

Article

Evaluation of Life Cycle Cost of Excavation and Trenchless Cured-in-Place Pipeline Technologies for Sustainable Wastewater Applications

Gayatri Thakre , Vinayak Kaushal * , Eesha Karkhanis  and Mohammad Najafi 

Civil Engineering Department, The University of Texas at Arlington, P.O. Box 19308, Arlington, TX 76019, USA; gxt2250@mavs.uta.edu (G.T.); exk6311@mavs.uta.edu (E.K.); najafi@uta.edu (M.N.)

* Correspondence: vinayak.kaushal@uta.edu

Abstract: Sanitary sewer pipelines frequently experience blockages, structural failures, and overflows, underscoring the dire state of U.S. wastewater infrastructure, which has been rated a D-, while America's overall infrastructure scores only slightly better at C-. Traditional open-trench excavation methods or excavation technology (ET) for replacing deteriorated pipes are notoriously expensive and disruptive, requiring extensive processes like route planning, surveying, engineering, trench excavation, pipe installation, back-filling, and ground restoration. In contrast, trenchless technologies (TT) provide a less invasive and more cost-effective alternative. Among these, cured-in-place pipe technology (CIPPT), which involves inserting resin-impregnated fabric into damaged pipelines, is widely recognized for its efficiency. However, a comprehensive life cycle cost analysis (LCCA) directly comparing ET and TT, accounting for the net present value (NPV) across installation, maintenance, and rehabilitation costs, remains unexplored. This study aims to establish an LCCA framework for both CIPPT and ET, specifically for sanitary sewer pipes ranging from 8 to 42 inches in diameter. The framework incorporates construction, environmental, and social costs, providing a holistic evaluation. The key costs for ET involve pipe materials and subsurface investigations, whereas TT's costs center around engineering and design. Social impacts, such as road and pavement damage, disruption to adjacent utilities, and noise, are pivotal, alongside environmental factors like material use, transportation, project duration, and equipment emissions. This comprehensive framework empowers decision makers to holistically assess economic and environmental impacts, enabling informed choices for sustainable sewer infrastructure renewal.



Academic Editor: Agostina Chiavola

Received: 24 January 2025

Revised: 19 February 2025

Accepted: 4 March 2025

Published: 6 March 2025

Citation: Thakre, G.; Kaushal, V.; Karkhanis, E.; Najafi, M. Evaluation of Life Cycle Cost of Excavation and Trenchless Cured-in-Place Pipeline Technologies for Sustainable Wastewater Applications.

Sustainability **2025**, *17*, 2329.

<https://doi.org/10.3390/su17052329>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: life cycle cost; construction cost; social cost; environmental cost; wastewater; sanitary sewer; sustainability

1. Introduction

Sewers are interconnected pipelines designed to transport wastewater or stormwater to designated downstream locations for treatment or disposal. There are three primary types: sanitary, storm, and combined sewers [1]. Sanitary and combined sewers convey wastewater from residences, institutions, and businesses to centralized treatment facilities. While sanitary sewers handle only wastewater, combined sewers carry both wastewater and stormwater. As a critical component of urban infrastructure, sewer systems play a vital role in maintaining public health and sanitation. Sanitary sewer systems collect and transport domestic, commercial, and industrial wastewater, along with limited stormwater and infiltrated groundwater, to treatment plants for proper processing [1].

The American Society of Civil Engineers (ASCE), in its 2021 Report Card for America's Infrastructure, assigned a D+ grade to the nation's wastewater infrastructure, indicating that many systems are in poor condition, nearing the end of their service life, and urgently require repair [2–4]. Without timely interventions, these deteriorating systems risk collapsing, threatening public safety and urban stability. The nation's wastewater infrastructure encompasses over 800,000 miles of public sewers and an additional 500,000 miles of private lateral sewers that link homes and businesses to public lines [5].

The Environmental Protection Agency (EPA) reports that in 2019, utilities allocated over USD 3 billion—averaging more than USD 18 per wastewater customer—to replace approximately 4700 miles of pipeline nationwide [4]. The overall cost of pipeline projects is highly variable, influenced by factors such as pipe size, material, depth, length, project location, subsurface conditions, and the type of application involved [6–10].

1.1. Excavation Technology

Excavation technology (ET), also known as open-cut, cut-and-cover, or trenching, involves excavating a trench in the open rather than constructing a tunnel. This method is the simplest approach to install new pipes or replace old ones, requiring excavation to the necessary depth, backfilling, and restoring the surface [6,8,11]. The ET exposes existing pipes for repair or replacement, followed by backfilling. As a traditional approach to underground infrastructure work, it typically includes trench excavation, installation of trench wall supports, pipe bedding and laying, embedment, backfilling, compaction, and surface restoration.

While widely used, ET is less cost-effective and environmentally friendly. The high costs and inefficiencies stem from numerous tasks, including fabrication, the use of heavy vehicles for transportation, and substantial manpower requirements. Reducing these aspects can significantly lower costs and enhance productivity. This method requires digging a trench along the entire pipe length, preparing a suitable base for the new pipe, and subsequently backfilling the full length. Trenchless technologies offer effective solutions to the challenges associated with ET [8,10,12]. ETs are costly and contribute to higher fossil fuel usage and CO₂ emissions.

Historically, underground pipe rehabilitation was carried out using the ET, which involves removing and replacing the old pipe. However, this technique is disruptive and expensive [8,10,12]. It can cause significant disruptions to daily life, including road closures, traffic delays, and loss of access to businesses and homes, along with the noise and pollution associated with the work [13]. The reinstatement of ground surfaces, such as sidewalks, pavements, and landscaping, is particularly costly [14]. In fact, around 70 percent of the direct costs in an ET are attributed to surface reinstatement rather than the pipe installation itself [8,10,11,15,16].

As there is increasing emphasis on sustainability in infrastructure development, it is crucial to manage construction practices responsibly to avoid irreversible environmental damage, including air and water pollution, and waste [11]. Therefore, improving the construction methods and designing infrastructures that prioritize sustainable development is essential.

1.2. Trenchless Technology

Over the past two decades, trenchless technologies (TT) have been increasingly utilized for constructing and rehabilitating buried utilities, including gas pipelines, water distribution networks, sewer collection systems, and drainage culverts [8,13,17]. The adoption of these technologies is growing rapidly as engineers and governments seek innovative methods for underground utility construction. Trenchless technologies encompass a variety

of methods, materials, and equipment for inspecting, stabilizing, rehabilitating, renewing, and replacing existing pipelines, as well as installing new ones, with minimal surface and subsurface disruption [8]. This broad category includes techniques such as Cured-in-Place Pipe Technology (CIPPT), Microtunneling, Horizontal Directional Drilling (HDD), Sliplining, Fold-and-Reformed Pipe, Pipe Jacking, Pipe Bursting, Spot Repair, Spiral Wound, and Shotcrete [18,19].

1.3. Cured-in-Place Pipe Technology

CIPPT is recognized as a safe, efficient, cost-effective, and highly productive option for pipe rehabilitation [8,20]. A survey of U.S. sanitary and storm sewer systems conducted by Hashemi and Najafi [20] revealed that CIPPT was the most frequently used trenchless method during 2007 and 2008. This technique enables the installation of a new, structurally sound pipe within the original, deteriorated pipe, effectively eliminating infiltration and exfiltration caused by open joints, holes, and fractures. CIPPT achieves these results at a reduced cost, in less time, and with minimal disruption to property owners and surrounding communities. The process involves inserting a resin-impregnated fabric tube, made of polyester felt or reinforced fiberglass, into the damaged pipe using air inversion. The liner is then cured using steam or water, forming a new, durable pipe within the old one [21–23].

Key climate factors, such as temperature extremes, seasonal variations, precipitation levels, and freeze–thaw cycles, have been considered. For instance, in Arctic regions, the ground-freezing effect increases excavation costs and challenges the curing process in CIPPT, necessitating special resin formulations. Conversely, in equatorial regions, high temperatures may accelerate resin curing but pose additional challenges in terms of material stability and worker safety.

CIPPT is a prominent technique for sewer system rehabilitation in the U.S., which involves inserting a flexible fabric tube infused with resin into the existing pipeline. The tube is then expanded or inflated and cured using heat (e.g., hot water or steam) or ultraviolet (UV) light, creating a hard, anti-corrosive, and anti-seepage lining that adheres tightly to the inner wall of the original pipe [8,10,17,19,24–28].

CIPPT trenchless renewal is suitable for pipes with diameters ranging from 4 to 120 inches and installation lengths from 1000 to 3000 feet [8]. The two primary insertion methods are inversion and pull-in, with the pull-in method requiring extra care to prevent liner damage during the dragging process [8]. The curing process predominantly employs one of three heat sources—hot water, steam, or UV light—each requiring the resin to reach its exotherm curing temperature.

The CIPPT liner comprises a hollow cylinder made of nonwoven or woven material, or a combination of both, impregnated with a thermosetting resin and often coated with plastic. This liner is formed in situ within the existing pipe, conforming tightly to its shape. During installation, the liner is inserted into the host pipe either by inversion—using water or air pressure to turn the resin-impregnated tube inside out—or by pulling it into place and inflating it to fit snugly against the pipe walls. Figure 1 depicts the Cured-in-Place renewal process, showing the delivery and insertion of an uncured resin tube into a damaged pipe, inflation with air, curing through thermal or UV methods, trimming of ends, and finally, the restoration of the pipe, ready for service.

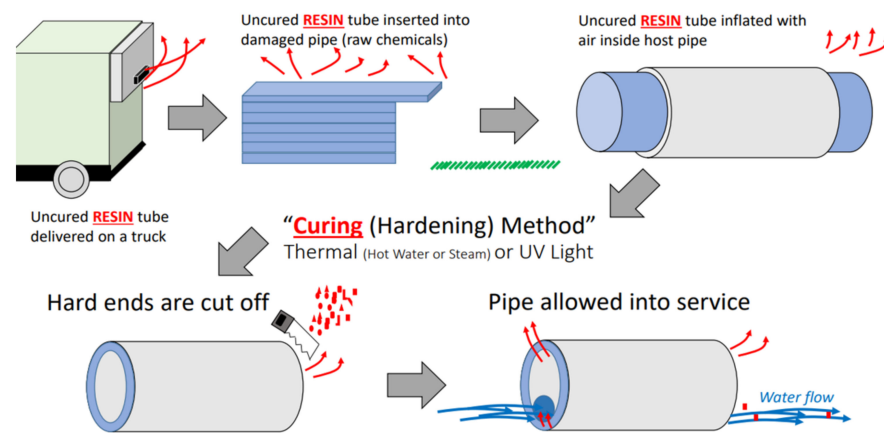


Figure 1. CIPPT installation process [10].

The adoption of CIPPT technology for underground infrastructure rehabilitation provides numerous advantages that enhance the efficiency and effectiveness of pipeline restoration. A summary matrix comparing the advantages and limitations of ET and CIPPT is presented in Table 1 [14,27,29–36].

Table 1. Advantages and disadvantages of CIPPT installation.

	Advantages	Challenges
ET	- Often more cost-effective than trenchless methods in non-paved areas. - Essential for repairing collapsed pipes or those with significant slope loss, as removal of the damaged pipe is necessary. - Ideal for pipes heavily obstructed by roots and debris, as removal of blockages is not required before replacement. - Does not necessitate the extraction of roots or debris from the existing pipe. - Rural areas experience less disruption compared to urban settings, particularly regarding vehicular traffic. - Straightforward installation process, especially for large-diameter pipelines.	- Long-term impacts may include deformation or settlement of buildings affected by construction activities. - Recently, some municipalities have introduced utility-cut fees to offset the costs of underground utility projects [8]. - A common risk with ET arises during backfill compaction, as incomplete compaction can cause the soil or existing utilities to settle over time, leading to uneven road surfaces or ground conditions, such as in concrete or asphalt [17]. - For river crossings, the ET typically routes pipelines under bridges, significantly accelerating wear and reducing the lifespan by 50–75%. - Open trenching carries a notable risk of soil contamination, which can result from construction equipment and maintenance activities. Contaminated soil often requires proper treatment and disposal, typically at the contractor's expense.
CIPPT	- CIPPT necessitates minimal excavation, thereby occupying a reduced subterranean footprint and curtailing the duration of construction activities. - The CIPP lining establishes a seamless interface with the existing pipeline, eliminating the requirement for supplementary grouting procedures, providing enhanced structural integrity. - CIPPT demonstrates remarkable adaptability to diverse conduit morphologies, accommodating a wide spectrum of cross-sectional configurations encountered in aging infrastructure systems. - A single CIPPT operation can effectively rehabilitate extended pipeline segments, producing a monolithic, joint-free lining. - The smooth interior surface of CIPP linings results in a diminished friction coefficient. - CIPPT materials exhibit superior resistance to corrosive agents and demonstrate exceptional impermeability characteristics. - The composite nature of the CIPPT–host pipe system leverages the residual structural capacity of the existing pipeline in conjunction with the mechanical properties of the CIPPT lining.	- Higher construction costs compared to conventional rehabilitation methods. - Requires significant investment in specialized equipment and skilled labor. - Difficult implementation in structurally compromised pipelines. - Demands specialized construction equipment. - High technical expertise required from workers.

2. Literature Review

2.1. Construction-Cost-Related Studies

Beaudet et al. [37] presented a life cycle cost (LCC) analysis framework for evaluating collection system rehabilitation projects. Using a theoretical case study, the analysis revealed that trenchless CIPPT lining with pre-engineered rubber gaskets had the lowest net present value (NPV) over a 50-year period (USD 3192.42) compared to adhesive-based seals (USD 6185.37) and a “do-nothing” alternative (USD 9494.85). The study highlighted that while the initial costs of some trenchless solutions are higher, they offer significant savings in maintenance and leakage reduction over time, making them the most cost-effective option for long-term infrastructure rehabilitation.

Kaushal et al. [10] compared the cost of CIPPT renewal to ET for sanitary sewer pipes. Their analysis showed that trenchless CIPPT is 57%, 63%, and 18% less expensive for small, medium, and large-diameter pipes, respectively. The study emphasized that most costs in ET stem from surface reinstatement and disruptions, which are significantly reduced with CIPPT. The findings suggest that trenchless methods are highly cost-effective, particularly in urban areas, offering substantial savings over the life cycle of pipeline projects.

Serajiantehrani et al. [38] analyzed the construction costs of trenchless technologies, specifically Spray-Applied Pipe Linings (SAPL) and CIPPT, for the rehabilitation of large-diameter culverts (30–108 inches). The study revealed that CIPPT generally had lower mean construction costs compared to SAPL, especially for larger diameters. For instance, the cost difference between the two methods widened significantly as the diameter increased, with CIPPT being up to 500% cheaper than SAPL for 72-inch culverts.

The mean costs for CIPPT ranged from USD 224 to USD 433 per linear foot, depending on location and diameter, while SAPL costs ranged from USD 350 to USD 813 per linear foot. These findings underscore CIPPT’s economic advantage in larger-diameter projects.

Xu et al. [39] reviewed the evolution of machine learning in the construction industry, transitioning from shallow learning (e.g., decision trees, logistic regression, support vector machines) to deep learning (e.g., convolutional neural networks, recurrent neural networks). The study highlighted that ML can significantly improve construction efficiency, including safety monitoring, defect detection, and project planning. However, it also noted challenges, particularly data acquisition and model adaptation to complex construction environments. The paper suggested that future advancements should integrate domain-specific knowledge with ML algorithms to develop customized models.

Ref. [40] research focuses on developing a cost prediction model for sewerage projects using artificial neural networks. The study analyzes data from 125 sewerage projects in the Czech Republic (2018–2022) and proposes an ensemble-based approach for early-stage cost estimation. The results indicate that ensemble neural networks outperform traditional multiple linear regression models, achieving a prediction accuracy within $\pm 30\%$ for over 90% of cases. The study underscores the significance of AI in infrastructure planning, enabling cost-effective and timely project execution. The findings are especially relevant for public-sector funding and urban development.

Sousa and Meireles [41] examine how construction technology impacts time–cost relationships in sewerage projects. The study analyzes 70 projects (Chicago, 1994–2002), comparing traditional open-cut excavation with trenchless technologies like Cured-in-Place Pipe (CIPP). The study finds that trenchless technologies reduce surface disruptions but show different time–cost dynamics compared to traditional methods. Using Bromilow’s time–cost model, the research demonstrates that project size correlates with time efficiency, especially for open-cut methods. The study suggests separate cost models for different technologies to improve project planning accuracy.

2.2. Environmental-Cost-Related Studies

Joshi [42] compares the CO₂ emissions of ET and pipe-bursting methods for sewer pipeline replacement, finding that pipe bursting results in 72.6% less CO₂ emissions. The environmental benefits stem from reduced excavation, shorter project durations, and minimized traffic disruption. Economically, pipe bursting offers cost savings associated with reduced fuel consumption and decreased labor requirements, highlighting its superiority as a sustainable construction method.

The environmental and economic impacts of VOC emissions during CIPPT sewer rehabilitation are underscored by quantitative data from a study by Ajdari [12]. VOC emissions from the CIPPT process were significantly lower compared to traditional replacement methods, with total VOC emissions at 0.042 tons for CIPPT activities over 22 workdays versus 0.181 tons for ET over 110 days. Similarly, CO₂ emissions were substantially reduced, with 52.76 tons for CIPPT versus 185.33 tons for ET. These reductions reflect the shorter operational duration and minimized equipment use in CIPPT. The study utilized EPA's MOVES (Motor Vehicle Emission Simulator) and SimaPro, a life cycle assessment tool, to quantify the emissions and assess the environmental impacts associated with CIPPT rehabilitation projects. SimaPro was particularly instrumental in calculating greenhouse gas and VOC emissions by integrating data on resin and material use, curing processes, and operational durations. These tools provided a comprehensive analysis of the environmental costs, enabling precise identification of emission sources and their corresponding impacts.

Chilana et al. [43] compare the greenhouse gas emissions of steel and prestressed concrete cylinder pipe (PCCP) for large-diameter water transmission pipelines. Using a case study from Texas, they evaluate four life cycle phases: material production, transportation, installation, and operation. The results indicate that steel pipe manufacturing has a significantly higher carbon footprint (32% larger) than PCCP due to its energy-intensive production. However, PCCP has higher transportation emissions because of its heavier weight. The findings provide insights for pipeline material selection and emission reduction strategies.

Kaushal et al. [10] discuss the significant chemical emissions during CIPPT installations, focusing on styrene, a primary component in the resin. Styrene emissions were measured at levels ranging from 20 to 300 ppm near termination manholes during steam curing, exceeding both short-term and long-term exposure limits. These emissions pose health risks to workers and nearby residents. The key tools employed included photoionization detectors (PIDs) for real-time monitoring and gas chromatography/mass spectrometry (GC/MS) for precise chemical analysis. The research calls for more robust field measurements, especially under varying meteorological conditions, to better understand emission dispersion and mitigate health risks effectively.

Visentin et al. [44] determined the life cycle assessment (LCA) and life cycle cost assessment (LCC) of nanoscale zero-valent iron (nZVI) production, revealing critical environmental and economic trade-offs between methods. The sodium borohydride reduction method has the lowest environmental impact, producing 30.23 kg CO₂ equivalent per kg of nZVI, while the hydrogen gas reduction method generates up to 58.56 kg CO₂ equivalent, making it the least sustainable option. Material costs dominate the sodium borohydride method, with sodium borohydride alone accounting for 86.8% of total costs, whereas energy consumption is the largest cost factor in the hydrogen gas method, contributing 73.35% to total expenses. Tools like SimaPro, coupled with the Eco invent database, were pivotal in evaluating climate change, ecosystem quality, and resource use impacts, highlighting that sodium borohydride reduction is environmentally preferable despite its high material costs, making it suitable for lab-scale and selective industrial applications.

Fuselli et al. [45] examine the environmental benefits of trenchless pipe rehabilitation methods, particularly Cured-in-Place Pipe (CIPP), compared to traditional open-cut

methods. Using a case study in Monza, Italy, they assess the carbon emission reductions achieved by trenchless technology. The results indicate that CIPP methods can reduce CO₂ emissions by approximately 65% and fuel consumption by 69%. Among different CIPP curing techniques, ultraviolet (UV) curing had the lowest environmental impact due to lower energy requirements and material efficiency.

Chorazy et al. [46] conducted a comparative study on the restoration of a sewage network in Brno, Czech Republic, using trenchless technology (TT) and traditional excavation (OT) methods, focusing on cost effectiveness and the environmental impact. While TT had higher initial costs, it resulted in significant long-term savings by reducing traffic disruption, waste disposal, and fuel consumption, ultimately lowering indirect costs. The carbon footprint of TT was 9.91 t CO₂ eq. compared to 24.29 t CO₂ eq. for OT, marking a 59.2% reduction in emissions. The study assessed fuel consumption, energy demands, and construction time, finding that TT completed the project in 60 days versus 90 days for OT, making it more efficient. OT had a higher environmental impact due to greater reliance on fossil-fuel-based machinery and extensive excavation work. The authors recommend prioritizing TT for urban infrastructure projects, integrating environmental impact assessments into planning, and investing in sustainable construction technologies. The study concluded that TT is a more environmentally friendly and cost-effective alternative to OT in sewer network restoration.

The Environmental Prices Handbook 2024 [47] provides updated environmental prices, representing the social cost of pollution in euros per kilogram of pollutants. It covers over 3000 pollutants and assigns values based on their impact on human health, ecosystems, and resource availability. These prices are crucial for cost–benefit analyses, life cycle assessments, and corporate sustainability reporting. The methodology considers dose–effect relationships and scientific updates since the last edition (2018). It emphasizes that environmental prices are conservative estimates, likely to increase with further scientific advancement.

2.3. Social-Cost-Related Studies

Xueqing et al. [48] emphasize the importance of integrating social costs into bid evaluations to reflect the true cost of construction projects. For example, the inclusion of traffic delays, environmental impacts, and business interruptions in project bids showed that trenchless methods scored 25% higher in cost effectiveness compared to ET. A case study revealed that incorporating social costs reduced the apparent cost disparity between the two methods, favoring trenchless technologies in competitive bid environments.

Ormsby [49] develops a framework for evaluating total costs, including indirect and external costs, such as traffic delays and business losses. A case study of a trenchless project in Montreal found that indirect and external costs accounted for 25% of total costs for ET but were reduced to 10% with trenchless approaches. This reduction resulted in savings of over USD 400,000 for a USD 2 million project. The framework underscores the need to consider all cost components to accurately assess the economic benefits of trenchless technologies.

Maldikar [50] demonstrates that outdoor noise significantly impacts productivity, with an average reduction in labor efficiency of about 28.57% when noise levels exceed 87.49 dB. The economic analysis calculated productivity loss using Equation (1):

$$\begin{aligned} \text{Cost of Productivity Loss} \\ &= \text{Time Lost per Day} \times \text{Number of Workers} \times \text{Wage Rate} \\ &\quad \times \text{Duration in} \end{aligned} \quad (1)$$

This highlights substantial project cost increases due to delays caused by environmental noise. Additionally, workers exposed to noise levels above 90 dB experience an increased

accident risk, averaging 1.35 incidents per person per year compared to 0.26 incidents for noise levels below 80 dB. These findings underline the critical economic and safety costs tied to insufficient noise mitigation strategies at construction sites.

Matthews et al. [51] examine the monetary valuation of social costs, emphasizing their importance in infrastructure project planning. The study identifies eight categories of social costs, including traffic delays and environmental degradation. For example, urban pipeline projects using trenchless methods were shown to reduce traffic delay costs by up to 50% compared to ET, with savings ranging from USD 10,000 to USD 45,000 depending on project scale. The findings stress the need for incorporating social costs into project evaluations to capture true economic impacts.

Çelik et al. [52] provide a quantitative analysis of social costs in construction projects, revealing that traffic delays alone can cost USD 10,000–USD 50,000 per project depending on the scale and duration. Noise pollution and dust control costs were estimated to add an additional 10–15% to the overall project expenses in urban settings. The study emphasizes that these social costs, often overlooked, can form up to 30% of the total project costs, particularly in densely populated areas. For example, in a mid-sized urban project, the cumulative social costs from delays, pollution, and business interruptions were calculated to exceed USD 150,000. The paper advocates for incorporating these expenses into project planning to ensure a more accurate assessment of total costs.

Kaushal [10] compares CIPPT with ET for sanitary sewers. The results show that the total social and environmental costs for CIPPT were 90% lower than for ET. The key cost factors for ET included detour delays and pavement restoration, which contributed approximately 75% of the social cost. For small-diameter sewers (8–12 inches), the total cost savings were estimated at over USD 100,000 per mile of pipeline replaced.

A meta-analysis by Mohanty and Rath [53] reviews the methodologies for quantifying social costs in the construction sector. It reveals wide variations in the cost estimation approaches but emphasizes that social costs, such as the environmental impact and public disruption, often remain under accounted for. Estimates suggest that incorporating these costs can increase total project cost assessments by 20–40%. The analysis underscores the necessity for standardized methods to integrate social costs into cost planning.

3. Results and Analysis

3.1. Construction Cost Analysis

The methodology for this study includes a comprehensive literature review and an initial statistical analysis using regression techniques. Regression analysis is particularly effective for identifying the relationships between one parameter and one or more variables. In this study, the dependent variable (y) is the price per foot for CIPPT and ET, while the independent variable (x) is the diameter of the pipeline project.

Regression analysis is a statistical method used to explore and model relationships between dependent and independent variables. It is widely utilized for analyzing multifactor data due to its ability to represent relationships systematically through mathematical equations [54]. This methodology finds extensive application across various fields, including construction engineering and management.

A critical component of regression analysis is the quality of data collection, as the accuracy of the results hinges on the reliability of the data. Data for regression can be obtained through three main methods: retrospective studies using historical data (as employed in this study), observational studies, and designed experiments. Engineers and scientists frequently use regression analysis to derive equations that summarize or characterize datasets, making it a valuable tool for tasks such as data description, parameter estimation, forecasting, and system control.

In this study, one intercept parameter and one primary variable were evaluated. The intercept parameter represents the price per foot for CIPPT and ET, while the variable analyzed is the pipeline diameter. As shown in Figure 2, data from each project are presented as price (dollars per foot) relative to diameter (inches).

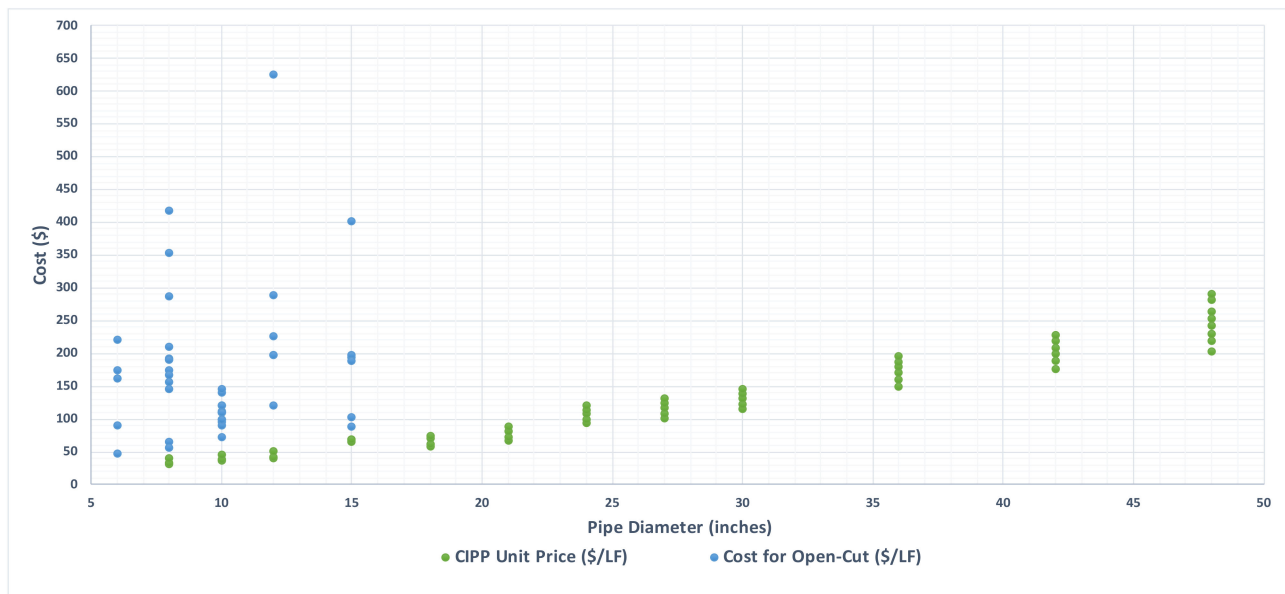


Figure 2. Scatter plot of cost versus pipe diameter for open-cut and CIPPT.

Following the organization and analysis of the collected data, regression analysis was utilized to compare the construction costs of the CIPPT and ET. Figure 3 illustrates the mean construction costs (USD /ft) of the CIPPT method compared to ET for sanitary pipe diameters ranging from 8 to 42 inches.

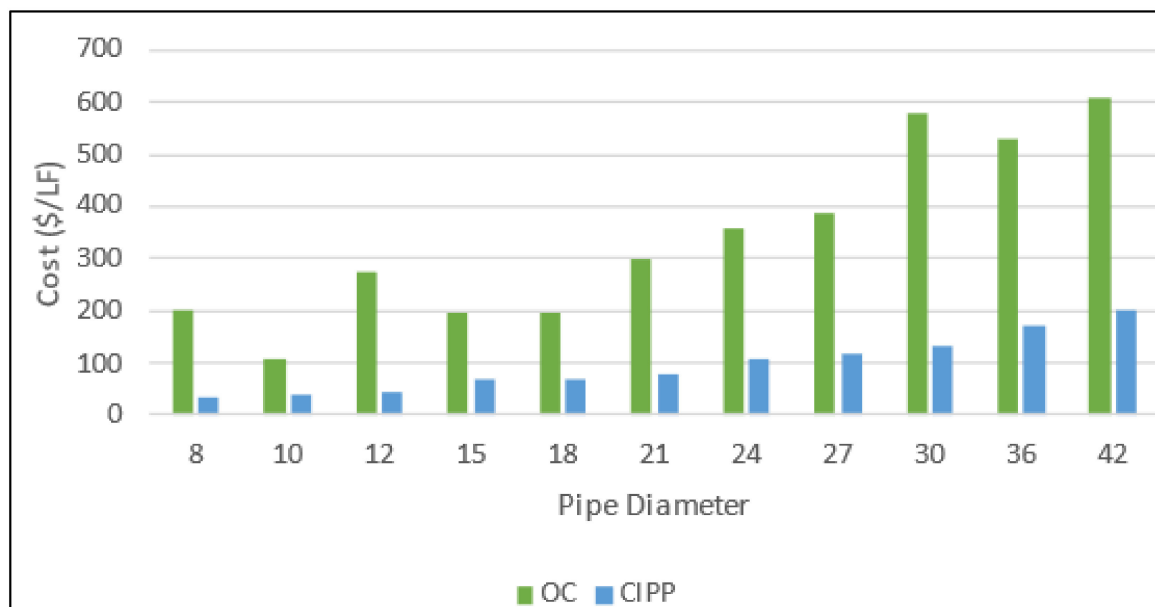


Figure 3. Mean construction cost comparison.

The results demonstrate an exponential relationship between the mean construction cost of CIPPT and pipe diameter, whereas the ET exhibits a linear relationship between the construction cost and diameter. Additionally, the correlation coefficients (R^2) for CIPPT renewal and ET are 0.862 and 0.96, respectively, indicating a strong fit between the models.

and the observed data (Figure 4). With various regression methods available, including linear, exponential, logarithmic, and power models, selecting the best-fit trend line for the scatter plot is essential. The relationship ratio between two parameters, represented by R^2 , serves as an effective criterion for this decision. Generally, a higher R^2 value indicates a more accurate and reliable trend line.

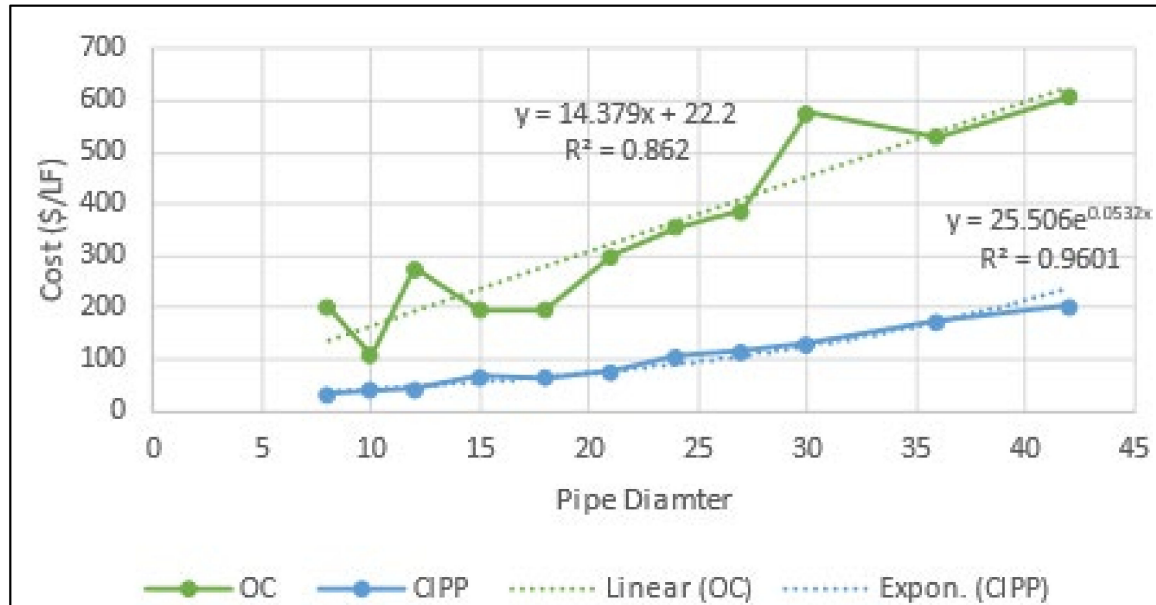


Figure 4. Mean construction cost comparison—Regression analysis.

3.2. Environmental Cost Analysis

EIA. Environmental Impact Assessment (EIA): EIA is a systematic approach to identifying and evaluating the environmental impacts of energy use and resource consumption across a product's life cycle [55]. Conducted in compliance with [56], the process involves four key stages: (1) defining the goal and scope, (2) compiling a detailed inventory of system inputs and outputs, (3) assessing the environmental, health, and resource impacts, and (4) interpreting the results to determine their significance.

SimaPro. SimaPro 2017 is a software tool specifically designed for conducting life cycle assessment (LCA) studies, enabling users to perform inventory analyses and environmental impact evaluations. It features comprehensive databases containing detailed information on energy consumption, material requirements, and emissions for more than 10,000 industrial and commercial processes [57]. The tool also models end-of-life waste management scenarios, such as landfilling, incineration, and recycling, focusing primarily on material flow. Using predefined boundaries, SimaPro processes data and evaluates the impacts through key indicator substances, converting emissions into equivalents (e.g., CO_2 for global warming). The results are presented in user-friendly charts, enabling a proportional visualization of the impacts for comparative analysis.

TRACI 2.1. Developed by the USEPA, TRACI 2.1 (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) analyzes ten key environmental categories, including ozone depletion, climate change, smog formation, acidification, and eutrophication, carcinogenic and noncarcinogenic effects, respiratory impacts, ecotoxicity, and fossil fuel depletion. TRACI normalizes the results against the annual average impact of a U.S. or Canadian citizen, facilitating qualitative comparisons across categories (PRé, 2016).

An environmental impact assessment is conducted to analyze the environmental costs associated with CIPPT renewal and ET. An environmental impact assessment is conducted using SimaPro 2017 with the TRACI 2.1 methodology to estimate emissions.

These emissions are then translated into costs using standards from the USEPA (2019) and other relevant sources, providing a comprehensive analysis of environmental costs for small to large sanitary sewer systems.

3.3. Social Cost Analysis

The diagram (Figure 5) illustrates the social cost classification, categorizing the negative externalities into four main domains: Traffic, Economic Activities, Pollution, and Ecological/Social Health. Under Traffic, increased accident rates, road rage, and delays contribute to inefficiencies, leading to additional fuel consumption and loss of parking space. These traffic-related issues further affect Economic Activities, resulting in loss of income, property damage, tax revenue decline, and reduced productivity. Simultaneously, Pollution emerges as a critical cost, impacting air and water quality while generating noise, dust, and vibration-related disturbances. Lastly, Ecological and Social Health costs manifest through restoration expenses, compromised mental health, and a decline in life quality. Collectively, these interconnected social costs highlight the broad-ranging consequences of urban congestion and environmental degradation.

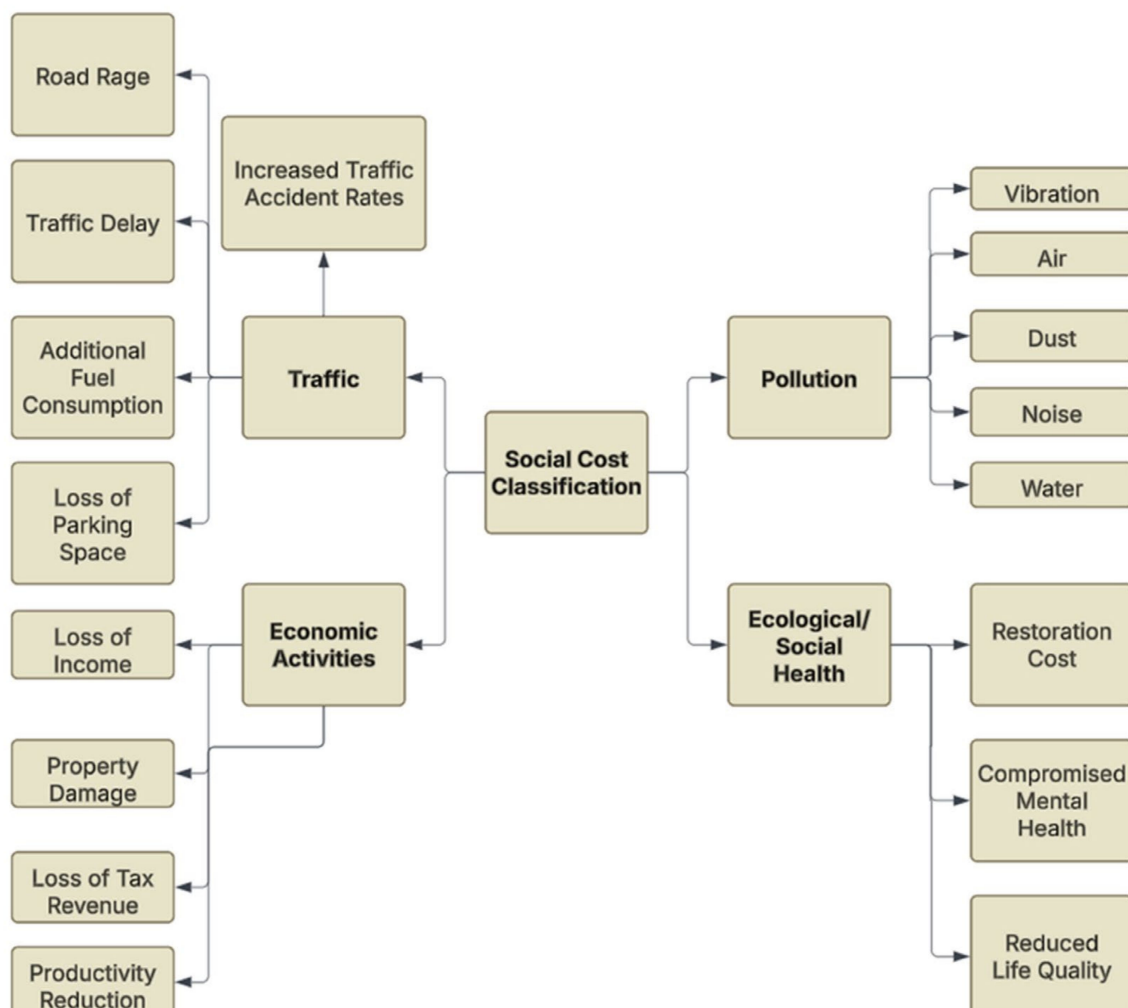


Figure 5. Social cost categories (adapted from [51–54]).

To assess the social costs associated with CIPPT renewal and OCCM methods for 8-, 10-, and 12-inch diameter pipes, researchers utilized a set of equations developed by Najafi and Gokhale (2021) [8], supplemented by reasonable assumptions drawn from various relevant sources. These equations and methodologies address diverse aspects of social costs, including factors such as project duration, fuel consumption for detours, travel time delays, road damage, loss of sales tax revenue, reduced productivity caused by noise, and dust control measures. The key social cost concepts and calculation methods [22,32,58–62] are outlined as follows:

- A. **Duration of the Project.** The duration of a project is a critical determinant of social costs, with extended timelines typically resulting in increased expenses due to
 1. Extended lane closures causing prolonged traffic congestion.
 2. Increased commuter delays and frustration.
 3. Higher cumulative fuel consumption and emissions.
 4. Short-duration projects generally having lower social costs, while longer projects can lead to substantial increases in traffic disruption expenses.
- B. **Cost of Fuel.** Open-cut installation often necessitates lane closures, resulting in traffic congestion and increased fuel consumption. The duration of traffic delays directly correlates with the amount of fuel wasted, which in turn affects the overall fuel cost. To estimate this cost, the calculation considers the amount of fuel consumed by vehicles idling in traffic or using alternate routes. By applying the average fuel consumption rate of a standard vehicle, the total fuel wasted during traffic disruptions is determined. The costs associated with fuel consumption for detour routes or delays per vehicle are calculated using Equation (2).

$$\frac{\text{Cost of fuel for detour roads}}{\text{vehicles}} = \left(\frac{\text{Avg gal}}{\text{mile}} \right) \times (\text{Avg additional mile}) \times \left(\frac{\text{Avg cost of fuel}}{\text{gal}} \right) \quad (2)$$

- C. **Travel Time Cost.** The value of time related to travel varies significantly based on a complex interplay of factors, including the nature of the trip, travel distance, individual traveler characteristics, and prevailing travel conditions. Business trips and longer journeys often carry higher time values compared to personal or local travel. Individual factors, such as income level and personal preferences for leisure time, also influence how travelers value their time. The travel environment plays a crucial role, with comfortable conditions potentially reducing the perceived time costs, while congestion and discomfort tend to increase them. The mode of transport, trip duration, and time of day further contribute to this variability. Notably, passengers typically assign higher per-minute costs to their travel time when faced with uncomfortable or congested conditions, reflecting the increased stress and inconvenience associated with such situations. The cost of detour delays can be determined using Equation (3).

$$\text{Cost of detour delay} = \left(\frac{\text{Avg time}}{\text{mile}} \right) \times (\text{Additional miles to travel}) \times (\text{Value of time in dollars}) \quad (3)$$

- D. **Road Damage.** Utility construction projects can result in two distinct forms of road damage. The first is direct pavement damage caused by utility cuts, trenching operations, and inadequate patching procedures, which manifests as potholes, increased surface roughness, and cracks in the road surface. This damage is a direct consequence of the construction work itself. The next form is indirect damage to detour roads resulting from the increased volume of traffic, especially heavy vehicles, which are diverted during the construction period. This additional stress on alternative routes can lead to accelerated wear and tear, causing premature deterioration of roads not

originally designed to handle such high traffic loads. Both types of damage contribute significantly to the overall social and economic costs associated with utility construction projects, underscoring the importance of comprehensive planning and effective mitigation strategies. To estimate the cost of pavement restoration, Equation (4) can be used:

$$\text{Pavement restoration cost} = \left(\frac{\text{Restoration cost}}{\text{ft}^2} \right) \times (\text{number of ft}^2) \quad (4)$$

- E. **Loss of Sales Tax.** Utility construction projects can have significant financial repercussions for nearby businesses and shops, primarily due to reduced customer traffic. As people tend to avoid areas with lane closures and construction-related disruptions, the affected businesses experience a decline in patronage. This reduction in customer visits directly translates to decreased income for these establishments. Consequently, the lower revenue generated by these businesses leads to a decrease in tax revenue for the local government. Equation (5) can be used in calculating the loss of sales tax:

$$\text{Loss of sales tax} = \left(\frac{\text{Average dollar loss}}{\text{day}} \right) \times (\text{Duration of project in days}) \quad (5)$$

- F. **Loss of Productivity.** Noise pollution from construction activities can significantly impact productivity, though its effects are challenging to quantify precisely. Individual responses to noise vary considerably, with some people experiencing minor productivity decreases, while others find it intolerable. Research indicates that noise levels above 60 dB can hinder complex task performance, and exposure to high noise levels (110 dB) notably reduces overall performance and increases error rates. The impact of noise on productivity depends on factors such as sound intensity, duration of exposure, and the nature of the work being performed, making it a complex issue in workplace environments. The loss of productivity is provided by Equation (6).

$$\text{Cost of productivity} = \left(\frac{\text{Time lost}}{\text{day}} \right) \times (\text{Number of persons}) \times (\text{Value of time}) \times (\text{Duration of project in days}) \quad (6)$$

- G. **Dust.** One method for quantifying the expense associated with dust is to evaluate the incremental cleaning time required. This approach considers the additional labor hours needed to address dust accumulation, which can be translated into monetary costs. By measuring the extra time spent on cleaning activities, such as dusting, sweeping, or operating specialized dust control equipment, organizations can estimate the financial impact of dust on their operations. This calculation may include factors such as employee wages, cleaning supply costs, and potential productivity losses due to more frequent cleaning interventions. Equation (7) can be used to calculate the dust and dirt control cost:

$$\begin{aligned} \text{Cost of dust control} &= \left(\frac{\text{Increased cleaning time in hours}}{\text{Day}} \right) \\ &\times (\text{Hourly pay rate})(\text{Number of units impacted}) \\ &\times (\text{Duration of project in days}) + (\text{Cost of cleaning materials}) \end{aligned} \quad (7)$$

- H. **Cost of Fuel.** OCCM often necessitates lane closures, resulting in traffic congestion and increased fuel consumption. The duration of traffic delays directly correlates with the amount of fuel wasted, which in turn affects the overall fuel cost. To estimate this cost, calculations are based on the quantity of fuel consumed by vehicles idling in traffic or traversing alternate routes. The computation utilizes the average fuel consumption rate of a typical car to determine the total fuel wasted during these traffic

disruptions. The costs of fuel for detour roads or delay per vehicle are calculated according to Equation (8).

$$\frac{\text{Cost of fuel for detour roads}}{\text{vehicles}} = \left(\frac{\text{Avg gal}}{\text{mile}} \right) \times (\text{Avg additional mile}) \times \left(\frac{\text{Avg cost of fuel}}{\text{gal}} \right) \quad (8)$$

3.4. Life Cycle Cost Analysis Framework

The LCCA framework provides a structured approach to evaluate the long-term costs associated with trenchless renewal methods for sanitary sewers, encompassing three primary cost components: construction, environmental, and social costs. Construction costs focus on factors such as pipe dimensions, material type and thickness, and the rehabilitation design life. Environmental costs are influenced by material components, transportation logistics, project location, equipment use, and energy consumption. Social costs address impacts such as traffic disruptions, noise, road restoration needs, and overall public inconvenience.

This framework integrates diverse parameters to calculate a comprehensive life cycle cost. It accounts for quantifiable factors, including project specifics (e.g., length and diameter of the culvert, material properties), environmental considerations (e.g., emissions, energy use, and material sourcing), and socio-economic factors (e.g., traffic control, noise, and community impacts). Advanced computational tools like Minitab (<https://www.minitab.com> (accessed on 25 December 2024)) and Microsoft Excel (<https://www.microsoft.com/excel> (accessed on 25 December 2024)) software are employed for construction cost analysis. SimaPro (<https://simapro.com/> (accessed on 25 December 2024)) software is employed to quantify environmental impacts based on metrics such as global warming potential, smog generation, and resource depletion.

The LCCA can be used as an important and effective decision-making tool to determine the cost of rehabilitation alternatives based on each alternative's full life cycle (service life). A survey of the largest municipalities in the U.S. indicated that 40% of municipalities use LCCA and that some have been using it for over 20 years [63–65]. The reasons why 60% of municipalities did not use LCC analysis include the lack of formal guidelines and the difficulty in estimating future expenses and income. The life cycle cost of the project, from its design to the decommissioning of the utility, includes the following categories [23,66–70] (Figure 6):

- Preconstruction cost: Land acquisitions, design fees, planning, and legal costs;
- Construction cost: Direct cost, indirect cost, and social cost;
- Post-construction: Cost operation and maintenance.

The life cycle cost analysis (LCCA) for trenchless rehabilitation projects is calculated by combining three key cost components: construction cost (C), environmental cost (E), and social cost (S), as expressed in Equation (9):

$$LCCA = CC + EC + SC \quad (9)$$

This method requires careful consideration of material service life, ensuring the costs of replacing limited-life materials are balanced with initial investments. To account for the monetary differences over time, Equation (10) provides a framework for evaluating the total effective cost of various trenchless rehabilitation methods [71,72]:

$$EC(LCCA) = LCCA \times \left\{ 1 + \frac{(1+I)^n}{(1+i)} \right\} \quad (10)$$

where

EC(LCCA): Total effective cost.

LCCA: Life cycle cost analysis expressed in current dollars.

I: Inflation rate throughout the project period.

i: Interest rate applicable during the project period.

n : Number of years until disposal or the end of the design life.

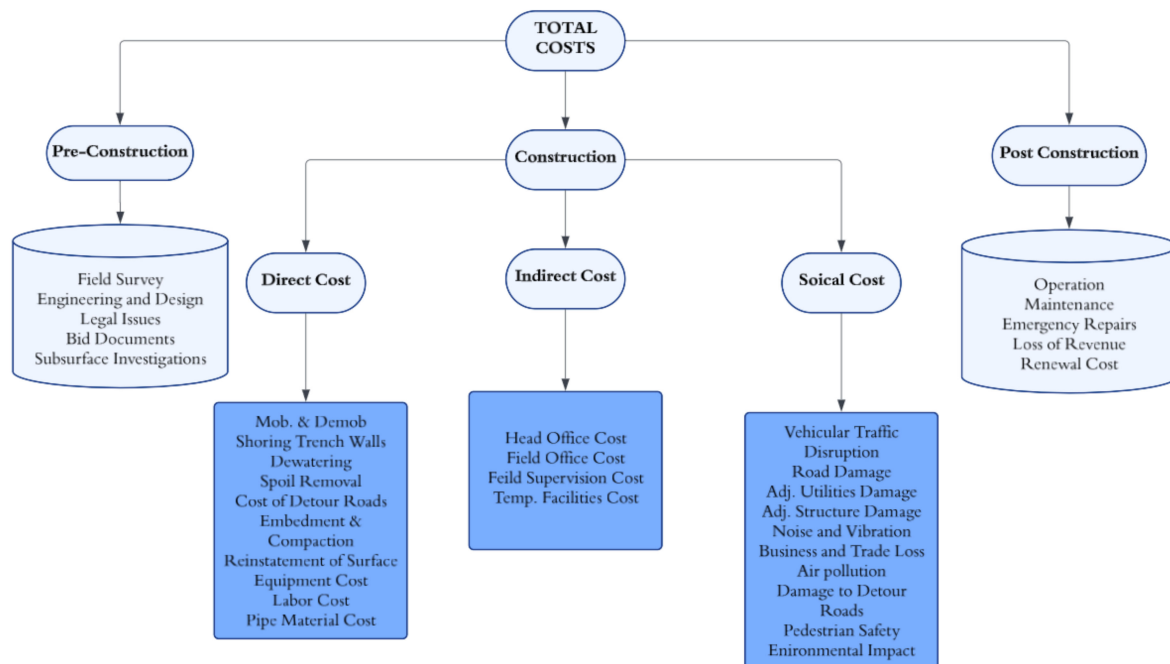


Figure 6. Total cost categories (adapted from [8]).

The methodology of the research includes a systematic process designed for the development and analysis of machine-learning models, emphasizing a structured approach to data and cost evaluation. It begins with a comprehensive data collection and literature review, followed by an exploration of case studies and previous studies to establish foundational knowledge. The process then integrates various costs (construction, social, and environmental) using their respective methods, such as machine learning for construction costs, equations for social costs, and SimaPro for environmental costs. This is combined into a life cycle cost evaluation framework. The methodology incorporates supervised and unsupervised machine-learning techniques. The models are trained, tested, and iteratively refined to identify the optimal solution, culminating in the presentation of results and conclusions. The methodology of the life cycle cost prediction is depicted in the flowchart (Figure 7).

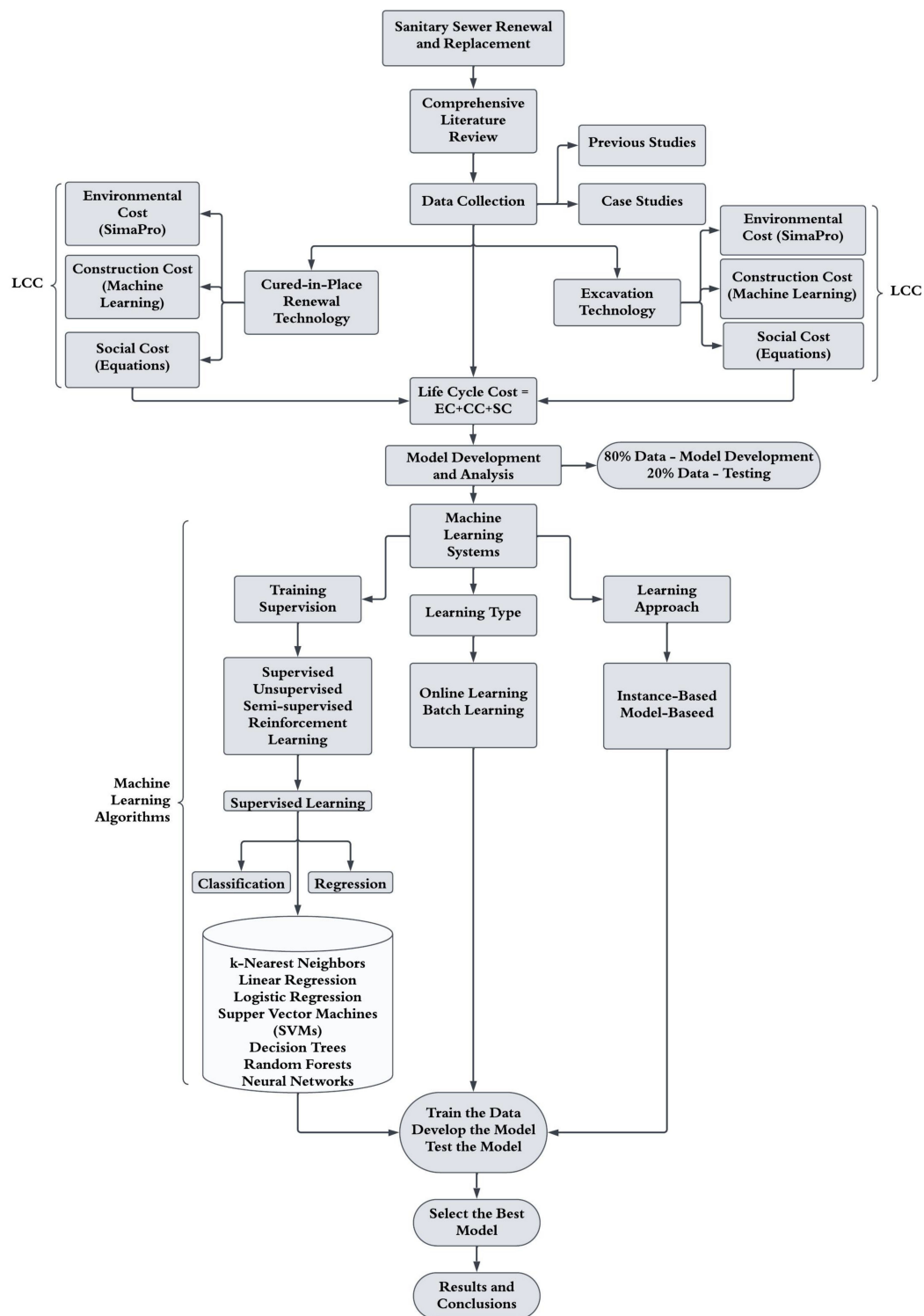


Figure 7. Life cycle cost evaluation flowchart.

4. Evaluation, Conclusions, and Recommendations

This study underscores the critical importance of adopting a comprehensive life cycle cost analysis (LCCA) framework to evaluate the economic and environmental trade-offs in trenchless pipeline renewal methods. By aggregating the social, environmental, and construction costs associated with CIPPT renewal and ET, a holistic understanding of their impacts is achieved. The literature review demonstrates that CIPPT offers significant advantages in reducing environmental burdens, including lower greenhouse gas emissions

and resource consumption, while also minimizing indirect social costs, such as traffic disruption and public inconvenience.

Furthermore, the analysis highlights the necessity of tailoring LCCA approaches to account for project-specific factors, such as pipe size, location, and end-of-life design considerations. For small, medium, and large-diameter pipeline projects, the methodology provides a scalable tool for municipalities and engineers to make informed decisions that balance cost efficiency with sustainability goals. The inclusion of actual case studies and empirical data reinforces the applicability of this framework in real-world scenarios, enabling a nuanced comparison of the cumulative costs associated with sanitary sewer rehabilitation methods.

Overall, this research emphasizes that adopting trenchless technologies like CIPPT can yield substantial cost savings and environmental benefits over their life cycle, positioning them as preferred solutions in the sustainable development of underground infrastructure. By integrating LCCA into planning and decision making, stakeholders can enhance the economic viability, environmental integrity, and social acceptance of infrastructure renewal projects, ensuring long-term benefits for communities.

The LCCA framework presented in this paper serves as a valuable tool for comparing alternative trenchless rehabilitation methods for sanitary sewer pipes. Its primary advantage lies in its ability to support decision making by identifying the most cost-effective rehabilitation method for trenchless projects. Project managers often aim to maximize the efficiency of capital budgets while addressing the extensive needs for pipeline rehabilitation within utility systems. A thorough LCCA not only helps select the best alternative based on more than just the lowest initial costs but also aids decision makers in making informed, long-term choices for their clients. Future LCCA studies are encouraged to explore applications for storm and sanitary sewers across varying pipe lengths, sizes, and locations.

5. Contributions to the Body of Knowledge

This study makes significant contributions to advancing the understanding and application of LCCA in pipeline rehabilitation, particularly in the comparison of ET and TT, including CIPPT. One of the primary contributions is the development of a comprehensive LCCA framework that integrates construction, environmental, and social costs. Unlike existing approaches that often focus narrowly on one or two cost dimensions, this framework enables a holistic evaluation of pipeline rehabilitation methods, providing a more robust basis for long-term decision making.

The study also addresses critical gaps in the application of LCCA by incorporating advanced tools, such as SimaPro and TRACI 2.1, to quantify the environmental impacts and convert them into cost metrics. This integration bridges the disconnect between environmental assessments and economic analyses, ensuring that environmental factors, such as greenhouse gas emissions, material usage, and energy consumption, are systematically included in LCCA evaluations for ET and TT. Furthermore, the research incorporates dynamic social cost components—such as traffic disruptions, noise pollution, and detour-related road damage—into the LCCA framework, highlighting their significance in determining the true life cycle costs of rehabilitation methods.

Another key contribution lies in the empirical validation of the LCCA framework across diverse project conditions, including varying pipeline diameters, subsurface characteristics, and urban versus rural settings. By providing granular insights into the cost effectiveness of CIPPT under different scenarios, this study ensures that the LCCA framework is both scalable and adaptable, enhancing its relevance for real-world applications.

Ultimately, this research not only extends the theoretical understanding of LCCA but also provides a practical tool for municipalities, engineers, and policymakers to optimize

rehabilitation strategies. By aligning economic, environmental, and social considerations, the study promotes sustainable infrastructure management and sets a benchmark for future LCCA applications in underground utility systems.

6. Research Gaps

Although LCCA has emerged as a critical tool for evaluating the economic, environmental, and social implications of infrastructure projects, its application to comparing ET and TT, specifically CIPPT, remains underexplored. Existing studies often focus on individual cost components—such as direct construction costs or emissions—without providing a comprehensive, integrated framework that considers the full spectrum of LCCA categories: construction, environmental, and social costs. This fragmented approach limits the ability to holistically assess the long-term benefits and trade-offs of TT and ET methods.

Moreover, while CIPPT is recognized for its efficiency and reduced surface disruption, its life cycle costs under varying conditions—such as pipe diameter, material types, urban density, and subsurface characteristics—are insufficiently studied. The current LCCA models fail to adequately incorporate dynamic project variables, such as variations in fuel consumption due to detours, extended traffic delays, and region-specific regulatory impacts. Additionally, many LCCA studies lack empirical validation, relying instead on theoretical assumptions that do not capture the complexity of real-world pipeline rehabilitation projects.

Environmental impact assessments using tools like SimaPro and TRACI 2.1 are also underutilized in LCCA frameworks for CIPPT and ET. While these tools provide valuable insights into emissions and resource use, their integration into cost analysis frameworks is incomplete, particularly in translating environmental impacts into quantifiable costs for decision making. Furthermore, the social cost factors—such as productivity losses due to noise, road damage from detours, and community disruptions—are inconsistently quantified and rarely compared across TT and ET methodologies in existing LCCA studies.

To address these gaps, there is a pressing need for a standardized LCCA framework tailored to pipeline rehabilitation methods, incorporating validated data from diverse geographic regions and project types. Such a framework would enable stakeholders to make well-informed, sustainable decisions that balance economic, environmental, and social objectives over the full life cycle of sanitary sewer systems.

Author Contributions: Conceptualization, G.T., V.K. and M.N.; Methodology, E.K.; Formal analysis, G.T. and V.K.; Investigation, V.K.; Resources, E.K.; Writing—original draft, G.T.; Writing—review & editing, V.K., E.K. and M.N.; Supervision, V.K. and M.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Kg	Kilogram
CO ₂	Carbon Dioxide

LCCA	Life Cycle Cost Analysis
CIPPT	Cured-in-Place Pipe Technology
ET	Excavation Technologies
TT	Trenchless Technology
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
EPA	Environmental Protection Agency
ASCE	American Society of Civil Engineers
VOC	Volatile Organic Compounds
EIA	Environmental Impact Assessment
NPV	Net Present Value
AADT	Average Annual Daily Traffic
USD	United States Dollar
m ²	Square Meter
ft	Foot

References

1. EPA. Collection Systems O&M Fact Sheet. In *Trenchless Sewer Rehabilitation*; United States Environmental Protection Agency: Washington, DC, USA, 1999.
2. Chapman, D.N.; Rogers, C.D.F.; Burd, H.J.; Norris, P.M.; Milligan, G.W.E. Research Needs for New Construction Using Trenchless Technologies. *Tunn. Undergr. Space Technol.* **2007**, *22*, 491–502. [CrossRef]
3. Carlisle, M. The Feasibility of Slip-Lining. 2015. Available online: https://www2.latech.edu/~bmagee/writing_contest/2015-2016/303-02-long_report_2016.pdf (accessed on 23 January 2025).
4. 2021 Infrastructure Report Card. Available online: www.infrastructurereportcard.org (accessed on 23 January 2025).
5. Clean Watersheds Needs Survey 2012 Report to Congress. 2012. Available online: https://www.epa.gov/sites/default/files/2015-12/documents/cwns_2012_report_to_congress-508-opt.pdf (accessed on 23 January 2025).
6. Kramer, S.R.; Gary, G.A. Comparison of Trenchless vs. Open-Cut Construction Methods for the Replacement of a Leaking Water Distribution System. In *Environmental and Pipeline Engineering 2000*; American Society-Civil Engineers: Reston, VA, USA, 2012; pp. 289–298. [CrossRef]
7. Kramer, S. Advantages and Disadvantages of Trenchless Construction Approach as Compared to the Traditional Open Cut Installation of Underground Utility Systems. In *Proceedings of the Creative Construction Conference 2018*, Ljubljana, Slovenia, 30 June–3 July 2018; pp. 129–138.
8. Najafi, M.; Gokhale, S.B. *Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal*; McGraw-Hill: New York, NY, USA, 2021; ISBN 978-0-07-142266-6.
9. Lee, H.; Matthys, J. Cost Comparison of Pipeline Asset Replacement: Open-Cut and Pipe-Bursting. In *Proceedings of the Pipelines 2007*, American Society of Civil Engineers, Boston, MA, USA, 6 July 2007; pp. 1–11.
10. Kaushal, V. *Comparison of Environmental and Social Costs of Trenchless Cured-in-Place Pipe Renewal Method with Open-Cut Pipeline Replacement for Sanitary Sewers*; The University of Texas at Arlington: Arlington, TX, USA, 2019.
11. Monfared, M.A.N. Comparison of Trenchless Technologies and Open Cut Methods in New Residential Land Development. 2018. Available online: <https://era.library.ualberta.ca/items/02ee2380-c42a-4d96-b4b4-0a4076050a7c> (accessed on 23 January 2025).
12. Ajdari, E.B. *Volatile Organic Compound (VOC) Emission during Cured-in-Place-Pipe (CIPP) Sewer Pipe Rehabilitation*; University of New Orleans: New Orleans, LA, USA, 2016.
13. Loss, A.; Toniolo, S.; Mazzi, A.; Manzardo, A.; Scipioni, A. LCA Comparison of Traditional Open Cut and Pipe Bursting Systems for Relining Water Pipelines. *Resour. Conserv. Recycl.* **2016**, *128*, 458–469. [CrossRef]
14. Hashemi, S.B. *Construction Cost of Underground Infrastructure Renewal: A Comparison of Traditional Open-Cut and Pipe Bursting Technology*; The University of Texas at Arlington: Arlington, TX, USA, 2008.
15. Kim, K. *Cost Analysis for Renewal of Sewer System in the City of Grand Rapids, Michigan*; Michigan State University: East Lansing, MI, USA, 2005.
16. Kim, G.-H.; An, S.-H.; Kang, K.-I. Comparison of Construction Cost Estimating Models Based on Regression Analysis, Neural Networks, and Case-Based Reasoning. *Build. Environ.* **2004**, *39*, 1235–1242. [CrossRef]
17. Zhao, J.Q.; Rajani, B.B. *Construction and Rehabilitation Costs for Buried Pipe with a Focus on Trenchless Technologies*; National Research Council of Canada: Ottawa, ON, Canada, 2002; Volume RR-101.
18. Jafari, M.R.; Cotter, W.J. A Quantitative Comparison between Trenchless Technology and Open-Cut Method. In *Proceedings of the NASTT's No-Dig Show and ISTT's 35th International No-Dig*, Washington, DC, USA, 9–13 April 2017; International Society for Trenchless Technology: 201 Waterfront Street, National Harbor, MD, USA, 2017.

19. Das, S. Evaluation of Cured-in-Place Pipe Lining Installations. 2016. Available online: https://era.library.ualberta.ca/items/b02cf9f8-581b-4df1-9d69-2134bff44ebe/view/36b285e3-64bc-4e4a-9657-91cc90058e48/Das_Susen_201601_MSc.pdf.pdf (accessed on 23 January 2025).
20. Hashemi, B.; Iseley, T.; Raulston, J. Water Pipeline Renewal Evaluation Using AWWA Class IV CIPP, Pipe Bursting, and Open-Cut. In Proceedings of the ICPTT 2011, Beijing, China, 7 October 2011; pp. 1257–1266.
21. Matthews, J.C.; Selvakumar, A.; Condit, W. Demonstration and Evaluation of an Innovative Water Main Rehabilitation Technology: Cured-in-Place Pipe (CIPP) Lining. *Water Pract. Technol.* **2012**, *7*, wpt2012028. [CrossRef]
22. Youssef, S.; Nachabe, M. Rehabilitation Technologies to Abate Infiltration in Sanitary Sewers. *J. Environ. Eng.* **2023**, *149*, 04023025. [CrossRef]
23. Yon, Z. Application of Cured-in-Place Pipe in Repair of Urban Sewer. *China Water Wastewater* **2014**, *30*, 106–108.
24. Xin, J. Application of Trenchless Pipeline Rehabilitation Technology. In Proceedings of the ICPTT 2014, Xiamen, China, 13–15 November 2014; pp. 473–477.
25. Alsadi, A. *Evaluation of Carbon Footprint During the Life-Cycle of Four Different Pipe Materials*; Louisiana Tech University: Ruston, LA, USA, 2019.
26. Mitchell, C. Investigation into the Process of Cured-in-Place Pipe Sewer Rehabilitation. *Plymouth Stud. Sci.* **2020**, *13*, 290–327.
27. Jin, Y. Evaluating Infrastructure Performance to Assist Facility Management Toward Sustainable Systems. Ph.D. Thesis, Michigan Technological University, Houghton, MI, USA, 2013.
28. Alam, S.; Sterling, R.L.; Allouche, E.; Condit, W.; Matthews, J.; Selvakumar, A.; Simicevic, J. A Retrospective Evaluation of the Performance of Liner Systems Used to Rehabilitate Municipal Gravity Sewers. *Tunn. Undergr. Space Technol.* **2015**, *50*, 451–464. [CrossRef]
29. Donaldson, B.M. Environmental Implications of Cured-in-Place Pipe Rehabilitation Technology. *Transp. Res. Rec. J. Transp. Res. Board* **2009**, *2123*, 172–179. [CrossRef]
30. Murray, D.J., Jr. EPA Aging Water Infrastructure Research Program: State of the Technology for the Condition Assessment and Rehabilitation of Wastewater Collection Systems. In Proceedings of the World Environmental and Water Resources Congress 2009, Kansas City, MO, USA, 12 May 2009; pp. 1–7.
31. Sterling, R.; Simicevic, J.; Allouche, E.; Condit, W.; Wang, L. State of Technology for Rehabilitation of Wastewater Collection Systems. 2010. Available online: https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=226504 (accessed on 23 January 2025).
32. Apeldoorn, S. Comparing the Costs—Trenchless Versus Traditional Methods. 2000. Available online: https://www.waternz.org.nz/Attachment?Action=Download&Attachment_id=1344 (accessed on 23 January 2025).
33. Argyrou, C.; Bouziou, D.; O'Rourke, T.D.; Stewart, H.E. Retrofitting Pipelines with Cured-in-Place Linings for Earthquake-Induced Ground Deformations. *Soil Dyn. Earthq. Eng.* **2018**, *115*, 156–168. [CrossRef]
34. Serajiantehrani, R. *Development of a Machine Learning-Based Prediction Model for Construction and Environmental Costs of Trenchless Spray Applied Pipe Linings, Cured-in-Place Pipe, and Sliplining Methods in Large Diameter Culverts*; The University of Texas at Arlington: Arlington, TX, USA, 2020.
35. Hicks, J.; Kaushal, V.; Jamali, K. A Comparative Review of Trenchless Cured-in-Place Pipe (CIPP) With Spray Applied Pipe Lining (SAPL) Renewal Methods for Pipelines. *Front. Water* **2022**, *4*, 904821. [CrossRef]
36. Wang, L.; Yan, C.; Xu, J. *Technology Standard of Pipe Rehabilitation*; Springer: Singapore, 2021; ISBN 978-981-334-983-4.
37. Beaudet, B.A.; Tobey, B.; Harder, S.E. Life Cycle Cost Analysis for Decision Making in Collection System Rehabilitation. In *Proceedings of the Pipelines 2019*; American Society of Civil Engineers: Nashville, TN, USA, 2019; pp. 187–197.
38. Serajiantehrani, R.; Najafi, M.; Malek Mohammadi, M.; Kaushal, V.; Jalalediny Korky, S. Construction Cost Analysis of Trenchless Cured-in-Place Pipe and Spray-Applied Pipe Linings Rehabilitation Methods in Gravity Conveyance Conduits. In *Proceedings of the Pipelines 2021*, Virtual, 29 July 2021; pp. 210–220.
39. Xu, Y.; Zhou, Y.; Sekula, P.; Ding, L. Machine Learning in Construction: From Shallow to Deep Learning. *Dev. Built Environ.* **2021**, *6*, 100045. [CrossRef]
40. Juszczak, M.; Hanák, T.; Výskala, M.; Pacyno, H.; Siejda, M. Early Fast Cost Estimates of Sewerage Projects Construction Costs Based on Ensembles of Neural Networks. *Appl. Sci.* **2023**, *13*, 12744. [CrossRef]
41. Sousa, V.; Meireles, I. The Influence of the Construction Technology in Time-Cost Relationships of Sewerage Projects. *Water Resour. Manag.* **2018**, *32*, 2753–2766. [CrossRef]
42. Joshi, A. A Carbon Dioxide Comparison of Open Cut and Pipe Bursting. 2012. Available online: https://scholarworks.bgsu.edu/cgi/viewcontent.cgi?article=1008&context=ms_tech_mngmt (accessed on 23 January 2025).
43. Chilana, L. Carbon Footprint Analysis of a Large Diameter Water Transmission Pipeline Installation. Master's Thesis, The University of Texas at Arlington, Arlington, TX, USA, 2011.
44. Visentin, C.; Trentin, A.W.D.S.; Braun, A.B.; Thomé, A. Lifecycle Assessment of Environmental and Economic Impacts of Nano-Iron Synthesis Process for Application in Contaminated Site Remediation. *J. Clean. Prod.* **2019**, *231*, 307–319. [CrossRef]

45. Fuselli, F.; Huber, S.; Mambretti, S. Environmental Aspects of Trenchless Pipe Rehabilitation Methods. *Urban Water J.* **2022**, *19*, 879–887. [CrossRef]
46. Chorazy, T.; Hlavínek, P.; Raček, J.; Pietrucha-Urbanik, K.; Tchórzewska-Cieślak, B.; Kepřdová, Š.; Dufek, Z. Comparison of Trenchless and Excavation Technologies in the Restoration of a Sewage Network and Their Carbon Footprints. *Resources* **2024**, *13*, 12. [CrossRef]
47. Environmental Prices Handbook 2024: EU27 Version. 2024. Available online: https://cedelft.eu/wp-content/uploads/sites/2/2024/12/CE_Delft_230107_Environmental-Prices-Handbook-2024-EU-version_def.pdf (accessed on 23 January 2025).
48. Wang, X.; Liu, B.; Allouche, E.N.; Liu, X. Practical Bid Evaluation Method Considering Social Costs in Urban Infrastructure Projects. In Proceedings of the 2008 4th IEEE International Conference on Management of Innovation and Technology, Bangkok, Thailand, 21–24 September 2008; pp. 617–622.
49. Ormsby, C. A Framework for Estimating the Total Cost of Buried Municipal Infrastructure Renewal Projects. Master's Thesis, McGill University, Montréal, QC, Canada, 2009.
50. Maldikar, S.D. An Investigation of Productivity Loss Due to Outdoor Noise Conditions. Master's Thesis, The University of Texas at Arlington, Arlington, TX, USA, 2010.
51. Matthews, J.C.; Allouche, E.N.; Sterling, R.L. Social Cost Impact Assessment of Pipeline Infrastructure Projects. *Environ. Impact Assess. Rev.* **2015**, *50*, 196–202. [CrossRef]
52. Çelik, T.; Kamali, S.; Arayici, Y. Social Cost in Construction Projects. *Environ. Impact Assess. Rev.* **2017**, *64*, 77–86. [CrossRef]
53. Mohanty, S.S.; Rath, A. Capturing Social Cost in Construction Sector: A Review of Literature through Meta-Analysis. *J. Stud. Dyn. Change JSDC* **2021**, *8*, 17–30.
54. Montgomery, D.C.; Peck, E.A.; Vining, G.G. *Introduction to Linear Regression Analysis*; John Wiley & Sons: Hoboken, NJ, USA, 2012.
55. Theis, T.; Tomkin, J. *Sustainability-a-Comprehensive-Foundation*; 12th Media Services: Suwanee, GA, USA, 2018.
56. ISO 14044; LCA Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
57. Database & Support Team at PRé Sustainability SimaPro Database Manual Methods Library 2024. Available online: <https://simapro.com/wp-content/uploads/2024/04/DatabaseManualMethods.pdf> (accessed on 23 January 2025).
58. Gangavarapu, B.S.; Najafi, M.; Salem, O. Quantitative Analysis and Comparison of Traffic Disruption Using Open-Cut and Trenchless Methods of Pipe Installation. 2003. Available online: [https://ascelibrary.org/doi/abs/10.1061/40690\(2003\)186](https://ascelibrary.org/doi/abs/10.1061/40690(2003)186) (accessed on 23 January 2025).
59. Gilchrist, A.; Allouche, E.N. Quantification of Social Costs Associated with Construction Projects: State-of-the-Art Review. *Tunnel Underground. Space Technol.* **2005**, *20*, 89–104. [CrossRef]
60. Tighe, S.; Knight, M.; Papoutsis, D.; Rodriguez, V.; Walker, C. User Cost Savings in Eliminating Pavement Excavations through Employing Trenchless Technologies. *Can. J. Civ. Eng.* **2002**, *29*, 751–761. [CrossRef]
61. Hoffman, J.; Harold, C.; Adderley, V. Portland's Sewer Rehabilitation Program Development and Implementation. In *Pipelines 2014: From Underground to the Forefront of Innovation and Sustainability*; American Society of Civil Engineers: Reston, VA, USA, 2014.
62. Kamat, S. *Comparison of Dust Generation from Open Cut and Trenchless Technology Methods for Utility Construction*; The University of Texas at Arlington: Arlington, TX, USA, 2011.
63. Arditi, D.; Messiha, H.M. Life Cycle Cost Analysis (LCCA) in Municipal Organizations. *J. Infrastruct. Syst.* **1999**, *5*, 1–10. [CrossRef]
64. Gao, X.; Pishdad-Bozorgi, P. A Framework of Developing Machine Learning Models for Facility Life-Cycle Cost Analysis. *Build. Res. Inf.* **2020**, *48*, 501–525. [CrossRef]
65. Azeez, K.; Zayed, T.; Ammar, M. Fuzzy- versus Simulation-Based Life-Cycle Cost for Sewer Rehabilitation Alternatives. *J. Perform. Constr. Facil.* **2013**, *27*, 656–665. [CrossRef]
66. Alam, S.; Matthews, J.; Sterling, R.; Allouche, E.; Selvakumar, A.; Condit, W.; Kampbell, E.; Downey, D. Evaluation of Testing Methods for Tracking CIPP Liners' Life-Cycle Performance. *Cogent Eng.* **2018**, *5*, 1463594. [CrossRef]
67. Schwarz, P.E.; Patrick White, P.E.; Mark, S.; Mihm, P.E. *ASCE Guideline of Sustainable Design of Pipelines by American Society of Civil Engineers*; American Society of Civil Engineers: Reston, VA, USA, 2019.
68. Allouche, E.; Sterling, R.; Condit, W. National Database Structure for Life Cycle Performance Assessment of Water and Wastewater Rehabilitation Technologies (Retrospective Evaluation). Available online: <https://nepis.epa.gov/Adobe/PDF/P100LDG0.pdf> (accessed on 23 January 2025).
69. Morera, S.; Remy, C.; Comas, J.; Corominas, L. Life Cycle Assessment of Construction and Renovation of Sewer Systems Using a Detailed Inventory Tool. *Int. J. Life Cycle Assess.* **2016**, *21*, 1121–1133. [CrossRef]
70. Kere, K.J.; Huang, Q. An Analytical Approach to Evaluate Life-Cycle Cost of Deteriorating Pipelines. *Reliab. Eng. Syst. Saf.* **2024**, *250*, 110287. [CrossRef]

71. ASTM F1675-13; Practice for Life-Cycle Cost Analysis of Plastic Pipe Used for Culverts, Storm Sewers, and Other Buried Conduits. Committee ASTM International: West Conshohocken, PA, USA, 2022. [\[CrossRef\]](#)
72. Alaloul, W.S.; Altaf, M.; Musarat, M.A.; Faisal Javed, M.; Mosavi, A. Life Cycle Assessment and Life Cycle Cost Analysis in Infrastructure Projects: A Systematic Review. *Civ. Eng.* **2021**, preprint. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.