Carbon Footprint Assessment of Maintenance and Rehabilitation Techniques of Sewer Systems

Bachelor Thesis Report Civil Engineering

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Preface

Before you lies the bachelor thesis "Carbon footprint assessment of maintenance and rehabilitation techniques of sewer systems". This thesis was written to fulfil the graduation requirements for the degree of Bachelor of Science in Civil Engineering at the University of Twente. The research work that it presents was carried out at Roelofs Groep in Den Ham at the department "Water, Riolering en Ecologie" (Water, Sewage and Ecology) from April to July 2020.

Firstly, I would like to give a very special thanks to my supervisors, João Miguel Oliveira dos Santos and Peter Wonink, for their excellent guidance during the execution of my thesis project. Without their expertise, involvement, and insightful suggestions, the completion of my project would not have been possible. I am greatly indebted to João Miguel Oliveira dos Santos, whose warmth, professionalism, and encouragement helped me very much in my research project. My sincere gratitude goes to Peter Wonink as well for his friendliness, his willingness to help, his expert advice, and for providing me with the opportunity to conduct my research project at Roelofs Groep.

Additionally, I would like to acknowledge the effort of Luuk Heijmen from Flua Leidingrenovatie, Robby van den Broek and Tobias Strating from the department "Energie en Milieu" (Energy and Environment) of Roelofs Groep. Their occasional help and input were very much appreciated. I also want to thank the entire Water, Sewage and Ecology department of Roelofs Groep for including me in their weekly meetings.

Last but not least, I would like to express my deepest gratitude to my parents, brothers, and friends for always believing in me.

I hope you enjoy reading my work!

Omar Sharif

Enschede, July 3, 2020

Abstract

Purpose: The main aim of this thesis was to get a better understanding of the environmental impacts that are associated with the maintenance and rehabilitation of conventional gravity sewer systems. Results obtained in this study should support decision-making processes in sewer system management.

Methods: In this study, a carbon footprint assessment was performed according to the ISO14067:2018 standard. Open trench replacement, trenchless renovation, open trench and trenchless repair, inspection, and cleaning of sewer pipes were the object of the assessment. The life cycle stages considered were raw material extraction, manufacturing processes, maintenance/rehabilitation, and transportation. The functional unit was defined as: *"To maintain the original function of a gravity sewer section with an average length of 45 meters and a diameter of 200 to 1500 mm during a period of 100 years in the Netherlands".* Widely recognised embodied carbon databases for construction materials were used to calculate the environmental impacts. Finally, a sensitivity analysis was performed in this study to assess how the results vary as a consequence of changes in inputs.

Results and discussion: Considering open trench pipe replacement, the reinforced concrete has the worst environmental performance (highest kg CO_2-eq emissions) whereas the replacement using concrete pipes was found to be the best performer. The production of pipe materials and asphalt are the main contributors to the CF score of pipe replacement. With regard to trenchless renovation, cured-in-place pipe (CIPP) lining with fibreglass material was found to be significantly more environmentally sustainable than CIPP lining using needle felt material. The results also show that fibreglass CIPP lining is much more favourable than open trench replacement (including asphalt rehabilitation). Furthermore, trenchless sewer repair technologies have a slightly better environmental performance than open trench repair. Finally, the results suggest that sewer inspection using the so-called "Manhole-Zoom" camera approach is by far the most environmentally sustainable option. As far as the sensitivity analysis is concerned, the results show that the environmental impact results are most sensitive to changes related to the material properties of components, such as, for instance, the asphalt pavement width, CIPP liner thickness, sewer pipe length, etc.

Conclusions: The findings of this study suggest that the main opportunities for reduction in the environmental impacts of pipe replacement lie in the choice of pipe materials and design of asphalt pavement. Furthermore, adopting trenchless technologies can significantly reduce the environmental burdens of sewer pipe rehabilitation. For sewer maintenance, the use of the Manhole-Zoom camera approach for pipe inspections should be encouraged and promoted.

Keywords*:* Carbon footprint assessment; Sewer pipe; Replacement; Cured-in-place pipe; Repair; Sewer maintenance.

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List of Abbreviations

CF	Carbon footprint
CCTV	Closed-circuit television
CIPP	Cured-in-place pipe
CO_2-eq	Carbon dioxide equivalent
DN	Diameter nominal (internal diameter of pipe)
ECI / MKI	Environmental cost indicator / Milieukostenindicator
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
ICE	Inventory of Carbon & Energy
ISO	International Organisation for Standardisation
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCI	Life cycle inventory analysis
MZC	Manhole-Zoom camera (NL: put-buis camera)
M&R	Maintenance and rehabilitation
SA	Sensitivity analysis
SBK	Stichting Bouwkwaliteit (Dutch Foundation for Building Quality)
SR	Sensitivity ratio
tkm	tonne-kilometre
UV	Ultraviolet

1 Introduction

Modern civilisation as we know it is no longer conceivable without properly functioning sewage collection systems. Such systems provide protection against floods in urban environments and prevent transmission of water-borne diseases. This is done by safely conveying wastewater from the urban environment to the location of treatment through an extensive network of pipes and drains. Therefore, maintaining a well-functioning sewer system is crucial. Frequent maintenance is required to assure that it operates properly during its service life. Various sewer maintenance techniques exist for this purpose. For example, a sewer can be rehabilitated by means of replacement, renovation or repair, in case the system is no longer able to perform its regular function. Furthermore, the transportation of wastewater through a pipeline might get obstructed due to the accumulation of material (e.g. fats, sediments, etc.). To remove these obstructions, sewage cleaning is needed. There are various mechanical and hydraulic cleaning methods to remove blockages that interfere with the proper functioning of a sewer system. However, sewer problems are not always apparent. Therefore, to evaluate the condition of a certain sewer object, inspection is needed. Different condition assessment methods and sewer inspection techniques are available for this as well. One can, for example, use camera inspection by means of a robotic CCTV crawler or a Manhole-Zoom camera (MZC).

Each maintenance scenario is (directly and indirectly) associated with certain environmental impacts. The environmental impacts that are associated with sewer maintenance practices are not sufficiently well known at the moment (Alnoaimi & Rahman, 2019). It is within this context that Roelofs Groep wants to evaluate these impacts and compare sewer maintenance strategies based on their environmental performance (namely the carbon footprint (CF)). Ultimately, Roelofs Groep wants to be able to take environmental considerations into account when selecting certain techniques to rehabilitate and maintain sewer systems (Roelofs, 2020).

1.1 Problem Description

Currently, the decision-making processes in sewer management are often driven exclusively by financial, quality and social considerations (Alnoaimi & Rahman, 2019). Traditionally, sewer infrastructure management was mainly focussed on maximising economic benefits. This approach can be considered unsustainable, as only short-term costs are taken into account while the environmental implications are ignored (Akhtar, et al., 2015). To illustrate this, sewer component materials are generally selected based on short-term market trends (i.e. cheapest material is chosen). However, the most economic option is not necessarily the most environmentally friendly. Moreover, recent developments show that the sewer infrastructure management paradigm in the Netherlands is shifting towards a more risk-based approach (Stichting RIONED, 2018). With this approach, other aspects such as social implications (e.g. nuisance, traffic diversions, etc.) and quality (i.e. performance of sewer) are considered as well to support decision-making. Nevertheless, current sewer maintenance and rehabilitation (M&R) practices continue to favour traditional approaches, which entails using mainly economic considerations to support decision-making processes (Alnoaimi & Rahman, 2019). This means that the environmental aspects are barely considered when a certain technique has to be selected to maintain or rehabilitate a sewer. The main reason for this is that the environmental impacts that are associated with different sewer management techniques are not sufficiently well known. Because of this, engineering firms are not able to make environmental-based well-informed decisions. With this research, Roelofs Groep wants to contribute to a more sustainable sewer management sector in the Netherlands (Roelofs, 2020). They want to achieve this by gaining a better understanding of the environmental performance of different sewer M&R techniques.

1.2 Research motivation

The last years have witnessed an increasing concern on how humans are affecting the natural environment. The need for sustainable development is as high as ever, and it will be even more pressing in the near future. In the field of civil engineering, many sectors have designed specific plans for realising sustainable development goals (Bui, Woloszyn, Wets, & Cajka, 2018). However, the sewer infrastructure management sector is lagging behind in this respect (Mulder, 2019). As mentioned before, this is mainly because the knowledge about environmental impacts and their implications is insufficient.

Furthermore, sewer systems in the Netherlands face many challenges. At the moment, there are roughly 150.000 km of sewer pipes and drains in the Netherlands (Stichting RIONED, 2019). This entire system is susceptible to deterioration, structural failure, disruptive events, and many other threats (Alnoaimi & Rahman, 2019). In addition to that, in many locations in the Netherlands, sewer systems are expected to be facing major problems in the near future due to ageing (StadLandWater Management en Advies, n.d.). Therefore, the expectation is that a substantial quantity of M&R activities will be undertaken in these sewer systems in the coming years. This claim is supported by a benchmark of sewer M&R in the Netherlands which was commissioned by Stichting RIONED in the year 2013. The purpose of this benchmark was to evaluate the performance of Dutch municipalities with regards to sewer system M&R. In total, 392 out of 408 municipalities in the Netherlands took part in this benchmark (Stichting RIONED, 2013). According to its results, a sharp increase in the quantity of required sewer M&R activities can be expected in the coming decennia. Figure 1 shows the estimated extension (% of total length) of gravity sewer pipes to be rehabilitated as a function of time for different municipality population's sizes. With this in mind, to effectively improve sustainable development in the field of sewer infrastructure management, it is essential to gain a better understanding of the environmental impacts that are associated with sewer M&R techniques.

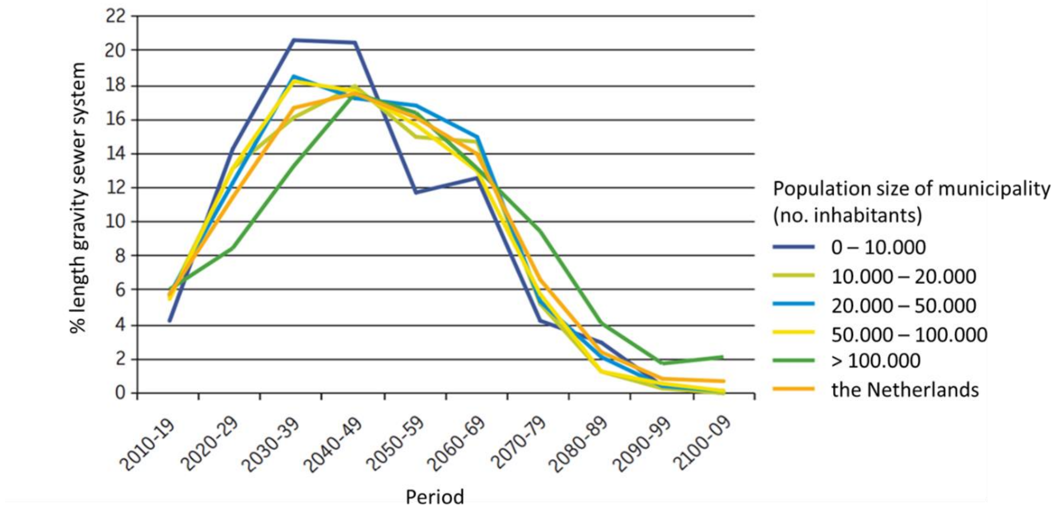

Figure 1: Prediction of extension (% of total length) of gravity sewers to be rehabilitated as a function of time. Source: (Stichting RIONED, 2013)

1.3 Research methodology

In this section, the research approach is briefly explained. The research objective, questions and methods are summarised.

1.3.1 *Research goal*

The main goal of this research is to *assess the environmental impacts that are associated with sewer maintenance and rehabilitation techniques in terms of carbon footprint*. This bachelor thesis aims to provide an overview of the potential environmental impacts that are generated from maintaining and rehabilitating gravity sewer collection systems. These impacts will then be used to compare the environmental performance of different techniques

1.3.2 *Research questions*

The main research question of this thesis is as follows:

"What is the carbon footprint of the maintenance and rehabilitation techniques of a conventional gravity sewer system?"

Next to the main research question, several sub-questions were constructed. These sub-questions are partially based on the four phases of life cycle assessment (LCA) as proposed in the international standard for CF of products “ISO14067:2018” (ISO, 2018), which are: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and life cycle interpretation. The following sub-questions have been formulated to help answering the main research question:

1. ***What are the most relevant techniques to maintain and rehabilitate gravity sewer systems, what are their characteristics and which procedures are involved?***

2. ***What is the scope of the carbon footprint assessment in this study?***

3. ***Which material inputs, greenhouse gas (GHG) emissions, energy flows, activities and processes can be identified for each maintenance and rehabilitation technique?***

4. ***What are the environmental impacts associated with the inputs and releases that were identified in sub-question 3?***

5. ***How can the results of this CF assessment help to improve the environmental performance of sewer management systems?***

1.3.3 *Research methods*

The sub-question 1 is addressed by conducting extensive desk research and communicating closely with Roelofs Groep’s experts. In this way, deep knowledge of all relevant aspects of sewer M&R was acquired. To address the sub-question 2, the system under study and its functions had to be determined. This was done in close communication with the client (i.e. external supervisor), in order to ensure that the system boundaries and goals of the CF assessment are aligned with the client’s needs. To answer the sub-question 3, the compilation of the inventory of all relevant input and outputs of each sewer M&R technique had to be made. This was done by conducting desk research and frequently involving experts. Expert elicitation is especially important for validation of the LCI results. For the sub-question 4, the inventory of flows from sub-question 3 was translated into potential environmental impacts expressed in terms of CO_2-eq emissions. Carbon emission factors from literature and databases (e.g. ICE v2.0 and CO2-emissiefactoren) were used for this purpose. To be able to properly answer the sub-question 5, the results of the environmental impact assessment were interpreted according to the guidelines and requirements as described in the ISO14067:2018 standard (ISO, 2018). Finally, the aforementioned results were used to draw up recommendations for improving the environmental performance of sewer M&R techniques.

1.4 Thesis structure

This thesis is organised as follows: C*hapter 1* starts with a brief introduction of the thesis topic and then continues to describe the problem context, research motivation and research methodology. *Chapter 2* consists of two main parts. The first part elaborates on the main characteristics of relevant procedures of several sewer M&R techniques. In the second part, a comprehensive description is given of the CF assessment methodology; more specifically, the goal and scope of the CF assessment are defined, the methodology for the LCI is described, a calculation model for the impact assessment (LCIA) is presented, and the sensitivity analysis (SA) method is discussed. *Chapter 3* presents the results of the impact assessment phase and the discussion of the results. Furthermore, the results of the SA are presented and discussed at the end of *Chapter 3*. In *Chapter 4* a summary of the thesis is given and answers to the research questions are provided. Finally, in *Chapter 5* recommendations for improving the environmental performance of sewer M&R techniques are given and suggestions for further research are provided.

In the appendices, an extensive overview of the results that were obtained in this study is presented. Specifically, Appendix A provides an overview of the LCI of different sewer M&R techniques. In turn, Appendix B contains the results that were obtained during the impact assessment phase. Finally, in Appendix C, selected results from the impact assessment of this study are compared to the results of another (valid) model for validation purposes.

2 Methodology

2.1 General description of sewer maintenance and rehabilitation phases and processes

The M&R techniques that were considered in the CF assessment include replacement, renovation (i.e. renewal), repair, inspection, and cleaning. Each technique can be divided into several phases. In this section, the main characteristics, steps and relevant processes will be briefly described for each technique.

2.1.1 *Sewer pipe replacement*

Replacement can be defined as replacing an existing sewer component with a new unit to restore or upgrade the performance of a sewer system (NEN-EN 752, 2017). Replacement can be done by means of open trench (open cut) and trenchless replacement techniques. Since trenchless sewer replacements (e.g. pipe bursting, pipe eating, pipe extraction, etc.) are not commonly applied in the Netherlands (Roelofs, 2020), only open trench replacement is considered in this study. Open trench replacement requires excavation of soil; in many cases, pavement needs to be rehabilitated as well. According to Morera, Remy, Comas, and Corominas (2016), six steps can be identified for open trench sewer pipe replacement (see Figure 2). They include: (1) removing the asphalt layer (if necessary); (2) excavating the trench; (3) extraction of the existing sewer pipe unit; (4) placement of the new sewer pipe unit; (5) backfilling of the trench and compacting the soil; (6) road rehabilitation (if necessary). During this process, material wastes get generated (i.e. asphalt and old sewer pipe). Therefore, it is also necessary to include the disposal of these waste materials in the CF assessment.

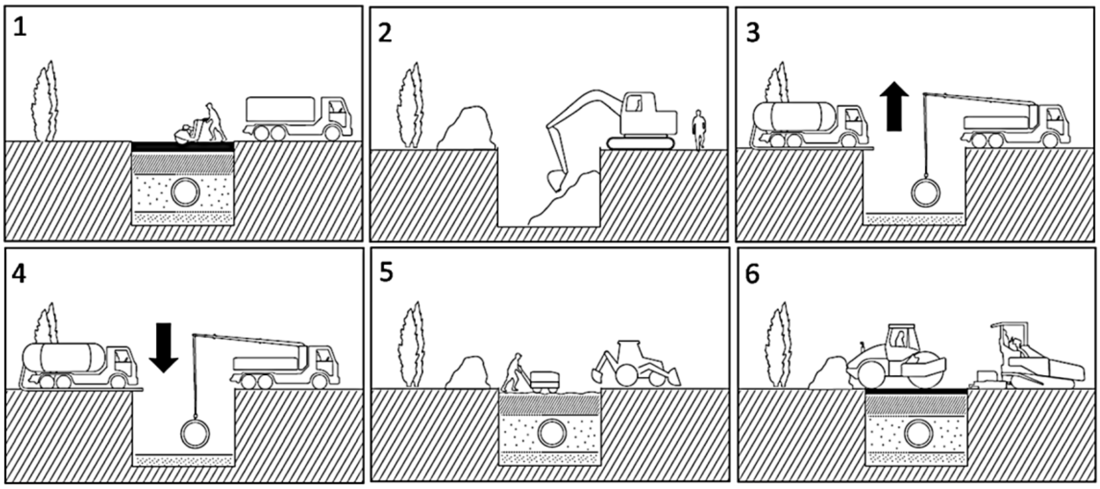

Figure 2: Main steps of open trench pipe replacement. Source: (Morera, Remy, Comas, & Corominas, 2016)

2.1.2 *Sewer pipe renovation*

Many different techniques exist to renovate a gravity sewer. Renovation of sewer pipes in the Netherlands is commonly done by means of relining. Other techniques, such as spraying, are less common (Roelofs, 2020). Therefore, in this study, the focus will be on relining with cured-in-place pipe (CIPP) techniques. The main purpose of a CIPP liner is to restore the structural integrity of sewer pipes (Water Environment Federation (WEF), 2009). CIPP refers to a collection of techniques which insert a flexible sleeve into an existing sewer pipe. The flexible sleeve contains a thermosetting resin which hardens permanently after being exposed to heat for a certain period, this creates a new pipe within the existing pipe (Almeida, Covas, & Beceiro, 2015). The CIPP liner itself is made from either felt material or fibreglass. The CIPP liner then is saturated with epoxy resin, vinyl ester resin or polyester resin (Water Environment Federation (WEF), 2009). In most cases, polyester resin is used in CIPP liners (VROM Inspectie, 2006). The liner can be cured by exposing the resin to heat, this is generally done using ultraviolet (UV) light. Warm water or steam is can also be used to cure the resin (for needle felt CIPP liners only).

The typical sequence of works in CIPP lining is illustrated in Figure 3 (Almeida, Covas, & Beceiro, 2015). The typical process is as follows: (1) the sleeve is prepared to be inserted in the existing pipe; (2) a protective plastic sheet is applied in the sewer pipe; (3)(4) the sleeve is inserted in the pipe (through inversion or winching) in the total length between two manholes; (5) the resin is being cured; (6) a new pipe within the existing pipe is formed. Usually, before inserting the sleeve, the sewer pipe in question needs to be cleaned and obstructions, if any, need to be removed (Aarsleff, 2020).

Figure 3: The process of CIPP lining to renovate a sewer section. Source: (Almeida, Covas, & Beceiro, 2015)

2.1.3 *Sewer pipe repair*

In this study, repair is defined as mending local damage in sewer pipes (NEN-EN 15885, 2018). Similar to replacement, sewer rehabilitation by repair can be characterised by two alternative approaches: open trench and trenchless repair (Roelofs, 2020). Open trench repair partially consists of the same phases as open trench sewer replacement, phases of open trench repair include removal of pavement, excavation of the trench, manual rectification of local damage, backfill and compaction of the trench, rehabilitation of pavement, and disposal of old asphalt. In contrast to open trench sewer replacement, repair is limited to solely the rectification of local damages rather than replacing an entire component.

Trenchless repairs do not require excavation and pavement reconstruction works. Trenchless (internal) repair is generally done by robotic means under CCTV control as sewer pipes are often not accessible by man (Stein & Stein, 2004). Trenchless repair techniques that will be considered in this study are: repair with CIPP short liners and repair using mechanical seals. Repair with a CIPP short liner is very similar to the CIPP lining process which is used for end-to-end sewer renovations. In this case, a short resin-based fibreglass sleeve is placed on the inside which is then cured-in-place to rectify local damage of a pipe (Almeida, Covas, & Beceiro, 2015). Repair with mechanical seals refers to the process of inserting a sleeve structural body made of stainless steel and synthetic rubber on the inside of the sewer pipe (Stein & Stein, 2004). The aforementioned repair techniques are generally executed using the same robotic device (Roelofs, 2020).

Figure 4: Sewer pipe point repair using a mechanical seal. Source: (Rausch, n.d.)

2.1.4 *Maintenance: cleaning and inspection*

This study differentiates between two types of cleaning: hydraulic and mechanical cleaning. Moreover, two different inspection methods are considered. They include sewer inspection using a robotic remotely controlled CCTV camera and a MZC. Cleaning works are often carried out prior to inspections and rehabilitation works of gravity sewer systems (Almeida, Covas, & Beceiro, 2015). The hydraulic cleaning method which will be evaluated is high-pressure water jetting with suction. This method is a combination of a water jetting device which discharges water at a high flow rate and a suction device which removes sewer deposits. Typically, one vehicle is present at the project location in case of hydraulic cleaning (see Figure 5 left). This vehicle is equipped with water jetting equipment (and a water tank) and a vacuum pump for suction of sewage sludge, this vehicle is commonly known as a so-called “combined sewer cleaning vehicle” or “combi truck”. Conventionally, two separate vehicles for sewer cleaning are used (see Figure 5 right). However, this is not applied very often anymore in the Netherlands. Nevertheless, both sewer cleaning approaches will be considered and compared in this study.

Maintenance is generally less process-intensive than sewer rehabilitation techniques. This is mainly because no material is produced (apart from fuel and the equipment itself) and construction works are not required. Three main on-site activities of high-pressure water jetting with suction are identified by Jansen Rioolreiniging BV (2015): (1) intake of water from surface water using pumps, (2) cleaning of sewer section using a high-pressure water jetting device, (3) removing deposits from the sewer using a suction module. Step (2) and (3) are executed simultaneously. According to Almeida, Covas, & Beceiro (2015), mechanical cleaning comprises many different techniques. Examples of equipment are mechanical root cutters, rodders and chain flails. Selection of this equipment depends on the nature of the problem within the sewer (e.g. intruding roots). Mechanical cleaning techniques are typically used after identification of problems by means of visual inspection (Roelofs, 2020).

The main purposes of inspecting a sewer are: assessing the condition of sewer components (i.e. problem detection) and preventing the development of problems (Stein & Stein, 2004). For example, with inspection, observations relating to the fabric of a sewer component can be done. With this, deformations, fissures, collapses/breaks, surface damage, defective repair, etc. can be identified. Moreover, observations relating to the operational performance of a sewer section can be done. This means that obstructions, accumulation of solid matter, roots growing into the structure, infiltration/exfiltration, etc. are identified through inspection. Two techniques are evaluated in this study, sewer inspection using a robotic remotely controlled CCTV camera and a MZC. The main difference is that inspection with a MZC does not require hydraulic cleaning beforehand. Moreover, the inspection times can be drastically reduced when using a MZC (Plihal & Šikman, 2018). Inspection using a remotely controlled robotic CCTV camera does require hydraulic cleaning beforehand (Roelofs, 2020).

Figure 5: Sewer cleaning using a combi truck (left) and two separate vehicles (right). Source: (vandervalk+degroot, n.d.)

2.2 Carbon Footprint (CF) Assessment

In this thesis, a CF Assessment was conducted. The standard used to guide this assessment was the "NEN-EN ISO14067:2018 GHGs - Carbon Footprint of Product (CFP)" (ISO, 2018). This international standard is largely based on the ISO14040/44 standards for LCA. However, the ISO14067 only focusses on climate change instead of multiple impact categories. The CF of products is calculated based on the LCA methodology of ISO14040/44 (PRé Consultants bv, n.d.). These standards offer a comprehensive and systematic way to address and evaluate the environmental performance of product or service systems. ISO14040 specifies the principles and framework for conducting an LCA study. It includes: (1) goal and scope definition, (2) LCI, (3) LCIA, and (4) life cycle interpretation (ISO, 2006). In turn, the ISO14044 specifies the requirements and guidelines for conducting an LCA study. This study was performed according to the principles and framework of the aforementioned standards.

2.2.1 *Goal and scope definition*

The goal and scope definition is an essential step of a CF assessment. A clearly and well-formulated goal will help to define the scope of the study and the boundaries of the system to be studied. The definition of the goal and scope in this study has been established following the requirements and guidelines as described in ISO14067:2018 (ISO, 2018). The goal definition includes the explanation of the intended use, motivation for conducting the study and the intended communication (ISO, 2006). The scope describes the system under study and its main functions, the boundaries of the system, the functional unit (FU), data quality goals, assumptions and limitations (ISO, 2018).

2.2.1.1 Purpose of the study

This CF assessment was commissioned by Roelofs Groep to get an overview of the environmental impacts that are associated with the M&R of gravity sewer systems. The main goal of this study was to assess the potential environmental impacts that are generated from maintaining and rehabilitating gravity sewer collection systems. In addition to the aforementioned goal, specific objectives were formulated:

- To compare the environmental performance of different M&R techniques;
- To determine which processes, activities and phases contribute the most to the environmental impacts of each M&R technique;
- To identify possibilities for improving the environmental performance of the sewer management system.

As stated earlier, the main reason for carrying out this study is that the environmental impacts that are associated with different sewer management techniques are not sufficiently well known at the moment (Alnoaimi & Rahman, 2019). Because of this, engineering firms in the Netherlands are not able to make environmental-based well-informed decisions when it comes to selecting techniques for maintaining and rehabilitating sewer systems (Mulder, 2019). Therefore, with the aforementioned objectives in mind, the expected result of this study is the quantification of the environmental performance of each relevant sewer M&R technique expressed in terms of CF. In particular, Roelofs Groep wants to be able to take environmental considerations into account when selecting certain strategies to maintain or rehabilitate sewer systems (Roelofs, 2020). For example, from an environmental viewpoint, a trenchless renovation of a certain sewer section might be more beneficial than a replacement (or vice versa). Therefore, different techniques must be compared with each other based on their relative environmental performance.

The intended use of the results of the CF assessment is to inform Roelofs Groep about the environmental burdens that are associated with different techniques for M&R of sewer systems. Roelofs Groep is mainly interested in comparing different techniques based on their environmental performance and identifying possibilities for improvement of business operations from an environmental perspective. It is therefore of great importance that the requirements, as presented in international standards for CF assessments (i.e. ISO14067:2018), are strictly followed. In addition to that, the results of this study will be incorporated into the sewer management software tool "Rasmariant". This means that the results are intended for both internal and external (business-to-business) communication as well.

2.2.1.2 Functions and functional unit

Because of the comparative nature of this study, a FU has to be selected which allows the environmental performance of each technique to be compared with each other. One of the main functions of a gravity sewer is to ensure that wastewater and/or surface water runoff is properly conveyed from the gravity sewer system to the place of disposal (NEN-EN 752, 2017).

As a reference, a gravity sewer system as typically used in an urban area in the Netherlands was considered. Therefore, the average length of a sewer section between two manholes in the Netherlands was selected, which is approximately 45 to 50 m (Roelofs, 2020). Moreover, diameters of sewer pipes of gravity systems in the Netherlands typically range between 200 and 1500 mm (Stichting RIONED, 2019), with 300 and 400 mm being the most common.

To ensure that a sewer is able to continuously deliver its original function during its lifetime, M&R are required. For sewer maintenance (including inspection), a maintenance cycle of 15 years is considered during a period of 100 years (i.e. 6 interventions). In addition to that, a one-time open trench replacement and a one-time renovation by means of CIPP lining are considered in this study. Hence, the FU of the entire study is defined as follows: *"To maintain the original function of a gravity sewer section with an average length of 45 meters and a diameter of 200 to 1500 mm during a period of 100 years in the Netherlands."* With this in mind, the environmental performance of each sewer M&R technique is expressed in terms of kg CO_2-eq per FU.

2.2.1.3 Scope and boundaries

The main focus of this study is the M&R of conventional gravity sewer systems. The life cycle of a gravity sewer system comprises different phases (Figure 6): raw material extraction, manufacturing, construction, use and end-of-life (Risch, Gutierrez, Roux, Boutin, & Corominas, 2015). The boundary conditions of the system under study are defined by the use phase of this system. The use phase can be considered as a subsystem of a larger system where the M&R operations considered in this study are expected to take place (i.e., replacement, renovation (renewal), repair, cleaning, and inspection).

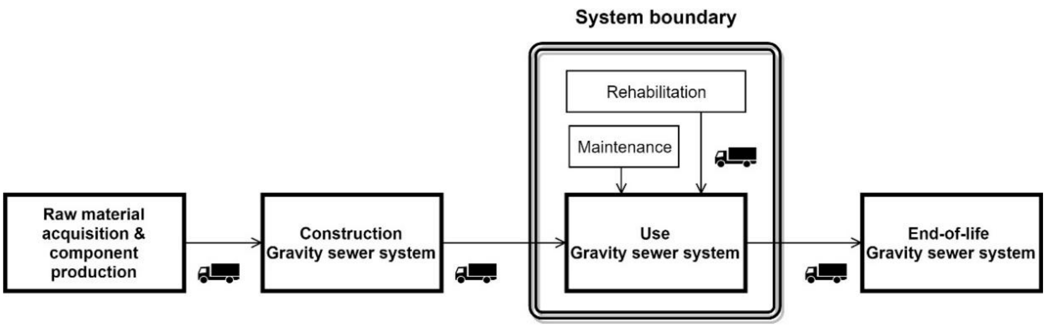

Figure 6: Cradle-to-grave system description of gravity sewer systems in its totality and system boundary

Each M&R operation comprises many different techniques. The CF assessment performed in this study is constrained to the most relevant techniques for the Netherlands. These techniques were selected in close communication with a Roelofs Groep's expert (Roelofs, 2020). In Table 1, an overview of the techniques for each M&R alternative assessed in this study is shown.

Table 1: Assessed techniques for each alternative in the CF assessment

Alternative	Technique included
Replacement	Open trench
Renovation	Cured-in-place pipe (CIPP) lining
Repair	Open trench
	Trenchless
Cleaning	Hydraulic cleaning
	Mechanical cleaning
Inspection	Robotic CCTV camera inspection
	Manhole-Zoom camera (MZC) inspection

In Figure 7 the system under study and its main components, activities and processes are illustrated. The system boundaries include direct GHG emissions generated in the project location (e.g. GHG emissions from combustion of diesel) and indirect GHG emissions (e.g. emissions from material production). Therefore, the study focusses on environmental impacts related to raw material acquisition, production processes, construction works, disposal of wastes, transport, and other relevant activities (e.g. refrigeration) that can be associated with the M&R of conventional gravity sewer systems. These processes have been identified by conducting desk research and through personal communication a Roelofs Groep's expert (Roelofs, 2020).

The ISO140467:2018 standard states that several requirements should be met in case comparisons of alternatives are performed (ISO, 2018). To meet these requirements, it is ensured that the FU is identical, the system boundaries are equivalent, the assumptions are the same (if relevant) and the data quality goals are the same for each alternative.

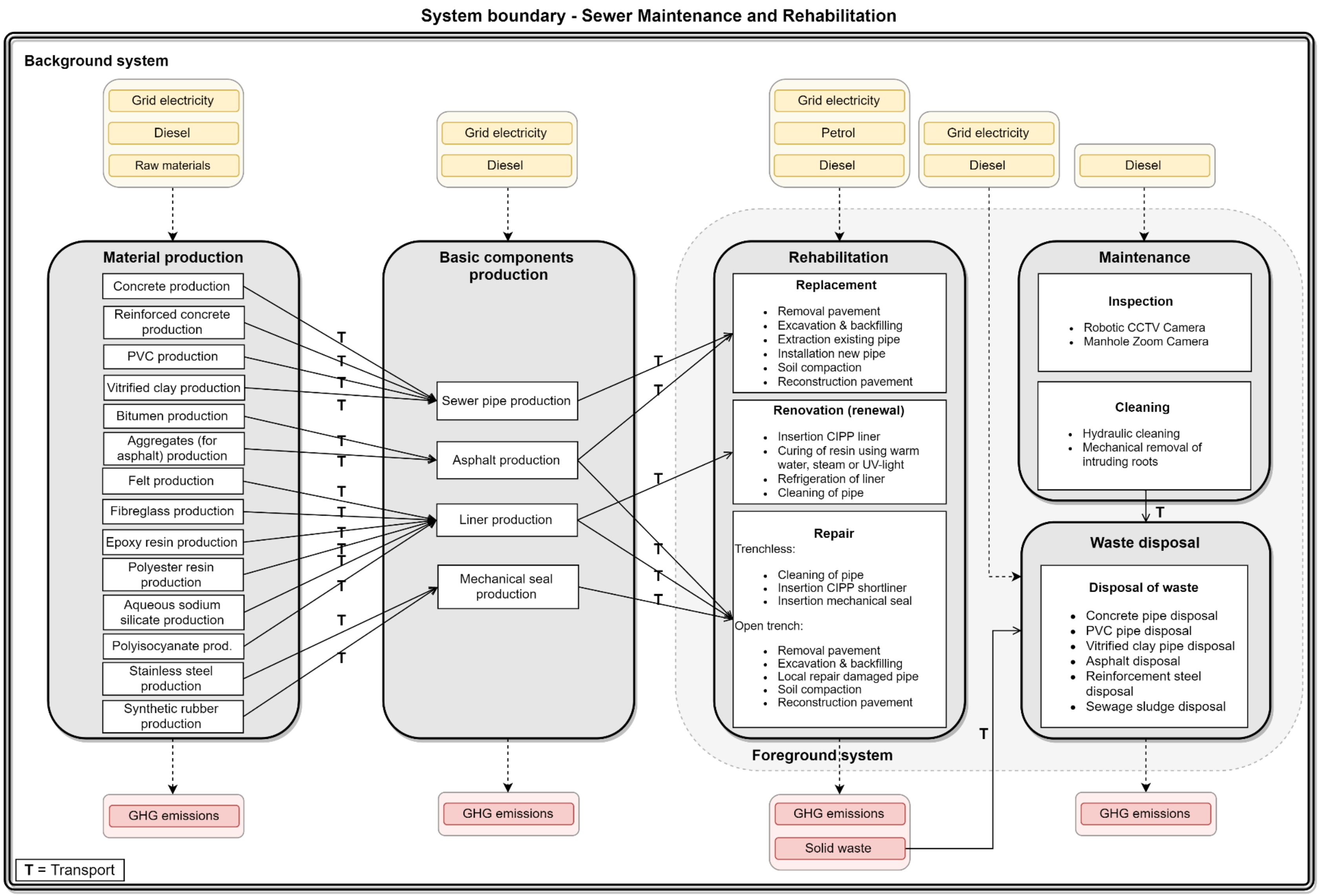

Figure 7: Boundaries of the system under study and its main phases and components.

2.2.1.4 System boundaries description

In the following sections, the processes included and excluded from the system boundaries considered in this study are presented for each M&R technique.

Sewer pipe replacement

As stated before, only the open trench replacement of sewer pipes was considered. Activities of sewer pipe replacement as illustrated in Figure 2 were included. Each phase consists of several processes and activities. In Table 2, an overview of specific items which were included and excluded from the CF assessment is given.

For the production phase, the production of asphalt and sewer pipes was considered. Sewer pipe materials which were considered include concrete, reinforced concrete, polyvinyl chloride (PVC) and vitrified clay. The transportation phase consists of fuel consumption during transportation of raw materials, transportation of asphalt and sewer pipes from distributor to the project location, transportation of equipment and machinery from the depot to the project location, and transportation of waste (old pipe and asphalt) to the disposal location. Finally, diesel consumption during the rehabilitation phase was evaluated. This includes diesel consumption during excavation, backfilling, soil compaction, pipe extraction, paving, and asphalt compaction. The disposal of the extracted pipe and removed asphalt was considered as well. The end-of-life of the newly placed pipe and asphalt was not included in this study, since decommission of the sewer system is outside the scope of this study.

Table 2: Overview of included and excluded items of the CF assessment of sewer pipe replacement.

Sewer pipe replacement		
Phase	**Items included in the study**	**Items excluded from the study**
Production	Asphalt, sewer pipe materials (concrete, reinforced concrete, PVC, vitrified clay)	Protective coatings for pipes, production and maintenance of equipment
Transportation	Transportation of raw materials, transportation of pipes and asphalt from distributor to project site, transportation of equipment from depot to project location, transportation of waste from project site to disposal location	Production and maintenance of vehicles, commuting of personnel
Rehabilitation	Pipe extraction (breaking/cutting pavement, excavation trench, pipe extraction), pipe installation (pipe laying, backfilling trench, compacting), asphalt rehabilitation (paving, compacting)	Increased emissions due to traffic diversions, construction dewatering using pumps, production and maintenance of equipment, underpinning of trenches
Disposal	Disposal old sewer pipe, disposal old asphalt	End-of-life of newly placed pipe and asphalt

Sewer pipe renovation

Sewer pipe renovation using CIPP lining is relatively less process- and labour-intensive compared to open trench sewer pipe replacement since pavement rehabilitation and excavation works are not required. For that reason, each phase includes fewer items for CIPP lining than open trench replacement.

In this study, two different materials for the production of the CIPP liner were evaluated. They include fibreglass and needle felt, as these materials are most commonly used for liner production (VROM Inspectie, 2006). In addition to that, polyester resin is a material which was considered in the production phase. According to (VROM Inspectie, 2006), the market share of vinyl ester resin in the Netherlands is negligible and was, therefore, excluded from this study. To prevent the (felt) liner from curing before installation, it needs to be refrigerated (Almeida, Covas, & Beceiro, 2015). Therefore, energy consumption as a result of the refrigeration of the liner was also considered. Furthermore, the transportation of raw materials and transportation of the liner and equipment to the project location was included in the study. Finally, in the rehabilitation phase, energy consumed during the insertion process of the liner, curing process and cleaning/inspection of the pipe were evaluated. Two curing methods were taken into account: curing using warm water for needle felt liners and UV-light for fibreglass liners. See Table 3: Overview of included and excluded items of the CF assessment of pipe renovation.Table 3 for an overview of all included items.

Table 3: Overview of included and excluded items of the CF assessment of pipe renovation.

Sewer pipe renovation		
Phase	**Items included in the study**	**Items excluded from the study**
Production	Liner materials (felt material, fibreglass), thermosetting resin (polyester resin, epoxy resin), refrigeration of liner	Production and maintenance of equipment
Transportation	Transportation of raw materials, transportation of components from distributor to project site, transportation of equipment to project location	Production and maintenance of vehicles, commuting of personnel
Rehabilitation	Insertion of liner, curing of resin (using UV-light, warm water), cleaning of existing pipe	Production and maintenance of equipment
Disposal	-	End-of-life of CIPP liner

Sewer pipe repair

For the production phase of open trench repair, the following materials were considered: fibreglass, (thermosetting) resin, synthetic rubber, and stainless steel. These are the main materials required to produce the components for trenchless sewer reparation works (Almeida, Covas, & Beceiro, 2015). In the transportation phase, transportation of raw materials, transportation of components from the distributor to the project location and transportation of equipment were considered. Moreover, for open trench repair, transportation of asphalt to disposal was included. In the rehabilitation phase, open trench repair partially includes the same steps as an open trench replacement. The following activities for open trench repair were included in this study: removal of pavement, excavation, backfill, soil compaction, pavement reconstruction and disposal of asphalt. Trenchless repair does not require excavation and pavement rehabilitation works. Hydraulic cleaning and inspection of the entire sewer section prior to the reparation works were included. See Table 4 for a summary of all included items.

Table 4: Overview of included and excluded activities/processes/items of the CF assessment of pipe repair.

Sewer pipe repair		
Phase	**Items included in the study**	**Items excluded from the study**
Production	Short liner materials (fibreglass), resin (aqueous sodium silicate, polyisocyanate), mechanical seal (stainless steel, synthetic rubber)	Production and maintenance of equipment
Transportation	Transportation of raw materials, transportation of components from distributor to project site, transportation of asphalt from manufacturer to project site, transportation of equipment to project location, transportation of waste to disposal location	Production and maintenance of vehicles, commuting of personnel
Rehabilitation	**Trenchless approach** Repair using CIPP short liner, repair using mechanical seal, inspection, hydraulic cleaning **Open trench approach** Excavation trench, backfilling trench, compacting soil, pavement cutting/breaking, asphalt rehabilitation, inspection, hydraulic cleaning	Increased emissions due to traffic diversions, construction dewatering using pumps, production and maintenance of equipment, underpinning of trenches
Disposal	Disposal old asphalt, disposal deposits from sewer	End-of-life of CIPP short liner and mechanical seal

Maintenance: cleaning and inspection

It is assumed that no raw materials are acquired and no materials are produced for the maintenance of sewer systems. The transportation phase only considered the transportation of equipment to the project location and transportation of sludge to disposal. Furthermore, the maintenance phase considered the energy consumption of two types of cleaning methods: hydraulic and mechanical cleaning. Regarding hydraulic cleaning, this study evaluated the energy consumption due to pumping of water from a water source, cleaning of a sewer using waterjets and suction of deposits from a sewer. Mechanical cleaning only included the energy consumption as a result of removing intruding roots in the sewer using a mechanical device. Additionally, in the maintenance phase, the energy consumption of sewer inspection using a remotely controlled robotic CCTV camera and a MZC was evaluated.

Table 5: Overview of included and excluded activities/processes/items of the CF assessment of sewer cleaning.

Maintenance: cleaning and inspection		
Phase	**Items included in the study**	**Items excluded from the study**
Production	-	Production and maintenance of equipment
Transportation	Transportation of equipment to project location, transportation of sludge to disposal	Production and maintenance of vehicles, commuting of personnel
Maintenance (cleaning)	**Hydraulic cleaning**	Production and maintenance of equipment
	Filling up of tank with water using pumps, cleaning of sewer using a waterjet, vacuum pumping of sludge	
	Mechanical cleaning	
	Mechanical removal of intruding roots in a sewer	
Maintenance (inspection)	Robotic CCTV camera, Manhole-Zoom camera	
Disposal	Disposal deposits from sewer	-

2.2.1.5 Data sources and data quality goals

The aim is to collect data from credible published sources and licenced databases whenever possible to ensure credibility and transparency. However, it should be mentioned that this is a fictitious case study. This means that the collection of site-specific data may not be practicable in certain cases. With this in mind, the use of secondary data was unavoidable (ISO, 2018). On top of that, generic data was used for processes which are considered less important, insignificant, or too complex/time consuming to analyse in full detail. In this case, the choices performed were documented and justified accordingly. However, whenever possible, the study used data and assumptions which are credible and representative for the processes for which the data was collected and which are relevant for sewer management practices in the Netherlands (or Europe).

In this study, several CF calculators were used. The CF calculators for construction materials that were mainly used in this study are the ICE Database (Circular Ecology Ltd, 2019), Highways England Carbon Tool v2.2 (Highways England, 2019) and the UK Government GHG Conversion Factors for Company Reporting calculator (UK Governement, 2019). These CF calculators contain embodied carbon emission factors calculated based on global warming potential (GWP) values over a 100-year period. Embodied carbon emission factors account for all relevant GHG emissions related to a certain material from cradle to (factory) gate. These factors include emissions as a result of raw material extraction, material refining, manufacturing, assembly activities, transport, etc. (Circular Ecology Ltd, 2019).

The data existing in these calculators are mainly applicable for the United Kingdom (Circular Ecology Ltd, 2019). It was assumed that the data taken from these sources are geographically representative and appropriate enough to satisfy the goal of this study. In addition to that, the most recent conversion factors and GWP values (over a 100-year period) presented by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2019) and CO2-emissiefactoren (CO2-emissiefactoren, 2019) were used in the

LCIA of this study. To estimate the environmental impacts of transport of goods, the reference of Otten, ‘t Hoen and, Den Boer (2017) was used. This reference was commissioned by CE Delft in the year of 2016 (CE Delft, 2017). Finally, since the results of this study are intended to be used in the Dutch context, the calculations and assumptions must be suitable for this context. Therefore, in addition to the other guidelines, some relevant parts of the calculation method as proposed by Stichting Bouwkwaliteit (SBK) (2019) were used as a guideline for conducting the CF assessment. The SBK calculation method provides extensive guidelines and calculation rules for determining the (material-related) environmental performance of civil engineering projects in the Dutch context (Stichting Bouwkwaliteit, 2019). This calculation method is widely used by Dutch sustainable construction calculators such as DuboCalc (DuboCalc, n.d.) and is in compliance with the NEN-EN-15804 standard. Moreover, it strictly follows the requirements and guidelines as proposed by the ISO international standards for LCA (ISO14000 series) (Stichting Bouwkwaliteit, 2019). Collection of data for other processes in this study relied on published sources, design specifications, technical specifications of machinery from online sources and experts' interviews.

2.2.1.6 Delimitations

An overview of the delimitations is listed below:

- This study focusses exclusively on M&R of sewer pipes. Therefore, other components of gravity sewer systems, such as manholes, were not included;
- The GHG emissions resulting from traffic diversions were not considered. Their calculations were too complex and time-consuming for the time available to perform this study;
- Commuting of personnel was not considered;
- Dewatering of trenches using pumps in open trench rehabilitation works was excluded from the study. Energy consumption as a result of dewatering of trenches depends on several uncertain factors, such as, for example, the groundwater table conditions, duration of project works, weather conditions, use of dewatering method, etc. (Rodriguez, 2019). Providing a credible estimate was considered too complex and time-consuming for this study;
- Manufacturing and maintenance of machinery, transportation vehicles and other equipment was outside of the scope of this study;
- Materials which are considered insignificant (i.e. negligible contribution to CF) were also excluded from this study. Examples are: production of consumables, charging of electrical power tools, etc.;
- Inspection of manholes using camera technologies and the rehabilitation of sewer pipes through injection were not considered in this study;
- Mechanical cleaning is a term which refers to the collection of techniques to physically remove obstructions in a sewer pipe using mechanical devices. In this study, only removal of intruding roots in sewer pipes was considered;
- Restoration of inlets after open trench replacement of sewer pipes is not considered;
- Re-opening connections of inlets to the sewer pipe after CIPP lining using a robotic cutter is not considered.

2.2.1.7 Assumptions and simplifications

Below a brief overview of the most important assumptions and simplifications that were made in this study is given:

- Environmental burdens related to the underpinning of trenches were assumed to be negligible. According to a study conducted by Morera, Remy, Comas, and Corominas (2016), the underpinning of trenches in open trench sewer rehabilitation works is insignificant.
- It was assumed that the soil to be excavated is compact sand;
- It was assumed that all the excavated materials were re-used for backfilling of the trench;
- In case of open trench rehabilitation works, the width of the pavement to be removed and reconstructed was assumed to be the same as the width of the trench to be excavated;
- In case of a brick-paved road on top of the sewer, it was assumed that all paving bricks were re-used for the road reconstruction after open trench pipe replacement.

2.2.1.8 Limitations of CF assessment

The standard ISO14067:2018 (ISO, 2018) identifies two main inherent limitations of assessing environmental impacts by means of a CF approach. ISO14067:2018 (ISO, 2018) states that a CF assessment does not adopt a multiple-indicator approach and therefore does not give a full overview of the environmental performance of a certain product or service system. Instead of multiple impact categories, a CF study focusses exclusively on the climate change impact category expressed in terms of CO_2-eq emissions. Because of this, the findings of this study might give a misleading picture of the impacts associated with sewer M&R techniques. Therefore, the results of a CF assessment should not be considered as the main deciding factor of a decision-making process of sewer management practices. Nevertheless, a CF is still able to be a valid indicator for comparisons of product or service systems in most cases (Weidema, Thrane, Christensen, Schmidt, & Løkke, 2008). According to Pandey, Agrawal, and Pandey (2011), the importance should not be underestimated. They state that CF assessments can play an important role in emission management, evaluation of alternatives and evaluating possibilities for mitigation of impacts. Therefore, valuable insights in the environmental performances of systems can be provided. Another limitation that was identified by ISO14067:2018 was that a CF assessment also has limitations related to the methodology. Some relevant limitations include availability, representativity and appropriateness of data sources, assumptions related to transportation, user behaviour and the formulation of the FU. The data taken from published sources and databases, as mentioned in the previous section, might only be representative for a certain geographical area (ISO, 2018). Furthermore, certain processes and activities might be too complex to analyse in full detail and to identify all possible emissions (Pandey, Agrawal, & Pandey, 2011). These limitations should be kept in mind when conducting the CF assessment. In conclusion, performing a CF assessment is sufficient to satisfy the main goal of this study. However, it should be mentioned that it is important to be aware of the (over)simplification of such an assessment and that these simplifications might lead to results that differ from results that would otherwise have been obtained from LCA software.

2.2.2 *Inventory analysis*

2.2.2.1 Open trench sewer pipe replacement

Sewer pipes

As mentioned in the scope definition, four different sewer pipe materials are considered for open trench pipe replacement: concrete, reinforced concrete, PVC, and vitrified clay. The weight properties of sewer pipes per pipe diameter for each material type has been determined using the product programs of various sewer pipe manufacturers. Pipe diameters ranging from 200 to 1500 mm were considered in this study. However, this range is not applicable for every pipe material. Concrete pipes are typically produced in diameter sizes from 250 to 1500 mm. For reinforced concrete pipes, diameter sizes are available from 300 to 1500 mm. Furthermore, a range from 200 to 1000 mm was considered for PVC pipes and 200 to 600 mm for vitrified clay pipes.

To compile the inventory of concrete and reinforced concrete sewer pipes, the technical design specification of "Vereniging Van Producenten Van Betonleidingsystemen" (VPB) (VPB, 2008) was consulted. The vitrified clay sewer pipe product program of "DYKA Plastic Pipe Systems" (DYKA, 2013) was consulted for the inventory of vitrified clay pipes. Finally, the paper by Morera, Remy, Comas, and Corominas (2016) was used to retrieve PVC pipe properties.

In the CF assessment of this study, the concept of embodied energy and embodied carbon was used to estimate the amount of energy consumed and CO_2 emitted as a result of raw material extraction, material refinement and sewer pipe manufacturing processes. As stated earlier, the ICE v2.0/v3.0 database is used to collect primary production data.

Excavation, backfill, and compaction of trenches

To estimate the volume of soil to be excavated and backfilled for each different pipe diameter group, guidelines as presented by Morera, Remy, Comas, and Corominas (2016) were used. The trench characteristics depend on several factors. These factors mainly include the pipe diameter, length of the sewer section, trench angle (α) (see Figure 8) and whether there is traffic on top of the trench or not

(Morera, Remy, Comas, & Corominas, 2016). Two scenarios were established to determine the depth of the trench, as can be seen in Figure 8. The trench depth depends on whether there is traffic in the upper part of the trench or not. In case of the absence of traffic, scenario (b) of Figure 8 can be considered to determine the trench depth. Scenario (a) should be considered if traffic is present. For the hypothetical sewer section of this study, scenario (a) was selected. Moreover, Morera, Remy, Comas, and Corominas (2016) present calculation rules to determine the minimum width of the bottom part of the trench (see Table 6). As the pipe diameter increases, the trench width increases as well. In this study, a trapezoidal trench was assumed with an angle (α) of 60° between the trench wall and the bottom part of the trench. Based on the aforementioned trench characteristics and sewer section length (i.e. 45m), the excavation/backfill volume of the trench could be determined for each pipe diameter group.

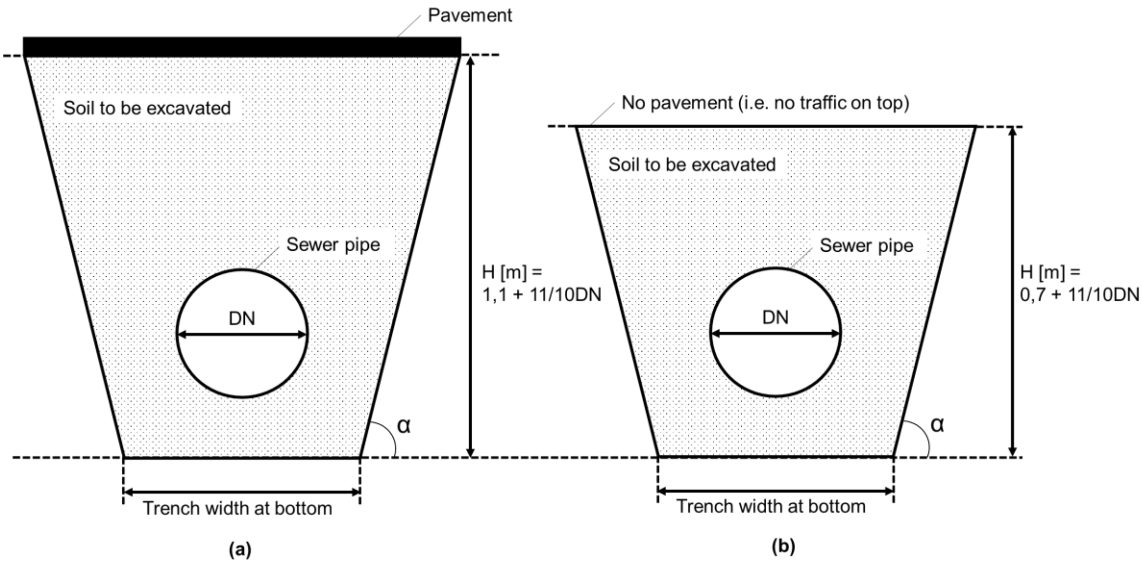

Figure 8: Trench characteristics and specifications. Source: (Morera, Remy, Comas, & Corominas, 2016)

Table 6: Calculation rules to determine the width of the bottom of the trench. Source: (Morera, Remy, Comas, & Corominas, 2016)

	Minimum trench width at bottom [m]	
Pipe diameter [mm]	**For α > 60°**	**For 30° < α ≤ 60°**
DN ≤ 225	DN+0,40	DN+0,40
225 < DN ≤ 350	DN+0,50	DN+0,40
350 < DN ≤ 700	DN+0,70	DN+0,40
700 < DN ≤ 1200	DN+0,85	DN+0,40
DN > 1200	DN+1,0	DN+0,40

After the trench volumes for each pipe diameter group have been determined, the operation times of various construction machinery could be estimated. For excavation and backfill of trenches, a hydraulic excavator is used. As a reference, the Caterpillar 315D L excavator has been selected to determine the energy consumption as a result of trenching and backfilling. The Caterpillar 315D L was found to be a common hydraulic excavator at construction sites in the Netherlands. To estimate the energy consumption per m^3 soil to be excavated, the "Caterpillar performance handbook 47" has been consulted (Caterpillar, 2017). The Caterpillar performance handbook contains comprehensive and relevant information about, among other things, the operating times and fuel consumption of various Caterpillar construction machinery. In Table 7, the technical specifications as described in the handbook are shown. The cycle time refers to the amount of time it takes for the excavator to load, swing, and dump its bucket. It has been assumed that the job efficiency is 45min/h. Furthermore, since the excavator operator may not be able to fully load its bucket because of obstructions (i.e. sewer pipes), it is assumed that the excavator's bucket is filled for 70% of its maximum capacity for each digging cycle. These assumptions were used for excavation as well as backfilling of trenches.

Table 7: Caterpillar 315D L hydraulic excavator technical specifications. Source: (Caterpillar, 2017).

Excavator model	Average fuel cons. [l/h]	Bucket capacity [m^3]	Bucket capacity (70%) [m^3]	Estimated cycle time [min]	Effective soil displacement capacity [m^3/h]	Fuel cons. [l/m^3]	Fuel cons. [MJ/m^3]
Caterpillar 315D L	10,85	0,520	0,364	0,28	57,8	0,19	6,76

After backfilling the trench, it is necessary to compact the soil. It is assumed that the Caterpillar CS64B roller is used for soil compaction in this case. The technical specifications can be found in Table 8. The fuel consumption of the roller has been determined using the Caterpillar performance handbook (Caterpillar, 2017). The rolling capacity per hour of the roller was calculated using the methodology proposed by Stripple (2001).

Asphalt rehabilitation

The asphalt pavement design considered in this study was based on the dimensions of the trench and the asphalt pavement and mix design as proposed by Butt (2014). It has been assumed that the asphalt pavement to be rehabilitated has a width equal to the upper width of the trench and a length equal to the length of the sewer section (45m). The thickness of the asphalt pavement was set at 16,5cm. Furthermore, it was assumed that the asphalt mix design consists of 5% bitumen 70/100 and 95% aggregates (by mass). Finally, according to de Vos-Effting, et al. (2018), the density of asphalt is 2.400 kg/m^3.

In order to be able to excavate the trench and extract the sewer pipes, the asphalt layer on top has to be removed. To remove the asphalt, a cold milling machine is used. The cold milling machine model which has been selected for this study is the Wirtgen W150 CF (Wirtgen Group, 2018). The milling capacity per hour of the cold milling machine was retrieved from site-specific data as described by Arcadis (2018). Fuel consumption data of the Wirtgen W150 CF was obtained from its corresponding product specification (Wirtgen Group, 2018). Two types of machinery were considered for the asphalt paving works, they include an asphalt compactor (roller) and an asphalt paver. The selected model of the roller is a Caterpillar CB54B roller, the technical specifications (e.g. fuel consumption) were retrieved from the Caterpillar performance handbook (Caterpillar, 2017). To estimate the rolling capacity per hour of the asphalt roller (see Table 8), the methodology of Stripple (2001) as used earlier in this paper has been used with the same assumptions. For asphalt paving, it was assumed that a Dynapac SD1800W paver is used. Stripple's (2001) calculation method was used to determine the paving capacity of the paver.

Table 8: Roller machinery specifications. Sources: (Caterpillar, 2017); (Stripple, 2001)

Roller model	Average fuel cons. [l/h]	Covering drum width [m]	Theoretical rolling capacity [m^2/h]	Effective rolling capacity [m^2/h]	Fuel cons. [l/m^2]	Fuel cons. [MJ/m^2]
Caterpillar CB54B (asphalt)	9,5	1,45	963,33	802,56	0,012	0,43
Caterpillar CS64B (soil)	13,55	1,81	1209,90	1007,30	0,014	0,49

Disposal

During the rehabilitation works of open trench replacement, construction material wastes get generated. Waste types which were considered in this study are the extracted sewer pipes and the removed asphalt pavement. As stated earlier, the end-of-life of the newly installed sewer pipes and the new asphalt pavement is outside the scope of this study.

To determine the disposal scenarios of the waste materials, Stichting Bouwkwaliteit (2019) has been consulted. The waste management scenarios as reported by Stichting Bouwkwaliteit (2019) properly reflects the current market and is representative for the Netherlands (Nationale Milieudatabase, 2019). Stichting Bouwkwaliteit (2019) provides comprehensive information on disposal route (e.g. landfill, re-use, etc.) fractions that should be considered for a variety of construction material wastes. The disposal route fractions as shown in Table 9 ought to be considered (Stichting Bouwkwaliteit, 2019). Regarding the waste management scenario of concrete, asphalt, and vitrified clay, 99% of the total waste mass is recycled and 1% ends up at the landfill site. For PVC pipes, 70% of the total mass is recycled, 20% is incinerated and 10% ends up at the landfill site. Finally, for reinforcement steel, 95% of the steel is recycled and the remaining 5% is destined for landfilling.

Table 9: Waste management scenarios. Source: (Stichting Bouwkwaliteit, 2019).

Waste management scenarios				
Waste type	**Landfill [%]**	**Incineration [%]**	**Recycling [%]**	**Re-use [%]**
Concrete	1	0	99	0
Steel, rebar	5	0	95	0
PVC pipes	10	20	70	0
Vitrified clay	1	0	99	0
Asphalt	1	0	99	0

Transportation

As stated earlier in the scope definition, four scenarios for the transportation phase were considered. It was assumed that a Lorry > 20 metric ton with a trailer attached (maximum payload of 28t), as described by Otten, 't Hoen, & den Boer (2017), is used to transport freight in all transportation scenarios.

To determine the transportation distances of each transportation scenario, the method of determination as presented by Stichting Bouwkwaliteit (2019) was used. Stichting Bouwkwaliteit (2019) states that the following transportation distances should be considered in case the transportation distances are unknown (i.e. in case of hypothetical project locations):

- For transportation of construction products in bulk (e.g. sewer pipes) to the project location, a one-way distance of 50km shall be considered;
- For transportation of waste from the project location to the location of disposal, a one-way distance of 50km shall be considered.

It was assumed that the value of 50 km also applies for transportation of machinery from the depot to the workplace. In Table 10, the transportation scenarios with the corresponding transportation distances are shown.

Table 10: Transportation data used for open trench replacement.

Transportation data for LCI					
Transportation scenario	**From**	**To**	**Vehicle and fuel type**	**Max. payload vehicle [t]**	**Distance [km]**
Sewer pipe transport	Pipe distributor	Workplace	Lorry > 20 tonne + trailer – Diesel	28	50
Asphalt transport	Asphalt manufacturer	Workplace	Lorry > 20 tonne + trailer – Diesel	28	50
Machinery transport	Machinery depot	Workplace	Lorry > 20 tonne + trailer – Diesel	28	50
Waste transport	Workplace	Disposal site	Lorry > 20 tonne + trailer – Diesel	28	50

2.2.2.2 Renovation by means of fibreglass and felt CIPP lining

CIPP liner materials

This study differentiated between two types of liner materials and two types of thermosetting resin. The included liner materials are fibreglass and needle felt. Furthermore, unsaturated polyester resin and epoxy resin were considered in this study.

To determine the volume/weight of the liner, the wall thickness needs to be determined. The thickness of the liner wall depends on several factors, these are mainly the modulus of elasticity of the liner material, the sewer pipe diameter and the groundwater level (Merkblatt DWA-M 144-3, 2015). To make a valid estimate of the thickness of the felt and fibreglass CIPP liner, the German "DWA-M 144-3" (2015) standard has been used. The DWA-M 144-3 (2015) standard presents an overview of the minimum required liner thicknesses for each material group for different pipe diameters (DN 150 – 1200mm) and groundwater levels.

The parameters were determined after personal communication with experts from the sewer renovation company Flua Leidingrenovatie (Flua, 2020). According to the Flua experts, to estimate the felt CIPP liner thickness, "material group 4" (with e-modulus = 1.400 N/mm^2) as stated in DWA-M 144-3 (2015) should be considered. Furthermore, "material group 24" (with e-modulus = 12.000 N/mm^2) should be considered for fibreglass CIPP liners. The groundwater levels which should be assumed are 1,5m for pipe diameters up to 600mm and 2,0m for diameters larger than 600mm (Flua, 2020).

Table 11: CIPP liner thickness for fibreglass and felt according to DWA-M 144-3 standard.

DN [mm]	Thickness fibreglass liner [mm]	Thickness felt liner [mm]
200	3	3
250	3	3
300	3	3,5
400	3	4,7
500	3	5,9
600	3,3	7
700	3,8	8,2
800	4,8	10,5
900	5,4	11,8
1000	5,9	13,1
1200	7,1	15,7

According to the "DIBt No. Z-42.3-365" (2018) IMPREGliner technical approval, the density of fibreglass liners which belong to "material group 24" is approximately 1.640 kg/m^3. Moreover, the fibreglass content of the fibreglass liner is approximately 55% of the total liner mass (DIBt No. Z-42.3-365, 2018). Therefore, the resin content of the fibreglass liner is assumed to be 45% of the total liner mass.

The density of needle felt as typically used in felt CIPP liners is set at 305,5 kg/m^3 (Ji, Yoo, Kim, & Koo, 2018). According to Ji, Yoo, Kim, and Koo (2018) the density of unsaturated polyester resin is 1.130 kg/m^3. The density of epoxy resin is approximately 1.160kg/m^3 (DIBt No. Z-42.3-468, 2016). The felt liner is completely saturated with resin, which means that it can be assumed that the volume of resin is equal to the total volume of the liner.

Refrigeration

Fibreglass liners can generally be stored at temperatures between 5 and 35 °C (Persson, 2010). Therefore, fibreglass liners are generally not refrigerated during transport (Aarsleff, 2020). Felt liners, on the other hand, need to be cooled or iced to prevent premature curing. In this study, refrigeration using dry ice during transport of the felt liner was considered. This might not be entirely representative since other refrigeration methods (e.g. reefer) can be used as well.

It was assumed that the total volume of dry ice to be produced is equal to 50% of the total volume of the felt liner. This is a rough estimation because the actual volume of ice to be used for refrigeration is not fixed and may vary for different contractors. This assumption is considered acceptable since the contribution of dry ice production to the total CF is relatively insignificant. For the LCI, the dry ice maker “IceMaker PR750H” is selected.

Curing

In Table 12, reference values of the curing speeds of various UV-light curing devices are given. The curing speed of fibreglass liners mainly depends on the number of UV lamps used, the power output of the UV lamps, the pipe diameter and the liner thickness (DIBt No. Z-42.3-365, 2018). In Table 12, the curing speeds of several UV-light chains are shown for pipe diameters from 200 to 1200 mm as reported by the “DIBt No. Z-42.3-365” (2018) technical approval. For pipe diameters up to 700mm, a chain (or train) of UV-lights with 12 lamps of 400 Watts each was assumed to be used to cure fibreglass liners. It was assumed that a chain of UV-lights with 8 lamps of 1000 Watts each is used to cure liners with a diameter larger than 600mm.

Table 12: Reference values of fibreglass liner curing speeds. Source: (DIBt No. Z-42.3-365, 2018)

Fibreglass CIPP liner UV-light curing speeds				
DN [mm]	**Chain of 12 x 400W lamps speeds [m/h]**	**Chain of 8 x 400W lamps speeds [m/h]**	**Chain of 8 x 1000W lamps speeds [m/h]**	**Chain of 4 x 1000W lamps speeds [m/h]**
200	72	57	-	-
250	66	51	-	-
300	60	45	-	-
400	54	39	-	-
500	39	27	-	-
600	21	15	57	24
700	-	-	51	24
800	-	-	45	18
900	-	-	39	9
1000	-	-	27	9
1200	-	-	15	9

The fibreglass liner is inserted using a winch (NL: lier). It was assumed that a Bagela RKW5 winch is used (Aarsleff, 2020). The UV-light chains are powered by an on-site diesel generator set. It was assumed that the energy consumption of UV curing is equal to the running time of the diesel generator set. A diesel generator with a power rating of 125kVA (100ekW) is used. The Caterpillar D100-6 diesel generator set is selected for this study.

In contrast to fibreglass liners, needle felt liners are not cured using UV-light. Instead, needle felt liners are cured using either hot water or steam (Stichting RIONED, 2019). Unfortunately, due to the unavailability of data, the energy consumption of the curing process of needle felt CIPP liners could not be determined with sufficient accuracy. It was assumed that the energy consumption of curing using hot water is equal to that of the curing process using UV-light. Therefore, it is important to keep in mind that the actual energy consumption of the curing process of needle felt CIPP liners is likely to be much different than presented in this study.

Transportation

For the transportation phase of sewer pipe renovation, only two transportation scenarios were included (see Table 13). The reason for this is that renovation by means of CIPP lining is relatively less process- and labour-intensive. For example, asphalt rehabilitation is not necessary and the generated solid waste during rehabilitation works is negligible. For transport of the CIPP liners and machinery to the workplace, it was assumed that a lorry 10-20 tonne with a maximum payload of 7,5 tonnes is used.

Table 13: Transportation data used for open trench replacement.

Transportation data for LCI					
Transportation scenario	**From**	**To**	**Vehicle and fuel type**	**Max. payload vehicle [t]**	**Distance [km]**
CIPP liner transport	CIPP liner distributor	Workplace	Lorry 10-20 tonne – Diesel	7,5	50
Machinery transport	Machinery depot	Workplace	Lorry 10-20 tonne – Diesel	7,5	50

2.2.2.3 Trenchless sewer pipe repair

Mechanical seal

A mechanical seal consists of two main components: a stainless-steel sleeve structural body and a synthetic rubber (EPDM) gasket surrounding the steel sleeve (DIBt No. Z-42.3-374, 2012). For the LCI of trenchless pipe repair, the so-called "Quick-Lock" system for sewer pipe point repair was considered. The technical approval "DIBt No. Z-42.3-374" (2012) of the Quick-Lock systems, granted by the DIBt German technical authority, contains relevant and comprehensive information on the technical properties and design of mechanical seals for sewer pipe diameters from 150 to 1600mm. Therefore, DIBt No. Z-42.3-374 (2012) has been consulted to compile an inventory of the used materials. For the mechanical seal, a standard length of 60 cm is taken. See Appendix A Table 20 for a detailed overview of the mechanical seal properties per pipe diameter.

CIPP short liner

Another sewer reparation technique considered in this study is the rectification of local damage in a sewer pipe by means of a so-called CIPP short liner. In contrast with end-to-end relining, rehabilitation with a short liner is limited to a small part of a sewer section. The main materials of CIPP short liners are fibreglass and resin (Stichting RIONED, 2019).

An inventory was compiled with the help of a Flua Leidingrenovatie expert. Flua Leidingrenovatie adopts a so-called "CarboLith Spot Repair System" short lining method as proposed by Minova CarboTech GmbH (Flua, 2020). This method suggests that fibreglass material saturated with a three-component resin system should be used for trenchless pipe repair. The three-component resin system consists of three chemical substances: aqueous sodium silicate (component A), a polyisocyanate (component B), and (optionally) a catalysing additive (component C). The CarboLith Spot Repair System was granted technical approval by the DIBt German technical authority (DIBt No. Z-42.3-383, 2015). The fibreglass material and resin system collectively form a solid pipe section when exposed to a certain temperature.

The repair length, and therefore the length of the short liner, is heavily dependent on the nature of the damage in the pipe (Stichting RIONED, 2019). Typically, a length of 60 cm is adopted (DIBt No. Z-42.3-383, 2015). Therefore, a length of 60 cm was considered in this study. It takes approximately 20 to 30 minutes on average to place the short liner, this is generally done by a robotic device powered by a diesel generator. Furthermore, short liners can be applied in pipe diameter ranging from 50 to 800 mm (Flua, 2020). According to an expert from Flua Leidingrenovatie (Flua, 2020), CIPP short liners are generally cured through ambient temperature. Therefore, it can be assumed that no energy is consumed to cure short liners. See Table 14 for an overview of the short liner properties considered in this study:

Table 14: CIPP short liner properties. Source: (Flua, 2020)

CIPP short liner properties				
DN sewer pipe [mm]	**Length short liner [cm]**	**Fibreglass weight [kg]**	**Component A weight [kg]**	**Component B weight [kg]**
200	60	0,93	0,75	1,13
250	60	1,20	0,89	1,36
300	60	1,47	1,19	1,81
400	60	1,87	1,42	2,15
500	60	3,25	2,53	3,84

600	60	3,91	2,98	4,52
700	60	5,96	4,62	7,01
800	60	8,30	6,11	9,49

Transportation

Transportation scenarios which were included are shown in Table 15.

Table 15: Transportation data used for trenchless repair.

Transportation data for LCI					
Transportation scenario	**From**	**To**	**Vehicle and fuel type**	**Max. payload vehicle [t]**	**Distance [km]**
Material transport	Distributor	Workplace	Lorry < 10 tonne – Diesel	3	50
Machinery transport	Machinery depot	Workplace	Lorry < 10 tonne – Diesel	3	50

2.2.2.4 Open trench sewer pipe repair

Civil engineering works

Similar to open trench pipe replacement, open trench repair requires removal of pavement (if there is any) and excavation works to be able to rectify damages in the pipe. For this reason, open trench sewer pipe repair largely follows the same methodology as open trench replacement with regards to on-site civil engineering works (e.g. excavation, asphalt rehabilitation, etc.). In case of open trench repair, a mini excavator is typically used for trenching. See Table 16 for the technical specifications of the selected mini excavator. A job efficiency of 45min/h and a bucket capacity of 70% of the original capacity was assumed for excavation as well as backfilling. Site-specific data from Arcadis (2018) was used to determine the energy consumption of soil compaction using a soil plate compactor. For this study the length of the trench is assumed to be equal to an average sewer pipe length of 2,5 m, the trench angle (α) is set at 60°.

For asphalt rehabilitation, three types of machinery were considered: a floor saw, asphalt paver and utility compactor. The methodology as proposed by Stripple (2001) has been used again to estimate the rolling capacity of the utility compactor (see Table 17). Finally, the technical specifications of the floor saw were retrieved from the product program of Wacker Neuson (2020).

Table 16: Caterpillar 304E2 CR mini excavator technical specifications. Source: (Caterpillar, 2017).

Mini excavator model	**Average fuel consumption [l/h]**	**Bucket capacity [m^3]**	**Bucket capacity (70%) [m^3]**	**Estimated cycle time [min]**	**Effective soil displacement capacity [m^3/h]**	**Fuel cons. [l/m^3]**	**Fuel cons. [MJ/m^3]**
Caterpillar 304E2 CR	4,25	0,160	0,112	0,285	17,6	0,24	8,62

Table 17: Utility asphalt compactor specifications. Sources: (Caterpillar, 2017); (Stripple, 2001)

Utility compactor model	**Average fuel cons. [l/h]**	**Covering drum width [m]**	**Theoretical rolling capacity [m^2/h]**	**Effective rolling capacity [m^2/h]**	**Fuel cons. [l/m^2]**	**Fuel cons. [MJ/m^2]**
Caterpillar CB22B	5,5	0,85	566,7	472,2	0,012	0,43

Transportation

The transportation scenarios as shown in Table 18 were considered for open trench repair.

Table 18: Transportation data used for open trench repair.

Transportation data for LCI					
Transportation scenario	**From**	**To**	**Vehicle and fuel type**	**Max. payload vehicle [t]**	**Distance [km]**
Reparation material transport	Distributor	Workplace	Lorry 10-20 tonne – Diesel	28	50
Asphalt transport	Asphalt manufacturer	Workplace	Lorry > 20 tonne – Diesel	28	50
Machinery transport	Machinery depot	Workplace	Lorry > 20 tonne – Diesel	28	50
Waste transport	Workplace	Disposal site	Lorry > 20 tonne – Diesel	28	50

2.2.2.5 Maintenance

Hydraulic cleaning

In this study, hydraulic cleaning with two separate vehicles was considered: a vehicle containing a water tank and a vacuum truck for suction of sewage sludge. Moreover, hydraulic cleaning using a single vehicle (i.e. combi truck) was evaluated as well. The so-called “combi truck” incorporates a water jetting device (including a water tank) and a suction module into a single vehicle.

As the pipe size and/or sewer section length increases, the total cleaning time also increases (Stichting RIONED, 2015). Therefore, the energy consumption of the cleaning vehicles has been determined for each relevant pipe diameter group. The average daily cleaning capacity for gravity sewer systems for each pipe diameter was obtained from key figures as reported by Stichting RIONED (2015), these values are presented in Appendix A Table 21 and Table 22 for both cleaning methods. The sewage sludge to be disposed per meter per pipe diameter was estimated using key figures from Stichting RIONED (2015) as well.

Average hourly diesel consumption data of sewer cleaning trucks were retrieved from Jansen Rioolreiniging BV (2015), a sewer cleaning company located in the Netherlands. The effective cleaning capacity of a vacuum truck can be assumed 5,5 hours per day, 7 hours per day for the water truck and 5,5 hours per day for the combi truck (Jansen Rioolreiniging BV, 2015). This means, for example, that it takes up to 7 hours to clean 800 metres for a pipe diameter of 400 mm for the water truck. The reason that the operating time of the water truck is 7 hours instead of 5,5 hours per day, is that it takes approximately 1,5 hours per day to fill the water tank (Jansen Rioolreiniging BV, 2015). See Appendix A Table 21 and Table 22 for detailed information about hydraulic cleaning.

Mechanical removal of intruding roots

In this case, mechanical cleaning refers to the procedure of removing intruding roots from sewer pipes using a mechanical device. For simplification purposes, it was assumed that the cleaning time does not vary for different pipe diameters. Instead, the cleaning time was assumed to be only dependent on the number of roots to be removed. The time required to remove intruding roots from sewer pipes is heavily dependent on several factors, these factors include the number of roots in the sewer section, the thickness of the roots, the type of mechanical cleaning device, job efficiency of the contractor, etc. (Stichting RIONED, 2019). It is therefore very difficult to accurately determine the average time required to mechanically clean a sewer section. However, after close communication with Roelofs Groep experts, credible assumptions could be made. In this study, it was assumed that an average gravity sewer section with a length of 45 m has intruding roots at two locations. It takes approximately 10 minutes to mechanically remove an intruding root at one location in the sewer. In addition to that, it was assumed that it takes 20 minutes in total to insert and remove the mechanical device. Thus, the total cleaning time per sewer section was set at 40 minutes. Diesel consumption data was retrieved from Gemeente Amersfoort (2019).

Inspection

As mentioned in the scope definition, two sewer pipe inspection techniques were considered: inspection using robotic CCTV camera and a MZC. The main difference between a robotic CCTV and a MZC is that a MZC does not require hydraulic cleaning of the sewer section before the inspection. Moreover, these methods significantly differ in inspection speeds. Plihal and Šikman (2018) argue that the inspection speed of a conventional CCTV robot is approximately 40 minutes per sewer section with an average length of 45 to 50 metres. In contrast, the inspection speed of a MZC is approximately 10 minutes per sewer section (Plihal & Šikman, 2018). It was assumed that the pipe diameter does not influence the inspection speed.

Transport

For simplification purposes, it was assumed that the location of water intake (to fill the water tank) is relatively close to the workplace. Hence, the fuel consumption as a result of driving between the location of water intake and the workplace was neglected. In Table 19, the transportation scenarios considered for sewer maintenance are shown.

Table 19: Transportation data used for sewer maintenance.

Transportation data for LCI					
Transportation scenario	**From**	**To**	**Vehicle and fuel type**	**Max. payload vehicle [t]**	**Distance [km]**
Inspection vehicle	Depot	Workplace	Big van >2 tonne – Diesel	1,2	50
Water truck	Depot	Workplace	Lorry 10-20 tonne – Diesel	7,5	50
Vacuum truck	Depot	Workplace	Lorry 10-20 tonne – Diesel	7,5	50
Combi truck	Depot	Workplace	Lorry 10-20 tonne – Diesel	7,5	50
Mechanical cleaning vehicle	Depot	Workplace	Lorry <10 tonne – Diesel	3	50
Waste disposal	Workplace	Disposal site	Lorry 10-20 tonne – Diesel	7,5	50

2.2.3 *Environmental impact assessment*

In this phase, the environmental impacts were evaluated based on the compiled LCI of the system in question. Hence, the environmental impacts that can be associated with the material and energy consumptions of various sewer M&R techniques were quantified. In the case of a CF assessment, the environmental impact category is the potential climate change. Therefore, the GHG emissions were translated into units of CO_2-eq (ISO, 2018). As mentioned before, a single-indicator (i.e. climate change) approach is deemed satisfactory for the main objective of this study.

It should be mentioned that the "UK Government Conversions for Company Reporting" database was used to quantify emissions associated with the treatment of wastes which are generated during maintenance or rehabilitation works. This database accounts for emissions from open- and closed-loop recycling using guidelines proposed by the GHG Protocol (UK Governement, 2019) Furthermore, the database in question accounts for emissions from incineration (with energy recovery).

2.2.3.1 Carbon footprint calculation model

The general carbon footprint calculation model of a certain sewer maintenance or rehabilitation technique is defined as:

$$CF = n \times \sum_{i=1}^{U} CF_i \tag{1}$$

Where *CF* is the total carbon footprint of a maintenance or rehabilitation technique; CF_i is the carbon footprint of the *i*th stage of the life cycle of the technique in question; and *U* is the total number of life cycle stages (i.e., four consisting of production, maintenance/rehabilitation, disposal, and transportation respectively). Furthermore, in Equation (1), *n* refers to the number of interventions for the sewer maintenance or rehabilitation technique in question within the specified time frame (i.e. 100 years); for open trench sewer replacement and CIPP lining, a value of 1 was considered. For sewer pipe inspection, a value equal to 6 was adopted.

Equation (2) shows the model used to calculate the total CF of the production stage (CF_a):

$$CF_a = \sum_{k=1}^{M_a} M_k \times EF_k \tag{2}$$

Where M_a is the total number of material types in stage *a*, M_k is the consumption (amount) of the *k*th material type and EF_k is the embodied carbon emission factor corresponding to the *k*th material type. The embodied carbon emission factors used in this study account for all relevant GHG emissions related to a certain material from cradle to (factory) gate.

Equation (3) was used to calculate total GHG emissions associated with the maintenance or rehabilitation stage (CF_m) of a certain technique:

$$CF_m = \sum_{p=1}^{P} \sum_{q=1}^{Q} U_q \times T_p \times EF_q \tag{3}$$

Where *P* is the total number of machinery and equipment types used during M&R works; *Q* is the total number of energy types; U_q is the quantity of the *q*th energy type consumed per time unit by machine *p; T_p* refers to the total effective operating time of machine *p*; EF_q is the (well-to-wheel) carbon emission factor corresponding to the *q*th energy type. The energy types considered are, for example, diesel, petrol, and grid electricity. The well-to-well carbon emission factors account for direct and indirect emissions, i.e., emissions related to the production, distribution and transmission of a certain energy type (CO2-emissiefactoren, 2019).

Equation (4) represents the model used to calculate the emissions at the disposal stage:

$$CF_u = \sum_{r=1}^{W_u} \sum_{d=1}^{D} W_r \times DF_{rd} \times EF_{rd} \tag{4}$$

CF_u is the sum of GHG emissions across the waste treatment methods applied for different waste types; W_u is the total number of waste types generated for a certain technique during maintenance or rehabilitation activities; *D* is the total number of disposal routes (including landfill, incineration with energy recovery, open-loop recycling, and re-use); W_r is the quantity of the *r*th waste type, DF_{rd} is the disposal route fraction of the *r*th waste type for the *d*th disposal route. For example, if *r* is concrete and *d* is landfill, then DF_{rd} is 0,01 (i.e. 1% of concrete goes to landfill). Finally, EF_{rd} is the carbon emission factor of the *d*th disposal route for the *r*th waste type.

Finally, the carbon footprint related to transportation is calculated according to the following equation:

$$CF_t = \sum_{v=1}^{V} F_v \times DT_v \times EF_v \tag{5}$$

V represents the total number of vehicles types for freight transport considered in this study as presented by Otten, 't Hoen, and den Boer (2017); F_v is the total quantity of freight to be transported by a certain vehicle type v expressed in metric tonnes (t); DT_v is the total distance (km) travelled by vehicle type v; and EF_v is the well-to-wheel carbon emission factor (kg CO_2-eq/tkm) corresponding to vehicle type v.

2.2.4 *Method for sensitivity analysis*

The CF assessment performed in this study was based on several assumptions. These assumptions might have a certain effect on the outcomes of the impact assessment. ISO 14067:2018 states that, in order to get a better understanding of the uncertainties and sensitivity of the results of the impact assessment, a SA should be conducted (ISO, 2018). In the impact assessment phase, contributions of various life cycle stages, processes, and activities to the CF of the sewer M&R techniques were quantified and compared through basic contribution analyses (i.e. using stacked columns). Based on the relative contributions, key parameters were selected and varied individually according to a one-factor-at-a-time SA method. Thus, the influence of their variability on the result can be assessed.

The sensitivity ratio (SR) was used to assess the sensitivity of the final results (Equation (6)). This ratio can be defined as the ratio between the relative change of the result (i.e. CF) and the relative change of the selected parameter (Clavreul, Guyonnet, & Christensen, 2011):

$$SR = \frac{\Delta X}{X} \cdot \frac{p}{\Delta p} \tag{6}$$

Where X is the baseline CF value; ΔX is the change of the CF; p is the baseline value of a single parameter; and Δp is the change of the value of the parameter p. A SR value of 2 suggests that, if a parameter value increases by 10%, the total CF increases by 20%. A negative SR of a parameter implies that the CF will decrease when a parameter value increases. Moreover, the higher the SR value of a parameter, the higher the sensitivity of the final result to variations of that parameter. Thus, by calculating this ratio, the most sensitive inputs can be identified (Clavreul, Guyonnet, & Christensen, 2011). For the SA performed in this study, SR values were computed by generating variations of +10% and -10% for the selected parameters. From the two SR values that were obtained for each parameter, only the highest absolute SR value was retained.

3 Results and discussion

3.1 Environmental impact assessment

3.1.1 *Sewer replacement environmental impact profile*

The environmental impacts results generated from the sewer pipe replacement are presented in this section.

Figure 9 shows the comparison of CF scores of the replacement of a sewer section with a length of 45 m and a pipe diameter of 400 mm for different pipe materials. This figure shows that among the four types of pipe materials, reinforced concrete was found to be the worst overall performer, followed by vitrified clay and PVC, respectively. On the contrary, the replacement of a concrete sewer section was found to have the best environmental performance. Figure 9 shows that the replacement using concrete pipes has an estimated CF score of $6{,}2{\cdot}10^3$ kg CO_2-eq. Reinforced concrete, on the other hand, has a CF score of $8{,}2{\cdot}10^3$ kg CO_2-eq. Specifically, the CF score of concrete sewer replacement is approximately 25% lower than reinforced concrete, 15% lower than PVC and 22% lower than vitrified clay for a pipe diameter of 400 mm. These differences become more substantial as the pipe diameter increases. One of the main reasons for this result is that the GHG emissions per kilogram related to the production of PVC, reinforcement steel and vitrified clay pipe production is considerably higher than concrete (Morera, Remy, Comas, & Corominas, 2016). Therefore, a sharper increase of the CF score of the production phase can be observed for these material types as the pipe diameter increases (see Figure 10). For a detailed overview of the life cycle impacts associated with sewer pipe replacement, the reader is referred to Appendix B.

Figure 11 presents the results of a contribution analysis. From the analysis of this figure, it can be concluded that the CF score of each material type per pipe diameter group is predominantly dominated by asphalt pavement rehabilitation and pipe production. Furthermore, as the diameter increases, the preponderance of the pipe production tends to overshadow the contribution of the remaining phases. This is especially true for the asphalt pavement rehabilitation phase. Its relative contribution to the CF score decreases as the pipe diameter increases. This phenomenon originates from the fact that, as the pipe diameter increases, the amount of materials required for the sewer pipe production increases at a much higher rate than the amount of asphalt mixture production required for pavement rehabilitation. Furthermore, the contribution of the transportation phase also decreases gradually as the pipe diameter increases. The contribution of the waste disposal phase and pipe installation to the total CF score remains quite similar for different pipe diameters.

Asphalt pavement contains bitumen, which is a product obtained from petroleum refining processes. Its production is a resource- and energy-intensive process which can have a significant negative impact on the environment (de Vos-Effting, et al., 2018). The results of the impact assessment confirm that the asphalt rehabilitation phase is an important contributing factor to the total CF score. It was found that the production and construction of asphalt pavement has a contribution between 43 and 56% (for DN 400 mm) depending on the pipe material. Thus, the exclusion of the asphalt rehabilitation phase can result in a considerable underestimation of the CF score.

On the other hand, diesel and petrol combustion in construction equipment during the pipe installation phase has a relatively low contribution to the CF score. However, it might happen that the actual energy consumption of construction equipment is different from the values presented in this study. This is mainly due to the fact that theoretical values are used for equipment operating times instead of actual and site-specific data. Furthermore, contractors may use different construction equipment, have a lower or higher job efficiency, use more equipment than those considered in this study, etc. (de Vos-Effting, et al., 2018). For this reason, the results of this impact assessment were validated to determine whether they fall within a satisfactory range of accuracy. Sargent (1998) suggests that, as a validation technique, the model results of the study in question can be compared to the results of another (valid) model. Therefore, to validate the environmental impacts associated with the fuel combustion in construction machinery during the pipe installation phase, the results of this study were compared to the environmental impacts of pipe installation which were calculated using DuboCalc software. A further elaboration on this comparison can be found in Appendix C. Based on the findings of this comparison, the results of this study with regards to the environmental impacts of sewer pipe installation are considered satisfactory.

Finally, the transportation and disposal phase were found to have a fairly notable impact. The transportation of (reinforced) concrete pipes was found to be most impactful. However, the differences between overall impacts as a result of transportation were relatively small. The reason for this is that for each type of pipe material the same amount of asphalt was transported. The differences become more prominent as the pipe size increases.

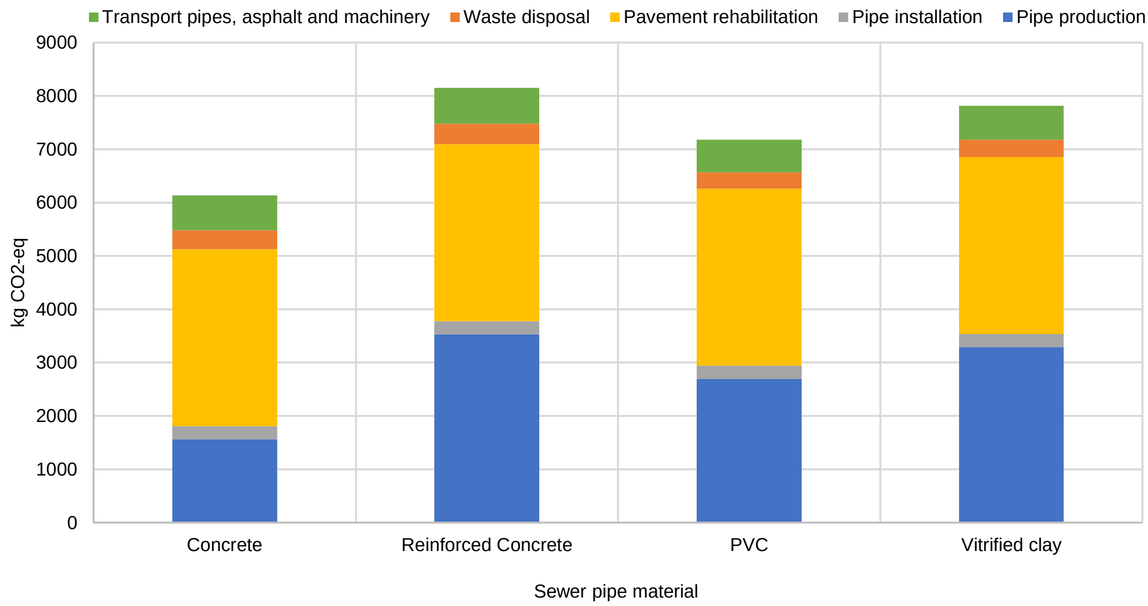

Figure 9: CF scores of replacements of a 45 m sewer section with a nominal diameter (DN) of 400 mm using different pipe materials

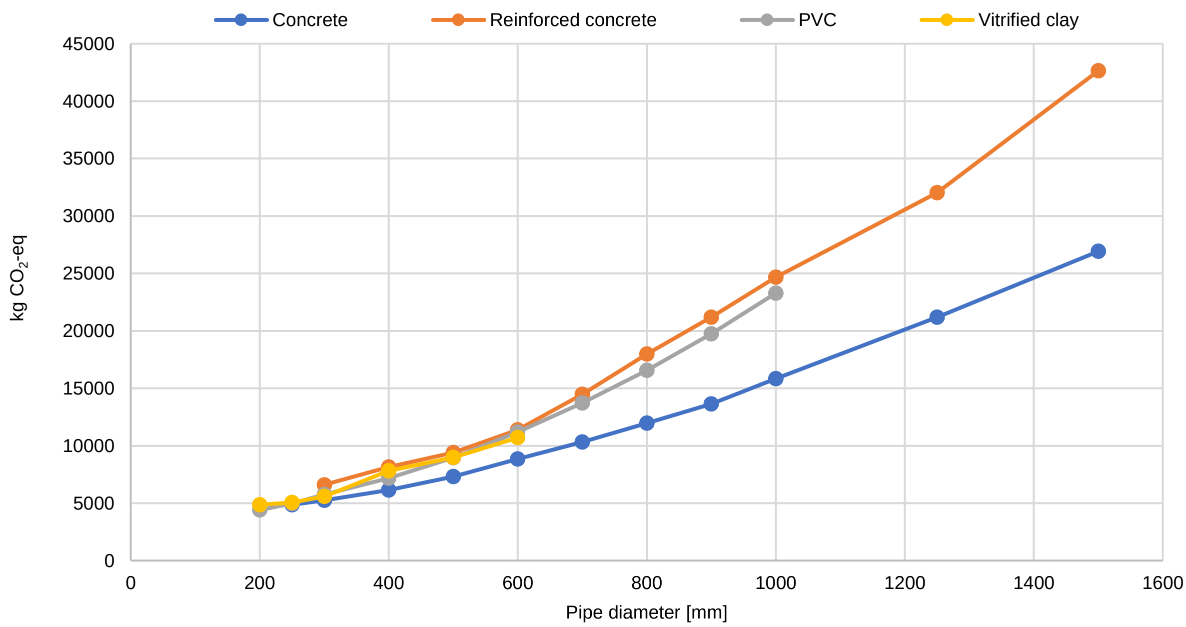

Figure 10: CF scores of replacements of a 45 m sewer section with a DN varying between 200 and 1500 mm using different pipe materials

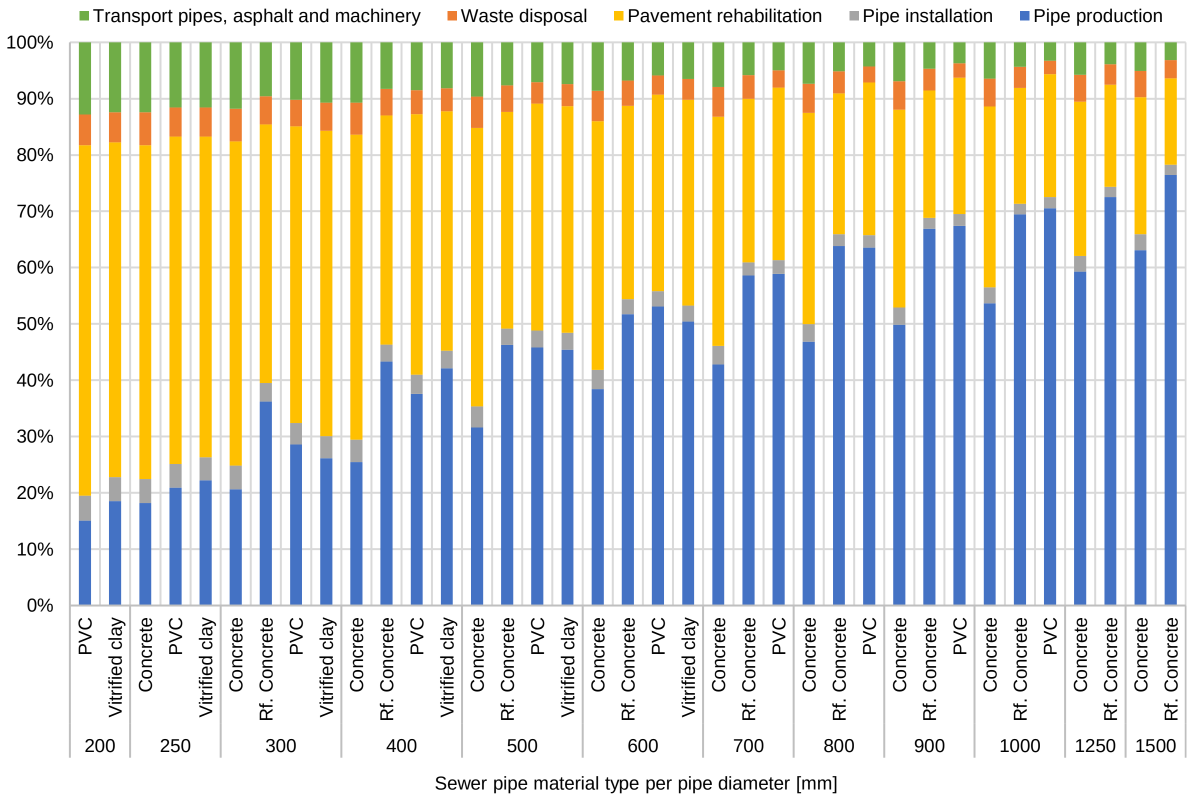

Figure 11: Contribution analysis of sewer replacement for DN 200 to 1500 for different pipe materials

3.1.2 *CIPP lining environmental impact profile*

Figure 12 presents the CF scores of trenchless sewer pipe renovation by means of fibreglass and needle felt CIPP lining. The results in this figure suggest that CIPP liners made of fibreglass have the best overall environmental performance. Considering a pipe diameter of 400 mm, the CF score of fibreglass CIPP lining is $2{,}5 \cdot 10^3$ kg CO_2-eq, whereas the CF score of needle felt CIPP lining is $3{,}2 \cdot 10^3$ kg CO_2-eq. Therefore, the results suggest that for a pipe diameter of 400 mm, an impact reduction of roughly 22% can be achieved when a fibreglass liner is used instead of a felt liner. Moreover, it was found that, for pipe diameters ranging from 200 to 300 mm, the CF score of the production stage of both materials are fairly similar. This is mainly because the wall thicknesses of the liners are almost the same for these pipe diameters (see Table 11). In addition to that, the GHG emissions per kg material is approximately the same for fibreglass and needle felt CIPP liners. As the pipe diameter increases, the differences between the CF scores become more prominent. The reason for this is that needle felt liners are significantly thicker than fibreglass liners for larger pipe diameters (see Table 11). This means that much more resin has to be used to saturate the needle felt liner.

It is important to note that, due to the unavailability of data, the environmental impacts associated with the curing process of needle felt CIPP liner using hot water could not be determined. This means that the results obtained in the impact assessment with regards to needle felt CIPP lining might not be entirely representative of the actual environmental impacts.

Figure 13 shows the results of a contribution analysis. These results reveal that the production stage of the CIPP liner originates the highest contribution to the CF score. For fibreglass CIPP liners, the curing process using UV-light does not seem to be an important contributor. The transportation phase was also found to have a low contribution. This is because transportation of heavy construction machinery, large amounts of material and waste is not required for trenchless renovation. Finally, hydraulic cleaning and inspection prior to the installation of the liner has a somewhat noticeable impact. The environmental burdens of sewer cleaning and inspection will be discussed later in this report.

It should be mentioned that the total running time of the diesel generator is assumed to be equal to the curing time of the liner. However, the diesel generator might run on idle mode for a certain period of time when not in use (Aarsleff, 2020). Idling can result in additional fuel consumption and therefore additional exhaust emissions as well (Rahman, Masjuki, Abedin, Sanjid, & Sajjad, 2013). These emissions are not accounted for since the actual running time of the diesel generator is deemed too difficult to be determined. Thus, the actual impacts associated with fuel consumption are likely to be higher. However, it is expected that this does not have a considerable influence on the total CF score of CIPP lining.

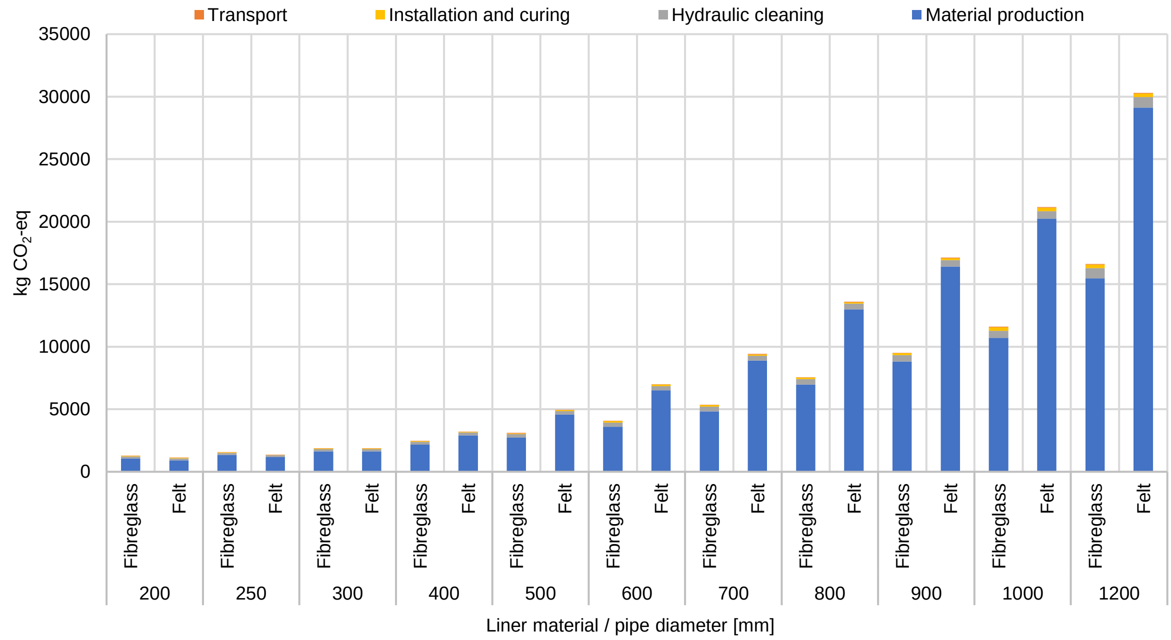

Figure 12: CF scores of a one-time trenchless sewer renovation for a 45 m sewer section with a DN varying between 200 and 1200 mm using different CIPP liner materials

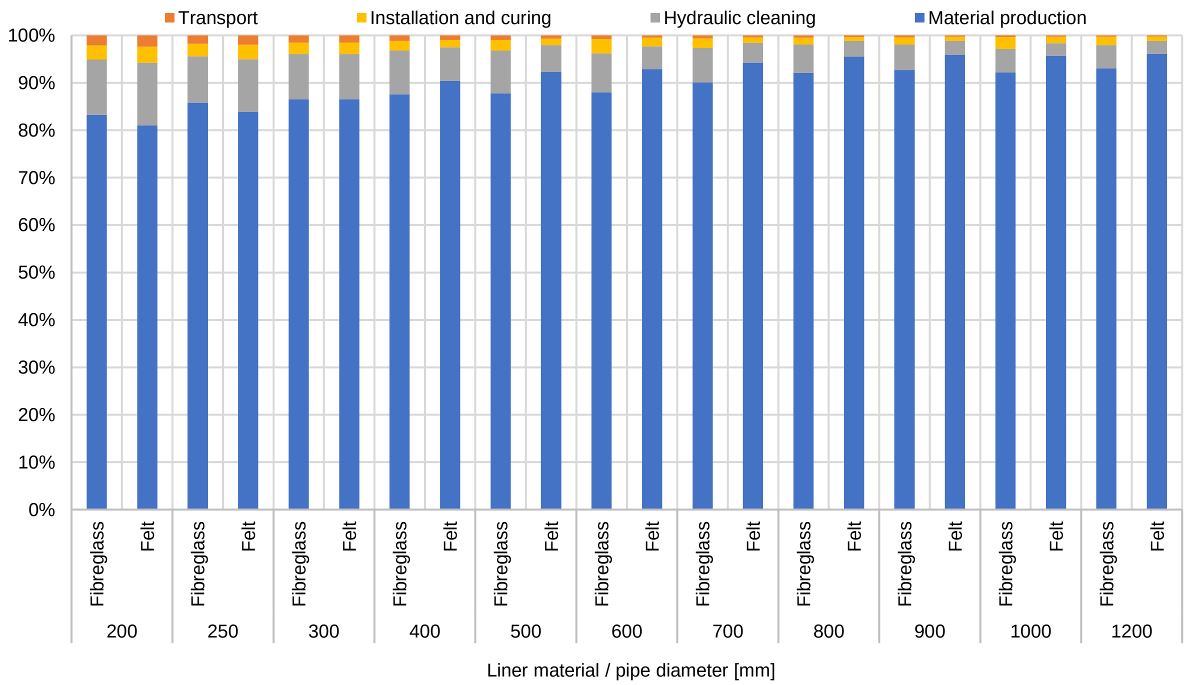

Figure 13: Contribution analysis of CIPP lining for DN 200 to 1200 for different CIPP liner materials

3.1.3 *Sewer pipe repair environmental impact profile*

As mentioned in the scope definition, two sewer repair approaches were evaluated in this study: open-trench and trenchless sewer repair. Open trench pipe repair requires excavation and (often) asphalt rehabilitation, whereas trenchless repair does not. Two techniques were considered for trenchless repair: repair by means of placing a CIPP short liner and placing a mechanical seal.

In Figure 14 the results of the impact assessment of a one-time trenchless repair are depicted. It is assumed that only one mechanical seal or short liner is used for repair. However, it is possible that multiple seals or short liners are installed on one occasion. This will result in a higher environmental impact. Overall, repair by mechanical seal performs the worst. However, there is not much difference. Depending on the pipe diameter, the environmental performance of pipe repair using a mechanical seal is 11 to 26% worse than repair using a CIPP short liner.

The results of the contribution analyses are depicted in Figure 15. This figure supports the conclusion that the highest overall contributor to the CF score in both trenchless techniques is the hydraulic cleaning with an inspection. The material production stage has, to a lesser extent, a significant contribution to the CF scores as well. The amount of material used for trenchless repair is limited (i.e. liner/seal length is 60 cm). Therefore, it can be expected that the impact of the material production stage is less substantial comparatively to that of the trenchless renovation techniques. The environmental burdens of cleaning and inspecting will be discussed in the next section.

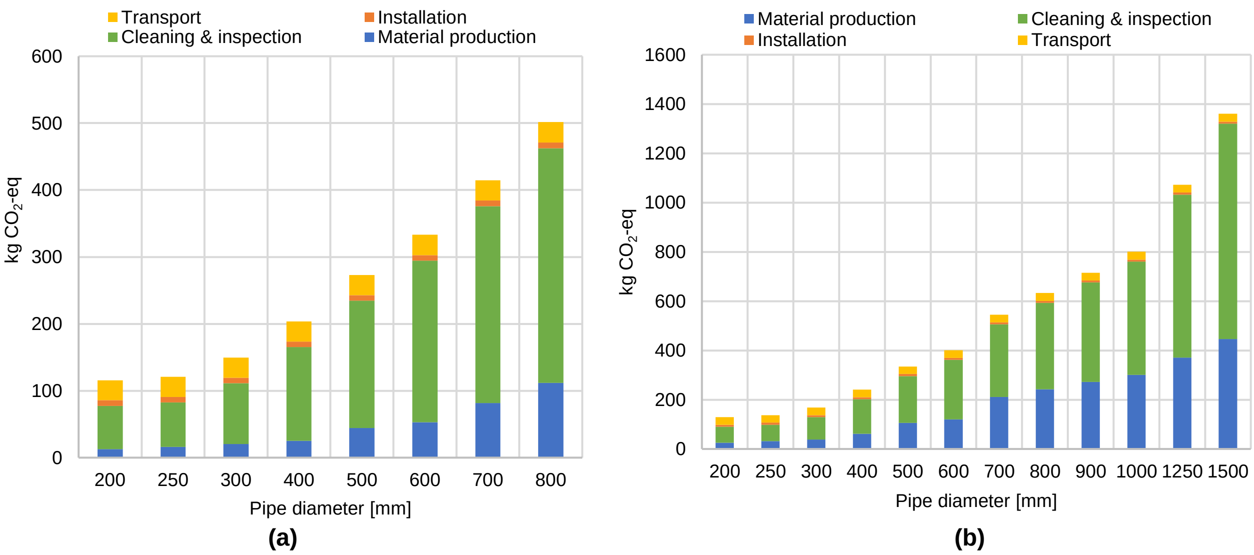

Figure 14: CF of trenchless sewer repair techniques. (a) CIPP short liner. (b) Mechanical seal.

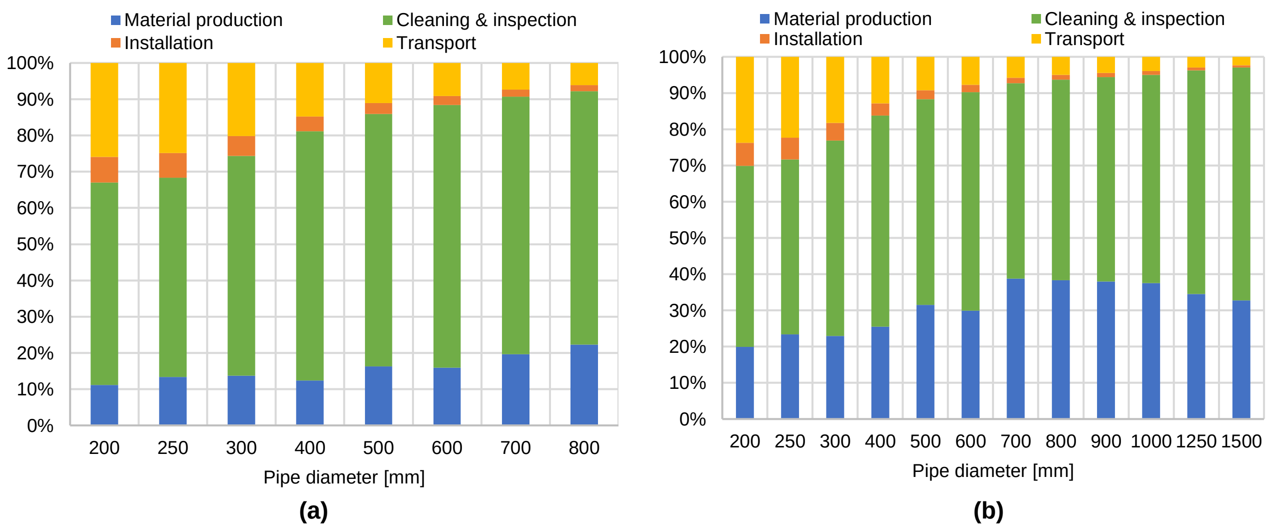

Figure 15: Contribution analysis of trenchless sewer repair. (a) CIPP short liner. (b) Mechanical seal.

The results of the impact assessment of open trench sewer pipe repair are presented in Figure 16. The results show the estimated CF scores for a one-time open trench repair with a trench length of 2,5 m for pipe diameters ranging from 200 to 1500 mm. Inspection and hydraulic cleaning of an entire sewer section with a length of 45 m were also included in the impact assessment. It was found that, depending on the pipe diameter and the trenchless repair method, an impact reduction of 33 to 65% can be achieved when selecting a trenchless repair method rather than an open trench repair method.

Figure 17 presents the results of the contribution analysis corresponding to open trench pipe repair. As previously seen in open trench sewer replacement, asphalt rehabilitation can have a substantial contribution to the total CF score. The same holds true for open-trench sewer pipe repair. Next to asphalt production, hydraulic cleaning and inspection has a considerable contribution as well. It should be recalled that the material production stage does not include the production of material (e.g. grout, injection fluid, etc.) for mending the damage of the pipe. The reason is that the amount and type of material are heavily dependent on the nature and extent of the pipe damage. Even in certain cases, no material is used at all. It is therefore considered too complex to accurately determine the GHG emissions associated with this. It should, therefore, be kept in mind that the actual impacts are possibly higher than the results in this study. Furthermore, the transportation phase has a notable impact as well, this is due to the transportation of fairly heavy equipment (e.g. mini excavator) and materials (asphalt). It is worth mentioning that theoretical values for operating times of construction machinery are used here as well, it is possible that the actual operating times (and therefore the energy consumptions) are different.

Figure 16: CF of open-trench sewer repair (including asphalt rehabilitation)

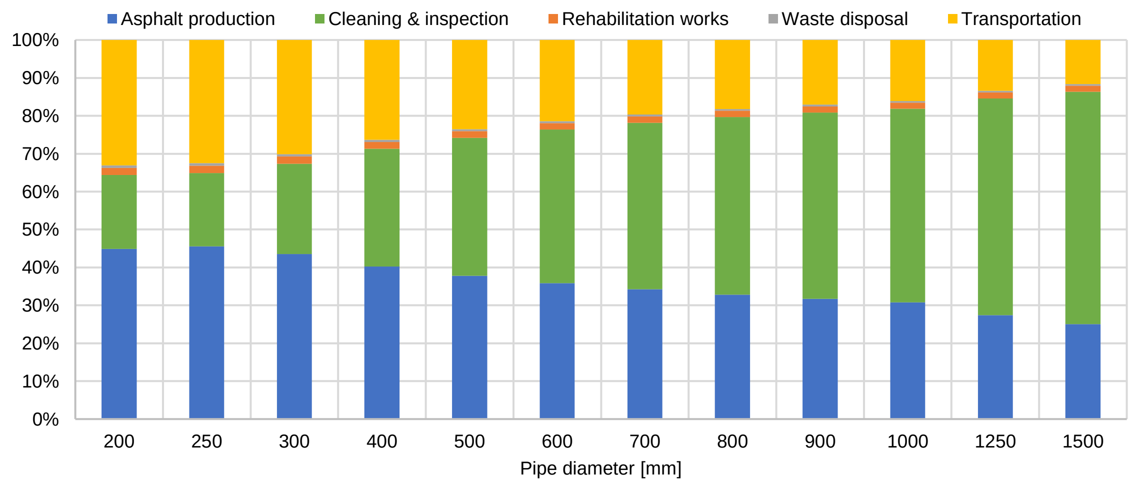

Figure 17: Contribution analysis of open-trench sewer repair

3.1.4 *Inspection and cleaning environmental impact profile*

The results for the environmental impact produced by sewer inspection using the robotic CCTV camera and a MZC method are presented in this section. Figure 18 reports the CF scores of a one-time inspection, whereas Figure 19 shows the CF scores over a period of 100 years with a 15-year inspection cycle time (i.e. 6 inspections). As one would expect, the MZC inspection method is undoubtedly the best performer. By adopting the MZC inspection method, a reduction of 88 to 98% in the GHG emissions can be achieved. The main reason for this is that inspection by MZC does not require hydraulic cleaning beforehand. Finally, the impact associated with mechanical cleaning was found to be 71 kg CO_2-eq per intervention for a gravity sewer section in average situations. For a more detailed overview of the carbon emissions per maintenance activity the reader is referred to Appendix B.

One of the key characteristics of the MZC camera inspection method is that the inspection time is considerably lower than that required by the inspection using a robotic CCTV camera (Plihal & Šikman, 2018). However, this benefit does not appear to be an important differentiating factor between the CF scores of both inspection methods. This is because the environmental burdens associated with fuel consumption during the inspection process is relatively small.

Figure 20 presents the results of the contribution analysis. From this analysis it can be concluded that sludge disposal is one of the main contributors to the CF score of robotic CCTV inspection. A possible explanation for this is that the treatment of raw sewage sludge is a fairly energy-intensive process (Sharma, 2017). Furthermore, water jetting and suction (i.e. hydraulic cleaning) has a considerable effect as well. Thus, hydraulic cleaning (including sludge disposal) has a significant contribution to the CF score of CCTV inspection, which ranges from 19 to 79% depending on the pipe diameter. The cleaning duration is directly linked to the pipe size. Therefore, an increase of the CF score can be observed as the pipe size increases. In contrast, the total CF score of inspection by MZC does not vary for different pipe diameters. The reason for this is that the inspection time remains the same regardless of the pipe diameter.

Finally, it was also interesting to compare traditional cleaning (using two separate vehicles) with cleaning using a so-called combi truck (see Figure 5). As can be seen from the comparison presented in Figure 21, depending on the pipe size, a reduction in the CF score of 18 to 47% can be achieved when using a combi truck for hydraulic cleaning of a sewer section instead of two separate vehicles. This is mainly because a combi truck consumes less diesel during the cleaning process.

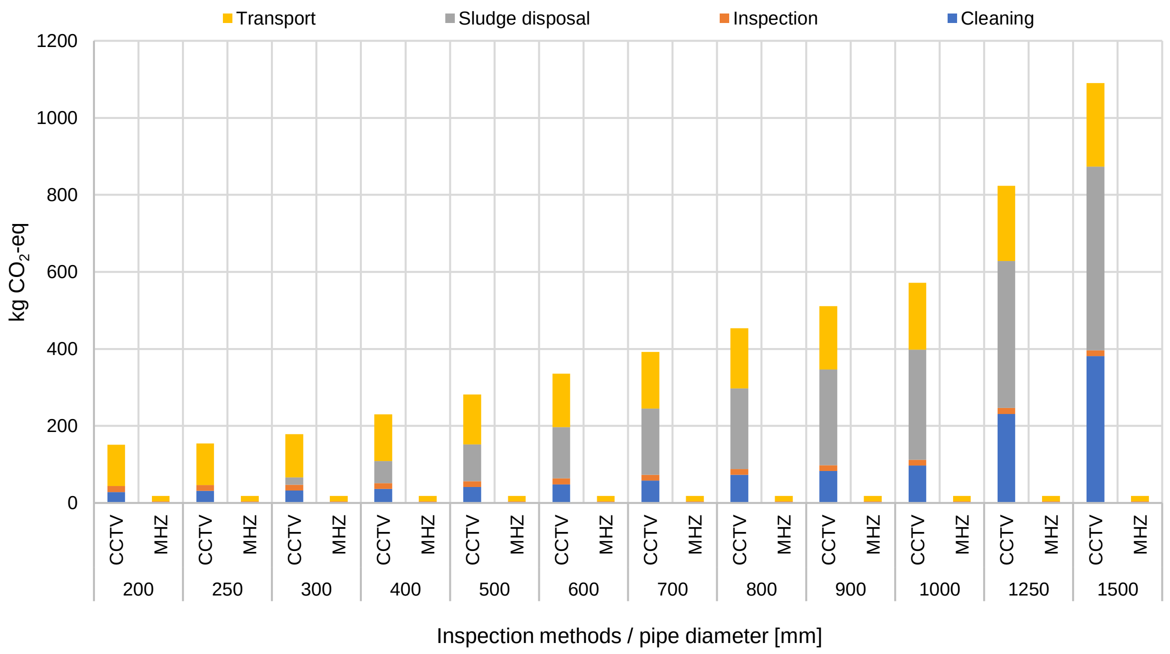

Figure 18: CF scores of a one-time inspection of a 45 m sewer section for DN 200 to 1500 mm

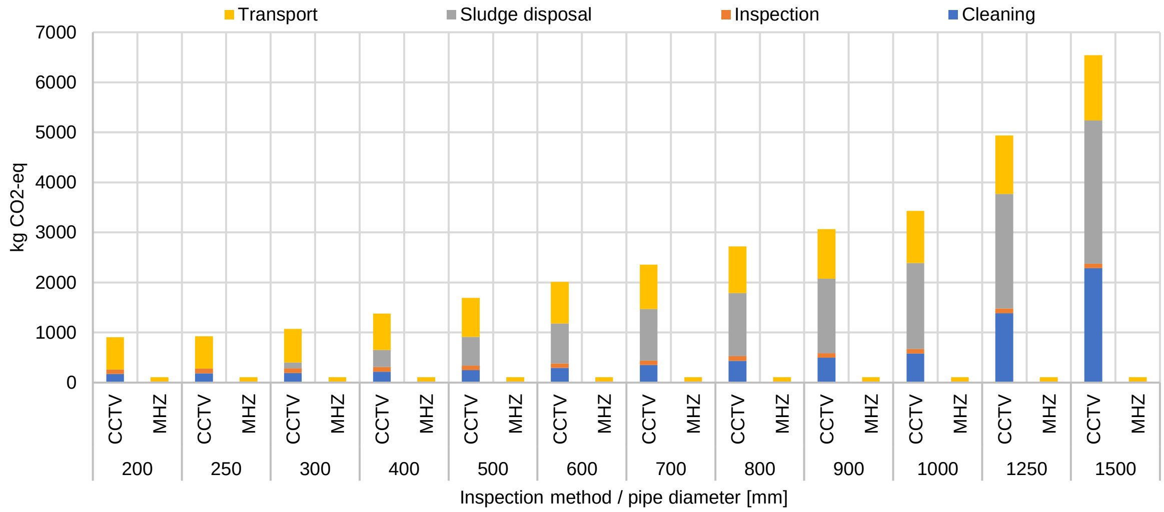

Figure 19: CF of inspection of a 45 m sewer section for DN 200 to 1500 mm over a period of 100 years

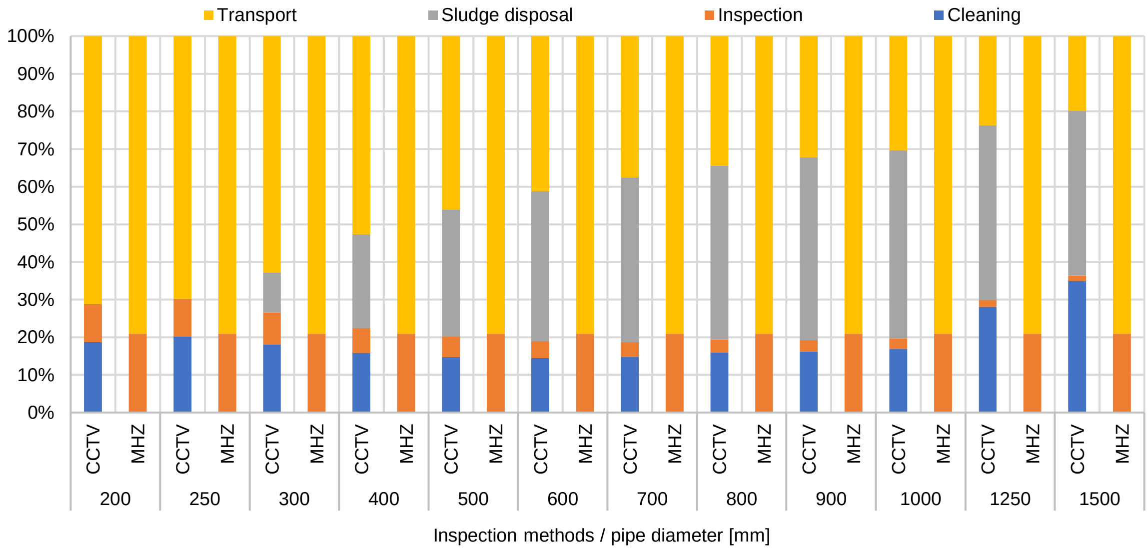

Figure 20: Contribution analysis of sewer inspection for DN 200 to 1500

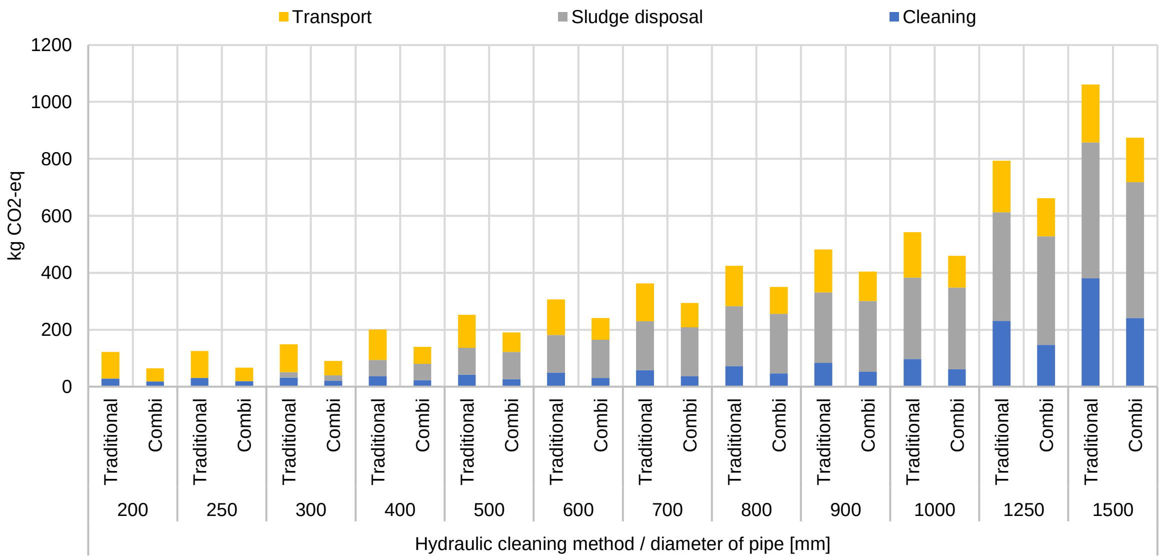

Figure 21: Comparison methods for one-time hydraulic cleaning for DN 200 to 1500 mm: hydraulic cleaning using the traditional approach (i.e. two vehicles) vs using a combi truck.

3.1.5 *Comparisons between open-trench replacement and CIPP lining*

An entire sewer section between two manholes can be rehabilitated using open trench as well as trenchless techniques. The purpose of the comparison provided in this section was to determine which sewer rehabilitation approach is most favourable from an environmental viewpoint. Sewer rehabilitation techniques included in this comparison consist of open trench sewer pipe replacement and trenchless sewer pipe renovation by means of CIPP lining. For open trench replacement, the following pipe materials were considered: concrete, reinforced concrete, PVC, and vitrified clay. CIPP liner materials that were considered are fibreglass and needle felt saturated with polyester resin.

In this study, the quantification method of the CF scores of sewer replacement and CIPP lining were identical and in line with the requirements as proposed by the ISO14067:2018 standard. This allowed for a proper comparison of the two different sewer rehabilitation techniques (ISO, 2018). For the comparison of the two rehabilitation techniques, two scenarios were considered:

1. One-time replacement including asphalt pavement rehabilitation vs one-time CIPP lining
2. One-time replacement excluding asphalt pavement rehabilitation vs one-time CIPP lining

For scenario 2, it was assumed that the pavement on top of the sewer section consists of paving stones instead of asphalt. Figure 22 presents the CF results of the comparisons:

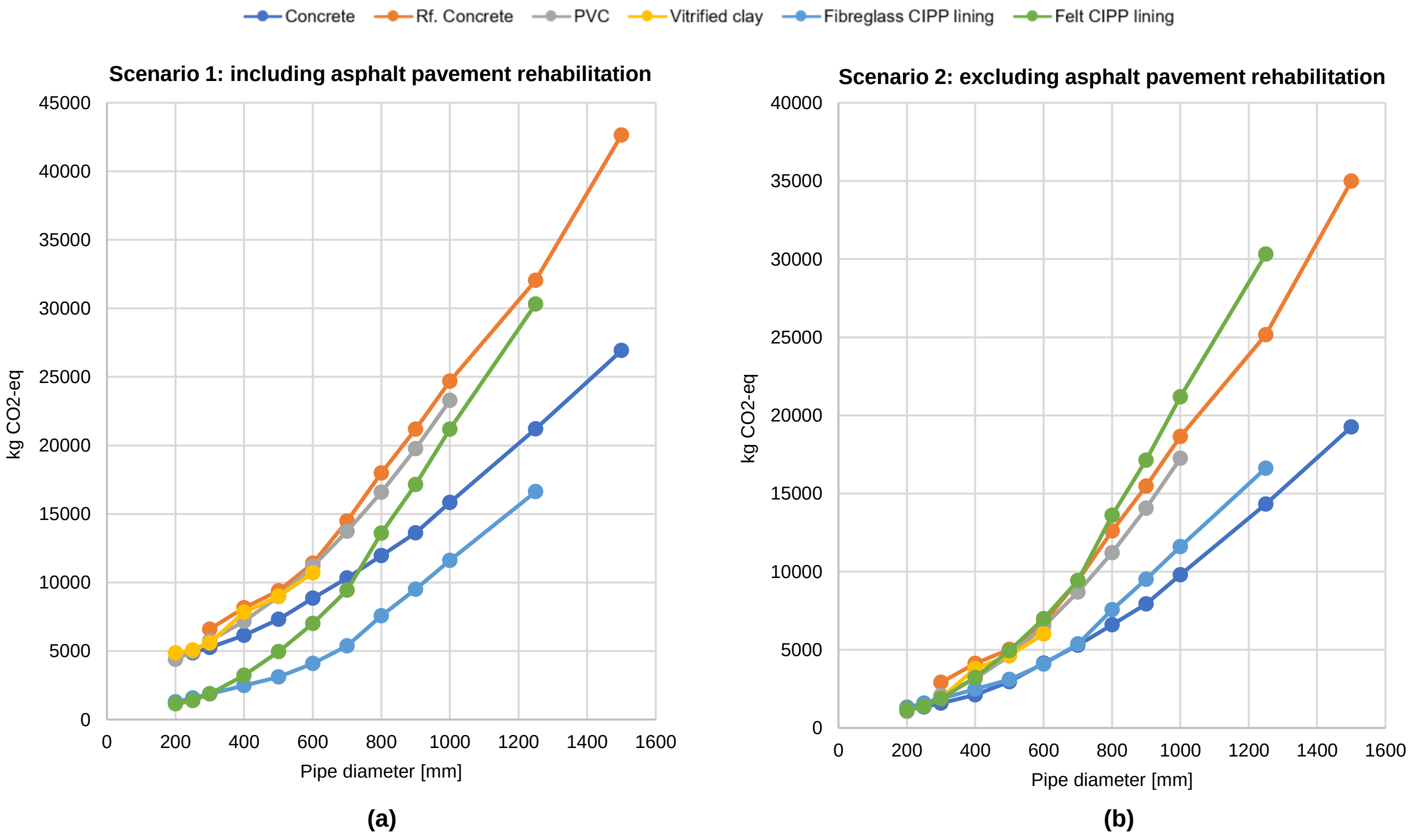

Figure 22: Comparison between open-trench replacement and CIPP lining for different scenarios

The findings presented in Figure 22a suggest that trenchless pipe renovation using a fibreglass CIPP liner is the most favourable rehabilitation technique in case of scenario 1. By adopting CIPP lining with fibreglass material as a sewer rehabilitation technique instead of open trench replacement with concrete pipes, an environmental impact reduction of 27% to 67% can be achieved depending on the pipe size (in case of scenario 1). CIPP lining using needle felt material can be a fairly good alternative to open trench replacement as well. However, as can be seen from Figure 22, needle felt lining becomes a relatively unsustainable alternative (from the environmental viewpoint) for sewer sections with a pipe diameter larger than 700 mm. The reason for this is that needle felt liners become drastically thicker as the pipe diameter increases, meaning that much more thermosetting resin is required to saturate the liner. In case of scenario 2, open trench replacement using concrete pipes and fibreglass CIPP lining seems to have a fairly comparable impact. Needle felt CIPP lining turned out to be not environmentally friendly that case. The same holds true for pipe replacement using PVC, reinforced concrete, and vitrified clay pipes in both scenarios. The comparative results presented in Figure 22 confirms the conclusion that asphalt pavement rehabilitation is an important factor to take into account when selecting a rehabilitation technique.

3.2 Sensitivity analysis

From the overall results presented in the previous sections, it can be concluded that the pipe production stage and asphalt rehabilitation stage are the largest contributors to the CF score of open trench replacement. Likewise, the transportation stage is, to a lesser extent, a relatively notable contributor as well. With this in mind, a number of key parameters were selected for the SA. They are as follows: trench angle (α), asphalt pavement thickness, bitumen content of the asphalt mixture, transportation distance, and sewer section length. The reason for including the trench angle (α), is that the dimensions of the asphalt pavement are directly linked to the dimensions of the trench. The trench angle (α) can range between 30° and 90°. Furthermore, the average sewer section length in the Netherlands ranges between 45 and 50 m. Therefore, the length of the sewer section cannot be neglected. Figure 23 presents the results of the SA of open trench sewer pipe replacement for a pipe diameter of 400 mm. From the results presented in this figure it can be concluded that the dimensioning of the trench, and therefore the dimensioning of the asphalt pavement, can have a substantial overall effect on the CF score of pipe replacements. The negative SR values suggest that, if the trench angle (α) is increased by 10%, the CF score will decrease by 14 to 18% (i.e. SR of -1,4 to -1,8) depending on the pipe material. Changing the sewer section length was also found to have a notable effect, as denoted by the SR value of approximately 0,95 observed for all pipe materials. For the asphalt thickness, SR values were found to range between 0,47 and 0,63, meaning that the CF score will increase with 4,7 to 6,3% if the asphalt thickness increases by 10%. Finally, slight changes in the asphalt mixture properties were found to result in relatively small changes.

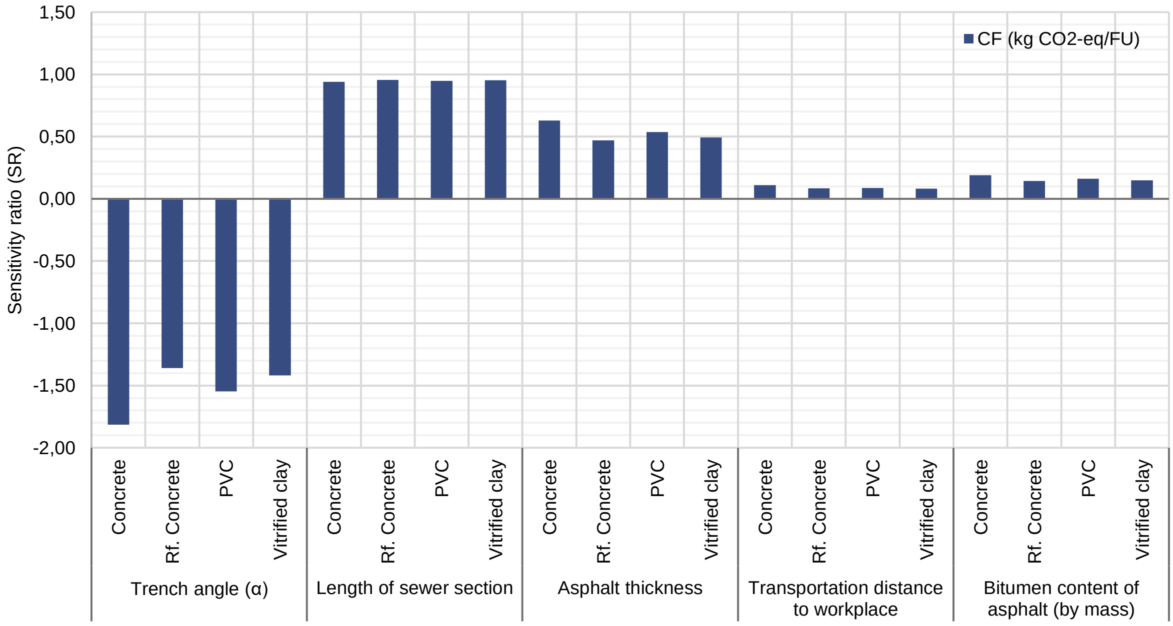

Figure 23: Sensitivity ratios for sewer replacement for DN 400 mm

The main contributor to the CF score of CIPP lining is the production phase of the liner. Average values have been adopted for the thicknesses of the liners. However, the DWA-M 144-3 (2015) standard shows that the thickness of fibreglass and felt liners varies depending on de groundwater level and material group (i.e. elastic modulus of material). Hence, the SA evaluated the effects of changing the liner thickness. Other parameters considered are the liner length, transportation distance and curing time.

The results of the SA for CIPP lining are presented in Figure 24. From the SR values presented in this figure it can be concluded that, as expected, the liner properties are by far the most important influencing factors. The SR related to the thickness of fibreglass CIPP liners was found to be 0,87 where for needle felt the it was 0,91. This means that an increase of 10% of the liner thickness can result in an increase in the impact of roughly 9% for both material types. The same holds true for the liner length, as SR values of 0,90 and 0,92 were observed for fibreglass and needle felt, respectively. The effects of the other selected parameters seem to have a negligible effect on the final results. This is confirmed by the SR values corresponding to the hydraulic cleaning capacity parameter. For this parameter, SR values of -0,01 and -0,02 were found for fibreglass and needle felt CIPP liners, respectively. The negative SR indicates that the impact will decrease if the sewer cleaning capacity per day increases. For the curing time, the SR values were observed to be lower than 0,02.

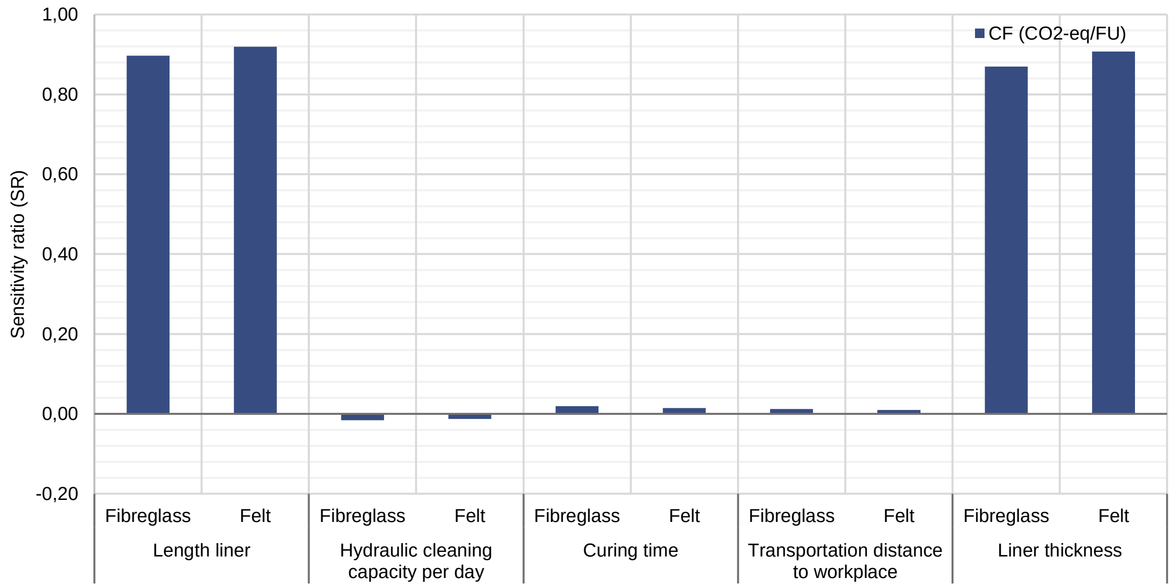

Figure 24: Sensitivity ratios for CIPP lining for DN 400 mm

The largest contributors to the CF scores of trenchless sewer pipe repair are the production and hydraulic cleaning/inspection stage. Since the length of the pipe section to be repaired is heavily dependent on the nature of the damage, the effects of changing the length of the mechanical seal and CIPP short liner was evaluated. Other key parameters considered were the transportation distances, hydraulic cleaning capacity and installation time. Figure 25 presents the results of the SA of trenchless sewer pipe repair. This figure supports the conclusion that the length of the short liner or mechanical seal is the most sensitive parameter. The SR corresponding to this parameter is 0,12 for pipe repair using a CIPP short liner and 0,26 for repair by mechanical seal. It should be noted that the results in this study, regarding sewer repair, can have a large degree of uncertainty. However, since 60 cm is a common length for short liners and mechanical seals (Flua, 2020), the results are considered representative and satisfactory for the goal of this study. Furthermore, as expected, a small increment of the hydraulic cleaning capacity has a relatively large effect on the final CF score. In addition to that, from the previous sections it can be concluded that the exclusion of hydraulic cleaning and inspection prior to the reparation works can result in a very large underestimation of the CF (58 to 69% lower for DN 400 mm). This is reflected in the SA results presented in Figure 25 since a SR of -0,11 and -0,13 was found for the hydraulic cleaning capacity per day. Likewise, the transportation distance has a fairly large influence on the environmental impact as well. Finally, the installation time can be considered a very uncertain factor. However, as it can be seen from Figure 25, the effects as a result of varying the installation time are fairly small (SR of 0,03 and 0,04).

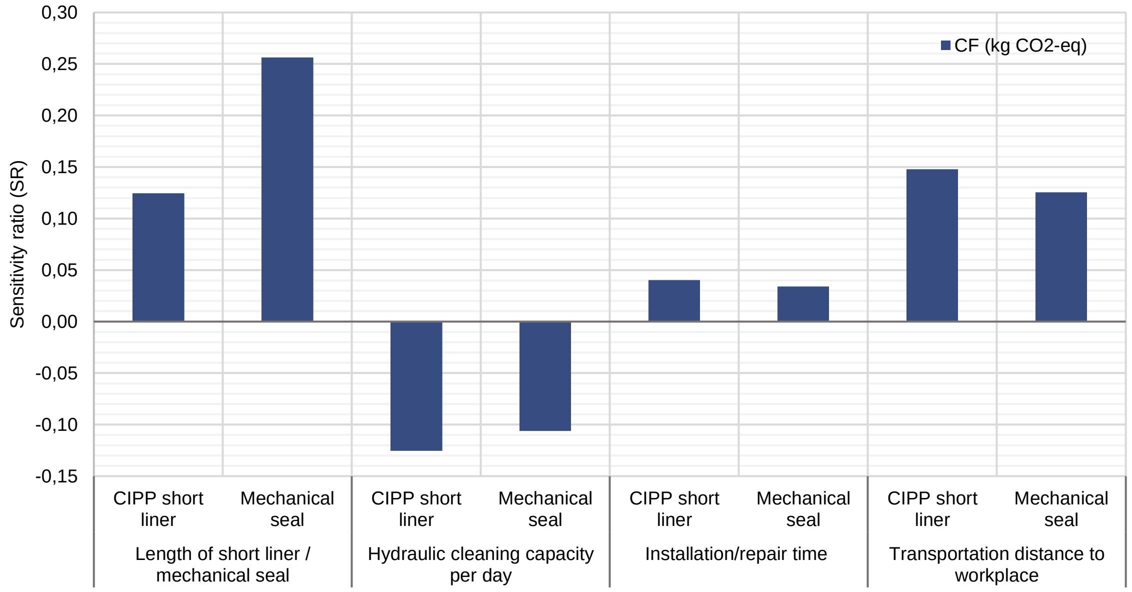

Figure 25: Sensitivity ratios for trenchless sewer repair for DN 400 mm

The calculated SR values for sewer inspection are shown in Figure 26. Based on the contribution analysis conducted in the impact assessment, the following key parameters were selected: hydraulic cleaning capacity, transport distance, amount of sludge to be disposed, and inspection time. The transportation distance was found to be a key influencing factor for both inspection methods. The reason for these results is that transport is the largest contributor to the CF score for a sewer section with a pipe diameter of 400 mm. It is expected that the sensitivity of the CF with regards to the transport distance will decrease as the pipe diameter increases (except for the MZC inspection method). To a lesser extent, the amount of sludge to be disposed can have a fairly significant effect on the CF scores as well (i.e. SR is 0,31). The overall effect of the remaining parameters on the CF score is relatively insignificant, because the absolute SR of all these parameters were found to be lower than 0,21. Finally, in this study, it was assumed that an average sewer section is inspected on a 15-year cycle. However, this can vary for different municipalities in the Netherlands. It is therefore interesting to evaluate the effects of a different inspection cycle. Thus, a 10-year cycle during a period of 100 years was also evaluated. This scenario results in an increase of the CF score of approximately 67% for both inspection methods.

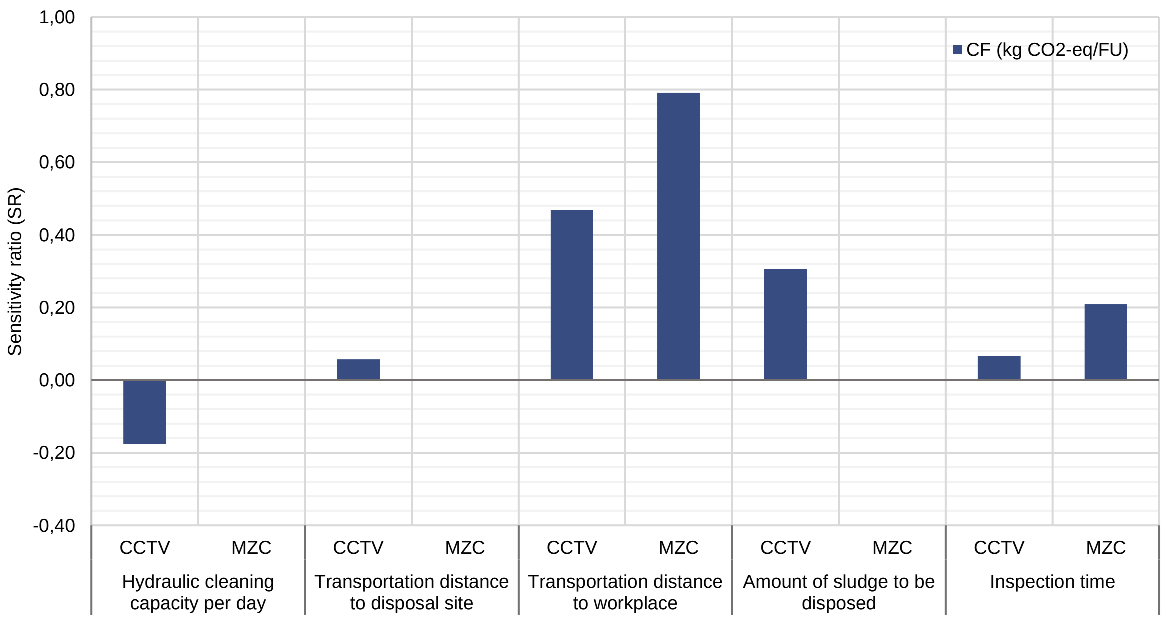

Figure 26: Sensitivity ratios for sewer inspection for DN 400 mm

4 Summary and conclusions

Currently, there are approximately 150.000 km of sewer pipes and drains in the Netherlands (Stichting RIONED, 2019). This entire system is susceptible to deterioration, structural failure, disruptive events, and many other threats. These systems are expected to face major problems due to ageing. Therefore, the expectation is that a substantial quantity of sewer maintenance and rehabilitation (M&R) activities will be undertaken in the near future. Currently, the selection of techniques to maintain or rehabilitate sewers are predominantly based on financial and quality considerations. Engineering firms are not able to make environmental-based well-informed decisions, because the environmental impacts that are associated with different sewer management techniques are not sufficiently well known at the moment. As a result, environmental aspects are barely considered to support decision-making processes in sewer management systems. For this reason, this study was commissioned by Roelofs Groep, who is an civil engineering firm based in the Netherlands. The main aim of this thesis was to estimate the environmental impacts that are generated from maintaining and rehabilitating conventional gravity sewer systems. This was done by means of a carbon footprint (CF) assessment according to the guidelines and requirements as presented by the ISO14067:2018 international standard for carbon footprints of products. The methodology proposed by the ISO14067:2018 standard was applied through four main phases: (1) goal & scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation of the results.

Several M&R techniques exist to ensure that a sewer is able to continuously deliver its original functioning. In this case, “original functioning” of a sewer system is defined as properly conveying municipal wastewater and/or surface water runoff from the gravity sewer system to the location of treatment or disposal. Relevant sewer M&R techniques to be evaluated in this study were identified and selected in close communication with a Roelofs Groep’s expert. This study included the following techniques: open trench sewer pipe replacement, trenchless renovation by means of cured-in-place pipe (CIPP) lining (or relining), trenchless and open trench pipe repair, pipe inspection and cleaning. Open trench replacement is mainly characterised by the fact that excavation works are required to rehabilitate a certain sewer section. In many cases, asphalt pavement reconstruction is also required. CIPP lining refers to the procedure of inserting a flexible sleeve (made from either needle felt or fibreglass) saturated with thermosetting resin in a sewer section. This sleeve is then cured in place through heat exposure, creating a new pipe within the existing pipe is created. CIPP lining does not require excavation works and/or asphalt rehabilitation. Sewer pipe repair is defined as a measure to rectify local damages in sewer pipes. Open trench, as well as trenchless technologies, exist for this purpose. Trenchless repairs are carried out from the inside of the sewer pipe, using a robotic device or by man, without the need for excavation and pavement rehabilitation works. Finally, inspection and cleaning are required both to assess the condition of a sewer and to prevent the development of problems.

In this study, a cradle-to-site CF assessment was performed. This means that this study focussed on greenhouse gas (GHG) emissions related to raw material extraction, manufacturing and assembly processes, civil engineering works, disposal of wastes (which are generated on-site) and transportation. For each of the aforementioned technique, a comprehensive inventory was compiled. The inventory analysis phase is concerned with quantifying all relevant inputs (e.g. materials, energy, etc.) and identifying outputs (e.g. GHG emissions to air) of the product or service system in question. Data for the inventory was collected by conducting extensive desk research and frequently consulting experts. From the inventory phase can be concluded that open trench sewer pipe replacement is a very labour-intensive procedure (i.e. the required labour to produce goods and services is high) compared to trenchless technologies. This is mainly because large amounts of materials (heavy pipes and asphalt) need to be produced, disposed and transported, and many different construction machinery are used. The same holds true for open trench sewer pipe repair. In contrast, trenchless technologies (e.g. CIPP lining) are relatively less labour-intensive, as they do not require a high number of different activities to rehabilitate a sewer section. The next step of the CF assessment was to calculate the climate change impacts (expressed in kg CO_2-eq) based on the quantified inputs of the inventory analysis. Carbon emission factors were obtained from embodied carbon databases for construction materials, such as the Inventory of Carbon & Energy (ICE) v2.0/3.0 database and CO2-emissiefactoren.nl. The obtained results show that the production stage is the highest contributor to the CF score of sewer rehabilitation techniques. For open trench sewer replacement, pipe production and the asphalt manufacturing process are responsible for the high environmental impact. Four pipe material types were considered for sewer pipe replacement: concrete, reinforced concrete, PVC and vitrified clay. It was found that replacements using concrete pipes result in a lower environmental impact, whereas reinforced concrete was found to be the worst performer. Concerning CIPP lining, fibreglass liners were found to have a considerably better environmental performance than needle felt liners. The primary reason for this result lies in the fact that needle felt liners are generally much thicker and therefore require much more thermosetting resin. On the basis of the impact assessment, it can be said that trenchless sewer renovation by means of fibreglass CIPP lining can be much more favourable than open trench replacement from an environmental perspective, provided that asphalt rehabilitation is required in case of replacement. Furthermore, two inspection methods were compared in this study: inspection using a robotic CCTV camera and a Manhole-Zoom camera. Inspection by a Manhole-Zoom camera was found to be undoubtedly the most sustainable inspection method. Compared to a one-time sewer rehabilitation, a one-time inspection of a sewer section was found to have a relatively insignificant impact on the environment. However, when considering a long time period (e.g. 100 years) and depending on the number of sewer sections to be maintained, the impact of sewer inspection and hydraulic cleaning can be substantial. Thus, inspections by means of a Manhole-Zoom camera instead of the traditional inspection should be encouraged and promoted.

Finally, several assumptions were made in this study. These assumptions may affect the final results at different levels. Therefore, a sensitivity analysis was conducted to assess the extent to which the final results are sensitive to those assumptions. Based on the largest contributing factors, key parameters were selected for each sewer M&R technique. These parameters were then varied by small increments and the effects on the final results were observed. Based on this analysis, it was found that changes in the dimensioning (especially the width) of the asphalt pavement resulted in significant changes to the total CF of sewer pipe replacement. For CIPP lining, the liner thickness turned out to be an important influencing factor. Considering the trenchless sewer pipe repair, changes to the length of the pipe damage and the transportation distances resulted in relatively significant effects on the total CF.

5 Recommendations

5.1 Recommendations for improvement of sewer management systems

In the impact assessment of this study, sewer M&R activities and phases which contribute significantly to the environmental burdens of sewer management systems were identified. These so-called “hot spots” can be used to design targeted measures to improve the environmental performance of a specific technique or sewer management system as a whole. To illustrate this, it has been observed that asphalt pavement rehabilitation can have a substantial contribution to the environmental impact of open trench sewer pipe replacement. To improve the environmental performance of sewer pipe replacement, one can decide to reduce the trench size (width) such that the amount of asphalt mixtures to be manufactured will be (greatly) reduced. Another improvement opportunity for open trench pipe replacement lies in the choice of pipe materials. The environmental impacts of pipe replacement might be effectively reduced by choosing concrete pipes rather than reinforced concrete, PVC or vitrified clay. Furthermore, adopting trenchless technologies for pipe rehabilitation, such as fibreglass CIPP lining, can also reduce drastically the environmental impact. With regards to sewer inspection, the findings suggest that the use of the MZC approach for sewer inspections should be encouraged and promoted. In brief, the results of this study can be useful to set up concrete plans to optimise sewer management practices from an environmental perspective. However, it is important to note that the results of this study should not be seen as the main deciding factor for decision-making processes related to sewer management practices. They can also be used to raise awareness and educate the public about the environmental implications of M&R of sewer systems.

5.2 Recommendations for further research

This study aimed to estimate the environmental impacts of M&R of a conventional gravity sewer system. However, not all components of a conventional gravity sewer system were included in this study. Such a system consists of many different components. Some basic components of a conventional gravity sewer system, besides pipes, are manholes, gully inlets, and lateral connections. Each component has a particular function within the system and is made of a certain type of material. Different techniques exist to maintain and rehabilitate these components, which are directly and indirectly associated with different environmental impacts. Therefore, to get a complete and comprehensive overview of the environmental burdens that are associated with M&R of an entire gravity sewer system, the other sewer components should be included as well. Furthermore, it would be interesting to perform a CF assessment (or a complete LCA analysis) on the M&R of pressurised sewer systems.

In addition to that, only a limited number of M&R techniques were considered in this study. However, many other techniques exist as well. For instance, trenchless technologies for sewer pipe replacements (e.g. pipe bursting, pipe eating, pipe extraction, etc.) were not considered in this study. Likewise, different inspection techniques exist to monitor and assesses the condition of sewer components, such as, for instance: visual inspection by man, radar measuring, vacuum testing, smoke testing, etc. (New England Interstate Water Pollution Control Commission, 2003). Another aspect worth mentioning is that sewer pipe repair by means of injection (e.g. using grout, resin, etc.) was not included in this study, even though it is a quite common technique to rectify local damages in sewer components (Flua, 2020). It might be interesting to evaluate the environmental impact of the aforementioned (and other relevant) M&R techniques. In addition to that, due to the unavailability of data, the energy consumption associated with the curing process of needle felt CIPP liners could not be determined with sufficient accuracy. To increase the accuracy, and therefore the quality, of the results, the actual energy consumption of needle felt CIPP liner curing should be determined. Moreover, it is worth noting that it was assumed that the width of the asphalt pavement to be removed in case of open trench pipe replacement is equal to the width of the trench. In reality, it is possible that contractors remove more asphalt pavement (i.e. a greater pavement width is taken), which can result in a significantly higher environmental impact. It might be interesting to study how much pavement contractors actually remove normally.

In this study, a CF assessment was conducted instead of a full LCA. An inherent limitation of a CF assessment, compared to a complete LCA, is that such an assessment is limited to a single impact category (i.e. climate change). As stated earlier before, the findings of a CF assessment might give a misleading picture of the overall impacts associated with a certain product or service system, and thus leading to partially environmentally supported decisions. A complete LCA, on the other hand, includes a wider set of impact categories (e.g. ozone depletion, eutrophication, acidification, etc.). Therefore, to acquire a global picture of the environmental burdens, other impact categories should be studied by modelling the system under study with an LCA software.

Finally, one can argue that the life cycle inventory compiled in study is not entirely complete. As mentioned in the delimitations (*Chapter 2*), certain items, processes, and activities (e.g. traffic diversions) were excluded from the system boundaries, since they were considered to be too complex and/or time consuming to be accounted for with sufficient accuracy. However, it might be possible that the exclusion of these items resulted in a significant underestimation of the CF score of certain sewer maintenance or rehabilitation techniques. Thus, for future research, it would be interesting to investigate the importance of these excluded items.

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7 Appendix

Appendix A: Life cycle inventory

Table 20: Quick-Lock mechanical seal design properties. Source: (DIBt No. Z-42.3-374, 2012)

Quick-Lock mechanical seal properties						
DN sewer pipe [mm]	**Max. DN stainless steel sleeve [mm]**	**OD stainless steel sleeve [mm]**	**Thickness steel [mm]**	**Max. DN rubber gasket [mm]**	**OD rubber gasket [mm]**	**Thickness rubber [mm]**
200	212	214,4	1,2	214,4	218,4	2
250	265	267,4	1,2	267,4	271,4	2
300	319	321,4	1,2	321,4	325,4	2
400	413	416	1,5	416	420	2
500	542	546	2	546	550	2
600	615	619	2	619	623	2
700	722,5	728,5	3	728,5	734,5	3
800	830	836	3	836	842	3
900	930	936	3	936	942	3
1000	1030	1036	3	1036	1042	3
1250	1270	1276	3	1276	1282	3
1500	1530	1536	3	1536	1542	3

Table 21: Hydraulic cleaning key figures traditional cleaning. Source: (Jansen Rioolreiniging BV, 2015); (Stichting RIONED, 2015)

Hydraulic cleaning with two separate vehicles (i.e. traditional cleaning)						
DN [mm]	**Daily cleaning capacity [m]**	**Sewage sludge to be disposed [kg/m]**	**Operating time water truck [h/m]**	**Diesel cons. water truck [l/m]**	**Operating time vacuum truck [h/m]**	**Diesel cons. vacuum truck [l/m]**
200	1027	-	0,0068	0,109	0,0054	0,086
250	929	-	0,0075	0,121	0,0059	0,095
300	900	8	0,0078	0,124	0,0061	0,098
400	800	24	0,0088	0,140	0,0069	0,110
500	700	40	0,0100	0,160	0,0079	0,126
600	600	56	0,0117	0,187	0,0092	0,147
700	500	72	0,0140	0,224	0,0110	0,176
800	400	88	0,0175	0,280	0,0138	0,220
900	350	104	0,0200	0,320	0,0157	0,251
1000	300	120	0,0233	0,373	0,0183	0,293
1250	126	160	0,0557	0,891	0,0437	0,700
1500	76	200	0,0918	1,468	0,0721	1,154

Table 22: Hydraulic cleaning key figures combi truck. Source: (Jansen Rioolreiniging BV, 2015); (Stichting RIONED, 2015)

Hydraulic cleaning with a single vehicle (i.e. combi truck)				
DN [mm]	**Daily cleaning capacity [m]**	**Sewage sludge to be disposed [kg/m]**	**Operating time [h/m]**	**Diesel consumption [l/m]**
200	1027	-	0,0068	0,129
250	929	-	0,0075	0,142
300	900	8	0,0078	0,147
400	800	24	0,0088	0,165
500	700	40	0,0100	0,189
600	600	56	0,0117	0,220
700	500	72	0,0140	0,264
800	400	88	0,0175	0,330
900	350	104	0,0200	0,377
1000	300	120	0,0233	0,440

1250	126	160	0,0557	1,050
1500	76	200	0,0918	1,731

Table 23: Life cycle inventory of one-time open trench sewer pipe replacement for pipe diameters of 200 to 1500mm for a sewer section with a length of 45 m.

[Due to confidentiality agreements with Roelofs Groep, Table 23 is excluded from this version of the thesis report!]

Table 24: Life cycle inventory of a one-time CIPP lining for pipe diameters of 200 to 1200mm for a sewer section with a length of 45 m.

[Due to confidentiality agreements with Roelofs Groep, Table 24 is excluded from this version of the thesis report!]

Table 25: Life cycle inventory of a one-time open-trench and trenchless repair for pipe diameters of 200 to 1500mm.

[Due to confidentiality agreements with Roelofs Groep, Table 25 is excluded from this version of the thesis report!]

Table 26: Life cycle inventory of a one-time inspection and cleaning for pipe diameters of 200 to 1200mm for a sewer section with a length of 45 m.

[Due to confidentiality agreements with Roelofs Groep, Table 26 is excluded from this version of the thesis report!]

Table 27: Inventory of machinery and equipment

[Due to confidentiality agreements with Roelofs Groep, Table 27 is excluded from this version of the thesis report!]

Appendix B: Impact assessment results

Table 28: Impact assessment results for a one-time sewer replacement for DN 200 to 1500 mm for a 45 m sewer section

[Due to confidentiality agreements with Roelofs Groep, Table 28 is excluded from this version of the thesis report!]

Table 29: Impact assessment results for a one-time CIPP lining for DN 200 to 1200 mm for a 45 m sewer section

[Due to confidentiality agreements with Roelofs Groep, Table 29 is excluded from this version of the thesis report!]

Table 30: Impact assessment results for a one-time trenchless repair using a fibreglass CIPP short liner

[Due to confidentiality agreements with Roelofs Groep, Table 30 is excluded from this version of the thesis report!]

Table 31: Impact assessment results for a one-time trenchless repair using a mechanical seal

[Due to confidentiality agreements with Roelofs Groep, Table 31 is excluded from this version of the thesis report!]

Table 32: Impact assessment results for a one-time open trench repair (incl. asphalt rehabilitation)

[Due to confidentiality agreements with Roelofs Groep, Table 32 is excluded from this version of the thesis report!]

Table 33: Impact assessment results for mechanical removal of two intruding roots in sewer section.

[Due to confidentiality agreements with Roelofs Groep, Table 33 is excluded from this version of the thesis report!]

Table 34: Impact assessment results for a one-time sewer inspection for DN 200 to 1500 mm for a 45 m sewer

[Due to confidentiality agreements with Roelofs Groep, Table 34 is excluded from this version of the thesis report!]

Appendix C: Comparison of results with DuboCalc software

DuboCalc software is often referred to as an important tool to evaluate the environmental burdens of civil engineering works in the Netherlands (Nationale Milieudatabase, 2019). DuboCalc calculates the environmental impacts of material and energy consumptions associated with the entire life cycle of a certain construction project using the LCA methodology. These environmental impacts are aggregated into single-score indicator, this indicator is expressed in a monetary number (i.e. Euro), also known as the Environmental Cost Indicator (ECI) (or Milieukostenindicator (MKI) in Dutch) (DuboCalc, n.d.). To calculate the ECI, the DuboCalc software takes 11 environmental impact categories into account, such as, for instance: climate change, acidification, ozone depletion, human toxicity, etc. (DuboCalc, n.d.). This study only considers the impact category “climate change”. As stated earlier, according to Pandey, Agrawal, and Pandey (2011), the importance of the climate change impact category should not be underestimated. They state that this impact category can still give a good indication of the environmental burdens of a particular product or service system. Furthermore, according to Ecochain (2019), the climate change impact category is one of the main contributors to the ECI in many cases.

A multitude of engineering consulting firms in the Netherlands, including Roelofs Groep, use DuboCalc with the purpose of achieving environmental benefits in product designs and tenders. It is therefore interesting to know how the results of this study would stack up against results that are obtained with use of DuboCalc software. Therefore, as a quality check, the environmental impacts acquired in this study were compared to results from DuboCalc. For this comparison, the environmental impact category “climate change” was exclusively used. Moreover, a one-time open trench construction of a concrete sewer section with length of 45 m and a diameter of 400 and 800 mm was considered. To make this a valid comparison, the same system boundary was considered for the DuboCalc calculation, which is cradle-to-site. It should be mentioned that the inventory of the pipe installation phase in this study was partially based on the inventory of DuboCalc. The operating times of two construction machines, i.e., tractor and wheel loader, and were taken from the database of DuboCalc (DuboCalc, n.d.).

Comparison construction concrete sewer pipes DN 400 mm

In Figure 27, one can see the inventory of materials and processes which is adopted by the DuboCalc software for concrete sewer pipe production and installation. The operating times of construction machinery can be seen in Figure 27 as well, these operating times are expressed in hours per unit pipe length (or per 220 kg pipe). Furthermore, for each construction machine type (e.g. excavator, see Figure 28), DuboCalc presents the environmental impact (kg CO_2-eq) per hour operating time. Based on this inventory and the environmental effects data from the DuboCalc database, the CF of a one-time sewer pipe construction of a section length of 45 m and a diameter of 400 mm was calculated. See Table 35 and Table 36 for the inventories and impacts used for comparison. Based on the results presented in Table 36, the CF of this study was found to be 6,8% higher than the results which were obtained with DuboCalc. This difference is considered as acceptable.

	Type..	Name	Quantity..	Unit	Phase	MKI..	Contribution %..	Construction MKI..	Usage MKI
		Betonbuis (gemiddeld)	0.22	ton	Bouw	2.43	54.41	2.43	0
		Gr.mach.hydr. (gemiddeld)	0.0444	h	Bouw	0.41	9.18	0.41	0
		Tractor verm. 40-110 kW: 4x4	0.0444	h	Bouw	0.25	5.51	0.25	0
		Trilplaat 250-700 kg	0.0444	h	Bouw	0.01	0.14	0.01	0
		Wals (gemiddeld)	0.0444	m2	Bouw	0.39	8.64	0.39	0
		Wiellaadschop	0.0444	h	Bouw	0.34	7.59	0.34	0
		Gr.mach.hydr. (gemiddeld)	0.0333	h	EindeLevensduur..	0.31	6.88	0	0
		Transport bulk (over de weg)...	0.22	tonkm	Bouw	0.34	7.66	0.34	0

Figure 27: Inventory of concrete pipe production and construction for DN 400 mm. Source: (DuboCalc, n.d.)

Figure 28: Example of environmental impact data from DuboCalc database. Source: (DuboCalc, n.d.)

Table 35: Inventory of materials and processes for DN 400 mm for DuboCalc comparison.

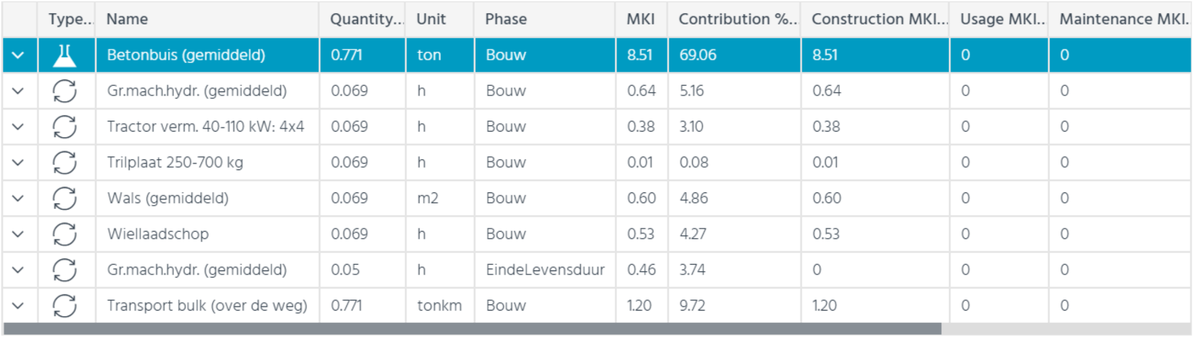
			Quantity	
Phase	**Item**	**Unit**	**DuboCalc**	**This study**
Production	Concrete	t	9,9	10,35
Construction	Excavator	h	3,48	3,56
	Plate compactor	h	1,98	-
	Roller	h	-	0,11
	Tractor	h	1,98	2,11
	Wheel loader	h	1,98	2,11

Table 36: Environmental impacts for DN 400 mm for DuboCalc comparison.

		Environmental impact (kg CO_2-eq)	
Phase	**Item**	**DuboCalc**	**This study**
Production	Concrete	1356	1563
Construction	Excavator	183	125
	Plate compactor	3,6	-
	Roller	-	5,1
	Tractor	62	67
	Wheel loader	86	46
	Total	**1691**	**1806**
		Difference: 6,8%	

Comparison construction concrete sewer pipes DN 800 mm

Likewise, a comparison was done for a pipe diameter of 800 mm. See Table 37 for the inventories and see Table 38 for the environmental impacts of a concrete sewer section with a length of 45 m and a pipe diameter of 800 mm. In this comparison, it was found that the total CF of this study is approximately 13,3% higher than the DuboCalc result. The main reason for this is that the amount of concrete per unit length sewer pipe is higher in this study.



Type..	Name	Quantity..	Unit	Phase	MKI	Contribution %..	Construction MKI..	Usage MKI..	Maintenance MKI.
	Betonbuis (gemiddeld)	0.771	ton	Bouw	8.51	69.06	8.51	0	0
	Gr.mach.hydr. (gemiddeld)	0.069	h	Bouw	0.64	5.16	0.64	0	0
	Tractor verm. 40-110 kW: 4x4	0.069	h	Bouw	0.38	3.10	0.38	0	0
	Trilplaat 250-700 kg	0.069	h	Bouw	0.01	0.08	0.01	0	0
	Wals (gemiddeld)	0.069	m2	Bouw	0.60	4.86	0.60	0	0
	Wiellaadschop	0.069	h	Bouw	0.53	4.27	0.53	0	0
	Gr.mach.hydr. (gemiddeld)	0.05	h	EindeLevensduur	0.46	3.74	0	0	0
	Transport bulk (over de weg)	0.771	tonkm	Bouw	1.20	9.72	1.20	0	0

Figure 29: : Inventory of concrete pipe production and construction for DN 800 mm. Source: (DuboCalc, n.d.)

Type..	Name	Quantity..	Unit	Phase	MKI	Contributic
	Betonbuis (gemiddeld)	0.771	ton	Bouw	8.51	69.06
	Gr.mach.hydr. (gemiddeld)	0.069	h	Bouw	0.64	5.16

General

Name	Gr.mach.hydr. (gemiddeld)
Default quantity	1
Default unit of measure	h

Environmental effects

Abiotic depletion	0,0000122 kg Sb
Greenhouse effect	52,593239 kg CO2
Stratospheric ozone depletion	0,00000653 kg CFK11
Smog	0,05240328 kg ethyleen

Figure 30: Example of environmental impact data from DuboCalc database. Source: (DuboCalc, n.d.)

Table 37: Inventory of materials and processes for DN 800 mm for DuboCalc comparison.

			Quantity	
Phase	**Item**	**Unit**	**DuboCalc**	**This study**
Production	Concrete	t	34,7	37,1
Construction	Excavator	h	5,36	6,25
	Soil plate compactor	h	3,11	-
	Roller	h	-	0,16
	Tractor	h	3,11	2,75
	Wheel loader	h	3,11	2,75

Table 38: Environmental impacts for DN 800 mm for DuboCalc comparison.

		Environmental impact (kg CO_2-eq)	
Phase	**Item**	**DuboCalc**	**This study**
Production	Concrete	4753	5606
Construction	Excavator	282	218
	Soil plate compactor	5,65	-
	Roller	-	6,87
	Tractor	98	86
	Wheel loader	135	60
	Total	**5274**	**5978**
		Difference: +13,3%	