,357	$4,439,462	$5,950,662
$40,556	$218,715	$1,001,357	$4,439,462	$5,950,662
$40,556	$218,715	$1,001,357	$4,439,462	$5,950,662
$40,556	$218,715	$1,001,357	$4,439,462	$5,950,662
		Cumulative Costs		
$59,506,618	**$119,013,235**	**$178,519,853**	**$238,026,470**	**$297,533,088**

Figure A8: Cumulative cost of inspection scenario 3

Appendix B



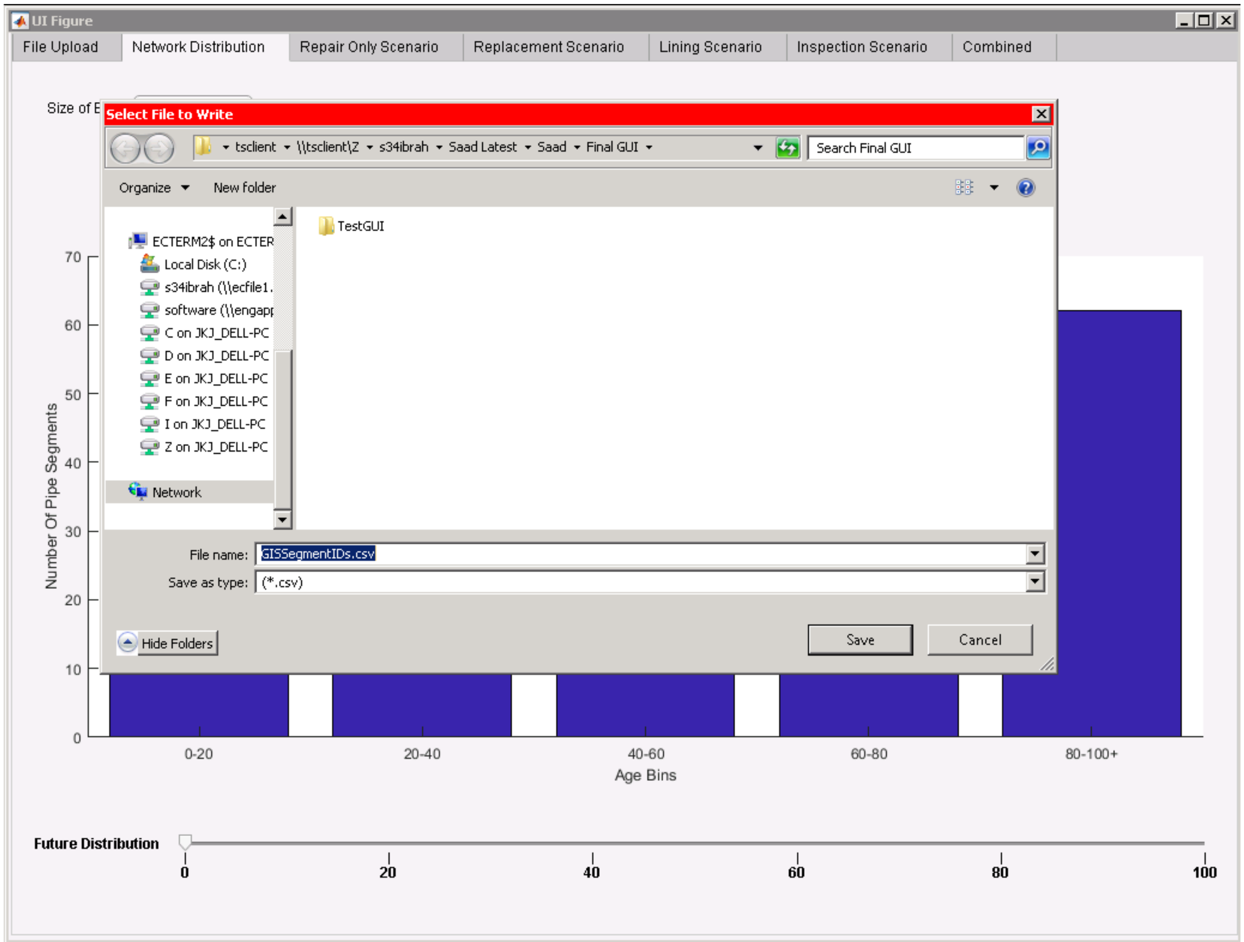
File name: Test City.xlsx

(*.xlsx)

Pipe				ment Age (Years)
				90
				30
				58
				52
				29
				63
				53
				37
				26
				19
				100
				65
				88
				5
				100
				88
17	2001	42	91	17
18	1998	10	124	20
19	1931	61	70	87
20	2001	64	72	17
21	1920	15	136	98
22	1988	96	102	30
23	1918	36	151	100

Before Pressing the upload button please upload your data to the attached excel file called Test City in the same heading order

Figure B1: Excel sheet pop-up window



File name: GISSegmentIDs.csv

Save as type: (*.csv)

Figure B2: GIS readable file in csv format created by LCE tool

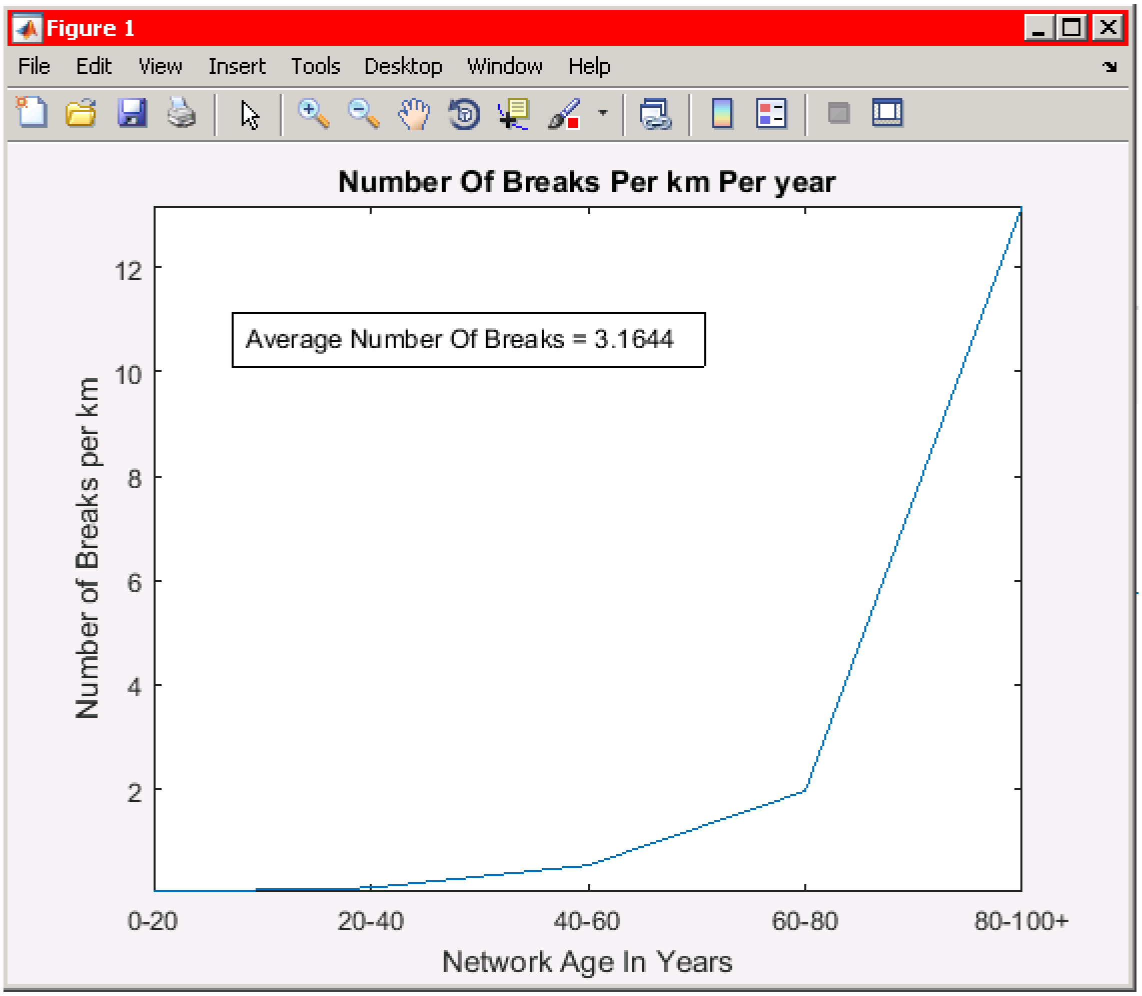


Figure B3: Pop-up window for creating a plot for pipe breaks simulation over the network`s life cycle

Appendix C

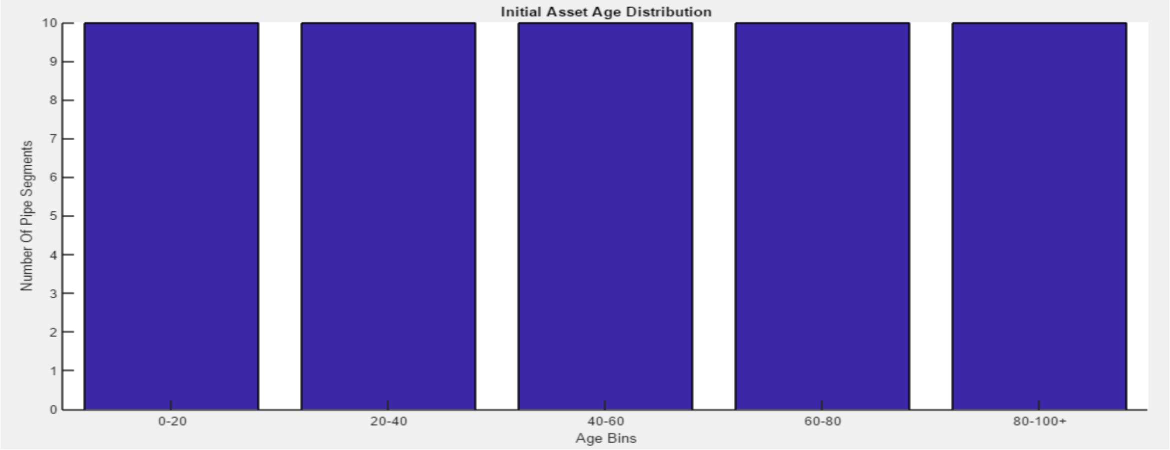
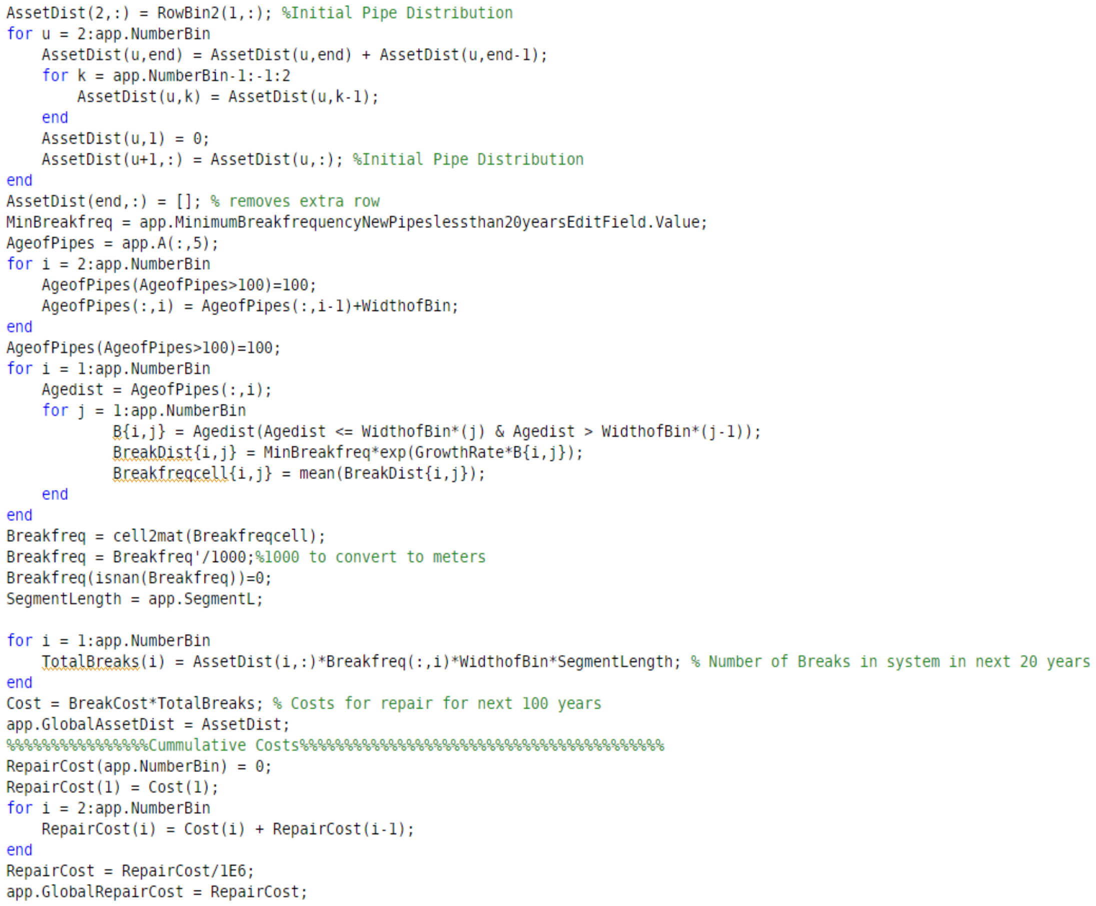


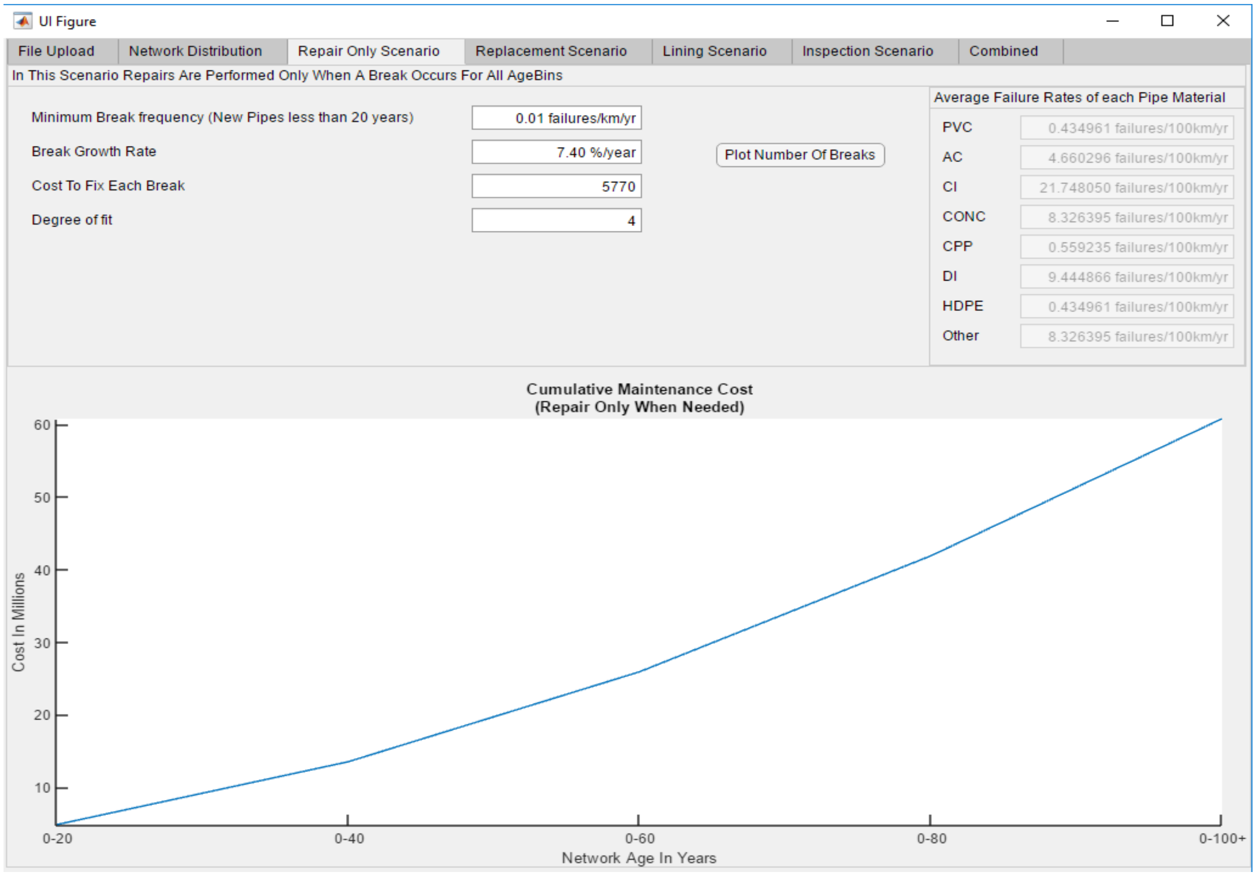
Figure C1: Shows network distribution by tool of the hypothetical distribution network



```
AssetDist(2,:) = RowBin2(1,:); %Initial Pipe Distribution
for u = 2:app.NumberBin
    AssetDist(u,end) = AssetDist(u,end) + AssetDist(u,end-1);
    for k = app.NumberBin-1:-1:2
        AssetDist(u,k) = AssetDist(u,k-1);
    end
    AssetDist(u,1) = 0;
    AssetDist(u+1,:) = AssetDist(u,:); %Initial Pipe Distribution
end
AssetDist(end,:) = []; % removes extra row
MinBreakfreq = app.MinimumBreakfrequencyNewPipeslessthan20yearsEditField.Value;
AgeofPipes = app.A(:,5);
for i = 2:app.NumberBin
    AgeofPipes(AgeofPipes>100)=100;
    AgeofPipes(:,i) = AgeofPipes(:,i-1)+WidthofBin;
end
AgeofPipes(AgeofPipes>100)=100;
for i = 1:app.NumberBin
    Agedist = AgeofPipes(:,i);
    for j = 1:app.NumberBin
            B{i,j} = Agedist(Agedist <= WidthofBin*(j) & Agedist > WidthofBin*(j-1));
            BreakDist{i,j} = MinBreakfreq*exp(GrowthRate*B{i,j});
            Breakfreqcell{i,j} = mean(BreakDist{i,j});
    end
end
Breakfreq = cell2mat(Breakfreqcell);
Breakfreq = Breakfreq'/1000;%1000 to convert to meters
Breakfreq(isnan(Breakfreq))=0;
SegmentLength = app.SegmentL;

for i = 1:app.NumberBin
    TotalBreaks(i) = AssetDist(i,:)*Breakfreq(:,i)*WidthofBin*SegmentLength; % Number of Breaks in system in next 20 years
end
Cost = BreakCost*TotalBreaks; % Costs for repair for next 100 years
app.GlobalAssetDist = AssetDist;
%%%%%%%%%%%%%%%%Cummulative Costs%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
RepairCost(app.NumberBin) = 0;
RepairCost(1) = Cost(1);
for i = 2:app.NumberBin
    RepairCost(i) = Cost(i) + RepairCost(i-1);
end
RepairCost = RepairCost/1E6;
app.GlobalRepairCost = RepairCost;
```

Figure C2: Programming code for fix upon break cost model



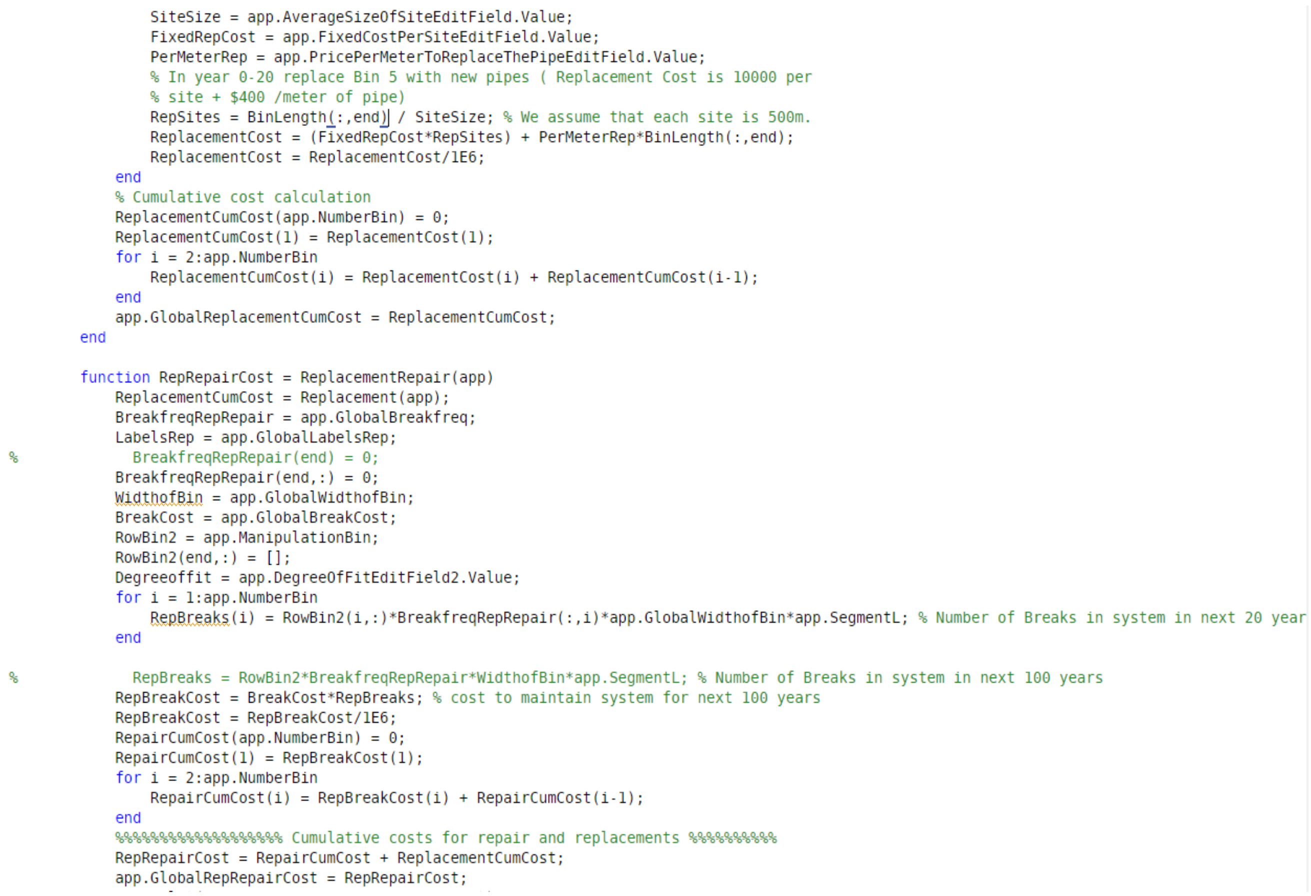
In This Scenario Repairs Are Performed Only When A Break Occurs For All AgeBins

Minimum Break frequency (New Pipes less than 20 years): 0.01 failures/km/yr
Break Growth Rate: 7.40 %/year
Cost To Fix Each Break: 5770
Degree of fit: 4

Average Failure Rates of each Pipe Material

PVC	0.434961 failures/100km/yr
AC	4.660296 failures/100km/yr
CI	21.748050 failures/100km/yr
CONC	8.326395 failures/100km/yr
CPP	0.559235 failures/100km/yr
DI	9.444866 failures/100km/yr
HDPE	0.434961 failures/100km/yr
Other	8.326395 failures/100km/yr

Figure C3: Cumulative cost estimation of fix upon break cost model by LCE tool



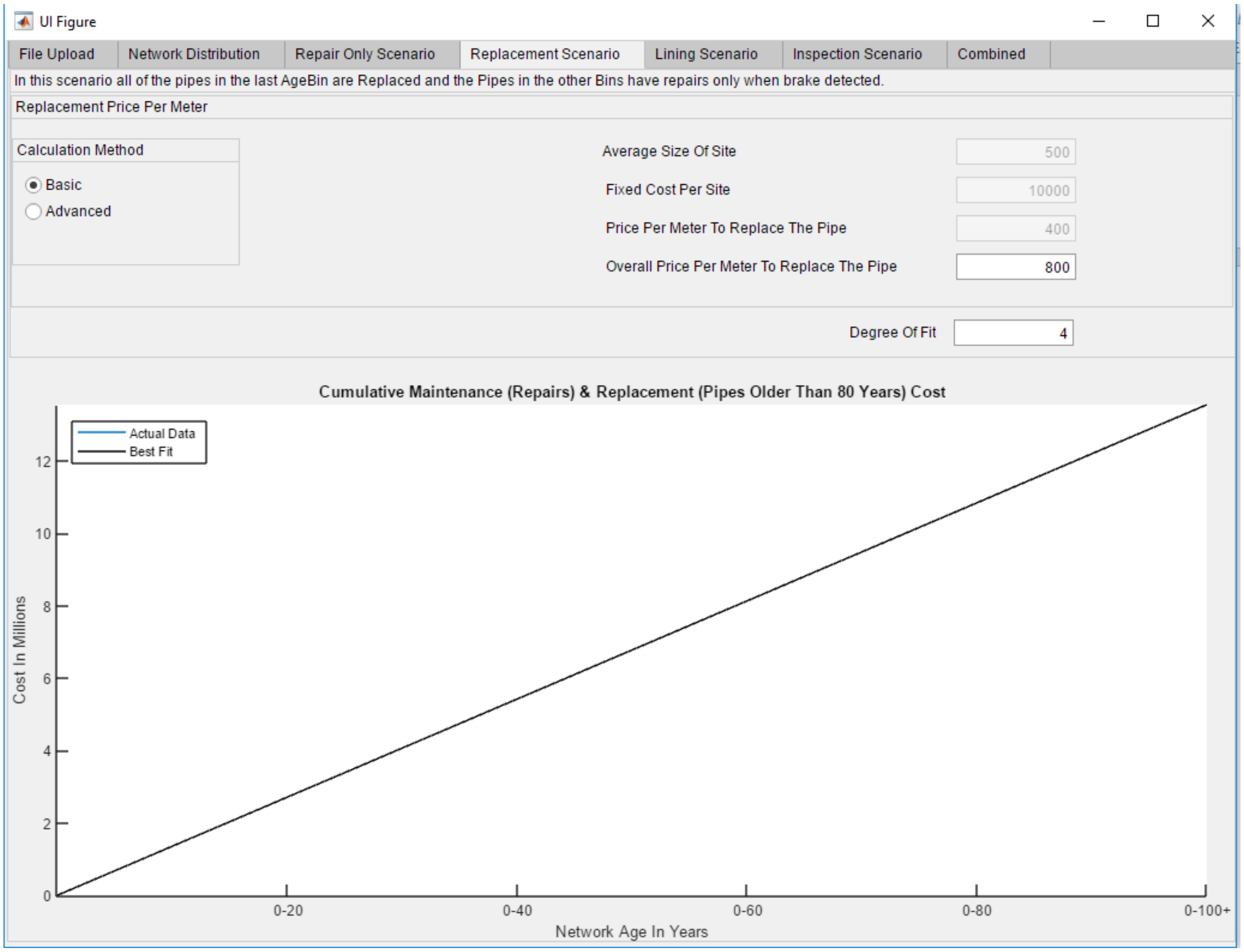
```
            SiteSize = app.AverageSizeOfSiteEditField.Value;
            FixedRepCost = app.FixedCostPerSiteEditField.Value;
            PerMeterRep = app.PricePerMeterToReplaceThePipeEditField.Value;
            % In year 0-20 replace Bin 5 with new pipes ( Replacement Cost is 10000 per
            % site + $400 /meter of pipe)
            RepSites = BinLength(:,end) / SiteSize; % We assume that each site is 500m.
            ReplacementCost = (FixedRepCost*RepSites) + PerMeterRep*BinLength(:,end);
            ReplacementCost = ReplacementCost/1E6;
        end
        % Cumulative cost calculation
        ReplacementCumCost(app.NumberBin) = 0;
        ReplacementCumCost(1) = ReplacementCost(1);
        for i = 2:app.NumberBin
            ReplacementCumCost(i) = ReplacementCost(i) + ReplacementCumCost(i-1);
        end
        app.GlobalReplacementCumCost = ReplacementCumCost;
    end

    function RepRepairCost = ReplacementRepair(app)
        ReplacementCumCost = Replacement(app);
        BreakfreqRepRepair = app.GlobalBreakfreq;
        LabelsRep = app.GlobalLabelsRep;
%         BreakfreqRepRepair(end) = 0;
        BreakfreqRepRepair(end,:) = 0;
        WidthofBin = app.GlobalWidthofBin;
        BreakCost = app.GlobalBreakCost;
        RowBin2 = app.ManipulationBin;
        RowBin2(end,:) = [];
        Degreeoffit = app.DegreeOfFitEditField2.Value;
        for i = 1:app.NumberBin
            RepBreaks(i) = RowBin2(i,:)*BreakfreqRepRepair(:,i)*app.GlobalWidthofBin*app.SegmentL; % Number of Breaks in system in next 20 year

        end

%         RepBreaks = RowBin2*BreakfreqRepRepair*WidthofBin*app.SegmentL; % Number of Breaks in system in next 100 years
        RepBreakCost = BreakCost*RepBreaks; % cost to maintain system for next 100 years
        RepBreakCost = RepBreakCost/1E6;
        RepairCumCost(app.NumberBin) = 0;
        RepairCumCost(1) = RepBreakCost(1);
        for i = 2:app.NumberBin
            RepairCumCost(i) = RepBreakCost(i) + RepairCumCost(i-1);
        end
        %%%%%%%%%%%%%%%%%%% Cumulative costs for repair and replacements %%%%%%%%%%
        RepRepairCost = RepairCumCost + ReplacementCumCost;
        app.GlobalRepRepairCost = RepRepairCost;
```

Figure C4: Programming code for Basic Replacement cost model



In this scenario all of the pipes in the last AgeBin are Replaced and the Pipes in the other Bins have repairs only when brake detected.

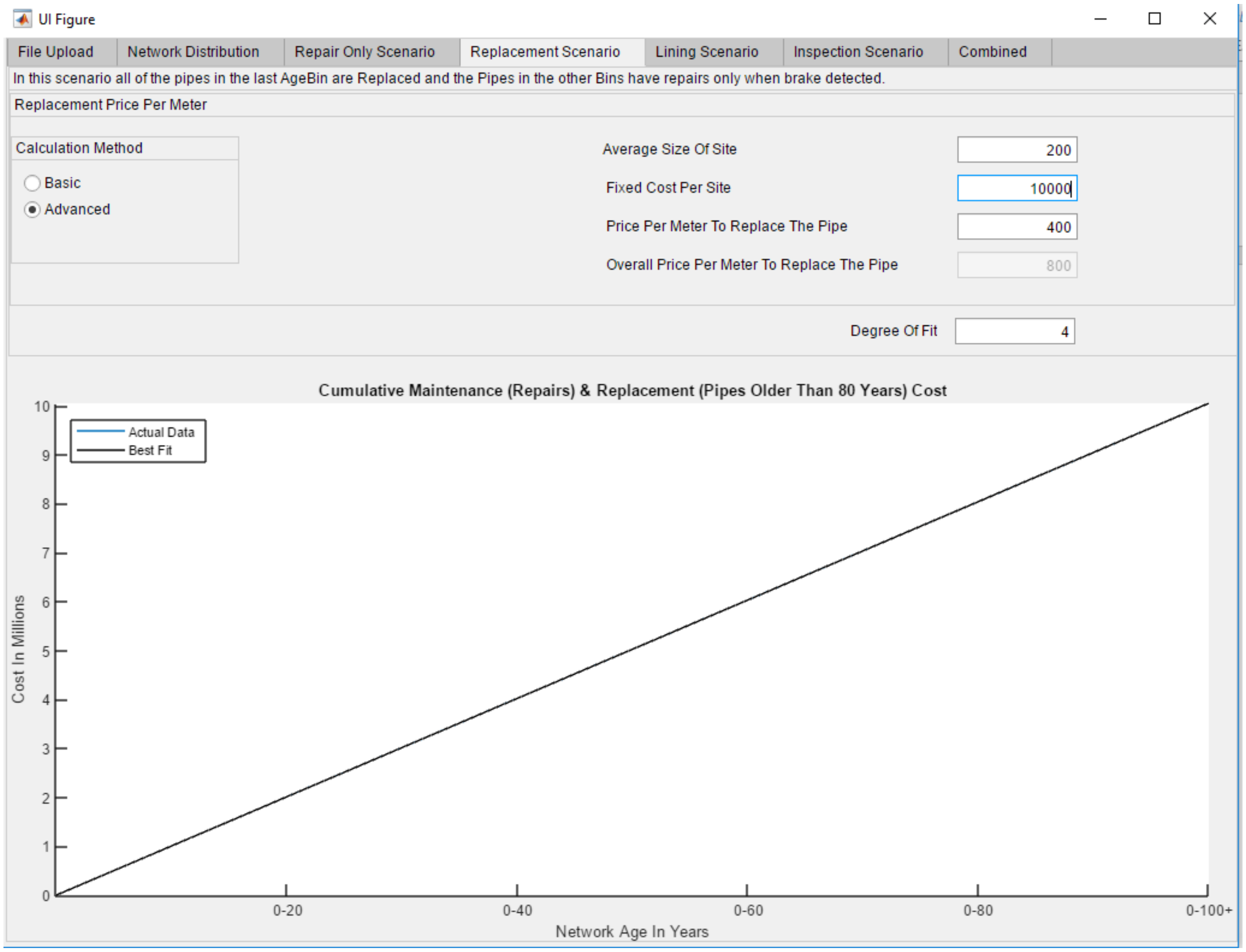
Replacement Price Per Meter

Calculation Method
● Basic
○ Advanced

Average Size Of Site: 500
Fixed Cost Per Site: 10000
Price Per Meter To Replace The Pipe: 400
Overall Price Per Meter To Replace The Pipe: 800

Degree Of Fit: 4

Figure C1: Cumulative cost estimation of Basic Replacement cost model by LCE tool



In this scenario all of the pipes in the last AgeBin are Replaced and the Pipes in the other Bins have repairs only when brake detected.

Replacement Price Per Meter

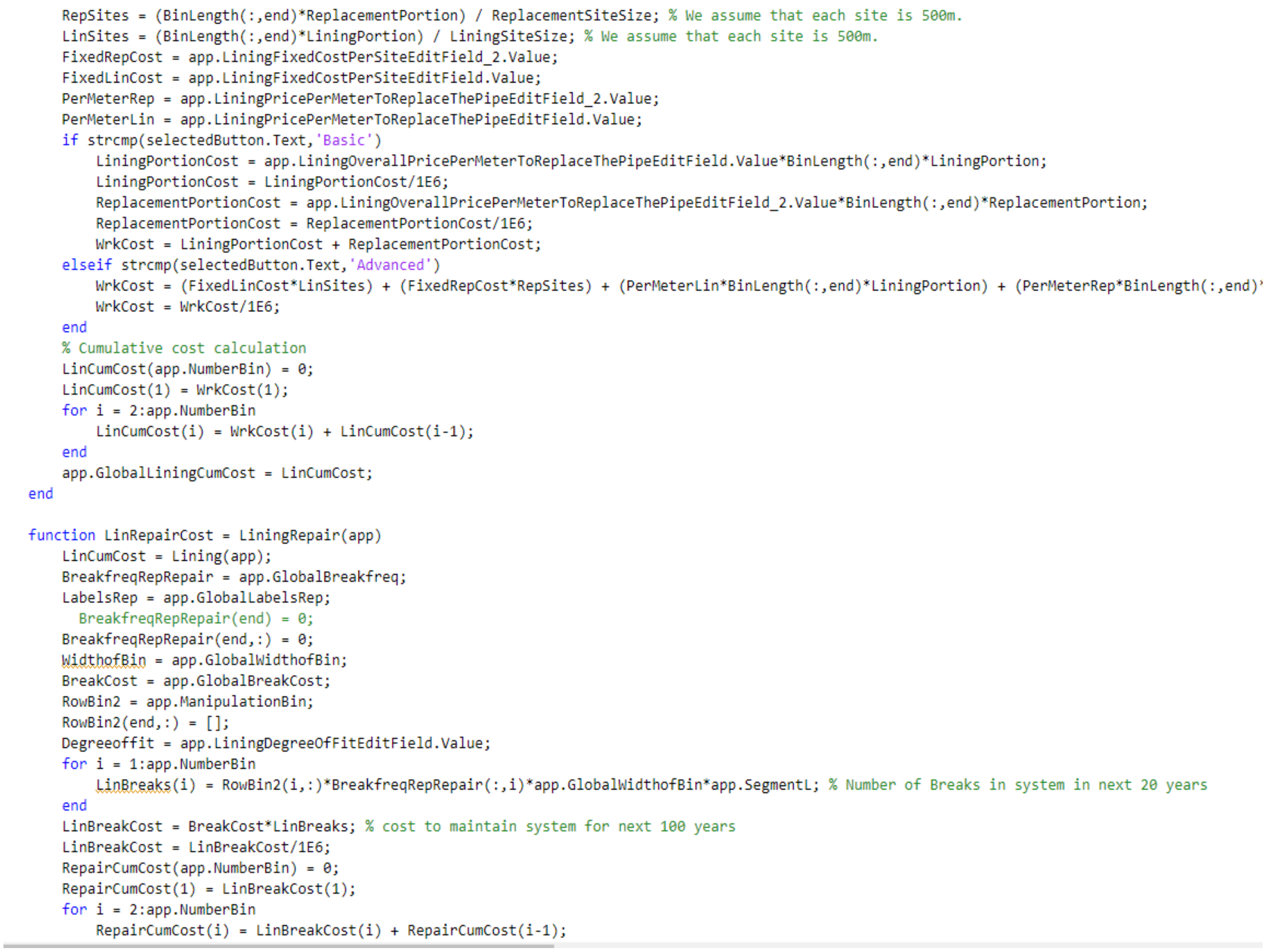
Calculation Method

○ Basic
● Advanced

Average Size Of Site: 200
Fixed Cost Per Site: 10000
Price Per Meter To Replace The Pipe: 400
Overall Price Per Meter To Replace The Pipe: 800

Degree Of Fit: 4

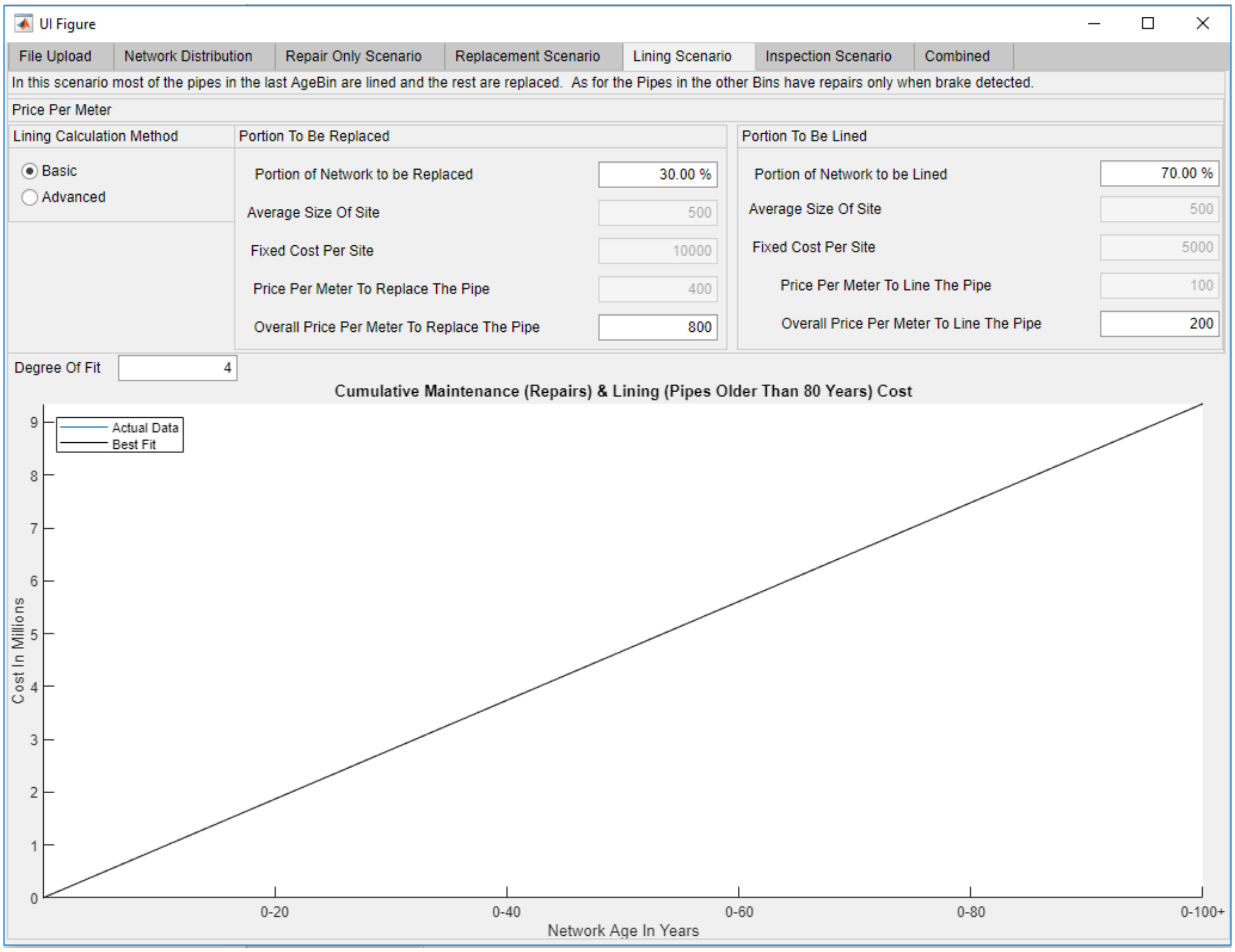
Figure C2: Cumulative cost estimation of Advancement Replacement cost model by LCE tool



```
        RepSites = (BinLength(:,end)*ReplacementPortion) / ReplacementSiteSize; % We assume that each site is 500m.
        LinSites = (BinLength(:,end)*LiningPortion) / LiningSiteSize; % We assume that each site is 500m.
        FixedRepCost = app.LiningFixedCostPerSiteEditField_2.Value;
        FixedLinCost = app.LiningFixedCostPerSiteEditField.Value;
        PerMeterRep = app.LiningPricePerMeterToReplaceThePipeEditField_2.Value;
        PerMeterLin = app.LiningPricePerMeterToReplaceThePipeEditField.Value;
        if strcmp(selectedButton.Text,'Basic')
            LiningPortionCost = app.LiningOverallPricePerMeterToReplaceThePipeEditField.Value*BinLength(:,end)*LiningPortion;
            LiningPortionCost = LiningPortionCost/1E6;
            ReplacementPortionCost = app.LiningOverallPricePerMeterToReplaceThePipeEditField_2.Value*BinLength(:,end)*ReplacementPortion;
            ReplacementPortionCost = ReplacementPortionCost/1E6;
            WrkCost = LiningPortionCost + ReplacementPortionCost;
        elseif strcmp(selectedButton.Text,'Advanced')
            WrkCost = (FixedLinCost*LinSites) + (FixedRepCost*RepSites) + (PerMeterLin*BinLength(:,end)*LiningPortion) + (PerMeterRep*BinLength(:,end)
            WrkCost = WrkCost/1E6;
        end
        % Cumulative cost calculation
        LinCumCost(app.NumberBin) = 0;
        LinCumCost(1) = WrkCost(1);
        for i = 2:app.NumberBin
            LinCumCost(i) = WrkCost(i) + LinCumCost(i-1);
        end
        app.GlobalLiningCumCost = LinCumCost;
    end

    function LinRepairCost = LiningRepair(app)
        LinCumCost = Lining(app);
        BreakfreqRepRepair = app.GlobalBreakfreq;
        LabelsRep = app.GlobalLabelsRep;
          BreakfreqRepRepair(end) = 0;
        BreakfreqRepRepair(end,:) = 0;
        WidthofBin = app.GlobalWidthofBin;
        BreakCost = app.GlobalBreakCost;
        RowBin2 = app.ManipulationBin;
        RowBin2(end,:) = [];
        Degreeoffit = app.LiningDegreeOfFitEditField.Value;
        for i = 1:app.NumberBin
            LinBreaks(i) = RowBin2(i,:)*BreakfreqRepRepair(:,i)*app.GlobalWidthofBin*app.SegmentL; % Number of Breaks in system in next 20 years
        end
        LinBreakCost = BreakCost*LinBreaks; % cost to maintain system for next 100 years
        LinBreakCost = LinBreakCost/1E6;
        RepairCumCost(app.NumberBin) = 0;
        RepairCumCost(1) = LinBreakCost(1);
        for i = 2:app.NumberBin
            RepairCumCost(i) = LinBreakCost(i) + RepairCumCost(i-1);
```

Figure C3: Programming code for lining cost model



In this scenario most of the pipes in the last AgeBin are lined and the rest are replaced. As for the Pipes in the other Bins have repairs only when brake detected.

Price Per Meter

Lining Calculation Method

● Basic
○ Advanced

Portion To Be Replaced

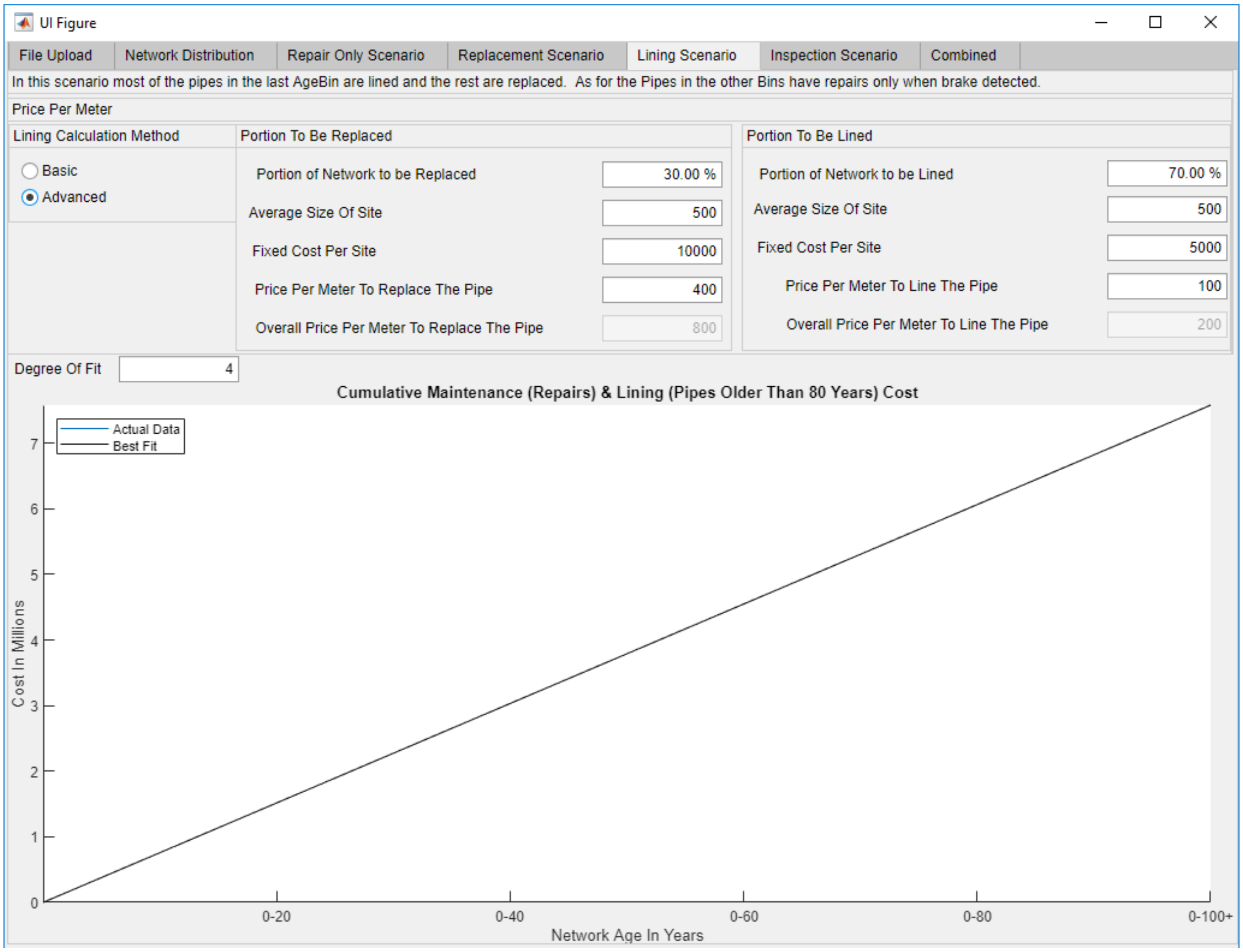
Portion of Network to be Replaced 30.00 %
Average Size Of Site 500
Fixed Cost Per Site 10000
Price Per Meter To Replace The Pipe 400
Overall Price Per Meter To Replace The Pipe 800

Portion To Be Lined

Portion of Network to be Lined 70.00 %
Average Size Of Site 500
Fixed Cost Per Site 5000
Price Per Meter To Line The Pipe 100
Overall Price Per Meter To Line The Pipe 200

Degree Of Fit 4

FIgure C4: Cumulative cost estimation of Basic Lining cost model by LCE tool



In this scenario most of the pipes in the last AgeBin are lined and the rest are replaced. As for the Pipes in the other Bins have repairs only when brake detected.

Price Per Meter

Lining Calculation Method

○ Basic
● Advanced

Portion To Be Replaced

Portion of Network to be Replaced	30.00 %
Average Size Of Site	500
Fixed Cost Per Site	10000
Price Per Meter To Replace The Pipe	400
Overall Price Per Meter To Replace The Pipe	800

Portion To Be Lined

Portion of Network to be Lined	70.00 %
Average Size Of Site	500
Fixed Cost Per Site	5000
Price Per Meter To Line The Pipe	100
Overall Price Per Meter To Line The Pipe	200

Degree Of Fit: 4

Figure C5: Cumulative cost estimation of Advanced Lining cost model by LCE tool