A Framework to Evaluate the Life Cycle Costs and Environmental Impacts of Water Pipelines

Albert Thomas¹; Bharadwaj R. K. Mantha²; and Carol C. Menassa³

¹Dept. of Civil and Environmental Engineering, Univ. of Michigan, 2350 Hayward St., Ann Arbor, MI 48109. E-mail: albertth@umich.edu
²Dept. of Civil and Environmental Engineering, Univ. of Michigan, 2350 Hayward St., Ann Arbor, MI 48109. E-mail: baddu@umich.edu
³Dept. of Civil and Environmental Engineering, Univ. of Michigan, 2350 Hayward St., Ann Arbor, MI 48109. E-mail: menassa@umich.edu

Abstract

The true value of a pipeline as an asset should be based on several factors that impact its service life. Those considerations include the consumption and production of raw materials, design, installation, operation and maintenance, and planning for the end of the pipeline’s service life; as well as, the corresponding environmental impacts at each of these life cycle phases. In this paper, a model is presented that allows utilities and engineers to evaluate the total life cycle cost associated with a water transmission pipeline. The model is designed to compare Ductile Iron (DI) versus PVC pipe, two of the most commonly used pipe materials. In addition to the tangible cost comparisons, the model also includes an evaluation of environmental impacts that need to be considered by utilities to build or replace a transmission pipeline. Results from scenario analysis for 8” and 24” pipes illustrate that although PVC pipes have initial economic benefits (due to lower material costs), DI tends to be more cost effective and also comparatively environmentally sustainable (less CO₂ emissions) over its service life.

1.0 Introduction

Water distribution systems consist of an interconnected series of pipes, storage facilities, and components that convey drinking water and required fire protection needs for cities, homes, schools, hospitals, businesses, industries and other facilities (EPA 2015). More than one million miles of water mains are located across the United States (US). Based on the number of people being served, the American Water Works Association (AWWA) classifies water distribution system into four major categories: (1) very small systems (serving fewer than 3,300, 84.5% of community water systems); (2) small systems (3,300-9,999, 8.5%); (3) medium systems (10,000-49,999, 5.5%); and (4) large systems (>50,000, 1.5%). The main stakeholders involved in these infrastructure facilities include federal, state and municipal governments and the city local bodies.

The US Environmental Protection Agency (EPA) has estimated that, approximately 4,000 to 5,000 miles of water mains are being replaced annually and this rate is projected to increase in the coming years (EPA 2013). This is mostly because many pipes in the US are reported to be nearing the end of their useful service life, and the cost to replace those pipes for the next 25 years are estimated to reach more than $1 trillion USD to maintain the current levels of water service.
(ASCE 2013). Hence, in the coming decades there is a strong need for new water infrastructure projects especially in the US and the selection of a sustainable and cost effective pipe material is one of the important parameters for ensuring efficient water distribution systems for the future. There are several factors that affect the selection process of a suitable pipe material, which demands meticulous and systematic analysis of various pipe alternatives to arrive at the best solution. It is also required that the analysis not be limited to initial economic benefits but should also consider the engineering, practical, operational and environmental factors. The main objective of this paper is to develop a user-friendly tool that performs a life cycle analysis on the major pipe materials, which can be used by various stakeholders/designers to determine/design the most sustainable and efficient water distribution system, in the long run.

2.0 Research Background and Objectives

There are various types of pipe materials used for water distribution networks such as Ductile Iron (DI), Poly Vinyl Chloride (PVC), High Density Polyethylene (HDPE), Cast Iron (CI) and pipes made of Asbestos and Concrete. However, PVC and DI are the most commonly used pipe materials (Moser et al. 2008, Rajani 2003, EPA 2002b).

Several existing life cycle based studies have attempted to analyze the cost as well as environmental impacts for the pipe materials at various life cycle stages such as manufacturing, transportation, construction, operation and end-of-life phases (Piratla et al. 2012, Du et al. 2013, McPherson 2009, Lundi et al. 2005, Recio et al. 2005, Filion et al. 2004, Dennison et al. 1999). The general methodology reported in these studies involves selecting specific case studies and analyzing the life cycle cost/environmental impact of that particular scenario. However, there is a need to develop a general framework that can analyze the life cycle cost impacts for various scenarios (such as different pipe sizes, flow parameters, and locations). In addition, most of the existing studies considered a study period less than 50 years. Generally, a pipe system is designed for longer service lives (around 100 years) and the ideal modeling tool should be able to mimic the performance for a longer period.

Hence, despite the significant contributions of these aforementioned studies, there is an emerging need for a comprehensive life cycle analysis of major pipe materials under varying conditions of operation and actual service life scenarios. Accordingly, this research study aims to develop a Pipe Material Life Cycle Assessment tool (PM-LCA) that is capable of analyzing different pipe material scenarios (for all the major diameters) and suggesting the best option to the various decision makers (such as stakeholders, utility companies, owners, and consumers). The major objectives of this study are as listed below:

1. Develop a comprehensive tool to conduct a Life Cycle Cost Analysis (LCCA) of alternative pipe materials with different service lives in consideration of all costs: initial, installation, operation and maintenance, service life, and a Life Cycle Assessment (LCA) of environmental impacts. In this example, we compare Life Cycle Costs and Life Cycle Assessment (LCC+LCA) of DI and PVC pipes.
2. Perform a Sensitivity/Scenario analysis to evaluate the total life cycle impact.
3.0 Methodology

The overall framework adopted to achieve the above objectives is provided in Fig.1 below. It follows a hybrid approach combining LCC and LCA thereby allowing various stakeholders to weigh different aspects of a piping project. The LCC analysis determines the cost impacts of a particular pipe project by considering all of the life cycle phases from the pipe production, installation, operation and maintenance and the end-of-life. In a similar fashion, LCA analysis determines the corresponding environmental impact associated with the various life cycle phases.

![Figure 1: Overview of the proposed framework](image)

One major step in performing any life cycle analysis is to determine the life span of the pipe material. PVC pipes have been operational from early 1970's resulting in approximately 40 years of performance history. However, the manufactures of PVC pipes predict a service life that ranges from 20-100 years depending on trench bedding design, temperature and other environmental conditions (Pennoni Associates Inc, 2008). Thus, an extensive literature review was conducted on the reported service lives of PVC and DI pipes and the results are tabulated in Table 1, below. After reviewing all the studies, service lives of 100 and 50 years are considered for DI and PVC, respectively, in the case study considered in this paper. However, while the literature suggests a service life around 50 years for PVC and 100 years for DI, the model allows the user to test the impact that service life has on the results of the LCC analysis.

<table>
<thead>
<tr>
<th>DI (in years)</th>
<th>PVC (in years)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>~150</td>
<td></td>
<td>DIPRA (2015)</td>
</tr>
<tr>
<td>100-120</td>
<td></td>
<td>PWD (2015)</td>
</tr>
<tr>
<td>&gt;100</td>
<td>&lt;55</td>
<td>AWWA (2015)</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>DIPRA (2012)</td>
</tr>
<tr>
<td>100</td>
<td>50-100</td>
<td>EPA (2002a)</td>
</tr>
<tr>
<td>60-80</td>
<td>41-60</td>
<td>Folkman (2012)</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>Swamee and Sharma (2008)</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>Paradkar (2013); Marques (2013)</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>PPI (2015); AWWA (2007); JM Eagle (2010); Burn et al. (2005); McPherson et al. (2009)</td>
</tr>
</tbody>
</table>

Table. 1: Literature with focus on service life of DI and PVC pipes
3.1 LCCA Module

The production phase involves costs for material extraction, pipe production and pipe transportation. Various industry standards as well as the RSMeans cost database are used for populating the unit cost of the pipe material (RSMeans 2015). The standard pipe material costs assumed for in this case study were obtained from suppliers. For DI and PVC, lowest pressure classes (including a surge allowance of 100 psi) and the pressure class of 235 psi (DR 18) are assumed respectively. The user will also have the option to consider the pipe material costs based on RSMeans cost database, industry standards or if the preference is to input a different unit cost for the pipe material that feature is also available in the model. This option provides more flexibility for the decision makers (e.g., utilities) to evaluate the cost impacts of various pipe options.

Similarly, costs associated with the installation of pipes are determined from the RSMeans (2015) database. The typical installation procedure for DI and PVC pipes are adopted as per the relevant AWWA standards and other industry reference manuals (AWWA M41, AWWA M23, DIPRA 2015). The unit rates assumed for the typical activities in a pipe installation phase are summarized in Table 2, below. The costs associated with the transportation of pipe materials to the project site are assumed to range between 5 and 7 percent of the pipe material costs (US ITC 2000).

Table 2: Unit Rates assumed for Installation phase (Source RSMeans 2015)

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Rate ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobilization of Equipment</td>
<td>Ea.</td>
<td>$641.89</td>
</tr>
<tr>
<td>Excavation</td>
<td>BCY</td>
<td>$2.11</td>
</tr>
<tr>
<td>Bedding Placement</td>
<td>LCY</td>
<td>$32.27</td>
</tr>
<tr>
<td>Bedding Compaction</td>
<td>S.Y</td>
<td>$0.62</td>
</tr>
<tr>
<td>Structural Backfill</td>
<td>ECY</td>
<td>$0.78</td>
</tr>
<tr>
<td>Final Compaction</td>
<td>ECY</td>
<td>$0.27</td>
</tr>
<tr>
<td>Demobilization of Equipment</td>
<td>Ea.</td>
<td>$641.89</td>
</tr>
</tbody>
</table>

The operation phase in a water distribution project involves costs associated with pumping the water and carrying out the necessary repairs and regular maintenance activities. Prior studies have identified pumping costs to constitute a significant portion of the total life cycle costs (Piratla 2012, McPherson 2009). For a given scenario, this cost can be computed using the Hazen–Williams equation by taking flow rate \((Q)\), unit cost of electricity \((a)\), and efficiency of the pump system \((E)\) as inputs. The relevant equations used to estimate this cost are provided below (equations 1-3). In the case of the costs and the frequency of repair activities,
standard failure rates obtained from industry sources and the typical costs suggested in the literature for each repair (Haas 2012) are assumed.

\[
V = \frac{Q}{2.448 \ d^2} \quad \text{eq}(1)
\]

Where, \(V\) = Velocity (fps), \(Q\) = Flow rate (gpm) and \(d\) = Actual inside diameter (in.)

\[
H_L = 1000 \left[ \frac{V}{0.115 \ C \ (d)^{0.63}} \right]^{1.852} \quad \text{eq}(2)
\]

Where, \(H_L\) = Head loss (ft./1000 ft.), \(V\) = Velocity of flow (fps), \(C\) = Hazen Williams factor, \(d\) = Actual inside diameter (in.)

\[
PC = 1.65 \ H_L Q \frac{a}{E} \quad \text{eq}(3)
\]

Where \(PC\) = Pumping Cost in $/year/1000 ft. of pipe based on 24 hr./day pump operation, \(H_L\) = Hydraulic gradient or head loss in ft./(1000 ft.), \(Q\) = flow rate, gpm), \(a\) = unit cost of electricity in $/KWH, \(E\) = total efficiency of pump system

When the pipe reaches its End-Of-Life (EOL) phase, i.e., after completing its service life and the pipe is no longer useful for operation, it is either exhumed for salvage, recycling or disposal; or will be abandoned-in-place. From discussions with industry experts, these pipes are usually abandoned because of the manpower, resources, time and money involved to unearth the pipe. In addition, the energy required to take the pipe out of the trench overshadows the benefits arising out of possible recycling of the buried materials. Thus, it is assumed that pipes are abandoned at the end of their service lives and any salvaging values are omitted from the scope of this study.

Carrying out an LCCA as outlined above can provide a model to evaluate the economic benefits of alternative pipe materials of differing service lives to decision-makers. Figure 2, below, gives a view of the input sheet of the Life Cycle Cost Analysis (“LCCA”) model through which the user can select the various options for which the life cycle impacts need to be ascertained.

3.2 LCA Module

LCA is a well-established analytical method for assessing the environmental balance of a product, process or service (Horvath 2004). It is learnt from the LCCA study that out of the total energy requirement for a pipe’s life cycle, the most important energy requirements come from pipe production and from pumping costs during operation. Hence, for this version of the model, only those environmental impacts from pipe production and operational phases are considered.

The embodied energy required for producing the material include the energy associated with the production of raw materials and pipe casting or extrusion processes. The energy required for producing unit quantity of pipe material is adopted based on various literature studies (Piratla et al. 2012, Ambrose et al. 2002).
Based on the quantity of pipe selected for the case study, the total embodied energy is computed. All the corresponding assumptions along with their references are tabulated in Table 3. The major energy required in the operation phase is with regards to the pumping of water. The Hazen Williams equation is used to compute the pumping energy in this phase. As mentioned before, the model is designed in such a way that the pumping energy of any flow parameters and pumping percent can be generated.

![User Inputs Table](image)

**Figure 2:** A screenshot of the user interface for the LCCA model

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Inputs</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embodied Energy (PVC)</td>
<td>MJ/Kg</td>
<td>74.9</td>
<td>Ambrose et al. (2002)</td>
</tr>
<tr>
<td>Embodied Energy (DI)</td>
<td>MJ/Kg</td>
<td>38.2</td>
<td>Ambrose et al. (2002)</td>
</tr>
<tr>
<td>Wt. of 8” dia (PVC) pipe</td>
<td>lbs./ft.</td>
<td>9.1</td>
<td>NPP (2016)</td>
</tr>
<tr>
<td>Wt. of 8” dia (DI) pipe</td>
<td>lbs./ft.</td>
<td>21.1</td>
<td>AWWA (2010)</td>
</tr>
<tr>
<td>Wt. of 24” dia (PVC) pipe</td>
<td>lbs./ft.</td>
<td>76.5</td>
<td>NPP (2016)</td>
</tr>
<tr>
<td>Wt. of 24” dia (DI) pipe</td>
<td>lbs./ft.</td>
<td>80.8</td>
<td>AWWA (2010)</td>
</tr>
</tbody>
</table>
Once the energy requirements are obtained for a particular scenario, the corresponding CO$_2$ emissions are calculated based on US EPA data that provide the corresponding environmental impact for all the US states based on a zip code (EPA 2016). Once the emissions are calculated in this fashion, they are converted to an equivalent dollar value for easy comparison with the LCCA analysis and for measuring the total savings for any given scenario.

### 4.0 Case Study and Scenario Analysis

In order to understand the cost impacts ranging from lower to higher diameters, the LCCA of an 8-inch pipe project and a 24-inch pipe project for both DI and PVC are considered for the case study. A preliminary analysis was conducted to observe the general trends of the cost break-even points and the annual emissions for these two pipe diameters. For making a fair comparison, similar nominal diameter and pressure classes of the pipe are used as per American Water Works Association (AWWA) standards. Some of the key details adopted for this case study are shown in Table 4 below. In addition, most of the values considered for analysis were obtained from the RS Means data and pertinent AWWA standards and manuals such as C900, C905, C151, M23, M41 and C150.

**Table 4: Key assumptions considered for the LCCA**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Inputs</th>
<th>Description</th>
<th>Units</th>
<th>Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of the job site</td>
<td>NA</td>
<td>Michigan</td>
<td>Bare pipe costs (DI/PVC) 8” dia pipe</td>
<td>$</td>
<td>51.4/61.9</td>
</tr>
<tr>
<td>Total length of pipe</td>
<td>Ft</td>
<td>1000</td>
<td>Hazen William factor (C) DI/PVC</td>
<td>NA</td>
<td>140/150</td>
</tr>
<tr>
<td>Diameter of the pipe</td>
<td>Inches</td>
<td>8 and 24</td>
<td>Discount rate</td>
<td>%</td>
<td>2</td>
</tr>
<tr>
<td>DI (Pressure Class*)</td>
<td>psi</td>
<td>350 (8’’) and 200 (24’’)</td>
<td>Escalation rate</td>
<td>%</td>
<td>1.9</td>
</tr>
<tr>
<td>PVC (DR 18)</td>
<td>psi</td>
<td>235 (8’’ and 24’’)</td>
<td>% of Pumping</td>
<td>%</td>
<td>25</td>
</tr>
<tr>
<td>Project life Span</td>
<td>Years</td>
<td>100</td>
<td>Rate of Electricity</td>
<td>$/KWh</td>
<td>0.06</td>
</tr>
<tr>
<td>Service Life (DI/PVC)</td>
<td>Years</td>
<td>100/50</td>
<td>Efficiency of Pump</td>
<td>Percent</td>
<td>70</td>
</tr>
<tr>
<td>Bare pipe costs (DI/PVC) 8” dia pipe</td>
<td>$</td>
<td>12.91/6.33</td>
<td>Q (Flow rate)</td>
<td>gpm</td>
<td>1000 (8’’) and 6000 (24’’)</td>
</tr>
</tbody>
</table>

*DI pipe is adequate for the rated working pressure indicated, plus a surge allowance of 100 psi.

Fig. 3 below shows the results obtained for both 8-inch and 24-inch diameter pipes. It can be seen from the graphs that the annual CO$_2$ emissions significantly increase for 24-inch PVC pipe compared to 8-inch PVC pipe, which is obvious because of the heavy pipe weight and increased emissions associated with the pipe production. In the cost break-even analysis, it is shown that operational savings
associated with an alternative material over the entire design life of a pipeline may overshadow initial savings for another pipe material. In our example, while a typical PVC pipe has initial cost advantages, when considering the entire life cycle of 100 years, there are considerable savings with DI pipe. The sudden rise in the break-even analysis graph is due to lesser service life for PVC (50 years), which demands installing new PVC pipeline. It can also be seen that the energy savings achieved when pumping water through DI pipes is very important and improves significantly with increase in diameter. The major energy and impacts were observed from the pumping phase and hence an exclusive scenario analysis is performed to understand the cost sensitivity to various pumping scenarios. For the scope of this paper, this scenario analysis is only limited to the LCCA.

4.1 Scenario Analysis

Based on the inference obtained from the above case study, LCCA break-even graphs are generated for various percent of pumping ranging from 0% to 100%. In the Fig. 4 and Fig. 5 below, each line corresponds to a particular pumping percentage as indicated in the graph labels. Since pumping costs have a dominating effect, the cumulative savings for DI over PVC for varied pumping levels are recorded for each year and plotted. These values were calculated by taking the difference between the accumulated cost of DI and PVC pipe (including the initial pipe costs and annual operational costs) at each year respectively. Fig. 4 and Fig. 5 depict the LCC for each year for different pumping scenarios. It can be seen that the savings (for DI over PVC) for both 24-inch and-8 inch pipes are significant for a 100-year analysis period.

Figure 3: Total (production) and annual (operation) CO$_2$ emissions (top two including the replacement of PVC pipe) and cost breakeven analysis (bottom two with cumulative costs) for 8 inch (left) and 24 inch (right) respectively.
In addition, with an increase in percent of pumping, the break-even starts to happen at a much earlier time.

Figure 4: LCC scenario/breakeven analysis for a 24” dia. pipe with varied pumping percentages.

Figure 5: LCC scenario/breakeven analysis for an 8” dia. pipe with varied pumping percentages.

5.0 Discussions and Conclusions

This paper conducted a life cycle analysis on the two of the most common pipe materials (DI and PVC) used for water distribution pipelines. In the case study example considered, though PVC pipes had initial economic benefits (due to lower material costs, especially in smaller sizes), DI turned out to be more cost effective and also comparatively environmentally more sustainable (less CO₂ emissions) in the
long run. In addition, for higher diameter pipes (more than 12” dia), DI tends to have more cost savings (around $100,000 to $1000,000 depending on the % of pumping and length of pipe for the entire life span) in comparison to PVC pipes.

Furthermore, sensitivity/scenario analyses were conducted to investigate which of the life cycle phases has the most impact on the LCCA results. It was found that, the operation and maintenance phase (pumping costs in particular) contributes the most to the life cycle costs. A case study was conducted to investigate the individual impact of percent of pumping on the dollar value of the savings. The overall results of the case study indicate that the percent of pumping is important for arriving at the life cycle cost savings.

Water distribution projects are generally planned for a longer period mainly because of the huge initial investment. Given the general nature of this model, utilities and various stakeholders can effectively use this tool to determine the optimum pipe material for any given scenario (for e.g., varied life spans, diameters, flow rates, and locations). Currently, the model incorporates specific pipe classes and materials.

As part of future studies, the authors plan to include other pipe classes and perform additional case study scenarios.

6.0 Acknowledgements

This research was sponsored by the Ductile Iron Pipe Research Association (DIPRA). The authors would also like to thank all the member companies for providing the necessary data for the LCCA model developed. We specially thank Gregg Horn (Vice president – Technical services, DIPRA) for his continued support throughout the development of the tool.

7.0 References


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