Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Alexander Nydal

Decision support tool for sustainable sewage pipe rehabilitation

Master's thesis in Civil and Environmental Engineering
Supervisor: Franz Tscheikner-Gratl, Marius Møller Rokstad, Bardia Roghani
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Sammendrag

Denne avhandlingen har som mål å utvikle et støtteverktøy for å velge den mest gunstige metoden for å rehabilitere avløpsrør basert på bærekraftige kriterier. Verktøyet bruker flerkriteriebeslutningsteknikken Fuzzy Analytic Hierchy Process (FAHP) for å evaluere rehabiliteringsmetodene basert på tre kriterier: økonomiske kostnader, sosiale kostnader og miljøkostnader. Metodene som evalueres er den konvensjonelle Open Cut-metoden (OC) og de gravefrie løsningene Cured-In-Place-Pipe (CIPP), Spray-In-Place Pipe (SIPP), Sliplining (SL) og Pipe Bursting (PB). Verktøyet bruker en elimineringsfunksjon for å fjerne ugjennomførbare metoder basert på prosjektspesifikke data. Verktøyet ble laget ved hjelp av Excel-programvaren.

Hver rehabiliteringsmetode ble evaluert basert på resultatene for hvert underkriterium. En Monte Carlo-simulering ble brukt til å tildele tilfeldige vektinger til de globale og de lokale parvise sammenligningsmatrisene. Resultatene viser at SIPP-metoden var den metoden som fikk best resultater for de fleste kombinasjoner av vekter.

Resultatene viser at FAHP-metoden tar hensyn til beslutningstakernes preferanser på en god måte, med høy stabilitet og nøyaktighet. På grunn av usikkerheten i dataene og det faktum at verktøyet sannsynligvis ikke tar god nok hensyn til lokale forhold, er verktøyet ikke klart til å gi pålitelige resultater i byggeprosjekter ennå. Det kan imidlertid fungere som et rammeverk for fremtidig utvikling av støtteverktøy for bærekraftig rehabilitering av avløpsrør.

Abstract

This thesis aims to develop a generalized decision support tool for selecting the optimal sewage pipe rehabilitation method based on sustainable criteria. The decision support tool utilizes the Multi-Criteria Decision Making (MCDM) technique Fuzzy Analytic Hierchy Process (FAHP) to evaluate the performance of each rehabilitation method based on three criteria: economic cost, social cost, and environmental cost. The methods evaluated are the conventional Open Cut (OC) method and the trenchless methods Cured-In-Place-Pipe (CIPP), Spray-In-Place Pipe (SIPP), Sliplining (SL), and Pipe Bursting (PB). The decision support tool uses an elimination feature to eliminate unfeasable methods based on project-specific data. The decision support tool was created using the Excel software.

Each rehabilitation method was ranked based on its performance in each sub-criterion. A Monte Carlo simulation was used to assign random weights to the global and local pairwise comparison matrices. The results show that the SIPP method was the best performing pipe rehabilitation method for most combinations of weights.

The results show that the FAHP methodology cosideres the preferences of the decision makers well, with high stability and accuracy. However, due to the uncertainty of the data and the likely failure of the tool to take into account local considerations, the tool is not yet ready to provide reliable results in a real-world application. However, it can serve as a framework for the future development of a decision support tool for sustainable sewage pipe rehabilitation.

Acknowledgements

This thesis marks the end of my master's program in Civil and Environmental Engineering at the Norwegian University of Science and Technology. It has been an honor to have been taught by so many passionate and talented lecturers, and for that, I would like to give the biggest gratitude. This thesis is my first contribution to the field of Water and Wastewater Engineering and it will mark my beginning to work for sustainable and resilient development of cities.

I would like to give a special thanks my supervisors:

- Associate Professor Franz Tscheikner-Gratl
- Associate Professor Marius Møller Rokstad
- Postdoc Bardia Roghani

Your expertise, insights, support, and encouragement have been instrumental for the quality of my work. Thank you for your revisions and for our discussions. I am grateful that I had you to assist me throughout this endeavor.

This thesis marks the end of five of the most challenging, but also most enjoyable years of my life. I would like to thank my fellow students, friends, and future colleagues for all the help and encouragement they gave me both in and out of the classroom. I would like to thank all the friends I have made along the way, both in Trondheim, and in Porto. Additionally, I would also like to thank my roommates, who have made my stay some of the best years of my life.

Finally, I would like to give my deepest gratitude to my parents and sister for always having believed in me and supported me through all of this. I could not have made it without you.

Alexander Nydal

Trondheim, June 14th, 2024

Contents

Figures

Tables

Equations

Abbreviations

AHP	Analytic Hierarchy Process
CI	Consistency Index
CO2	Carbon Dioxide
COA	Center of Area method
CIPP	Cured-In-Place-Pipe
CR	Consistency Ratio
FAHP	Fuzzy Analytic Hierarchy Process
FL	Fuzzy Logic
GRP	Glass fiber Reinforced Polyester
HDPE	High-Density Polyethylene
ICE	Inventory of Carbon and Energy
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
MADM	Multi-Attribute Decision Making
MDPE	Medium-Density Polyethylene
OC	Open Cut method
PCCP	Pre-stressed Concrete Cylinder Pipe
PB	Pipe Bursting method
PVC	Polyvinyl Chloride
RI	Random Index
SAPL	Sprayed Applied Pipe Linings
SI	International System of Units
SIPP	Spray-In-Place Pipe
SL	Sliplining
TFN	Triangular Fuzzy Number
TCM	Trenchless Construction Method
TRM	Trenchless Renewal Method

1 Introduction

The public water distribution systems are facing significant challenges worldwide. As demographics change, with cities growing and declining, the need to construct, maintain, and rehabilitate water networks is increasing. In addition, new challenges due to climate change force the upgrading of the network's capacity. These challenges are not just technical, but also bring huge financial and environmental concerns.

In Norway, the situation is no different. The estimated investment needed for water distribution renovation for 2016-2040 is approximately 183 billion NOK (Rostad, 2017). This financial burden is the responsibility of the municipalities and their inhabitants, and it is expected to lead to an increase in taxes (Rostad, 2017). However, these investments are necessary to ensure sustainability and resilience in the face of climate changes and population growth. The decision-makers in charge of the development must make the necessary considerations to reduce these burdens on society.

Pipe rehabilitation is a complex technical process with limited room for errors. These processes require huge amounts of time and resources and must be done to maintain a modern functional society. It is also required that the solutions are sustainable. Given these challenges, there is a growing need to develop tools to help the decision-makers navigate through these issues in order to ensure sustainable development and reduce social burdens.

The objective of this master's thesis is to develop a generalized tool to assist decision-makers in selecting the optimal sewage pipe rehabilitation method based on sustainable criteria. The tool must be based on a strong foundation of reliable information, and the criteria must be measurable, objective, and useful in determining the optimal pipe rehabilitation method. The information which represents the foundation of this tool is based on a comprehensive literature review from various written sources and publications.

2 Background (Theory)

2.1 The rehabilitation methods

Trenchless technology is considered the state of the art regarding wastewater engineering. Trenchless technology can be divided into two categories: trenchless construction methods (TCMs) and trenchless renewal methods (TRMs) (Najafi, 2005, p. 4). Both types of methods have the advantage of requiring a minimum amount of excavation to either construct or renew a pipeline. Not requiring excavation has proven to have several advantages compared to conventional open cut solutions. This includes advantages such as in general having a reduction in economic costs, reduction in social burdens in the form of social costs, and a reduction in environmental footprints (Kaushal and Najafi, 2020). This thesis will only focus on trenchless rehabilitation methods. This is because the main goal of the decision support tool is to help improve existing sewage pipe systems, not create new ones.

Trenchless renewal methods include all methods regarding renewing, rehabilitating, and/or renovation of an existing pipeline or utility system (Najafi, 2005, p. 4). Which method should be implemented depends on the specific nature of the problem of the pipe, and local conditions. All methods discussed below require a thorough inspection of the existing pipe before implementation. This is to determine the condition of the pipe, to ensure that the appropriate preparations are made, and to make sure that the choice of rehabilitation method is based on informed decisions (Wirahadikusumah *et al.*, 1998). It will therefore be no focus on variables such as inspection costs and other preparatory costs in the decision support tool, as these variables are required as a preparation for all methods.

For the purposes of this thesis, repair methods will not be discussed. Instead, the focus will solely be on trenchless rehabilitation and replacement methods. The difference between these two methods is that rehabilitation methods aim to prolong the operational life of an already existing pipe (Zhao and Whittle, 2012), whereas the pipe replacement methods aim to replace an already existing pipe (Lueke and Ariaratnam, 2001). In this thesis, the term “pipe rehabilitation” will be used for all renewing methods. Which method you should implement depends on the specific nature of the problem of the pipe, and local conditions. A brief overview of the five rehabilitation methods chosen for this thesis is provided below. One is the conventional open cut solution. The other four are trenchless methods. These were chosen based on data availability and popularity.

2.1.1 Open cut

This is method is considered as the "conventional" way for installing, replacing, and maintaining conduits or cables (Najafi, 2005, p. 435). According to Najafi (2013, p. 29): "This method includes trenching the ground surface for either placing a new or replacing an existing pipeline and then reinstating of the surface". While trenchless rehabilitation methods may to a greater degree use the pathway of an already existing pipe with a minimal amount of excavation, the open cut solutions require the excavation of a trench for the entire length of the pipeline (Pyzoha, 2013). Furthermore, transport of excavated material and backfill is required, in addition to transport of the new pipe, and the disposal of the old pipe (Alsadi and Matthews, 2022).

2.1.2 Cured-in-place pipe

The Cured-in-place pipe (CIPP) method is regarded as one of the most popular trenchless rehabilitation methods for structural and non-structural purposes (Kaushal *et al.*, 2019). "The CIPP process involves a liquid thermoset resin-saturated material that is inserted into the existing pipeline by hydrostatic, air inversion, or mechanically pulling with a winch and a cable and inflating" (Najafi, 2005, p. 295). "The system is then cured using water, steam or UV light" (Najafi, 2005, p. 297). As further described by Najafi (2013, p. 360): a major advantage of this method is that it may only require manholes as access pits during installation. Additionally, it may also be applicable in pipes with varying cross sections. However, this method requires that existing flows are bypassed. Furthermore, the liner also requires to be specifically constructed for each project.

2.1.3 Sliplining

Sliplining (SL) is regarded as one of the first trenchless pipe rehabilitation methods (Arjun *et al.*, 2023). "This method may be used for structural and nonstructural purposes" (Najafi, 2013, p. 378). "Sliplining include continuous, segmental, and spiral wound. Sliplining is the installation of a new pipe (commonly used materials are HDPE, glass fiber reinforced polyester (GRP), and PVC) within the existing pipe" (Atalah, 2021). The method requires cleaning before implementation. Additionally, some excavation of rather long access pits is needed if suitable manholes are not available (Najafi, 2013, p. 373). The method also requires grouting (Najafi, 2013, p. 375). According to Arjun *et al.*, (2023): "The main limitation of sliplining is shown to be the reduction in the pipe section area which will not meet the hydraulic capacity requirement of the host pipe and therefore this loss of capacity will not meet the sustainability criteria which is associated with the rapid rise in the water demand and wastewater emission."

2.1.4 Spray-in-place pipe

Spray-in-place pipe (SIPP) is a variant of Sprayed Applied Pipe Linings (SAPLs). "Spray applied pipe linings (SAPLs) are trenchless technology solutions for large diameter gravity stormwater conveyance conduits rehabilitation that prevent further deterioration, such as corrosion, abrasion, etc., and can provide structural support for severely damaged host pipes" (Hicks, Kaushal and Jamali, 2022). The materials used are traditionally cement mortar, but polymers are also utilized. Each material has its own strengths and functions (Najafi, 2013, p. 479). As the name implies, the material is applied by spraying directly on the existing pipe surfaces, either manually by hand or by machine. Furthermore, pre-inspection and cleaning are required before applying the materials (Najafi, 2013, p. 492). In addition, the curing time depends on the material, and local conditions such as dryness and temperature (Najafi, 2013, p. 492). As explained by Marlow, Gould and Lane (2015): "Non-structural spray lining can generally be done without requiring existing service connections to be excavated, which means it is relatively cheap in areas with numerous customer connections."

2.1.5 Pipe bursting

The pipe bursting method is recognized as a pipe replacement method similarly to the open cut method (Kakde *et al.*, 2022). "It is recognized as the only method of trenchless pipe rehabilitation in which a buried pipe can be replaced with a completely new pipe that functions independently of the existing line and permits the diameter of the new line to be increased" (Lueke and Ariaratnam, 2001). According to Najafi (2013, p. 421), there are two common methods of pipe bursting: static bursting, and pneumatic bursting. Although there are a few differences between the two methods, the essence of pipe bursting is that a bursting head/expander is either pushed or pulled through an existing pipe while a new pipe of the desired diameter is replacing the old pipe. The material of the burst pipe is scattered into the remaining soil. This method requires excavation of access pits. As further described by Najafi (2013, p. 427): the most commonly used materials to replace the old pipe are high- and medium density polyethylene (HDPE and MDPE) and later polyvinyl chloride (PVC).

2.2 Multi-criteria decision making

Rehabilitation of wastewater networks is a significant undertaking. There are several stakeholders' opinions and needs to consider, and misguided decisions could have enormous consequences for financial and public health. Fortunately, there are methodologies in place to assist in a decision-making process. These methodologies aim to achieve more favorable outcomes. These are called multi-criteria decision-making techniques (MCDMs).

As described by Syed Hassan, Tan and Yusof (2018): "MCDM was one of the most widely applied decision methodologies in engineering, management science, and business. The MCDM approaches have gained much attention from practitioners and researchers, particularly among academia due to its ability to improve the quality of decisions by creating the policy development more effective, rational and explicit."

As further explained by Zhang and Balakrishnan (2021), MCDMs are: "a decision support tool widely used by government agencies for evaluating, assessing, and prioritizing project alternatives in circumstances where conflicting and competing objectives are to be achieved." A general overview of the methodology of MCDMs are also further explained by Zhang and Balakrishnan (2021): "MCDA is implemented in several stages, focusing on identification of project alternatives, definition of relevant criteria, assessment of performance of alternatives based on those objectives, and identification of the best alternative(s)."

There are several different MCDM techniques, each with their own advantages and degrees of usefulness depending on the scenario. The usefulness of the model is determined by several factors within the model's problem-solving structure. These factors include the number of alternatives, the choice of criteria, robustness, sensitivity, computation time, the quality of input data, and the outputs (Ghaleb *et al.*, 2020). Furthermore, the usefulness of the MCDM may be determined by its ability to capture the preferences and values of the decision makers and stakeholders (Baydaş and Pamučar, 2022). However, it is further explained that: "choosing the best MCDM method is a challenge and the ideas recommended as solutions might include personal opinions since there is literally no objective verification mechanism" (Baydaş and Pamučar, 2022). Therefore, it can be argued that there is no single best MCDM method for all problems. It is therefore necessary to choose the most appropriate model based on the specific context and objectives.

The decision support tool developed in this project is designed to take multiple decision makers' preferences into consideration. It was also desired that the decision should be made based on already established criteria and a limited number of alternatives. It is therefore wise to look into Multi-Attribute Decision Making (MADM) methods, as they are reported to be considering these concerns quite well (Yalcin, Kilic and Delen, 2022).

The point of using MCDMs is that the decision is based on reliable information and criteria that are transparent and defendable. Whether or not the MCDM leads to a good decision remains to be seen. The process of selecting criteria to base the decision on is explained further down.

2.3 The decision making process

For a multi criteria decision-making process to be useful, the model must be based on clear objectives and goals. This is to help us make informed decisions. According to Baker *et al.*, (2001) there are several steps for good decision support:

- Step 1. Define the problem
- Step 2. Determine requirements
- Step 3. Establish goals
- Step 4. Identify alternatives
- Step 5. Define criteria
- Step 6. Select a decision-making tool
- Step 7. Evaluate alternatives against criteria
- Step 8. Validate solutions against problem statement

The first step in establishing a decision support tool for the optimal wastewater pipe rehabilitation method has already been resolved. The question is clear: What is the optimal rehabilitation method for this project? Steps two and three are also resolved as the decision support is based on user input, where priorities and goals are already established by the user. Regarding step four, the alternatives are based on the limitations of available data and other factors as mentioned before. The decision support tool's usefulness relies on the strengths and robustness of the three following steps. The final step determines the final usefulness of the tool and is entirely based on the subjective meaning of the decision maker. Nevertheless, the decision support tool's purpose is to help make informed decisions. Therefore, step five to seven in Baker's model are the most crucial parts of the decision support structure. These steps are discussed in detail below.

2.4 Defining the criteria

The criteria (attribute) serve as a means measure the effectiveness of an alternative (option). To be effective, the criteria must be able to be measured either quantitatively or qualitatively. Additionally, they must be able to be compared to other criteria based on a universally understood and transparent scale. This is because the criteria will use weights to rank the alternatives. According to Baker *et al.*, (2001), a criterion should be:

- Able to discriminate among the alternatives
- Complete – include all goals
- Operational – meaningful to the decisionmaker's understanding of the implications of the alternative
- Non-redundant – avoid double counting
- Few in number – to keep the problem dimensions manageable

This prompts the question of what criteria are appropriate to evaluate the performance of an alternative. In the context of wastewater engineering, it is advisable to choose criteria that consider the interests of the relevant stakeholders. The stakeholders in this regard are the municipality, the wastewater network's subscribers, and the contractors. The course of action was to seek guidance from the EU parliament concerning wastewater treatment. According to European Parliament (2023): "Water is a primary good which belongs to everyone and is for everyone and which, as a natural resource that is essential, irreplaceable and indispensable to life, needs to be considered and integrated in its three dimensions: social, economic and environmental."

The three dimensions mentioned are part of the "three pillars of sustainability," which are described as core components that support sustainable development (Hansmann, Mieg and Frischknecht, 2012). Considerations regarding the sustainable aspects of a construction project should always be made. A sustainable solution should not only be in the stakeholders' best interest, but also as the general goal as a society. Choosing these dimensions as criteria may be beneficial as they are few, strive towards a common goal, are relatively distinctive, and operational as they are quantifiable. Furthermore, Štilić and Puška, (2023) claim that the synergy between these criteria can be useful as: "the methods used in MCDM are especially beneficial when applied to sustainable engineering, where decision-making requires balancing economic, environmental, and social considerations".

Once the global criteria were decided, the next step was to find sub-criteria for each dimension to evaluate the rehabilitation alternatives.

2.5 The environmental criterion

There are many factors that should be considered when evaluating the environmental performance of a pipe rehabilitation project. Similarly with other construction projects, considerations such as energy consumption, greenhouse gas emissions, resource use, and pollution should also be considered in pipe rehabilitation projects. According to Moshood, Rotimi and Shahzad (2024) measures should be made to minimize environmental impacts to ensure long-term sustainability. In order to evaluate the environmental performance of a pipe rehabilitation project, it has been decided that the carbon emissions produced from each method will be the focus of the assessment.

2.5.1 Carbon emissions

It is well documented that carbon dioxide (CO_2) and other greenhouse gases contribute to the trapping of heat in the atmosphere. This phenomenon, known as the greenhouse effect, has been identified as a significant contributor to climate change (Cassia *et al.*, 2018).

According to a rapport by IEA, (2019): “The buildings and construction sector accounted for 36% of final energy use and 39% of energy and process-related carbon dioxide (CO_2) emissions in 2018, 11% of which resulted from manufacturing building materials and products such as steel, cement and glass.” Although pipe rehabilitation only contributes to a part of these emissions, efforts should be made to reduce the carbon footprint of this sector to ensure long-term sustainability. One popular method for estimating the environmental impacts of pipe rehabilitation projects is through the use of a life cycle assessment (LCA).

2.5.1.1 Life cycle assessment

Life Cycle Assessment (LCA) is a method for considering the environmental dimensions of what makes up the term “sustainability” (Guinée and Heijungs, 2017). According to the European Commission: **“**Life Cycle Assessment takes into account a product’s full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste” (European Commission. Joint Research Centre. Institute for Environment and Sustainability., 2010). Regarding waste management, Bai et al., (2018) claims that the LCA methodology is a reliable way to estimate environmental impacts.

As mentioned above, the LCA can be divided into several phases. Based on the literature reviewed, it is common to divide the life cycle of the pipe into a variant of these four phases: fabrication phase (production phase), installation phase, operational phase, and disposal phase (Alsadi and Matthews, 2022; Berglund *et al.*, 2018). According to Kaushal, Najafi and Serajiantehrani (2020), few studies have directly compared the trenchless pipe rehabilitation methods in regard to carbon emissions. However, studies have been conducted to measure the carbon emissions related to the production of pipe materials. Therefore, to assess the environmental impact of each rehabilitation method, it is essential to examine the performance of both the rehabilitation methods and the life cycle of the pipe materials.

2.5.1.2 Environmental impact estimation

Production phase

According to the authors Alsadi and Matthews (2022), from which the data for the decision support tool will be heavily based on, the production phase includes the energy consumption from the beginning until the factory gate. This includes: “material extraction, material production, and pipe fabrication” (Alsadi and Matthews, 2022). The article uses a common measurement of the LCA called “embodied energy,” which encompasses all the energy consumed during the production of any goods and services (Alsadi and Matthews, 2022). The database utilized for the embodied energy calculation in the production phase is the Inventory of Carbon and Energy (ICE). It should be noted that the numbers are from data collected in the United Kingdom. The study utilized these pipe dimensions of 910 mm diameter, and 30 m in length.

The study focuses on carbon emissions from four common pipe materials:

- Pre-stressed Concrete Cylinder Pipe (PCCP)
- Polyvinyl Chloride (PVC)
- High-Density Polyethylene (HDPE)
- Cured-In-Place Pipe (CIPP)

The article found that when “optimizing” the production phase for each pipe material, the production of the CIPP lining was the biggest contributor to carbon emissions. Following CIPP, the next most significant contributors were HDPE, PVC, and finally PCCP. By “optimizing” the production phase, the authors meant that they reduced the amount of carbon emissions emitted in the phase. They did this by using recycled materials wherever possible.

They also tried to substitute certain components in the pipe material with less carbon-emitting substitutes. The emissions generated in the production phase are shown in Figure 1. The measurements have been converted from pounds (lb) to SI (kg).

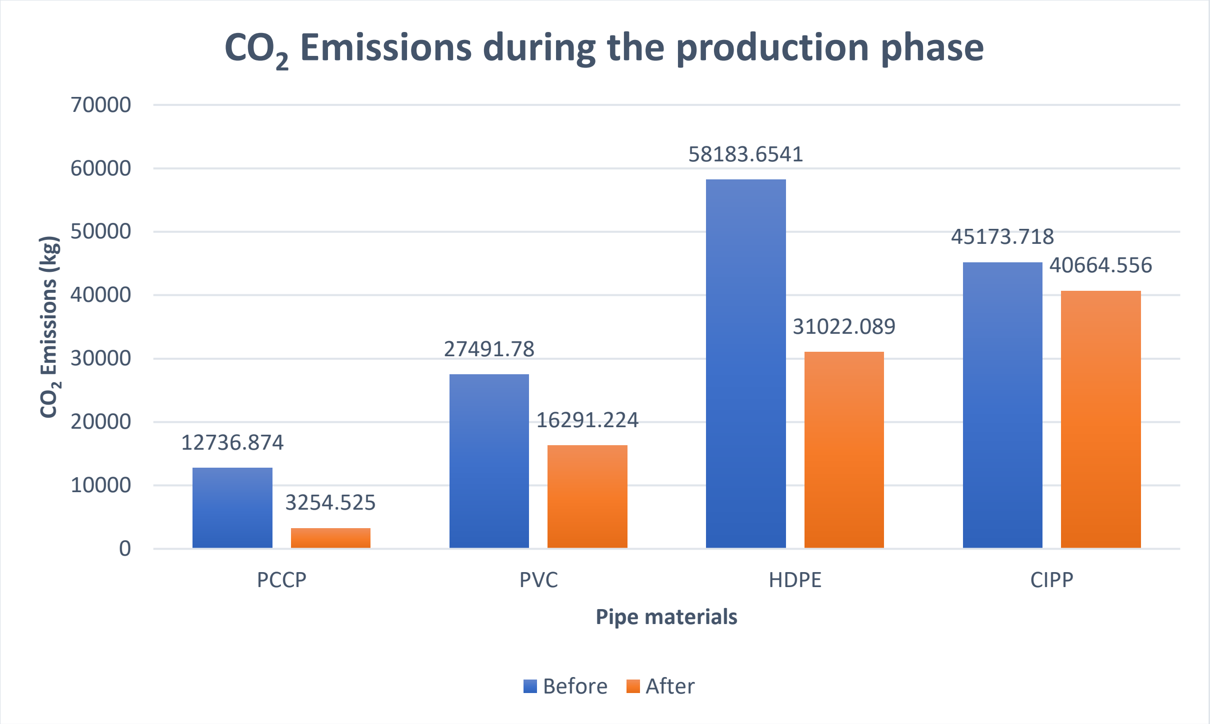


Figure 1: CO_2 emissions during the production phase of the pipe materials. The figure is an adaptation from (Alsadi and Matthews, 2022)

Installation phase

The installation phase includes the following activities: "excavation, loading, backfilling, compaction, and repaving" (Alsadi and Matthews, 2022). This also includes transportation of the excavated material, backfill, and pipes. Depending on the method, the study found that between 61 and 75 % of the carbon emissions in this step were generated from the transportation and production of backfill materials. In this phase they utilized the e-calc software to calculate the carbon emissions.

The results of the three methods evaluated by Alsadi and Matthews (2022) indicate that when the installations are "optimized," the open cut method emits the most CO_2. This is followed by pipe bursting and then CIPP. The "optimization" relied heavily on whether the excavated material was reused in the backfill or not. It also relied on if it was asphalt or concrete used for the repaving. In this context, concrete repaving was the least carbon-emitting method.

Pipe bursting was used to install the HDPE and PVC pipes. Open cut was utilized to install the PCCP pipe. The CIPP method was used to install the CIPP epoxy lining. The results from the installation phase are shown in Figure 2.

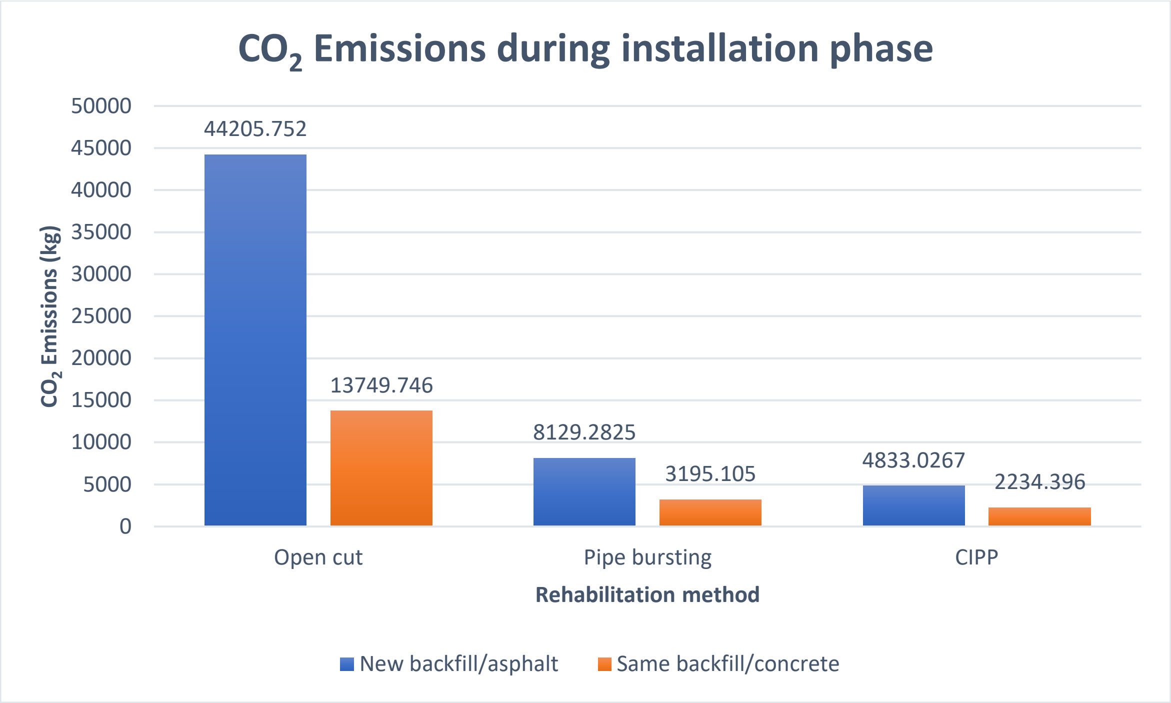


Figure 2: CO_2 emissions during the installation phase. The figure is an adaptation of (Alsadi and Matthews, 2022)

Operational phase

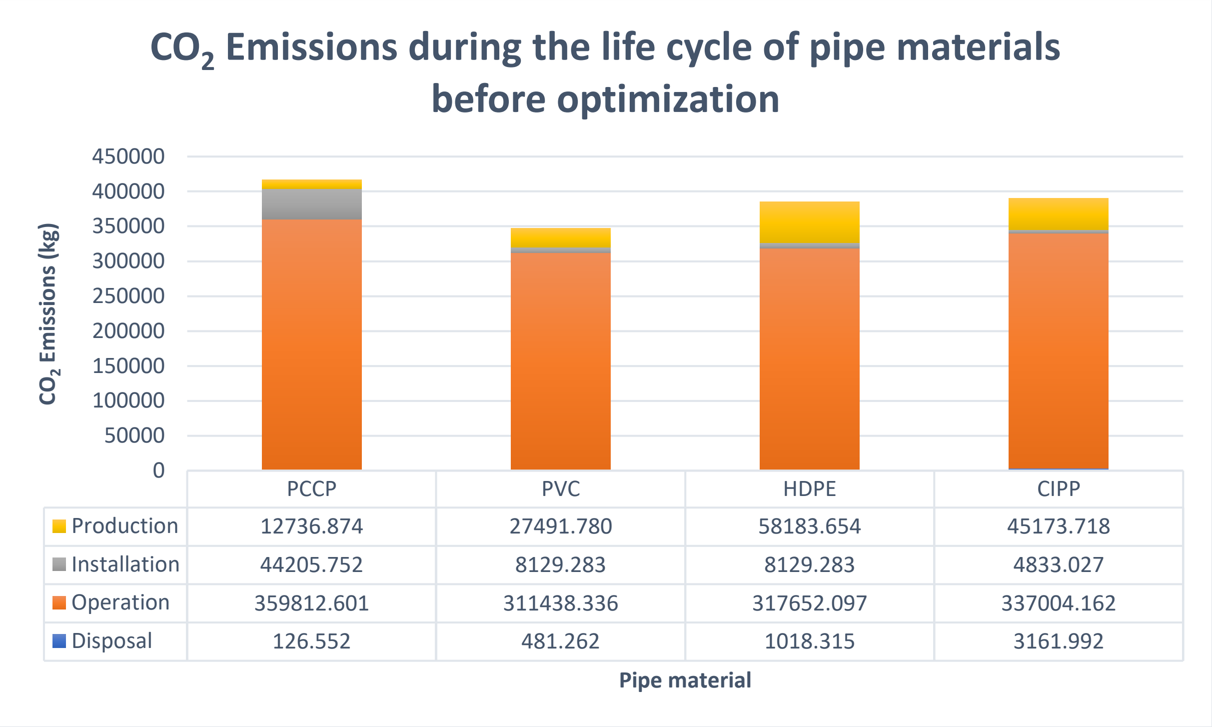
According to the article, the emissions generated during the pipe's service life are significantly influenced by pumping characteristics, pipe roughness, and cleaning. This phase will not be addressed in depth as it does not differentiate between the methods in a very meaningful way. This is despite the fact that this phase accumulates the most emissions during the pipe's expected service life, as reported in a previous study by the same authors (Alsadi, Matthews and Matthews, 2020). This can be seen in Figure 3.

Disposal phase

According to the article, this is the least significant step of the four phases discussed. The recycling of these materials contributed the least to carbon emissions. Therefore, this step will not be discussed in detail. It is, however, worth noting that the CIPP material cannot be recycled according to the authors (Alsadi and Matthews, 2022).

Results

The findings of Alsadi and Matthews (2022), indicate that CIPP is the pipe material with the highest CO_2 emissions over its entire life cycle, with 50-year life expectancy. This is followed by HDPE, PCCP, and finally PVC. HDPE is believed to be the highest emitter if CIPP were to have a 100-year life expectancy, which the authors consider unlikely (Alsadi and Matthews, 2022). The results can be seen in Figure 3.



	PCCP	PVC	HDPE	CIPP
Production	12736.874	27491.780	58183.654	45173.718
Installation	44205.752	8129.283	8129.283	4833.027
Operation	359812.601	311438.336	317652.097	337004.162
Disposal	126.552	481.262	1018.315	3161.992

Figure 3: CO_2 Emissions during the life cycle of pipe materials before optimization. The figure is an adaptation from (Alsadi, Matthews and Matthews, 2020)

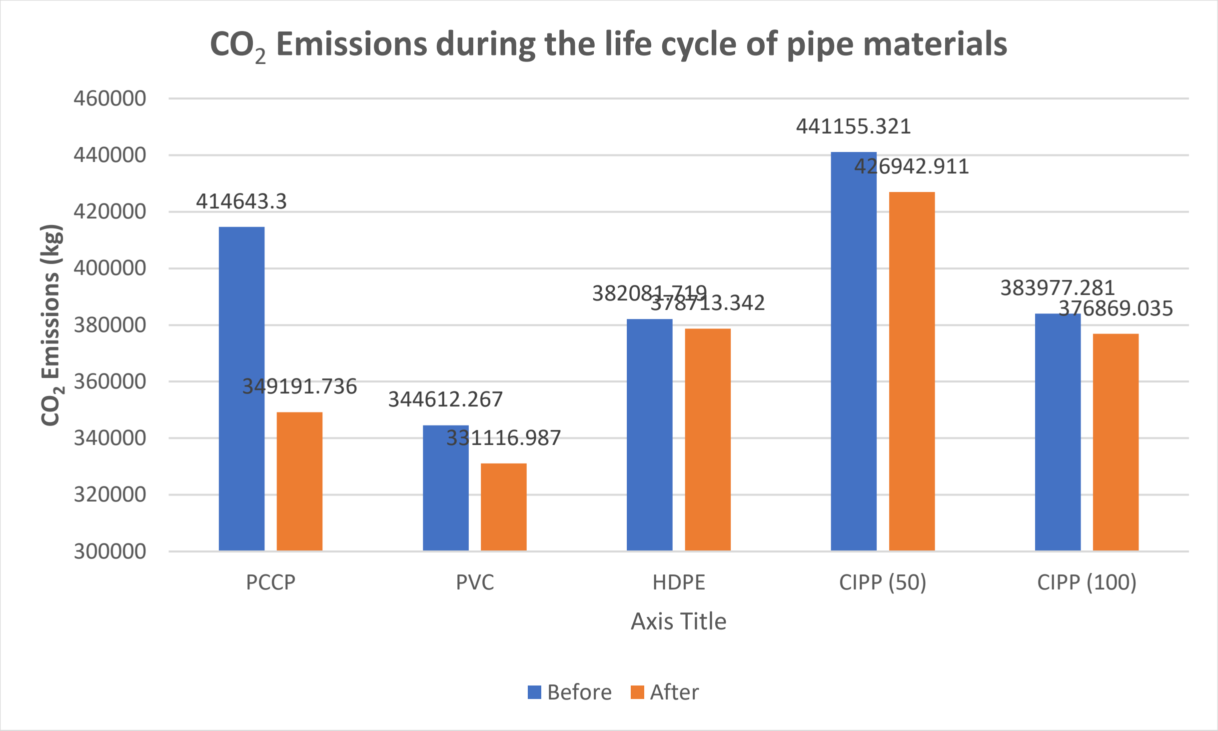


Figure 4: CO_2 Emissions during the life cycle of pipe materials. The figure is an adaptation from (Alsadi and Matthews, 2022).

Ranking

It is challenging to rank the environmental performance of rehabilitation methods due to the lack of comprehensive studies evaluating the LCA performance of the sliplining and the SIPP methods. Therefore, rough estimates based on available data have been made. These assumptions are based on the literature reviewed.

The first method to be discussed is the open cut method. A review by Kaushal, Najafi and Serajiantehrani (2020) found that open trench excavation techniques are generally less environmentally friendly than trenchless methods. The study by Alsadi and Matthews (2022) found that this is only the case if the open cut method is highly unsuitable, and the design life of CIPP is not 100-years. However, one significant environmental factor not considered in this study is the CO_2 generated from traffic disruptions and congestion. Furthermore, depending on the location, asphalt is typically the material used for repaving surfaces, which means that the open cut solutions are rarely optimized. Open cut solutions may, however, be a preferred option for non-paved surfaces compared to, for example, CIPP. However, most rehabilitation projects tend to be happening in urban environments, which means that the open cut solutions in general are a larger source of emissions than trenchless methods. The results do not improve significantly by changing the pipe material.

The second method is the CIPP method. This method had by far the highest emissions made during the production phase of all the methods evaluated, according to the results above. CIPP also had higher emissions during the disposal phase and operational phase. It also had the highest amount of emissions during the installation phase, assuming the CIPP method had to be relined due to its 50-year life expectancy, compared to the other materials' 100-year life expectancy. Furthermore, the method had the least amount of emissions saved when optimized. Based on the study, it is therefore assumed that the CIPP method may in general be the most emission-emitting trenchless method of the methods evaluated.

The third method is the sliplining method. It is assumed that the sliplining method uses HDPE as a pipe material (Wang, Yan and Xu, 2021b). Of all the methods reviewed, it is argued that the sliplining method has more in common with the CIPP method regarding installation than any of the other methods reviewed. The sliplining method does not require curing, which is an energy-intensive step of the CIPP installation phase (Wang, Yan and Xu, 2021a). This is because a prefabricated pipe is directly inserted into the old pipe. Therefore, if it is assumed that the emissions from the installation phase fall somewhere in between the CIPP and the pipe bursting method, it can be deduced that the emissions generated from this method are slightly less than that of the CIPP method. However, if PVC were to be used as a material instead of HDPE, the pipe bursting method might result in higher emissions than sliplining, depending on the material used in the pipe bursting process.

The fourth method is the pipe bursting method. The study by Alsadi and Matthews (2022) found that the pipe bursting method produced significantly less emissions during the installation phase than the open cut solution. A study by Loss *et al.* (2018) agrees with these results, stating: "the pipe bursting method presented lower impacts than the traditional relining system due to lower volumes of soil excavated and transported to the landfill, lower volumes of gravel and sand during the backfill process and lower volumes of asphalt during the restoration of the urban pavement." However, the pipe bursting method produced more CO_2 than the CIPP method in the installation phase. This is because the pipe bursting method required more excavation due to the sizes of the entrance and exit pits compared to CIPP (Alsadi and Matthews, 2022). However, due to the significantly lower emissions produced during the fabrication of PVC and HDPE, the pipe bursting method produces fewer overall emissions.

The final method is the SIPP method. The SIPP method is typically expected to use a cement mortar, or a polymer (Azimi *et al.*, 2021). If SIPP uses a cementitious material, this could arguably make this method more closely related to the PCCP pipe material. According to an article by Serajiantehrani *et al.* (2020), the production of the required Portland cement accounted for nearly all of the global warming potential in the rehabilitation project. This made the emissions in the installation phase almost negligible in comparison to those of the production phase. In the study, a diesel engine was used to acquire the required power for the application Serajiantehrani *et al.* (2020). It is also assumed that the volume of cement coating used to rehabilitate the pipe is of smaller volume than that of the PCCP pipe. Therefore, it is assumed that the total emissions are expected to be slightly lower than that of the PCCP pipe. It is also assumed that the SIPP method tends to be less emission-emitting than the CIPP method. Finally, due to the low emissions during the installation and production phase, there are overall less emissions are expected to be lower than those of the pipe bursting method. The ranking of the rehabilitation methods from the least to the most CO_2 emitted is shown in Table 1.

Table 1: Ranking of each methods' carbon emissions

Method	Rank
SIPP	1
Pipe bursting	2
Sliplining	3
CIPP	4
Open Cut	5

It is important to recognize that the emissions generated from each method are significantly influenced by the diameter of the pipe rehabilitated (Kaushal, Najafi and Serajiantehrani, 2020). According to Serajiantehrani *et al.* (2020) there is no linear correlation between the size increase in pipe diameter and the emissions emitted. Further studies should be conducted to more accurately determine the global warming potential of each method taking into account the pipe diameter. Local conditions for each project are also a significant variable.

2.6 The social criteria

Social costs are the costs of a project that are not included in the direct costs of the construction bid (McKim, 1997). “It includes the costs associated with the inconvenience to the general public and the damage to existing structures” (Najafi (2005), p. 27). The social cost of open cut methods can be a significant part of the total cost of the project, although it may not be a direct part of the contractor’s cost estimates when choosing rehabilitation methods (Najafi (2005), p. 28). From the municipality’s point of view, social costs can be very helpful in estimating the true total cost of a rehabilitation project, and therefore help selecting the most economically efficient bid (McKim, 1997). According to Gilchrist and Allouche (2005), the total cost of a construction project can be defined using Equation 1.

Equation 1: Total cost of a construction project

$$Total\ cost = construction\ costs + social\ costs$$

As argued by Gilchrist and Allouche (2005): “The consideration of social costs during the bid evaluation process is an important component of the paradigm shift needed to move the construction industry toward a more sustainable oriented frame of mind.” From a contractor’s point of view, showing the municipality that they have considered potential social costs can also be a major advantage when bidding for contracts.

According to Najafi, (2005, p. 28), the social costs of an open cut construction method include these major categories:

- Vehicular traffic disruption
- Road and pavement damage
- Damage to adjacent utilities and structures
- Noise and vibration
- Heavy construction and air pollution
- Pedestrian safety
- Business and trade loss
- Damage to detour roads
- Site and public safety
- Citizen complaints
- Environmental impacts

In terms of decision support, not all social costs can be considered when choosing a rehabilitation method. This is because many of the methods require a significant amount of data to be calculated, which may be difficult to obtain. In addition, some considerations are significantly more important and have much greater impact on the total estimated social cost than others. Furthermore, because each project is unique, it is extremely difficult to capture the essence of a project using a generalized tool. It is even more difficult to try to differentiate between different rehabilitation methods. Therefore, to make the decision support easier and to differentiate between the methods in a more representative way, two methods have been chosen based on the literature reviewed. These two criteria are:

- Surface disruptions
- Installation time

These two criteria selected make up a large part of the social costs, as they can indirectly represent major social disruptions such as traffic disruptions, noise, pollution, business disruptions, and other inconveniences.

2.6.1 Surface disruptions

There have been several attempts to try to quantify the social costs of a construction project. Many of these attempts to quantify the costs using conventional estimation methods and classify them according to “traffic, economic activities, pollution impacts and social/ecological/health impacts” (Gilchrist and Allouche, 2005). Many of these formulas require very specific data, such as the value of time, time duration, fuel price, traffic density, number of people affected, and so on (Najafi, 2005, p.34-38). Although these methods may be useful for estimating the social cost of a rehabilitation project (Matthews, 2015), very few studies have attempted to directly compare the social cost impacts of trenchless rehabilitation methods.

According to the literature reviewed on pipe rehabilitation, trenchless technologies tend to be favored over open cut solutions when estimating social costs. This is because trenchless techniques tend to be less disruptive to the public than open trench excavation techniques. The reason for this is because surface excavation tends to be one of the largest contributors to increased social costs. Surface excavation slows down traffic, uses more surface space, uses more heavy machinery, causes more damage to public and private property, is more prone to accidents, uses more construction time, and so on (Najafi, 2005; Kaushal, 2019). In order to evaluate the performance of this sub-criterion, an attempt is made to combine the categories of social costs that together make up the surface disruption criterion. The categories chosen are surface space needed, excavation required, and damage caused. These are believed to cause the most direct disturbances to the public.

The first trenchless method discussed is pipe bursting. This method requires the excavation of service, entrance, and exit pits (Lueke and Ariaratnam, 2001). Furthermore, according to Shi, Wang and Ng (2013): "Pipe bursting, however, inevitably induces outward displacements of surrounding soil, and subsequently leads to potential damages to adjacent structures and utilities". Furthermore, Najafi (2013, p. 435) claims that there must be enough space for construction equipment such as cranes. Although less disruptive than open cut solutions, it can be considered as the most disruptive of the trenchless methods reviewed.

The second method is SIPP. According to Marlow, Gould and Lane (2015): "Non-structural spray lining can generally be done without requiring existing service connections to be excavated, which means it is relatively cheap in areas with numerous customer connections." However, according to Wang, Yan and Xu (2021c): "When the work pit needs to be excavated at both ends of the original pipeline, the size of the work pit along the axis of the pipeline should not be less than 2.5 m, the width of the pit should not be less than 1.5 m, and the depth of the pit is 0.5 m lower than the bottom of the pipe." The SIPP method tends to use very compact specialized equipment and does only require heavy machinery during the excavation of the pits. Only one service truck during the installation is required during installation for the pumping of the cement mortar (Serajiantehrani *et al.*, 2020). The SIPP method is therefore considered less disruptive than the pipe bursting method.

The third method is sliplining. In terms of space requirements, a formula has been introduced by Wang, Yan and Xu (2021b). According to them, the minimum length of a working pit for sliplining can be described using Equation 2.

Equation 2: Minimum length of a sliplining working pit. An equation by (Wang, Yan and Xu, 2021b).

$$L = [H * (4R - H)]^{\frac{1}{2}}$$

Where:

L = length of working pit (m)
H = Buried depth of pipeline (m)
R = Allowable bending radius of polyethylene pipe (m), and R > 25 dn
dn = Outer diameter of new tube (m)

This means that for pipes with dn = 200 mm and a depth of 0.6 m, the minimum required working length is 3.41 m. Assuming that the width of the pit is the same as for the SIPP method, the space requirements for sliplining tends to be larger than for SIPP in most cases. Adding all the necessary equipment, such as grouting equipment, the traction device, and guide pulley (Wang, Yan and Xu, 2021b), one can expect a higher surface space requirement, and therefore surface disruption, than for the SIPP method. You can also assume a higher rate of surface deterioration due to the larger need for heavy machinery during the installation process. However, it is stated that an access pit is only required if the manholes does not provide enough space (Najafi, 2013, p. 379). It is still assumed that sliplining requires more space than SIPP in most cases.

The final method is the CIPP method. For sewers, access pits are usually not required (Wu *et al.*, 2021). However, some excavation may sometimes be required if there is no manhole access, such as when rehabilitating water mains (Wu *et al.*, 2021). One study assumed these dimensions: “For CIPP, the size of the two pits is 2.4 m (8 ft) long, 2.4 m (8 ft) wide, and 3 m (10 ft) deep” (Alsadi and Matthews, 2022). In this study the dimension of the pipe was 910 mm. This is still smaller than other methods reviewed. In addition, the pipe in this study was larger than the one proposed in the sliplining example. Similar to SIPP, CIPP does not require heavy equipment during the installation process. One service truck may be enough, depending on the size of the project (Najafi, 2005, p. 300). Table 2 shows the ranking of each method reviewed from least to most surface disturbance created.

Table 2: Ranking of surface disruptions

Method	Rank
CIPP	1
SIPP	2
Sliplining	3
Pipe bursting	4
Open cut	5

2.6.2 Installation time

Time is of the essence in construction projects. Saving time on rehabilitating pipes means reducing labor costs and minimizes the disruptions to the community. To reduce the social costs of a pipe rehabilitation project, it is therefore necessary to investigate which method requires the least amount of construction time.

There are several factors that affect the duration of a pipe rehabilitation project. To limit the scope, only factors that directly affect the methods being reviewed will be considered. This means that delays due to factors such as administration, accidents, breakage, and supply chain problems are not considered. It is also assumed that time used for inspections, bypass installations, and cleaning is the same for all methods that require them. This means that the focus on factors such as excavation required, curing time, grouting, and other factors that may be unique to each method during the installation phase. The manufacture of the pipe materials is not considered as these factors do not affect the time spent on site and therefore do not directly affect the social cost.

The first method discussed is open cut. As described earlier, the open cut solution tends to be much more time consuming than the trenchless methods due to the need to excavate, expose, replace, backfill, and then restore the surface for the entire length of the pipeline (Wu *et al.*, 2021). Therefore, this method is expected to be the worst performing rehabilitation method reviewed in terms of installation time.

The second method is pipe bursting. As explained previously, the pipe bursting method requires less excavation than the open cut solution. According to Environmental Protection Agency (2006), a typical pipe bursting rate can be expected to be about 30 meters per hour. However, according to Najafi (2013, p. 430), the time can vary greatly based on the nature of the project, as upsizing, soil conditions and deterioration of the pipe can affect bursting time by increasing complexity.

The third method is sliplining. According to Wang, Yan and Xu (2021b), when installing the sliplining, the pulling rate should not exceed 0.3 meters per second (1080 meters per hour) and requires a 24-hour tensile deformation recovery time at the end. The method also requires grouting (Wang, Yan and Xu, 2021b). As mentioned above, the sliplining method can use manholes as access pits for some projects. Therefore, sliplining tends to be faster than pipe bursting because of the faster installation rate and less excavation required.

The third method is CIPP. As mentioned earlier, the CIPP method can use manholes, and therefore does not require excavation of access pits for small to medium diameters (Najafi, 2013, p. 351). The method still requires curing. The curing time is expected to be 1 to 5 hours depending on the curing method (Najafi, 2013, p. 360). According to Gay (2016), the curing of large diameter pipes may significantly increase installation time.

The final method is SIPP. According to a case study by Serajiantehrani *et al.* (2020), the time it took to install a 500 ft (152.4 m) 30 in (762 mm) pipe was 24 hours over 3 days. This is an installation rate of 21.8 meters per hour. The spraying was done by hand and did not require excavation before the installation. It is assumed that site inspection and cleaning was done prior to the installation and is not included in the 24 hours. The curing time can be expected to be 24 hours for cementitious materials, and 1 to 2 hours for other liners (Najafi, 2013, p. 499-500). Therefore, depending largely on the diameter of the pipe and the material used in the SIPP method, the CIPP method is the fastest of the two in most scenarios for small to medium sized pipes. The ranking of the methods based on installation time is shown in Table 3.

Table 3: Ranking of installation time

Method	Rank
CIPP	1
SIPP	2
Sliplining	3
Pibe bursting	4
Open cut	5

The biggest differentiator between these methods became the needed excavation. The need for excavation varies greatly depending on the pipe size. Pipe bursting may for example do a lot better once excavation is needed for the CIPP and SIPP methods. SIPP can be the fastest method if epoxy lining is used instead of cement. This is because of curing time.

2.7 The economic criteria

The economic cost of a rehabilitation project is usually a very decisive factor when choosing a rehabilitation method. The economic costs of a rehabilitation project are usually determined by the contractor, and include the labor, material, and administrative costs (Najafi, 2005, p. 25). It is usually in the stakeholders' best interest to choose the most cost-effective solution, as it is necessary to uphold economic sustainability.

There are many factors that determine the cost of a rehabilitation project. One approach to ensure economic sustainability is to conduct a life cycle cost analysis (LCCA). According to Kubba (2010, p. 8): "Life-cycle cost analysis (LCCA) is a method for evaluating all relevant costs over time of a project, product, or measure. It takes into consideration all costs including first costs, such as capital investment costs, purchase, and installation costs; future costs, such as energy costs, operating costs, maintenance costs, capital replacement costs, financing costs; and any resale, salvage, or disposal cost, over the lifetime of the project or product."

According to Najafi (2005, p. 24), the following phases are considered when evaluating a pipe rehabilitation projects life cycle cost:

- Preconstruction cost
- Construction costs (direct and indirect)
- Postconstruction costs
- Social costs
- Other costs (legal, financing, administrative cost)

Each pipe rehabilitation project is unique, and it therefore almost impossible predict the cost using a generalized tool. To make the tool manageable, simplifications have been made. For the sake of this tool, the criteria will be mainly focused on direct and indirect construction costs. This is because of data availability and time constraints. Additionally, many pre -and postconstruction costs are not very different based on the rehabilitation method used. Therefore, costs like land acquisition are therefore not considered. The following criteria have been chosen:

- Unit construction costs
- Service life extension

The criteria were chosen due to their important roles in the LCCA and data accessibility. Given the limited number of sub-criteria, these two sub-criteria aimed to represent a comprehensive range of cost considerations for the economic criteria. The reasoning will be further discussed in this chapter. To assess the total cost of a rehabilitation project, it is also essential to include social costs as well as economic costs. Social costs will be discussed later.

2.7.1 Unit construction costs

The construction cost of a rehabilitation project may be defined as the sum of the contractor's direct and indirect costs (Najafi, 2013, p. 2). Direct costs usually include labor, material, equipment, and subcontractor's costs. While indirect cost may include all construction costs not directly associated with the construction operations of the pipeline (Najafi, 2013, p. 2). These costs may include "overhead costs" such as head-and-field office costs, rental of temporary facilities and equipment, and supervisory personnel (Najafi, 2013, p. 2). Although the direct costs are quite straight forward to estimate Najafi, (2005, p. 26) notes that: "The determination of indirect costs requires considerable construction knowledge and includes the greatest variation in construction cost estimating and can be approximately 20 percent of the direct costs of a utility project."

There have been several attempts to try to find a correlation between rehabilitation methods and costs. One such attempt was conducted by Najafi (2013). The author attempted to determine the unit construction costs of five rehabilitation methods by comparing several case studies from the CUIRE database. The data for the methods was gathered through quantitative data collection from multiple different case studies with varying soil conditions, pipe diameters, lengths, and materials. The relationship between the cost of each method was compared in relation to the pipe's diameter and length. For the regression analysis, cost was used as the dependent variable and diameter and length as the predictors. The costs are in US dollars and are adjusted for inflation to align with 2012 prices. It was used inches. In the decision support tool, the data was converted to metric units. The results are presented as regression equations in Table 4.

Table 4: Unit cost equations for each pipe rehabilitation method

Method	Equation [in, ft]	Source
CIPP	13*Diameter-0.00032*Lenght-65.8	(Najafi, 2013, p. 20)
Sliplining	11.2*Diameter-0.00909*Lenght-21.3	(Najafi 2013, p. 23)
SIPP	1.69*Diameter-0.00122*Lenght+106	(Najafi 2013, p. 25)
Pipe bursting	12.4*Diameter-0.00099*Lenght+12.3	(Najafi 2013, p. 29)
Open cut	172*Diameter-0.25*Lenght-1229	(Najafi 2013, p. 30)

There are studies that chooses to use the correlation between cost, and the parameters pipe length and diameter in order to estimate the cost of a rehabilitation project for the purpose of future estimation of planned construction projects (Loubser *et al.*, 2022). There are several reasons why this approach may be chosen. For instance, this allows for the calculation of the unit cost of the project for each pipe diameter and unit of length. They can do this by comparing total costs using historical data from contract bids and find a relationship between parameters through the use of empirical equations (Balaji, Mariappan and Senthamilkumar, 2015). According to Loubser *et al.* (2022): "With the approximate total length of pipework and associated length per diameter known, a budget estimate is enabled by the utility for the future construction of planned assets." When comparing case studies, it is important to have an idea of the scope of cost estimations. Some case studies may consider the total cost of the project, including social costs, while others may include the construction costs provided by the entrepreneurs in bids. For instance, (Najafi, 2013, p. 2) claims the data is solely from bids for construction, although it is acknowledged that there may have been oversights.

The use of the cost estimation equations derived from case studies reduces the complexity of calculating the cost of a rehabilitation project in the early stages (Loubser *et al.*, 2022). This is because this method provides a relationship between the cost of a project and project variables. Using this technique, we may do a rough estimation of a pipe rehabilitation project using minimal data. This approach simplifies the project by integrating the averaged indirect and direct costs of a pipe rehabilitation project. It is therefore unnecessary to know the exact cost of a pipe material, the value of time, or site-specific considerations. It should be noted that Najafi's estimations are based on project data gathered in North America. It is therefore important to recognize that these estimates may not apply outside of the United States. Furthermore, the data used to create the equations was published in 2013. Significant changes may have happened since then, such as the cost of labor and production materials. Despite this, the equations should still be sufficient to provide an understanding of the cost proportions when comparing methods in the decision support tool.

In order for this project to conduct a case study later, it is needed to establish a temporary ranking of the performance of each method. The ranking is based on the average cost based on pipe diameter and length estimated by (Najafi, 2013, p. 38). This is presented in Table 5. The equations in Table 4 will still be kept for the decision support tool to ensure flexibility.

Table 5: The ranking of the methods' unit cost

Method	Overall Average Cost ($/in D/ft Length)	Rank
CIPP	9.45	3
Sliplining	9.17	2
SIPP	4.10	1
Pipe bursting	13.75	4
Open cut	57.31	5
Source	(Najafi, 2013, p. 38)	

2.7.2 Service life extension:

According to Najafi (2016, p. 7): “Service life extension can be broadly defined as any technology that can be applied to an existing, aging, and deteriorated infrastructure system to increase its useful life.” When calculating the life cycle cost (LCC) of a pipe system, one parameter that tends to be a deciding factor is the estimated service life (Marlow, Gould and Lane, 2015). This variable can be extremely important, as both the LCC and the overall environmental impacts of the pipe rehabilitation can be spread over the pipe’s service life. This means that even if, for example, one method has a higher total cost than another method, the method may still be the most economically and potentially environmentally beneficial as it extends the time until the next necessary rehabilitation or replacement of the pipe.

It is usually extremely difficult to predict the service life of a pipe. There are several reasons for this. For example, because the infrastructure is underground, it is difficult to see the condition of the pipe without doing scheduled maintenance. In many cases the condition is determined when there are reports of leakages or structural failures (Fan and Yu, 2023). Furthermore, the conditions of the pipe locations are extremely varying and very decisive for the pipe’s service life. According to Dawood *et al.* (2020); “the pipe structural capacity could be assessed by a combination of parameters, e.g., external loads (traffic, frost), internal loads (operating and surge pressures), temperature fluctuations, loss of bedding support, and the existence of corrosion pits.” Furthermore, as commented by Karbhari and Lee (2011, p. 263): “While it is almost impossible to predict when a pipe will collapse, it is feasible to estimate whether a pipe has deteriorated sufficiently for collapse to be likely.” According to Micevski, Kuczera and Coombes (2002), one method used to estimate deterioration rates is the “Markov model,” a stochastic model that uses probabilistic forecasting based on the current state of the pipe. There are also other methods, such as creep tests, creep rapture tests, and the tensile fatigue tests (Shannon *et al.*, 2021). However, concrete numbers were hard to find in the literature search.

The service lives of the pipes are for the reasons mentioned above very dependent on local conditions. It is also very reliant on the materials used. This is why manufacturers choose to operate on design life thresholds rather than trying to predict their service life (Karbhari and Lee, 2011, p. 263). This means that the manufacturers will rather give a guarantee on the pipe’s minimum service life under reasonable conditions than attempt to predict its entire service life. Nevertheless, two sources have been found trying to estimate a typical asset life of a pipe rehabilitation method. Their results are presented in Table 6.

Table 6: Estimated asset life from two studies based on pipe material

Method	Generalized material	Typical design life threshold	Asset life hot climate	Asset life temperate climate
CIPP	Thermoset plastic	50 +	50	50
Sliplining	Thermoplastics	50 +	100 +	100 +
SIPP	Cementitious	50 +	50 +	100 +
Pipe bursting	Thermoplastics	50 +	100 +	100 +
Open cut	Any	N/A	Depends	Depends
Source		Karbhari and Lee (2011, p. 266)	(Baur et al., 2003)	(Baur et al., 2003)

According to Baur et al. (2003), methods based on thermoplastics have an estimated asset life of over 100 years, while cement-based methods have an estimated asset life of 50 years in temperate temperatures. Their estimations also view thermoset plastic materials as inferior compared to thermoplastics. Karbhari and Lee (2011) also estimates the service life of thermoplastics to be over 100 years. This is despite the fact that they remain very conservative regarding the asset lives of the other materials.

Asset life should not be confused with design life. This is because asset lives, also known as service lives, tend to be much longer than actual design lives. This is because design lives estimations are based on laboratory tests mentioned earlier. Here they use continuous loads, and safety factors to estimate the pipe's durability (Parvez, 2018). Several instances where the pipe is still operational after the traditional 50-year design life threshold has been reached are evidence that real-world conditions do not fully represent laboratory conditions. As pointed out by McPherson (2012): "Potable water pipelines (any material) over 50-years of age are generally taken out of service or replaced due to increases in demand rather than durability and reliability issues."

While it is difficult to fully justify any pipe life estimate, we may still do some conservative estimates. Both Baur et al. (2003) and Karbhari and Lee (2011): gave thermoplastics a 100-year design life. This may have to do with confidence in the material. As pointed out by Parvez (2018): "PVC pipe is assigned a 100-year service life based on 60 years of experience, extensive industry studies, dig-up field samples and historical data demonstrating low failure and water main break rates.” According to Najafi (2005, p. 179), this may be due to the material’s viscoelasticity and corrosive resistant nature.

The material used in the CIPP method is underperforming according to Baur et al. (2003) as the estimated asset life is only 50 years. Karbhari and Lee (2011) suggests it is at least 50 years. The suggestion of Karbhari and Lee (2011) is supported by Selvakumar *et al.* (2014): “The examination of CIPP liners with up to 34 years in service and other rehabilitation technologies with up to 19 years of service has shown that all of the rehabilitation technologies are showing little evidence of deterioration in service. The test results for 18 CIPP samples from nine cities across North America indicate that properly designed and installed CIPP liners should meet and likely exceed the typical 50-year expected design life.” However, there was not a much evidence to suggest that the CIPP liners would exceed 100 years. Modern CIPP methods and material production may exceed this threshold, but more research is needed to confirm this. Therefore, the expected service life of the CIPP method will be maintained at 50 years in the decision support tool.

The assumed cementitious material used in the SIPP method has an expected service life of 50 to over 100 years according to Baur et al. (2003). Conservatively, Karbhari and Lee (2011) expects the service life to be at least 50 years. Similar to the CIPP method, there is not much other evidence suggesting that the method should exceed the 100-year threshold. Therefore, the estimated asset life of 50 years will be kept in the tool.

The estimated asset lives used in the tool and their rankings are presented in Table 7. These values are based on the findings discussed earlier. The open cut solution can install any pipe material. Therefore, the open cut solution was determined to have a high ranking in the decision support tool.

Table 7: Ranking of the methods' estimated service life

Method	Generalized material	Typical design life threshold	Typical life expectancy	Rank
CIPP	Thermoset plastic	50	100 +	4
Sliplining	Thermoplastics	100	100 +	1
SIPP	Cementitious	50	100 +	4
Pipe bursting	Thermoplastics	100	100 +	1
Open cut	Any	50	100 +	1

2.8 Analytic hierarchy process

“The Analytic Hierarchy Process (AHP) is one of the most widely used multi-attribute decision-making (MADM) methods” (Demirel, Demirel and Kahraman, 2008). In this approach, “each criterion is assigned a weight, which indicates the importance of the criterion, then a numerical score for each alternative is calculated and the one with highest score prevails” (Wu and Abdul-Nour, 2020). The method was developed by Thomas L. Saaty in the 1970s (Forman and Gass, 2001), and follows a basic structure which has since been recognized as an extremely useful method used in several fields of science and engineering (Ishizaka, 2019). The AHP method has also proven its usefulness in multiple scenarios regarding wastewater engineering and pipe rehabilitation decision-making (Aşchilean *et al.*, 2017; Hassoun, Djebbar and Djemili, 2023; Wu and Abdul-Nour, 2020).

2.8.1 Concepts

There are four key concepts regarding the AHP decision-making process that should be considered in particular.

2.8.1.1 Hierarchical structure

This step is designed to combine the goals, criteria, sub-criteria, and alternatives and present the AHP structure in a more intuitive manner. This is meant to better visualize the hierarchical relations between the elements in the model (Brunelli, 2015a). An example of the AHP hiearachial structure is shown in Figure 5.

According to Saaty (1990), there are two reasons why a goals and attributes should be arranged into a hierarchy: “It provides an overall view of the complex relationships inherent in the situation; and helps the decision maker assess whether the issues in each level are of the same order of magnitude, so he can compare such homogeneous elements accurately."

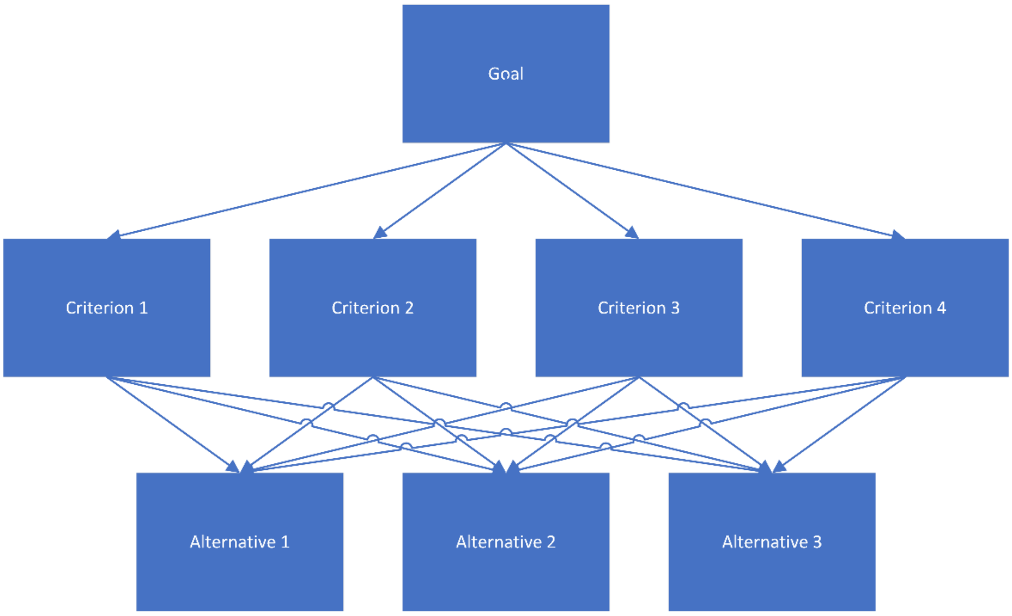
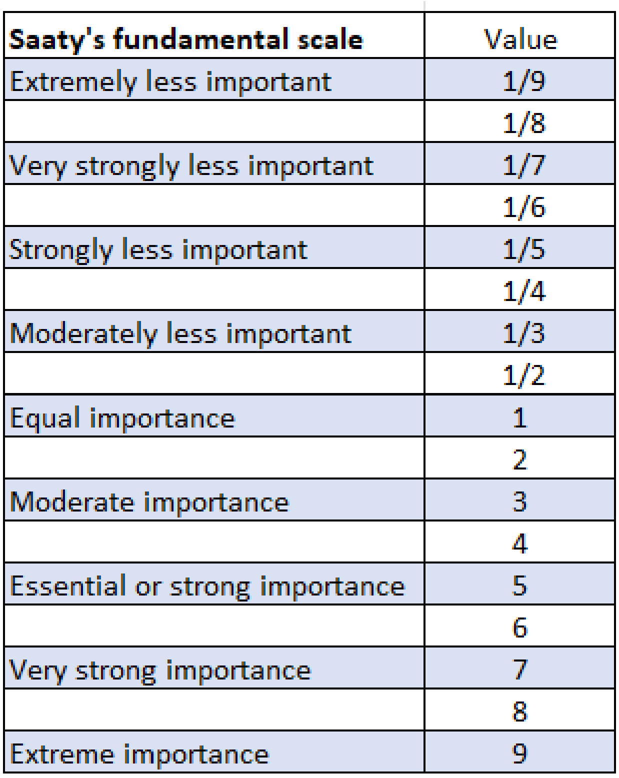


Figure 5: An example of an AHP structure

2.8.1.2 Pairwise comparison matrix

The AHP method considers several attributes that can be compared using a pairwise comparison matrix. This matrix is designed to easily compare the overall preference of each criterion by comparing them two at a time. The comparing process begins by assigning a numerical value to one criterion based on its relative importance to the criterion being compared. In his own work, Saaty (1990) proposed a "fundamental scale" for ranking the relative importance of different attributes on a scale from 1/9 to 9. An adaptation of the fundamental scale is shown in Table 8. Number 1 would signify that the attribute would be of equal importance to another attribute, while number 9 would represent a most extreme preference in importance. Similarly, a value of 1/9 would indicate that the criterion in question would be of extremely less importance than the given criterion. The relative importance of each attribute may be determined by a group of experts, but it may also be determined by the preferences of any user. The pairwise comparison matrix would then generate weights based on these preferences. This can be done for both the global and local sub-criteria. The resulting weights can then be used to rank the available alternatives based on performance. The process of weighing will be further described below.

Table 8: Saaty's fundamental scale for pairwise comparison matrices. An adaption from (Saaty, 1990)



Saaty's fundamental scale	Value
Extremely less important	1/9
	1/8
Very strongly less important	1/7
	1/6
Strongly less important	1/5
	1/4
Moderately less important	1/3
	1/2
Equal importance	1
	2
Moderate importance	3
	4
Essential or strong importance	5
	6
Very strong importance	7
	8
Extreme importance	9

2.8.1.3 Priority vectors

The priority vectors are the eigenvectors that represent the overall weight of each criterion based on the result from the pairwise comparison matrix. According to Saaty (1990), the purpose of the vectors is to help quantify the judgments of each expert and use them to weigh each criterion against alternative in order to determine the best alternative.

There are several different mathematical methods that may be used to calculate the priority vectors. Saaty himself proposed the principal eigenvector method (Brunelli, 2015b). However, as pointed out by Brunelli (2015b), a popular alternative is the geometric mean method. How to calculate the priority vectors will be discussed in the methodology chapter.

2.8.1.4 Consistency ratio

The consistency ratio (CR) is value used to indicate the consistency of the experts' preferences. This value was introduced by Saaty, and the pairwise comparison matrix is considered consistent if CR ≤ 0.1, where 0 represents perfect consistency (Saaty, 1990). This implies that "the vector of the weights is well determined" (Aşchilean *et al.*, 2017). This further means that if the CR > 0.1 then the pairwise comparison matrix is too inconsistent, and the preferences should be revisited (Wu and Abdul-Nour, 2020).

2.8.1.5 Advantages

As described by Brunelli (2015a): “Broadly speaking, the AHP is a theory and methodology for relative measurement. In relative measurement we are not interested in the exact measurement of some quantities, but rather on the proportions between them.” He further describes that this approach to relative measurements greatly simplifies the decision analysis and may be of great advantage when it is important to find the optimal solution, rather than the precise quantity of it (Brunelli, 2015a). This gives more flexibility when trying to quantify the decision criteria, as it is more important to examine the proportions of the criteria, than focusing too much on the details. It is therefore possible to eliminate parts of the criteria that are insignificant and concentrate on the variables that have the greatest impacts on the overall ranking of the criteria. This enables the best option to be decided based on a limited amount of information.

2.8.1.6 Limitations

There are limitations to the AHP method. For instance, as pointed out by Chen *et al.* (2022): “Uncertainty in AHP processes can be very high in transferring human judgments into calculable numbers. Subjective evaluations from human perception could not be fully captured by objective mechanisms of AHP.” Furthermore, as mentioned by Pant *et al.* (2022): “The main disadvantage of AHP is a large number of pairwise comparisons, which can certainly cause errors to arise.” This is because of the high difficulty of staying consistent when there are too many pairwise comparisons. Therefore, the number of sub-criteria should be kept to a minimum (Cimadamore *et al.*, 2021).

2.9 Fuzzy logic and fuzzy set theory

The AHP method is a well-known approach to decision-making when we are dealing with absolute truths and falsehoods. However, this is not always the case. This chapter will demonstrate how fuzzy logic and fuzzy set theory can be used when we are processing information with vague and ambiguous interpretation.

Fuzzy logic (FL) was first introduced by Lotfi A. Zadeh in 1965 (Chrysafiadi, 2023). According to the inventor himself: “unlike classical logical systems, it aims at modeling the imprecise modes of reasoning that play an essential role in the remarkable human ability to make rational decisions in an environment of uncertainty and imprecision. This ability depends, in turn, on our ability to infer an approximate answer to a question based on a store of knowledge that is inexact, incomplete, or not totally reliable” (Zadeh, 1988). He further explains that fuzzy logic may be used when the language is vague. He explains that in addition to “two-valued logical systems”, whereas something is absolutely true of absolutely false, there is also a spectrum of “relative trueness”. These relative truths may come in the form of “linguistic variables” by for example using terms like “many”, “few”, “large”, and “small”. These linguistic variables are vague and do not give a lot of information. The wording of the values is interpreted differently depending on the person interpreting them (Zadeh, 1988). For example, drinking four cups of coffee per day may be considered a large amount by some, but might be considered below the average for teachers and engineers.

Fuzzy logic seeks to quantify these vague expressions into “fuzzy numbers,” which may be scaled from 0 to 1. Here “0” means absolutely false, and “1” is absolutely true. As explained by Kosko and Isaka (1993), it is then possible to make decisions based on a range of “overlapping patches” (data) instead of one discrete data point. This approach enables the generation of more accurate results. It is further argued by Kosko and Isaka (1993) that: “investigators in many fields may find that fuzzy, commonsense models are more useful or accurate than are standard mathematical ones”.

This form of “overlapping patches” may be explained by using a probability theory called “triangular possibility distributions” (Zadeh, 1988), a technique often referred to by users as “triangulation,” or “triangular membership function.” As shown in Equation 3, the triangular membership function wishes to convert a single crisp number into a range of three data points. These three data points are often referred to as “triangular fuzzy numbers” (TFNs). Figure 6 shows the triangular membership function in relation to Saaty’s fundamental scale. This way, as explained above, the crisp number no longer represents a single absolute truth, but rather a range of relative truths (Zadeh, 1988). This may be extremely helpful when processing the opinions of experts. Equation 3 is an adaption from (Kwong and Bai, 2002).

Equation 3: Triangular membership function. The equation is an adaption from (Kwong and Bai, 2002).

$$\mu_{Pn}(x) = \begin{cases} 0, & x < a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ \dfrac{c-x}{c-b}, & b \le x \le c \\ 0, & x > c \end{cases}$$

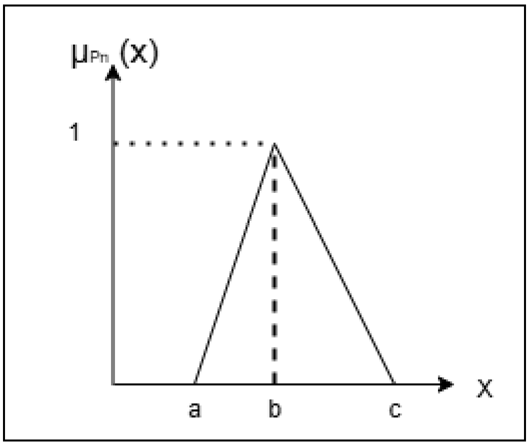


Figure 6: Visualization of the triangular fuzzy membership function. The figure is an adaption from (Kwong and Bai, 2002)

2.10 Fuzzy Analytic Hierarchy process

The Fuzzy Analytic Hierarchy Process (FAHP) is an extension of the AHP method that incorporates fuzzy logic and fuzzy set theory with the objective of improving the model. There are several different methods for implementing fuzzy logic into the AHP (Demirel, Demirel and Kahraman, 2008). They all try to fix the AHP method's shortcomings regarding uncertainty factors such as linguistic vagueness, ambiguity, and uncertain data (Karczmarek, Pedrycz and Kiersztyn, 2021).

As mentioned earlier, the MCDM tool developed aims to consider the preferences of several experts. As expressed by Hosseinzadeh Lotfi *et al.* (2023), the FAHP method offers a significant advantage in this regard: "Fuzzy AHP allows decision-makers to express preferences in a flexible and nuanced manner, capturing uncertainties and ambiguity present in real-world scenarios. Its advantage lies in handling vague and imprecise information systematically, enabling the effective incorporation of subjective assessments and expert opinions." For the sake of the tool, it allows the experts to voice their preferences in the form of a range of fuzzy numbers rather than having crisp, precise preferences. This may have advantages regarding the selection of the optimal alternative, as the preferences may be more representative of the average opinion of the experts. This may result in a more accurate representation of the weighting that gives the criteria priority.

There are several reports showing the usefulness of the FAHP algorithm in water and wastewater engineering (Hassoun, Djebbar and Djemili, 2023). For instance, a report by Romero, Fandiño and Ariza (2021) demonstrated how the fuzzy logic verbalization of pipe rehabilitation variables enhanced the quality of the decision-making process by removing some of the uncertainty in the data variables. Another study by Karasneh and Moqbel (2023) used FAHP do get the opinions of 23 experts simultaneously to decide the optimal strategy to rehabilitate a water network. The study found that: “The test results showed that the model was successful in providing a sound priority list of network rehabilitation projects to the decision-maker” (Karasneh and Moqbel, 2023). The method has already been proven to be helpful in these case studies. The FAHP method exploits the hierarchal problem-solving structure of the AHP. The method also reduces uncertainty in the data, and to a better degree can represent the subjective opinions of the experts. This gives confidence that FAHP may be useful to decide priority vectors for this decision support tool as well.

3 Method

3.1 The decision support tool

The decision support tool is programmed using the Microsoft Excel software. The user will begin by entering the project-specific information into a “questionnaire.” The questionnaire is a simple list of yes or no questions, as well as some questions requiring more detailed inputs. Additionally, the questionnaire requires the expert to complete the local and global pairwise comparison matrices based on their preferences. The preferences will be determined by using a fuzzified Saaty’s fundamental scale. The questionnaire will examine the opinions of three experts at the time. The matrices include a consistency ratio to assist the users in maintaining consistency.

Once the questionnaire is completed, the program will initiate the “elimination step” of the tool. In this step, the program will assess the feasibility of each method based on the information provided in the questionnaire. The program will then compare the questionnaire with the method feasibility database, which is found in one of the spreadsheets. Here, the answers from the questionnaire will be compared to each control factor in the database. The control factors are the limitations to each rehabilitation method. If the method is deemed applicable, the method will receive a “1”; otherwise, the method will receive a “0.” If the method receives a “0” at any point during the elimination step, it is not applicable.

The information from the questionnaire will be used to help rank the rehabilitation methods. The alternatives will be ranked from 1 to 5 based on their performance in each criterion. The alternative with the best performance will receive 5 points, while the alternative with the worst performance will receive 1 point.

Finally, the criteria weights will be used to determine the optimal alternative. Here, the weights will be aggregated with each of the scores from the rankings to determine the final score. The result is a list of the alternatives where non-applicable methods will receive a “N/A,” while the applicable methods will receive a ranking. Figure 7 provides a flowchart of the different steps of the decision support tool.

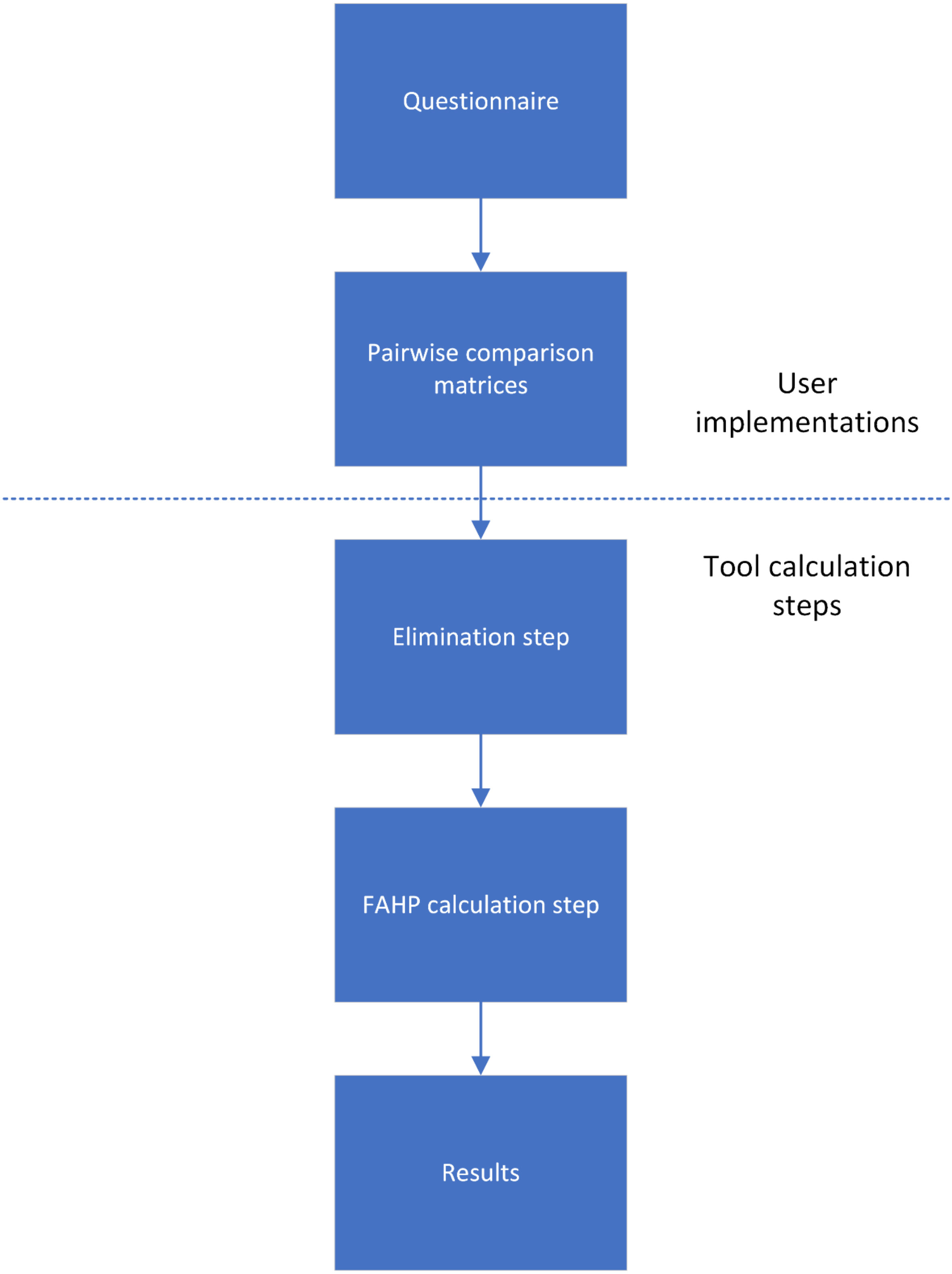


Figure 7: Decision support tool flowchart

3.2 The elimination step

There are many considerations that must be made to be able to choose a rehabilitation method. In addition to the stakeholder's preferences, one of the most important considerations is the technical feasibility of the method for the specific project.

The elimination step aims to introduce a feature to the tool that helps determine the feasibility of the method. This feature ensures that the chosen rehabilitation method will always provide a working solution, assuming there is at least one option remaining at the given project. This is also assuming that the tool's questionnaire is robust enough to ask the correct questions and capture the project sites possibilities. The elimination step will focus on the technical limitations of each rehabilitation method. The elimination step will also take into consideration the project-specific limitations. The project-specific limitations are considerations regarding the project's location and the nature of the problem. These limitations will be known in the tool as "control factors."

3.2.1 The project limitations (Control factors)

Pipe diameter: Many methods are limited by the diameter of the pipe. This may be due to the limitations in the methods' production and material (Shehab-Eldeen and Moselhi, 2001).

Section length: Some methods cannot be implemented on some pipe lengths without some sort of intervention from humans or machines, such as through manholes or excavation pits. This may be due to the limited capabilities of pushing or pulling equipment, for example during the installation of sliplining (Shehab-Eldeen and Moselhi, 2001).

Structural problems: Some rehabilitation methods provide a self-supporting solution. Semi-structural, or non-structural methods may partially or entirely rely on the existing pipe for support (Aas et al., 2016). Therefore, experts must consider whether the pipe segments are structurally intact and if they can withstand the loads required during their prolonged service life. If the existing pipe segment is, for example, experiencing pipe collapse, it is evident that many methods may be unsuitable.

Inadequate hydraulic capacity: Not all methods may sufficiently help improve hydraulic capacity. On the contrary, some methods may reduce the pipe's cross section, which would consequently reduce the hydraulic capabilities of the pipe. If the project requires upgrading capacity, many methods may therefore be unfit (Najafi, 2005).

Change in cross-section is allowed: Some methods may increase or decrease the cross-section of the pipe. According to Najafi (2005, p. 138): **“**the pipeline hydraulics needs to be checked for those renewal techniques that reduce cross-sectional area of existing pipe.” This is to ensure sufficient hydraulic capabilities such as flow.

Varying cross-sections: Some methods rely on a consistent uniform fit throughout the entire pipe length. This includes some sliplining methods (Aas et al., 2016). This may be due to design constraints, as the methods may for example not provide adequate structural support or hydraulic capabilities with varying cross sections.

Flow bypass/rerouting considerations: “Most renewal technologies require that the flow in the line be temporarily rerouted during the time that the renewal work is being conducted. Depending on the circumstances, this can be a significant cost consideration, amounting up to one-third of the total cost for a pipeline renewal job” (Najafi, 2005, p. 138). This is due to some methods “require controlled environment, in terms of temperature and dryness, necessary for curing the resin used” (Shehab-Eldeen and Moselhi, 2001).

Degree of bends on pipe segments: “Certain products allow for bends and others do not. The products that allow for bends could also have restrictions on the degree of the bend (i.e., 45° or 90°) that could be applied” (Shehab-Eldeen and Moselhi, 2001).

Misalignment: Misalignment refers to the structural failure of pipes where the pipe no longer follows its designed axis. Misalignments may be caused by external loads or installation failure. According to Romero, Fandiño and Ariza (2021), misalignments are a problem for rehabilitation methods that require the original pipe for support. Some methods still work with some degree of misalignment.

Please note that the open cut solution is assumed to work in any project. However, in real-life applications, there may be instances where this is not the case.

Table 9: Applicability of the CIPP method

	Applicability	Source
Minimum diameter [mm]	100	Najafi, 2016, p. 11
Maximum diameter [mm]	4000	Najafi, 2016, p. 11
Maximum pipe segment [m]	1000	Najafi, 2016, p. 11
Suitable for pipes with varying cross sections	Yes	Najafi, 2013, p. 354
Needs bypass	Yes	Najafi, 2005, p.136
Causes more than 10 % loss of diameter	No	Najafi, 2005, p.136
Works when pipes are misaligned	Yes	Najafi, 2005, p.136
Usable when there is inadequate hydraulic capacity of the pipe?	No	Najafi, 2005, p.135
Works when the pipe is not structurally intact?	Yes	Najafi, 2005, p.135
Fixes corrosion issues?	Yes	Najafi, 2005, p.135
Non-circular pipes	Yes	Najafi, 2013, p. 354
Maximum bend [degrees]	90	Najafi, 2013, p. 354
Deformations	Yes	Najafi, 2013, p. 354

Table 10: Applicability of the sliplining method

	Applicability	Source
Minimum diameter [mm]	100	Najafi, 2016, p. 13
Maximum diameter [mm]	4000	Najafi, 2016, p. 13
Maximum pipe segment [m]	300	Najafi, 2016, p. 13
Suitable for pipes with varying cross sections	No	Najafi, 2013, p. 369
Needs bypass	No	Najafi, 2005, p.136
More than 10 % loss of diameter	Yes	Najafi, 2005, p.136
Works when pipes are misaligned	No	Najafi, 2005, p.136

Usable when there is inadequate hydraulic capacity of the pipe?	No	Najafi, 2005, p.135
Works when the pipe is not structurally intact?	Yes	Najafi, 2005, p.135
Fixes corrosion issues?	Yes	Najafi, 2005, p.135
Non-circular pipes	Yes	Najafi, 2013, p. 369
Maximum bend [degrees]	0	Najafi, 2013, p. 369
Deformations	Yes	Najafi, 2013, p. 369

Table 11: Applicability of the pipe bursting method

	Applicability	Source
Minimum diameter [mm]	100	Najafi, 2016, p. 15
Maximum diameter [mm]	3500	Najafi, 2016, p. 15
Maximum pipe segment [m]	250	Najafi, 2016, p. 15
Suitable for pipes with varying cross sections	Yes	Najafi, 2013, p. 423
Needs bypass	Yes	Najafi, 2005, p.136
More than 10 % loss of diameter	No	Najafi, 2005, p.136
Works when pipes are misaligned	Yes	Romero, Fandiño and Ariza, 2021
Usable when there is inadequate hydraulic capacity of the pipe?	Yes	Najafi, 2005, p.135
Works when the pipe is not structurally intact?	Yes	Najafi, 2005, p.135
Fixes corrosion issues?	Yes	Najafi, 2005, p.135
Non-circular pipes	Yes	Najafi, 2013, p. 423
Maximum bend [degrees]	20	Najafi, 2013, p. 423
Deformations	Yes	Najafi, 2013, p. 423

Table 12: Applicability of the SIPP method

	Applicability	Source
Minimum diameter [mm]	100	Najafi, 2013, p. 23
Maximum diameter [mm]	No upper limit	Najafi, 2013, p. 495
Maximum pipe segment [m]	150	Najafi, 2013, p. 23
Suitable for pipes with varying cross sections	Yes	Zhu *et al.*, 2021
Needs bypass	Yes	Selvakumar *et al.*, 2013
More than 10 % loss of diameter	No	Selvakumar *et al.*, 2013
Works when pipes are misaligned	Yes	See note
Usable when there is inadequate hydraulic capacity of the pipe?	No	Najafi, 2016, p. 24
Works when the pipe is not structurally intact?	No	Najafi, 2013, p. 484
Fixes corrosion issues?	Yes	Najafi, 2013, p. 484
Non-circular pipes	Yes	See note
Maximum bend [degrees]	90	Zhu *et al.*, 2021
Deformations	Yes	See note

Note: There are structurally available options for SIPP, however, the focus has mainly been on the cement mortar linings, which is considered non-structural (Selvakumar *et al.*, 2013). Epoxy linings may for example have other abilities (Najafi, 2013, p. 484).

Since the SIPP method is applied by spraying directly on the wall, it does not have the same limitations as many other lining methods. For instance, there is no limit on the size of the diameter that SIPP may be applicable (Najafi, 2013, p. 495; Zhu *et al.*, 2021). Since the manual SIPP method is so versatile, it is assumed that the method may accommodate pipes that are misaligned, non-circular, and deformed. In many cases, the addition of more cement can be a viable solution to many of these problems.

3.3 Step-by-step guide to FAHP

The creation of the fuzzy-AHP began by establishing a hierarchal structure following the original AHP methodology introduced by Saaty (1990). The first step was to establish a goal, then find global criteria and sub-criteria which could be useful to evaluate the performance of the alternatives. As explained earlier, the three global criteria selected were economic, social, and environmental cost. These criteria were chosen because they represent the three pillars of sustainability. Based on these three criteria, a total of five sub-criteria were chosen to assist in evaluating the performance of the five rehabilitation methods reviewed. The hierarchal structure was structured as shown in Figure 8.

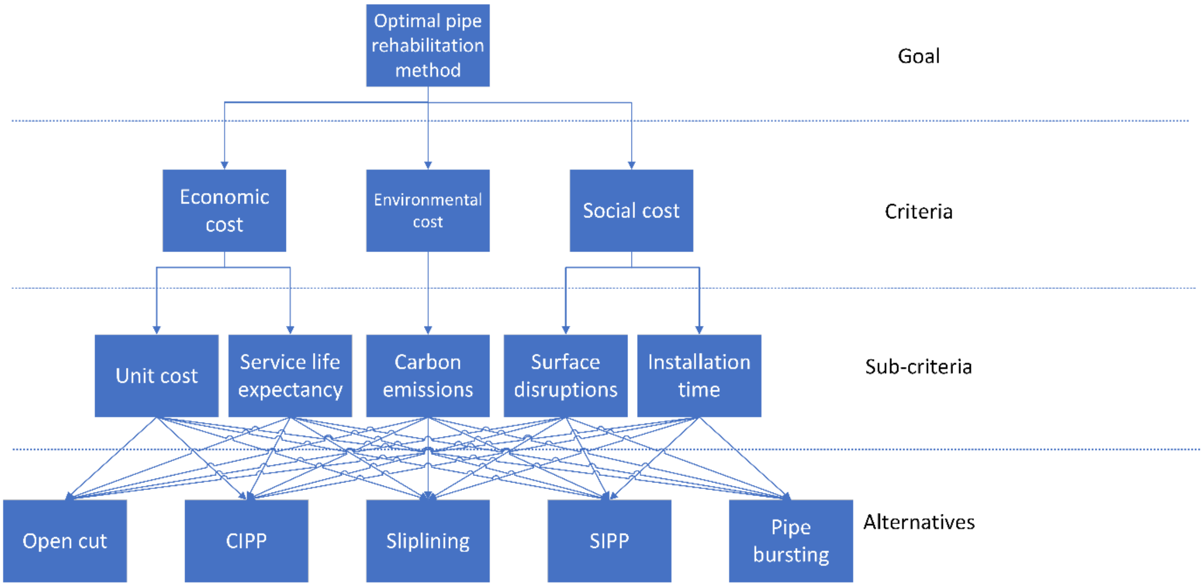
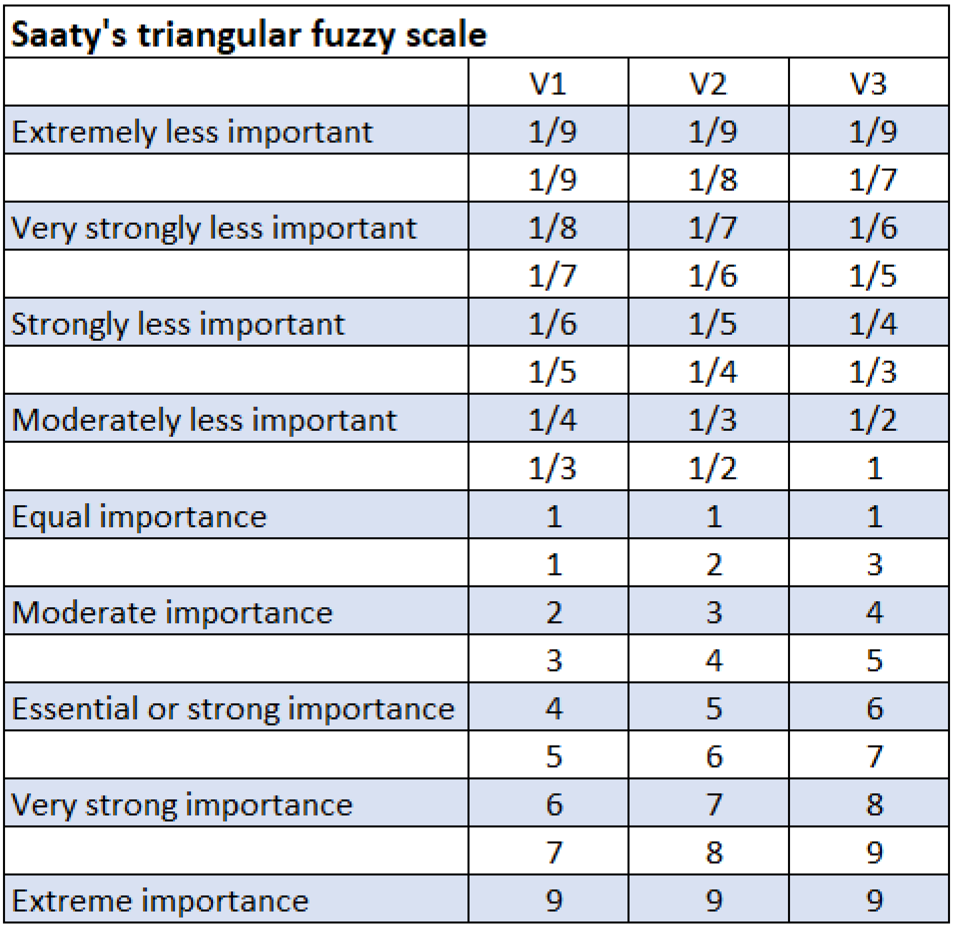


Figure 8: The hierarchal structure of the FAHP

The second step was to create the pairwise comparison matrices. These pairwise comparison matrices are similar to the one used in the original AHP method. However, instead of using the original fundamental scale introduced by Saaty (1990), a modified fundamental scale includes triangular fuzzy numbers (TFNs). Here, we introduce the fuzzy logic triangulation described earlier to turn the crisp numbers on the fundamental scale into a fuzzy range. The TFNs are used as values in the pairwise comparison matrices. Table 13 presents an adapted triangular fuzzy scale based on a study by Kaganski, Majak and Karjust (2018).

Table 13: Saaty's fuzzified fundamental scale. An adaption from (Kaganski, Majak and Karjust, 2018)



Saaty's triangular fuzzy scale

	V1	V2	V3
Extremely less important	1/9	1/9	1/9
	1/9	1/8	1/7
Very strongly less important	1/8	1/7	1/6
	1/7	1/6	1/5
Strongly less important	1/6	1/5	1/4
	1/5	1/4	1/3
Moderately less important	1/4	1/3	1/2
	1/3	1/2	1
Equal importance	1	1	1
	1	2	3
Moderate importance	2	3	4
	3	4	5
Essential or strong importance	4	5	6
	5	6	7
Very strong importance	6	7	8
	7	8	9
Extreme importance	9	9	9

The modified fundamental scale is used by the experts to express their opinions in the form of a range. In the questionnaire, each expert must provide their preference a total of five times divided over the three pairwise matrices. Here, there is one matrix for the global criteria, one for the social sub-criteria, and one for the economic sub-criteria. There is no matrix for the environmental criterion, as it is not possible to compare only one sub-criterion.

Equation 4 illustrates a triangular fuzzy number. The symbols "l", "m", and "u" represent the lowest, middle, and highest values respectfully.

Equation 4: The structure of a triangular fuzzy number

$$Pn = (l, m, u)$$

Equation 5 illustrates an inverse triangular fuzzy number ordered from lowest to highest value.

Equation 5: Inverse triangular fuzzy number

$$Pn^{-1} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right)$$

Table 14 illustrates how the TFNs are applied in a pairwise comparison matrix. The diagonal columns are always Pn = (1, 1, 1). This is because when you compare the same criteria with each other, they will always be of equal importance. Matrix “Mn” represents the pairwise comparison matrix of one expert.

Table 14: An applied pairwise comparison matrix

$$Mn = \begin{bmatrix} & C1 & C2 & C3 \\ C1 & (1,1,1) & P1 & P2 \\ C2 & P1^{-1} & (1,1,1) & P3 \\ C3 & P2^{-1} & P3^{-1} & (1,1,1) \end{bmatrix}$$

Equation 6 demonstrates how the preferences of each expert in a pairwise comparison matrix gets averaged (Kaganski, Majak and Karjust, 2018). In this context, “n” represents the number of matrices averaged.

Equation 6: Averaged TFNs

$$\overline{P}n = \left(\frac{l_1 + \cdots + l_n}{n}, \frac{m_1 + \cdots + m_n}{n}, \frac{u_1 + \cdots + u_n}{n}\right)$$

Table 15 shows how each of the averaged TFNs gets combined into an averaged comparison matrix. Here, “$\overline{M}$” represents the averaged pairwise comparison matrix.

Table 15: Averaged pairwise comparison matrix

$$\overline{M} = \begin{bmatrix} & C1 & C2 & C3 \\ C1 & (1,1,1) & \overline{P}1 & \overline{P}2 \\ C2 & \overline{P}1^{-1} & (1,1,1) & \overline{P}3 \\ C3 & \overline{P}2^{-1} & \overline{P}3^{-1} & (1,1,1) \end{bmatrix}$$

The third step is to process the preferences from the averaged pairwise comparison matrix. This step includes calculating the fuzzy weights and transforming them back into crisp numbers so that they may be used as weights to evaluate the alternatives. The reason we do this is pointed out by Liu, Eckert and Earl (2020a): “Fuzzy sets are difficult to compare directly because they are partially ordered rather than the linear or strictly ordered crisp values.”

The method used to calculate the fuzzy weights, and later the consistency ratio is a partial adaptation of a method and Excel template by Ahmad and Qahmash (2020). The methodology used to find the fuzzy weights is based on what Ahmad and Qahmash (2020) refer to as "Buckley's Fuzzy AHP", a technique originally proposed by Buckley (1985). The reason Ahmad and Qahmash (2020) chose Buckley's method is because: "it outperforms other algorithms for smaller sizes." Buckley's approach will be used for the same reason in this tool.

In the article by Buckley (1985), the geometric mean method is used. According to Buckley (1985): "The geometric mean method is employed to calculate the fuzzy weights for each fuzzy matrix, and these are combined in the usual manner to determine the final fuzzy weights for the alternatives." The geometric mean method may be described by using Equation 7.

Equation 7: Geometric mean equation

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \overline{P}_{ij} \right)^{\frac{1}{n}}, i = 1, 2, \dots, n$$

In this context, the positive reciprocal matrix "$\overline{P}_{ij}$,“ represents the pairwise comparison matrix, where "i" represents the rows and "j" represents the columns. The symbol "n" represents the number of criteria in each row. The geometric mean is calculated for each of the rows in the in the pairwise comparison matrix (Ahmad and Qahmash, 2020). The geometric means form a new vector "ri," which are used to form a new geometric mean matrix. In the Excel spreadsheet, the geometric mean is calculated using the Excel function "GEOMEAN". The fuzzy weights are then found using Equation 8.

Equation 8: Fuzzy weight equation

$$\widetilde{w_i} = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \dots \oplus \tilde{r}_n) = (lw_i, mw_i, uw_i)$$

In this context, each row in the geometric mean matrix is summarized and then inverted. The inverted values are then multiplied with each of the values in the geometric mean matrix. The results are the fuzzy weights of the pairwise comparison matrix. The fuzzy weights are then defuzzified into crisp numbers using the "center of area method" (COA), as shown in Equation 9. This process may also be referred to as ”de-fuzzy numbers" (Ahmad and Qahmash, 2020).

Equation 9: Center of area method

$$DFN_i = \frac{lw_i, mw_i, uw_i}{3}$$

The de-fuzzy numbers are then normalized using Equation 10 (Ahmad and Qahmash, 2020). The normalized weights are the weights that will be used to rank each alternative, both for the global and local criteria.

Equation 10: Normalized defuzzified numbers

$$N = \frac{DFN_i}{\sum_{i=1}^{n} DFN_i}$$

The fourth step is then to aggregate the scores. Here, the global normalized weights are multiplied with the local normalized sub-criteria weights to create the final Aggregated Criteria Weights (ACW) for each alternative. Each sub-criterion is multiplied with the scoring received based on the alternative's ranking in each sub-criterion. This is referred to as Sub-Criteria Score (SCS). This is shown in Equation 11.

Equation 11: Final score for an alternative

$$Final\ score\ alternative = ACW_i * \sum_{i=1}^{n} SCS_i$$

The Excel function "RANK.AVG" was used to score each alternative based on their performance in each sub-criterion. This was to handle potential ties in rankings.

The fifth step is to determine the consistency ratio of the pairwise matrix. To do this, we must first find the weighted sum values. To find the weighted sum values using "Buckley's Fuzzy AHP", we must first transform the TFNs in the averaged pairwise matrix into crisp numbers. According to Kwong and Bai (2003), we may do this by again utilizing a variant of the COA method. However, in their study, Kwong and Bai (2003) chose to give the middle value (m) the highest value. They did not specifically mention why they did this. The values were also kept by Ahmad and Qahmash (2020). The assumption is that people tend to see the middle value as more accurate than the lower and upper values. However, in this thesis, the original center of area method was chosen to defuzzify the TFNs. This approach seems to be the most common of the other COA methods according to a review by Liu, Eckert and Earl (2020b). The equation used in this tool to defuzzify the TRNs are therefore the one shown in Equation 12.

Equation 12: Defuzzify TRNs into crisp numbers equation

$$Pn, crisp = \frac{l + m + u}{3}$$

The crisp numbers are organized into a new, crisp matrix. The crisp numbers are thereafter normalized. In this context, the crisp number is divided by the sum of all the crisp numbers for each column. This process was repeated for all the numbers in the crisp matrix. The result is a normalized matrix. The normalized matrix is used to identify the priority vectors. The priority vectors are simply the average of the sum of each row in the normalized matrix (Ahmad and Qahmash, 2020).

The priority vectors are then used to find the weighted sum of the crisp number matrix. The weighted sum values are the matrix product of the crisp number matrix and the priority vectors. This is shown in Table 16. In the Excel spreadsheet, the command “MMULT” was utilized to calculate the weighted sums.

Table 16: Approach used to find the priority vectors

$$\begin{bmatrix} Pcn & i & j & k \\ i & Pii & Pij & Pik \\ j & Pji & Pjj & Pjk \\ k & Pki & Pkj & Pkk \end{bmatrix} \times \begin{bmatrix} pv1 \\ pv2 \\ pv3 \end{bmatrix} = \begin{bmatrix} WS1 \\ WS2 \\ WS3 \end{bmatrix}$$

The maximum eigenvalue (λ_{max}), may then be calculated by using Equation 13. In this context, λ_{max} is the average sum of the priority vectors “pv_i” divided on the weighted sums “WS_i”. In this context, “n” is the number of criteria.

Equation 13: Maximum eigenvalue equation

$$\lambda_{max} = \frac{\left(\sum_{i=1}^{n} \frac{pv_i}{WS_i}\right)}{n}$$

The consistency ratio (CR) value is a ratio between the consistency index (CI) and the random index (RI). The CR can be calculated using Equation 14.

Equation 14: Consistency ratio (CR)

$$CR = \frac{CI}{RI}$$

The consistency index (CI) is calculated using Equation 15.

Equation 15: Consistency index (CI)

$$CI = \frac{\lambda_{max} - \mathrm{n}}{n - 1}$$

In this context, “n” is once again the number of criteria.

The value of the random index (RI) depends on the number of criteria in the pairwise matrix. For AHP, these values were found using a table introduced by (Saaty, 1990). However, for FAHP, another table is employed. The random index table for FAHP, ordered from n = [0, 10], is presented in Table 17. This table is based on a survey by El-Din *et al.* (2019).

Table 17: Random consistency index table. This table is based on a survey by (El-Din *et al.*, 2019).

1	2	3	4	5	6	7	8	9	10
0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

It is important to note that the RI for one or two alternatives is equal to 0. This is because the pairwise comparison consistency of one and two alternatives always equal to 0. This is because there are no comparisons to be made, or only one comparison to be made, meaning there is no room for inconsistency (Saaty, 1990).

3.4 Monte Carlo simulation

A Monte Carlo simulation was utilized to do a sensitivity analysis of the FAHP. A Monte Carlo Simulation is a simulation that uses random sampling of inputs and statistical analysis to analyze the outputs of a mathematical model (Raychaudhuri, 2008). As further explained by Raychaudhuri (2008): “We can use the sampling statistics of the output parameters to characterize the output variation.” The method was programmed in python.

The Monte Carlo simulation has been used in other studies utilizing FAHP with satisfying results. One study by Díaz, Teixeira and Guedes Soares (2022) claim that: “This method allows the investigation of the effect of the decision-makers opinion variability on the results and obtains the confidence level allocated to score for each alternative.” Another study by Spanidis, Roumpos and Pavloudakis (2021) concluded that: “The combination of FAHP results with Monte Carlo and PERT methods in the analysis of hazardous scenarios allows mining executives to make reasonable decisions for the budget and implementation of mechanisms that ensure quick recovery of a mining system after a natural hazard has occurred.”

The simulation randomized each value in both the global and local pairwise comparison matrices. For each simulation, the values from each weighting were then aggregated to determine the most suitable option. Here, the randomized criteria weights are the inputs, and the aggregated score for each alternative is the output. The Monte Carlo simulation was iterated 100,000 times. The output of the simulation was used to create a histogram, which made it easier to analyze the usefulness of the simulation.

4 Results and discussion

The results are based on the scores obtained from the Fuzzy Analytic Hierarchy Process (FAHP) and the Monte Carlo simulations. The scores are used to evaluate the performance of each pipe rehabilitation method previously reviewed. The methods reviewed were the Open Cut (OC) method, Cured-In-Place-Pipe (CIPP), Sliplining (SL), Spray-In-Place-Pipe (SIPP), and Pipe Bursting (PB). The sub-criteria used to determine the ranking of each method were the unit cost, service life extension, surface disruptions, installation time, and carbon emissions. This section is intended to analyze and discuss the implications of these results.

4.1 Final ranking of the alternatives

Table 18 presents the final ranking of the alternatives reviewed based on their performance in each sub-criterion. In this context, "1" represents the highest ranking, and "5" represents the lowest ranking. The ranking of the methods is based on the assessments discussed in the criteria chapters, and is only ment as an example for one case. The results are only relevant for these particular rankings.

Table 18: Final performance ranking of all the methods for each sub-criterion

Method	Unit cost	Service life extension	Surface disruption	Installation time	Carbon emissions
Open cut	5	1	5	5	5
CIPP	3	4	1	1	4
Sliplining	2	1	3	3	3
SIPP	1	4	2	2	1
Pipe bursting	4	1	4	4	2

The rankings show that the SIPP method consistently performs well across all the sub-criteria. The open cut method performs the least well overall, except in regard to service life extension. This is due to the fact that trenchless solutions are heavily favored in these criteria.

4.2 The Monte Carlo simulation

Figure 9 presents the Monte Carlo simulation results for the performance of each alternative. The results show the combined score of each alternative using a range of random weightings from 1/9 to 9. The figure shows the mean score and standard deviation. This highlights the variability and stability of each method. It is worth noting that the small circles at the end of the standard deviation lines also represent results. There were 100,000 iterations. The simulations were conducted using Python.

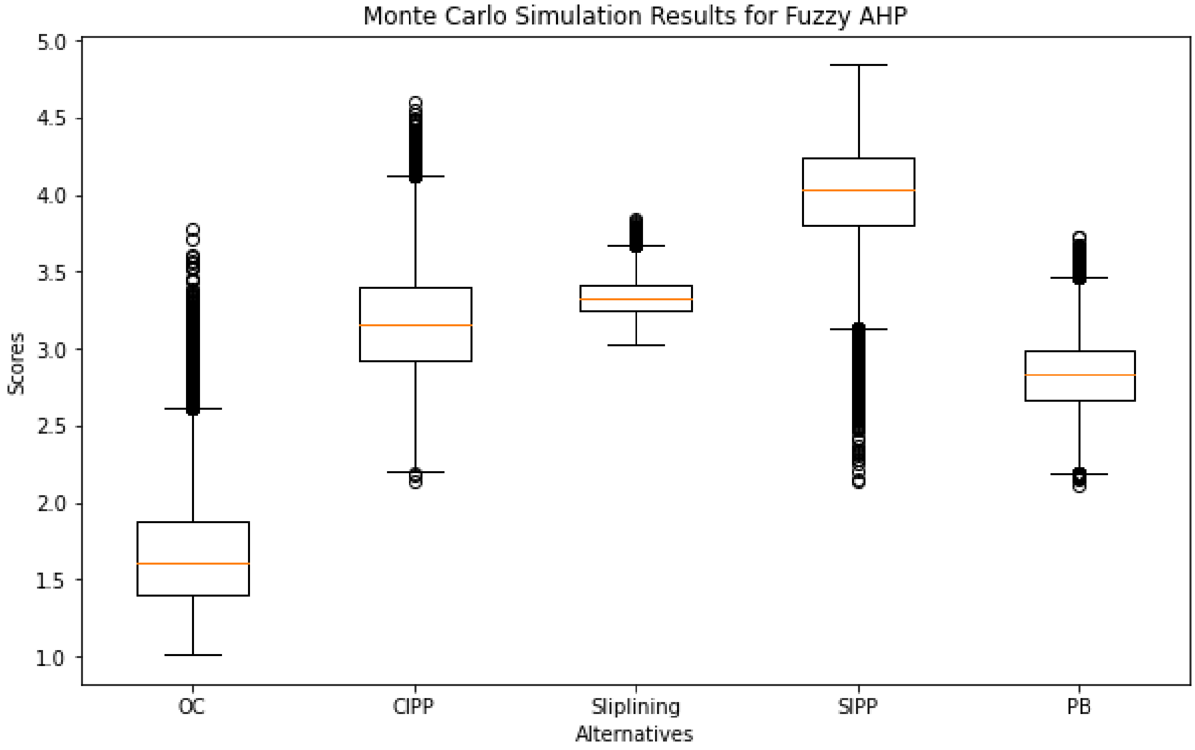


Figure 9: Monte Carlo simulation results for Fuzzy AHP

Histogram analysis

Figure 10 shows a histogram representing the distribution of scores for each alternative in the simulation. The frequency represents the number of times an alternative achieved a particular score. The histogram suggests that the distribution of samples is relatively normalized and contains few outliers. This indicates that the Monte Carlo simulation is consistent and predictable, making the results more reliable for comparing alternatives.

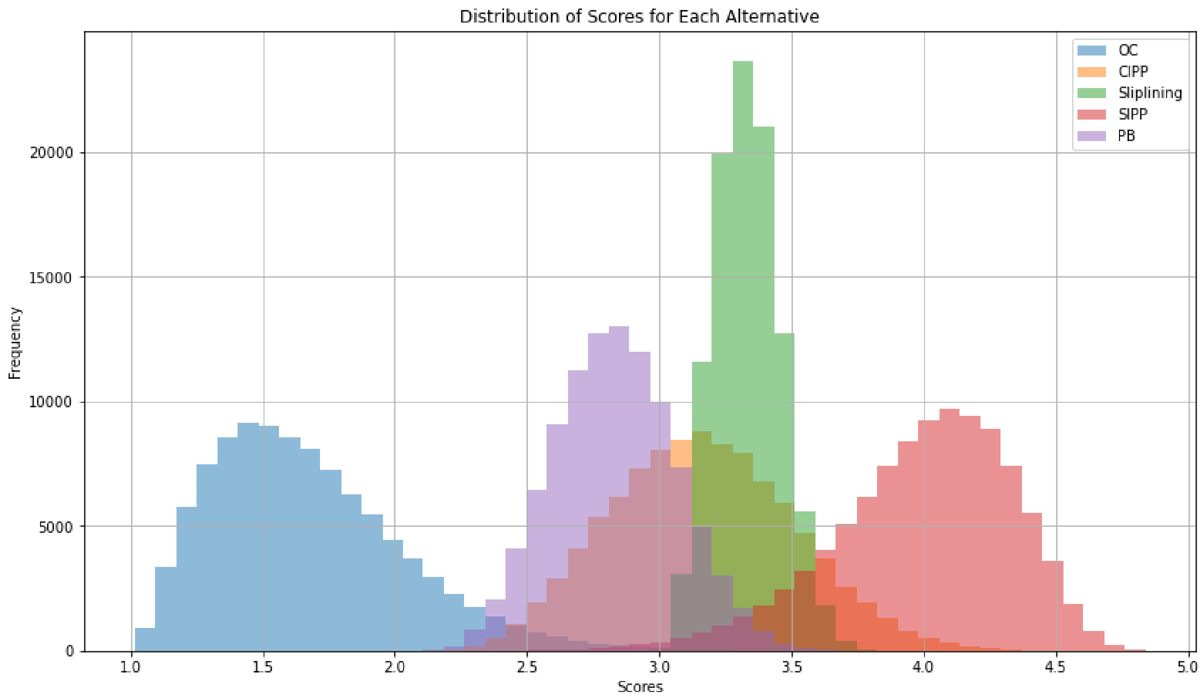
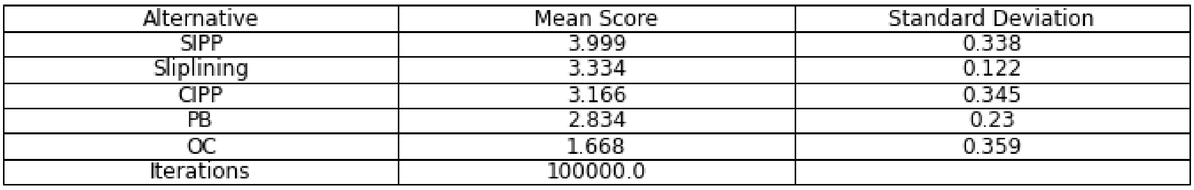


Figure 10: Monte Carlo histogram

Mean score and standard deviation

Table 19 presents the mean score and standard deviation for each alternative. The alternatives are sorted from highest to lowest mean score. The mean score is used to determine the overall performance of each alternative in the context of these particular set of rankings. The standard deviation indicates the stability of each alternative.

Table 19: Mean score and standard deviation for each method



Alternative	Mean Score	Standard Deviation
SIPP	3.999	0.338
Sliplining	3.334	0.122
CIPP	3.166	0.345
PB	2.834	0.23
OC	1.668	0.359
Iterations	100000.0	

The results show that the SIPP method is the best performing method for the most combinations of weightings. However, it is surpassed by other methods for some combinations of weights. The CIPP method had the greatest level of deviation, meaning that it was the least stable method. This means that the CIPP method was the most sensitive, as this method was the most affected by weightings across the different scenarios. This can be explained by the fact that the CIPP method had the greatest inconsistency in its rankings. The most stable method was the sliplining method, followed by the pipe bursting method. This is because these methods demonstrated the most consistent rankings overall. The results also show that the open cut solution is the least favorable option for the majority of weighting combinations.

The results indicate that the alternative scores are highly dependent on the weightings of each criterion and sub-criterion. This can be seen in Figure 10. If the decision-makers were to prioritize unit cost, then the scoring would heavily favor cost-effective methods such as the SIPP method. However, if they were to prioritize installation time or surface disruptions, then the scoring would shift towards the CIPP method.

The results suggests that the FAHP structure is a useful tool for conisdering the preferences of the decision-makers in an objective manner. If the decision-makers were to prioritize certain sub-criteria, this will affect the overall performance of each alternative. This does not imply that the method with the best performance is the optimal method in a real-world application. However, it does demonstrate that the FAHP decision support structure can calculate the performance of each alternative in a reliable manner. The usefulness of the decision support tool is therefore arguably heavily reliant on the quality of the data and the rankings, rather than the reliability of the FAHP calculations.

Ranking sensitivity

As mentioned, Figure 10 only show the outcomes from a specific set of rankings. In the Excel decision support tool, the ranking of the unit cost varies considerably based on the length and the diameter of the pipe of the project. This is because the ranking of the alternatives are based on the equations shown in Table 4, rather than a fixed set of rankings. Changing the placement of these methods will have an impact on the overall performance scoring of the alternatives. This means that, if the rankings were to change, the resulting scores would be significantly different from those currently observed. As mentioned before, there is evidence indicating that the results may be reliable, despite the potential for alterations in the rankings.

4.3 Comparative analysis

There have been attempts to use social, environmental and economic criteria as performance indicators in the FAHP and AHP methodology before. Additionally, there have been previous attempts to develop decision support tools for water and wastewater engineering. One thing these studies have in common is that they utilize significantly more criteria and sub-criteria than this thesis. For example, Hastak, Gokhale and Thakkallapalli (2004) used a total of 32 criteria and sub-criteria to evaluate the performance of the open cut method and three trenchless methods. In addition to economic and social considerations, they used need-based criteria, technological criteria, project-specific criteria, and safety/risk criteria. Similarly to this thesis, the trenchless methods tended to perform better than the open cut method. However, one result in the same study showed that the open cut solution performed better than a trenchless solution at one instance. A similar result was found by Aşchilean *et al.* (2017), although with other criteria. This demonstrates that there are other considerations beyond sustainability that experts consider when evaluating the performance of an alternative. It is worth noting that neither of the two studies considered environmental factors, which places the open cut method at a significant disadvantage.

4.4 Uncertianty of data

As previously stated, although the FAHP-methodolgy appears to be a useful tool for calculating the overall scoring of each alternative, it must be recognized that the Monte Carlo simulation does not account for the consistency of preferences in the pairwise comparison matrices. This implies that a substantial proportion of the outcomes may be deemed irrelevant, given that they are deemed inconsistent. Nevertheless, the results may still be reliable in determening the performance of the alternatives. This is because 100,000 iterations may be sufficient to overcome the lack of consistency and still provide an accurate representation of the truth. Nevertheless, these are only speculations, and will not be investigated further due to time constraints.

A second consideration is that the scoring is based on interpretations of data gathered from various sources. This means that, the usefulness of the decision support tool is heavily reliant on the quality of the data gathered beforehand. For instance, the results in Figure 10 show that the open cut solution is almost never a favorable alternative. If this were true, then the open cut solution would rarely be applied in real life. It is evident that the SIPP method would have been the only viable option, which is not the case. This indicates that there are significant considerations not assessed in this tool that play a pivotal role in determining the most suitable method. For instance, the open cut solution may be highly beneficial when there are multiple pipes in the same trench that needs to be rehabilitated. Another instance is when the pipe has collapsed, and cannot be repaired by conventional trenchless solutions. One possible explanation is that the trenchless methods were deemed unfesible for other reasons. However, this indicates that the rankings of each method are very generalized, and may not be accurate for all projects and locations. Another possible explanation is that there are other criteria not based on sustainability that experts also consider when selecting which rehabilitation method to use.

A third consideration is the age of the data. The unit cost estimates from Najafi (2013) are from 2013, and a lot may have changed since then. Methods that may have been the cheapest then may have undergone significant changes in the supply chain, or there may be markedly different market conditions. Using a generalized ranking system based on these data fails to account for the influence of local variables, such as geography and method availability. In a real-world application, the manufacturer of the pipe material may be too far away to make the alternative economically and environmentally feasible.

4.5 Recommendations for future development

Although generalized information is necessary to make the decision support useable, the focus should be on reducing the scope to a country-scale or adding local condition modifiers to provide a more accurate ranking of the methods. The data should also be continuously updated to better represent local considerations. Furthermore, the questionnaire should be expanded to better accommodate project limitations and concerns.

The focus of this tool have been to promote sustainable pipe rehabilitation. However, significant simplifications have been made due to data limitations, ensure user-friendliness, and time constraints. Currently, there are three global criteria and five sub-criteria. The addition of more criteria may be beneficial to better accommodate the concerns of the experts. For instance, the incorporation of environmental criteria, such as other greenhouse gases or groundwater pollution, could enhance the decision-making process. Furthermore, broad criteria such as “surface disruptions” can be further divided into sub-criteria to better accommodate concerns such as noise and dust generation.

Furthermore, it is difficult to validate the usefulness of the tool without testing it on case studies. Based on what is discussed above, a significant concern regarding the potential performance of the tool is that it may not be comprehensive enough to consider all of the most important factors associated with a pipe rehabilitation project. While the data gathered in the literature review may be accurate, it may not be comprehensive enough to get the whole picture. For future development of the tool, input from the contractors and experts could be invaluable to increase the accuracy and the comprehensiveness of the tool.

Conclusion

The objective of this study was to create a decision support tool for selecting the optimal sewage pipe rehabilitation method based on sustainable criteria. The study used the Fuzzy Analytic Hierarchy Process (FAHP) decision support model, and the Excel software to determine the performance of the alternatives.

The study suggest that using the three criteria of economic cost, social cost, and environmental cost, may be a productive way to evaluate the sustainability performance of pipe rehabilitation methods. The results of this evaluation indicate that the cement mortar Spray-In-Place-Pipe (SIPP) method outperformed the other methods, particullary in terms of carbon emissions and unit costs. The Monte Carlo simulations demonstrated that the SIPP method was the optimal pipe rehabilitation method in the majority of scenarios, regardless of the specific criteria weightings for one set of performance rankings.

The study also found that the FAHP methodology can process the preferences of the decision-makers in an objective manner with high amounts of accuracy and stability. However, data uncertainty and the absence of sufficient consideration for local conditions may render the results unreliable in a real-world application.

As of right now, the decision support tool is likely not comprehensive enough to give reliable advise in a rehabilitation project. Nevertheless, the study suggests that the framework of the decision support tool has potential. Therefore, it is recommended that continuous improvements and extensions should be implemented to enhance the accuracy and usefullness of the tool. For future development, expanding the questionnaire to better incorporate local considerations would enhance the accuracy of the performance rankings. This may also increase the quality of the elimination step. Furthermore, it is recommended that the databases of each method should be continuously updated. An increase in the number of sub-criteria, particularly the environmental ones, could also be beneficial to better accommodate the concerns of the experts. Finally, case studies should be used to map out further shortcomings of the tool and to further test its usefulness.

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