A Framework for Holistic Life Cycle Cost Analysis for Drinking Water Pipelines

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ABSTRACT

Life Cycle Cost Analysis (LCCA) forms an important part of asset management practices and provides an informed decision support. The holistic nature of LCCA includes life cycle assessment (LCA) as an important component alongside economic life cycle cost analysis. The drinking water industry is right now lacking a reliable cost data structure which will ensure that all the utilities capture the same set of cost data. Also, models and tools currently available in the academia and industry are purely deterministic in nature and do not cater to uncertainty in the data. This study provides a framework for a holistic life cycle cost analysis tool which will help drinking water utilities to prioritize the activities and optimize the cost spending of the utility. The methodology includes the development of a cost data structure, a life cycle cost analysis and a life cycle assessment model in the form of an excel spreadsheet. The LCCA model has the capability to compare different pipe materials, installation, condition assessment, rehabilitation and replacement technologies. Whereas, LCA model can compare different pipe materials based on greenhouse gas emissions calculations. The final step of the methodology includes piloting the model with data from utility A. The analysis has been shown in the form of three case studies - comparison of two pipe materials, two pipe installation technologies and two pipe rehabilitation technologies. The case studies provide results in the form of comparison of total life cycle costs for different alternatives and hence a better alternative can be chosen.

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GENERAL AUDIENCE ABSTRACT

The drinking water industry is right now lacking a reliable cost data structure which will ensure that all the utilities capture the same set of cost data. Also, models and tools currently available in the academia and industry do not cater to uncertainty in the data. This study provides a framework for a holistic life cycle cost analysis tool which will help drinking water utilities to prioritize the activities and optimize the cost spending of the utility. The methodology includes the development of a cost data structure, a life cycle cost analysis and a life cycle assessment model in the form of an excel spreadsheet. The LCCA model has the capability to compare different pipe materials, installation, condition assessment, rehabilitation and replacement technologies. Whereas, LCA model can compare different pipe materials based on greenhouse gas emissions calculations. The final step of the methodology includes piloting the model with data from utility A. The analysis has been shown in the form of three case studies - comparison of two pipe materials, two pipe installation technologies and two pipe rehabilitation technologies. The case studies provide results in the form of comparison of total life cycle costs for different alternatives and hence a better alternative can be chosen.

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Acronyms and Abbreviations

AASHTO	American Association of State Highway Officials
AC	Asbestos Cement
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Materials
AWWA	American Water Works Association
BCA	Benefit Cost Analysis
BLCC	Building Life Cycle Cost
CCTV	Closed-circuit Television
CI	Cast Iron
CIP	Capital Improvements Program
CIPP	Cured in Place Pipe
CMMS	Computerized Maintenance Management System
COF	Consequence of Failure
DI	Ductile Iron
DOT	Department of Transportation
EIO	Economic Input Output
EM	Electromagnetic
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
FHA	Federal Highway Administration
FRP	Fiberglass Reinforced Pipe
GIS	Geographic Information System
HDD	Horizontal Directional Drilling
HDPE	High Density Polyethylene
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LOS	Level of Service

NASSCO	National Association of Sewer Service Companies
NIST	National Institute of Standards and Technology
NPV	Net Present Value
O&M	Operations and Maintenance
PACP	Pipeline Assessment and Certification Program
PCCP	Pre stressed Concrete Cylinder Pipe
PCR	Product Category Rule
PE	Polyethylene
PIPEiD	Pipeline Infrastructure Database
PVC	Poly Vinyl Chloride
RCCP	Reinforced Concrete Cylinder Pipe
RCP	Reinforced Concrete Pipe
SDP	Study Design Parameters
SWIM	Sustainable Water Infrastructure Management
TBL	Triple Bottom Line
USDOT	United States Department of Transportation
USEPA	United States Environmental Protection Agency
WE&RF	Water Environment and Reuse Foundation

Chapter 1 : Introduction and Background

Civil infrastructure forms a major part of the monetary investment in a country and the Drinking Water Industry forms a significant portion of it. Drinking Water Pipeline Infrastructure is crucial to the quality of life as one failure of a water pipeline can affect a large population and disrupts the normal life.

A majority of water pipelines were installed in the early to mid-20th century with a lifespan of 75 to 100 years. Water Pipelines are deteriorating at an ever increasing pace and failure events have become more frequent. The estimated number of water main breaks is close to 240,000 breaks per year in the United States of America (ASCE 2017). American Society of Civil Engineers (ASCE) has graded Drinking Water and Wastewater Infrastructure a D+ in 2017 Report card. Every day, nearly six billion gallons of treated water is lost due to leaking pipes. It will require at least $1 trillion to upgrade the existing water system and to meet the drinking water infrastructure needs of a growing population (ASCE 2017). Therefore, it becomes imperative to completely understand the design requirements and prioritize the cost spending to efficiently utilize our limited funds.

The design and planning requirements of water infrastructure projects are ever involving. Engineers and public officials face the difficult task of designing and managing the water distribution systems to satisfy the future water demands and at the same time limiting the amount of repair and replacement costs (Haas 2012). There has been a paradigm shift in the approach towards handling the pipeline during its lifespan. The approach has changed from a reactive to a proactive one and the efforts have been aimed at extending the life of the pipelines. The Operations and Maintenance phase of the life is the most uncertain one as far as the costs are concerned and this is the area where more attention is now being given.

Water Industry professionals are constantly looking for better ways to understand and capture the true cost of the work including the burden on the water utility, society and the environment. A sound knowledge of the parameters affecting the pipe during its life can enable the decision makers to make cost effective decisions. Drinking Water Pipeline Projects are now being approached in a performance based manner while keeping the whole life cycle in mind (WERF 2013). So, it is becoming more important to consider the whole life cycle of the pipeline rather than just designing it to install. This approach is called Life Cycle Approach which compares different design alternatives by considering all the life cycle phases of the pipe into analysis to choose the cheapest alternative.

1.1. Life Cycle of an Asset

Life Cycle of an asset is generally termed as the life span of the asset starting from the cradle and extending till the grave. It includes phases of life starting from planning and design, to the phase where the asset is in its raw form and then to the phase where the asset gets constructed or installed. These first three stages of life are termed as baseline phases where the asset is getting ready for its service to the society. After the baseline phase, next phase is when the asset performs its regular operations with periodic repairs and rehabilitation. These two phases combined together are termed as Operations and Maintenance phase. The last phase of the life cycle is the phase where the performance of the asset goes below the level of service and it gets disposed of and gets replaced by a new asset. Now, the life cycle gets completed and gets started again. Figure 1-1 below shows a typical life cycle of an asset.

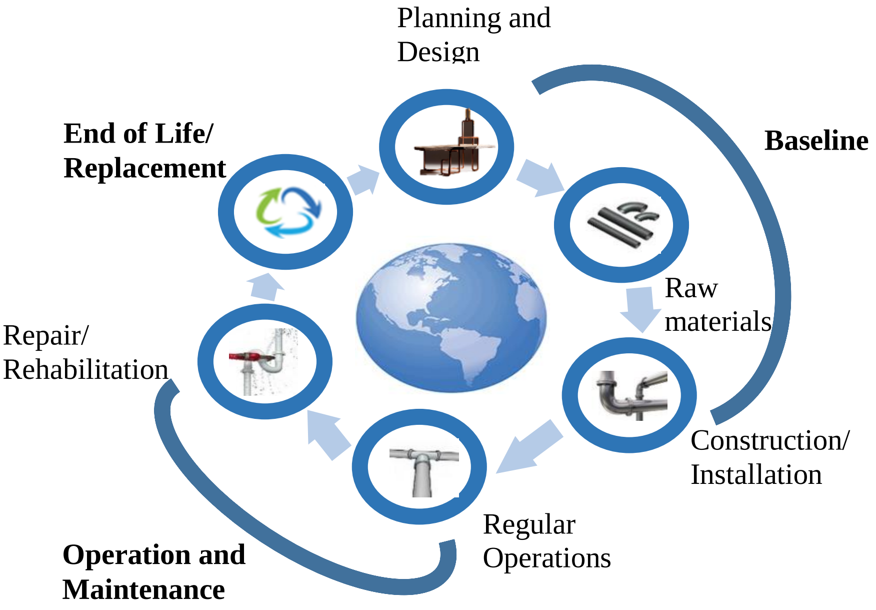


Figure 1-1: Typical Life Cycle of an Asset

1.2. Life Cycle Costs of an Asset

Corresponding to each phase of the asset, there are some costs associated with it. Baseline Phase includes Planning and Design Costs, Manufacturing Costs and Installation Costs. Operation and Maintenance Phase includes Regular Operation Costs and Periodic Repair and Rehabilitation Costs. End of Life Phase includes the cost to replace the asset and disposal of the waste material. Figure 1-2 below shows the different life cycle costs of an asset and the corresponding life cycle phases are shown in bold.

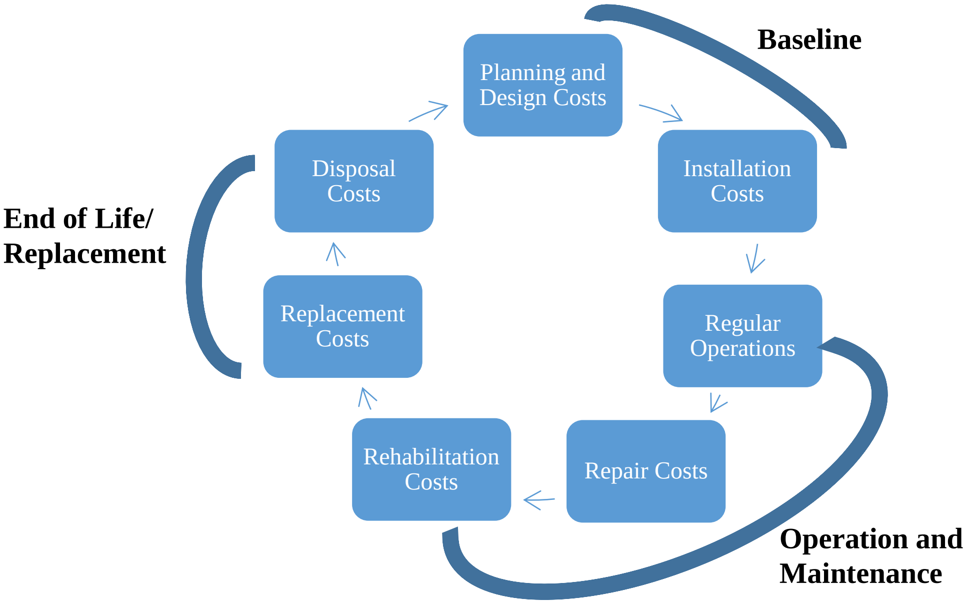


Figure 1-2: Different Life Cycle Costs of an Asset

1.3. Life Cycle Cost Analysis

Life Cycle Cost Analysis (LCCA) is an economic tool used to compare different design alternatives by calculating all the costs incurred during the life span of the asset. For each alternative, economic impacts are calculated over the lifespan of the asset and the cheapest feasible alternative is selected. Life cycle cost analysis can be used for a part of the system or for the whole asset. It provides a better insight into the use of the resources and assists in better decision making. Some of the benefits of life cycle cost analysis are:

- LCCA helps engineers to justify the selection process of an asset or a part of the asset based on the total life cycle costs rather than just the initial purchase price (Korpi and Ala-Risku 2008).

- LCCA benefits the finance team by assuring that all the budget decisions have been made based on the lowest life cycle costs.
- LCCA benefits an organization as a whole with justified staffing levels and budgets, better identification of costs and risks to provide informed rates and avoidance of unfunded mandates (Shankar Kshirsagar et al. 2010).
- Usually the Operation and Maintenance Costs exceed the costs incurred in other phases and is a major contributor towards the total life cycle costs. Therefore, LCCA helps in total cost visibility and identification of life phases with high costs (Barringer and Weber 1996). O&M costs vary significantly between different alternatives depending upon the operational needs. Initial Costs might be less for one alternative but if O&M costs are higher, then it increases the life cycle costs significantly. Figure 1-3 below shows a hypothetical scenario where two different design alternatives are compared. The initial costs and installation costs of Alternative 1 are less than the Alternative 2 which may initially drive the decision towards choosing Alternative 1 as the better option, but the O&M costs for Alternative 1 are higher than the Alternative 2 which makes the total life cycle cost for Alternative 1 higher. Therefore, LCCA helps in better decision making and increases the visibility of costs over the whole lifespan of the asset.

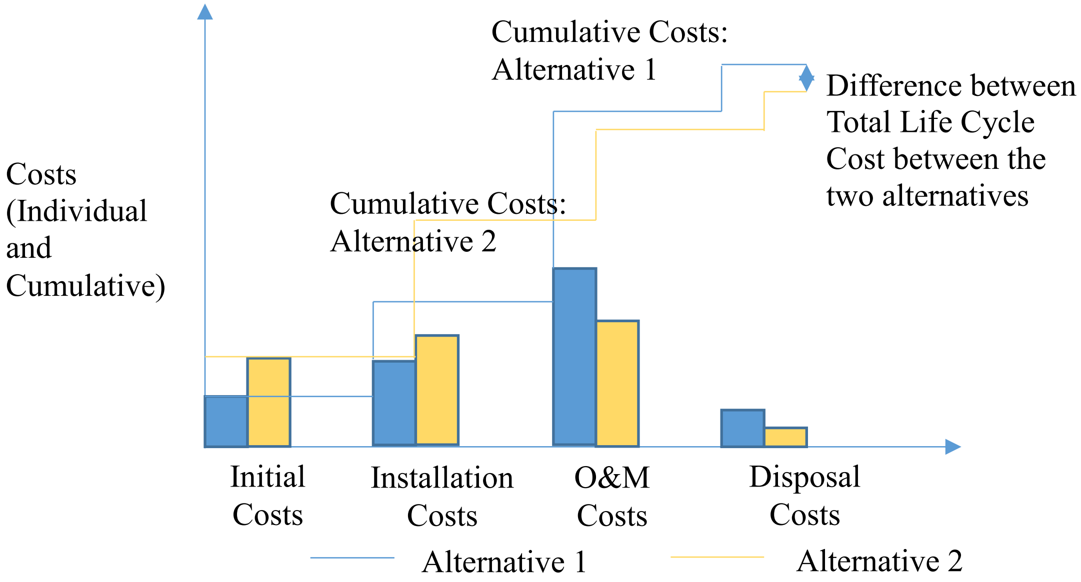


Figure 1-3: Hypothetical Scenario of Cost Comparison of two Design Alternatives

LCCA also provides a better understanding of potential areas where cost savings can be made and hence, provide the structure to track and audit the potential cost savings. This means early identification of potentially high risk areas and subsequent elimination of possible areas of risk (Blanchard 1996).It is estimated that 70-90 percent of the life cycle costs are defined in the design stage of the life and hence there is a potential to reduce the cost risks very early in the life cycle (Lindholm and Suomala 2005). The following Figure 1-4 shows the opportunity available to influence the life cycle costs with respect to different life cycle phases.

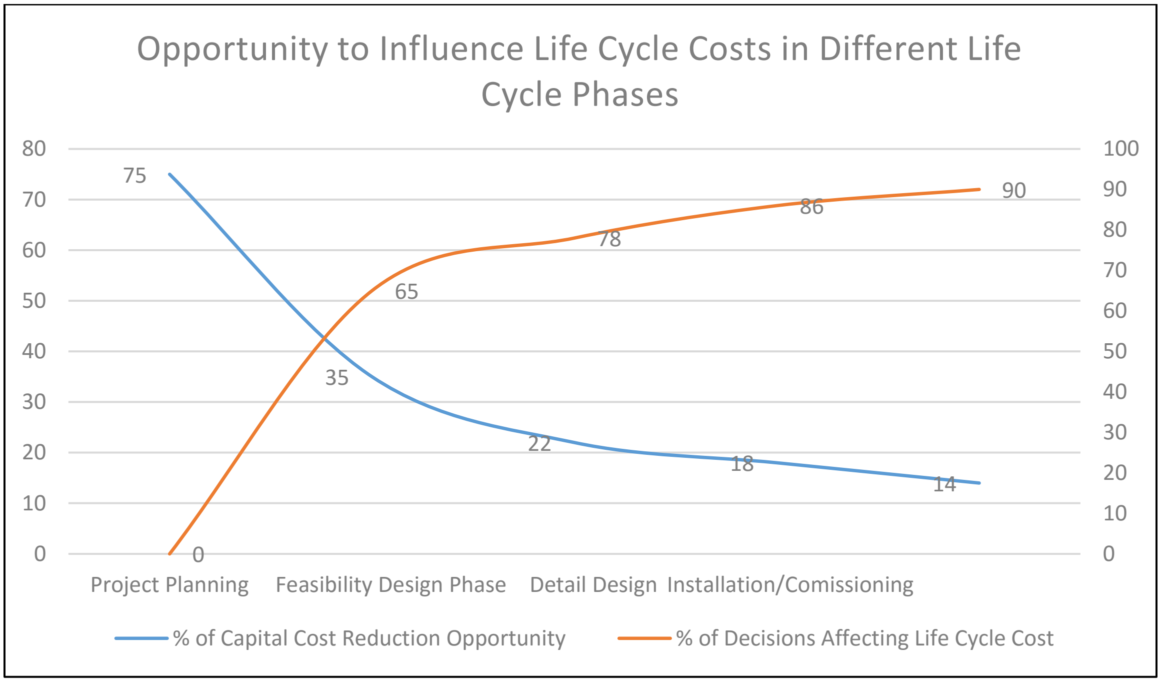


Figure 1-4: Opportunity to Influence Life Cycle Costs (Life Cycle Cost Tool 2011)

Governmental approach generally includes incremental budgeting over the years, but in scenarios of affordability concerns, agencies may restrict increase of budget and continue with last year's amount. In this case, without life cycle costing elements, there is a high probability of decrease of service levels and increase in customer complaints. The limit over the operations budget will only stay for a shorter period of time since there will be premature failures which in turn will increase the capital budgets. Therefore, incremental budgeting should be replaced with proper life cycle cost analysis based budgeting.

1.4. History of Life Cycle Cost Analysis

The concept of life cycle cost analysis was first introduced in the transportation industry in the 1960s. The concept was introduced in the" Red Book", put together by engineering economist, Winfrey and American Association of State Highway Officials (AASHTO). The United States Department of Defense also encouraged the use of life cycle cost analysis in the 1960s. After some initial years, National Cooperative Highway Research Program started a project 20-5 FY 1983 with the aim to promote life cycle cost analysis. The project wanted to document the current state of practice of life cycle cost analysis in the transportation domain and how it can be improved. Life cycle cost analysis got its major endorsement through pavement design guides of 1983 and 1993, where AASHTO recommended the use of LCCA as a tool to carry out economic evaluation and to support better decisions. After the AASHTO design guides, National Highway System (NHS) Designation Act was introduced in 1995 which mandated the states to perform life cycle cost analysis on NHS projects costing $25 million or more. In 1998, a demonstration project titled "Life–Cycle Cost Analysis in Pavement Design" was started by the Federal Highway Administration (FHWA), to advance the applicability of LCCA in State Highway Authorities and developed an instructional LCCA workshop. Also, a technical bulletin describing the best practice of LCCA was published in that year. In the year 2000, life cycle cost analysis came under the charge of the office of asset management within FHWA. Since then, life cycle cost analysis has spread from transportation domain to other industrial and consumer product areas. LCCA has also gained importance at the international level through the introduction of World Bank's evaluation model "Highway Development and Management" (Ozbay et al. 2003).

1.5. Comparison of Life Cycle Cost Analysis and Benefit Cost Analysis

Benefit Cost Analysis (BCA) is an economic tool which calculates the total benefits and costs for different projects and selects the optimal project with the highest benefit to cost ratio. So, it compares different projects which have different benefits during the life span of the project. On the contrary, life cycle cost analysis is used to compare different alternatives which yield almost same level of service and benefits over the life span. Life cycle cost analysis can be considered as a subset of benefit cost analysis.

Benefit Cost Analysis is generally done before selecting a project to decide whether the project is worth undertaking or not. On the other hand, once the project gets selected, life cycle cost analysis is then carried out to compare different alternatives in which the project can be performed in the most cost effective manner. For example, life cycle cost analysis can be used to compare costs of different repair technologies which can be performed for a pipe. So, in summary, life cycle cost analysis is done to compare different alternatives which yield identical benefits unlike benefit cost analysis which compares different alternatives yielding different benefits. Table 1-1 below shows comparison of LCCA and BCA with respect to different project elements (USDOT 2002).

Table 1-1: Comparison of LCCA and BCA with respect to Different Project Elements

Project Element	**LCCA**	**BCA**
Construction, Rehabilitation and Maintenance costs	Yes	Yes
Normal Operation Costs	Yes	Yes
User Benefits Resulting from the Project	No	Yes
Externalities Resulting from the Project	No	Yes

Chapter 2 : Holistic Life Cycle Cost Analysis

Different agencies generally carry out life cycle cost analysis to maximize the economic advantages and often ignore the environmental impacts and long term socio-economic consequences. Life Cycle Assessment is a tool which calculates and compares the environmental impacts of different alternatives and choose the least impacting alternative. Life cycle cost analysis when combined with life cycle assessment provides a holistic approach, which is the right and complete way to carry out cost analysis.

2.1. Different Corporate Accounting Tools

A lot of tools have been developed in the last decade that carry out cost analysis and calculate environmental impacts separately but a holistic tool hasn't been developed till now. Most of these tools cater to a specific domain such as buildings, bridges etc. Table 2-1 below shows description of different accounting tools.

Table 2-1: Different Corporate Accounting Tools (Gluch and Baumann 2004).

Tool	Description
Full Cost Accounting (FCA)	Identifies and quantifies the total life cycle costs of a product, service or an activity
Full Cost Environmental Accounting (FCEA)	Performs the same tasks as FCA but highlights the environmental impacts instead
Total Cost Assessment (TCA)	Is long term and provides a comprehensive financial analysis of total costs and savings of an investment
Life Cycle Assessment (LCA)	Calculates the environmental impacts during the life span
Life Cycle Cost Assessment (LCEA)	Deals with the costing aspect of life cycle assessment and converts the environmental impacts into monetary terms
Life Cycle Costing (LCC)	Sums up the total costs of a product or service over its lifetime and discounts it to the present value.
Life Cycle Cost Analysis (LCCA)	Compares life cycle costs of different alternatives discounted to the present

2.2. Life Cycle Assessment

Life Cycle Assessment (LCA) is defined as a methodology to calculate environmental impacts associated with a product over its lifetime (Vahidi et al. 2016). It interprets the environmental impacts by considering the flows in and out of the environment. Inflows include emissions to air, water and land and outflows include consumption of energy out of the environment. It provides a comprehensive view of the environmental aspects related to a product over its lifespan.

2.2.1. Product Life Cycle for Life Cycle Assessment

A typical birth to death cycle of a product considered for LCA involves following phases:

1. Raw Materials Extraction and Processing
2. Manufacturing to get a Finished Product
3. Transportation
4. Installation
5. Operations and Maintenance (Regular Operations, Repair and Rehabilitation)
6. Recycling and Disposal

Figure 2-1 below shows the product life cycle of a pipe as an example.

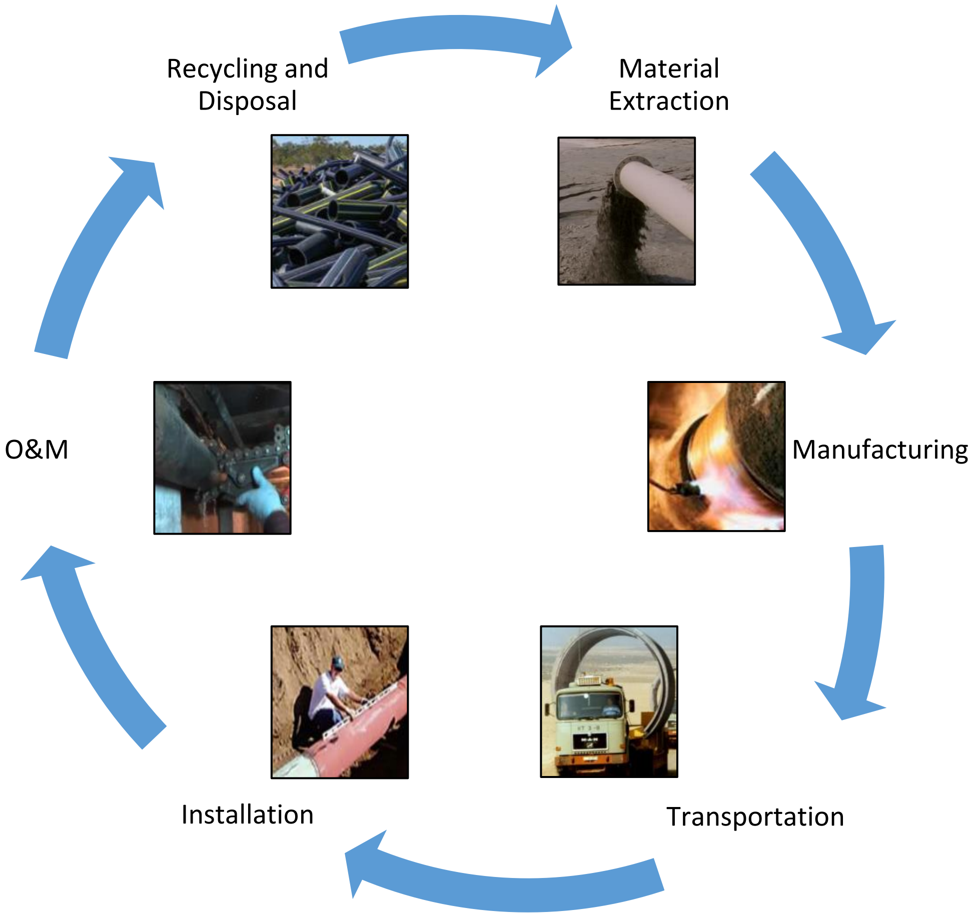


Figure 2-1: Product Life Cycle to carry out LCA

During each of these phases, there are some outflows from the environment in the form of energy and there are some inflows into the environment in the form of emissions and wastes. The emissions include pollutants released into the air such as carbon dioxide and the wastes include solid and liquid wastes such as sewage. Life cycle assessment considers all these inflows and outflows during the life span and calculates the total environmental impacts (Vahidi et al. 2016). Following are the main objectives of life cycle assessment:

- LCA investigates each phase of a product's life cycle for the environmental impacts and identifies the most impacting phases.
- LCA quantifies these environmental impacts and compares the performance of different products.

- LCA can also compare different technologies to manufacture, install and recycle different products and choose the most sustainable technology.

A more detailed explanation of life cycle assessment has been provided in Chapter 4 which discusses the International Organization for Standardization (ISO) framework to carry out life cycle assessment and various impact categories considered for the assessment.

2.3. Difference between LCCA and LCA

There is a lot of confusion between life cycle cost analysis and life cycle assessment due to some similarity between their names but they are functionally very different. Life cycle cost analysis is performed from an economist's perspective to compare the costs of different products during their life span to make cost effective investments or business decisions. On the other hand, life cycle assessment is done from an environmentalist's perspective to choose the most sustainable alternative or product. LCCA and LCA are carried out to answer very different questions (Norris 2001). Table 2-2 below shows the comparison of life cycle cost analysis and life cycle assessment.

Table 2-2: Major Differences between LCCA and LCA

Criteria	**Life Cycle Cost Analysis**	**Life Cycle Assessment**
Purpose	Determines cost effectiveness of different alternatives from an economist's point of view.	Compares environmental performance of different alternatives from sustainability point of view.
Activities Considered	All activities during the life span which have direct and indirect costs associated with them.	All activities during the lifespan which have inflows and outflows from the environment.
Flows considered	Cost and monetary flows	Material and energy flows.
Time treatment and scope	Consideration of timing of costs is crucial since it affects the present value.	Consideration of timing of flows is generally ignored.

2.4. Integrating LCCA and LCA (Holistic Life Cycle Cost Analysis)

It is imperative to integrate life cycle cost analysis and life cycle assessment to carry out a comprehensive and robust cost analysis. This integration will satisfy the economic as well as sustainability considerations. Combining these two is not easy and requires the ability to create and work with probabilistic scenarios in order to capture uncertainties and risks. Without integrating these two, there is a limited relevance of the cost analysis and there is a potential to miss economically important consequences which are environmentally related (Norris 2001).

2.4.1. Triple Bottom Line Analysis

Triple Bottom Line analysis is a new concept of sustainability accountability which is gaining importance nowadays and more companies have started using it. Triple Bottom Line Analysis takes into consideration economic, social and environmental consequences while making business decisions from the perspective of an analyst or a company. Figure 2-2 below shows the concept of triple bottom line analysis in detail.

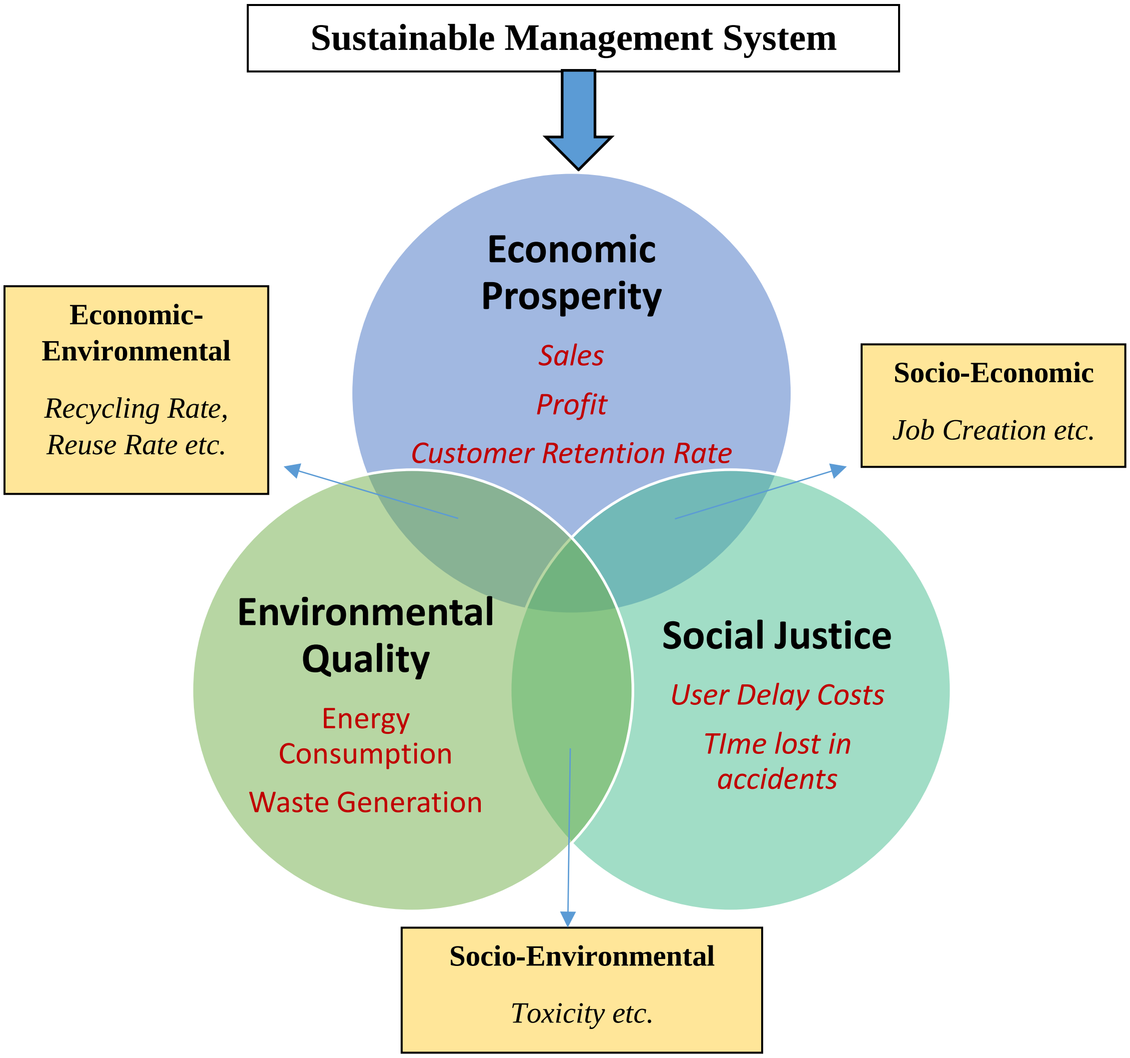


Figure 2-2: Concept of TBL analysis in detail (Wang and Lin 2004)

Chapter 3 : Life Cycle Cost Analysis: Detailed Explanation

This chapter provides background information related to costs calculation, a detailed explanation of life cycle cost analysis and delves into the five steps required to carry out the analysis.

3.1. Analysis Period

The analysis period is the time period for which the life cycle cost analysis is done. Different design alternatives might have different service lives but a common analysis period is considered to compare the costs of different alternatives over a fixed period of time. This enables a comparative analysis of different alternatives. All the activities associated with different alternatives should be considered only during this time period. The analysis might include installation and one repair activity for an alternative and installation and two repair activities for the other alternative. So, different alternatives need not have the same number of repair activities during the analysis period (USDOT 2002).

3.2. Compounding

Compounding is the process where a particular amount of money invested increases over a period of time due to the interest accumulated over the amount invested. This compound growth differs from the linear interest growth because the compounding includes interest accumulation over the interest of the previous year whereas in the linear interest pattern, the interest accumulated is same in each year. Figure 3-1 below illustrates the concept of compounding.

$$\$\boldsymbol{P} = \$\boldsymbol{F} \times (\mathbf{1} + \boldsymbol{r})^{\boldsymbol{n}}$$

Figure 3-1: Concept of Compounding

Where, P is the amount invested today and F is the future amount accumulated after n years at the interest rate of r%. Here $(1+r)^n$ is the compounding factor.

3.3. Discounting

Discounting is the exact opposite of compounding. If we know the amount of cash flows in the future, we can discount them to the present and know their present worth. Costs at different points of time in future cannot be compared and therefore, discounting is applied to consider the opportunity value of time. The Figure 3.2 below illustrates the concept of discounting.

$$\$\boldsymbol{P} = \$\boldsymbol{F}/(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{n}}$$

Figure 3-2: Concept of Discounting

Where, F is the future cash flow after n years and P is the discounted value to the present at the rate of r%. Here $1 / (1+r)^n$ is the discounting factor.

3.3.1. Discount Rate

Discount rate represents the exchange rate between the present and the future. Discount rates are very important for carrying out life cycle cost analysis and it is imperative to choose a reasonable discount rate for the analysis. Its value should reflect the historical trends over long periods of time (USDOT 2002).

3.3.2. Net Present Value

When we have a series of cash flows in the future and we calculate their discounted values to the present, the process is called net present value analysis and the final value calculated is called the net present value (NPV). Net present value can be used to compare different alternatives and choose the best alternative. Higher the net present value, better is the alternative and zero NPV indicates the break-even point for an alternative.

$$\boldsymbol{NPV = \sum_{n=0}^{N} C_n/(1+r)^n}$$

Where, C_n represents the total cost in a particular year n and r is the discount rate assumed.

3.4. Life Cycle Cost Analysis: Five Steps

Life cycle cost analysis is a five step process. It starts with the identification of the design alternatives which need to be compared, determining different activities and their timings for each alternative, estimating costs associated with each of these activities, computing the life cycle costs and finally analyzing the results. These steps have been explained in detail below.

3.4.1. Step 1: Establish Design Alternatives

Once the asset is selected, the first step in carrying out life cycle cost analysis is to select different alternatives which have to be compared. These alternatives can be selected based on the historical trends or agency practices. Also, an appropriate analysis period and discount rate is selected in the first step. The analysis period should at least include the installation and one major repair or rehabilitation for each alternative. The number of rehabilitation activities might differ for different alternatives but the analysis period should include minimum one repair activity for each alternative. At least two different alternatives must be selected which differ in the installation or maintenance activities in economic terms. This step also includes listing down all the activities during the analysis period for each alternative. Typically, activities include planning and design, installation of the asset, regular operations, repair and finally replacement and disposal. Figure 3-3 below shows an example of activities for one design alternative during the analysis period.

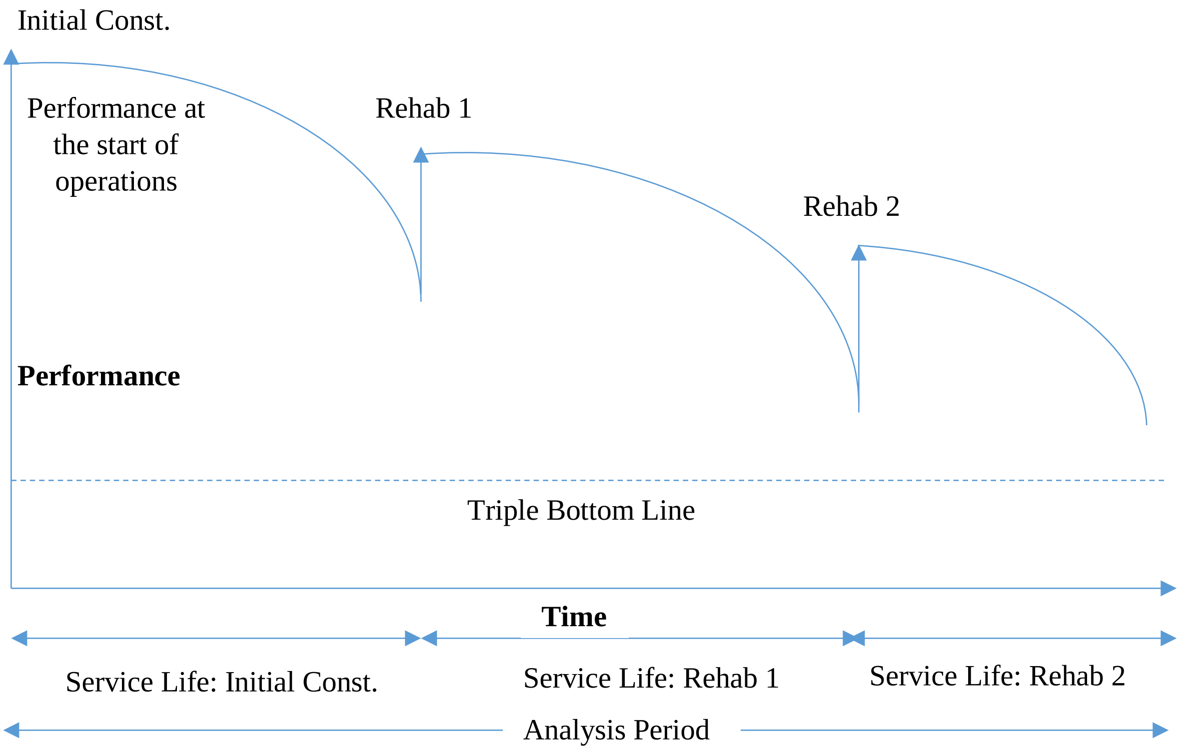


Figure 3-3: Example of Activities for one Design Alternative (USDOT 2002)

3.4.2. Step 2: Determine Activity Timing

This step involves determining the timing of occurrence for all the activities of different alternatives listed in the first step. So, this basically involves developing a maintenance plan with respect to different alternatives. Most of the assets start with a perfect performance level and deteriorate over time and hence need repair and rehabilitation during their lifespan. Different agencies have different levels of minimum performance required i.e. triple bottom line and hence the timings of repair differ with agencies. The timings can be determined by analysis of the utility data with respect to the performance criteria. But, if sufficient data is not available, heuristic knowledge can also be used to determine activity timings. It is very crucial to determine the activity timings correctly since a small change in the timings can affect the life cycle costs majorly.

3.4.3. Step 3: Estimate Costs

After determining the various activities during the life span of the asset and also their timings, the next step is to determine the costs associated with these activities. They can be direct costs such as cost of technology used, labor costs, equipment costs etc. or indirect costs such as delay to the user due to repair activities, noise pollution etc. Direct Costs are easier to collect and store as compared to the indirect costs. Also, it is not necessary to calculate the costs of all the activities mentioned in the maintenance plan. Only those need to be calculated which differ from one alternative to the other and hence create a difference in the life cycle costs. Cost of the activities common to all the alternatives can be ignored.

3.4.4. Step 4: Compute Life Cycle Costs

In the first three steps, different alternatives, all the activities during the analysis period and their timings for all the alternatives and costs associated with all these activities have been determined. The next step is to calculate the life cycle costs. Different types of tools and models are available with respect to life cycle cost calculation and can be divided into three major categories:

1. *Deterministic Approaches*

The deterministic approach includes assigning a fixed value to different inputs and calculating a final output based on that. So, the analyst has to provide initial values to get the final result. It is similar to a hit and trail method where input values are changed several number of times to get the optimal result. Traditionally, applications of life cycle cost analysis have been using only the deterministic approach. This approach doesn’t take into consideration the uncertainty and ambiguity in the data which are inherent to life cycle cost calculations (Christensen et al. 2005). A typical equation to calculate the life cycle costs with the deterministic approach has been provided below (Chen et al. 2004).

$$\mathbf{LCC} = \mathbf{Initial\ Cost} + \sum_{\mathbf{k=1}}^{\mathbf{n}} \mathbf{Future\ Cost} \times \left(\mathbf{1}/(\mathbf{1}+\mathbf{i})^{\mathbf{k}}\right)$$

Where, LCC = net present value of initial cost and any future costs during the analysis period, n discounted at a discount rate of i%.

2. *Probabilistic Approaches*

Probabilistic approaches are different from deterministic approaches since they cater to the uncertainty in the data. The probabilistic programming randomly draws inputs from the probability distributions and use these values to calculate the life cycle costs, unlike the deterministic approach where the inputs are defined by the user. This is an iterative process where all possible combinations of the inputs are considered. This results in a probability distribution of the life cycle costs. The probability distributions of life cycle costs for different alternatives can be compared and the optimal alternative can be selected (Christensen et al. 2005).

3. *Soft Computing Approaches*

Soft Computing Approaches consist of all computational tools which cater to uncertainty and imprecision. The Table 3-1 below shows different soft computing techniques:

Table 3-1: Different Soft Computing Techniques

Artificial Neural Networks	These are basically used for pattern recognition. It can be trained to store information, recognize and make generalizations to do optimization tasks. It requires reliable training pattern information.
Fuzzy Logic Approach	Fuzzy logic includes membership functions and inference rules to predict behavior. Expert knowledge can be used to develop membership function ranges and if and then statements.
Evolutionary Computation	They can be used to tune fuzzy logic systems and train neural networks.

Other soft computing techniques include hybrid systems, chaotic programming and machine learning (Chen et al. 2004).

3.4.5. Step 5: Analyze the results

This step involves the comparison of life cycle costs for different alternatives after they have been calculated in the previous step. The procedure to analyze deterministic and probabilistic results is very different since the final output in the deterministic method is a single value, whereas probabilistic analysis gives a probability distribution.

- Analysis of deterministic results

The most basic analysis of deterministic results is to compare the net present value of different alternatives. But, it doesn’t cater to the uncertainty in the life cycle costs. However, sensitivity analysis can be applied in this case which can reveal which are the most uncertain costs.

- Analysis of probabilistic results

Probabilistic results provide a full range of possible net present value outcomes and also provides the likelihood of a particular scenario. These results assist all types of risk involved in the project. For example, if a user is comfortable with high risk, he can choose an alternative with high net present value and be comfortable with chances of cost overrun (USDOT 2002).

3.5. Performance Based Life Cycle Cost Analysis

Before and during 1960s and 1970s, maintenance of the assets was done only on the need only basis. If only there was a failure or a break reported, the maintenance officials will do the repair activities. The situation got worse when a lot of failures took place and it started costing the utilities a lot more than just repairing the asset. This resulted in the need to properly maintain the asset i.e. to show a proactive approach rather than a reactive approach. So, the bridge and highway departments started proposing asset management plans. But, there were lot of limitations with these plans since they did not consider the uncertainty involved in the asset management process. So, a concept called reliability based bridge management was introduced in which a reliability index was used as a measure of bridge safety, similar to triple bottom line being used currently (Frangopol et al. 2001).

3.6. Fuzzy Logic Based Life Cycle Cost Analysis

Chen et al. 2004 has provided a framework for life cycle cost analysis using fuzzy logic techniques for pavement maintenance and rehabilitation. The study suggests that the uncertainty in the life cycle costs comes from the operations and maintenance phase of the life and hence proposes fuzzy logic approach to develop a robust LCCA tool. It involves comparison of the pavement configuration (structural condition and functional condition) with the minimum allowed performance of the pavement to determine if the priority of repair activities is higher than doing nothing. If repair activities are not required in the current year, then no action is taken and the comparison is again done next year assuming a performance deterioration in that year. If repair activities are needed in the current year, then the cost of repair gets added into the life cycle costs and the structural and functional condition gets updated after that. Next year, the updated performance is again compared with minimum required performance level and the priority is checked. The methodology used has been described in the following Figure 3-4:

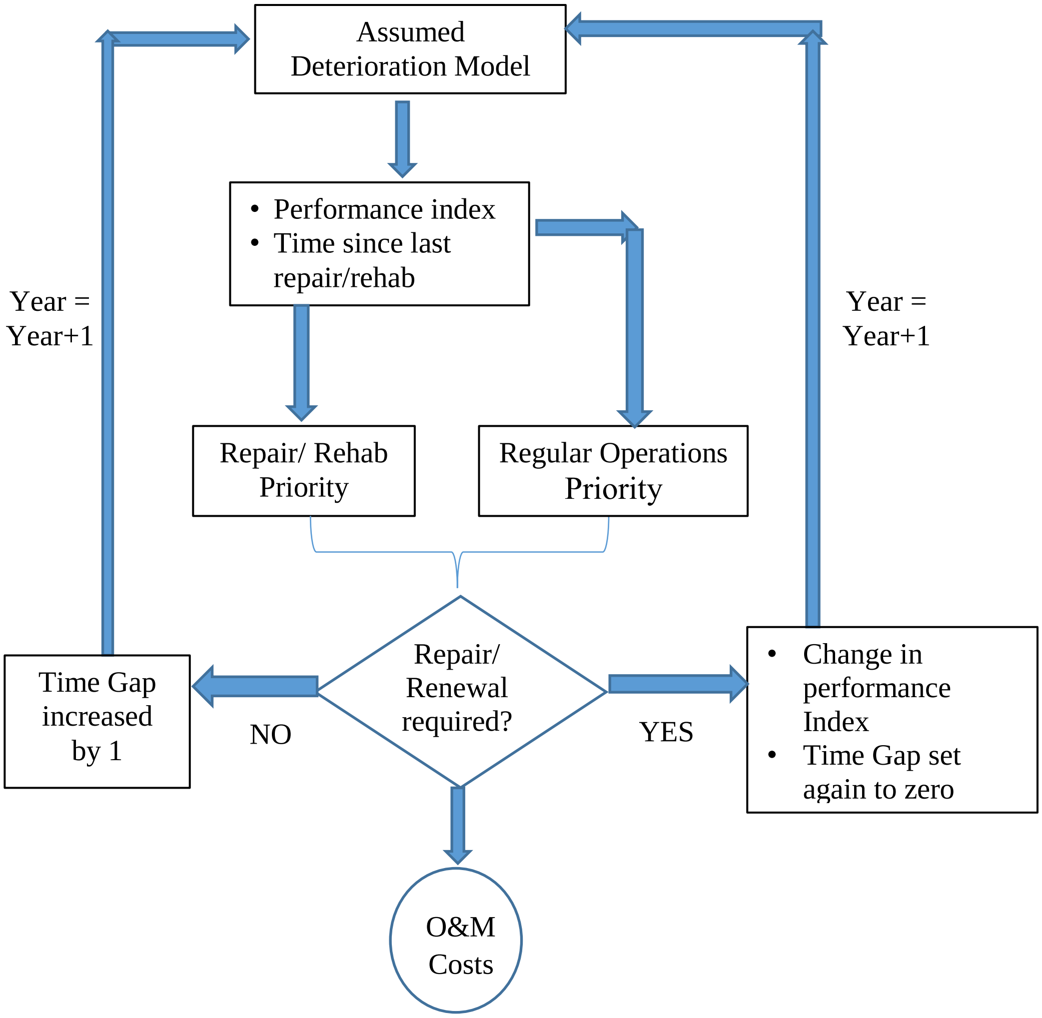


Figure 3-4: Methodology of Fuzzy Logic based Pavement Management System

3.7. A Framework to Calculate Life Cycle Costs and Environmental Impacts for Drinking Water Pipelines (Thomas et al. 2016)

A framework has been provided to calculate the life cycle costs and environmental impacts for drinking water pipelines. It is used to compare life cycle costs for Ductile Iron and PVC pipes. This article's source is a University of Michigan LCA study which is currently being challenged on the assumptions made in the study and the results being favorable towards one pipe material. Some of the main considerations are:

- Life cycle phases considered are pipe material production, installation, operations and maintenance and end of life.
- RS means cost database is used to calculate costs during pipe production and installation phase.
- Pumping costs are considered to be the significant portion of the operating costs.
- LCA component considers the pipe production and operations to be the major contributors of energy requirements.
- This study concludes the ductile iron pipe to be more cost effective and environmentally less impacting as compared to the PVC pipe.

Researchers have made certain assumptions which tend to favor the DI pipes in the results. The authors assumed that the design life of DI and PVC pipes as service life and conduct their analysis for PVC and DI pipes lasting 50 and 100 years in service respectively. In reality, the service life of these assets vary greatly according to structural, operation, maintenance, environmental, and financial factors. The service life of PVC life is more than 100 years (Folkman 2014) and therefore assuming its service life to be 50 years is an incorrect assumption.

The assumption of the head loss being constant for DI pipe throughout the life is an incorrect assumption. Hazen Williams factor and the effective diameter decrease with time due to internal corrosion and tuberculation in the DI pipe. The Figure 3-5 below shows the declining Haze-Williams factor for DI pipe with age. Also, the assumption that cement mortar lining never fails or needs a major repair is an incorrect assumption. Additionally, regular maintenance, condition assessment, rehabilitation, and replacement costs have not been considered while calculating the life cycle costs for these materials.

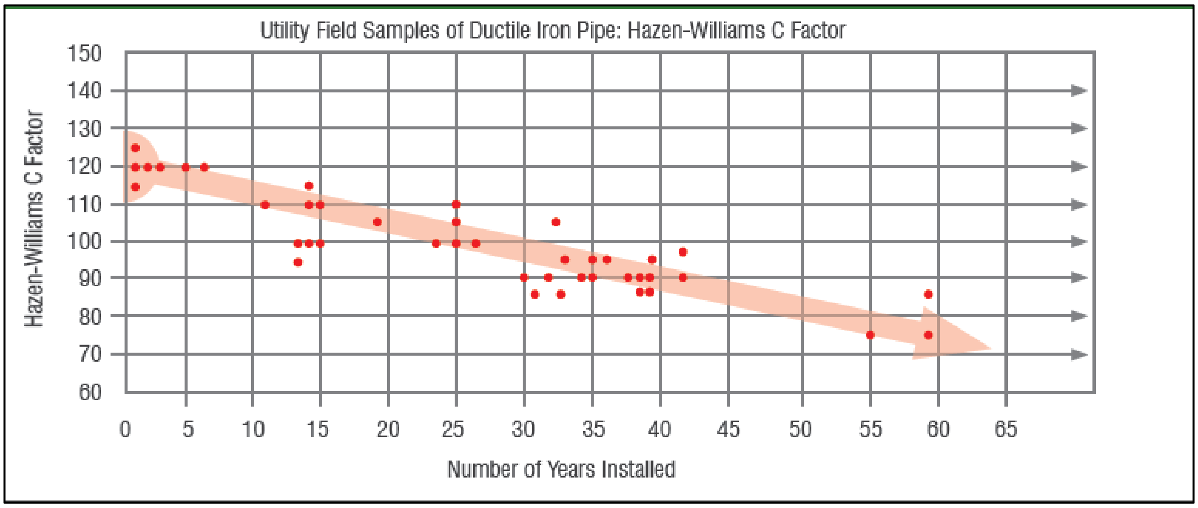


Figure 3-5: Declining Hazen - Williams Factor for DI Pipe with Age (SSC 2017)

Chapter 4 : Life Cycle Assessment: Detailed Explanation

This chapter provides a detailed explanation of ISO's Life Cycle Assessment Framework. ISO's LCA framework is very important which sets the guidelines for carrying out life cycle assessment. Different people performing LCA at the same time might come up with different results and hence this framework is important. But, the guidelines in this framework are not too much restrictive. It helps in setting up the goals and scope of the study, helps in setting up the inventory, provides guidelines on how to do impact assessment and show results. It is up to the user to choose what categories they want to choose to do the assessment. Therefore, the framework helps in making better informed decisions (Matthews et al. 2015). The ISO LCA standard has two parts: ISO 14040 which is the basic overview of LCA and ISO 14044 which includes the guidelines.

4.1. ISO Life Cycle Assessment Framework

The ISO framework consists of four steps: goal and scope definition, inventory analysis, impact assessment and interpretation. Figure 4-1 below shows the ISO LCA framework:

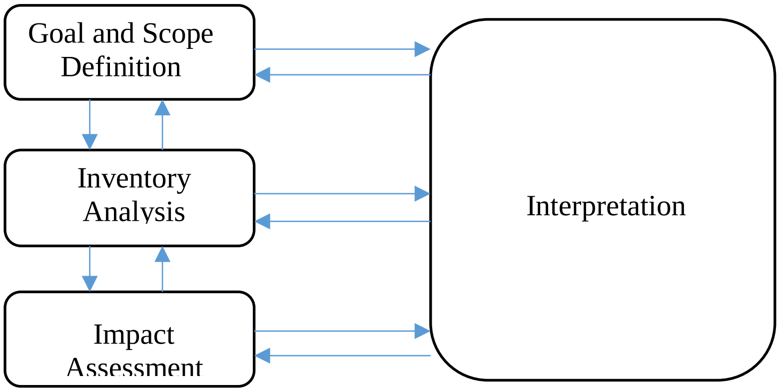


Figure 4-1: ISO LCA Framework

Phase 1: Goal and Scope Definition

The first phase involves qualitatively and quantitatively defining the parameters important for setting up the framework called the Study Design Parameters. These parameters are very important since they define what the study covers and hence should be described carefully. Some of the study design parameters are discussed below:

- Goal of the study

The goal of the study should answer following four questions: what are the reasons for carrying out the study, who is the audience, what is the intended application and whether the results will be used in comparative assertions (SSC 2017).

- Scope Items

The scope is a more detailed description of the qualitative and quantitative information regarding what is included in the study and key parameters included. There are 14 different elements in the scope but the major 4 are listed below (Matthews et al. 2015).

Table 4-1: Four Major Study Design Parameters

Product System	Collection of activities that provide a certain function
Function	Describes what a product system does. For example, the function of a pump is to pump water
System Boundary	Collection of activities which are considered in this study
Functional Unit	It relates the function to the inputs and outputs of the product system. Inputs include energy requirements and outputs include emissions. For example, the functional unit of a pump is 1 mgd of water pumped.

Phase 2: Inventory Input and Output

This phase involves listing down all the inputs and outputs that have to be considered for the system boundary. This is not mentioned clearly in the framework as to what inputs and outputs should be considered and it is left to the user to select on their own.

Phase 3: Impacts Assessment

Different inputs and outputs from the system have been described in the previous phase. This phase involves determining what impacts have to be considered due to these inputs and outputs. For example, greenhouse gas emissions are one type of output and the impacts caused are ozone depletion, global warming etc.

Phase 4: Interpretation of results

The impact assessment results should be carefully analyzed whether they are conforming to the goal and scope defined, system boundary and functional unit considered. Sensitivity analysis can be applied on the results to identify crucial areas where the impact is highest. Also, identifying the areas where the goal and system boundary should be modified for better results.

4.2. Environmental Product Declaration (EPD)

An Environmental Product Declaration is a standardized way of documenting and publishing the life cycle assessment results. These comply with the ISO 14025 standards. EPDs aim at providing a transparent platform to show the environmental impacts of different products. All Environmental Product Guidelines have to comply with Product Category Rule (PCR), a specific set of rules and guidelines for these type of declarations.

4.3. Assessment Methods

There are various Life Cycle Inventory Analysis methodologies that are applicable. The choice of the methodology to be used is user and case specific. These methodologies differ with respect to the impact categories they cover, selection of different indicators and geographical focus. The list of methodologies has been provided below (Lehtinen et al. 2011).

- CML 2002
- Eco-Indicator 99
- Ecological Scarcity Method (Ecopoints 2006)
- EDIP97 and EDIP2003
- EPS 2000
- IMPACT 2002+
- LIME
- LUCAS
- ReCiPe
- TRACI
- MEEuP

One of the methodologies has been discussed below as an example to show various impact categories that are covered under the assessment.

TRACI Impact Assessment Method

Tool for the reduction and assessment of chemical and other environmental impacts (TRACI) has been developed by Environmental Protection Agency (EPA) for sustainability metrics, life cycle assessment etc. to develop more sustainable systems or products (EPA 2012). There are some impact categories described by TRACI which are used for impact assessment stage of life cycle assessment. Some of the impact categories have been mentioned below:

- *Ozone Depletion Potential*

  This category measures the decline of the ozone in the earth's stratosphere. Decrease in the ozone leads to passage of ultraviolet rays to the earth's surface which can lead to skin cancer, cataracts and decrease in the crop yield.

- *Acidification Potential*

  This category measures the conversion of pollutants into acidic substances which can affect the natural environment causing acidified lakes and rivers, damage to forests and buildings.

- *Photochemical Smog Formation*

  This category measures the ground level smog which is formed due to chemical reactions between sunlight, nitrogen oxide and volatile organic compounds. This causes respiratory problems and damage to vegetation.

- *Eutrophication Potential*

  This category measures the increase in the level of nutrients released to the environment. This can lead to oxygen depletion, impacts on water quality affecting aquatic and plant life.

- *Global Warming Potential*

  This category measures the increase in the average earth temperature. The increase in the temperature is due to the release of greenhouse gases into the atmosphere. This can lead to natural disasters and sea level rise.

4.4. Limitations of Life Cycle Assessment

Some of the limitations of life cycle assessment have been mentioned below:

- The life cycle assessment decisions made are generally uncertain. The consequences of the decision might occur a long time after the decisions are made (Gluch and Baumann 2004). The environmental decisions depend upon a lot of external factors such as regulations etc. and these are prone to changes with time.
- Life cycle assessment is a data intensive process and requires good quantitative and qualitative data. It is difficult for the utilities and companies to get hold of such amount and quality of data. Moreover, there is also a lack of industrial standards which limits the use of life cycle assessment.
- There is a lot of conceptual confusion regarding life cycle assessment. Some approaches have similar names but different meanings. This creates a confusion amongst the users (Gluch and Baumann 2004).
- Life cycle assessment results are sometimes prone to decision making in the user's personal benefit.

4.5. Environmental Life Cycle Analysis of Sewer Systems at Purdue University

Vahidi et al. 2016 at Purdue University carried out an environmental life cycle analysis study with the goal to compare different pipe materials for sewer systems. The analysis was done using the SimaPro Software and the functional unit considered was 1 cubic meter of wastewater collected and transported for a period of 50 years. The impact assessment included an Eco Indicator methodology where the results will be compared in terms of eco indicators. Impact categories considered were global warming, eutrophication, carcinogenic, non-carcinogenic, radiation, respiratory effects, ozone depletion, land use, resource depletion and eco toxicity. Four pipe phases were considered in this study: pipe production, transport, installation, and use. Figure 4-2 below shows the results of this study where different pipe materials have been compared.

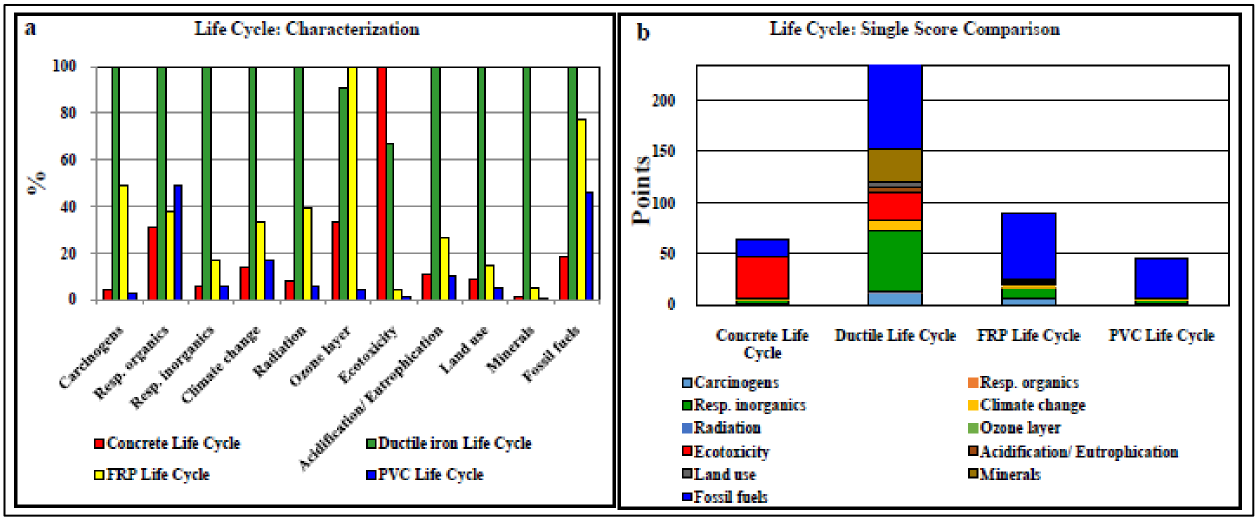


Figure 4-2: Comparison of Different Pipe Materials with respect to Different Impact Categories

Some of the main results of this study are:

- The production phase is the major contributor of the environmental impacts.
- Metallic and plastic pipes contribute most in the fossil fuel category, whereas concrete pipes are major contributor in eco toxicity.
- Ductile Iron pipe has the maximum and PVC pipe has the least environmental impacts.

4.6. LCA Study by Sustainable Solutions Corporation (SSC 2017)

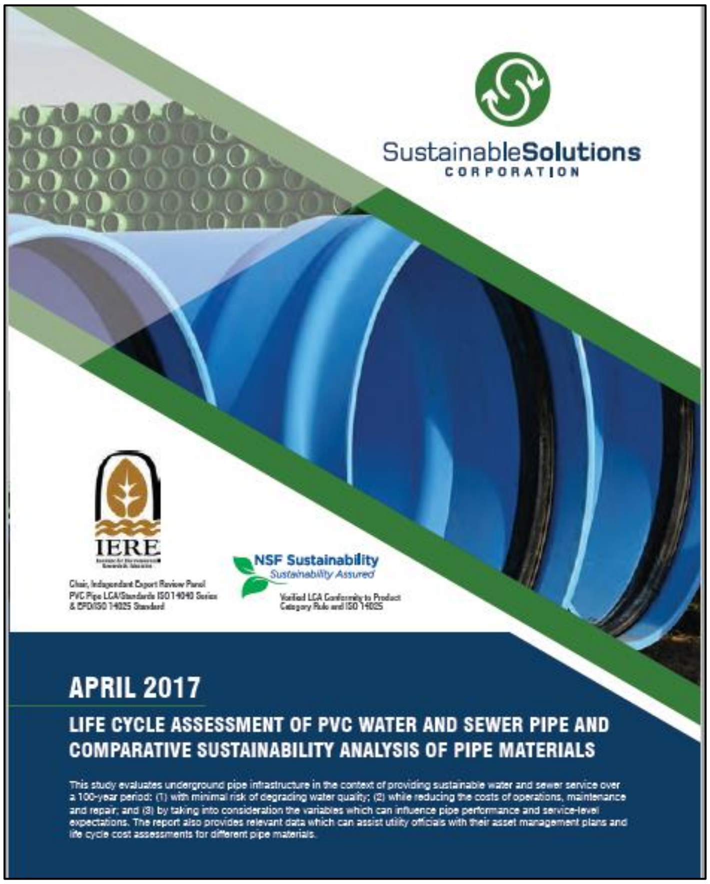
Sustainable Solutions Corporation published a report on a LCA study in 2017 comparing PVC pipe with other pipe materials.

Some of the main points of this study include:

- Seven PVC pipe products were compared.
- Comparison with other pipe materials was done with respect to performance and durability.
- LCA was conducted in accordance with ISO LCA Standard 14040 series.
- The study was peer reviewed to ensure transparency.
- All the life cycle phases were considered to carry out LCA.
- The service life for Ductile Iron and PVC pipe assumed here is 50 years and 100 years respectively.

Some of the key findings include that PVC pipe was found out to be the least environmentally impacting in raw material production and transportation phase, installation, operations and maintenance and end of life phase. Also, this study confirms that PVC pipe is a low initial cost option and provides long-term savings because of its superior pumping efficiency, corrosion resistance and longevity. The only limitation this study possess is the assumption of the service life of Ductile Iron pipe considered to be 50 years which is an incorrect assumption.

The following Figure 4-3 gives a snapshot of the Sustainable Solutions study.



SustainableSolutions
CORPORATION

IERE

Chair, Independent Expert Review Panel
PVC Pipe LCA/Standards ISO 14040 Series
& EPD/ISO 14025 Standard

NSF Sustainability
Sustainability Assured

Verified LCA Conformity to Product
Category Rule and ISO 14025

APRIL 2017

LIFE CYCLE ASSESSMENT OF PVC WATER AND SEWER PIPE AND
COMPARATIVE SUSTAINABILITY ANALYSIS OF PIPE MATERIALS

This study evaluates underground pipe infrastructure in the context of providing sustainable water and sewer service over a 100-year period: (1) with minimal risk of degrading water quality; (2) while reducing the costs of operations, maintenance and repair; and (3) by taking into consideration the variables which can influence pipe performance and service-level expectations. The report also provides relevant data which can assist utility officials with their asset management plans and life cycle cost assessments for different pipe materials.

Figure 4-3: Snapshot of Sustainable Solutions LCA Study

Chapter 5 : Summary of Literature Review

Life cycle cost analysis (LCCA) helps in justifying the selection process of a particular system, product or activity based on the total life cycle cost rather than the initial design and installation cost. It enables a transparent selection process. Life cycle cost analysis helps in the identification of high cost areas during the life cycle of the product and helps in minimizing them. It helps in better understanding of the inter relationships between different system components and cost elements. So, potentially high risk areas are identified early in the life cycle and can be easily mitigated. Attributing costs to each phase in an asset's lifecycle and understanding the full cost to deliver services is important for determining costs for various service levels, maintenance and renewal decision making and rate setting.

Life cycle assessment (LCA) is a tool used to measure the environmental impacts of different products or systems during their life cycle. By measuring the environmental impacts throughout the life cycle, life cycle assessment provides a complete picture related to sustainability and helps in providing true environmental tradeoffs in the product selection. There are a lot of corporate accounting tools available in the market such as full cost accounting, life cycle costing, life cycle assessment etc. but there is a conceptual confusion with respect to all these tools. Some of these tools have different names but perform the same function.

Despite the similarity in their names, life cycle cost analysis and life cycle assessment, perform different functions. These differences arise from the fact that they are designed to provide answers to different questions. Life cycle cost analysis provides justification from the economic point of view to make better investment decisions, whereas life cycle assessment provides justification related to sustainability issues. It is important to integrate both life cycle cost analysis and life cycle assessment to provide a holistic picture to the decision maker. Leaving LCA out of LCCA will result in an inability to capture the relationship between environmental and cost consequences. The holistic approach helps in balancing investment, performance and risk.

Performing either life cycle cost analysis or life cycle assessment is a data intensive process since a lot of complexities are involved in the process. Therefore, appropriate quantity and quality of the data is imperative for an informative life cycle analysis and results.

Types of models from the literature include: deterministic, probabilistic and soft computing. Uncertainty in the life cycle data majorly comes from the operation and maintenance phase and deterministic models do not capture this uncertainty involved in the data. Probabilistic models help in overcoming this uncertainty. A lot of probabilistic models have been proposed in the transportation industry based on performance using fuzzy logic and other soft computing techniques. But, it is very difficult to develop a universal life cycle analysis model applicable to all domains due to different requirements of different industries.

Chapter 6 : Real World Applications

This chapter discusses different real world applications related to life cycle cost analysis and life cycle assessment from transportation and other sectors. The first two applications mentioned are related to LCCA and applicable to pavements and buildings respectively. The last four tools mentioned are related to LCA and applicable to many industries including water industry. Real world examples from the water industry related to LCCA have been explained in Chapter 8.

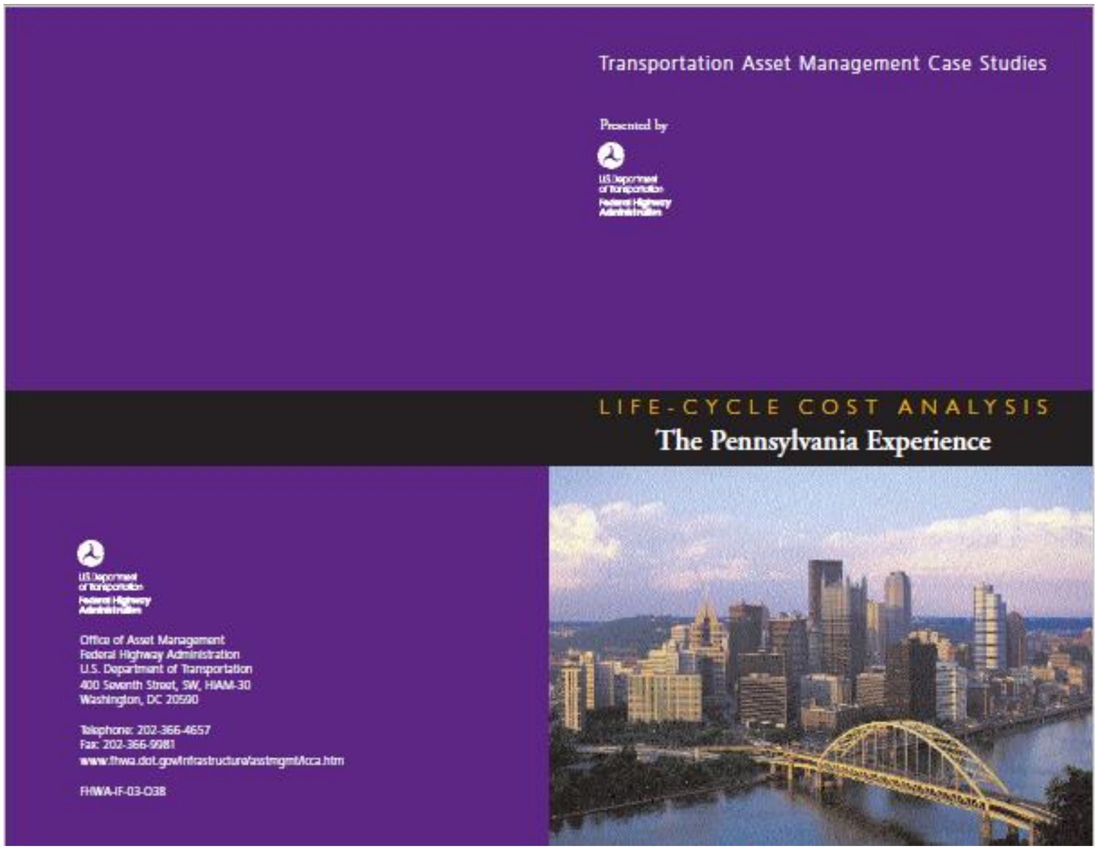
6.1. The Pennsylvania Experience (FHA 2003)

This case study explains how PennDoT employed life cycle cost analysis successfully into their decision making framework. During the late 1970s, there was a steep increase in the rehabilitation spending for the pavements under the jurisdiction of PennDoT and the user delays were mounting up due to the repair activities. Up until now, all the pavements were designed according to American Association of State Highway and Transportation Officials (AASHTO) standards but the selection of the projects was not a standardized process. The selection was generally based upon the initial costs rather than the life cycle costs.

In the mid-1980s, PennDoT identified life cycle cost analysis as a supporting tool for decision making and the selection process. LCCA would ensure selection of least cost alternative as well as considers effects of work zones into analysis. PennDot initiated a policy which required LCCA to be performed for all interstate highway projects with estimated initial costs of more than $1 million and for all the other projects with estimated initial cost greater than $10 million. Further, if an LCCA is required, PennDoT pavement design selection guidelines state that the engineers require to compare at least one bituminous and one Portland cement concrete design alternative for each project. The analysis period was considered to be 40 years. If the difference between the least and the second least cost alternative is greater than 10%, then the least cost alternative is selected. Otherwise, other factors are taken into account to select the alternative.

PennDoT successfully implemented LCCA into its decision making system and found that the pavement performance increased after the implementation of LCCA. Also, PennDoT engineers became more knowledgeable regarding pavement rehabilitation and other maintenance practices rather than just the initial costs. This process set a benchmark for other DOTs to implement LCCA into their system. PennDoT, in the process of implementing LCCA learned that to carry out a reliable LCCA, historical data is the most reliable source of data to carry out LCCA rather than the expert opinion. Also, 10% rule of difference in costs also cater to uncertainty in the life cycle cost data.

The analysis currently done is a deterministic one and PennDoT is currently looking for other analysis methods to take care of uncertainty in the data such as probabilistic methods. Also, the cost structure currently used by PennDoT is not comprehensive and doesn't take into consideration the breakdown of different cost categories which are essential to identify high risk cost elements. Figure 6-1 below shows a snapshot of the PennDoT experience.



Transportation Asset Management Case Studies

Presented by

U.S. Department of Transportation
Federal Highway Administration

LIFE-CYCLE COST ANALYSIS

The Pennsylvania Experience

U.S. Department of Transportation
Federal Highway Administration

Office of Asset Management
Federal Highway Administration
U.S. Department of Transportation
400 Seventh Street, SW, HIAM-30
Washington, DC 20590

Telephone: 202-366-4657
Fax: 202-366-9981
www.fhwa.dot.gov/infrastructure/asstmgmt/lcca.htm

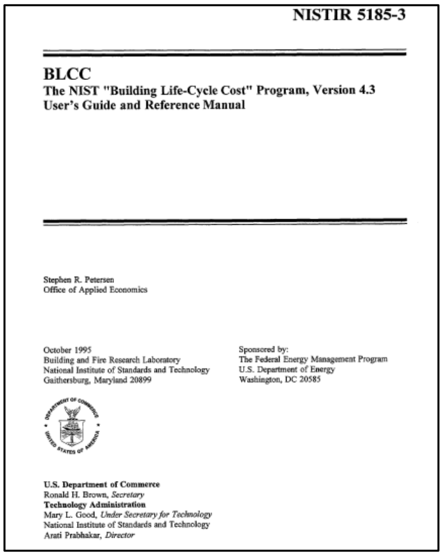
FHWA-IF-03-038

Figure 6-1: Snapshot of PennDoT Experience with LCCA Case Study (FHA 2003)

6.2. NIST’s Building Life Cycle Cost Program

The National Institute of Standards and Technology (NIST) has developed a Building Life Cycle Cost (BLCC) Program which calculates and compares the cost effectiveness of alternative buildings or building related components or systems. It compares the total life cycle costs instead of the initial costs and is more useful for evaluating cost and benefits of energy and water conservation and renewable energy projects. The economic measures such as net savings, savings to investment ratio, adjusted internal rate of return and years to payback can be calculated. BLCC is programmed in Java with an XML file format (Petersen 1995).

The inputs required for the model include project details (name, location, discount rates, base date, service date, analysis period etc.), capital investment details (investment costs, replacement costs and timing, residual values etc.), operating values (regular operation and maintenance costs, energy consumption costs, water consumption costs etc.) and contract values (annual recurring contract payment etc.). The output is a report showing design costs, annual savings and discounted savings for each alternative. Figure 6-2 below shows the snapshot of the BLCC program’s manual by NIST.



NISTIR 5185-3

BLCC
The NIST "Building Life-Cycle Cost" Program, Version 4.3
User’s Guide and Reference Manual

Stephen R. Petersen
Office of Applied Economics

October 1995
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

Sponsored by:
The Federal Energy Management Program
U.S. Department of Energy
Washington, DC 20585

U.S. Department of Commerce
Ronald H. Brown, *Secretary*
Technology Administration
Mary L. Good, *Under Secretary for Technology*
National Institute of Standards and Technology
Arati Prabhakar, *Director*

Figure 6-2: Snapshot of BLCC Manual by NIST (Petersen 1995)

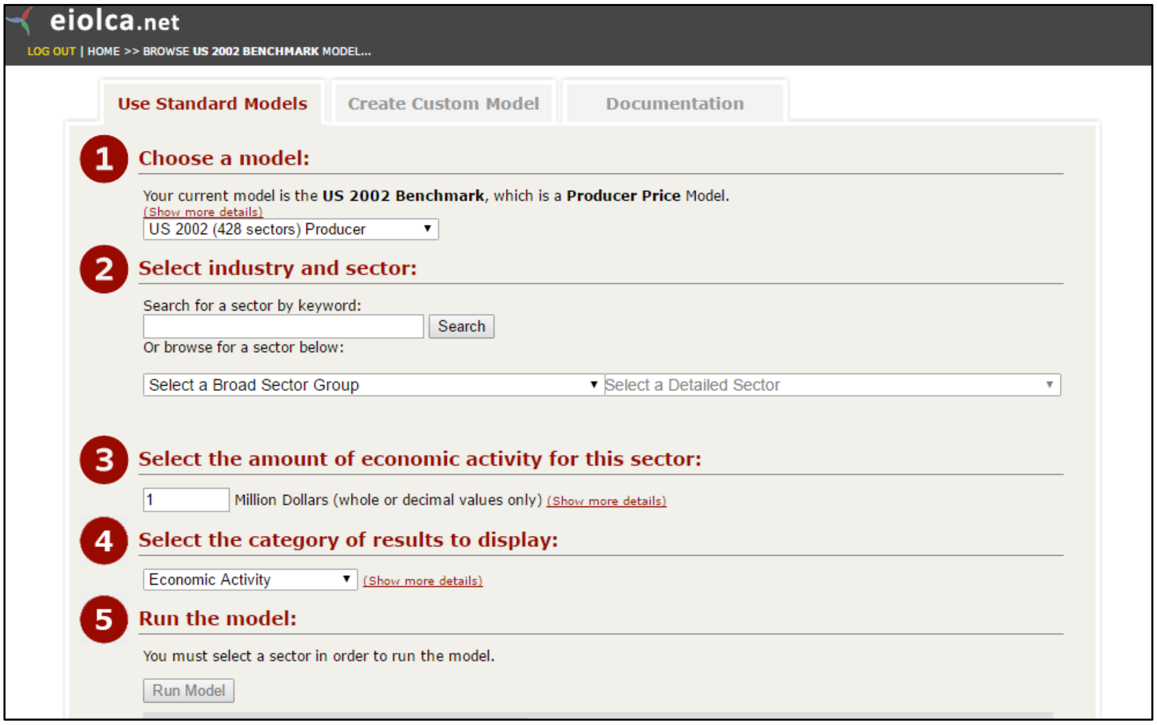
Limitations of BLCC Spreadsheet (Addison 1999)

- Only two energy alternatives are available to compare - electricity and a fuel type (natural gas, LPG etc.)
- Only end of year cost calculation is possible.
- BLCC permits user input for number of years and months for the analysis period but the analysis assumes whole year time steps.

6.3. Economic Input Output (EIO) LCA by Carnegie Mellon University

The Economic Input Output method takes into consideration the monetary transactions between different industries. Inputs of one industry will be the outputs of some other industry. So, it records the flow of inputs and outputs from different industries. For example, inputs of the airplane industry include outputs from tire industry, leather industry, computers (to design) and electricity (to operate) and many more. EIO models are generally represented in a matrix form where different industries are represented in the form of rows and columns and the intersection represents the flow of goods or services from one industry to the other.

The Economic Input Output Life Cycle Assessment tool has been developed by the Green Design Institute at Carnegie Mellon University in 2008. This includes addition of a separate column of environment in the input output matrix and the intersection of different industries in the rows and the environment column represents the pollutants from different industries into the environment. Figure 6-3 below shows a snapshot of the EIO-LCA model.



1 Choose a model:

Your current model is the **US 2002 Benchmark**, which is a **Producer Price** Model.
(Show more details)
US 2002 (428 sectors) Producer

2 Select industry and sector:

Search for a sector by keyword:
Or browse for a sector below:
Select a Broad Sector Group
Select a Detailed Sector

3 Select the amount of economic activity for this sector:

1 Million Dollars (whole or decimal values only) (Show more details)

4 Select the category of results to display:

Economic Activity (Show more details)

5 Run the model:

You must select a sector in order to run the model.

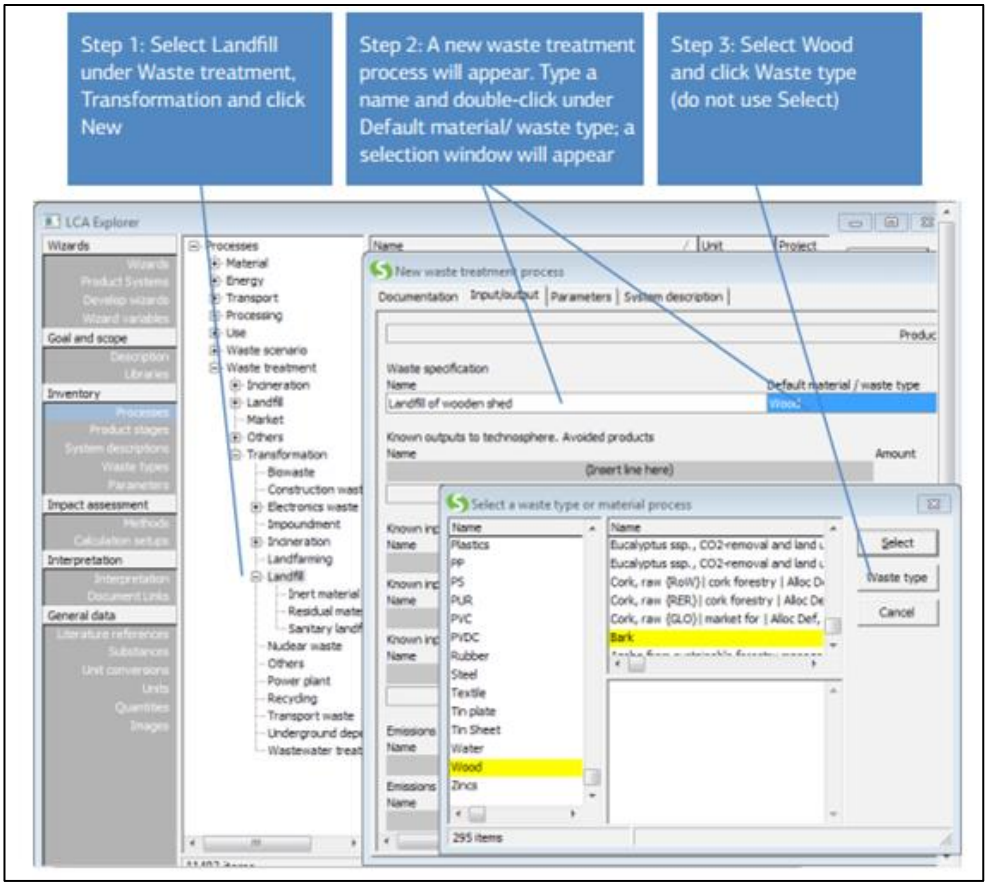
Figure 6-3: EIO-LCA Model by Green Design Institute at Carnegie Mellon University

Limitations of EIO-LCA model

- The model calculates the impacts for an industry sector as a whole but the sector consists of several industry types which differ in their operations. One industry might be having a lot of CO_2 emissions while the other might not have any. So the model is effective in providing effects of the sector as a whole rather than a single industry within that sector.
- The environmental effects considered in the model are limited and hence make the model incomplete.
- This model only creates the inventory of different environmental impacts by calculating flow from one industry to the other but doesn't carry out the impact assessment.

6.4. SimaPro Software

SimaPro software has been developed by Pre Sustainability in the late 1990s and measures environmental impacts of a product or a system. It is available for commercial and educational purposes but licenses have to be purchased. The library provided by SimaPro is a combination of ecoinvent, USLCI and many other databases. The datasets ae very comprehensive and include diverse inputs and outputs. The outputs are majorly divided into three categories, emission to air, water and to soil. A tutorial has also been published by Pre Sustainability which explains how to use SimaPro step by step. Figure 6-4 below shows a snapshot of the Simapro tool in which the inputs are being done in the waste water treatment process. Limitations of SimaPro include the lack of graphical interface, sensitivity analysis and possibly the DOS interface (Menke et al. 1996). Also, purchasing of licenses is required to get access to the software which are not cheap.



Step 1: Select Landfill under Waste treatment, Transformation and click New

Step 2: A new waste treatment process will appear. Type a name and double-click under Default material/ waste type; a selection window will appear

Step 3: Select Wood and click Waste type (do not use Select)

Figure 6-4: Snapshot of SimaPro Software

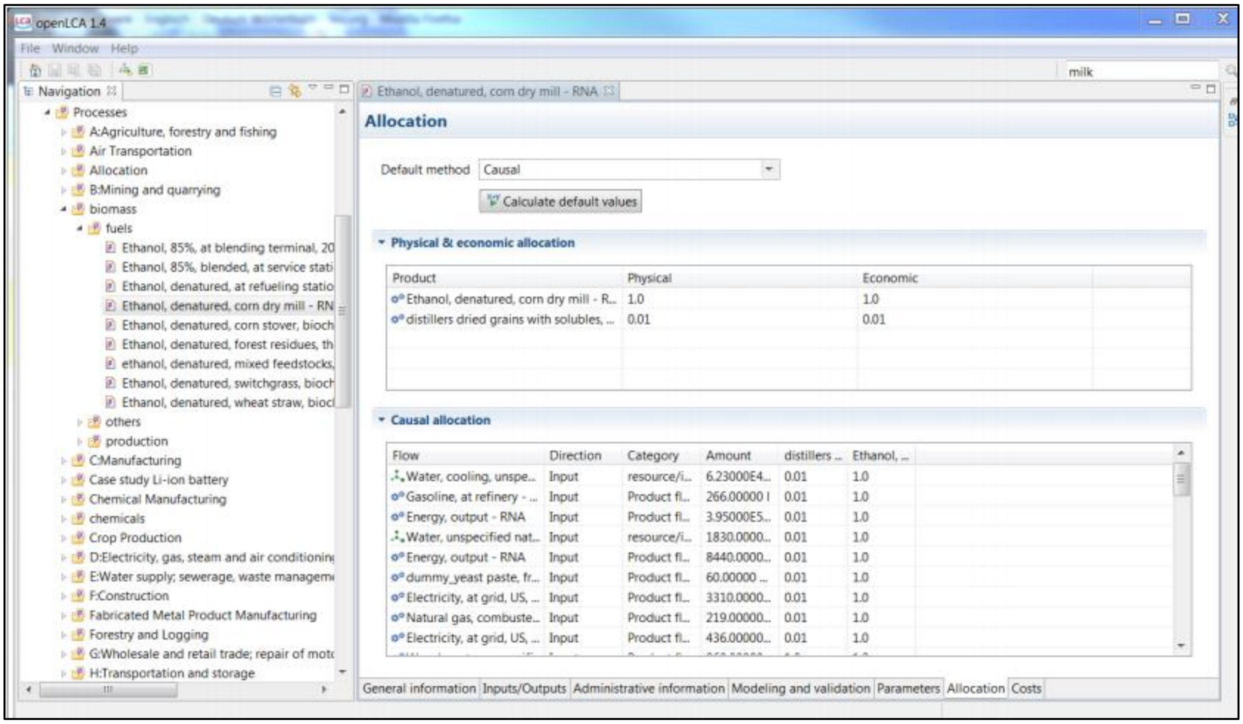
6.5. GaBi Software

Gabi is another software developed by Thinkstep company which provides life cycle assessment services. This software also requires purchasing of licenses similar to SimaPro software. GaBi software provides an easily accessible database which gets updated regularly. The database includes costs, energy and environmental impacts of every raw material. It provides a smart search tool for access to the database objects. It also enables easier life cycle creation and iteration. GaBi also provides a tutorial similar to SimaPro on how to use the software. Figure 6-5 below shows a snapshot of the software. Some of the limitations are that GaBi life cycle assessment software's tools, including iReport, often need to be downloaded and updated independently of the main program. It is also complex and is unable to support multiple users (Michalski 2015).

Figure 6-5: Snapshot of GaBi software

6.6. Open LCA

Open LCA is a free and open source software available in the market to carry out Life Cycle Assessment. The supplier for Open LCA is GreenDeltaTC GmbH. It has diversified from only one category i.e. CO_2 emissions to more than 15 impact categories recently. It follows the ISO LCA Framework 14040 and 14044. The software offers superior network and flow visualization tools, a high performance database management system on a local server, and easy import and export to important LCA data formats. The source code is completely open for those developers who want to improve it or supplement it. The Figure 6-6 below provides a snapshot of the Open LCA software. The major limitation of this tool is that the database used here is not comprehensive and there are more robust databases available in the market.



Allocation

Default method: Causal

Physical & economic allocation

Product	Physical	Economic
Ethanol, denatured, corn dry mill - R...	1.0	1.0
distillers dried grains with solubles, ...	0.01	0.01

Causal allocation

Flow	Direction	Category	Amount	distillers ...	Ethanol, ...
Water, cooling, unspe...	Input	resource/i...	6.23000E4...	0.01	1.0
Gasoline, at refinery - ...	Input	Product fl...	266.00000 l	0.01	1.0
Energy, output - RNA	Input	Product fl...	3.95000E5...	0.01	1.0
Water, unspecified nat...	Input	resource/i...	1830.0000...	0.01	1.0
Energy, output - RNA	Input	Product fl...	8440.0000...	0.01	1.0
dummy_yeast paste, fr...	Input	Product fl...	60.00000 ...	0.01	1.0
Electricity, at grid, US, ...	Input	Product fl...	3310.0000...	0.01	1.0
Natural gas, combuste...	Input	Product fl...	219.00000...	0.01	1.0
Electricity, at grid, US, ...	Input	Product fl...	436.00000...	0.01	1.0

Figure 6-6: Snapshot of Open LCA Software

Chapter 7 : Water Infrastructure

Most of the water infrastructure in the United States was built along the cities, with the majority of them developed during the mid-1800s. The initial water supply networks did not include any treatment facilities, and the raw water was either supplied from the nearby available surface water resources or the groundwater was extracted. As the cities grew rapidly, water bodies from further distances were used to supply the water, thus requiring larger diameter pipes to be constructed. These larger pipelines became part of the water supply infrastructure much quickly during the late 1800s and early 1900s. It was also during this time that water was treated with sand filters and chlorine before being supplied to the consumers. Figure 7-1 below shows the water infrastructure system currently in place.

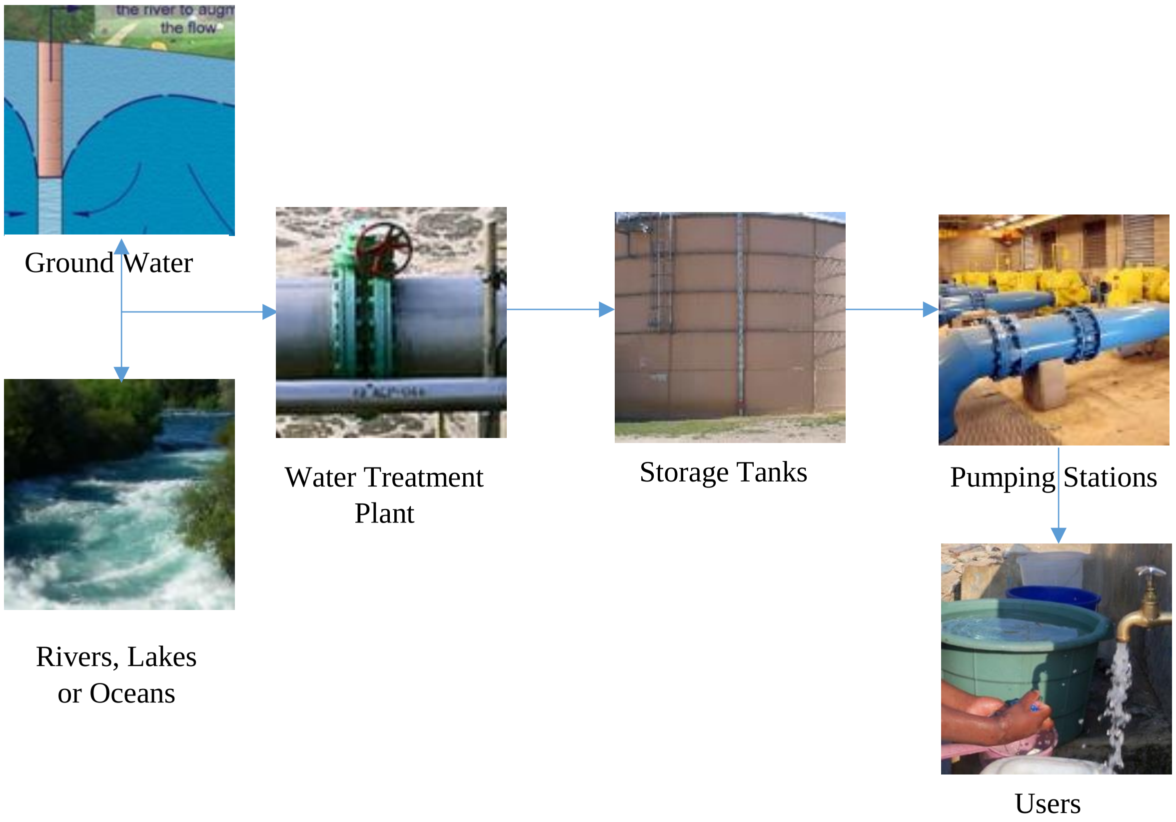


Figure 7-1: Description of Water infrastructure

So, the water infrastructure extracts the raw water from the environment and treats it and provides it to the users. The four main elements of water infrastructure are:

- Source Water (Rivers, Lakes, Oceans, Groundwater etc.)
- Storage Reservoirs
- Treatment Facilities
- Distribution Systems

7.1. Water Pipeline Infrastructure

Water pipeline is an invisible asset since most of the pipelines are buried under ground. So, the pipe condition is not visible and sudden leaks or failures can take place. So, condition assessment becomes very important to regularly access the condition of the pipes and take preventive actions before any leak or failure happens.

7.2. Pipe Design Standards

Majorly, AWWA standards are followed for the pipe design and it is the most regulated step of the whole life cycle. AWWA standards are also adopted as ANSI standards. Each standard designation consists of two elements connected by a hyphen, for example, the name C300-11 indicates that the standard is from the 300 series and received AWWA board of directors' approval in 2011. Latest revisions or updates were issued as recently as 2013. The ANSI/AWWA standards related to pipe products for manufacturing and installation guidelines are listed as follows:

- C100 Pit Iron and Spun Cast Iron Pipe
- C104 Cement-Mortar Lining for Ductile-Iron Pipe and Fittings for Water
- C105 Polyethylene Encasement for Ductile Pipe Systems
- C110 Ductile-Iron and Gray-Iron Fittings, 3" through 48", for Water and Other Liquids
- C151 Ductile Iron Pipe
- C200-12 for Steel Water Pipe, 6" (150 mm) and Larger
- C220-12 Stainless-Steel Pipe, ½" (13 mm) and Larger
- C300-11 Reinforced Concrete Pressure Pipe, Steel-Cylinder Type
- C301-07 Prestressed Concrete Pressure Pipe, Steel-Cylinder Type
- C302-11 Reinforced Concrete Pressure Pipe, Non-cylinder Type
- C303-08 Concrete Pressure Pipe, Bar-Wrapped, Steel-Cylinder Type
- C400 Asbestos Cement Pipe
- C600-10 Installation of Ductile Iron Mains and Their Appurtenances

- C602-11 Cement–Mortar Lining of Water Pipelines in Place—4” (100 mm) and Larger
- C604-11 Installation of Buried Steel Water Pipe—4” (100 mm) and Larger
- C605-05 Underground Installation of Polyvinyl Chloride (PVC) Pressure Pipe and Fittings for Water
- C606-11 Grooved and Shouldered Joints C620-07 Spray-Applied In-Place Epoxy Lining of Water Pipelines, 3” (75 mm) and Larger
- C900-07 Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4” Through 12” (100 mm Through 300 mm), for Water Transmission and Distribution
- C901-08 Polyethylene (PE) Pressure Pipe and Tubing, ½” (13 mm) Through 3” (76 mm), for Water Service
- C903-05 Polyethylene–Aluminum– Polyethylene & Cross-linked Polyethylene–Aluminum– Cross-linked Polyethylene Composite Pressure Pipes, ½” (12 mm) Through 2” (50 mm), for Water Service
- C904-06 Cross-Linked Polyethylene (PEX) Pressure Pipe, ½” (12 mm) Through 3” (76 mm), for Water Service
- C905-10 Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 14” Through 48” (350 mm Through 1,200 mm)
- C906-07 Polyethylene (PE) Pressure Pipe and Fittings, 4” (100 mm) Through 63” (1,600 mm), for Water Distribution and Transmission
- C907-12 Injection-Molded Polyvinyl Chloride (PVC) Pressure Fittings, 4” Through 12” (100 mm Through 300 mm), for Water, Wastewater, and Reclaimed Water Service
- C909-09 Molecularly Oriented Polyvinyl Chloride (PVCO) Pressure Pipe, 4” Through 24” (100 mm Through 600 mm), for Water Distribution
- C950-07 Fiberglass Pressure Pipe

Apart from AWWA, ASTM standards are also popular, especially for the metallic pipes. ASTM standards for Cast Iron pipe still exist, but the pipes are rarely installed by utilities now.

- A74 - 15 Standard Specification for Cast Iron Soil Pipe and Fittings
- A377 - 03(2014) Standard Index of Specifications for Ductile-Iron Pressure Pipe

- A674 - 10(2014) Standard Practice for Polyethylene Encasement for Ductile Iron Pipe for Water or Other Liquids
- A716 - 08(2014) Standard Specification for Ductile Iron Culvert Pipe
- A746 - 09(2014) Standard Specification for Ductile Iron Gravity Wastewater Pipe
- A861 - 04(2013) Standard Specification for High-Silicon Iron Pipe and Fittings
- A888 - 15 Standard Specification for Cast Iron Soil Pipe and Fittings for Sanitary and Storm Drain, Waste, and Vent Piping Applications.

7.3. Pipe Failure Theory

A pipeline lifecycle resembles a common behavior known as the bathtub theory which is a function of probability of failure over time. An example of such a representation of failure probability with age for a pipe is shown below in Figure 7-2.

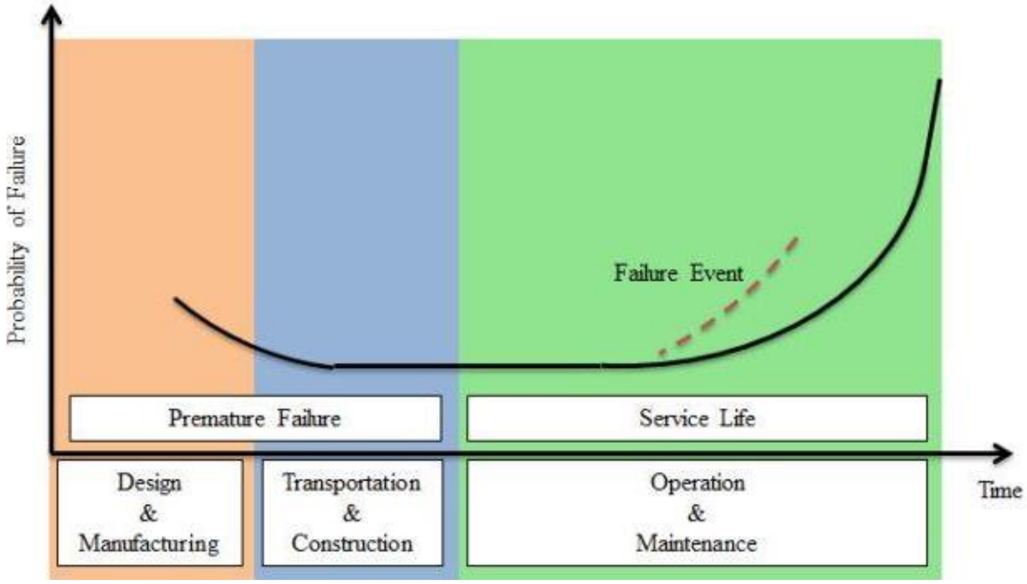


Figure 7-2: Pipe Failure Bathtub Theory (Angkasuwansiri and Sinha 2013)

According to the bathtub theory, the water pipe may have some defects and not be in perfect condition before being installed in the ground. Such damage might occur during design or manufacture processes. Some damage can also occur during the construction and installation phases and have a permanent effect on pipe failure. Operation and maintenance practices of the pipeline throughout its service also effects its performance through various intended or un-intended interferences and cause failure.

7.4. Water Pipeline Applications

Pipelines are considered to be the biggest component of a system. Some of the pipeline applications are shown in Figure 7-3 below:

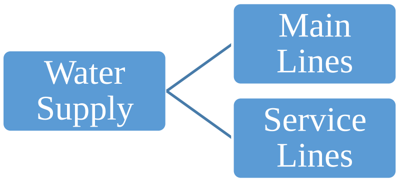


Figure 7-3: Water Pipeline Applications

- *Water Main Lines*

  Water main lines can further be divided into transmission and distribution lines. Distribution lines generally vary in diameter from 2” to 12” and vary in material also. Whereas, transmission lines are generally 12” and greater in diameter and vary in material as well.

- *Water Service Lines*

  The service lines generally vary from ¾ “to 1-1/2”. These also vary with respect to pipe material. Majorly pipe materials used for service lines are copper, polyvinyl chloride, poly ethylene, reinforced plastic etc.

7.5. Pipeline Materials

Pipeline materials can be divided into three categories: metallic, plastic and concrete. Following are the different types of pipe materials available:

- Cast Iron (no longer being installed)
- Ductile Iron
- Steel
- Copper
- Polyvinyl Chloride (PVC)
- High Density Polyethylene (HDPE)

- Reinforced Concrete Cylinder Pipe
- Pre stressed Concrete Cylinder Pipe (PCCP)
- Asbestos Cement (no longer being installed)

Table 7-1 below provides the general installation trend of different pipeline materials:

Table 7-1: Installation Trends for Different Pipe Materials

Pipe Material	1850s	1900s	1930s	1950s	1960s	1970s	1980s	1990s	2000s
Cast Iron (pit)	🟩	🟩	🟩	🟩					
Cast iron (spun)			🟩	🟩	🟩	🟩			
Ductile Iron					🟩	🟩	🟩	🟩	🟩
Steel	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
PVC				🟩	🟩	🟩	🟩	🟩	🟩
HDPE							🟩	🟩	🟩
Reinforced Concrete				🟩	🟩	🟩	🟩	🟩	🟩
Pre stressed Concrete				🟩	🟩	🟩	🟩	🟩	🟩
Asbestos Cement			🟩	🟩	🟩	🟩			

Figure 7-4 below shows the drinking water pipe material distribution in the United States (Folkman 2012)

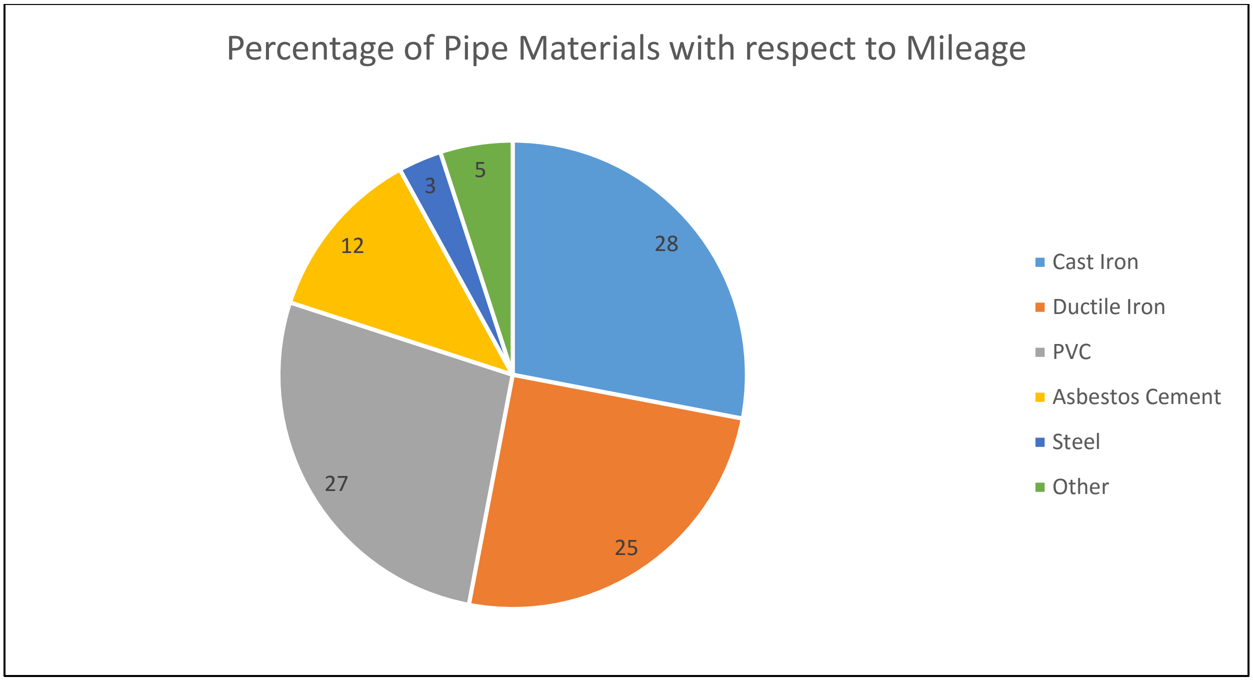


Figure 7-4: Distribution of Drinking Water Pipe Materials with respect to Mileage

Cast Iron Pipes (CI)

The majority of the pipes installed until 1960s were the cast iron pipes. There are two types of cast iron pipes differentiating mainly in the process through which they are manufactured. The first one is called the pit cast iron pipe which involves pouring molten iron into a sand mold end in a pit. The wall thickness of pit cast iron pipes was generally installed higher than the required thickness due to potential inconsistencies during manufacturing. The second process of centrifugally casting the pipe in sand mold started after 1920s. Due to centrifugal action, the possibility of inconsistencies was reduced and hence smaller thickness was used in this pipe. An interior cement lining was also introduced to prevent internal corrosion. The major advantage of the cast iron pipe is its low initial cost. But, the disadvantages include structural weakness and possible subjection to internal corrosion which can result water quality problems. This resulted in cast iron pipes not being installed in the water system after the 1960's and are being replaced with other materials.

Ductile Iron Pipes (DI)

Ductile Iron pipes were introduced after 1960s and have a different molecular arrangement than the cast iron pipes. The graphite in the ductile iron pipe is in a spheroidal from instead of the flaky from. Ductile iron pipes are stronger and also more corrosion resistant than the cast iron pipes. Ductile iron pipes are also less rigid than cast iron pipes and perform better in heavy loading conditions. These advantages of the ductile iron pipe make it one of the most used pipe materials today, but it still requires a protection lining to resist corrosion and with thinner walls, it is becoming a bigger problem (St Clair 2013).

Steel Pipes

Steel pipes were also installed in the 1850s as the cast iron pipes. They are also rigid and susceptible to internal and external corrosion. They are generally used in large diameters and high pressure applications.

Polyvinyl Chloride Pipes (PVC)

The use of PVC pipes started in 1950s as water distribution pipes. Polyvinyl Chloride is a synthetic polymer made up of smaller units to create chains and form a large molecule. The chains are made up of monomers made of carbon and hydrogen and other elements (Reed et al. 2007). The major advantage of PVC pipes is their corrosion resistance and high resistance to chemical attack. They are mostly used in low stress applications. The disadvantages include susceptibility to failure due to point loading and impacts.

Polyethylene Pipes (PE)

PE pipes were mostly manufactured in the 1950s and are available in three major categories: Low Density Polyethylene (LDPE), Medium Density Polyethylene (MDPE) and High Density Polyethylene (HDPE). The major advantage of PE pipes is their resistance to corrosion and ability to absorb impact loads, vibrations and ground movement. Disadvantages include susceptibility to permeation or degradation by certain organic contaminants, the necessity of selected or imported bedding, the requirement of stable support from ground to resist deformation, susceptibility to UV degradation and running the risk of floatation.

Asbestos Cement Pipes (AC)

The cement slurry for asbestos cement pipe contains approximately 2% of white asbestos by weight and Portland cement. AC pipes were primarily installed in heavy traffic regions where ground was subjected to minor movements. AC pipes don't require special bedding. Advantages include ability to withstand fluctuating pressure and surges and corrosion resistance in most soils and waters. Disadvantages include being susceptible to impact and accidental damage as well as vulnerability to chemical attack by soft water as it removes calcium hydroxide from the cement, eventually causing deterioration of the pipe interior (St Clair 2013).

Concrete Cylinder Pressure Pipes (CPP)

CPP were introduced in the United States in the 1940s as a way to deal with wartime steel shortage. But, they have gained popularity over time and are used worldwide now. They are generally manufactured in large diameters starting from 4 inches to even 21 feet.

Bar-wrapped concrete cylinder pipe (BWP) is a semi rigid pressure pipe. It is basically designed as a composite structure with the compressive strength of Portland cement and the tensile strength of steel.

Pre-Stressed concrete cylinder pipes (PCCP) were first developed in the early 1940s. There are two types of PCCP pipes, lined PCCP, where the concrete core is lined with a steel cylinder and embedded PCCP, where the steel is embedded within a concrete core. The advantages of using PCCP are their resistance to corrosion, high beam strength and rigidity and are impermeable to organic contaminants. Also, a high degree of compaction is not required. Disadvantages include that they are very heavy and are vulnerable to chemical attack from certain soils and waters. Caution should be used where there are aggressive soils and waters (Reed 2006). Table 7-2 below provides a summary of different pipe materials:

Table 7-2: Summary of Different Pipe Materials

Pipe Material	Advantages	Disadvantages	Common Defects
Cast Iron	• Low Cost	• Structurally weak	• Internal Corrosion

		• Prone to internal corrosion	• External Corrosion
Ductile Iron	• High Strength, Toughness and Ductility • Resistance to pressure fatigue • Well established methods of repair • Impermeability to organic contaminants	• Require protection against internal and external corrosion • Potential rise in pH when conveying soft waters • Susceptible to impact, accidental damage and stray currents	• Internal Corrosion • External Corrosion
PE (Polyethylene)	• Corrosion resistant, flexibility, toughness • Suitability for narrow trenching and trenchless applications • Lightweight	• Susceptible to permeation or degradation • Selected or imported bedding is required • Dependent on stable support from ground to resist deformation	• Yielding or creeping • Fatigue • Grease build-up
PVC (Polyvinyl Chloride)	• High resistance to chemical attack • Lightweight	• Susceptible to point loading and impact damage • Selected or imported bedding is required	• Excessive deflection • Grease build-up
PCCP (Pre-stressed Concrete Cylinder Pipe)	• High beam strength and rigidity • Impermeable to organic contaminants	• Heavy • Vulnerable to chemical attack from certain soils and waters	• Corrosion of Pre-stressed wires • Grease build-up

AC (Asbestos Cement)	• Strength and rigidity • Ability to withstand fluctuating pressure and surges	• Susceptible to impact and accidental damage • Vulnerable to chemical attack by certain soils and waters	• Cracks • Internal Corrosion
Steel	• Rigid and strong	• Susceptible to Internal and External Corrosion	• Internal corrosion • Welding failure at joints

7.6. Pipe Failure Characteristics

The performance of all pipes deteriorate with time and the rate of deterioration depends upon the pipe material, pipe diameter, external surroundings etc. It is important to understand the behavior of pipes in different conditions to predict their performance and plan maintenance activities ahead of time. Figure 7-5 below gives a description of different parameters that affect a pipe's performance.

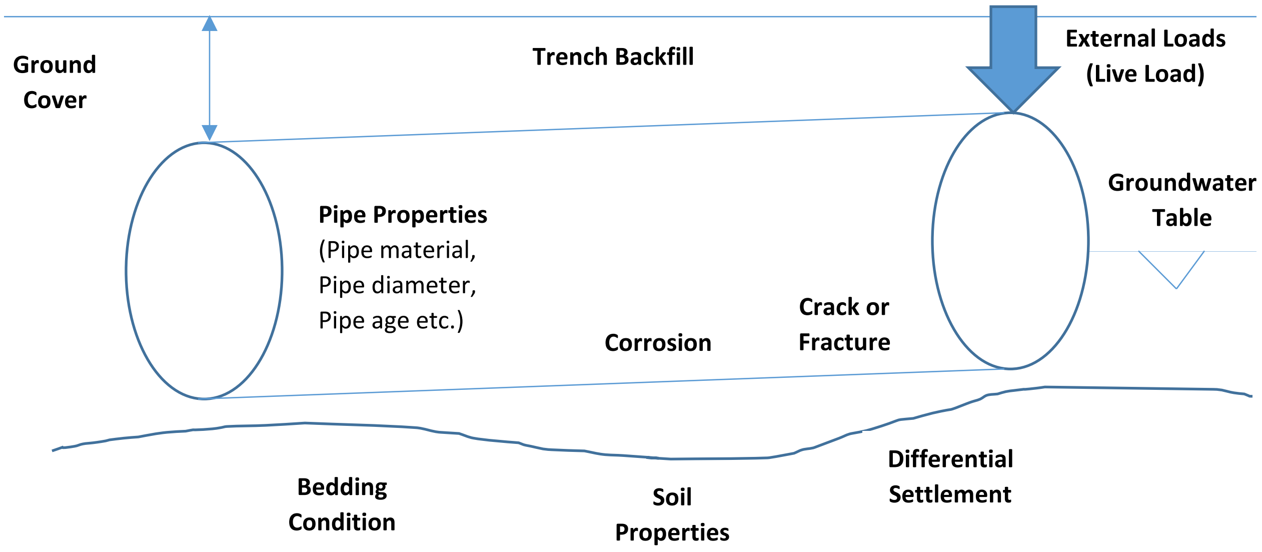


Figure 7-5: Parameters affecting Pipe Performance

7.6.1. Failure Modes and Mechanisms

Pipe Failure means that a leakage has been detected and a repair has been done (Folkman 2012). The failure process is complicated since there are a lot of interdependencies between different factors such as pipe properties, pipe internal and external environment.

The failure mode of a pipe is the type of failure and the mechanism is an event which causes the pipe to fail. The ultimate limit state defines a condition at which the strength of the pipe is reached, for example a pipe burst. The serviceability limit state defines a condition at which a particular function of the pipe is no longer achieved, for example pipe leaks reducing the pressure inside. A complete list of the various failure modes and mechanisms for different pipe materials are summarized in following Table 7-3.

Table 7-3: Failure Modes and Mechanisms (St Clair 2013)

Failure Mode	Pipe Material	Failure Type	Failure Mechanism
Cracking	All	Circumferential	Tensile Force on pipe due to bending moments on soil and pipe
		Longitudinal	High internal pressure; Compressive forces on pipe
		Spiral	Pressure surges; Bending forces combined with internal pressure
		Mixed	Combination of stresses causing longitudinal and spiral cracking
	HDPE, PVC	Ring	Axial tension; bending; horizontal loading; settlement; uplift; temperature; residual stresses; frost
		Axial	Internal pressure; bending; horizontal loads; residual stresses; frost
		Irregular	Chemical in environment; UV and stress cracking

		RCP	Dynamic loads at lower temperatures
Fracture	All	Circumferential	Tensile Force on pipe due to bending moments on soil and pipe
		Longitudinal	High internal pressure; Compressive forces on pipe
		Spiral	Pressure surges; Bending forces combined with internal pressure
		Mixed	Combination of stresses causing longitudinal and spiral cracking
Buckling	HDPE, PVC	Axial	External pressure; axial pressure; temperature, fire
		Ring/Transverse	External pressure; axial pressure; production; residual stresses; high temperature, fire
		Non Symmetric	Longitudinal bending; brazier effect
		Longitudinal	Axial Compression; thermal; effects
Burst Blisters or Voids	CI, DI, PCCP, RCP, AC	Blowout Holes	Internal pressure in thinned pipe
	HDPE, PVC	Voids	Chemicals; manufacture
		Blister	Manufacture; impact; Radiation; abrasion; chemicals
		Delamination	Internal or external pressures; axial compression; manufacture; impact; fatigue; abrasion; chemicals; frost
		Blazes	Osmosis
Surface Damage	PCCP, AC	Increased roughness	H2S i.e. hydrogen sulfide attack; chemical erosion
Blisters or Voids	PCCP	Visible Wires	H2S i.e. hydrogen sulfide attack; chemical erosion

		Surface Spalling	Chipped pipe; movement of pipe; expansive action of reinforcement
	CI, DI	Corrosion	Chemicals
	All	Tuberculation	Corrosion built up due to low flow speeds
	HDPE, PVC	Disintegration	Collapse; fire damage
Surface Damage Crazing Lining Failure Joint Failure	All	Change in color	Manufacture; High Temperatures; frost; chemicals; biological
		Abrasion	Flow velocity; Internal pressure; manufacture; chemicals
		Through/ External/Internal	Internal Pressure' axial tension; bending; settlement; uplift; fatigue; residual stresses
		Detached	Poor Installation; operations damage
		Blistered	Poor Installation; defective materials
		Buckled	Poor Installation; defective materials
		Wrinkled	Excess material on inside
		Loss of Tightness	Poor Installation; pull out; differential settlement; defective materials; damaged gasket; poor adhesion; degradation, corrosion, axial deflection
Crazing		Broken	Differential Settlement; External pressure; thermal expansion; corrosion; cracking

7.7. Pipe Operations and Maintenance

Pipe operations and maintenance is becoming more important for the water utilities with time since the major uncertainty in the performance of the pipelines comes from this phase. Operations and Maintenance practices play a crucial role in the performance of utility and the managers are increasingly looking for robust decision support tools as well as sound condition assessment (CA) and renewal engineering (RE) technologies for buried pipelines to run them with maximum efficiency before ultimately replacing them.

7.7.1. Pipe Condition Assessment

The primary components of any asset management program include the identification, location, and condition of assets. Condition assessment provides the critical information needed to assess the physical condition and functionality of a water system, and to estimate remaining service life and the asset value. There are lot of technologies available in the market related to condition assessment and their applicability depends upon a lot of factors such as pipe material, pipe diameter, access to the pipe and other factors. Therefore, it becomes imperative for the asset managers and utility personnel to be aware of all these technologies and their applicability in different scenarios to choose the most effective and the cheapest condition assessment technology. Based on synthesis reports for Condition Assessment for Drinking Water Pipelines (WERF 2013), the most common used technologies for condition assessment of water and wastewater pipelines are:

- Visual and CCTV inspections
- Electromagnetic (EM) Technology
- Remote Field Eddy current or Transformer coupling technology
- Sonic and Ultrasonic inspection technology
- Acoustic Emission Technology
- Impact Echo
- Leak Detection & Corrosion surveys

The most commonly used technologies have been discussed below:

Acoustic Technologies

a) *Sonar Profile System*

They provide an internal visual profile and therefore detects the internal defects below the waterline. This method is only applicable for service lines and the major advantage is that they can be operated without disrupting the service.

b) *Impact Echo*

This technique is used to determine the location and degree of surface cracks, voids and other damages. The major advantage is that it can detect the crack on both side on the pipe rather than from just one view of the pipe. However, only thickness and geometrical defects can be identified and other information is hard to obtain.

c) *Acoustic Emission*

Through the monitoring of the acoustic emissions, the appearance and the propagation of the microscopic cracks can be identified. It can be implemented as a real time monitoring system but the service gets interrupted while installing it. Any quantitative information regarding the crack is not obtained, only its presence can be identified.

Visual Inspection

a) *Manual Entry and Visual Inspection*

Manual inspection is suitable for large diameter mains where a person enters the pipe and inspect the condition of the pipe. The procedure is very simple and no special equipment is required. The major disadvantages are the difficulty to perform in highly congested areas and interruption in the service.

b) *CCTV Inspection*

CCTVs are relatively easy and cheap to operate. They are suitable for both small and large diameter mains. Latest advancements in the CCTV such as fish eyed technologies can record the full view of the pipe. The major disadvantage being only the quantitative data collected and the interpretation required.

Others

a) *Electrical/Electromagnetic Currents*

The electrical leak location method is used to detect leaks in surcharged non-ferrous pipes. Eddy Current Testing (ECT) and Remote Field Eddy Current (RFEC) technologies identify defects in ferrous pipes. Magnetic Flux Leakage (MFL) inspection is widely used in the oil and gas industry to measure metal loss and detect cracks in ferrous pipelines.

b) *Laser Profiling*

A laser is used to create a line of light around the pipe interior surface so that it identifies any deformation or change in the shape of the pipe. It can identify changes above water level without interrupting the flow, but service gets interrupted if the whole pipe has to be inspected. These techniques are generally used in combination with CCTV and SONAR.

7.7.2. Pipe Renewal

Once the pipe's condition is assessed, suitable renewal technologies can be applied to improve the pipe's condition. Pipe renewal can be divided into three components:

- Pipe Repair
- Pipe Rehabilitation
- Pipe Replacement

These three components of renewal vary with the pipe condition and the functions performed have been explained in the following Table 7-4.

Table 7-4: Different Renewal Components

Pipe Renewal Component	**Description of Applicable Uses**
Pipe Repair	• Done if the host pipe is structurally sound • Host pipe can serve as a support structure for the technology • Doesn't improve the current condition of the pipe, but helps in delaying the deterioration of the pipe condition
Pipe Rehabilitation	• Improves fully or partially the hydraulic and structural condition of the pipe • Extends the operational life of the pipe
Pipe Replacement	• Done if host pipe cannot provide the level of service in its current condition • Done if host pipe cannot act as a support system for repair/rehabilitation systems

Based on synthesis report for Renewal Engineering for Drinking Water Pipelines (WERF 2014), common methods employed in asset renewal plans for buried pressure pipelines are listed in Table 7-5 below:

Table 7-5: Different Renewal Component Technologies

Maintenance	**Repair**	**Rehabilitation**	**Replacement**
• Cleaning • Cathodic Protection	• Open Cut • Trenchless • Joint	• Spray on linings • Pipe Wrapping • Spiral wound liners • Panel lining • CIPP lining • Woven hose liners • Close-fit liners • Grout in place liners	On Line • Sliplining • Pipe Eating • Pipe Bursting • Pipe Splitting • Pipe Ramming Off Line • HDD • Micro Tunneling • Pilot Tube Boring • Auger Boring

Some of the most commonly used pipeline renewal technologies have been discussed below:

Rehabilitation: CIPP Liners

CIPP liners are used to improve the condition of the pipe structurally by sealing the pipe without excavating it. CIPP liner consists of a tube, impregnated with a liquid thermoset resin which is inserted into the pipeline and cured. The different classes of CIPP liners differ with tube construction (felt or fiber reinforced), insertion method (pulled in place or manually inserted), resins used (epoxy, polyester, silicate etc.) and the curing method (ambient cured or thermally cured). Therefore, structural capabilities differ with class in CIPP liners.

On Line Replacement: Pipe Bursting

With pipe bursting (for brittle materials) and pipe splitting (for ductile materials), the old pipe is ruptured and pushed into the surrounding soil while a new pipe follows the cone-ended bursting tool to replace the old pipe. The key advantage of pipe bursting is that the pipe size can be upgraded. Currently, the pipe size range varies from 2” to 54”. In addition, factors such as soil conditions and depth of pipe determine if pipe bursting is appropriate or not.

Off Line Replacement: Open Cut Replacement

Open cut replacement is the traditional way of replacing the pipe where the excavation is done and the surface is leveled, if necessary. The existing pipe can be excavated or abandoned in place. The bottom of the trench is normally lined with granular bedding material unless the project engineer deems the native material suitable for protecting the pipe. Compaction of backfill is an important factor in this method since it affects the pipe performance in the future. Open cut replacement causes traffic delays and it is slower than the trenchless technologies.

Off Line Replacement: Horizontal Directional Drilling

Horizontal directional drilling is a relatively new method for installing underground piping. It does not require an entire section of earth to be removed. Rather, pits are excavated on either end and space is drilled through the soil for piping. Applications of this type have been dubbed as “trenchless” and are expanding the opportunities for pipe installation and renewal across the globe. Many piping locations create extenuating circumstances for installation and maintenance, whether under a waterbody, major highway, or structure, wherein HDD can provide an excellent alternative to an open-cut excavation.

In HDD, a hole is bored by a cutting head attached to a steel drill string. A special mud is used to cool the cutting head and to help lubricate the process, as well as help to flush the tailings from the drilling. Once the destination is reached, a tool called a back reamer is attached that prepares the void for the installation of the new piping. The operators must take great care not to exceed the safe load limits of both the drill string and the pipe being inserted.

Chapter 8 : Real World Applications from Water Industry

This chapter provides real world applications related to life cycle cost analysis from the water industry. Applications include a life cycle cost tool by Water Environment and Reuse Foundation (WE&RF) which calculates and compares life cycle costs for different alternatives and Innovyze's Info master LCCA tool. These two are used to carry out economic life cycle cost analysis.

8.1. WE&RF's Life Cycle Cost Tool

Water Environment and Reuse Foundation (WE&RF) has developed a life cycle cost tool in the form of a step by step guide for an asset practitioner to carry out life cycle cost analysis. It proposes selecting six project alternatives for comparison – do nothing, status quo, renewal (repair, rehabilitation, replacement), non-asset solutions, change levels of service and dispose of. There are eleven steps to be followed in this tool as shown in the Figure 8-1 below:

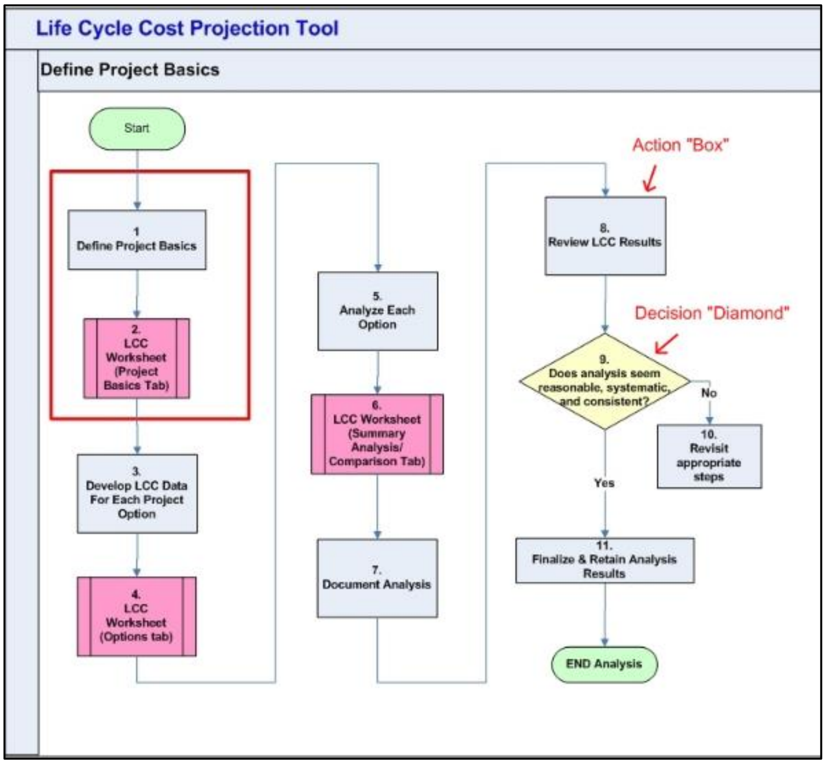


Figure 8-1: WE&RF's LCCA Tool Methodology

The inputs involve selecting a discount rate, analysis period and various life cycle costs. Some of the limitations of this tool are mentioned below.

- The cost structure provided in the tool is not comprehensive. For example, it requires input of planning and design costs but the breakdown has not been provided such as easement costs, permit costs etc.
- Indirect Costs or the consequence costs have not been considered which form a major part of the life cycle costs.
- Comparison of different pipe installation, condition assessment, repair, rehabilitation and replacement methods cannot be done.
- Life Cycle Assessment has not been considered.

8.2. Innovyze's Info Master LCCA Tool

Innovyze is a global provider of wet infrastructure business analytics software solutions for water and wastewater utilities, government agencies and engineering organizations. Infomaster LCCA tool predicts pipe deterioration and failure in the water network and determines the optimal time to replace the pipe. If the utility replaces the asset, then the prediction algorithm is run again the next year with the updated pipe performance. This helps the utility in effective allocation of funds and resources in the system. Net present value method is considered for calculations. The approach towards predicting the failure timings is the right way, but the limitation is that the costs associated with these activities have not been enlisted in detail. Figure 8-2 below shows a snapshot of this tool.

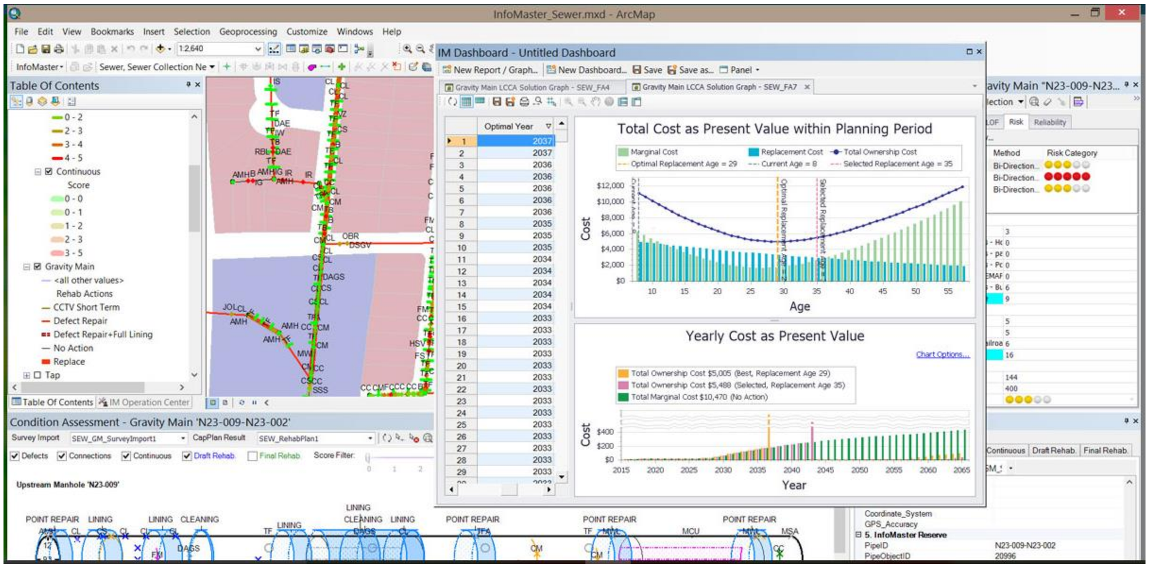


Figure 8-2: Snapshot of Infomaster LCCA tool

Chapter 9 : Research Gap

This chapter provides an explanation of the research gap after carefully reviewing the literature and real world applications related to life cycle cost analysis.

Data (Life Cycle Cost Analysis and Life Cycle Assessment Data)

- The literature on life cycle cost analysis is not connected. The focus of the literature is not in developing life cycle cost analysis further, but in displaying its use in a specific context.
- There are other cost structures available in the industry but there is a lack of a reliable cost structure which captures costs with utility perspective in mind to ensure that all the utilities capture same set of data. Some of the critical factors which affect pipe performance such as pipe material, surrounding environment and other related factors such as different failure modes, are sometimes not captured.
- Different parameters affecting cost and performance have not been enlisted in detail and have not been defined well which leads to insufficient collection of data. The utilities are not clear on what are the important parameters and what data to collect. Hence, a highly accurate life cycle cost analysis is not being done right now in the water industry.
- Also, utilities don’t have a good failure prediction model. So, they use maintenance costs from other projects of similar kind in which conditions are more or less different which leads to an incorrect cost estimation.
- A protocol on collecting, storing, analyzing the pipeline infrastructure data should be developed.
- Environmental impact and social impact costs throughout the life cycle of the pipe have not been considered to carry out life cycle cost analysis. It is difficult to measure and quantify them due to the uncertainty involved in these costs.

Life Cycle Cost Analysis (models and tools)

- Most of the utilities use deterministic approach to carry out life cycle cost analysis which leads to an unreliable analysis due to uncertainty in the operation and maintenance costs, environmental and social impact costs.
- There are no models in the water industry which can compare different installation, condition assessment and renewal techniques.

- Transportation Industry has been using probabilistic and soft computing techniques such as fuzzy logic techniques to carry out life cycle cost analysis for different alternatives available during the life span of a pavement. These alternatives include medium overlay, thick overlay etc. throughout the life span of the asset which is not an optimal method. An optimal solution of these alternatives should be calculated which has the least cost over the design life of the asset.
- Some probabilistic models have been used to carry out life cycle cost analysis in drinking water industry but they are still not reliable as compared to soft computing techniques such as fuzzy logic, neural networks etc.

Life Cycle Assessment (models and tools)

- Life cycle assessment does not get much importance while making investment decisions. It should be integrated with life cycle cost analysis while making important cost decisions.
- A lot of LCA tools are available in the industry such as life cycle assessment, full cost environmental accounting etc. and it is unclear about the purpose and function of some of the available tools in the industry.
- Since LCA is a data intensive process and utilities don’t capture environmental data, therefore, not much reliable models have been proposed till date.

Chapter 10 : Research Goals, Objectives and Methodology

This research provides a framework which can fill the current research gaps and helps in creating a holistic life cycle cost analysis tool which will help utilities in efficient allocation of resources and make decisions based on the life cycle costs.

10.1. Research Goals and Objectives

To address the current limitations and gaps, a comprehensive cost structure and a robust holistic life cycle cost analysis model is proposed in this research. The cost tool proposed here is in the form of an excel spreadsheet which helps in the prioritization of activities and optimization of the cost spending of a utility. The research gap explained in the previous chapter and the corresponding research goals have been shown in the Figure 10-1 below.

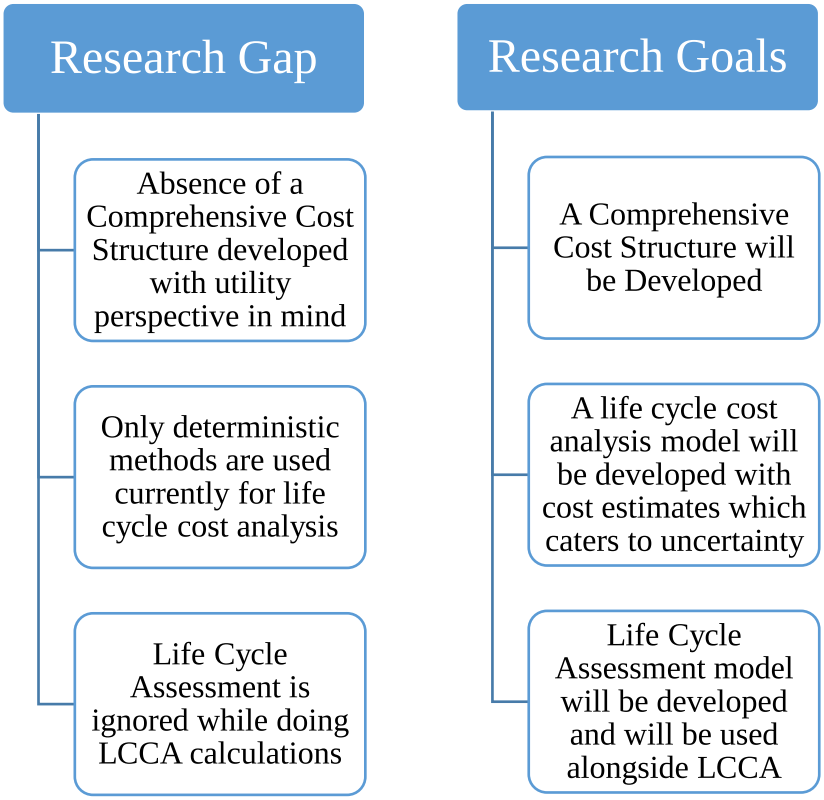


Figure 10-1: Research Gaps and Corresponding Research Goals

Research Goal 1: Comprehensive Cost Structure

The comprehensive cost structure is detailed and covers all the life cycle phases of the pipe. It includes all the technologies which can be used in a particular life phase and also other costs such as equipment, labor etc. for each life phase. This cost structure is explained in detail in the research methodology section of this chapter.

Research Goal 2: Life Cycle Cost Analysis Model

The life cycle cost analysis model includes calculating the net present value of life cycle costs of different alternatives and choosing the most economical alternative. The user can input their data or they can use approximate values of different costs provided in the model. Also, for some costs, there are values from more than 2 references which validates the approximate value provided in the model. This validation of costs caters to the uncertainty which is generally present in the cost data. This model has the capability to compare different:

a. Pipe Materials
b. Pipe Installation Technologies.
c. Pipe Condition Assessment Technologies.
d. Pipe Rehabilitation Technologies.
e. Pipe Replacement Technologies.

Research Goal 3: Life Cycle Assessment Model

This involves calculation of Greenhouse Gas emissions during the pipe production and operation phase and has been explained in detail in the research methodology section of this chapter.

10.2. Research Methodology

The methodology of this research involves four major steps depicted in the following Figure 10-2:

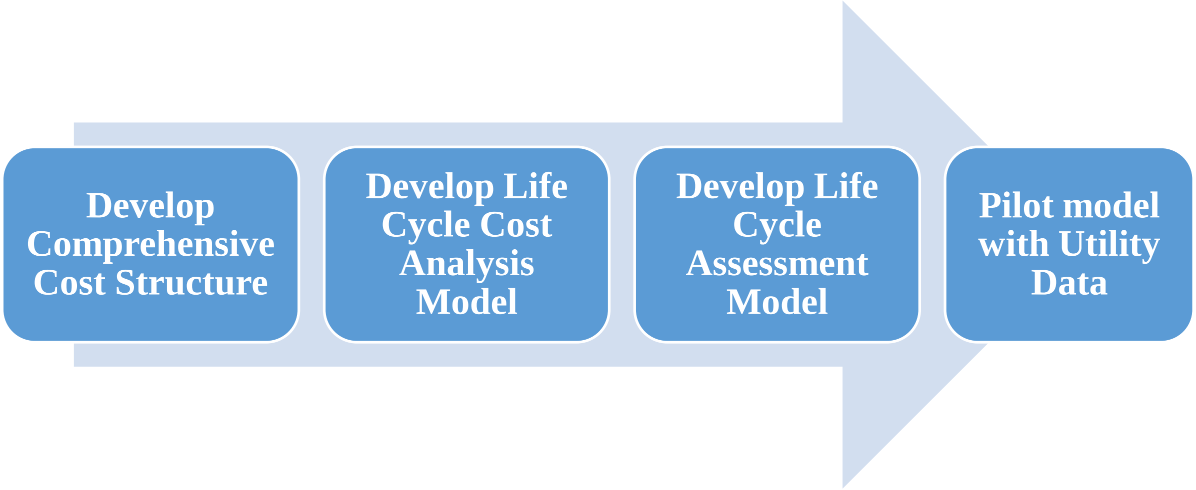


Figure 10-2: Research Methodology

The first step involves developing a cost structure to collect and maintain the data effectively. The second step is to develop the life cycle cost analysis model, third step is to develop life cycle assessment model and the last step is to pilot the model with a utility data and show the analysis results.

10.2.1. Objective 1: Develop a Data Structure for Pipeline Cost Data

A comprehensive cost structure has been prepared in this research through extensive literature review and water industry reports by EPA, WE&RF and others. This will help the utilities to know what cost data to collect and how to store them in a standardized format. The standardized data will help in further analysis and development of robust models. The cost categories considered have been shown in the Figure 10-3 below and the detailed cost structure prepared has been provided in Tables 10-1 to 10-9:

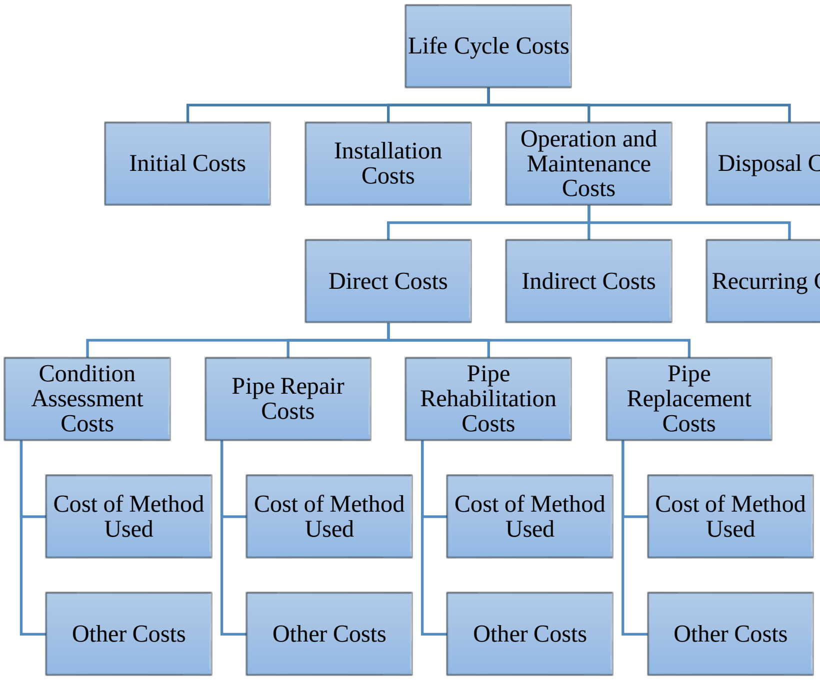


Figure 10-3: Cost Categories Considered

1. Initial Costs

Table 10-1: Structure for Initial Costs

Cost	Units	Description
Preliminary Study	$	Cost of doing preliminary study of the project
Feasibility Study	$	Cost of conducting feasibility study of the project
Easements	$	Cost of obtaining easements to use the land
Permits	$	Cost of obtaining other permits before the start of the construction
Conceptual Design	$	Cost incurred in conceptual design of the project
Detailed Design	$	Cost incurred in detailed design of the project
Design Contingencies	%	Cost incurred in percentage due to any design contingencies during design activities
Field Investigation and Surveying	$	Cost of doing field investigation and surveying

2. Installation Costs

Table 10-2: Structure for Installation Costs

Cost	Units	Description
Cost of Method Used (includes only cost of using the technology)		
Pipe Jacking	$/foot	Cost of Installation using pipe jacking (if used)
Utility Tunneling	$/foot	Cost of Installation using utility tunneling (if used)
Horizontal Boring	$/foot	Cost of Installation using horizontal boring (if used)
Pipe Ramming	$/foot	Cost of Installation using pipe ramming (if used)
Micro tunneling	$/foot	Cost of Installation using micro tunneling (if used)
Horizontal Directional Drilling (HDD)	$/foot	Cost of Installation using HDD (if used)
Pilot Tube Micro tunneling	$/foot	Cost of Installation using pilot tube micro tunneling (if used)
Impact Moling	$/foot	Cost of Installation using impact moling (if used)
Open Cut	$/foot	Cost of Installation using open cut (if used)
Other Costs		
Equipment	$/foot	Cost of equipment used during installation
Labor	$/foot	Cost of labor during installation
Material	$/foot	Cost of materials used during installation
Fittings, valves, hydrants etc.	$/foot	Cost of fittings, valves hydrants etc., used during installation
Trenching, Excavation and Backfill	$/foot	Cost of trenching, excavation and backfill done during installation
Dewatering	$/foot	Cost of dewatering (if done)
Pavement Removal and Replacement	$/foot	Cost of pavement removal and replacement (if done)
Traffic Control	$/foot	Cost incurred due to traffic control
Mobilization and Demobilization	$/foot	Cost incurred due to mobilization and demobilization activities

Construction Contingencies	%	Cost incurred in percentage due to construction contingencies during installation activities

3. Operation and Maintenance Costs

3.1. Condition Assessment (CA) Costs

Table 10-3: Cost Structure for Condition Assessment Costs

Cost	Units	Description
Cost of Method Used (includes only cost of using the technology)		
Visual Inspection	$/foot	Cost of Condition Assessment using visual inspection (if used)
Camera Inspection	$/foot	Cost of Condition Assessment using camera inspection (if used)
Acoustic Inspection for Structural Condition	$/foot	Cost of Condition Assessment using acoustic inspection (if used)
Smartball	$/foot	Cost of Condition Assessment using Smartball (if used)
LeakfinderRT	$/foot	Cost of Condition Assessment using LeakfinderRT (if used)
Permalog	$/foot	Cost of Condition Assessment using Permalog (if used)
MLOG	$/foot	Cost of Condition Assessment using MLOG (if used)
STAR ZoneScan	$/foot	Cost of Condition Assessment using STAR Zonescan (if used)
Sahara	$/foot	Cost of Condition Assessment using Sahara (if used)
Ultrasonic Testing	$/foot	Cost of Condition Assessment using Ultrasonic Testing (if used)
Electromagnetic Inspection	$/foot	Cost of Condition Assessment using Electromagnetic Inspection (if used)
Radiographic Testing	$/foot	Cost of Condition Assessment using Radiographic Testing (if used)

Thermographic Testing	$/foot	Cost of Condition Assessment using Thermographic Testing (if used)
Coupon and other sampling	$/foot	Cost of Condition Assessment using Coupon and other sampling (if used)
Tracer gas technique	$/foot	Cost of Condition Assessment using tracer gas technique (if used)
Other Method	$/foot	Cost of Condition Assessment using any other method
Other Costs		
Equipment	$/foot	Cost of equipment used during condition assessment
Labor	$/foot	Cost of labor during condition assessment
Cost of Valves, Fittings etc.	$/foot	Cost of fittings, valves etc., used during condition assessment

3.2. Pipe Repair Costs

Table 10-4: Cost Structure for Pipe Repair Costs

Cost	**Units**	**Description**
Cost of Method Used (includes only cost of using the method)		
Pipe Joint and Leak Seals	$/foot	Cost of pipe repair by using pipe joint and leak seals (if used)
Corrosion Control (Internal/External Pipe Wrap)	$/foot	Cost of pipe repair by using corrosion control techniques (if used)
External Repair Clamps	$/foot	Cost of pipe repair by using external repair clamps (if used)
Pipe Coatings (Epoxy Lining)	$/foot	Cost of pipe repair by using pipe coatings (if used)
Cement Mortar Lining	$/foot	Cost of pipe repair by using cement mortar lining (if used)
Other Method	$/foot	Cost of pipe repair by using any other method
Other Costs		
Equipment	$/foot	Cost of equipment used during pipe repair

Labor	$/foot	Cost of labor during pipe repair
Material	$/foot	Cost of materials used during pipe repair
Valves, Fittings etc.	$/foot	Cost of fittings, valves etc., used during pipe repair
Trenching, Excavation and Backfill	$/foot	Cost of trenching, excavation and backfill done during pipe repair
Dewatering	$/foot	Cost of dewatering (if done)
Mobilization and Demobilization	$/foot	Cost incurred due to mobilization and demobilization activities
Pavement Removal and Replacement	$/foot	Cost of pavement removal and replacement (if done)
Traffic Control	$/foot	Cost incurred due to traffic control
Construction Contingencies	%	Cost incurred in percentage due to construction contingencies during repair activities

3.3. Pipe Rehabilitation Costs

Table 10-5: Cost Structure for Pipe Rehabilitation Costs

Cost	**Units**	**Description**
Cost of Method Used (includes only cost of using the method)		
FFP Liner (Therformed Fiber-Reinforced PE)	$/foot	Cost of pipe rehab by using FFP liner (if used)
GIPP Liner (PE Tube)	$/foot	Cost of pipe rehab by using GIPP liner (if used)
SIPP Lining (Cementitious)	$/foot	Cost of pipe rehab by using SIPP lining, cementitious (if used)
SIPP Lining (Polymer Based)	$/foot	Cost of pipe rehab by using SIPP lining, polymer based (if used)
Sliplining	$/foot	Cost of pipe rehab by using sliplining (if used)
Modified Sliplining (Close-Fit pipe)	$/foot	Cost of pipe rehab by using modified sliplining (if used)
Cured-in-Place Pipe (CIPP)	$/foot	Cost of pipe rehab by using CIPP (if used)
Other Method	$/foot	Cost of pipe rehab by using any other method

Other Costs		
Equipment	$/foot	Cost of equipment used during pipe rehab
Labor	$/foot	Cost of labor during pipe rehab
Valves, Fittings etc.	$/foot	Cost of fittings, valves etc., used during pipe rehab
Material	$/foot	Cost of materials used during pipe rehab
Trenching, Excavation and Backfill	$/foot	Cost of trenching, excavation and backfill done during pipe rehab
Dewatering	$/foot	Cost of dewatering (if done)
Mobilization and Demobilization	$/foot	Cost incurred due to mobilization and demobilization activities
Pavement Removal and Replacement	$/foot	Cost of pavement removal and replacement (if done)
Traffic Control	$/foot	Cost incurred due to traffic control
Construction Contingencies	%	Cost incurred in percentage due to construction contingencies during rehab activities

3.4. Pipe Replacement Costs

Table 10-6: Cost Structure for Pipe Replacement Costs

Cost	**Units**	**Description**
Cost of Method Used (includes only cost of using the method)		
Pipe Bursting	$/foot	Cost of pipe replacement using pipe bursting (if used)
Pipe Jacking	$/foot	Cost of pipe replacement using pipe jacking (if used)
Utility Tunneling	$/foot	Cost of pipe replacement using utility tunneling (if used)
Horizontal Boring	$/foot	Cost of pipe replacement using horizontal boring (if used)
Pipe Ramming	$/foot	Cost of pipe replacement using pipe ramming (if used)

Microtunneling	$/foot	Cost of pipe replacement using micro tunneling (if used)
Horizontal Directional Drilling	$/foot	Cost of pipe replacement using HDD (if used)
Pilot Tube Microtunneling	$/foot	Cost of pipe replacement using pilot tube micro tunneling (if used)
Open Cut	$/foot	Cost of pipe replacement using open cut (if used)
Other Method	$/foot	Cost of pipe replacement using any other method
Other Costs		
Equipment	$/foot	Cost of equipment used during pipe replacement
Labor	$/foot	Cost of labor during pipe replacement
Valves, Fittings etc.	$/foot	Cost of fittings, valves etc., used during pipe replacement
Material	$/foot	Cost of materials used during pipe replacement
Trenching, Excavation and Backfill	$/foot	Cost of trenching, excavation and backfill done during pipe replacement
Dewatering	$/foot	Cost of dewatering (if done)
Mobilization and Demobilization	$/foot	Cost incurred due to mobilization and demobilization activities
Pavement Removal and Replacement	$/foot	Cost of pavement removal and replacement (if done)
Traffic Control	$/foot	Cost incurred due to traffic control
Construction Contingencies	%	Cost incurred in percentage due to construction contingencies during replacement activities

3.5. Indirect Costs

Table 10-7: Cost Structure for Indirect Costs

Cost	Units	Description
Indirect costs due to condition assessment		
Loss of Business revenues	%	Costs of lost business revenues due to condition assessment

Traffic Disruption	%	Costs of traffic disruption due to condition assessment
Noise Pollution	%	Costs of noise pollution due to condition assessment
Indirect costs due to renewal activities		
Loss of Buisness revenues (lost water/future impact on buisness)	%	Costs of lost business revenues due to renewal activities
Traffic Disruption / User Delay Costs	%	Costs of traffic disruption due to renewal activities
Noise Pollution Costs	%	Costs of noise pollution due to renewal activities
Bypass Pumping Costs	%	Costs if bypass pumping is done
Environmental impact costs	%	Costs of environmental impacts due to renewal activities

Recurring Costs

Table 10-8: Cost Structure for Recurring Costs

Cost	**Units**	**Description**
General Maintenance	$/year	Costs incurred due to general maintenance activities
Unavoidable Annual Real Loss (UARL) of Water due to Regular Operations	$/year	Costs due to water loss in regular operations
Labor	$/year	Costs of labor during regular operations
Regular Supplies	$/year	Costs of regular supplies during regular operations
Pumping Costs due to Frictional Head Loss	$/year	Costs of frictional head loss during pumping operations

4. Disposal Costs

Table 10-9: Cost Structure for Disposal Costs

Cost	**Units**	**Description**

Cost of Disposal	%	Costs incurred while disposing of the asset after replacement
Salvage Value	%	Salvage Value of the pipe after replacement

10.2.2. Objective 2: Develop Life Cycle Cost Analysis model

This step involves the development of life cycle cost analysis model. The methodology of the LCCA model includes ten steps to carry out the analysis as shown in the Figure 10-4 below:

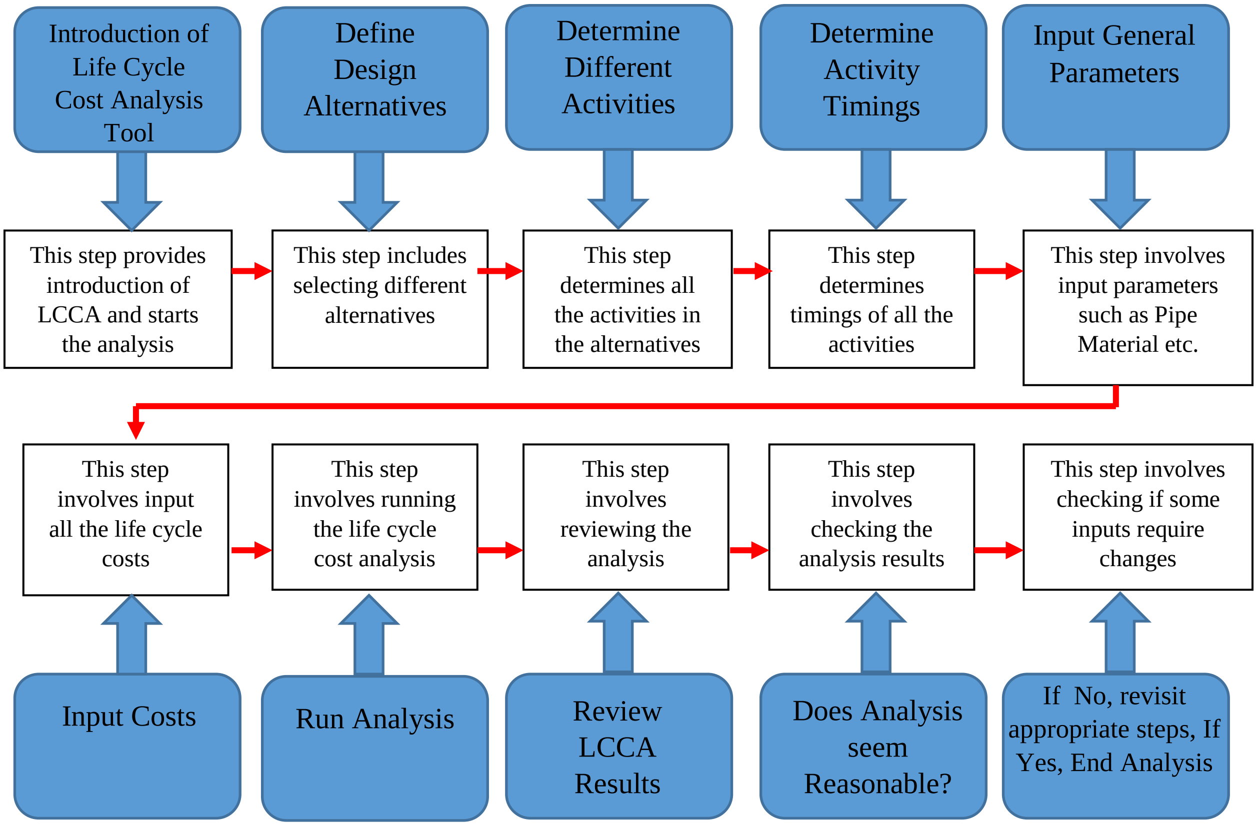


Figure 10-4: Life Cycle Cost Analysis Model Methodology

Step 1: Introduction to the Life Cycle Cost Analysis Tool

This steps acts as the starting point of the tool and provides introduction to the life cycle cost analysis and life cycle assessment. It also explains about the scope of the tool and what inputs are required to start the analysis.

Scope

This tool helps in comparison of following alternatives as explained earlier in research goals and objectives:

- Scenario 1: Different Pipe Materials
- Scenario 2: Different Installation Technologies and Methods
- Scenario 3: Different Condition Assessment Technologies
- Scenario 4: Different Rehabilitation Technologies
- Scenario 5: Different Replacement Technologies

Inputs Required

There are two types of inputs required to carry out the analysis, General Parameters and Life Cycle Costs.

General Parameters

General parameters include pipe related (pipe diameter, material etc.), environmental (soil conditions, traffic conditions etc.) and other factors (inflation rate, discount rate etc.).

Table 10-10: General Input Parameters for LCCA

Parameter	Description
Hazens William Factor	Hazen Williams C factor is used to determine the head loss in the flow.
Frequency of Installation of Fittings, Valves, Hydrants	Low Frequency: Fire hydrants every 800 ft. Medium Frequency: Fire hydrants every 500 ft. High Frequency: Fire Hydrants every 300 ft.
Fittings type	Fitting Material to be used (Ductile Iron Fittings, Steel Fittings etc.)
Average Flow	Water flow through the pipe (gallons per minute)
Approximate Proportion of pipe with water	This indicates how much pipe is full with water (Value 1 indicates that pipe is running full)
Soil Conditions	Type of Soil around the pipe (Sandy, Clay etc.)
Traffic Conditions	Traffic Flow near the pipe (Light, Medium, Heavy)

Analysis Period	Common period of time to assess cost differences between different alternatives
Inflation rate	Inflation is the rate at which the general level of prices for goods and services is rising and consequently, the purchasing power of currency is falling
Discount Rate	Discount Rate is the Exchange Rate between Present and Future
Unit Rate of Electricity	This indicate the cost of electricity per KWH
Total Efficiency of pump system	This indicates the efficiency of the pump system

Cost Inputs

Cost Inputs have been defined earlier in the Step 1 of the research methodology where a detailed breakdown of the life cycle costs has been provided. This model gives user the option to use their collected data as an input in the model. But, if the utilities don't have data in some of the categories, this model provides estimated values for most of the categories with the help of literature and previous academic and water industry surveys. Also, for some of the cost categories, the estimated values have been provided with reference to two or more sources which validates the cost estimated value provided in the model. This step just provides the information on what are the inputs but the actual inputting will be done later in Step 6.

Step 2: Define Design Alternatives

This step involves the selection of the scenario which the user wants to carry out and defines the design alternatives which the user wants to compare. For example, if Scenario 1 is selected which is the comparison of different pipe materials, Ductile Iron and PVC pipe materials can be one choice of design alternatives.

Step 3: Determine Different Activities

The next step is to select the analysis period and determine the activities which will be performed during the analysis period. For example, one alternative might have one repair activity and other might have two repair activities.

Step 4: Determine Activity Timings

The next step is to determine the timings of different activities during the lifespan of each design alternative (for example, while comparing different pipe materials, define when installation, repair, rehabilitation and replacement of the pipe will be done during the life of the pipe).

Step 5: Input General Parameters

The next step is to provide different inputs in the model. The general parameters include pipe related inputs, environmental inputs and other inputs as described earlier in Step 1.

Step 6: Input Cost Parameters

After inputting the general parameters, next step is to input various costs incurred during the life span. If the user has the data to input in the model, then go ahead and input it. If not, make selections in the estimated values column and approximate values will be inputted corresponding to the selection made.

Step 7: Run Analysis

Once all the inputs are done, click "Calculate Life Cycle Costs" box in the bottom and all calculations will be done. This step has to be performed for each alternative and also the scenario number has to be changed in the general parameters section every time while calculating the life cycle costs for different alternatives. VBA Macros has been used in the excel to run the analysis and calculate the life cycle costs. Net Present Value analysis is being used to calculate the life cycle costs which discounts all the life cycle costs to present. A suitable discount rate is assumed in the beginning.

Step 8: Review LCCA Results

Once, all the inputs for all the alternatives are done, you can go ahead and see the results on the "Results" tab. The results will provide the description of each cost during the life cycle and comparison of life cycle costs of different alternatives selected.

Step 9: Check if the results are reasonable

This step involves critically reviewing the results if there is any discrepancy visible in the overall results or any particular life cycle phase.

Step 10: Final Check

After critically reviewing the results, if the results seem appropriate, document the results and if any discrepancy occurs, you can go back any change the inputs and run the analysis again.

10.2.3. Objective 3: Develop Life Cycle Assessment Model

Life cycle assessment in this model involves calculation of the greenhouse gas production and comparing different materials. The greenhouse gas production is calculated for the pipe manufacturing and pipe operations phase with the formulas given below. The other life cycle phases – pipe transportation, installation, renewal and pipe disposal have not been considered here.

- **Capital Greenhouse Gas Production (Pipe Production) (Kang and Lansey 2010)**

$$\mathbf{GHG_{cap} = EF \times \sum_{i=1}^{n} EE(pipe_i)}$$

Where, EF is the emission factor converting the energy into GHG emissions and EE is the embodied energy required to produce a pipe. An emission factor of 1.042 kg CO_2 equivalent per kWh has been used (Wu et al. 2009). A specific value of total embodied energy for pipes has been provided in Ambrose et al. (2002). For example, for PVC pipes, total embodied energy is 74.9 MJ/kg. 1kWh is equivalent to 3.6 MJ.

- **Operating Greenhouse Gas Production (Pipe Operations) (Kang and Lansey 2010)**

$$\boldsymbol{GHG_{oprt} = EF \times NP_a \times AE \times LD_{pump}}$$

$$\boldsymbol{AE = 0.746 \times H_{pump} \times 24 \times {}^{365}/_{n}}$$

Where, AE is the annual electricity consumption of pumps in kWh, H_{pump} is the Horse power of the pump, LD_{pump} is the design period of the pump in years and n is the efficiency of the pump system.

10.2.4. Objective 4: Pilot the model with Utility Data

The model has been piloted with Utility A's data and the name of the utility has not been mentioned here due to confidentiality reasons. The ten step process was followed and the results have been shown in the next chapter.

Chapter 11 : Piloting with Utility A's Data

Based on the research gaps found and the research methodology explained in previous chapters, the holistic life cycle cost analysis model has been piloted with Utility A's data to validate the robustness of the cost structure and LCCA and LCA model proposed. As mentioned earlier, LCCA model can compare different pipe materials, pipe installation, condition assessment, rehabilitation and replacement technologies and three case studies have been provided here regarding comparison of pipe materials, installation technologies and rehabilitation technologies. Also, one case study has been provided for life cycle assessment with comparison of pipe materials as mentioned earlier. A sensitivity analysis has also been performed while comparing different pipe materials in the LCCA section.

11.1. Data Received from Utility A and Gaps Filled

The following Table 11-1 shows the data received from the utility in green filled boxes and the data gaps filled through estimated costs with the help of literature and previous surveys filled in blue.

Table 11-1: Data Received from Utility A and Filled Gaps

Cost Category	**Utility Data**	**Estimated Costs from Literature and Previous Surveys**
Planning and Design Costs		🟦
Pipe Installation Costs	🟩	
Pipe Condition Assessment Costs	🟩	
Pipe Repair and Rehabilitation Costs	🟩	
Pipe Replacement Costs		🟦
Consequence (Indirect) Costs due to Condition Assessment		🟦
Consequence (Indirect) Costs due to Pipe Renewal		🟦

Recurring Costs		
Disposal Costs		

11.2. Life Cycle Cost Analysis Piloting

11.2.1. Case Study 1: Comparison of Pipe Materials

The ten step process was followed here as shown below.

Step 1: Introduction to LCCA

According to the scope of this tool, one of the five scenarios can be considered. Scenario 1 has been chosen in this study which is the comparison of different pipe materials.

Step 2: Define Design Alternatives

Two pipe materials considered to be compared in this analysis are Material A and Material B of 4”-14” diameter range.

Step 3: Determine Different Activities

Following activities have been considered in this study shown in Table 11-2.

Table 11-2: Different Activities Considered in Case Study 1

Activity
Pipe Planning and Design
Pipe Installation
Pipe Repair
Condition Assessment
Pipe Rehabilitation
Pipe Replacement
End of Life

Step 4: Determine Different Activity Timings

Following Activity Timings have been considered as shown in Table 11-3.

Table 11-3: Activity Timings in Case Study 1

Activity	**Year**
Pipe Planning and Design	1
Pipe Installation	2
Pipe Repair	After every 15 years or 20 years
Condition Assessment	After every 15 years or 20 years
Pipe Rehabilitation	After year no. 25
Pipe Replacement	After year no. 50
End of Life	Year no. 50

Therefore, based on the activity timings, following six comparisons will be made in this case study as shown in Table 11-4.

Table 11-4: Six comparisons made in Case Study 1

No.	**Comparisons**			
	Pipe	Condition Assessment after every	Repair after every	Replacement after year no.
1	Material A	15 years	15 years	50
2	Material A	15 years	20 years	50
3	Material A	20 years	15 years	50
4	Material B	15 years	15 years	50
5	Material B	15 years	20 years	50
6	Material B	20 years	15 years	50

Step 5: Input General Parameters

Following general inputs have been considered in this case study as shown in Table 11-5.

Table 11-5: General Inputs used in Case Study 1

Pipe Related		
Parameter	Description	Value Assumed

Hazens William Factor	Hazen Williams C factor is used to determine the head loss in the flow.	Material A – 150 (New to year 10 and from 25 to 40), 140 (year 10 to 25 and 40 to 50)
		Material B - 150
Frequency of Installation of Fittings, Valves, Hydrants	Low Frequency: Fire hydrants every 800 ft. Medium Frequency: Fire hydrants every 500 ft. High Frequency: Fire Hydrants every 300 ft.	Medium
Fittings type	Fitting Material to be used (Ductile Iron Fittings, Steel Fittings etc.)	Ductile Iron Fittings
Average Flow	Water flow through the pipe (gallons per minute)	14000 gallons per minute
Approximate Proportion of pipe with water	This indicates how much pipe is full with water (Value 1 indicates that pipe is running full)	0.9
Environmental		
Soil Conditions	Type of Soil around the pipe (Sandy, Clay etc.)	Sandy clay Soil with 3/4:1 slope
Traffic Conditions	Traffic Flow near the pipe (Light, Medium, Heavy)	Heavy
Others		
Analysis Period	Common period of time to assess cost differences between different alternatives	50 years
Inflation rate	Inflation is the rate at which the general level of prices for goods and services is rising and, consequently, the purchasing power of currency is falling	2.5%
Discount Rate	Discount Rate is the Exchange Rate between Present and Future	5%
Unit Rate of Electricity	This indicate the cost of electricity per KWH	0.09 $/KWH

Total Efficiency of pump system	This indicates the efficiency of the pump system	0.9

Step 6: Input Cost Parameters

Alternative 1: Material A

Initial Costs

Table 11-6: Initial Costs for Material A

Assumed Value	10% of installation costs	

Installation Costs

Table 11-7: Installation Costs for Material A

Cost for Trenchless technology	$76.52/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	Included in the technology costs	
Labor Costs	Included in the technology costs	
Material Costs	Included in the technology costs	
Cost of Fittings, Valves, Hydrants	Included in the technology costs	
Trenching, Excavation and Backfilling Costs	Included in the technology costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the technology costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	Source: (Clark et al. 2002)
Construction Contingencies	8% of total installation costs	Source: (Welling and Sinha 2013)

Condition Assessment Costs

Table 11-8: Condition Assessment Costs for Material A

Condition Assessment Costs	$35/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	Included in the CA costs	
Labor Costs	Included in the CA costs	
Material Costs	Included in the CA costs	
Cost of Fittings, Valves, Hydrants	Included in the CA costs	
Trenching, Excavation and Backfilling Costs	Included in the CA costs	
Mobilization and Demobilization Costs	Included in the CA costs	

Repair Costs

Table 11-9: Repair Costs for Material A

Repair Costs	$16.08/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	$4.8/foot (2017 costs after inflation)	Source: (RSMeans 1996)
Labor Costs	$18.9/foot (2017 costs after inflation)	Source: (RSMeans 1996)
Material Costs	Included in the repair costs	
Cost of Fittings, Valves, Hydrants	N/A	
Trenching, Excavation and Backfilling Costs	3.6% of total repair costs	Source: (Rahman and Vanier 2004)
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the repair costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	Source: (Clark et al. 2002)
Construction Contingencies	8% of total repair costs	Source: Welling and Sinha 2013)

Rehabilitation Costs

Table 11-10: Rehabilitation Costs for Material A

Year	After year no. 25	
Rehabilitation Costs	\$69.5/foot (2017 costs after inflation)	Source: (Selvakumar et al. 2002)
Equipment Costs	\$4.8/foot (2017 costs after inflation)	Source: (RSMeans 1996)
Labor Costs	\$18.9/foot (2017 costs after inflation)	Source: (RSMeans 1996)
Material Costs	Included in the rehabilitation costs	
Cost of Fittings, Valves, Hydrants	N/A	
Trenching, Excavation and Backfilling Costs	Included in the rehabilitation costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the rehabilitation costs	
Traffic Control Costs	\$1.35/foot (2017 costs after inflation)	Source: (Clark et al. 2002)
Construction Contingencies	8% of total rehabilitation costs	Source: (Welling and Sinha 2013)

Replacement Costs

Table 11-11: Replacement Costs for Material A

Replacement Costs	\$120/foot (2017 costs after inflation)	Source: (Rahman and Vanier 2004)
Equipment Costs	\$4.8/foot (2017 costs after inflation)	Source: (RSMeans 1996)
Labor Costs	\$18.9/foot (2017 costs after inflation)	Source: (RSMeans 1996)
Material Costs	Included in the replacement costs	

Cost of Fittings, Valves, Hydrants	Included in the replacement costs	
Trenching, Excavation and Backfilling Costs	Included in the replacement costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the replacement costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	Source: (Clark et al. 2002)
Construction Contingencies	8% of total rehabilitation costs	Source: (Welling and Sinha 2013)

Indirect Costs

Table 11-12: Indirect Costs for Material A

Indirect Costs due to Condition Assessment	58% of Total Condition Assessment Costs	Source: (Welling and Sinha 2013)
Indirect Costs due to Repair	28% of Total Repair Costs	Source: (Welling and Sinha 2013)
Indirect Costs due to Rehabilitation	28% of Total Rehabilitation Costs	Source: (Welling and Sinha 2013)
Indirect Costs due to Replacement	28% of Total Replacement Costs	Source: (Welling and Sinha 2013)

Recurring Costs

Table 11-13: Recurring Costs for Material A

Pumping Costs due to Frictional Head Loss	$36.5/year/foot (New Pipe to year 10) $41.39/year/foot (Year 10 to 25) $36.5/year/foot (Year 25 to 40) $41.39/year/foot (Year 40 to 50)	

Disposal Costs

Table 11-14: Disposal Costs for Material A

Disposal Costs	2% of Replacement Costs	Source: (WERF 2013)

Alternative 2: Material B

Initial Costs

Table 11-15: Initial Costs for Material B

Assumed Value	10% of installation costs	

Installation Costs

Table 11-16: Installation Costs for Material B

Cost for Trenchless technology	$74.39/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	Included in the technology costs	
Labor Costs	Included in the technology costs	
Material Costs	Included in the technology costs	
Cost of Fittings, Valves, Hydrants	Included in the technology costs	
Trenching, Excavation and Backfilling Costs	Included in the technology costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the technology costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total installation costs	

Condition Assessment Costs

Table 11-17: Condition Assessment Costs for Material B

Condition Assessment Costs	$11/foot (2017 costs after inflation)	Source: Utility Data

Equipment Costs	Included in the CA costs	
Labor Costs	Included in the CA costs	
Material Costs	Included in the CA costs	
Cost of Fittings, Valves, Hydrants	Included in the CA costs	
Trenching, Excavation and Backfilling Costs	Included in the CA costs	
Mobilization and Demobilization Costs	Included in the CA costs	

Repair Costs

Table 11-18: Repair Costs for Material B

Repair Costs	$10.38/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the repair costs	
Cost of Fittings, Valves, Hydrants	N/A	
Trenching, Excavation and Backfilling Costs	3.6% of total repair costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the repair costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total repair costs	

Rehabilitation Costs

Table 11-19: Rehabilitation Costs for Material B

Year	After year no. 25	
Rehabilitation Costs	$69.5/foot (2017 costs after inflation)	Source: (Selvakumar et al. 2002)

Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the rehabilitation costs	
Cost of Fittings, Valves, Hydrants	N/A	
Trenching, Excavation and Backfilling Costs	Included in the rehabilitation costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the rehabilitation costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total rehabilitation costs	

Replacement Costs

Table 11-20: Replacement Costs for Material B

Replacement Costs	$120/foot (2017 costs after inflation)	Source: (Rahman and Vanier 2004)
Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the replacement costs	
Cost of Fittings, Valves, Hydrants	Included in the replacement costs	
Trenching, Excavation and Backfilling Costs	Included in the replacement costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the replacement costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total rehabilitation costs	

Indirect Costs

Table 11-21: Indirect Costs for Material B

Indirect Costs due to Condition Assessment	58% of Total Condition Assessment Costs	
Indirect Costs due to Repair	28% of Total Repair Costs	
Indirect Costs due to Rehabilitation	28% of Total Rehabilitation Costs	
Indirect Costs due to Replacement	28% of Total Replacement Costs	

Recurring Costs

Table 11-22: Recurring Costs for Material B

Pumping Costs due to Frictional Head Loss	$36.5/year/foot	

Disposal Costs

Table 11-23: Disposal Costs for Material B

Disposal Costs	2% of Replacement Costs	

Step 7: Run Analysis

“Click Here to Calculate Life Cycle Costs” tab has been provided and is used to run analysis.

Step 8: Review LCCA Results

Following Results are obtained:

Summary of Costs

Table 11-24: Summary of all Life Cycle Costs for both Material A and Material B

Costs	Material A	Material B
Initial Costs	$8.41/foot	$8.18/foot
Installation Costs	$84.1/foot	$81.8/foot
Condition Assessment Costs	$38/foot	$12/foot
Repair Costs	$46.1/foot	$22.1/foot

Rehabilitation Costs	$102.1/foot	$85.1/foot
Replacement Costs	$156.7/foot	$138.2/foot
Indirect Costs	$22.1/foot (CA), $13/foot (Repair), $28.6/foot (Rehab), $43.9/foot (Replace)	$7/foot (CA), $6.2/foot (Repair), $23.9/foot (Rehab), $38.7/foot (Replace)
Recurring Costs	$36.5/foot (year 1 to 10), $41.4/foot (year 15 to 25) $36.5/foot (year 25 to 40), $41.4/foot (year 40 to 50)	$36.5/foot (year 1 to 50),
Disposal Costs	$3.2/foot	$2.8/foot

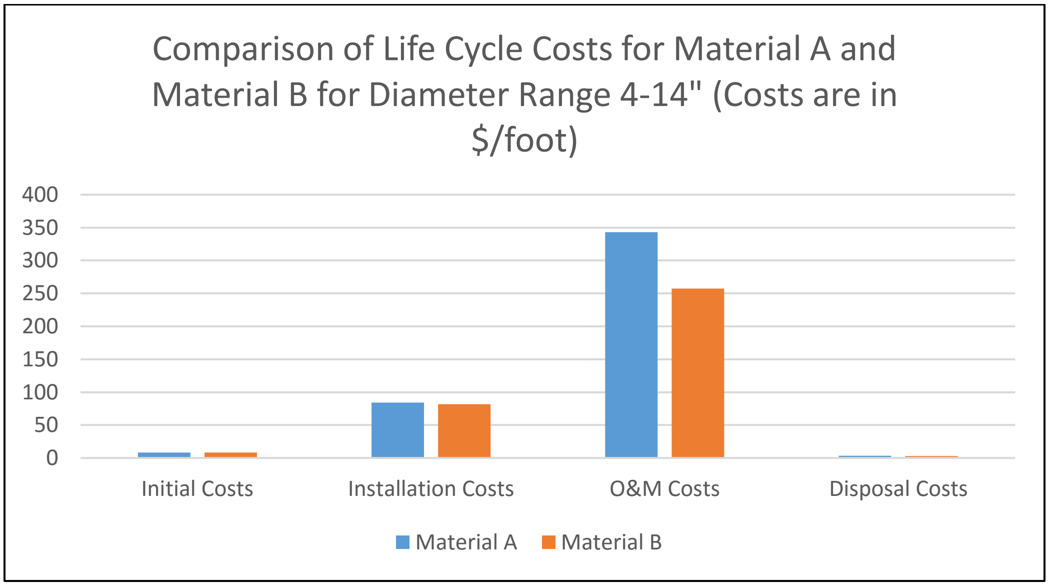


Figure 11-1: Comparison of Life Cycle Costs for Material A and Material B

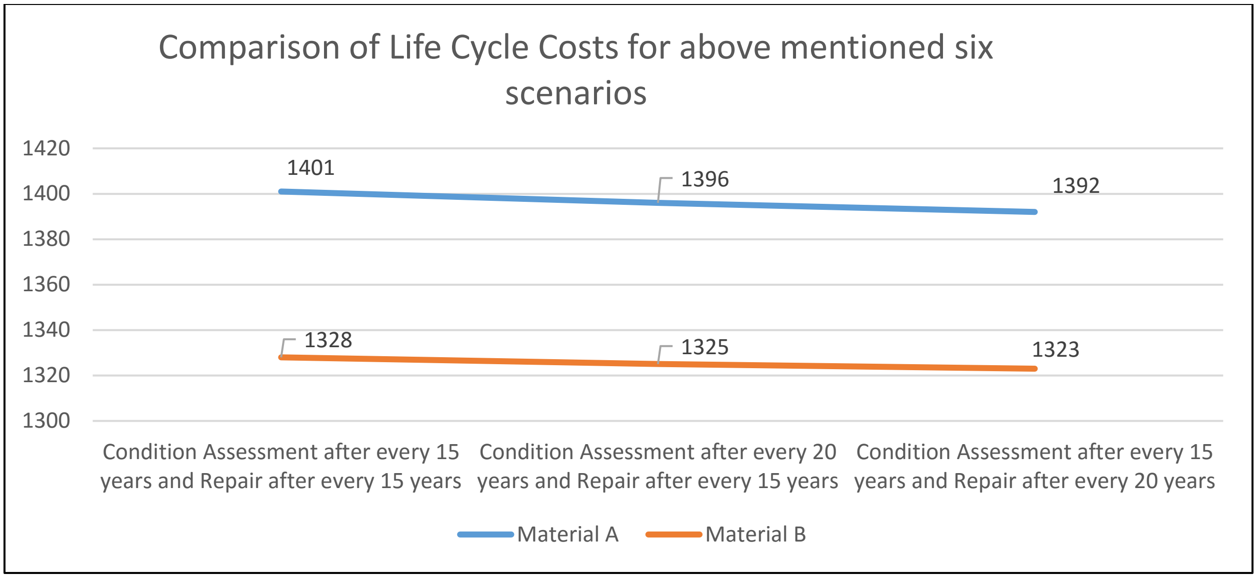


Figure 11-2: Comparison Shown for Six Cases for Material A and Material B

The following Table 11-25 shows a tabular summary of life cycle cost comparison shown in the Figure 11-2 above.

Table 11-25: Tabular Description of Life Cycle Costs for Six Different Comparisons

No.	Comparison Details	Life Cycle Costs
1	Material A, CA – 15 years, Repair – 15 years	$1401/foot
2	Material A, CA – 15 years, Repair – 20 years	$1396/foot
3	Material A, CA – 20 years, Repair – 15 years	$1392/foot
4	Material B, CA – 15 years, Repair – 15 years	$1328/foot
5	Material B, CA – 15 years, Repair – 20 years	$1323/foot
6	Material B, CA – 20 years, Repair – 15 years	$1325/foot

Step 9: Check if results are reasonable

The analysis shows that the life cycle costs of Material B are less than the costs for Material A. The major difference in the costs come from the Operation and Maintenance phase which seems reasonable because the pumping costs are a major factor in the operations phase and the Hazen Williams factor of Material A pipe is decreasing with time. This results in more pumping costs as compared to Material B.

Step 10: Final check

Since the results seems reasonable, the analysis ends here.

Sensitivity Analysis

A sensitivity analysis has also been carried out in this case study in which analysis period has been varied. Three scenarios of different analysis periods of 50 years, 75 years and 100 years respectively have been considered and results have been compared. The analysis for 50 years' service life has been carried out earlier and similarly analysis for 75 years and 100 years has been carried out. The scenarios considered are:

Table 11-26: Comparisons for Analysis Period = 75 years

No.	**Comparisons**				
	Pipe	Condition Assessment after every	Repair after every	Rehab after year no.	Replacement after year no.
1	Material A	15 years	15 years	35	75
2	Material A	15 years	20 years	35	75
3	Material A	20 years	15 years	35	75
4	Material B	15 years	15 years	35	75
5	Material B	15 years	20 years	35	75
6	Material B	20 years	15 years	35	75

Table 11-27: Comparisons for Analysis Period = 100 years

No.	**Comparisons**				
	Pipe	Condition Assessment after every	Repair after every	Rehab after year no.	Replacement after year no.
1	Material A	15 years	15 years	50	100
2	Material A	15 years	20 years	50	100
3	Material A	20 years	15 years	50	100
4	Material B	15 years	15 years	50	100
5	Material B	15 years	20 years	50	100
6	Material B	20 years	15 years	50	100

The results obtained are as follows:

Table 11-28: Analysis Results for Analysis Period = 75 years

No.	Comparison Details	Life Cycle Costs
1	Material A, CA – 15 years, Repair – 15 years	$1651/foot
2	Material A, CA – 15 years, Repair – 20 years	$1647/foot
3	Material A, CA – 20 years, Repair – 15 years	$1643/foot
4	Material B, CA – 15 years, Repair – 15 years	$1521/foot
5	Material B, CA – 15 years, Repair – 20 years	$1516/foot
6	Material B, CA – 20 years, Repair – 15 years	$1513/foot

Table 11-29: Analysis Results for Analysis Period = 100 years

No.	Comparison Details	Life Cycle Costs
1	Material A, CA – 15 years, Repair – 15 years	$1743/foot
2	Material A, CA – 15 years, Repair – 20 years	$1738/foot
3	Material A, CA – 20 years, Repair – 15 years	$1734/foot
4	Material B, CA – 15 years, Repair – 15 years	$1636/foot
5	Material B, CA – 15 years, Repair – 20 years	$1631/foot
6	Material B, CA – 20 years, Repair – 15 years	$1625/foot

11.2.2. Case Study 2: Comparison of Pipe Installation Technologies

The ten step process was followed here as shown below:

Step 1: Introduction to LCCA

According to the scope of this tool, one of the five scenarios can be considered. Scenario 2 has been chosen in this case study which is the comparison of different pipe installation technologies.

Step 2: Define Design Alternatives

Two pipe installation technologies considered to be compared in this case study are Technology A and Technology B for Material A.

Step 3: Determine Different Activities

Following activities shown in Table 11-30 have been considered in this case study:

Table 11-30: Different Activities Considered in Case Study 2

Activity
Pipe Planning and Design
Pipe Installation
Pipe Repair
Condition Assessment
Pipe Rehabilitation
Pipe Replacement
End of Life

Step 4: Determine Different Activity Timings

Following Activity Timings have been considered:

Table 11-31: Activity Timings in Case Study 2

Activity	**Year**
Pipe Planning and Design	1
Pipe Installation	2
Pipe Repair	After every 15 years or 20 years
Condition Assessment	After every 15 years or 20 years
Pipe Rehabilitation	After year no. 25
Pipe Replacement	After year no. 50
End of Life	Year no. 50

Therefore, based on the activity timings, following six comparisons will be made in this case study:

Table 11-32: Six Comparisons made in Case Study 2

No.	**Comparisons**			
	Installation Technology	Condition Assessment after every	Repair after every	Replacement after year no.
1	A	15 years	15 years	50

2	A	15 years	20 years	50
3	A	20 years	15 years	50
4	B	15 years	15 years	50
5	B	15 years	20 years	50
6	B	20 years	15 years	50

Step 5: Input General Parameters

Following general inputs have been considered in this case study:

Table 11-33: General Inputs in Case Study 2

Pipe Related		
Parameter	Description	Value Assumed
Hazens William Factor	Hazen Williams C factor is used to determine the head loss in the flow.	Material A - 150
Frequency of Installation of Fittings, Valves, Hydrants	Low Frequency: Fire hydrants every 800 ft. Medium Frequency: Fire hydrants every 500 ft. High Frequency: Fire Hydrants every 300 ft.	Medium
Fittings type	Fitting Material to be used (Ductile Iron Fittings, Steel Fittings etc.)	Ductile Iron Fittings
Average Flow	Water flow through the pipe (gallons per minute)	14000 gallons per minute
Approximate Proportion of pipe with water	This indicates how much pipe is full with water (Value 1 indicates that pipe is running full)	0.9
Environmental		
Soil Conditions	Type of Soil around the pipe (Sandy, Clay etc.)	Sandy clay Soil with 3/4:1 slope
Traffic Conditions	Traffic Flow near the pipe (Light, Medium, Heavy)	Heavy

Others		
Analysis Period	Common period of time to assess cost differences between different alternatives	50 years
Inflation rate	Inflation is the rate at which the general level of prices for goods and services is rising and, consequently, the purchasing power of currency is falling	2.5%
Discount Rate	Discount Rate is the Exchange Rate between Present and Future	5%
Unit Rate of Electricity	This indicate the cost of electricity per KWH	0.09 $/KWH
Total Efficiency of pump system	This indicates the efficiency of the pump system	0.9

Step 6: Input Cost Parameters

Alternative 1: Pipe Installation Technology A

Initial Costs

Table 11-34: Initial Costs for Alternative 1: Installation Technology A

Assumed Value	10% of installation costs	

Installation Costs

Table 11-35: Installation Costs for Alternative 1: Installation Technology A

Installation Trenchless Technology Used	Technology A	
Cost for Trenchless technology	$30/foot (2017 costs after inflation)	Source: (Selvakumar et. al 2002)
Equipment Costs	Included in the technology costs	
Labor Costs	Included in the technology costs	
Material Costs	Included in the technology costs	
Cost of Fittings, Valves, Hydrants	Included in the technology costs	

Trenching, Excavation and Backfilling Costs	Included in the technology costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the technology costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total installation costs	

Condition Assessment Costs

Table 11-36: Condition Assessment Costs for Alternative 1: Installation Technology A

Condition Assessment Costs	$11/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	Included in the CA costs	
Labor Costs	Included in the CA costs	
Material Costs	Included in the CA costs	
Cost of Fittings, Valves, Hydrants	Included in the CA costs	
Trenching, Excavation and Backfilling Costs	Included in the CA costs	
Mobilization and Demobilization Costs	Included in the CA costs	

Repair Costs

Table 11-37: Repair Costs for Alternative 1: Installation Technology A

Repair Costs	$10.38/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the repair costs	
Cost of Fittings, Valves, Hydrants	N/A	

Trenching, Excavation and Backfilling Costs	3.6% of total repair costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the repair costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total repair costs	

Rehabilitation Costs

Table 11-38: Rehabilitation Costs for Alternative 1: Installation Technology A

Year	After year no. 25	
Rehabilitation Costs	$69.5/foot (2017 costs after inflation)	Source: (Selvakumar et al. 2002)
Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the rehabilitation costs	
Cost of Fittings, Valves, Hydrants	N/A	
Trenching, Excavation and Backfilling Costs	Included in the rehabilitation costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the rehabilitation costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total rehabilitation costs	

Replacement Costs

Table 11-39: Replacement Costs for Alternative 1: Installation Technology A

Replacement Costs	$120/foot (2017 costs after inflation)	Source: (Rahman and Vanier 2004)
Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the replacement costs	
Cost of Fittings, Valves, Hydrants	Included in the replacement costs	
Trenching, Excavation and Backfilling Costs	Included in the replacement costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the replacement costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total rehabilitation costs	

Indirect Costs

Table 11-40: Indirect Costs for Alternative 1: Installation Technology A

Indirect Costs due to Condition Assessment	58% of Total Condition Assessment Costs	
Indirect Costs due to Repair	28% of Total Repair Costs	
Indirect Costs due to Rehabilitation	28% of Total Rehabilitation Costs	
Indirect Costs due to Replacement	28% of Total Replacement Costs	

Recurring Costs

Table 11-41: Recurring Costs for Alternative 1: Installation Technology A

Pumping Costs due to Frictional Head Loss	$36.5/year/foot	

Disposal Costs

Table 11-42: Disposal Costs for Alternative 1: Installation Technology A

Disposal Costs	2% of Replacement Costs	

Alternative 2: Pipe Installation Technology B

Initial Costs

Table 11-43: Initial Costs for Alternative 2: Installation Technology B

Assumed Value	10% of installation costs	

Installation Costs

Table 11-44: Installation Costs for Alternative 2: Installation Technology B

Installation Trenchless Technology Used	Technology B	
Cost for Trenchless technology	$22/foot (2017 costs after inflation)	Source: (Selvakumar et al. 2002)
Equipment Costs	Included in the technology costs	
Labor Costs	Included in the technology costs	
Material Costs	Included in the technology costs	
Cost of Fittings, Valves, Hydrants	Included in the technology costs	
Trenching, Excavation and Backfilling Costs	Included in the technology costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the technology costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total installation costs	

Condition Assessment Costs

Table 11-45: Condition Assessment Costs for Alternative 2: Installation Technology B

Condition Assessment Costs	$11/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	Included in the CA costs	
Labor Costs	Included in the CA costs	
Material Costs	Included in the CA costs	
Cost of Fittings, Valves, Hydrants	Included in the CA costs	
Trenching, Excavation and Backfilling Costs	Included in the CA costs	
Mobilization and Demobilization Costs	Included in the CA costs	

Repair Costs

Table 11-46: Repair Costs for Alternative 2: Installation Technology B

Repair Costs	$10.38/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the repair costs	
Cost of Fittings, Valves, Hydrants	N/A	
Trenching, Excavation and Backfilling Costs	3.6% of total repair costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the repair costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total repair costs	

Rehabilitation Costs

Table 11-47: Rehabilitation Costs for Alternative 2: Installation Technology B

Year	After year no. 25	
Rehabilitation Costs	\$69.5/foot (2017 costs after inflation)	Source: (Selvakumar et al. 2002)
Equipment Costs	\$0.65/foot (2017 costs after inflation)	
Labor Costs	\$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the rehabilitation costs	
Cost of Fittings, Valves, Hydrants	N/A	
Trenching, Excavation and Backfilling Costs	Included in the rehabilitation costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the rehabilitation costs	
Traffic Control Costs	\$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total rehabilitation costs	

Replacement Costs

Table 11-48: Replacement Costs for Alternative 2: Installation Technology B

Replacement Costs	\$120/foot (2017 costs after inflation)	Source: (Rahman and Vanier 2004)
Equipment Costs	\$0.65/foot (2017 costs after inflation)	
Labor Costs	\$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the replacement costs	
Cost of Fittings, Valves, Hydrants	Included in the replacement costs	
Trenching, Excavation and Backfilling Costs	Included in the replacement costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	

Mobilization and Demobilization Costs	Included in the replacement costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total rehabilitation costs	

Indirect Costs

Table 11-49: Indirect Costs for Alternative 2: Installation Technology B

Indirect Costs due to Condition Assessment	58% of Total Condition Assessment Costs	
Indirect Costs due to Repair	28% of Total Repair Costs	
Indirect Costs due to Rehabilitation	28% of Total Rehabilitation Costs	
Indirect Costs due to Replacement	28% of Total Replacement Costs	

Recurring Costs

Table 11-50: Recurring Costs for Alternative 2: Installation Technology B

Pumping Costs due to Frictional Head Loss	$36.5/year/foot	

Disposal Costs

Table 11-51: Disposal Costs for Alternative 2: Installation Technology B

Disposal Costs	2% of Replacement Costs	

Step 7: Run Analysis

“Click Here to Calculate Life Cycle Costs” tab has been provided and is used to run analysis.

Step 8: Review LCCA Results

Following Results are obtained:

Summary of Costs

Table 11-52: Summary of all Life Cycle Costs for both Installation Technology A and B

Costs	Technology A	Technology B
Initial Costs	$3.4/foot	$2.2/foot
Installation Costs	$34/foot	$22/foot
Condition Assessment Costs	$12/foot	$12/foot
Repair Costs	$22.1/foot	$22.1/foot
Rehabilitation Costs	$85.1/foot	$85.1/foot
Replacement Costs	$138.2/foot	$138.2/foot
Indirect Costs	$7/foot (CA), $6.2/foot (Repair), $23.9/foot (Rehab), $38.7/foot (Replace)	$7/foot (CA), $6.2/foot (Repair), $23.9/foot (Rehab), $38.7/foot (Replace)
Recurring Costs	$36.5/foot (year 1 to 50),	$36.5/foot (year 1 to 50),
Disposal Costs	$2.8/foot	$2.8/foot

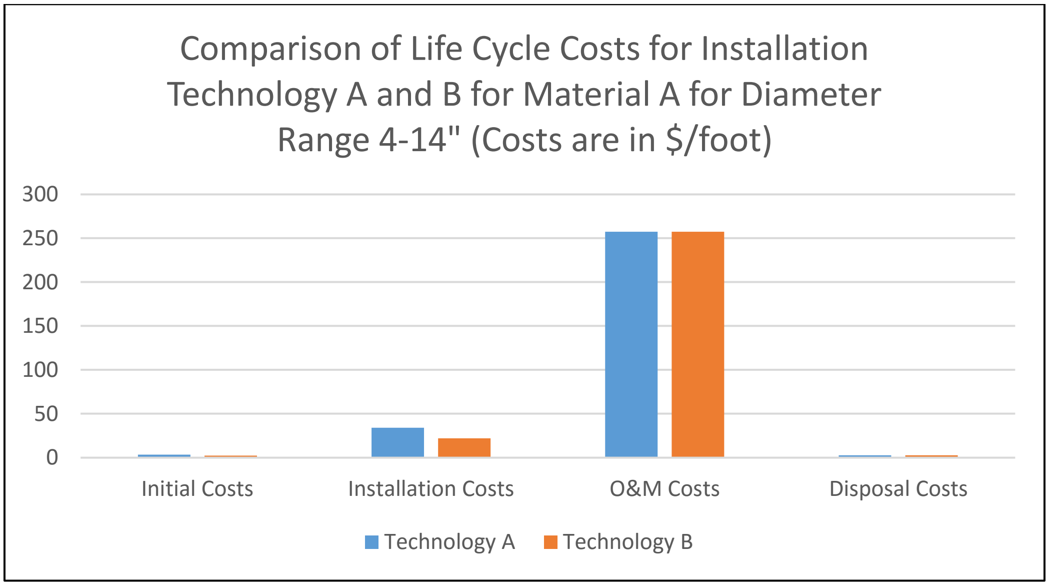


Figure 11-3: Comparison of Life Cycle Costs for Installation Technology A and B

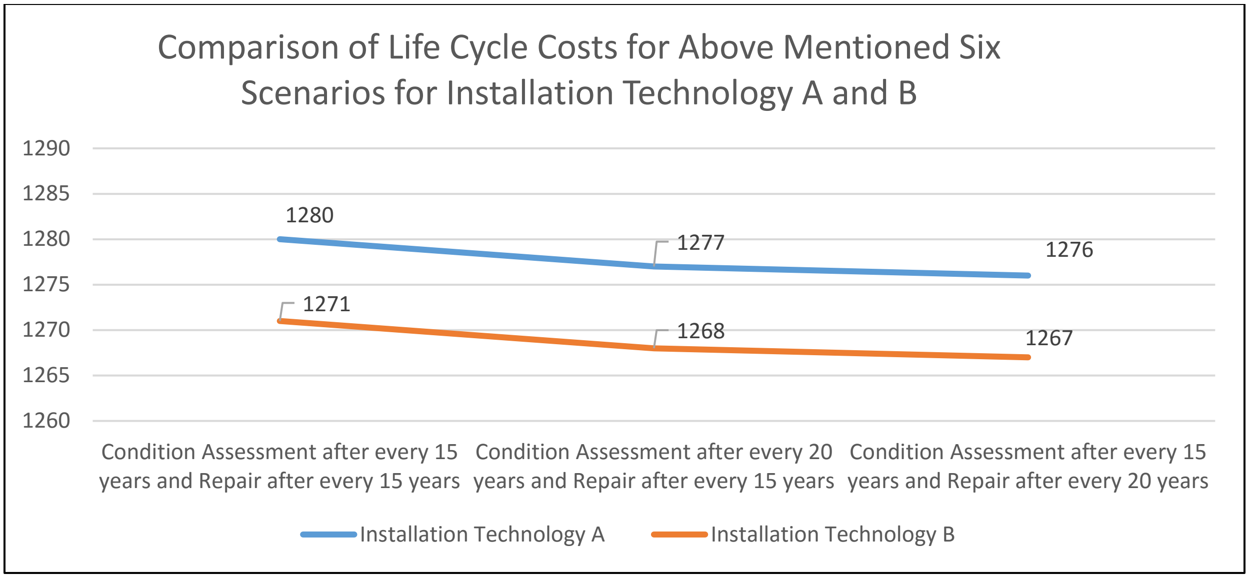


Figure 11-4: Comparison Shown for Six Cases for Installation Technology A and B

The following table shows a tabular description of comparison of life cycle costs for installation technology A and B with respect to six comparisons shown in Figure 11-4.

Table 11-53: Tabular Description of Life Cycle Costs for Six Different Comparisons for Installation Technology A and B

No.	Comparison Details	Life Cycle Costs
1	Installation Technology – A, CA – 15 years, Repair – 15 years	$1280/foot
2	Installation Technology – A, CA – 15 years, Repair – 20 years	$1277/foot
3	Installation Technology – A, CA – 20 years, Repair – 15 years	$1276/foot
4	Installation Technology – B, CA – 15 years, Repair – 15 years	$1271/foot
5	Installation Technology – B, CA – 15 years, Repair – 20 years	$1268/foot
6	Installation Technology – B, CA – 20 years, Repair – 15 years	$1267/foot

Step 9: Check if results are reasonable

The analysis shows that the life cycle costs for Technology A are more than the Technology B for Material A.

Step 10: Final check

Since the results seems reasonable, the analysis ends here.

11.2.3. Case Study 3: Comparison of Pipe Rehabilitation Technologies

The ten step process was followed here as shown below:

Step 1: Introduction to LCCA

According to the scope of this tool, one of the five scenarios can be considered. Scenario 3 has been chosen in this study which is the comparison of different pipe rehabilitation technologies.

Step 2: Define Design Alternatives

Two pipe rehabilitation technologies considered to be compared in this analysis are Technology A and Technology B for Material A.

Step 3: Determine Different Activities

Following activities have been considered in this study:

Table 11-54: Different Activities Considered in Case Study 3

Activity
Pipe Planning and Design
Pipe Installation
Pipe Repair
Condition Assessment
Pipe Rehabilitation
Pipe Replacement
End of Life

Step 4: Determine Different Activity Timings

Following Activity Timings have been considered:

Table 11-55: Activity Timings in Case Study 3

Activity	**Year**
Pipe Planning and Design	1
Pipe Installation	2
Pipe Repair	After every 15 years or 20 years
Condition Assessment	After every 15 years or 20 years
Pipe Rehabilitation	After year no. 25
Pipe Replacement	After year no. 50
End of Life	Year no. 50

Therefore, based on the activity timings, following six comparisons will be made in this case study:

Table 11-56: Six Comparisons made in Case Study 3

No.	**Comparisons**			
	Rehabilitation Technology	Condition Assessment after every	Repair after every	Replacement after year no.
1	A	15 years	15 years	50
2	A	15 years	20 years	50
3	A	20 years	15 years	50
4	B	15 years	15 years	50
5	B	15 years	20 years	50
6	B	20 years	15 years	50

Step 5: Input General Parameters

Following general inputs have been considered in this case study:

Table 11-57: General Inputs used in Case Study 3

Pipe Related		
Parameter	Description	Value Assumed

Hazens William Factor	Hazen Williams C factor is used to determine the head loss in the flow.	Material A - 150
Frequency of Installation of Fittings, Valves, Hydrants	Low Frequency: Fire hydrants every 800 ft. Medium Frequency: Fire hydrants every 500 ft. High Frequency: Fire Hydrants every 300 ft.	Medium
Fittings type	Fitting Material to be used (Ductile Iron Fittings, Steel Fittings etc.)	Ductile Iron Fittings
Average Flow	Water flow through the pipe (gallons per minute)	14000 gallons per minute
Approximate Proportion of pipe with water	This indicates how much pipe is full with water (Value 1 indicates that pipe is running full)	0.9
Environmental		
Soil Conditions	Type of Soil around the pipe (Sandy, Clay etc.)	Sandy clay Soil with 3/4:1 slope
Traffic Conditions	Traffic Flow near the pipe (Light, Medium, Heavy)	Heavy
Others		
Analysis Period	Common period of time to assess cost differences between different alternatives	50 years
Inflation rate	Inflation is the rate at which the general level of prices for goods and services is rising and, consequently, the purchasing power of currency is falling	2.5%
Discount Rate	Discount Rate is the Exchange Rate between Present and Future	5%
Unit Rate of Electricity	This indicate the cost of electricity per KWH	0.09 $/KWH
Total Efficiency of pump system	This indicates the efficiency of the pump system	0.9

Step 6: Input Cost Parameters

Alternative 1: Pipe Rehab Technology A

Initial Costs

Table 11-58: Initial Costs for Alternative 1: Rehab Technology A

Assumed Value	10% of installation costs	

Installation Costs

Table 11-59: Installation Costs for Alternative 1: Rehab Technology A

Cost for Trenchless technology	$30/foot (2017 costs after inflation)	Source: (Selvakumar et. al 2002)
Equipment Costs	Included in the technology costs	
Labor Costs	Included in the technology costs	
Material Costs	Included in the technology costs	
Cost of Fittings, Valves, Hydrants	Included in the technology costs	
Trenching, Excavation and Backfilling Costs	Included in the technology costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the technology costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total installation costs	

Condition Assessment Costs

Table 11-60: Condition Assessment Costs for Alternative 1: Rehab Technology A

Condition Assessment Costs	$11/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	Included in the CA costs	
Labor Costs	Included in the CA costs	
Material Costs	Included in the CA costs	

Cost of Fittings, Valves, Hydrants	Included in the CA costs	
Trenching, Excavation and Backfilling Costs	Included in the CA costs	
Mobilization and Demobilization Costs	Included in the CA costs	

Repair Costs

Table 11-61: Repair Costs for Alternative 1: Rehab Technology A

Repair Costs	$10.38/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the repair costs	
Cost of Fittings, Valves, Hydrants	N/A	
Trenching, Excavation and Backfilling Costs	3.6% of total repair costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the repair costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total repair costs	

Rehabilitation Costs

Table 11-62: Rehabilitation Costs for Alternative 1: Rehab Technology A

Rehabilitation Method Assumed	Technology A	
Year	After year no. 25	
Rehabilitation Costs	$60/foot (2017 costs after inflation)	Source: (Selvakumar et al. 2002)
Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	

Material Costs	Included in the rehabilitation costs	
Cost of Fittings, Valves, Hydrants	N/A	
Trenching, Excavation and Backfilling Costs	Included in the rehabilitation costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the rehabilitation costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total rehabilitation costs	

Replacement Costs

Table 11-63: Replacement Costs for Alternative 1: Rehab Technology A

Replacement Costs	$120/foot (2017 costs after inflation)	
Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the replacement costs	
Cost of Fittings, Valves, Hydrants	Included in the replacement costs	
Trenching, Excavation and Backfilling Costs	Included in the replacement costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the replacement costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total rehabilitation costs	

Indirect Costs

Table 11-64: Indirect Costs for Alternative 1: Rehab Technology A

Indirect Costs due to Condition Assessment	58% of Total Condition Assessment Costs	
Indirect Costs due to Repair	28% of Total Repair Costs	
Indirect Costs due to Rehabilitation	28% of Total Rehabilitation Costs	
Indirect Costs due to Replacement	28% of Total Replacement Costs	

Recurring Costs

Table 11-65: Recurring Costs for Alternative 1: Rehab Technology A

Pumping Costs due to Frictional Head Loss	$36.5/year/foot	

Disposal Costs

Table 11-66: Disposal Costs for Alternative 1: Rehab Technology A

Disposal Costs	2% of Replacement Costs	

Alternative 2: Pipe Rehab Technology B

Initial Costs

Table 11-67: Initial Costs for Alternative 2: Rehab Technology B

Assumed Value	10% of installation costs	

Installation Costs

Table 11-68: Installation Costs for Alternative 2: Rehab Technology B

Cost for Trenchless technology	$30/foot (2017 costs after inflation)	
Equipment Costs	Included in the technology costs	
Labor Costs	Included in the technology costs	
Material Costs	Included in the technology costs	
Cost of Fittings, Valves, Hydrants	Included in the technology costs	

Trenching, Excavation and Backfilling Costs	Included in the technology costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the technology costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total installation costs	

Condition Assessment Costs

Table 11-69: Condition Assessment Costs for Alternative 2: Rehab Technology B

Condition Assessment Costs	$11/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	Included in the CA costs	
Labor Costs	Included in the CA costs	
Material Costs	Included in the CA costs	
Cost of Fittings, Valves, Hydrants	Included in the CA costs	
Trenching, Excavation and Backfilling Costs	Included in the CA costs	
Mobilization and Demobilization Costs	Included in the CA costs	

Repair Costs

Table 11-70: Repair Costs for Alternative 2: Rehab Technology B

Repair Costs	$10.38/foot (2017 costs after inflation)	Source: Utility Data
Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the repair costs	
Cost of Fittings, Valves, Hydrants	N/A	

Trenching, Excavation and Backfilling Costs	3.6% of total repair costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the repair costs	
Traffic Control Costs	\$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total repair costs	

Rehabilitation Costs

Table 11-71: Rehabilitation Costs for Alternative 2: Rehab Technology B

Rehabilitation Method Assumed	Technology B	
Year	After year no. 25	
Rehabilitation Costs	\$120/foot (2017 costs after inflation)	
Equipment Costs	\$0.65/foot (2017 costs after inflation)	
Labor Costs	\$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the rehabilitation costs	
Cost of Fittings, Valves, Hydrants	N/A	
Trenching, Excavation and Backfilling Costs	Included in the rehabilitation costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the rehabilitation costs	
Traffic Control Costs	\$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total rehabilitation costs	

Replacement Costs

Table 11-72: Replacement Costs for Alternative 2: Rehab Technology B

Replacement Costs	\$120/foot (2017 costs after inflation)	

Equipment Costs	$0.65/foot (2017 costs after inflation)	
Labor Costs	$7.31/foot (2017 costs after inflation)	
Material Costs	Included in the replacement costs	
Cost of Fittings, Valves, Hydrants	Included in the replacement costs	
Trenching, Excavation and Backfilling Costs	Included in the replacement costs	
Dewatering	Not done	
Pavement removal and replacement	Not done	
Mobilization and Demobilization Costs	Included in the replacement costs	
Traffic Control Costs	$1.35/foot (2017 costs after inflation)	
Construction Contingencies	8% of total rehabilitation costs	

Indirect Costs

Table 11-73: Indirect Costs for Alternative 2: Rehab Technology B

Indirect Costs due to Condition Assessment	58% of Total Condition Assessment Costs	
Indirect Costs due to Repair	28% of Total Repair Costs	
Indirect Costs due to Rehabilitation	28% of Total Rehabilitation Costs	
Indirect Costs due to Replacement	28% of Total Replacement Costs	

Recurring Costs

Table 11-74: Recurring Costs for Alternative 2: Rehab Technology B

Pumping Costs due to Frictional Head Loss	$36.5/year/foot	

Disposal Costs

Table 11-75: Disposal Costs for Alternative 2: Rehab Technology B

Disposal Costs	2% of Replacement Costs	

Step 7: Run Analysis

"Click Here to Calculate Life Cycle Costs" tab has been provided and is used to run analysis.

Step 8: Review LCCA Results

Following Results are obtained:

Summary of Costs

Table 11-76: Summary of all Life Cycle Costs for Rehab Technology A and B

Costs	Technology A	Technology B
Initial Costs	\$3.4/foot	\$3.4/foot
Installation Costs	\$34/foot	\$34/foot
Condition Assessment Costs	\$12/foot	\$12/foot
Repair Costs	\$22.1/foot	\$22.1/foot
Rehabilitation Costs	\$75/foot	\$140/foot
Replacement Costs	\$138.2/foot	\$138.2/foot
Indirect Costs	\$7/foot (CA), \$6.2/foot (Repair), \$21/foot (Rehab), \$38.7/foot (Replace)	\$7/foot (CA), \$6.2/foot (Repair), \$38/foot (Rehab), \$38.7/foot (Replace)
Recurring Costs	\$36.5/foot (year 1 to 50),	\$36.5/foot (year 1 to 50),
Disposal Costs	\$2.8/foot	\$2.8/foot

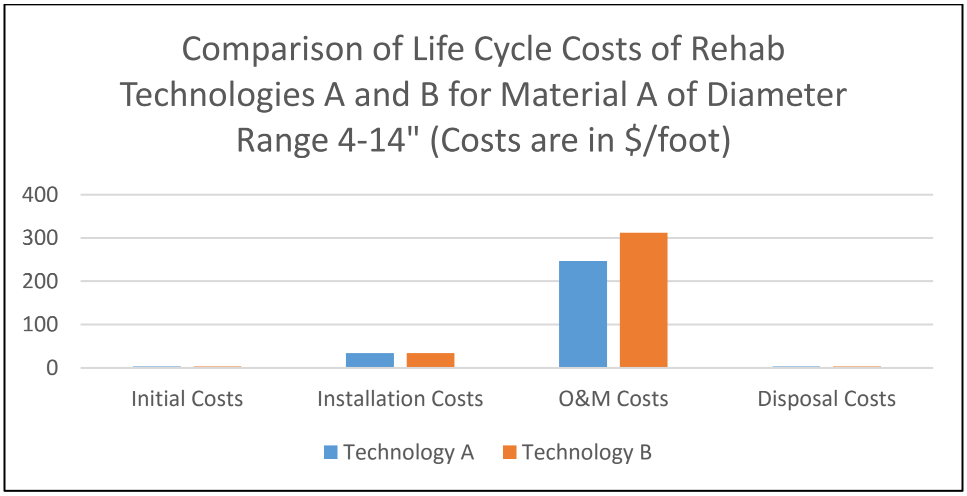


Figure 11-5: Comparison of Life Cycle Costs for Rehab Technologies A and B

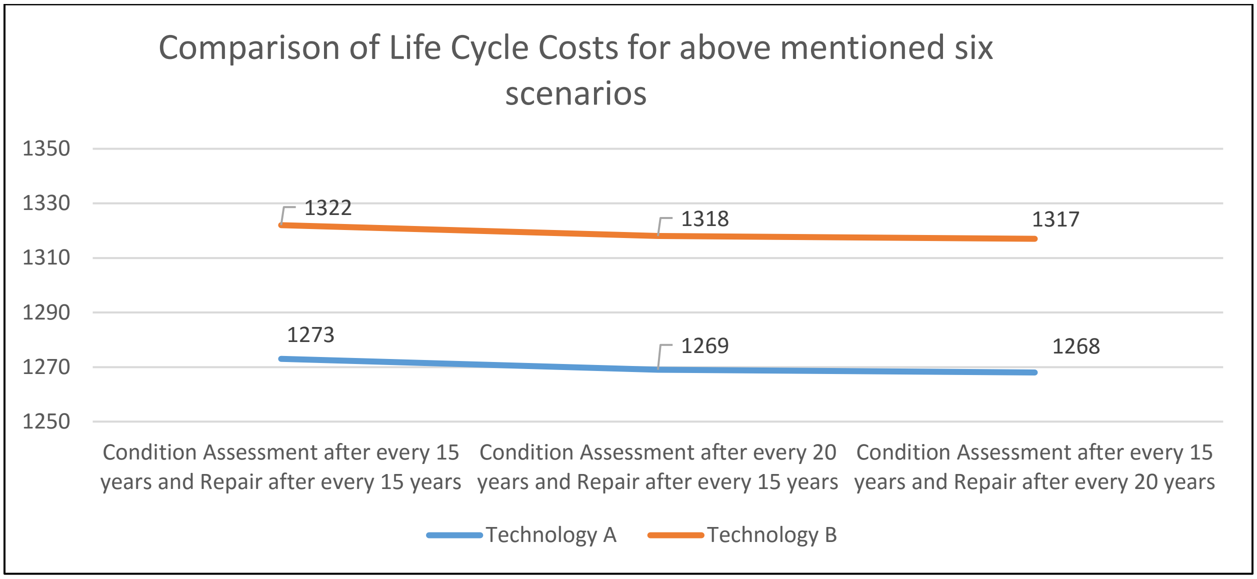


Figure 11-6: Comparison shown for six cases for Rehab Technology A and B

The following Table 11-77 shows a tabular description of comparison of life cycle costs for rehab technology A and B with respect to six comparisons shown in Figure 11-7.

Table 11-77: Tabular description of life cycle costs for six different comparisons

No.	Comparison Details	Life Cycle Costs
1	Rehabilitation Technology – A, CA – 15 years, Repair – 15 years	$1273/foot
2	Rehabilitation Technology – A, CA – 15 years, Repair – 20 years	$1269/foot
3	Rehabilitation Technology – A, CA – 20 years, Repair – 15 years	$1268/foot
4	Rehabilitation Technology – B, CA – 15 years, Repair – 15 years	$1322/foot
5	Rehabilitation Technology – B, CA – 15 years, Repair – 20 years	$1318/foot
6	Rehabilitation Technology – B, CA – 20 years, Repair – 15 years	$1317/foot

Step 9: Check if results are reasonable

The analysis shows that the life cycle costs of Technology B are more than for Technology A for material A.

Step 10: Final check

Since the results seems reasonable, the analysis ends here.

11.3. Life Cycle Assessment Piloting

Capital Greenhouse Gas Production

$$\mathbf{GHG_{cap} = EF \times \sum_{i=1}^{n} EE(pipe_i)}$$

Values Taken:

EF = 1.042 kg CO_2/kWh (Wu et al. 2010)

EE for Material A = 34.4 MJ/kg (Ambrose et al. 2002)

EE for Material B = 74.9 MJ/kg (Ambrose et al. 2002)

Therefore, GHG_cap for Material A (for 1 kg) = 1.042 x 34.4 / 3.6 = 9.95 kg CO_2

And, GHG_cap for Material B (for 1 kg) = 1.042 x 74.9 / 3.6 = 21.6 kg CO_2

Operating Greenhouse Gas Production

$$\boldsymbol{GHG_{oprt} = EF \times NP_a \times AE \times LD_{pump}}$$

$$\boldsymbol{AE = 0.746 \times H_{pump} \times 24 \times {}^{365}/_{n}}$$

Values Taken:

EF = 1.042 kg CO_2/kWh (Wu et al. 2010)

NP_a = 1

LD_{pump} = 50 years

H_{pump} = 5 horsepower (For Utility A)

n = 0.9 for Material B (For Utility A)

n = 0.7 for Material A (For Utility A)

AE for Material B = 0.746 x 5 x 24 x 365 / 0.9 = 36305 kWh

AE for Material A = 0.746 x 5 x 24 x 365 / 0.7 = 46680 kWh

GHG_oprt for Material A = 1.042 x 1 x 46680 x 50 = 2432 ‘000kg CO_2

GHG_oprt for Material B = 1.042 x 1 x 36305 x 50 = 1892 ‘000kg CO_2

Chapter 12 : Performance based Life Cycle Cost Analysis

The model in this research assumes the activity timings i.e. when the renewal activities will be carried out. This is not the optimal way to carry out life cycle cost analysis since variation from the right activity timings might result in incorrect life cycle cost calculations.

The ideal way to carry out life cycle cost analysis is to let the actual performance of the pipe dictate the timing of various activities. This means that the timing of the activity will be decided after predicting the performance of the pipe and optimizing the timing based upon that so that life cycle costs are the minimum. This is one way in which the model can be improved in the future by linking this study with the performance curve of the pipe rather than assuming the activity timings. An example of this type of linking has been shown in the following Figure 12-1.

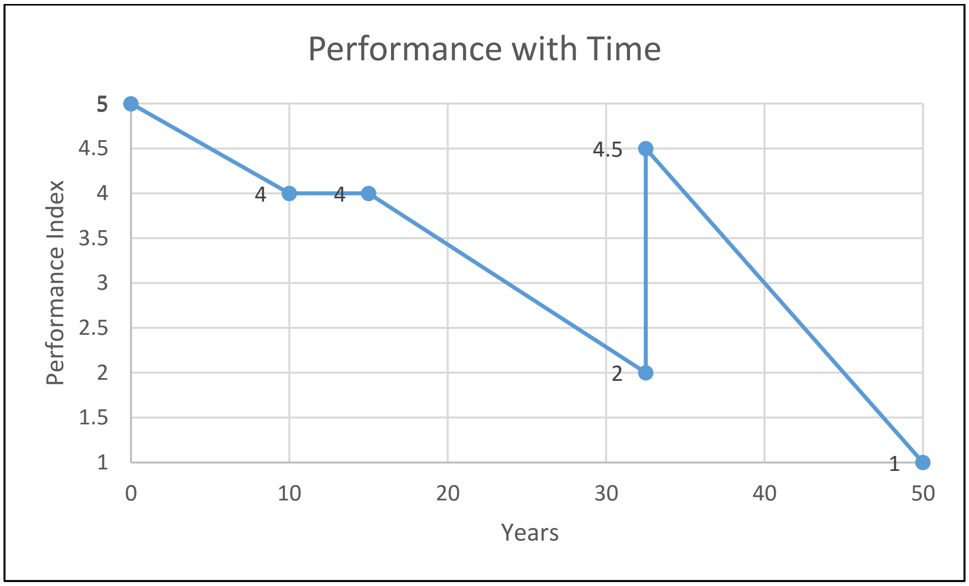


Figure 12-1: Performance Curve for a Pipe

The pipe age here has been assumed to be 50 years. The pipe performance of the pipe has been considered on a scale of 1-5 with 5 being the excellent performance and 1 being the failing performance. The pipe performance has been considered 5 after installation and it is assumed that the installation has been done in a correct way and there are no premature failures. The user has been given the option to decide their tolerance level i.e. at which performance index, the first repair activity should be done. It is assumed here that the first repair will be done when the pipe performance reaches a level of 4. Considering a straight line deterioration, the performance level becomes 4 in the year no. 10. So, first repair activity is done in the year no. 10. Since, we know that the repair activity doesn’t increase the performance level from the current level but it delays the deterioration process. So, it is assumed that the performance of the pipe will stay at a level of 4 for five more years and it will start deteriorating after that. The major rehabilitation activity is assumed to occur when the performance level drops down to a level of 2. The rehabilitation activity increases the current performance level of a pipe and it is assumed to jump up the performance level from a level of 2 to 4.5. The rehabilitation activity is performed in the year no. 33. After that, the performance deteriorates in a straight line pattern till it reaches a level of 1 where it is not able to perform the basic functions and it will be replaced. All the activities have costs associated with them and will be discounted to present and the net present value will be calculated.

This approach helps in optimizing the activity timings and reducing the uncertainty associated with the costs and timings. Rather than assuming different scenarios where different combinations of timings are considered to calculate the least life cycle cost, this approach helps in identifying the ideal timings of different activities based on the user preference and hence enables accurate life cycle cost calculations.

The deterioration process considered here is the straight line deterioration. The actual deterioration will not be a straight line and depends upon a lot of parameters such as pipe internal environment, pipe external environment etc. Therefore, a more accurate and applicable deterioration curve can be linked in future to improve the accuracy of results. Also, the deterioration curve will differ with respect to different pipe materials, different repair and rehabilitation activities performed and hence will create a difference in the life cycle costs.

Chapter 13 : Conclusions and Recommendations

13.1. Conclusions

This research has been aimed at providing a framework for holistic life cycle cost analysis of drinking water pipelines which includes both life cycle cost analysis and life cycle assessment. The interpretation regarding LCCA from the literature is that a universal life cycle cost analysis model is difficult to formulate for all the domains since different industries have different requirements. There is uncertainty involved in the life cycle cost data and the major uncertainty comes from the operation and maintenance phase. It is imperative for reliable models to cater to this uncertainty with the collection of enough data to support analysis. So, correct data collection is important for the utilities and this research provides a comprehensive cost structure which will help the utilities in collection of better quantity and quality data. Therefore, the methodology of this research starts by developing a comprehensive cost structure and then using that cost structure to develop the holistic life cycle cost analysis model.

The cost structure provided is better than previous researches since it provides more detailed breakdown of all the life cycle costs including planning and design costs, installation costs, renewal costs and disposal costs. It also lists down all the technologies which can be used for pipe installation, condition assessment, repair, rehabilitation and replacement. The main advantage of the cost structure provided is that utilities can input their collected data, but if there are some gaps in the collected data, estimated values of different technologies and other costs have been provided with the help of literature and previous academic and water industry surveys.

The life cycle cost analysis model developed in this research carries out the net present value analysis with a ten step process. This model has the capability to compare five scenarios including comparison of different pipe materials, installation technologies, condition assessment technologies, rehabilitation technologies and replacement technologies and methods. The initial steps require the user to select the scenario which they want to consider and different alternatives within that scenario that they want to compare. Then, the users are required to input various parameters. The inputs required in this model include pipe related (diameter, material etc.), environmental related (soil conditions, traffic conditions etc.) and other factors (discount rate, analysis period etc.). Based upon the scenario and alternatives considered, various cost inputs and other parameters, net present value of different alternatives is carried out which is almost an automated process using VBA Macros in excel. The last steps require the user to review the results and change the inputs if the analysis results don't seem appropriate.

The Life cycle assessment model presented in this research involves calculation of greenhouse gas emissions during the pipe production and pipe operation phases and comparison of different pipe materials based upon that. There are lot of databases and software available in the market which can be used to carry out life cycle assessment in the future for this project.

After the development of the model, it was piloted with the data from Utility A. The data collected was missing some categories and the gaps were filled with the help of estimated values provided in the model. A comparison was made between the life cycle costs of two pipe materials considering 50 years of analysis period. A sensitivity analysis was also done to compare the results with varying analysis periods of 50, 75 and 100 years.

13.2. Future Recommendations

The cost structure can be improved further by collection of more cost data from the utilities. This will also ensure elimination of the gaps from the data and less use of estimated values while doing the analysis. Also, the improved cost structure can be used as a standard by the professional organizations such as American Society of Civil Engineers (ASCE) etc. in future to ensure collection of same set of data by utilities.

The life cycle cost analysis model developed here is more based on a deterministic approach. More probabilistic approaches such as Monte Carlo Simulations, Fuzzy Logic can be used in future which will take care of the uncertainty in the life cycle cost data. The current model is basically a hit and trial method to optimize the inputs and scenario. So, probability distribution functions in the probabilistic approaches, if used in the future, will ensure selection of best scenarios such as timings and methods. This will help the user to employ the best scenario rather than using the hit and trail method. Probabilistic models require a robust data set to ensure they are reliable. Now, since a comprehensive dataset has been established, more data collection in this format in future will enable input of quality data into the models and hence probabilistic models can be employed to improve the LCCA practices.

As shown in the Chapter 12, the life cycle cost analysis can be linked with the performance curve of the pipe. The performance curve will vary with respect to different pipe materials, pipe repair and rehabilitation methods used. So, an accurate deterioration prediction will help in better identification of activity timings and hence will lead to more accurate life cycle cost calculations. Various failure prediction tools such as Innovyze's Infomaster LCCA can also be used to predict at what performance level various repair and rehabilitation activities will be required and can be further linked with the performance level to identify when these activities will occur. This will ensure that the user won't have to select the performance level at which they want to have the activities.

The impact category currently considered in the life cycle assessment model is only the greenhouse gas emissions. The LCA method in this research can be improved by using a commercial software available in the industry such as Sima Pro or GaBi which have better databases and include more impact categories such as CO_2 emissions, global warming potential etc. Utilities can also use free and open source software such as Open LCA to conduct a preliminary LCA. Also, the life cycle phases currently considered are pipe manufacturing and pipe operations whereas other life cycle phases such as pipe transportation, installation, renewal and disposal are also important contributors towards environmental impacts and should be considered in future.

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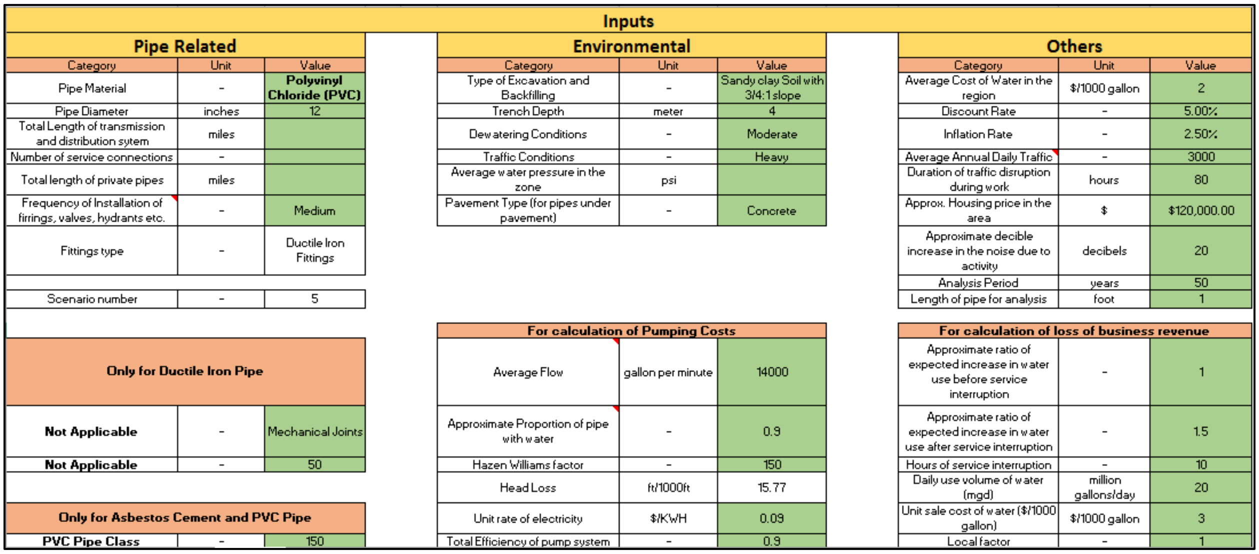
Appendix A: Snapshots of the Cost Structure, LCCA and LCA model

This appendix provides snapshot of the excel spreadsheet developed in this research which involves the cost structure, LCCA model and LCA model.

Cost Structure and LCCA Model

- **General Inputs in the LCCA model**



Inputs

Pipe Related

Category	Unit	Value
Pipe Material	-	**Polyvinyl Chloride (PVC)**
Pipe Diameter	inches	12
Total Length of transmission and distribution sytem	miles	
Number of service connections	-	
Total length of private pipes	miles	
Frequency of Installation of firrings, valves, hydrants etc.	-	Medium
Fittings type	-	Ductile Iron Fittings
Scenario number	-	5
Only for Ductile Iron Pipe		
Not Applicable	-	Mechanical Joints
Not Applicable	-	50
Only for Asbestos Cement and PVC Pipe		
PVC Pipe Class	-	150

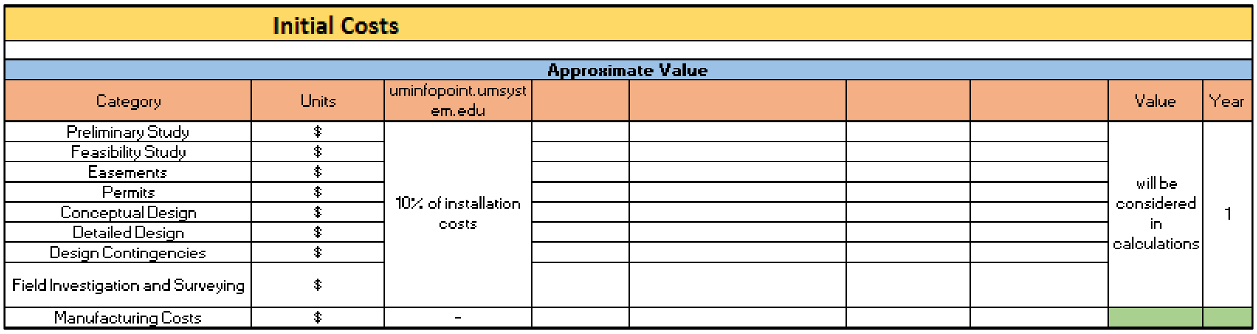
Environmental

Category	Unit	Value
Type of Excavation and Backfilling	-	Sandy clay Soil with 3/4:1 slope
Trench Depth	meter	4
Dewatering Conditions	-	Moderate
Traffic Conditions	-	Heavy
Average water pressure in the zone	psi	
Pavement Type (for pipes under pavement)	-	Concrete
For calculation of Pumping Costs		
Average Flow	gallon per minute	14000
Approximate Proportion of pipe with water	-	0.9
Hazen Williams factor	-	150
Head Loss	ft/1000ft	15.77
Unit rate of electricity	$/KWH	0.09
Total Efficiency of pump system	-	0.9

Others

Category	Unit	Value
Average Cost of Water in the region	$/1000 gallon	2
Discount Rate	-	5.00%
Inflation Rate	-	2.50%
Average Annual Daily Traffic	-	3000
Duration of traffic disruption during work	hours	80
Approx. Housing price in the area	$	$120,000.00
Approximate decible increase in the noise due to activity	decibels	20
Analysis Period	years	50
Length of pipe for analysis	foot	1
For calculation of loss of business revenue		
Approximate ratio of expected increase in water use before service interruption	-	1
Approximate ratio of expected increase in water use after service interruption	-	1.5
Hours of service interruption	-	10
Daily use volume of water (mgd)	million gallons/day	20
Unit sale cost of water ($/1000 gallon)	$/1000 gallon	3
Local factor	-	1

- **Initial Costs**

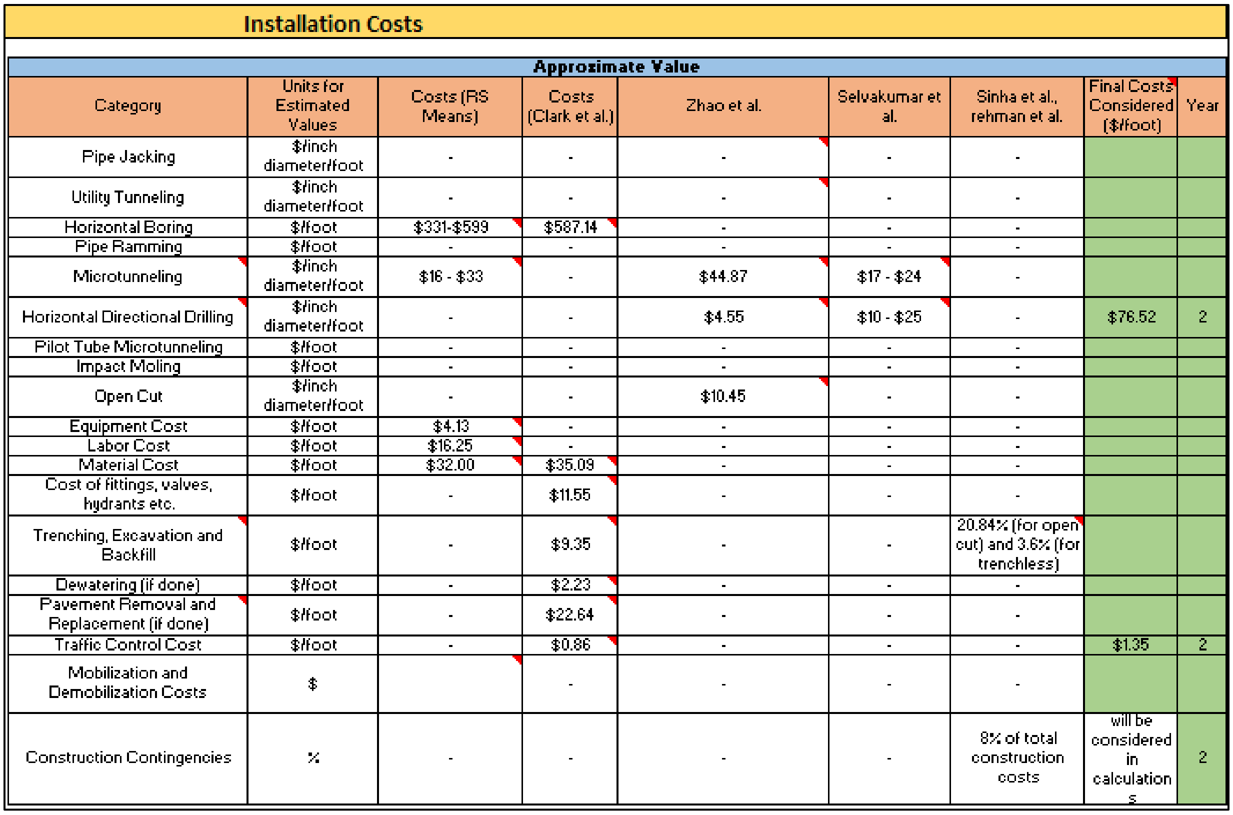


Initial Costs

Approximate Value

Category	Units	uminfopoint.umsystem.edu					Value	Year
Preliminary Study	$	10% of installation costs					will be considered in calculations	1
Feasibility Study	$							
Easements	$							
Permits	$							
Conceptual Design	$							
Detailed Design	$							
Design Contingencies	$							
Field Investigation and Surveying	$							
Manufacturing Costs	$	-						

Installation Costs

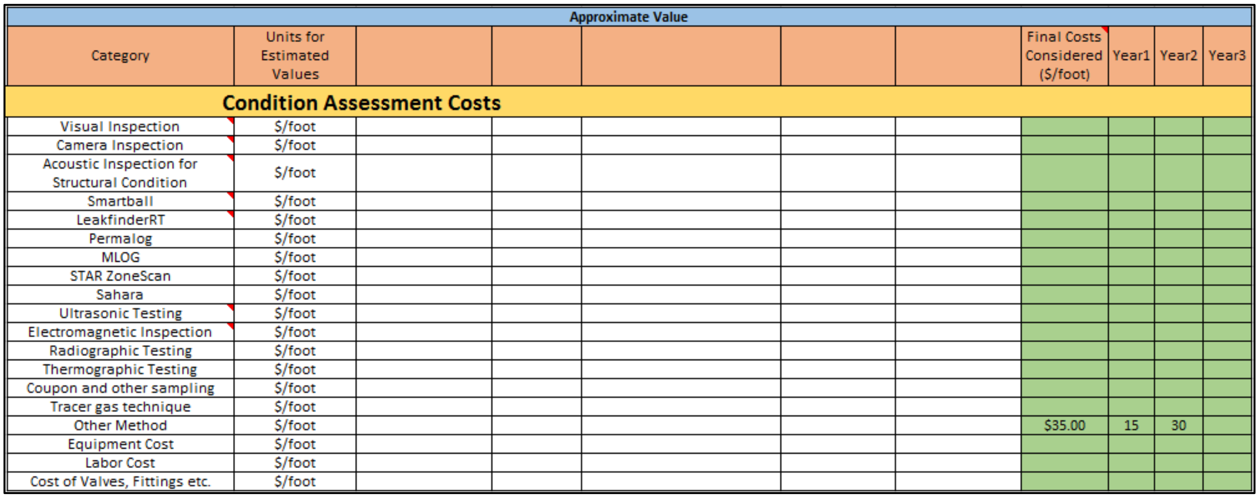


Installation Costs

Approximate Value

Category	Units for Estimated Values	Costs (RS Means)	Costs (Clark et al.)	Zhao et al.	Selvakumar et al.	Sinha et al., rehman et al.	Final Costs Considered ($/foot)	Year
Pipe Jacking	$/inch diameter/foot	-	-	-	-	-		
Utility Tunneling	$/inch diameter/foot	-	-	-	-	-		
Horizontal Boring	$/foot	$331-$599	$587.14	-	-	-		
Pipe Ramming	$/foot	-	-	-	-	-		
Microtunneling	$/inch diameter/foot	$16 - $33	-	$44.87	$17 - $24	-		
Horizontal Directional Drilling	$/inch diameter/foot	-	-	$4.55	$10 - $25	-	$76.52	2
Pilot Tube Microtunneling	$/foot	-	-	-	-	-		
Impact Moling	$/foot	-	-	-	-	-		
Open Cut	$/inch diameter/foot	-	-	$10.45	-	-		
Equipment Cost	$/foot	$4.13	-	-	-	-		
Labor Cost	$/foot	$16.25	-	-	-	-		
Material Cost	$/foot	$32.00	$35.09	-	-	-		
Cost of fittings, valves, hydrants etc.	$/foot	-	$11.55	-	-	-		
Trenching, Excavation and Backfill	$/foot	-	$9.35	-	-	20.84% (for open cut) and 3.6% (for trenchless)		
Dewatering (if done)	$/foot	-	$2.23	-	-	-		
Pavement Removal and Replacement (if done)	$/foot	-	$22.64	-	-	-		
Traffic Control Cost	$/foot	-	$0.86	-	-	-	$1.35	2
Mobilization and Demobilization Costs	$		-	-	-	-		
Construction Contingencies	%	-	-	-	-	8% of total construction costs	will be considered in calculation s	2

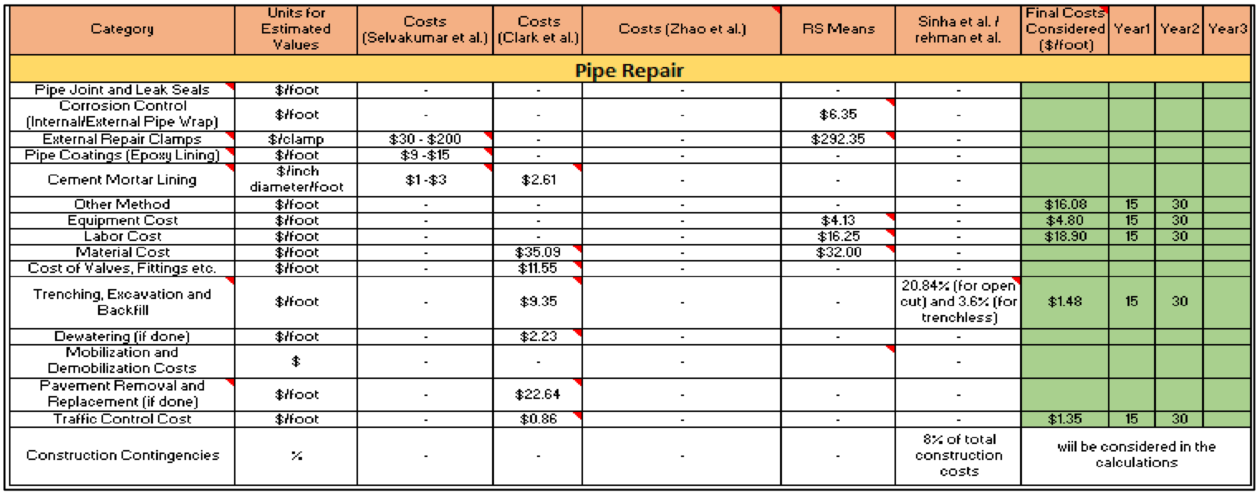
Condition Assessment Costs



Approximate Value

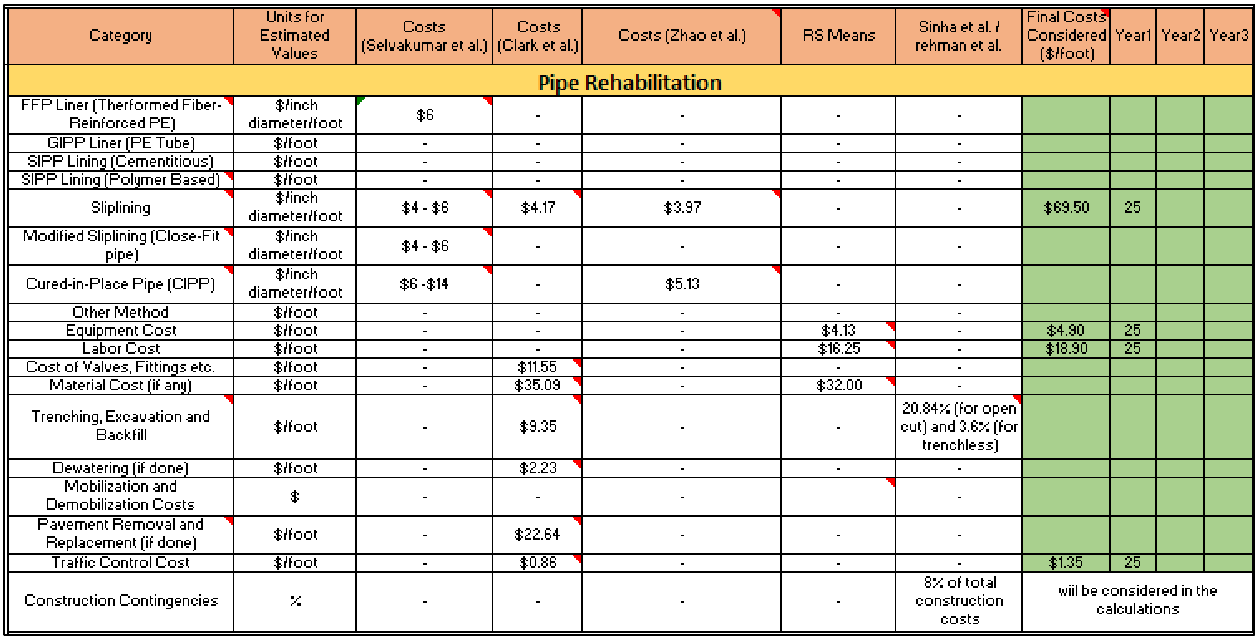
Category	Units for Estimated Values						Final Costs Considered ($/foot)	Year1	Year2	Year3
Condition Assessment Costs										
Visual Inspection	$/foot									
Camera Inspection	$/foot									
Acoustic Inspection for Structural Condition	$/foot									
Smartball	$/foot									
LeakfinderRT	$/foot									
Permalog	$/foot									
MLOG	$/foot									
STAR ZoneScan	$/foot									
Sahara	$/foot									
Ultrasonic Testing	$/foot									
Electromagnetic Inspection	$/foot									
Radiographic Testing	$/foot									
Thermographic Testing	$/foot									
Coupon and other sampling	$/foot									
Tracer gas technique	$/foot									
Other Method	$/foot						$35.00	15	30	
Equipment Cost	$/foot									
Labor Cost	$/foot									
Cost of Valves, Fittings etc.	$/foot									

- **Pipe Repair Costs**



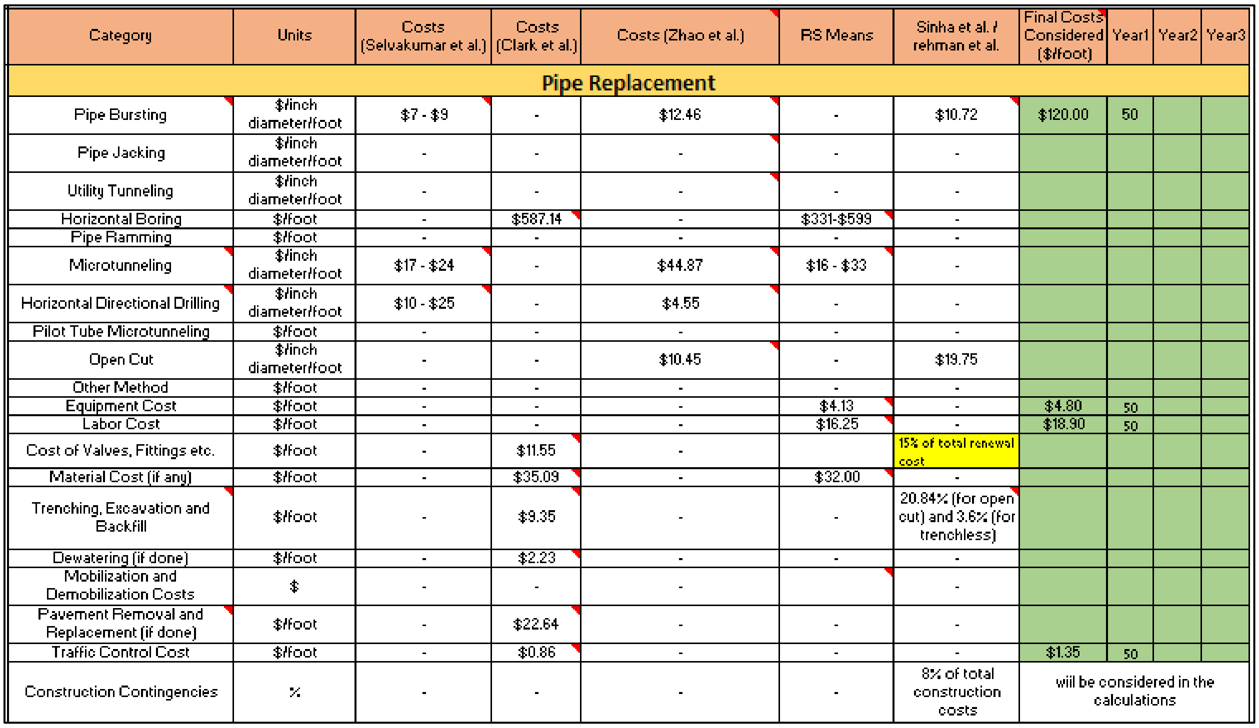
Category	Units for Estimated Values	Costs (Selvakumar et al.)	Costs (Clark et al.)	Costs (Zhao et al.)	RS Means	Sinha et al. / rehman et al.	Final Costs Considered ($/foot)	Year1	Year2	Year3
Pipe Repair										
Pipe Joint and Leak Seals	$/foot	-	-	-	-	-				
Corrosion Control (Internal/External Pipe Wrap)	$/foot	-	-	-	$6.35	-				
External Repair Clamps	$/clamp	$30 - $200	-	-	$292.35	-				
Pipe Coatings (Epoxy Lining)	$/foot	$9 -$15	-	-	-	-				
Cement Mortar Lining	$/inch diameter/foot	$1 -$3	$2.61	-	-	-				
Other Method	$/foot	-	-	-	-	-	$16.08	15	30	
Equipment Cost	$/foot	-	-	-	$4.13	-	$4.80	15	30	
Labor Cost	$/foot	-	-	-	$16.25	-	$18.90	15	30	
Material Cost	$/foot	-	$35.09	-	$32.00	-				
Cost of Valves, Fittings etc.	$/foot	-	$11.55	-	-	-				
Trenching, Excavation and Backfill	$/foot	-	$9.35	-	-	20.84% (for open cut) and 3.6% (for trenchless)	$1.48	15	30	
Dewatering (if done)	$/foot	-	$2.23	-	-	-				
Mobilization and Demobilization Costs	$	-	-	-		-				
Pavement Removal and Replacement (if done)	$/foot	-	$22.64	-	-	-				
Traffic Control Cost	$/foot	-	$0.86	-	-	-	$1.35	15	30	
Construction Contingencies	%	-	-	-	-	8% of total construction costs	will be considered in the calculations			

- **Pipe Rehabilitation Costs**



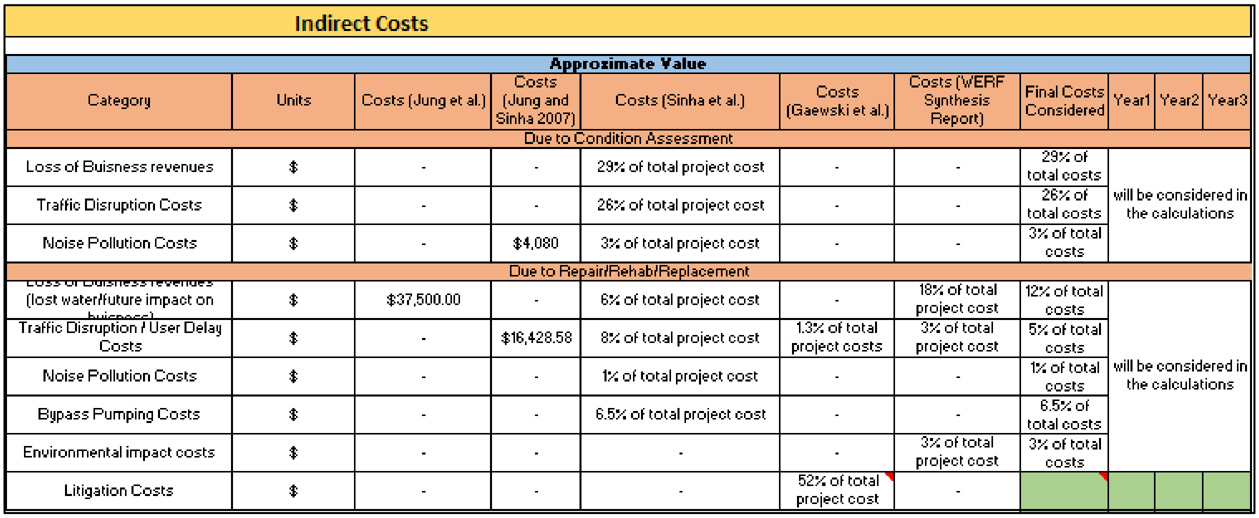
Category	Units for Estimated Values	Costs (Selvakumar et al.)	Costs (Clark et al.)	Costs (Zhao et al.)	RS Means	Sinha et al. / rehman et al.	Final Costs Considered ($/foot)	Year1	Year2	Year3
Pipe Rehabilitation										
FFP Liner (Therformed Fiber-Reinforced PE)	$/inch diameter/foot	$6	-	-	-	-				
GIPP Liner (PE Tube)	$/foot	-	-	-	-	-				
SIPP Lining (Cementitious)	$/foot	-	-	-	-	-				
SIPP Lining (Polymer Based)	$/foot	-	-	-	-	-				
Sliplining	$/inch diameter/foot	$4 - $6	$4.17	$3.97	-	-	$69.50	25		
Modified Sliplining (Close-Fit pipe)	$/inch diameter/foot	$4 - $6	-	-	-	-				
Cured-in-Place Pipe (CIPP)	$/inch diameter/foot	$6 -$14	-	$5.13	-	-				
Other Method	$/foot	-	-	-	-	-				
Equipment Cost	$/foot	-	-	-	$4.13	-	$4.90	25		
Labor Cost	$/foot	-	-	-	$16.25	-	$18.90	25		
Cost of Valves, Fittings etc.	$/foot	-	$11.55	-	-	-				
Material Cost (if any)	$/foot	-	$35.09	-	$32.00	-				
Trenching, Excavation and Backfill	$/foot	-	$9.35	-	-	20.84% (for open cut) and 3.6% (for trenchless)				
Dewatering (if done)	$/foot	-	$2.23	-	-	-				
Mobilization and Demobilization Costs	$	-	-	-		-				
Pavement Removal and Replacement (if done)	$/foot	-	$22.64	-	-	-				
Traffic Control Cost	$/foot	-	$0.86	-	-	-	$1.35	25		
Construction Contingencies	%	-	-	-	-	8% of total construction costs	will be considered in the calculations			

- **Pipe Replacement Costs**



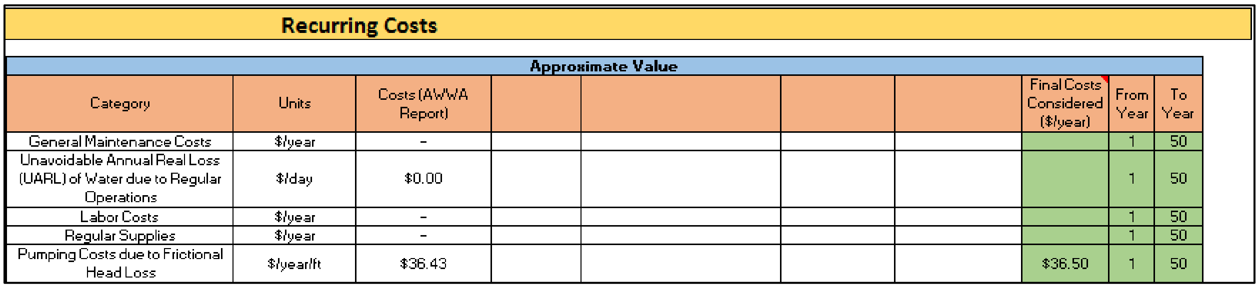
Category	Units	Costs (Selvakumar et al.)	Costs (Clark et al.)	Costs (Zhao et al.)	RS Means	Sinha et al. / rehman et al.	Final Costs Considered ($/foot)	Year1	Year2	Year3
Pipe Replacement										
Pipe Bursting	$/inch diameter/foot	$7 - $9	-	$12.46	-	$10.72	$120.00	50		
Pipe Jacking	$/inch diameter/foot	-	-	-	-	-				
Utility Tunneling	$/inch diameter/foot	-	-	-	-	-				
Horizontal Boring	$/foot	-	$587.14	-	$331-$599	-				
Pipe Ramming	$/foot	-	-	-	-	-				
Microtunneling	$/inch diameter/foot	$17 - $24	-	$44.87	$16 - $33	-				
Horizontal Directional Drilling	$/inch diameter/foot	$10 - $25	-	$4.55	-	-				
Pilot Tube Microtunneling	$/foot	-	-	-	-	-				
Open Cut	$/inch diameter/foot	-	-	$10.45	-	$19.75				
Other Method	$/foot	-	-	-	-	-				
Equipment Cost	$/foot	-	-	-	$4.13	-	$4.80	50		
Labor Cost	$/foot	-	-	-	$16.25	-	$18.90	50		
Cost of Valves, Fittings etc.	$/foot	-	$11.55	-		15% of total renewal cost				
Material Cost (if any)	$/foot	-	$35.09	-	$32.00	-				
Trenching, Excavation and Backfill	$/foot	-	$9.35	-	-	20.84% (for open cut) and 3.6% (for trenchless)				
Dewatering (if done)	$/foot	-	$2.23	-	-	-				
Mobilization and Demobilization Costs	$	-	-	-		-				
Pavement Removal and Replacement (if done)	$/foot	-	$22.64	-	-	-				
Traffic Control Cost	$/foot	-	$0.86	-	-	-	$1.35	50		
Construction Contingencies	%	-	-	-	-	8% of total construction costs	will be considered in the calculations			

- **Indirect Costs**



Indirect Costs										
Approximate Value										
Category	Units	Costs (Jung et al.)	Costs (Jung and Sinha 2007)	Costs (Sinha et al.)	Costs (Gaewski et al.)	Costs (WERF Synthesis Report)	Final Costs Considered	Year1	Year2	Year3
Due to Condition Assessment										
Loss of Buisness revenues	$	-	-	29% of total project cost	-	-	29% of total costs	will be considered in the calculations		
Traffic Disruption Costs	$	-	-	26% of total project cost	-	-	26% of total costs			
Noise Pollution Costs	$	-	$4,080	3% of total project cost	-	-	3% of total costs			
Due to Repair/Rehab/Replacement										
Loss of Buisness revenues (lost water/future impact on buisness)	$	$37,500.00	-	6% of total project cost	-	18% of total project cost	12% of total costs	will be considered in the calculations		
Traffic Disruption / User Delay Costs	$	-	$16,428.58	8% of total project cost	1.3% of total project costs	3% of total project cost	5% of total costs			
Noise Pollution Costs	$	-	-	1% of total project cost	-	-	1% of total costs			
Bypass Pumping Costs	$	-	-	6.5% of total project cost	-	-	6.5% of total costs			
Environmental impact costs	$	-	-	-	-	3% of total project cost	3% of total costs			
Litigation Costs	$	-	-	-	52% of total project cost	-				

- **Recurring Costs**

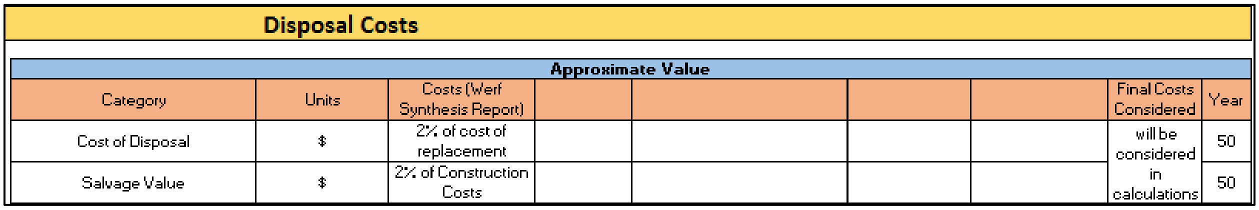


Recurring Costs

Approximate Value

Category	Units	Costs (AWWA Report)					Final Costs Considered ($/year)	From Year	To Year
General Maintenance Costs	$/year	-						1	50
Unavoidable Annual Real Loss (UARL) of Water due to Regular Operations	$/day	$0.00						1	50
Labor Costs	$/year	-						1	50
Regular Supplies	$/year	-						1	50
Pumping Costs due to Frictional Head Loss	$/year/ft	$36.43					$36.50	1	50

- **Disposal Costs**

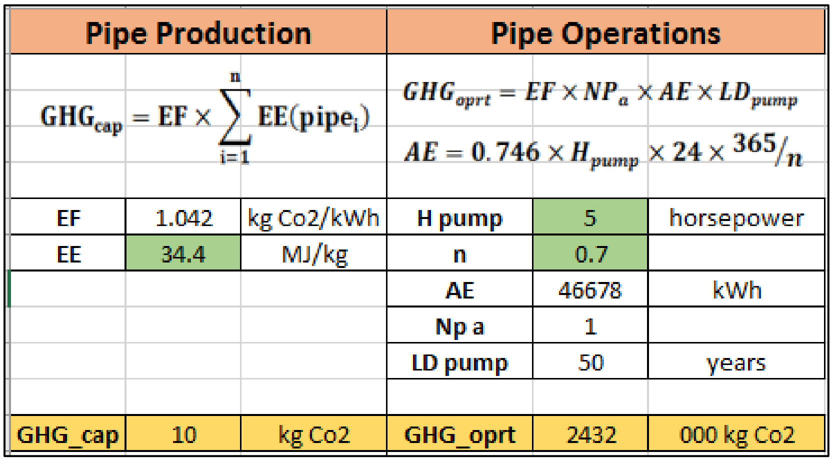


Disposal Costs

Approximate Value

Category	Units	Costs (Werf Synthesis Report)					Final Costs Considered	Year
Cost of Disposal	$	2% of cost of replacement					will be considered in calculations	50
Salvage Value	$	2% of Construction Costs						50

LCA Model



Pipe Production			**Pipe Operations**		
$\mathrm{GHG_{cap}} = \mathrm{EF} \times \sum_{i=1}^{n} \mathrm{EE(pipe_i)}$			$GHG_{oprt} = EF \times NP_a \times AE \times LD_{pump}$ $AE = 0.746 \times H_{pump} \times 24 \times {}^{365}/_{n}$		
EF	1.042	kg Co2/kWh	**H pump**	5	horsepower
EE	34.4	MJ/kg	**n**	0.7	
			AE	46678	kWh
			Np a	1	
			LD pump	50	years
GHG_cap	10	kg Co2	**GHG_oprt**	2432	000 kg Co2