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Faculty of Engineering and Technology

Development of a decision support model for the social costs of pipelines renovation projects

Camila Nunes Vasconcelos

M.Sc. Thesis in Civil Engineering and Management
August 2017

Supervisors:
Dr. S. H. (Saad). Al-Jibouri
Dr. Faridaddin Vahdatikhaki
Drs. C.C.D.F. (Derk) van Ree

Faculty of Engineering and Technology
Department of Construction Management & Engineering
University of Twente
P.O. Box 217
7500 AE Enschede

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Author:

Name	Camila Nunes Vasconcelos
Student number	s1627864
Contact	Vasconcelos.nc@gmail.com

Committee:

Dr. S. H. (Saad). Al-Jibouri	Graduation supervisor - University of Twente
Dr. Faridaddin Vahdatikhaki	Daily supervisor - University of Twente
Drs. C.C.D.F. (Derk) van Ree	Supervisor - Deltares

Date:	15th August 2017
Place:	Enschede, the Netherlands

Abstract

Construction projects are well known for the impacts and nuisances they may cause on the society and the surrounding environment. In the specific case of pipelines projects, there are safety issues involved, added to the magnitude of damage and disruption that can potentially affect the normal life of people.

The negative impacts due to construction (pipelines) projects are also called social costs and are those for which the society will not be compensated, affecting the communities near the construction site, the environment and the surrounding infrastructure. Actually, the choice between pipelines projects is mainly dictated by technical and economic aspects and the inclusion of social costs is not always evident. However, in order to know the real cost of a project, it is necessary to consider not only the direct and indirect cost but also the social costs.ai

As such, there is an increasing need for companies and governmental agencies to assess their pipelines projects based on total project costs by including social costs. This approach results in project choices that minimize the impacts on the surrounding neighbourhood, infrastructure, and environment. However, in practice, it is challenging to incorporate social costs in the decision-making and to represent in monetary units.

This research aims at developing a model that supports decision makers to take more informed decisions by quantifying and incorporating social costs in the decision making. The model considers not only direct and indirect costs, but also social costs and risks when choosing between open trench and trenchless pipelines projects.

This research used literature review, interviews and surveys for collecting data and developing the model. The data collection results allowed the selection of the social costs pertinent to the model, the equations for quantification of social costs, a qualitative approach for the risks assessment and the information to be provided by the model users.

The result of this research is an Excel model which uses valuation equations and a scoring system to calculate social costs and assess risks, respectively. The model is used to compare open trench and trenchless projects regarding social costs, based on inputs from the users. From a theoretical point of view, it provides a base for decision makers to recognize which social costs and risks might be present in their projects, where these social costs come from and which parameters influence these social costs and risks. The model was validated using "educated guess" projects provided by experts.

The results indicate that social costs are not systematically included in the decision making. One of the reasons is that the information needed to evaluate social costs is not always available or it is spread among different parties. It is suggested that a change in the way information is organized and communicated should help with filling this gap. Besides, the development of a common database with project information could be created and be used for social costs estimation in future projects.

It was also found that the incorporation of social costs would not always be used nor influences the decision making and in these cases a social costs model would not add much value. On the other hand, social costs can make a difference when the project owner wishes to reduce the nuisances to the society and have projects with the lowest cost to the society and the environment.

Keywords: social costs, pipelines projects, trenchless technologies, open trench.

Acknowledgments

“Where there is a will, there is a way”.

This saying expresses why I am here today, becoming a Master of Science in Civil Engineering and Management at University of Twente. I have always learned not to give up on my dreams and that if we really want something and go for it, we can make it. So, this report marks the end of a phase in my life and the beginning of a new, challenging journey. I would like to thank all those who helped me along these two years.

First of all, I would like to thank my graduation supervisor Saad for his support, valuable advices and for his flexibility during this period. To my daily supervisor Farid, thanks for having carefully read all my report versions and giving constructive comments and critics which helped me improving my work. To my company supervisor Derk, thank you for the practical comments and advices about my work and for making time in your agenda every time it was necessary to discuss. Thank you all for keeping the doors open, making me feel comfortable in our meetings and for steering my work on the right way with your knowledge.

I would also like to thank the experts who provided me a few hours of their valuable time to participate in my interviews, surveys and replied to my emails. Your insights were essential to develop my report and moreover gave me valuable practical knowledge.

I would like to thank the University of Twente for providing me a scholarship which allowed me to pursue my degree in the Netherlands. Thanks to Deltares for having hosted me for the past seven months and providing all the support for developing my work. Thanks to NSTT for providing me this project and especially to Jelle de Boer for his enthusiasm about my subject and valuable contacts.

Special thanks to Tim for always being present and supportive and to Deborah and Soundarya for the friendship and moments together. Thanks to all my friends from Calslaan 1 and Enschede with whom I lived so many amazing and unforgettable moments for one and half years in our campus. Thank you all for becoming my family in the Netherlands. Thanks to my friends from Delft and Deltares: you made my stay in Delft and my last months of student life full of amazing memories. Thanks to my friends in Brazil and abroad for keeping our friendship alive despite the distance.

Finally, I must express my very profound gratitude to my parents Lourdes and Robson and to my sisters Mariana and Carolina who had to accept that I would be far away for two years. Without their love, support and encouragement I wouldn’t be here today and have accomplished this master degree.

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1. Introduction

1.1 General background

In recent years the increasing rate of urbanization, on the one hand, and the aging urban infrastructure, on the other hand, has led to a rapid growth in number and scope of urban construction works. In many cases, reconstruction projects involve, in one way or another, interactions with underground utilities. In addition, the underground network infrastructure has become busier as the urban density increased and new services provided through subsurface infrastructure (e.g. glass-fiber networks) evolved. Besides safety concerns, there exist delicacies in works that involve underground utilities because of the magnitude of damage and disruption they can potentially cause to the surrounding environment and to the normal life of people.

Practitioners and engineers continually try to devise novel and innovative solutions that limit the detrimental social and environmental impact of urban projects. In the specific case of underground installation projects such as pipelines or cables, it is possible to choose between traditional excavation and trenchless technologies for new-installations or rehabilitation of subsurface utilities. Currently however, the selection of the construction technique and technology in this type of work is mainly dictated by technical and financial aspects and the social and environmental impacts are not fully taken into account.

The incorporation of social and environmental costs can play a significant role in determining the most viable option in urban construction works from a societal point of view (in extreme cases the cheapest solution may be the most expensive one from a societal cost point of view). For example, using a traditional open excavation method in very busy areas may be impractical and costly since it will require complete or partial closure of the street and hence the economic and social impact of such action can be very high. In such cases, trenchless methods may prove to be more attractive when considering the costs of negative effects to society and environment.

Social costs are related to the negative impacts suffered by communities located around or nearby the construction site. These costs refer to economic losses and can be felt in terms of loss of revenue, productivity and time, consumption of non-renewable resources and accelerated deterioration of secondary roads. Environmental effects mainly occur in the form of pollution such as air, water, noise, dust and vibration which also affect the population (Gilchirst & Allouche, 2005).

There is a growing awareness among practitioners and owners of utility infrastructure the importance of considering such costs in addition to the direct and indirect costs. The inclusion of social costs in the decision making might result is project choices which minimize impacts to the surrounding neighborhood, infrastructure and environment. Besides, taking into account project negative externalities a more realistic cost estimation of a project can be achieved.

1.2 Problem description

Socio-economic and environmental costs are difficult to incorporate in the decision-making process and represent in terms of monetary units. Commonly, in current practice, decision makers do not consider the adverse effects of construction works on society and environment, but select the most economically advantageous bids. This is also the case when deciding which technology to use for underground utilities intervention, such as pipelines renovation. According to Gilchrist and Allouche (2005), these social negative effects are often not considered in the initial cost estimation of a construction project and consequently they are not passed on to the design, planning and evaluation phases.

This practice can partly be explained by the fact that these social costs are not borne by the project owner but by the society. Social costs are usually not paid directly by the organization, but are mostly a "cost" borne by the population in the form of traffic delays or by business that will see their revenues decrease while the project is executed nearby. Second, the quantification of these costs is not as easy to calculate as direct costs (e.g. labour, material or administrative costs). Finally, the society will "pay" for these social costs as they are not part of the project planning and management process (Yu & Lo, 2005).

However, in order to know the real cost of a construction project, it is necessary to consider not only the direct and indirect cost but also the costs to society and environment (Matthews & Allouche, 2010). There have been research works that attempted to calculate social and environmental costs in order to have a more realistic overview of the total costs (Matthews and Allouche, 2010; Matthews, Allouche & Sterling, 2015; Alkema, 2015). Other works have been carried out to develop indicators that translate the effects and impacts of construction projects on society (Matthews and Allouche, 2010; Ariaratnam et al. 2013; Gilchrist and Allouche, 2015).

In 2015, a bachelor student from Delft University of technology (TU Delft) investigated social costs related to the renovation of pipelines and cables executed by open trench or trenchless techniques (Alkema, 2015). His project was part of cooperation between TU Delft and The Dutch Society of Trenchless Technologies (NSTT) to gain knowledge about social costs related to subsurface utilities projects.

The research was an attempt to define relevant effects of subsurface utilities projects on the society and environment and translate these into costs so that decision-makers could have an insight into the social costs before making the final decision about the most economic construction methods. The negative effects were converted into costs indicators (traffic, revenue loss, environment, damage/safety and nuisance to surroundings) with the help of engineering firms.

The resulted work produced a tool in the form of a matrix to support decision-making by means of comparing the costs of trenchless technologies and open trench excavation. The student attempted to convert the social effects into quantifiable scales and objectively reflect the pros and cons of both techniques by focusing on route-related costs and social costs. The tool was developed for local governments and companies that wanted to make choices at an early stage of the project.

However, the final product was not deemed practical for use by the problem owners. It was recommended to adapt the model to incorporate more reliable cost indicators and data. The main remarks about the work of Alkema (2015) were related to the inconsistency of terms used, validity of scales and indicators, generalization of location-specific costs that should be more region specific, and absence of consistent Social Costs and Benefit Analysis principles.

This research is a continuation of the research efforts conducted by TU Delft and NSTT because there are parties interested in having a model that gives insights into the social and environmental costs related to renovation of pipelines in The Netherlands. The model will be used to assist decision-makers to consider the magnitude of these costs and hence helping them in taking more informed decisions as to the most appropriate choice of the method to be used.

In this context, the research problem can be stated as follow:

"There is a need for Dutch companies and governmental agencies to assess their utilities projects based on total project costs, which include the costs to the society and environment."

1.3 Research objective

This research aims at developing a method that incorporates social costs in the evaluation of construction methods for pipelines renovation projects. The method should support decision-makers to quantitatively and qualitatively assess the social costs related to pipelines projects at an early stage; and consider the limitations of information at an early stage of the projects and information inputs/outputs.

The method should provide information on social costs so that a comparison between trenchless and open trench is possible. It will be used to support municipalities to find the best trade-off between direct construction costs and societal costs when making a decision. With this information, a decision-maker could improve decision-making and make a more informed choice between two techniques. Therefore, the main objective of the research can be stated as follows:

"To develop a model that incorporates social costs in the evaluation of different methods for pipelines renovation projects."

The secondary objectives of the research are:

a. To identify different negative externalities of subsurface utility projects on society, economy and environment;

b. To identify different cost indicators and valuation methods used to quantify social, environmental and economic impacts;

c. To investigate the most relevant valuation methods to quantify the external effects related to trenchless and open trench in renovation projects based on the availability of data.

d. To develop a prototype for the verification and validation of the model.

1.4 Research questions

The research questions that address the previous objectives are divided into main research question and sub-questions, which are related to the main objectives and secondary objectives, respectively.

Main research question:

- *How can the social costs be considered in the selection of (re-)construction methods in pipelines renovation projects?*

Secondary objectives and respective sub-questions:

a. To provide a general overview of the external effects of subsurface utility projects on society, economy and environment;

- *What are the impacts of subsurface utility projects on society, economy and environment?*
- *Which social costs are the most relevant for renovation projects using trenchless technologies and open excavation?*

b. To identify different social cost indicators and valuation methods used to quantity social, environmental and economic impacts;

- *Which social cost indicators and valuation methods are used to quantify social, economic and environmental impacts of pipeline renovation projects?*

c. To investigate the most relevant valuation methods to quantify the external effects related to trenchless and open trench in renovation projects based on availability of data.

- *Which costs indicators are relevant to the model?*
- *From the valuation methods investigated under (b), which ones are the most relevant to quantify the impacts of open trench and trenchless projects based on the selected cost indicators and data available?*
- *Which input data is necessary to calculate social costs through valuation methods?*
- *Are the required input data available to calculate social costs through valuation methods?*

d. To develop a prototype for verification and validation of the model

- *How can the social costs be integrated in a calculation tool?*

1.5 Research scope

The design of this research is based on preferences stated by the parties supporting this project; and on time and data constraints. The parties have provided guidelines and considered the feasibility of the research in a 6 months period. Based on these limitations, the research focus and scope have been defined.

This research focuses on social costs related to open trench and trenchless renovation projects for sewage systems (relining). The choice of renovation techniques (and not new installations, repair or replacement) was made to compare a traditional method that is widely used (open trench) with a method that can extend the lifetime of an existing pipeline (trenchless renovation) in terms of social costs during project execution. Therefore, new installations, repair and replacement are out of the scope of this project.

Another reason for focusing on renovation is due to the fact that renovation projects are usually smaller and take place in a street or neighborhood level, where most of the times one street pipeline project is executed at a time and the aim is to replace a certain type of utility. Besides, renovation projects are temporary in nature; (in many cases) their duration is limited to a few days; and the social costs are usually less significant than replacement.

Concerning the type of utility considered in this research, it was suggested that quantifying social costs in sewage projects is more meaningful than other utility types. The reasons are that in the Netherlands, trenchless renovation is mostly used for relining sewage pipelines. Besides, sewers are usually located under roads (usually in the middle of the roads) and when intervention is required it might cause more nuisances and social costs especially regarding traffic delays.

A concept of the research scope is presented are the highlighted rectangles represent the chosen scope (Figure 1).

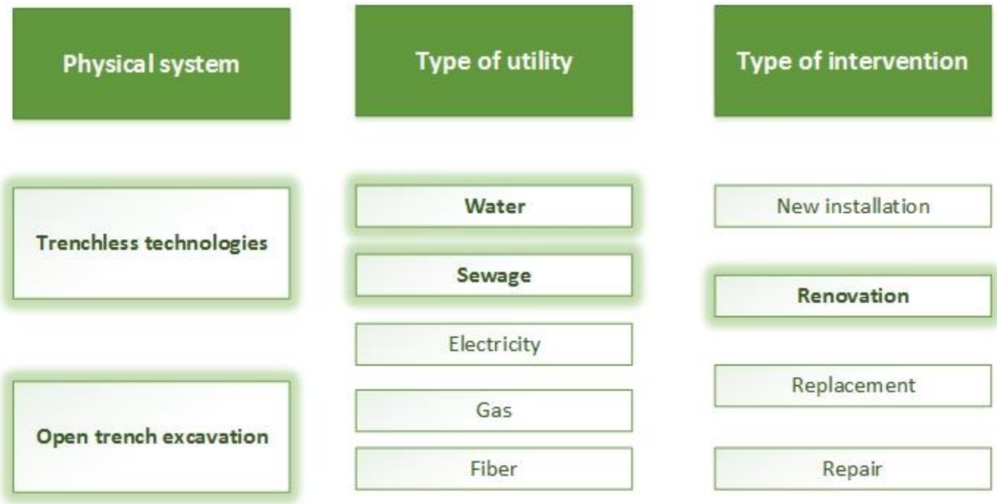


Figure 1: Scope of the research

Regarding the project stage that is more suitable for considering social costs, the focus is on the early stages where the strategic decision on the application of open trench or trenchless technologies needs to be made. As such, this research will look at the open trench and trenchless methods as a whole and, thus, do not draw a distinction between various specific trenchless/open trench technologies. Needless to say, the social cost analysis can be different for individual technologies, but a more detailed analysis can be performed at later design phases of the project when the selection of the technology is to be made. Although it can be assumed that the same principle that is presented in this research can be used to make more detailed comparison of technologies. This however is out of the scope in this research.

For the quantification of social costs, the valuation methods used depend on the availability of data and experts opinion. Therefore, companies that work with renovation of pipelines have been interviewed and based on the availability of data it was possible to select the most suitable valuation methods to include in the model.

In the scope of this research, a monetary quantification of risks did not take place because it was not possible to build a model to quantify and monetize risks in a general way. However, a qualitative risk analysis was proposed aiming at incorporating risks into the decision-making and comparing open trench and trenchless alternatives.

The envisaged users of the proposed model are the decision-makers from municipalities who are responsible to make a choice about which method to use when a pipeline has to be rehabilitated, usually by the end of its life cycle. In this research, the choice was restricted to open trench excavation and trenchless renovation methods in accordance with the research scope.

1.6 Research strategy

This section summarizes the steps involved in this research in order to produce the final outcome as a single model for quantifying and comparing social costs in pipelines projects. Figure 2 represents the sequence of the steps involved and Table 1 summarizes them.

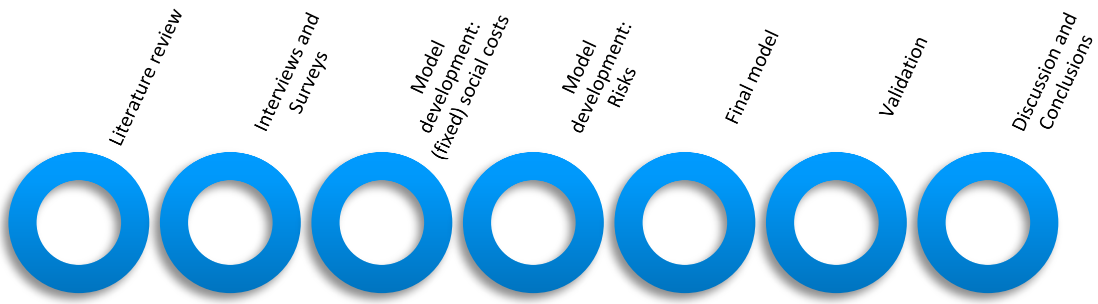


Figure 2: Research strategy

Table 1: Description of research methodology strategy

Step	Summary
Literature review	The first step in the research is to conduct a literature review to identify relevant information related to the social costs and pipelines construction projects fields, resulting in chapter 2 of this report.
Data collection: Interview and surveys	The second step is to collect data and validate assumptions using experts' opinions through interviews. Some key figures for the model have been found on literature and others were based on experts' opinion to: (1) fill in the gap of information that might not be provided by the users of the model and (2) provide general (official) values that can be used as parameters for quantifying social costs. After conducting and analysing the interview, the outputs are used for developing the survey questionnaire. This survey aims at collecting inputs from experts for developing the scales for the risk-related social costs matrix.
Developing the fixed social costs model	The first part of the social costs model is the development of the (fixed) social costs calculator. The calculator in the form of an Excel sheet is based on the social costs identified through the interviews; on the valuation methods researched on the literature, key figures and input data. In this part of the model, the aim is to monetize the social costs for each alternative based on the input data provided by the users. The main result of this part of the model is the total social cost in monetary units for open trench and trenchless renovation methods.
Developing the risk related social costs matrix	The goal of the second part of the social costs model is to analyse the social costs that cannot be monetized: Risks. This risk analysis is conducted through a matrix developed in Excel using 5-point scales and scores. Based on the scores for each risk type, a final score for Risks is produced for each alternative under analysis and a risk comparison can be made. Details about the risk matrix are described in Section 4.
Final model development: fixed social costs and risks	The model is presented in an Excel file which consists of several sheets that integrate the calculations of (fixed) social costs and risks. The model combines the final results of the calculations. Based on these results, a decision-maker can make their choices between open trench and trenchless alternatives based on a total costs approach that integrates direct/indirect costs, (fixed) social costs and risks.
Model validation	The model is validated using "educated guess" input data for two fictitious projects provided by experts.
Discussion and conclusions	In the last chapter, a brief discussion about the findings and limitations is presented. Finally, conclusions are drawn, research questions are answered and recommendations for future research are proposed.

1.7 Report outline

This section presents the structure of this report (Figure 3). The introductory chapter consists of an overview of the theme, the problem description, research questions, research objectives, scope and strategy. The second chapter comprises a literature review to introduce concepts and methods used in the model development. The third chapter explains the data collection methods used in this research: literature review, interviews and surveys. Based on chapter 3, the social costs model is developed and validated in chapter 4. The fifth chapter presents the discussion and conclusions comprising the limitations encountered, answers to the research questions and recommendations for future research.

Figure 3: Report outline

2. Literature Review

The literature review chapter will address the different social costs related to open trench and trenchless renovation technologies for pipelines projects. This chapter will be divided in the following manner: In the first subsection, methods for pipeline rehabilitation and new installation projects are presented where a comparison between open trench and trenchless is made and advantages and disadvantages are highlighted. In the second subsection, the definition of costs related to pipelines projects and social costs is presented. In the third subsection, the impact areas related to pipelines projects are summarized and the social costs related to each impact area are listed. In the fourth and last subsection, social costs are explained in more details together with the valuation equations and key figures that will incorporate the decision making model.

2.1 Pipeline rehabilitation methods

Before deciding on how to execute subsurface utilities projects, it is important to have an overview on the existing methods, their pros and cons and the barriers related to their applicability. The methods available for underground utilities projects (e.g., water, sewage, gas, industrial pipelines, and electrical conduits) can be either traditional open trench excavation methods or trenchless technologies. Each one presents advantages and disadvantages regarding costs, safety, environmental and social impacts that have to be weighed before a decision is made.

The choice between open trench and trenchless techniques goes beyond the technical and social aspects. Even though trenchless technologies become more and more known in the market, many parties do not even consider using them because they are used to working with open trench methods. Open trench is the traditional choice for subsurface utilities projects, while trenchless is seen as a “black box” that has to be more explored in practice until practitioners become familiar with it.

Several aspects have to be considered before deciding *when* or *whether* a pipeline will be rehabilitated and which method should be used. Asset management helps answering *when* an intervention should be carried out based on monitoring and prioritization of assets; while technical feasibility, financial aspects and social costs determine the technique to be used. The Federation of Canadian Municipalities and National Research Council (2003), has listed the main aspects that should be considered in the method selection (Table 2).

Table 2: Important aspects in the selection of (re-)construction methods for pipeline projects

Aspect	Description
Subsurface conditions	Depending on soil and ground water conditions, the options for rehabilitating, replacing, or repairing a sewer section may be limited. Therefore, an investigation of subsurface conditions is essential for any subsurface project. The investigation will determine soil conditions and possible conflicts with other subsurface utilities.
Financial aspects	The choice between rehabilitation and replacement depends on the financial resources available. Investments can be either reactive (e.g. repair) or preferably proactive (e.g. when inspection and rehabilitation of pipelines are conducted to preserve their physical integrity). The selection of the section of pipeline to be repaired or renewed should consider life cycle costing, disruption, local economic issues, business issues, and environmental impacts.
Size of contract	Initial mobilization and demobilization for some specialty technologies can be expensive and depending on the contract size it might not be economically viable to opt for a certain technology/method.
Risk assessment	It is essential to understand and identify the environmental project risks and risks associated with the applicable construction techniques. Risk assessment requires identification; quantification; evaluation/assessment; response development and control; and documentation and aims at identifying uncertainties and mitigating risks.
Local availability	Local availability of the technology should be considered early in the selection of the method to be used in pipelines projects.
Depth of sewer	Trenchless technologies are frequently the least expensive for deeper sewers in an urban setting. The depth that begins to favour trenchless methods will vary depending on local and project conditions (from four to eight meters). Factors that affect the depth of sewer are soil type, depth of ground water table, utility conflicts, road surface conditions, and traffic volume.
Density of lateral services	Even when a trenchless technology is used to rehabilitate or replace a sewer, the sewer laterals will be replaced using excavation methods (i.e., not using a trenchless technology). Consequently, a higher number of sewer laterals per length of sewer being rehabilitated favours open cut replacement as the most economical solution. However, if social costs are considered, trenchless technologies can be an option to avoid all the negative impacts related to excavation.
Surface condition and other factors	The rehabilitation method is dependent on the surface conditions in the area. For example, high traffic volumes favour trenchless technologies, while open areas, road surfaces in poor condition, capacity needs for the subject pipe and adjacent utilities needing rehabilitation tend to favour open cut methods and replacement.

As it can be noticed, there are many aspects to be considered during the decision making regarding whether to renew or rehabilitate a pipeline, and which method to use. The decision involves technical, economical, safety, social en environmental aspects that together influence the final decision. These aspects will be discussed in the following sub-sections with an overview of trenchless and open trench methods, advantages, disadvantages, applicability and technologies. Emphasis is given to the social costs involved in pipelines projects and ways of incorporating them in the decision-making process.

2.1.1 Open trench excavation

Open trench or open-cut excavation methods are the most traditional approach for executing pipelines installations and renewal projects. Most municipalities have good design and construction specifications to complete open trench projects because this technique is well documented (FCM, 2003). This method involves excavating a trench, placing bedding material to a desired grade, laying the pipe, backfilling around the pipe, and compacting the backfill. Open trench methods have evolved over time and its relatively simple installation procedures enable the use of a wide range of pipeline diameters. However, soil stability problems and complex logistics make open trench methods rather inefficient for deeper excavations.

One of the main disadvantages of trenching is the impact on surface infrastructures located on the excavation area such as pavements, sidewalks and trees. Besides, the impacts of excavation on traffic can be very high depending on the location of the project. Consequently, their use is more suitable (but not limited) for rural and non-congested areas; areas where adverse impacts on the environment can be tolerated; and when the installation depth does not exceed the reach of an excavator (Kramer & Gauthier, 1995; Ariaratnam, Piratla & Cohen, 2013).

The activities involved in open trench pipelines projects are described by Jung and Sinha (2007). First, a trench is excavated (usually using a backhoe) to the line and grade, followed by the bracing, sheeting, sloping of bank, shoring and pumping. Standard safety measures have to be followed strictly during this phase to avoid accidents such as caving in. Once the pipe is on the right line and grade the joint is made and the backfill material must be carefully placed and filled under the haunches of the pipe. Tamping of the bedding material must guarantee that the pipe will be supported over its entire length. Some pipeline trenches shapes are vertical sided, V-shaped, or stepped (Figure 4) (Jung and Sinha, 2007).

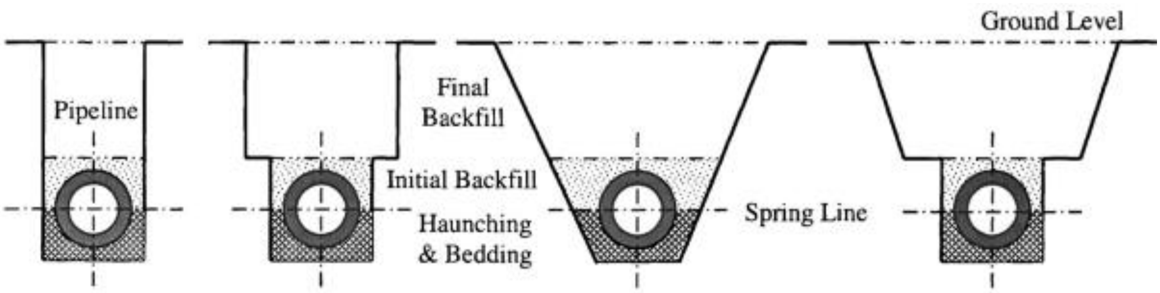


Figure 4: Conventional open trench methods for pipe laying (Jung and Sinha, 2007)

The main advantages and disadvantages of open trench methods for sewer installations provided by the Federation of Canadian Municipalities and National Research Council (2003) are listed in Table 3. It is important to highlight that similar pros and cons can be applied to other types of pipelines.

Table 3: Advantages and disadvantages of open trench methods for pipelines renewal projects (Federation of Canadian Municipalities and National Research Council, 2003)

Advantages	Disadvantages
Alignment of the sewer can be adjusted to meet local area needs	The costs can be substantial compared to some newer technologies
Longer expected life than that provided by trenchless technologies due to installation of new appurtenances	Construction is usually longer than with most trenchless technologies due to the quantity of disturbance to other infrastructure and traffic, and the amount of reinstatement work required following the installation of the sewer
Sewer connections can be replaced to meet current standards	Safety concerns due to traffic issues on road rights-of-way, the number of excavations required, and the large equipment needed to perform the work.
Sizing and/or grade can be changed to meet current and future hydraulic requirements	There can be disturbances to other surface and buried infrastructure
Other infrastructures can be rehabilitated or replaced at the same time	The social and economic costs of major open cut projects can be substantial during construction
Storm sewer laterals currently connected to the sanitary system can be disconnected	-

2.1.2 Trenchless technologies

Trenchless technologies consist of construction techniques and methods that involve new installations and rehabilitation of underground utilities with little or no excavation of the ground above (Piehl, 2005). Trenchless rehabilitation can be divided into renovation, replacement and repair of pipelines. Renovation aims at extending the lifetime of the existing pipeline by incorporating all or part of the original fabric of the old pipeline to improve its performance and does not involve the destruction of the old pipeline (Syachrani et al. 2010; ISTT, 2017). Usually a new pipeline will be inserted into the old one and a new renovated pipeline with a longer lifetime is produced.

Replacement involves installing a new pipeline on or off the line of the old pipeline and in many cases implies the destruction of the old pipeline (e.g. pipe bursting, pipe splitting). Repair aims at restoring or improving the structural integrity or performance of the existing pipeline, but the lifespan of a repaired pipeline is not as long as a replaced or renovated one (ISTT, 2017). A scheme of existent methods for pipelines projects is presented in Figure 5 and a brief description of some renovation techniques can be found in Appendix A.

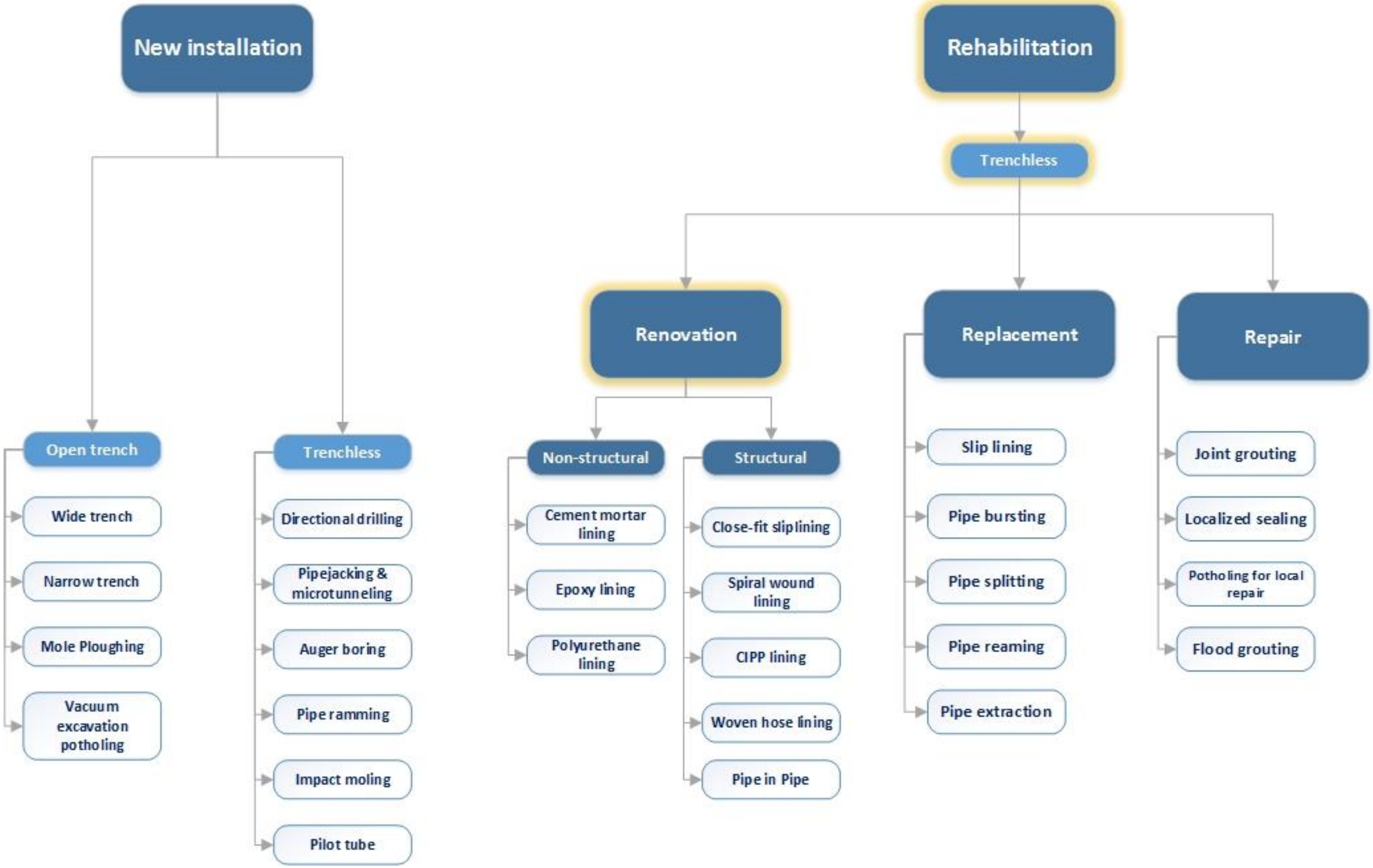


Figure 5: Underground construction techniques (ISTT, 2016)

The lesser surface disruption and project durations of trenchless renovation methods compared to open trench seem to generate less nuisance to the society and environment. The advantages of trenchless compared to open trench are hard to quantify in terms of social costs, which might lead to decision makers opting for the traditional open trench method if the social costs are left out of consideration. Nonetheless, these social costs have to be evaluated and quantified for different types of projects and situations to clarify decision-makers about which method is more advantageous in each situation.

In some cases trenchless technologies are potentially more cost-effective than traditional open trench methods such as (Iseley & Gokhale, 1997; Jung & Sinha, 2007; Woodroofe & Ariaratnam, 2009; ISTT, 2016):

- When a project takes place in urbanized areas with high traffic or pedestrian intensity;
- In socially and environmentally sensitive areas;
- In areas where access may be restricted due to the existence of structures or vegetation;
- In areas with high congestion of existing utilities and business districts. This is mainly applicable for trenchless renovation techniques that do not affect the surrounding buried utilities. Replacement or new installations can displace soil and damage utilities especially in congested undergrounds.

In other cases, trenchless methods can be disadvantageous when compared to open trench. Table 4 compares open trench excavation and trenchless technologies and highlights the advantages and disadvantages of the former (adapted from Piehl, 2005).

Table 4: Advantages and disadvantages of trenchless technologies (vs. open trench excavation) (Iseley & Gokhale, 1997; Piehl, 2005; Conway, 2008)

Advantages	Disadvantages
Costs: substantial cost savings are possible	Costs: less suitable than excavation where placement is shallow and traffic is not a constraint
Environment: less soil disturbance, impacts on adjacent nature and pollution	Flow capacity: some practices (e.g. lining pipes) with thick structural sections reduce pipe openings and flow capacity
Disruption: reduced or no traffic delays	Grade/alignment: effecting necessary changes to the existing grade and alignment are not always possible
Speed of installation: construction often takes less time regardless of the road fill depth	Design life: rehabilitation techniques (e.g. spot repair) have a shorter design life than new pipe installation
Engineering: less surveying, drawings and specifications may be required	Engineering: specialized expertise in related technologies and the impact on subsurface site conditions is required for some techniques
Reduction in the amount of soil that requires disposal and the need for dewatering	Risk of soil subsidence, ground displacement, vibration or leaking of drilling fluid
Safety: many safety concerns related to work inside trenches or traffic exposure are eliminated	Often higher risk inherent in a trenchless project compared to an open trench can make a failure considerably more expensive
Less relationship between cost and depth of installation. Flexibility in choosing depth of new installation also increases and may allow more favourable soil conditions to be used	Trenchless construction methods are more sensitive to adverse ground conditions than traditional open trench methods; therefore geotechnical data must be more accurate for trenchless construction.
Reduction in required surface restoration and damage to adjoining utilities	-
Less disturbance to local residents and business	-
Less volume of contaminated soil to be treated or disposed	-

According to Conway (2008), trenchless technologies can also affect the subsurface by causing heave, subsidence, frac-out, and collision with underground obstacles. However, these problems are mainly produced by technologies that cause soil displacement and drilling fluid, for instance horizontal directional drilling. Trenchless rehabilitation techniques have little to no effect on the existing soil, with the exception of replacement techniques such as pipe bursting and pipe splitting where soil expansion can result from the destruction of the old pipeline (Conway, 2008).

Important aspects related to trenchless projects have been listed by Conway (2008) based on a survey conducted with experts in trenchless technologies projects. The main considerations in a trenchless project are the following: conducting a geotechnical exploration before starting trenchless construction; accurately locating existing utilities; giving preference to experienced contractors; and using a high quality closed circuit television before placing a liner.

As it can be noticed, there is no unique technique that is the best for every situation. A trade-off has to be made in order to select the most suitable method for pipelines projects. This trade-off should ideally consider technical aspects (e.g. feasibility and limitations); economic aspects (e.g. direct and indirect costs; and the impacts of the project on society, economy and environment (social costs). The latter, which is the focus of this research, will be discussed in more details in the next sections.

2.2 Costs related to subsurface utilities renovation

Costs are one of the most important factors influencing the decisions of a project. The project costs are spread throughout the project life cycle, from the conception phase until the end of life. According to Najafi and Kim (2004), the costs associated with a project are divided into pre-construction, construction and post-construction costs and involve different costs components (Table 5).

Table 5: Life cycle cost of a project (Najafi and Kim, 2004)

Preconstruction	Construction	Post construction
▪ Land acquisition ▪ Easements ▪ Permits ▪ Design fees ▪ Planning ▪ Legal ▪ Preparation of contract drawings	▪ Direct costs ▪ Indirect costs ▪ Social costs	▪ Operation ▪ Maintenance ▪ Depreciation ▪ Loss of revenue due to emergency repairs

The *preconstruction costs* are related to planning and engineering costs; *construction costs* regard direct, indirect and social costs; while *post construction costs* involve operation and maintenance costs. A life-cycle-costs perspective encompasses these three cost groups and involves all the costs related to the project life cycle (Najafi and Kim, 2004).

The “construction costs” presented by the authors are treated as “total costs” in this research and represent the sum of the direct, indirect and social costs. Per definition, direct costs are directly linked to the physical construction of the project and relate to conception, development and implementation costs, which are usually calculated beforehand (e.g. construction costs with material, equipment and labour). They are project specific and directly borne by the owner/users of the project.

Indirect costs have two possible definitions and both of them are considered as valid. The first one assumes that indirect costs are those spread throughout the whole project and cannot be directly related or applied to the construction cost categories. They are usually proportional to the project duration and are calculated as a percentage of the project direct costs. They comprise overhead, taxes, costs of utilities during the construction, head office costs, costs of field supervision, insurance, profit, contingency, and sales and marketing costs (Najafi and Kim, 2004).

The second definition is that indirect costs are those paid by the owner or contractor to separate parties that are not directly involved in the construction contract (Matthews & Allouche, 2010). They are borne by the client organization and are usually incurred during or after construction due to unexpected factors and actions performed in the project (e.g. loss of parking ticket revenue, damage compensation, etc.) (Ormsby, 2009).

Social costs are those for which the society will not be compensated and affect the communities nearby the construction site, the environment and the surrounding infrastructure (Najafi and Kim, 2004; Matthews and Allouche, 2010). They cannot be classified as either direct or indirect costs incurred by the parties engaged in the contractual agreement (Allouche et al, 2000). They are associated with the negative effects or negative externalities of projects and include among others safety, business revenue loss, roads deterioration and damage to existing utilities and foundations.

Negative externalities take place “when an act of production or consumption on the part of an individual causes harm to other members of the society and the said act has a negative impact on them and they do not get any compensation for it” (Jain, Khanna, & Sen, 2010). Social costs usually cannot be assigned to a particular party because they are related to environment and safety. Consequently they are not borne by the project owner but by the third parties that bear the negative effects of the project (Ormsby, 2009; Decisio, 2016). Examples of negative externalities in construction projects are environmental pollution, traffic delay, increase in the number of accidents and inefficient use of space that is no longer available for other uses.

On the other hand, projects can also have positive effects or positive externalities “when the production or consumption of a commodity or a service has its positive effect on another person who is neither its buyer nor seller (…) and they cannot be reflected in market prices” (Jain, Khanna, & Sen, 2010). An example of positive externality is the result of a pipeline renovation projects that brings direct benefits to the utility owner (e.g. less water losses during distribution and increase in profits), but also to the users of the system who might e.g. have higher quality water in their homes (positive externality).

The scheme in Figure 6 correlates the costs that occur throughout a project life cycle. More attention is paid to the *construction costs*, especially to the social costs which are the main topic of this research.

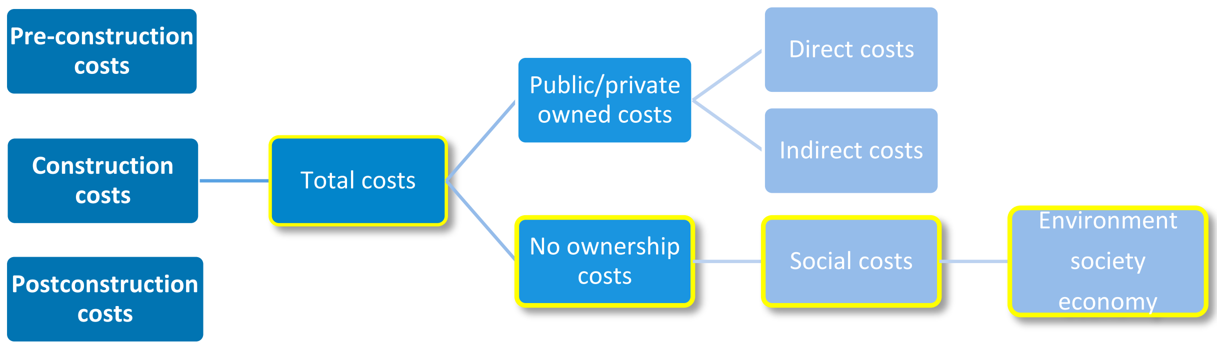


Figure 6: Cost involved in a construction project

2.3 Impact areas and negative effects related to pipelines projects

A deeper understanding on the negative impacts of subsurface utilities projects is important when social costs are used to assess projects. Factors such as the type of project, location and duration will influence the potential impacts of construction projects on society and environment. These impacts can be either temporary or permanent and vary in severity, predictability and nature (Gilchrist and Allouche, 2005).

In 2010, NSTT has conducted a research about the nuisance caused by excavation works in public spaces and its impacts in human behaviour, economy and environment in the Netherlands. A survey was conducted among inhabitants/costumers and retailers/shops and results showed that 72% of the interviewed retailers have experienced nuisance due to excavation activities in the past five years and 84% of the costumers have experienced nuisance in the past two years. As expected, the most affected groups were elderly and people with reduced mobility, emergency services, businesses and workers (NSTT, 2010).

The main complaints by the customers were related to increased travel time, traffic jams, higher fuel consumption due to detours, chaotic traffic, poor accessibility of shops, noise disturbance and dust. The interviewees also complained about the duration of activities, work stations where nobody is seen at work, regular excavation of the same street, traffic controls and when they do not know the reason the work is being conducted (NSTT, 2010).

The retailers' main complaints related to poor accessibility to customers, dirt, noise, revenue loss due to reduced number of customers, irritated customers, poor accessibility to suppliers, hindrance to the delivery of goods to customers and chaotic traffic. The interviews also revealed that accessibility issues impact the businesses revenues: 91% of businesses thought that customers avoided frequenting shops that are difficult to access and 72% said that there was a revenue loss of 10% in such situations.

As it can be noticed from the NSTT research, the nuisances created by construction works (e.g. excavation) can affect the population in different ways and the impacts vary according to project duration, location, age of affected persons, etc. In a more structured approach, Gilchrist and Allouche (2005) have defined four different areas that can suffer nuisances from construction projects: traffic, economy, pollution and Ecological/social/health (Figure 7). A brief explanation of each category is presented in Table 6.

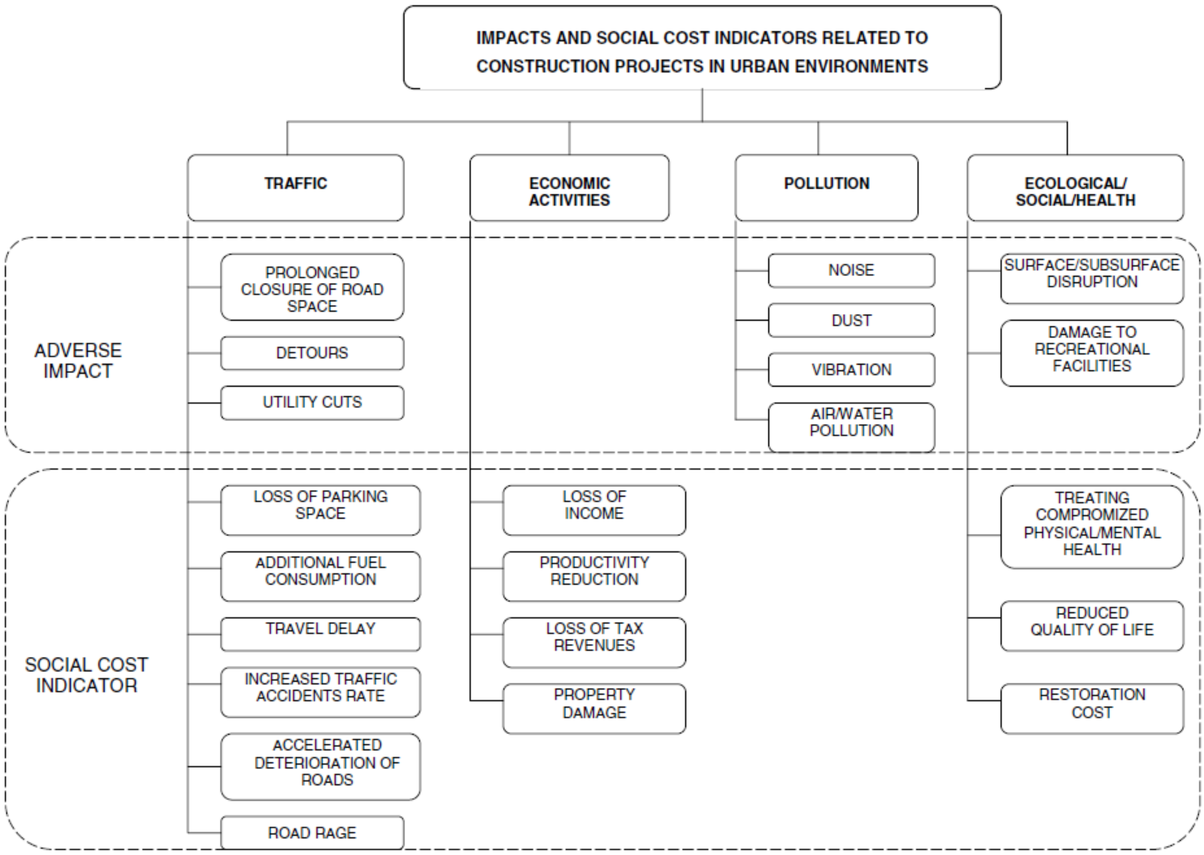


Figure 7: Potential impacts and social cost indicators associated with construction activities (Gilchrist and Allouche, 2005)

Table 6: Impact areas related to social costs in pipelines projects

Impact area	Description
Traffic	Interventions on roads usually require changes in the traffic flow, leading to traffic disruption and delays around the working zone. Besides, if heavy machinery and vehicles are present on site these disturbances can increase. The impact of traffic disruptions is more intense in busy areas where there is a high flow of pedestrians and vehicles. Some negative impacts associated with traffic disruption are prolonged closure of road space, detours and utility cuts which can increase the accident rates and incidents and reduce the useful life of the pavement (Gilchrist & Allouche, 2005). Social costs related to traffic consist of vehicle operating costs, traffic/travel delay, pedestrian delay, loss of parking space and pavement service life reduction (see 2.4.3).
Pollution	The pollution caused by construction works includes water, air, soil, noise, visual and urban congestion pollution. This impact area is wide in the sense that it considers not only the pollution to the environment itself such as water and soil pollution, but also to the society such as noise, visual pollution and vibrations (see 2.4.3).
Damage to environment and health	This category refers to the impacts of projects on the society and environment in terms of (risks of) damage to infrastructure, properties and subsurface utilities, besides (risks of) accidents involving workers and users (pedestrians, cyclists, vehicles, etc.) (see 2.4.4)
Economy	Construction activities can both boost the economy and contribute to area development, or bring negative impacts especially during project execution. Traffic disruption, user delays and decrease in accessibility are some factors that have a negative influence on the local economy. Inaccessibility of the streets, shopping centres and commercial areas might reduce sales and decrease the business income around a project's "influence zone" (radius or area whose economy is negatively affected by a project).

A literature review about social costs related to construction projects and subsurface utilities projects has resulted in Table 7. The table lists the most and least relevant social cost indicators that are used as a starting point for this research. Some authors (Ormsby, 2009; Matthews and Allouche, 2010; Ariaratnam et al., 2013; Matthews, Allouche and Sterling, 2015; Alkema, 2015) present social costs specific for subsurface utilities projects, while the others authors for construction projects in general.

Table 7: Review about social cost indicators and number of citations from different sources.

Cost indicators and impacts	**Literature**										
Traffic	Gillchrist and Allouche (2005)	Rahman et al. (2005)	Jung and Sinha (2007)	Yu and Lo (2007)	Xueqing et al. (2008)	Ormsby (2009)	Matthews and Allouche (2010)	Ariaratnam et al. (2013)	Welling and Sinha (2013)	Matthews, Allouche and Sterling (2015)	NSTT (2014)
Traffic/travel delay	•	•	•	•	•	•	•	•	•	•	•
Increased Vehicle operating costs	•	•			•	•	•			•	•
Pavement Service life reduction	•	•	•		•	•	•	•			
Loss of parking space	•					•	•	•		•	
Increased traffic accidents	•				•	•		•	•	•	•
Pedestrian delay		•	•			•	•				
Pollution											
Dust pollution	•	•	•		•	•	•	•		•	•
Air pollution	•	•	•	•	•	•	•				•
Noise pollution	•		•	•	•		•	•	•	•	•
Vibrations					•						•
Damage environment and health											
Accidental injury and death			•		•	•		•		•	•
Repair costs existing facilities/infrastructure	•				•	•					•
Adjacent buried utilities damage	•		•		•	•					
Quality of life reduction	•					•					
Property damage	•	•				•					
Economy											
Business revenue loss	•	•	•	•	•	•		•	•	•	•
Loss of property value	•					•					•

From Table 7 it is possible to identify that some social costs are more prevalent than others such as traffic/travel delay; vehicle operating costs; air and noise pollution and business revenue loss. The scheme in Figure 8 was built to represent the different impact areas and social cost indicators. The colours correlate each impact area with the pertinent social costs (same colour) and show the overlap between the categories in terms of social costs. For instance the social cost *traffic accidents* (in red) could relate to both *Traffic* and *Damage* (if it results in property damage and/or injury) and would be applicable to both impact areas in the scheme.

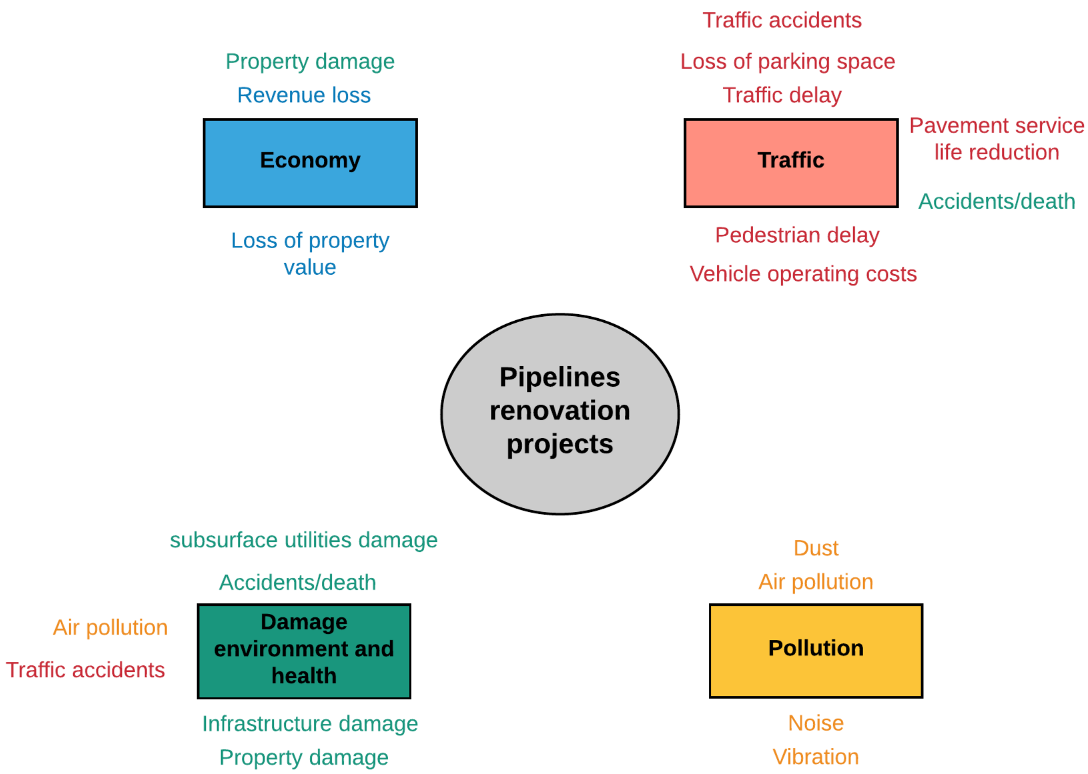


Figure 8: Model for social costs and impact areas

Once the most relevant negative impacts of pipelines projects on society and environment have been presented, the following step is to explain how these impacts can be translated into monetary units. This can be done through different valuation equations retrieved from literature.

2.4 Valuation methods: Quantifying social costs

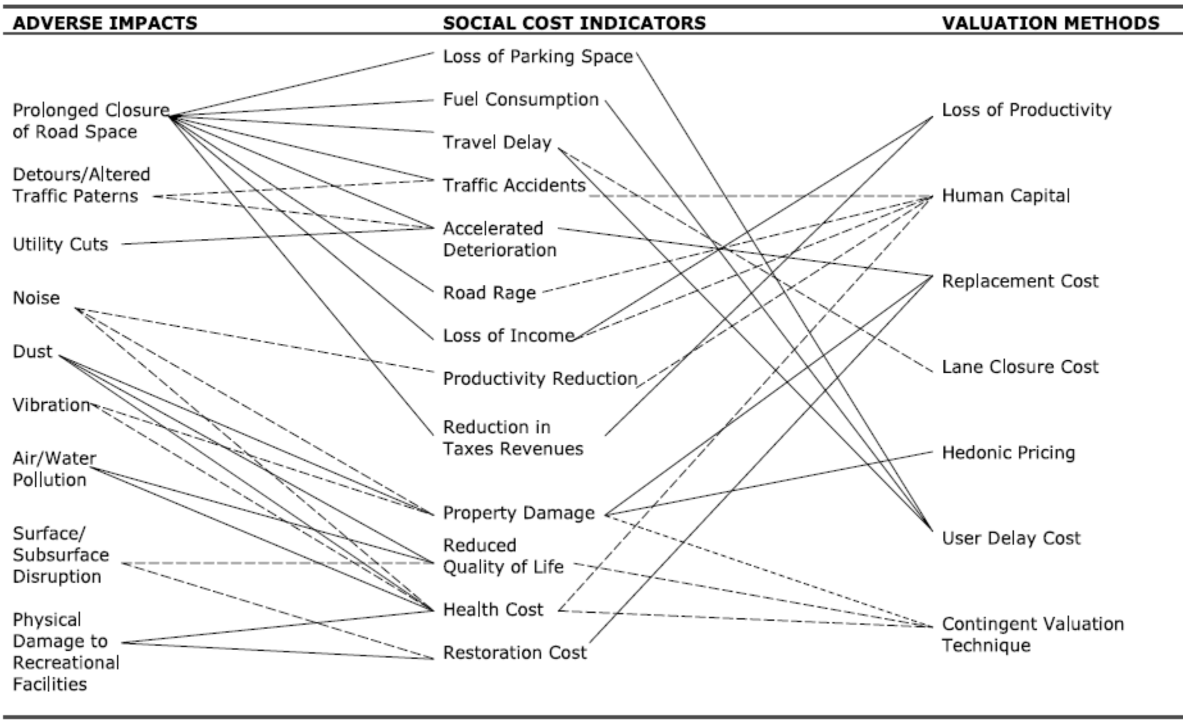
2.4.1 Introduction

The quantification of negative impacts related to construction projects is necessary to establish a basis for comparison between pipelines execution methods in terms of costs. Different methods of executing projects will result in different externalities and impact intensities. For instance, a pipeline project executed by excavating a trench will probably impact the surroundings differently than if it were executed using trenchless technologies. Even though the impacts of both methods are included in one (or more) of the previously described "impact areas", the effects intensity may vary.

The magnitude of impacts due to construction projects can be estimated through valuation methods, which consist of equations that can estimate social costs in monetary units. Since the project negative impacts cannot be directly quantified, it is necessary to make use of cost indicators (Gilchrist & Allouche, 2005; Ormsby, 2009; Matthews & Allouche, 2010). Cost indicators are an indication of the monetary value of the corresponding impact calculated through valuation methods.

Gilchrist & Allouche (2005) defined a social cost indicator as *"a measurable cost that can be quantified in monetary terms and is a result of one or more construction-related adverse impacts on the environment surrounding a construction site*". Table 8 presents the relationships between adverse impacts, social cost indicators and valuation methods (Gilchrist & Allouche, 2005).

Table 8: Relationships among impacts, social cost indicators and valuation methods (Gilchrist and Allouche, 2005)



The determination of social costs is usually based on estimating the negative impacts of carrying out the work on several social and environmental aspects. These aspects are often interrelated and one aspect may cause more than one impact, which needs to be taken into consideration by the valuation method used. For instance, medical costs due to traffic accidents are related to different social cost indicators (*traffic accidents* and *accidental injury and death)* and if they are considered in both valuation equations they would be double counted.

Another important point is that the valuation methods/equations for quantifying a certain social cost can vary depending on the approach used. Some valuation methods are more refined and need more precise or project-specific information, while others are more general and can make use of key figures or indicators. Consequently, depending on the valuation method adopted, different parameters and values will be observed in the calculations. The choice of the most relevant valuation method depends on the availability of input data to be used in the equations and the level of accuracy demanded by the user.

Key figures used in the valuation methods can be retrieved from official reports such as the Netherlands Institute for Transport Policy (Kennisinstituut voor Mobiliteit - KiM), RIGO Report (2012) and from literature. According to RWS (2016), "*a key figure is a value defined through extensive research that can be used to quantify an effect and create a common comparison base between different effects in a SCBA*". By using the same key figures (values) for comparing different projects, it is possible to avoid discrepancies in the calculations since the projects would be assessed using the same base values.

In the light of this reviewed literature, it is evident that quantifying impacts of construction projects is challenging and usually does not lead to precise results. Valuation methods can be used for this task, but a clear scope with limited boundaries has to be defined beforehand so that the valuation of social costs is feasible. Once the methodology for quantifying social costs is defined, it is possible to compare different pipelines projects (e.g. trenchless versus open trench) based on social or total costs.

2.4.2 Description of Valuation methods

Apart from the impact areas classification presented in section 2.3, this research proposes to distinguish social costs between "fixed social costs" and "risk related social costs". The fixed social costs refer to the social costs that are most of the times present in any pipelines renovation projects executed by open trench or trenchless technologies; and are easily calculated in monetary units. The valuation of fixed social costs does not depend on risk evaluation and information such as probability or severity.

For instance, it is possible to foresee whether traffic will be impacted by a pipeline project if a traffic plan is produced and extra travel time is estimated beforehand. Regarding pollution, the equipment and machinery used in the projects will inevitably produce some noise, pollutants and GHG. Therefore, it is possible to estimate air/noise pollution costs due to the use of equipment caused by pipelines projects. When a fixed social cost is considered negligible for a certain project this can be captured by valuation equations.

On the other hand, as the name suggests, risk related social costs are the costs whose occurrence is contingent upon the transpiration of certain probable events. The valuation of risk related social costs depends on a risk management plan where the probability and severity of impacts of various risks are investigated. The higher the probability and severity of these social costs, the higher the social costs will be.

The risk related social costs considered in this research are Accidents involving users and workers; and damage to property, infrastructure and buried pipelines. As explained, accidents and damage might happen in open trench or trenchless pipelines projects, but it is not possible to exactly predict the social costs associated to these risks in monetary terms. Therefore they are not included in the fixed social costs and considered apart. The list of fixed and risk related social costs in this research are the presented in Table 9.

Table 9: List of fixed and risk related social costs

Social costs

- **Fixed social costs**
  - *Vehicle operating costs*
  - *Traffic/travel delay*
  - *Pedestrian delay*
  - *Loss of parking space*
  - *Pavement service life reduction*
  - *Air/Noise/Dust pollution*
  - *Business revenue loss*
- **Risk related social costs**
  - *Accidents (workers and users)*
  - *Damage (property, infrastructure and buried pipelines)*
  - *Damage to the environment*

This research also presents valuation equations for the risk-related social costs; however it is not possible to provide general probability and severity of impacts for each social cost because they are project dependent. These social costs are influenced by several factors such as the technique used (either open trench or trenchless technologies), project location, project duration, soil conditions, depth of installation, type of utility, subsurface utilities density in the area, presence of nearby infrastructures, etc. Consequently, for each combination of factors a different risk profile should be built.

For each valuation method sub-section presented next, the equations retrieved from literature and reports are provided together with the necessary parameters. Some key figures (*kengetallen)* retrieved from (SCBA) Dutch reports are presented in the form of tables and can be used as input parameters for the equations. The advantage of using key figures is that they can replace some parameters and it is not necessary for the user to search for these values themselves. Even though these are general values, they can provide an estimation of the social costs for comparing open trench and trenchless methods.

2.4.3 Fixed social costs

This subsection describes the valuation methods for the fixed social costs considered in this research: vehicle operating costs, traffic/travel delay, pedestrian delay, loss of parking space, pavement service life reduction, air pollution, noise pollution, dust pollution and revenue loss.

2.4.3.1 Increased vehicle operating costs

Vehicle operating costs (VOC) are incurred to road users and depend on the mileage of the vehicle without considering fixed costs due to vehicle usage. The following situations contribute to an increase in Vehicle operating costs (Mallela and Sadasivam, 2011):

- speed change costs when the vehicle has to decelerate to the work zone speed and then accelerate to the normal speed when exiting the work zone;

- Stopping costs (stop-and-go) due to work zone conditions and then accelerating back to the normal speed after crossing the work zone;
- Queuing idling costs due to stop-and-go driving in a queue in the work zone;
- Detour costs due to extra distance travelled by selecting a detour route under unrestricted or restricted conditions. These are easier to be estimated than stopping costs.

The VOC are also dependent on the type of vehicle, price of fuel, condition of roads, etc. For example, the operating costs of commercial trucks is higher than passengers cars because of a lower fuel consumption and higher maintenance and tire costs due to increased wear (Barnes and Langworthy, 2003 cited by Matthews and Allouche, 2010). Therefore, it is possible to consider separately heavy vehicles VOC and passenger cars VOC if a more precise estimation is required and if the share of each vehicle type is known.

The estimation of VOC is given by the consumption of fuel, engine oil, tire-wear, repair and maintenance and mileage-related depreciation while a vehicle travels between two points, and by multiplying these quantities with the unit cost of each resource (Figure 9) (Mallela and Sadasivam, 2011).

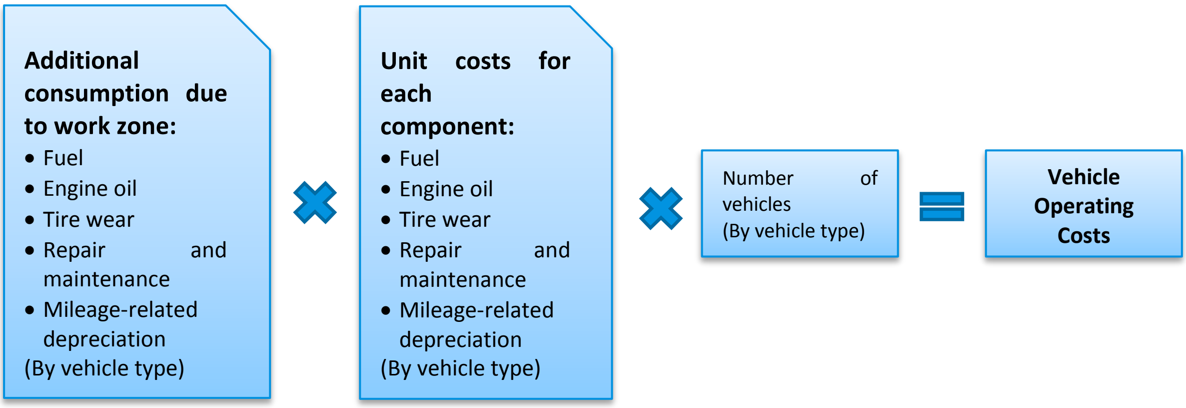


Figure 9: VOC components and computation of VOC (Mallela and Sadasivam, 2011)

Equations 1 and 2 are proposed to quantify the increase in Vehicle Operation Costs for different types of vehicles (Ormsby, 2009; Matthews and Allouche, 2010; Matthews, Allouche and Sterling, 2015). The total Increase in VOC is given by Equation 3.

$$\mathrm{IVOC}_1 = \mathrm{AD} \times \mathrm{VOC} \times \big(\mathrm{NVD} - (\mathrm{NVD} \times \mathrm{HV\%})\big) \times \mathrm{D} \qquad \text{Eq. 1}$$
$$\mathrm{IVOC}_2 = \mathrm{AD} \times \mathrm{VOC} \times (\mathrm{NVD} \times \mathrm{HV\%}) \times \mathrm{D} \qquad \text{Eq. 2}$$
$$\mathrm{IVOC\ Total} = \mathrm{IVOC}_1 + \mathrm{IVOC}_2 \qquad \text{Eq. 3}$$

Where:

$IVOC_1$= Increase in Vehicle Operation Costs for passenger vehicles

$IVOC_2$= Increase in Vehicle Operation Costs for heavy vehicles

AD = Additional distance

VOC = Vehicle Operating Costs (€/ vehicle-kilometre)

NVD = Number of vehicles per day (vehicle/ day)

HV% = Percentage of heavy vehicles (%)

D = Project duration (days)

As it can be noticed from Figure 9, the quantification of Vehicle operating costs is dependent on different components, unit costs and type of vehicles which can vary from a region to another. For this reason, some traffic agencies estimate Key figures of VOC in their region or countries and these values can be used to quantify the increase in VOC due to construction works. Table 10 presents VOC values in the Netherlands proposed by RIGO (2012)

Table 10: Vehicle Operating Costs in the Netherlands measured in 2011 (RIGO, 2012)

Vehicle Operating Costs for passenger vehicle		
Parameter	**Amount**	**Unit**
Variable costs	0,088	€/vehicle-kilometre
Excises costs	0,032	€/vehicle-kilometre
CO2 emissions	0,007	€/vehicle-kilometre
Total	**0,13**	**€/vehicle-kilometre**

2.4.3.2 *Traffic Delay*

Pipelines renovation projects can impact the traffic flow and consequently lead to traffic or travel delays to drivers. According to Matthews and Allouche (2010), traffic delay costs can account for more than 50% of the social costs. Traffic flow can be disturbed due to the presence of heavy vehicles nearby the construction site and due to changes in the traffic configuration such as partial or full block of streets and deviations in road works.

According to Tighe et al (1999), the two types of traffic delays are *"slowing delay"* due to a speed reduction in the work zone; and *"queuing delay"* when traffic demand exceeds road capacity generating congestion. The *slowing delay* duration is dependent on the normal speed and the reduced speed, whereas to calculate the *queuing delay* a capacity model is necessary to identify the length of time each vehicle must wait in addition to the speed delay. If a detour is set due to a full lane closure, the total travel delay would be the extra time necessary to drive the detour plus the speed and queuing delays (Tighe et al, 2002).

Mallela and Sadasivam (2011) present the delay time as the sum of the following five components: speed change delay, reduced speed delay, detour delay, stopping delay and queuing delay. This approach is similar to the one the authors use for the Vehicle Operating Cost, but in this case these components will contribute to a delay in the travel instead of vehicle operating costs. As it can be noticed, traffic delay and VOC are interrelated social costs, which mean that when one is present, most probably the other will also be.

There are different valuation methods for quantifying traffic delay but most of them have common principles. The information needed to quantify traffic delay for each valuation method may vary, but they are mostly related to traffic flow, Value of Time (VOT), number of passengers per vehicle, delay time, length of the work zone, vehicle operating costs, and speed reduction. The most complex methods use equations with more variables and demand more detailed information about the traffic plan in the area to calculate the delay time. In the early stage of pipelines renovation projects, complex traffic plans for the work zone might be unavailable and key figures can be used for the estimation.

For instance, the delay time due to a work zone can be estimated using mobility impact analysis methods such as demand-capacity analysis and simulation methods or the floating-car technique. The latter consists on "a test car driven by an observer along the work zone section a number of times to measure the travel time" (Mallela and Sadasivam, 2011).

Gillchrist and Allouche (2005) and Ormsby (2009) present valuation methods to quantify user delay costs and traffic delay costs. The user delay costs represent the value of time lost by users due to traffic circumstances and depends on the purpose of journey (e.g. work, leisure), characteristics of travellers (e.g. age, income), distance, day of the week, and hour of the day or traffic volume (Gillespie, 1998).

Travel delay costs are quantified by multiplying the following parameters: estimated time delays (per trip purpose such as personal travel, truck travel, and freight inventory) caused by the work zone; and the unit cost of travel time, also known as Value of Time (VOT) (Mallela and Sadasivam, 2011). If one wants to consider the total traffic delay costs for a certain road section, it is also necessary to consider the number of vehicles passing the area per day, vehicle occupancy and project duration.

The calculation of Traffic Delay costs is divided in three steps: (1) delay time; (2) cost of delay per vehicle; (3) and total cost of delay (Gillespie, 1998; Yu and Lo, 2005, Mallela and Sadasivam, 2011).

The first step is to calculate the Delay Time which consists of the extra time spent by the user to cross the work zone compared to the normal situation where no construction work is taking place. (Equation 4). If for instance a detour is needed, the length of work zone should be the total trajectory to cross the working zone, compared to the normal situation where the street is not blocked and no detour is needed.

Secondly, once the Delay Time is known, it is possible to calculate the Cost of Delay per vehicle (CD) through Equation 5 (Gillchrist and Allouche, 2005). Standard values of VOT provided in Official reports such as RIGO (2012) are proposed for the valuation (Table 11). When no trip purpose distribution for the location is available, it is suggested to use the average VOT values. Finally, the total Traffic Delay Costs (TDC) for the whole duration of the project can be calculated based on the outcomes of Equations 4 and 5 (Equation 6).

$$\mathrm{DT} = \frac{\mathrm{L_W}}{\mathrm{S_W}} - \frac{\mathrm{L_N}}{\mathrm{S_N}} \qquad \text{Eq. 4}$$

$$\mathrm{CD} = \mathrm{DT} \times \mathrm{VOT} \times \mathrm{ANP} \qquad \text{Eq. 5}$$

$$\mathrm{TDC} = \mathrm{CD} \times \mathrm{NVD} \times \mathrm{D} \qquad \text{Eq. 6}$$

Where:
L_W = Length of work zone including detours (km)
S_W = Speed through work zone (km/h)
L_N = Length of working zone in normal situation (km)
S_N = Normal speed (km/h)
DT = Delay Time (h)
VOT = Value of Time (€/person x hour)
ANP = Average Number of Persons per Vehicle (person/vehicle)
NVD = Number of vehicles per day (vehicle/ day)
D = Project duration (days)

Tables 11 and 12 present some key figures that can be used for calculating Traffic Delay costs. The values are related to The Netherlands and have been retrieved from RIGO (2012).

Table 11: Value of time (VOT) per person per trip reason in the Netherlands (RIGO, 2012)

Travel purpose	Commuting	Business	Remaining	Average*	unit
2007	9,48	32,83	6,55	10,59	€/person*hour
2010	9,79	33,92	6,76	10,94	€/person*hour
2017**	10,54	36,69	7,31	11,83	€/person*hour
2020	10,94	37,87	7,55	12,21	€/person*hour
2040	13,79	47,73	9,52	15,40	€/person*hour

Table 12: Average vehicle occupancy (ANP) for passengers' vehicle (Otten,'t Hoen and den Boer, 2015)

Trip purpose	2014	Unit
All purposes	1,39	Person/veh
Commuting	1,08	Person/veh
Business	1,06	Person/veh
Services/ personal care	1,46	Person/veh
Shopping/groceries	1,49	Person/veh
Education	1,77	Person/veh
Visiting	1,82	Person/veh
Sport and relaxation	1,85	Person/veh
Tours/walking	1,82	Person/veh

2.4.3.3 *Pedestrian Delay*

Pedestrian Delay takes place when there is an increase in pedestrian travel time and consequently a decrease in the productivity time (Matthews and Allouche, 2010). Similarly to traffic delay, pedestrian delays happen when sidewalks are occupied by construction works forcing pedestrians to take alternative crossing routes (Ormsby, 2009).

If safety measures are not correctly taken, pedestrians might become more exposed to risky situations related to traffic and proximity to construction equipment and material. The valuation of Pedestrian Delay Costs (PDC) is given by Equation 7 (Matthews and Allouche, 2010):

$$\mathrm{PDC} = (AD_{\mathrm{P}} \div \mathrm{S}) \times (0{,}5 \times \mathrm{HR_P}) \times \mathrm{P} \times \mathrm{D} \qquad \text{Eq. 7}$$

Where:
AD_P = Additional distance to cross the work zone (hours)
S= Pedestrian speed
HR_P = Average hourly rate (€/ hour)
P= Number of pedestrians affected per day
D = Project duration (days)

The value of time for pedestrians is considered 50% of the average hourly wage rate, estimated at 14,40€ in the year 2015 in the Netherlands (Loonwijzer, 2017).

Because it might be hard to know the number of pedestrians crossing an area, estimations can be done based on the number of houses and buildings in an area and correlating it with the population density or number of inhabitants per building type. For instance, the number of inhabitants per domicile in The Netherlands amounts to 2,17 in the year 2015 (CBS, 2015) and could be used for an estimation. The CBS report (2015) has detailed population information for each region and larger cities in the Netherlands.

2.4.3.4 Loss of parking space

The presence of a construction site can interfere in public parking spaces. Loss of parking spaces affects users who will be unable to park and municipalities that depend on the parking revenues and parking fines (Matthews and Allouche, 2010). The costs related to the Loss of Parking Space is composed by sum of the Loss of Parking Meter revenue (LPm) and Loss of Parking Ticket fines (LPt) given by Equations 8 and 9 respectively (Ormsby, 2009; Matthews and Allouche, 2010; Matthews, Allouche and Sterling, 2015).

$$\mathrm{LPm} = \mathrm{PM} \times \mathrm{R} \times \mathrm{Ho} \times \mathrm{O} \times \mathrm{D} \qquad \text{Eq. 8}$$

$$\mathrm{LPt} = \mathrm{PM} \times \mathrm{F} \times \mathrm{FT} \times \mathrm{D} \qquad \text{Eq. 9}$$

Where:
PM= Number of parking meters or spaces
R= Meter rate (€)
Ho= Meter operational hours (hours)
O= Occupancy (%)
D= Duration of parking obstruction (days)
F= Amount of fine (€)
FT= Frequency that fines normally occur (fines/space*day)

2.4.3.5 Pavement Service Life Reduction

Pavement excavation negatively impacts the long term integrity of pavement structure by reducing its service life and increasing costs of restoration and maintenance (Ormsby, 2009; Karim et al, 2014). According to the National Guide to Sustainable Municipal Infrastructure (cited by Karim et al, 2009), excavation disturbs pavement sub-base in such a way that the overall life of the pavement will be reduced no matter how well the utility cut is repaired.

According to Ormsby (2009), even though the restoration of an excavated pavement is conducted, the compaction does not lead to the same density levels as in new road construction. This is the case because the equipment used has to be small enough to fit the trenches and therefore it becomes hard to achieve the same level of compaction.

Consequently, open trench excavation methods used for pipelines projects have a higher impact on the pavement service life when compared to trenchless renovation technologies. Trenchless technologies can also affect pavement service life due to pressure on the subsoil caused when new installations or replacement (e. g. pipe bursting) take place. In the case of renovation techniques, the impacts on the existing soil and pavement are limited to the cases where excavation is needed.

Tighe et al. (2002) have estimated a decrease of 30% on the service life of pavements due to excavation, which also leads to an increase in maintenance and rehabilitation costs compared to a pavement that has not been dig. Tighe et al. found out that this increase in costs can range from 60 to 104 €/m^2 over the pavement lifetime depending on the age of pavement. For instance, older pavements will present lower service life reduction compared to new pavement because the former already presents distresses due to aging (Ormsby, 2009).

Matthews and Allouche (2010) proposed a conservative and simple equation for quantifying Pavement Service Life reduction (PSL) based on the area of excavation (A) (Equation 10). Kolator (1998, cited by Matthews, Allouche and Sterling, 2015) proposed another equation based on the length of excavation in meters (Ls) (Equation 11).

Karim et al (2014) have estimated a so called Pavement Degradation Fee (PDF) per square meter of excavation for different types of roads and road ages, what makes their approach more complete than the previous authors. According to Lakkavalli et al (2015), such a fee encourages stakeholders to coordinate construction projects and opt for trenchless technologies as a way to share and reduce pavement restoration costs.

The fee estimation of Karim et al (2014) were based on field data collection in Canada and aimed at compensating the municipalities for pavement service life reduction costs due to excavation. The authors recommend applying the degradation fee to the size of the trench plus the zone of influence (one meter on each side of the trench regardless size, location and layout of the trench) (Equation 12).

$$\mathrm{PSL} = \frac{101\ €}{\mathrm{m}^2} \times \mathrm{A} \qquad \text{Eq. 10}$$

$$\mathrm{PSL} = \frac{103\ €}{\mathrm{m}} \times \mathrm{Ls} \qquad \text{Eq. 11}$$

$$\mathrm{PSL} = \mathrm{PDF}\ \times \text{Excavated Area} \qquad \text{Eq. 12}$$

The degradation fee values have been exchanged into euros per square meter and can be used if no other key figure correlating pavement excavation and degradation costs is available (Table 13).

Table 13: Pavement degradation fee structure (Adapted from Karim et al, 2014)

Road classification	Road age at time of utility cut	Pavement degradation fee (€/m^2)
Arterial	0 to 5	40
	5 to 10	37
	10 to 20	33
	20 to 30	27
	30 to 70	20
Collector	0 to 5	36
	5 to 10	33
	10 to 20	30
	20 to 30	24
	30 to 70	18
Local	0 to 5	32
	5 to 10	30
	10 to 20	27
	20 to 30	21
	30 to 70	16

As it can be noticed, the methods proposed by the authors are based on the (same) principle to use a "pavement degradation fee" and the area of excavation to compensate for service life reduction. However, the research developed by Karim et al. (2014) is more complete because it incorporates road age and road type, that are important factors influencing the reduction in service life (Tighe et al., 2002). For this reason, Equation 12 (Karim et al., 2014) is the most complete to quantify Pavement service life reduction costs.

2.4.3.6 Air Pollution

The environmental impacts of pipelines renovation projects can also be expressed in terms of air pollution. According to RIGO (2012), local air quality is affected by the concentrations of sulphur dioxide, nitrogen oxides and particulate matters (air pollutants) which have to follow standard limits in order to protect human health. The emissions of carbon dioxide, which are also very significant, do not directly affect human health but contribute to climate change.

The emission of pollutants in the project zone is due to use of equipment/machinery and traffic control that rises fuel consumption by forcing detours or creating stop and go situations. Projects that opt for construction methods that require lighter equipment; interfere minimally on traffic flow; and short durations can minimize air pollution.

A study conducted by Rehan and Knight (2007) compared CO_2 emissions due to open trench and trenchless pipelines projects in three case studies. Their findings suggest that greenhouse gas emissions are 78% to 100% lower when trenchless technologies are used. Besides, they concluded that large amounts of CO_2 are generated due to traffic disruptions. Consequently, trenchless technologies resulted in less CO_2 emissions mainly due to shorter project durations and limited or no disruption to traffic.

The valuation of Air pollution costs can be conducted according to two different approaches. The first one is based on the cost of pollutant emission per unit (kilo or tones) and the amount of emissions related to a certain activity or project. The second approach is based on the cost of pollutant emissions per vehicle-kilometre.

The first valuation method for quantifying Air Pollution Costs (APC) is presented in Equation 13 where the total air pollution cost is the sum of the costs of each pollutant emitted during the project execution (Ormsby, 2009; Matthews and Allouche, 2010; RIGO, 2012). According to RIGO (2012), the use of a more detailed (per pollutant) or general (all pollutants together) volumetric emissions costs depends on the importance of the cost indicator in the project. For instance, for assessing the total social costs in a rural area where pollution levels are low, air pollution costs would be considered a secondary effect of the construction project and general values could be used. On the other hand, if improving air quality is between the main goals of a project, detailed values are more appropriate.

The estimation of the parameter *volume of pollutant emitted i (V_i)* due to each pollution source is given by Equation 14. The calculation of each component of V_i involves different equations and key figures that can be found in Appendix B. Only the volume of CO_2 is considered for means of simplification, but other pollutants (e.g. fine particles, NOx, SOx) can also be included if the emitted volumes are known.

$$APC = \sum_{i=0}^{i} V_i \times C_i$$ Eq. 13

$$V_i = V_F + V_D + V_M + V_T$$ Eq. 14

Where:
V_i = volume of pollutant emitted i (ton)
C_i = Cost of volumetric emissions per pollutant i (€/ ton)
V_F = Volume of pollutant due to extra fuel consumption (stop and go situations)
V_D= Volume of pollutant due to detours
V_M = Volume of pollutant due to equipment/machinery use
V_T= Volume of pollutant due to transport of materials to and from the site

The second possible valuation of APC is based on the concept of emission costs per vehicle-kilometre (RIGO, 2012). This approach is more suitable to calculate the costs related to traffic detour where there will be an increase in the travel distance due to construction activities. This equation considers general vehicle emission costs of all pollutants together, but making a distinction between the so called "air pollutants" that affect health and CO_2 emissions.

$$APC = \sum_{i=0}^{i} VEC_i \times L$$ Eq. 15

Where:
VEC_i = Vehicle emissions costs per pollutant i (€/ vehicle-kilometre)
L= Increased travel length (km)

The vehicle emission costs (VEC_i) are shown in Table 14 and the costs of CO_2 emission per ton (C_i) are presented in Table 15 (RIGO, 2012).

Table 14: Vehicle emission costs related to personal vehicles in 2011, The Netherlands (RIGO, 2012)

Vehicle emission costs			
Pollutant type	**Minimum value**	**Maximum value**	**Unit**
Air pollutants	0,00012	0,0012	€/ vehicle-kilometre
CO_2	0,0001	0,0007	€/ vehicle-kilometre

Table 15: Cost of emissions per ton (in EUR, values of 2011) based on European studies (RIGO, 2012)

CO_2 costs of emission in €/ton			
Year \ Value	**Low**	**Average**	**High**
2020	17	40	70
2030	22	55	100

The choice for one or the other valuation method will depend on the availability of data at the moment when pollution costs have to be quantified. If enough data is available, then the Equations 13 and 14 are preferred since they will provide more accurate results. If it is not the case, the Equation 15 is an option.

2.4.3.7 Noise pollution

Construction work noise has different sources, even though they are mostly related to the movement of heavy vehicles or machinery on site. The high noise level in the construction site may affect the surroundings and generate nuisance to the neighborhood. The noise level can also affect the property value and have effects on the peoples' health and quality of life depending on the project duration.

The Piek (Geluidsreductieprogramma), which is a Dutch noise reduction program, provides noise limits for different time windows in order to protect inhabitants from noise disturbance produced by working activities. The following limits have to be followed throughout the day:

- Between 07h and 19h - No restrictions
- Between 19h and 23h - limit 65 dB
- Between 23h and 07h - limit 60 dB

Most of the equations relate noise pollution costs to loss of property value. However, loss of property value is not the most suitable valuation method for short term projects such as pipelines renovation and renewal. In these cases, it is best to associate noise pollution and health issues by correlating the number of hindered people and a monetary value per decibel per person or domicile (Vermeulen et al, 2004). Noise levels above 65 dBA can damage human health and cause higher blood pressure and coronary disorders (Vermeulen et al, 2004) which can be considered a limit for noise pollution (Vermeulen et al, 2004; RIGO, 2012).

RIGO (2012) propose a valuation method for Noise Pollution Costs which relates noise nuisance and health problems that can be generated by high intensity noise exposition. Equation 16 incorporates the equations of Vermeulen et al (2004) and RIGO (2012) in the sense that a time perspective is also considered in the quantification. The project duration parameter is introduced because the costs per increase in one decibel relate to long term noise nuisance (e.g. noise due to road traffic) and do not reflect the temporary nature of pipelines projects.

$$\mathrm{NPC} = \mathrm{N_H} \times \mathrm{C_n} \times (\mathrm{N_c} - \mathrm{N_n}) \times \mathrm{D} \div 365 \text{ days} \qquad \text{Eq. 16}$$

Where:
N_H= number of disturbed domiciles
C_n= Cost per increase in one decibel (€/domicile*year)
N_c= noise during construction (dBA)
N_n = normal level of the noise (dBA)
D = project duration (days)

The calculation of noise during construction can be based on the machinery and equipment used during the project and their equivalent noise levels. Appendix C presents some examples of noise levels and an equation for the total noise level on site. The costs related to the increase in one decibel in noise intensity compared to the normal noise level for road works are presented in Table 16 (RIGO, 2012).

Table 16: Costs of noise nuisance due to road works per affected domicile (in euros per dBA, prices of 2011) (RIGO, 2012).

Noise intensity	< 55	55 - 65	66 -75	> 75
Euro per dBA	0	29	43	49

2.4.3.8 Dust pollution

The dust produced in the construction site due to pavement cutting, excavation, earth moving and site cleaning operations can disturb the surrounding neighborhood up to 150 meters (Ormsby, 2009). The social impacts associated with dust include the increase in cleaning and maintenance costs, reduced agricultural production and lower aesthetic quality of the environment (Gilchrist & Allouche, 2005).

This social cost is dependent on the number of hours spent on cleaning due to construction works that produce a significant amount of dust. Depending on the level of dust pollution, some adverse effects on human health can also be expected (WHO, 2016).

A valuation of Dust pollution costs (DPC) is presented in Equation 17 and relates cleaning time, wage rates and project duration (Ormsby, 2009; Matthews and Allouche, 2010; Matthews, Allouche and Sterling, 2015).

$$\mathrm{DPC} = \mathrm{AC} \times \mathrm{HR_p} \times \mathrm{D} \qquad \text{Eq. 17}$$

Where:

AC= additional cleaning time (h/week)
HR_p= average hourly wage rate (€/h)
D= project duration (weeks)

It is suggested to consider the average hourly wage rate of 14,40€ as estimated in the year 2015 in the Netherlands (Loonwijzer, 2017).

2.4.3.9 Business Revenue Loss

Businesses and companies are susceptible to revenue losses when located in the vicinity of construction sites. Difficult accessibility, dust, loss of parking spaces and noise are some of the negative aspects related to construction projects that can cause a loss in the revenue. In this regard, open trench has a higher impact on business activities compared to trenchless basically because of longer project durations and consequently longer periods of nuisance to the surroundings.

The estimation of future business loss due to construction activities is not evident because at early stages of decision-making it is difficult to predict how a project will affect local business. Valuation of business losses usually makes use of surveys with local business to know to what extent a current project is affecting their revenues (Yu and Lo, 2005; Ormsby, 2009). This method brings more reliable results because it uses primary data for estimating losses. However, if one wants to know the future revenue loss this method is not applicable and the use of previous similar project information might be useful.

Jung and Sinha (2007) have quantified business losses due to pipelines rehabilitation in eight projects executed by open trench and pipe bursting trenchless technologies. The percentage of business loss used in their calculations were retrieved from the Study of Business—Supplement to Socioeconomic Study (2001), while the business income was based on the annual average household income. The authors did not differentiate the percentage of business loss for the open trench and trenchless projects. The only considered parameter influencing the business revenue losses of the open trench and trenchless projects was the project duration.

For quantifying business revenue loss (BRL) the number of business units affected, the average daily income per business and the project duration must be known (Yu and Lo, 2005; Matthews, Allouche and Sterling, 2015). Besides, a percentage of revenue loss must be estimated or supposed. Equation 18 is proposed for estimating business revenue loss.

$$\mathrm{BRL} = \mathrm{U} \times \mathrm{ADI} \times \mathrm{D} \times \mathrm{P} \qquad \text{Eq. 18}$$

Where:
U = number of affected business units
ADI = Average daily income of business unit (€/unit/day).
D = project duration
P= Percentage of business loss during construction

The real average daily income of businesses might be unavailable because it depends on having information directly from the affected parties. If this is the case, some estimation of business income based on National businesses sales database in the Netherlands is provided in Appendix D, besides percentages of revenue losses that could be adopted when no primary data is available.

2.4.4 ***Risk related social costs***

This section describes the risk-related social costs considered in this research, consisting of the following: Increased accidents rate (workers and users) and damage to property, infrastructure and subsurface utilities.

2.4.4.1 ***Accidents involving workers and users***

The increase in accidents risks can affect the workers on site and the pedestrians, cyclists and vehicles (users) moving nearby the construction zone. For instance, risks are higher for road workers who are exposed to (road) traffic or for drivers who encounter a new traffic situation in the work zone such as changes in speed, traffic diversion, night works, barriers and (poor) signalization.

The presence of a work zone is inherent to any construction project, which is also the case in open trench and trenchless projects. However, the characteristics and duration of the work zone for each project type will differ and consequently influence the risks of accidents. Gundy (1998) produced a report based on empirical studies and literature to investigate the nature and extent of road work zone traffic accidents. Some of the conclusions drawn from his study are listed below:

- Accident rates in work zones are higher than in similar, non-work zone situations;
- Work zone accidents are mostly related to fair weather and daylight conditions;

- Work zones located on the side of the road do not necessarily have any negative safety impact;
- Exposure (e.g. traffic volumes and operational hours) and pre-work zone accident rates are the most efficient and reliable ways to predict work zone accidents.

Even though Gundy (1998) affirms that accidents rate increases in work zones, the relative safety risk for work zones found in literature indicates a wide range of values (between 7% and 450%), which makes it difficult to quantify how work zones safety differ. The two most relevant studies (Graham et al., 1978; NCRP, 1996) cited by Gundy (1998) analysed a high number of accidents cases and suggested a 7% increase in accident rates in work zones. Gundy also states that approximately 1-3% of all traffic accidents are work zone related.

Regarding road workers safety, a report produced by the Institute for Road safety Research in The Netherlands (SWOV) (2010) concluded that safety guidelines are not always followed, leading to higher exposition of workers to risky situations. This fact was observed in the year 2009 when almost 30% of the 223 inspected roadwork sites presented a risk of workers being crashed by a vehicle due to poor safety measures (Dutch Labour Inspectorate, 2010 cited by SWOV, 2010).

Due to project and context dependency of accidents risk for workers and users it is hard to predict risks beforehand. Alkema (2015) suggested using a matrix to assess the risks related to accidents, in which the risk is given by the probability of occurrence multiplied by the severity. Accidents severity can be classified as presented in Table 17.

Table 17: Classification of casualty severity (Bickel et al, 2006; SWOV, 2009)

Severity	Scope
Fatality	Accidents resulting in death
Serious injury	Accidents involving hospitalization and lasting injuries are likely
Slight injury	Accidents which whether do not lead to hospitalizations or, in case they do, they would not cause injuries with lasting effects
Damage-only accidents	Accident with no causalities

The accidents costs depend on how severe an accident is and how much damage is involved. The costs are given by the sum of the following cost components: medical costs, production loss, immaterial costs, property damage, settlement costs and congestion costs (SWOV, 2014). Each cost component is described in Table 18.

Table 18: Accident costs components (Linde & Donkelaar, 2012; SWOV, 2014)

Accident costs components	Description
Medical costs	Related to the number of days of hospitalization, the average costs per day of hospital or nursing home treatment and the annual number of ambulance trips.
Production loss	Refers to the monetary value of the contribution somebody would have made if he or she had not been injured or killed.
Immaterial costs	Intangible costs in the form of suffering, pain, sorrow, and loss of enjoyment of life. They are related to loss of quality of life for the victims and close people ('human losses').
Property damage	Refers to the cost for repairing or replacing a property due to accidents, such vehicles, cargo, road and road furniture damages.
Settlement costs	Relates to costs due to police, court and emergency service.
Congestion costs	Related to the time lost in traffic caused by traffic accidents.

The valuation of the increase in number of accidents due to road works can be conducted by different equations. Equation 20 considers the risks associated with each type of accidents and is appropriate when the effects of a project in terms of accidents/deaths, injuries and property damage are known (RIGO, 2012).

Another way is to valuate Traffic Accident Costs based on the costs of accident per vehicle-kilometre leading to less accurate results (Ormsby, 2009; RIGO, 2012). The advantage is the inclusion of the length of the work zone and project duration parameters, which are directly proportional to the accident costs (Equation 21).

$$\mathrm{TAC} = \sum \mathrm{R_i} \times \mathrm{C_i} \ \times \mathrm{N_i} \qquad \text{Eq. 20}$$

$$\mathrm{TAC} = \mathrm{C_C} \times \mathrm{L} \times \mathrm{NVD} \times \mathrm{D} \qquad \text{Eq. 21}$$

Where:
R_i= Additional risk of accident type i per day due to maintenance activities
C_i= Cost per accident type i
N_i= average number of accidents type i per day
C_c= average cost of collisions (€/vehicle-kilometre)
L= Length of work zone (km)
NVD= average number of vehicles per day (vehicles/day)
D= project duration (days)

The valuation of risks related to accidents in monetary units will not take place in this research as the parameters used in the equations are very project specific and might not reflect the real costs related to accidents risks. Therefore, equations 20 and 21 are only used to show which factors influence these risks and are not used for valuation.

2.4.4.2 *Damage to property, infrastructure and subsurface utilities*

The execution of construction works involving heavy machinery and vehicles, excavation, dewatering the soil and underground technique involving soil movement and vibrations can damage both underground and surface infrastructures. Besides, working on the subsoil can damage foundations and subsurface utilities and consequently affect the structural integrity of constructions.

According to Netherlands Environmental (PBL) (2016), the costs of repairing damage to infrastructure and maintenance due to land subsidence in peat lands amounts to billions of euros in the country. The impacts of subsidence are present in both urban and rural areas, being the subsidence in the former related to physical load and in the latter related to lowered water tables. Subsidence can affect both infrastructure and homes with poor foundations, besides increasing CO_2 emissions due to the deterioration of nature where areas become dry.

The restoration costs of damage caused by pipelines projects should be in the scope of the project direct costs. However, it is possible that the infrastructure or properties are not fully restored to their original conditions. In this case, the property owner would have to bear the reparation costs, tolerate the damage or try to find a solution in court. In cases where the contractor or project owner does not bear all the damage costs, the costs become part of social costs (Ormsby, 2009) (Equation 22).

Property damage depends on factors such as the construction method, contractor experience, location characteristics, time constraints, spatial constraints and quality of underground utility mapping (Ormsby, 2009). Consequently, it is difficult to predict general cost values and probability related to property damage and only a generic valuation based on risk is proposed (Equation 23).

$$\mathrm{PDC} = \text{Total damage costs} - \text{Damage costs paid by contractor or proj. owner} \qquad \text{Eq. 22}$$

$$\mathrm{PDC} = \mathrm{LD} \times \mathrm{LCD} \times \mathrm{N} \qquad \text{Eq. 23}$$

Where:

LD= Likelihood of damage
LCD = Likely cost of damage
N= Number of occurrences

2.4.4.3 Damage to the environment

Construction projects can have a high impact on the surrounding environment. This impact can be in the form of pollution, contamination, deforestation, etc. and contributes to nature degradation. As a result, the fauna, flora and the society would bear with the negative impacts of the projects.

According to Jung and Sinha (2007), open trench projects might affect environment conservation by damaging trees, grass and landscape due to excavation. Ormsby (2009) stated that pollution impacts due to pipelines projects can affect the water, soil and air due to fluids, particles and pollutants released in the environment. Besides, other consequences relate to bank erosion; flooding; modification of watercourses; reduction of water quality and so on (Gilchrist and Allouche, 2005 cited by Ormsby, 2009).

The quantification of environmental damage may be done through techniques such as stated and/or revealed preference and travel costs (Ormsby, 2009). However, no valuation method is proposed in this research and instead only a qualitative approach regarding vegetation damage is proposed.

2.4.4.4 Damage to workers' health

Construction workers are also susceptible to health damage, apart from the risks of accidents during work execution. The contact with contaminated soils and material are one of the reasons of health damage. An example of hazardous material is asbestos, present in different products such heat resistant textiles, decorative coatings, pipes, thermal insulation for pipes and boilers, brake and clutch friction linings, gaskets, floor tiles and packing materials (Department of Labour, 1995). Exposure to asbestos can cause different diseases, including lung cancer and therefore much attention should be paid to it.

According to Inspectie SZW (2014), there were 44 thousand kilometres of asbestos pipelines (gas, water and sewage) in the Netherlands in 2015. This means that workers in the utilities field might be subject to contact with asbestos, which requires safety measures in place to avoid risky situation. As a preventive measure to avoid health issues involving workers, companies should obligatory investigate the site conditions regarding soil contamination and the presence of asbestos pipelines and provide a safe work environment for the construction workers.

2.5 Conclusion

There are different valuation methods, proposed by literature, used for quantifying social costs. However, the valuation in monetary units is not always feasible or possible for all social costs in a project early stage. For tackling this issue it is proposed to split social costs into two groups: fixed social costs that can be easily monetized; and risk related social costs which depend on likelihood and severity information. The fixed social costs dealt in this research are quantified through the valuation equations presented in this chapter, whereas the risk related social costs will be assessed qualitatively as will be described in the Chapter 4.

3. Data collection and Analysis

This chapter aims at explaining the methods used in this research for collecting data. The results of the data collection phase are mainly used for the model development.

3.1 Data collection methods

The data collection used in this research consisted of three different methods: (1) literature review, (2) interviews and (3) surveys. The data collection methods sometimes overlapped but they basically happened in the order mentioned above. The type of data researched and the objectives related to each method are described next.

3.1.1 Literature review

In the literature review, different researches, papers and reports are analysed to provide a theoretical background for developing a framework for this research. The literature concerned the following topics: socioeconomic impacts of construction projects, social costs related to pipelines projects and valuation methods for quantifying social costs. This stage aimed at answering some of the research questions raised in the research proposal phase such as:

What are the impacts of subsurface utility projects on society, economy and environment?

Which social costs are the most relevant for pipelines renovation projects using trenchless technologies and open excavation?

Which social cost indicators and valuation methods are used to quantify social, economic and environmental impacts of pipelines renovation projects?

3.1.2 Interviews

The interviews were used to the collect primary data from professionals performing with pipelines projects. At the first moment, the literature review focused on the information to support the preparation of the interview questionnaire. At the same period, four internal meetings with employees within Deltares aimed at guiding into the topics of social costs and trenchless technologies. The subsequent step was to develop the questionnaire and apply the interviews.

The face-to-face interviews used a questionnaire consisting of 28 structured questions that allowed open answers. The interviews happened during the months of March and April 2017, when twelve professionals throughout the Netherlands have accepted to participate. The limited number of interviewees and the open answers did not allow a more statistical interpretation of the results.

The interviewees' contacts were provided by NSTT and Deltares and consisted of professionals involved in trenchless and open trench projects. They represented municipalities, engineering companies, contractors and asset owners (Figure 10). The companies were specialists in different utilities types such as water, sewage and gas pipelines.

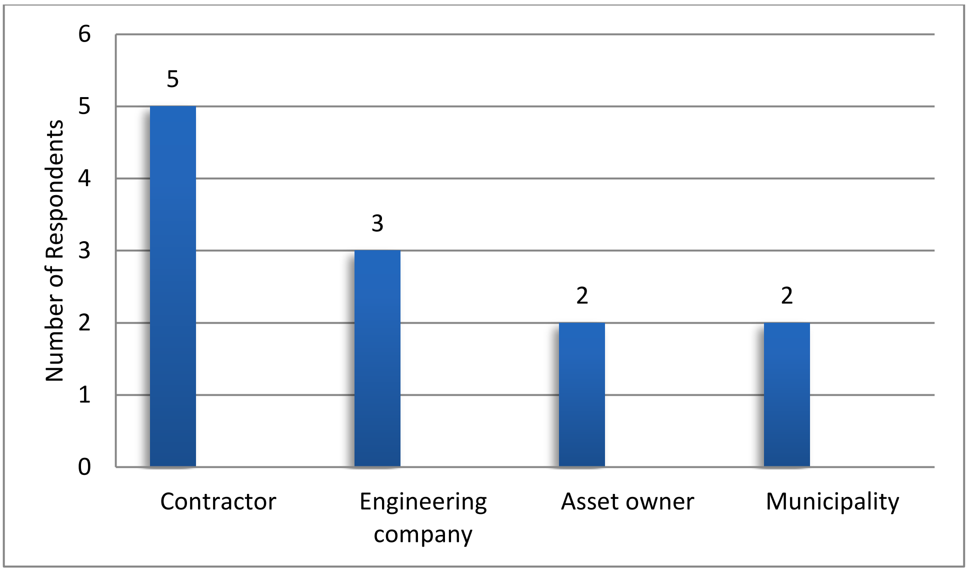


Figure 10: Background of interview respondents

The interview questions were developed by the researcher and aimed at corroborating the theoretical findings and adding a practical view about social costs, valuation methods, data availability and the development of key figures.

In some interviews, the questions have slightly changed depending on the interviewee's role since some of them were too specific and could mainly be answered by a specific stakeholder. Besides, some questions were added throughout the process because the researcher found out that the data that could be provided by the interviewees regarding specific aspects was very limited (e.g. questions about pollutant emissions and noise intensity of machines). To fill in this gap, more general questions were used to help developing general figures.

Regarding the structure, the interview questionnaire was divided into Part I and the Part II and applied at once. The questions from part I were divided into the following groups: *impacts of trenchless technologies, social costs compensation and consideration, social costs and risks, data availability* and *choice between open trench and trenchless technologies*. Part II consisted of a questionnaire to assess the availability of specific data needed to quantify social costs.

Interview Part I:

- Impacts of trenchless technologies

With these questions the researcher tried to focus on the specific impacts of trenchless technologies on renovation projects. From literature, not many social costs related to trenchless technologies are mentioned, so the goal was to investigate whether there are excusive social costs related to trenchless projects and what the specific negative impacts (if any) on the surroundings are.

- Social costs compensation and consideration

The questions in this group aimed at identifying, from the companies' perspective, social costs that are relevant to the model. The companies were asked to evaluate the adverse effects of trenchless renovation and open trench projects on society and environment based on their practical experience.

- Risk related social costs

This section basically consists of a table where the risks involved in open trench and trenchless renovation projects were investigated. The risk-related social costs list comprised different types of damages and accidents. The interviewees had to assess likelihood, severity and costs for each of the social costs and provide an overview of the differences between risks in trenchless and open trench projects.

- Data availability (rules of thumb)

Here, the questions aimed at collecting general values or rules of thumb for some parameters necessary in the valuation equations. To fill in the gap for the data that was not available, some general questions were asked to investigate certain parameters and develop general figures. For instance, it was asked about number of equipment used for trenchless and open trench projects so that estimations could be made for, instance, by relating air pollution/noise pollution and the number of equipment used.

- Choices between open trench and trenchless technologies

In this questions group, the researcher tried to find how choices are made between trenchless technologies and open trench and which aspects are taken into account in the decision making. Besides, it was investigated in which situations this choice is relevant and when it is more obvious to choose for one or another method.

Interview part II:

In the part II of the interview, the researcher tried to collect information about the availability of specific data that could be provided by the companies and that were necessary for the valuation equations. During the interviews, a list of parameters for the valuation of social costs was presented to the interviewees, who judged which information was usually available at early project stages

Both interview Part II and the *Data availability* section aimed at investigating data availability. The interview part II intended to investigate which of the listed parameters are usually available and where they could be found. Here, the focus was not to find values or numbers, but to investigate whether or not the parameters could be easily found and where.

On the other hand, the *Data availability* questionnaire aimed at collecting general values for developing key figures that could fill the gap of the data that could not be provided by the users of the model (investigated during Interview part II). Here, the focus was basically on numbers, values and correlations between information. The idea is that the data collected in Part II and the *Data availability* sections would be complementary.

The complete interview with all the questions is presented in Table 19. Briefly, the interview aimed at answering the following main questions:

Which social costs are more relevant in practice and should be included in the social costs model?

Are these social costs quantified? If yes, how is it done in practice?

Which data is necessary to quantify social costs and where can this information be retrieved from?

Are risks quantified in pipelines projects? How can these risks be quantified?

Table 19: Interview questionnaire

Interview questionnaire

1. How would you compare the risks (damage, accidents) between TT and OT projects? Do you have any probabilities or severity data? (e. g. in terms of volume excavated, based on older projects, etc.)? Which risks do you consider in pipelines (renovation) projects executed by OT and TT? Do you know the costs, probability and severity related to these risks?

Social costs (risks)	Cost, Probability, Severity	
	Open trench	Trenchless Technologies-renovation
Accidental injury or death		
Increase in traffic accidents		
Damage to facilities/ infrastructure/ utilities		
Property damage		
Loss of property value		
Other		

2. Do you keep track of complaints from the population related to pipelines projects involving OT or TT renovation (e. g. dust, noise, damage to properties or infrastructures, etc.)? Can you provide statistics for it?

3. Are the project direct costs usually available in the early stages when a choice has to be made between trenchless and open trench (budget estimation)?

4. Can you give an average direct cost per unit (euros/m3 or euro/m) of pipelines renovation projects executed by OT and TT?

5. Do you know any rule of thumb for quantifying pavement excavation of OT and TT renovation projects? (e. g. open trench requires N times more excavation in volume than TT)?

6. How faster is a project executed by TT compared to OT? Can you provide productivity rates for OT and TT renovation projects? (e.g. m3/h; m/h of renewed/renovated pipe)?

7. Do you know the average fuel consumption (or CO2/pollutant emission) of vehicle/equipment used for OT and TT renovation projects? Do you think the daily emissions related to equipment will differ much from TT and OT equipment/machinery? Can you give a ratio?

8. Air pollution:

   - Which machine/equipment is used for OT and TT projects?
   - Does the machine/equipment (emissions/fuel consumption) differ much between the TT renovation techniques?
   - Do you estimate CO2 and pollutant emissions of the machine/equipment used in OT and TT projects?
   - What is the fuel consumption for the machine/equipment used in OT projects? (liters/h, liters/day). List all equipment and respective fuel consumption or give a total consumption.
   - What is the fuel consumption for the machine/equipment used in TT renovation projects? (liters/h). List all equipment and respective fuel consumption or give a total consumption.
   - How do you estimate the number of equipment you use? Is there any role of thumb? Can you give any general value per day? (e.g. OT/TT project uses X equipment per day)
   - How does the number of equipment used differ per project?
   - What is the productivity of the equipment/machine used in OT and TT renovation projects? (e.g execution of m3/day or m/day)

Interview questionnaire

9. Noise:
   - Do you know the noise (in dBA) generated during an OT and TT renovation project?
   - Does the noise intensity differ much between OT and TT machinery/equipment?
   - Is there a maximum limit of noise intensity generated by an OT or TT project?
   - Do you know a ratio between noise complaints for OT and TT projects?
10. Which equipment/vehicle is used to transport dust/soil and what is their fuel consumption per hour?
11. Is the noise intensity generated by TT and OT equipment similar?
12. Is dust pollution existent in TT and OT projects? Is it similar for both methods?
13. Can you provide approximate values of lifetime expectancy of new installed pipeline executed by OT excavation and renovated pipeline using TT? Or can you give a ratio of the lifetime expectancy between a new installed pipeline and a renovated pipeline?
14. How many times can a pipeline be renovated using TT?
15. Before deciding between OT and TT, do you know what will the impact of the project on traffic be? Do you have this information based on previous projects? *(e.g. the street will be closed and there will be a detour of X meters, causing traffic delays of X minutes)*.
16. Do you estimate business losses due to open trench or trenchless projects? How? Do you use any rule of thumb for percentage of business losses (e.g. due to road closure, you expect a business loss of 10% per day)?
17. How is the choice made between open trench and trenchless technologies? What is taken into account during the decision making? (Costs, technical feasibility, contractor expertise, location….?)
18. In which situations is the choice between OT and TT renovation relevant? When would social costs make a difference in choosing TT instead of OT even if the direct costs of OT are higher?
19. What kind of measures are usually taken when open trench is used? (e. g. traffic detour, register conditions of nearby structures through photos, etc.)
20. Do you have any project that could be used to calculate social costs, either by TT or OT? (project with data available)

INTERVIEW PART 2

This survey aims at assessing the availability and reliability of the data necessary for quantifying the social costs previously presented. You are asked to fill in the table by informing (if known) where to find the parameters listed in the table and how reliable this information is.

Interview questionnaire

Social cost	Parameter	Data source	Possible source
Social costs (fixed)			
Social cost	**Parameter**	**Data source**	**Possible source**
Traffic delay costs	Length of work zone		project owner
	Speed during construction		project owner
	Additional distance		contractor
	Nº vehicles per day		Official traffic reports
	Additional time to cross the work zone		
	project duration		project owner
hic le op	% heavy vehicles		Official traffic reports
Pedestrian delay	Additional time to cross the work zone		Base on traffic detour planning (m) and pedestrian speed
	Nº of pedestrians affected per day		estimation on site
Loss of parking space	Nº of affected parking meters or spaces		project owner/municipality/Google earth
	meter rate		municipality
	Meter operational hours		municipality
	parking occupancy		municipality
	Amount of fines		municipality
	Frequency of fines		municipality
service life reduction due to	original construction cost of the pavement		asset owner/ municipality
	age of the pavement		asset owner
	designed service life		asset owner
Air pollution	Emitted volume of pollutant		emissions calculator/contractor
	Cost of volumetric emissions		RIGO/KiM Kengetallen
Noise pollution	noise due to the construction equipment		contractor and equipment manual
	normal level of the noise		municipality
	Noise Depreciation Index		Matthews and Allouche, 2010
	Average property value		municipality
	number of disturbed domiciles		contractor/municipality/Google maps
	Cost per dBA		RIGO/KiM Kengetallen
Dust pollution	Additional cleaning time		surveys locals/older projects
	Average hourly rate		official website
Revenue loss	total number of affected business units		contractor/Google maps
	average daily loss of earning per business unit		Detailhandel.info /older projects
Social costs (risks)			
Social cost	**Parameter**	**Data source**	**Possible source**
Increased traffic accidents	Additional risk of accident per day due to maintenance activities		company internal information
	Cost per accident type i		SWOV/RIGO/KiM
	average number of accidents type i per day		reports/company internal information
	average cost of collisions		RIGO/KiM
Property damage	Likelihood of damage		older projects
	Likely cost of damage		older projects
	Nº of occurrences		older projects
Adjacent buried utilities damage	Likelihood of damage		older projects
	Likely cost of damage		older projects
	Nº of occurrences		older projects
Accidental injury and death	Likelihood of damage		older projects
	Likely cost of damage		older projects
	Nº of occurrences		older projects

3.1.3 Surveys

The last data collection method used in this research was the application of online surveys. The respondents were the same experts involved in the interviews and some others contacted after the interviews period. In total, 11 questionnaires were sent and 4 responses were collected in the period from 13th to 21st of June 2017. The questionnaire used in the surveys can be found in Appendix E.

The survey was divided in survey Part 1 and Part 2 due to the online platform limitations, being both parts complementary. The survey Part 1 aimed at defining 5-point scales for qualitatively assessing risks of accidents and damage in pipelines projects. The respondents had to translate the 5-point scales into actual figures or numbers based on previous experience for each of the ten factors affecting risks proposed in this research: *project duration, amount of machines on site, excavation volume, size of work zone, transportation of material (offsite), area density (developments above ground), traffic density, pedestrian flow (incl. cyclists), density of buried pipelines underground, and naturalness of area (presence of green areas)*. These factors were defined based on findings from the literature and interviews.

The survey Part 2 aimed at identifying the factors that affect the probability of risks of accidents and damage in pipelines projects. The respondents had to correlate each risk type with the factors that influence/affects/impacts the likelihood of that risk to happen. Here, each question referred to a different risk type (*risks of accidents involving workers; risks of accidents involving users - pedestrians, drivers, cyclists; risks of damage to property/infrastructure; risk of damage to buried pipelines; and risks of damage to environment – vegetation*) to be correlated with the ten factors affecting risks as shown in Figure 11. The respondents had to indicate which of the factors were affecting each risk type according to their experience. Briefly, the survey aimed at answering the following questions:

Which factors affect the likelihood of risks of accidents and damage related to pipelines projects?

Which 5-point scales can be used for qualitatively assessing the risks of accidents and damage in pipelines projects?

List of 5 risk types

- *risks of accidents involving workers*
- *risks of accidents involving users - pedestrians, drivers, cyclists*
- *risks of damage to property/infrastructure*
- *risk of damage to buried pipelines*
- *risks of damage to environment – vegetation*

List of 10 factors affecting risks

- *project duration*
- *amount of machines on site*
- *excavation volume*
- *size of work zone, transportation of material (offsite)*
- *area density (developments above ground*
- *traffic density*
- *pedestrian flow (incl. cyclists)*
- *density of buried pipelines underground*
- *naturalness of area (presence of green areas)*

Figure 11: List of risk types and factors affecting risks used in the surveys

3.2 Data collection analysis

In this section, the findings from the interviews and surveys are presented and discussed separately. It was opted to split this section because surveys are based on the interviews results and was applied afterwards. The interview section reflects the experts' opinions and correlates these findings with the literature. These results are grouped into different topics in a similar way as the interview questions were formulated. The survey section reflects the opinions regarding the risks approach. The interview questionnaire answers can be found in Appendix F and the results of the surveys can be found in Appendix G.

*3.2.1 **Interviews***

The applicability and suitability of methods:

The interviews have revealed that open trench is the most preferred method for executing pipelines projects in the Netherlands. This is partially explained by the facts that (a) the open trench is a traditional method that people are used to work and (b) project leaders and engineering companies have less experience with trenchless technologies, since it is relatively new compared to open trench excavation. For example, some companies stated that around 80% to 90% of their projects are executed through digging.

The use of trenchless technologies is more limited than open trench, even though companies are trying to innovate and increase the number of trenchless projects due to their advantages. The main reasons relate to the need to reduce the impacts on the society and environment during the project execution, surface disruption and restoration costs.

In The Netherlands, among the trenchless technology for sewers pipelines, Cured in Place Pipe (CIPP) was mentioned by the contractors and some engineering companies as the most used method, accounting for 99% of the trenchless sewage renovation projects. A contractor expert mentioned that for pressure pipes such as gas and water the most used renovation technology is close-fit slipling, while Spiral Wound Lining and woven Hose Lining are not commonly used.

Strategies adopted by the municipalities and contractors to address social costs:

The strategies adopted by parties to address social costs have also been investigated. It could be concluded that even though the municipalities and other parties are aware of the social costs related to pipelines projects, in most cases the choice of the method is based on the experience and "feeling".

All of the interviewees expressed that they do consider social costs in their projects choices as they try to minimize the negative impacts to the society by, for example, following the regulations, but they do not quantify these social costs. Consequently, the decision making between open trench and trenchless projects regarding the social costs becomes rather subjective.

The fact that social costs are not quantified in practice can be considered a barrier for adopting trenchless technologies because reduced social costs is one of the main advantages compared to open trench. In most cases, when open trench method is not feasible then trenchless will be considered in the decision making. In other cases such as in the city of Rotterdam, the goal is that every project uses trenchless technologies unless it is not possible.

A common practice used by the interviewed municipalities is to communicate in advance with the residents and businesses when a project is going to take place in their neighborhood and inform about its duration and reasons. It was stated that a project will be better accepted when communication with affected parties is transparent and when it brings direct benefits to the community.

Another point regards the request for permits for executing pipelines projects: even though municipalities cannot enforce which technique to use for a pipeline project (as a licensing authority), they can give their opinion or indirectly influence it by imposing stricter rules. Besides, older cities are stricter in granting permits and they might enforce limited durations for the project execution or limited working periods in the day or weekends. For instance, it was mentioned by Alliander that it is often easier to obtain a permit for trenchless renovation projects because they tend to create less nuisances and be completed faster.

Nuisances to society and environment:

All the interviewees stated that the impacts of pipelines projects on the society and environment usually are not compensated. The main reason is that the nuisances related to pipelines project execution are temporary and consequently it becomes harder for the population to get the compensation. Besides, shorter project duration means that nuisance might be limited to that period and afterwards the area might be free from nuisances for a while.

The conclusion is that it is very hard (or impossible) to execute a project without any nuisance to the surroundings, so the solution is to try to minimize it as much as possible. Nuisances can be minimized for instance by reducing the project duration or opting for a method that carries less impact on the surroundings.

Regarding the damage compensation, if a contractor causes damages (e.g. to properties, buried utilities, infrastructure) the affected parties should be compensated (usually paid by the construction insurance company). For that reason, and to protect themselves against future (unfair) complaints, companies should scan the area and register the actual situation of the infrastructure and buildings around the construction site before the project starts. This can be done for instance by registering any existent damage (e.g. cracks on walls) by taking pictures or by measuring deformations. By taking preventive measures, companies can distinguish if a damage was caused by them or not and if they are liable for damages.

Comparison open trench and trenchless renovation technologies:

The choice between open trench and trenchless technologies is heavily dependent on the applicability and feasibility of the method. The main advantage of trenchless renovation technologies over open trench relates to the minimization of the nuisance to the surroundings due to usually shorter project durations. As a consequence, trenchless projects can be better accepted by the population and social costs can be reduced.

For instance, the following advantages were mentioned regarding the use of trenchless technologies: less impacts on the traffic; better accessibility; little impact on the pavement service life due to minimal or no excavation; use of lighter or less equipment during project execution which generates less vibration; less noise and less risk of damage.

There were not many specific social costs and impacts exclusively related to trenchless renovation technologies with the exception of the strong smell of the liner used in CIPP renovation mentioned by the experts who work with trenchless projects. The experts agreed on the different situations in which open trench and trenchless renovation technologies are the most suitable, which can be found in Table 20.

Table 20: Comparison between applicability of open trench and trenchless methods

Factors	Open trench is more suitable:	Trenchless technologies are more suitable:
Pavement age/ Conditions above the ground	When there is a pavement renovation project to be executed (e.g. due to pavement aging), others companies can use this opportunity to execute their replacement projects using open trench because the pavement would be rebuilt/renewed anyway. Like that they can cause fewer nuisances and save money because pavement reconstruction costs can be shared.	When the pavement is new or is still in the beginning of its life cycle, the costs related to restoration can be high. Besides, there might be resistance from the population if excavation works have recently been carried out in the area. In these situations, trenchless would be a more suitable solution to minimize costs and nuisance.
Combining works	When different utilities need to be replaced in an area at the same period open trench is preferable. Like that, only one/few trench will be opened and different companies can execute their projects in the same period. The advantage is that social costs will happen only once, and the restoration costs of pavement and surface utilities can be shared between the companies.	When (only) one type of utility has to be rehabilitated, it might be more advantageous to use trenchless and minimize restoration costs and nuisance.
Pipeline depth	Open trench is more applicable to shallow pipeline depths because deeper excavations might require soil stabilization. The deeper the pipeline, the more complicated and expensive the project will become.	Large and deep sewers that have many house connections on it can be partially executed by trenchless technologies. If the pipeline has to be replaced, they usually reline it and build a small sewage on top of it to connect to the houses. The connections would be executed by open trench while the relining by trenchless technologies.
Existence of connections along the main pipeline	When there are many connections along the pipeline that needs rehabilitation, open trench is more advantageous. Connections usually need digging in order to be replaced, so it is better to execute open trench for both pipeline and connections replacement together.	When the pipeline is extensive and there are few connections along, pipeline renovation using trenchless and connections replacement by open trench is a more cost effective solution.
Project location	In new development areas there are not (many) existing utilities or constructions, so usually every utility has to be installed. Since it is a combined work between different companies, open trench is more advantageous.	In busy roads, existence of trams around, busy utilities underground and pipeline with no (or few) house connections would be reasons to use trenchless renovation technologies. The benefits of trenchless are more applied to existing utilities.
Police, ambulance and fire brigade accessibility	Accessibility of police, ambulance and fire brigade has to be guaranteed independent of the execution method.	In older cities (e.g. narrow and busy streets) there are many governmental rules that apply regarding traffic control and accessibility for fire brigade, police and ambulances. In these areas, trenchless can be a good option for providing better accessibility and allowing a better traffic flow. Besides, the costs of removing pavement can be very high, making open trench an expensive option compared to trenchless

As it can be noticed from Table 20, different factors affect the choice between open trench and trenchless technologies. The decision involves (1) technical, (2) economic and (3) social aspects that together influence the decision-making in the order of importance. First of all, the method has to be technically feasible. Second, one would usually look into the project direct/indirect costs and afterwards into social costs. However, the social costs can become more important than project costs depending on the situation (e.g. an environmentally sensitive area might require a more expensive technique to minimize impacts in the area).

Some interviewees mentioned that possible situations where the choice between open trench and trenchless methods is at stake relate to projects in complex environments or with high impacts on the surroundings. In such cases, the choice is less obvious because the project owner should try to minimize as much as possible the negative effects of the project, which might be harder if opted for open trench. In this case, the technical feasibility, direct costs and social costs would together influence the decision making.

To conclude, when comparing open trench and trenchless options the first condition to be satisfied is that trenchless renovation technologies are technically feasible in the specific situation. Once this condition is fulfilled, one would look into direct/indirect costs and social costs. As an example, the following (technical) conditions would make the use of trenchless *renovation* techniques infeasible: (1) the host pipeline is too damaged over its length; (2) the capacity is fully used or higher capacity is needed in the near future or (3) the grading is not sufficient (sewage pipes).

Social costs list:

During the interviews, a table containing the fixed and risk related social costs was presented. The interviewees were asked about the relevance of the listed social costs, whether these were considered in their projects and if/how they were quantified. The social costs list is presented in Figure 12.

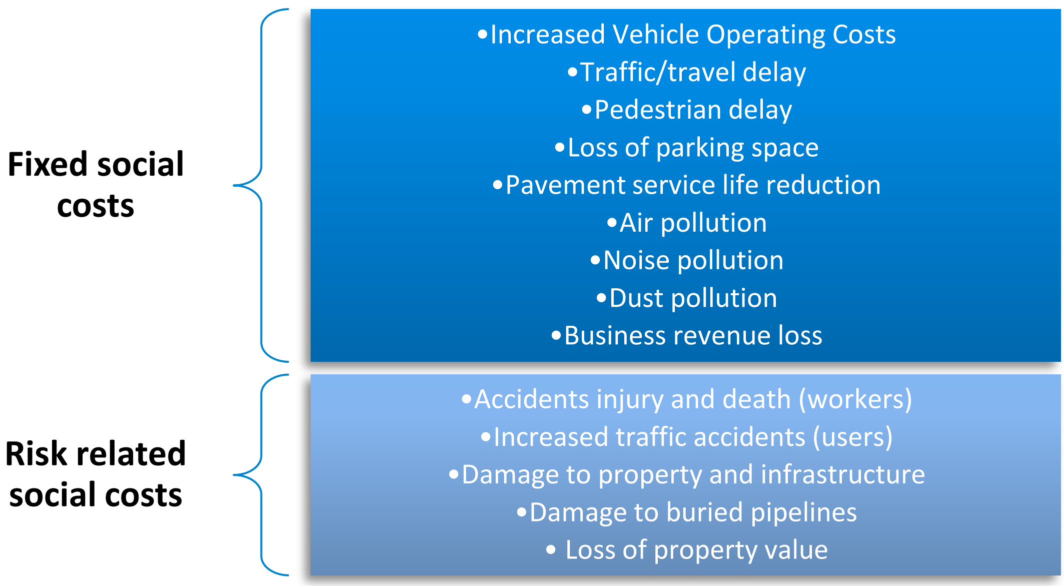


Figure 12: List of social costs proposed during the interviews

All the interviewees agreed with the social costs list, except for some disagreements regarding loss of property value. It was mentioned that the temporary projects do not influence the property value;

or that a positive effect might be noticed after the project once the utilities or the pavement are renewed. Therefore, loss of property value was disregarded in the model.

The social costs that were not mentioned in the list are related to unpleasant smell during installation of certain type of liner (trenchless renovation material) mentioned by contractors, pollutant emissions during transport of material and damage to trees. The pollutant emissions during transport of material was added to the fixed social costs within Air pollution costs; and the damage to trees was added to the risk related social costs as Damage to the environment. The smell of the liner was not included in the model due to the lack of a valuation method.

The following items present detailed information regarding some of the social costs used in the model. Some of the information provided is selected as key figures for the valuation equations.

❖ *Project duration*

The interviewees were asked to compare the duration of trenchless renovation and open trench projects. The opinions differed because project duration depends on the different factors such as complexity, location, depth of installation, groundwater level, soil type, unforeseen circumstances, etc. For instance, it was stated that open trench is more dependent on soil conditions, water level or depth and that these factors can influence the work speed. Therefore, the estimations given by the experts were roughly based on previous experiences and therefore subjective.

Trenchless projects speed is dependent on the limitations of the machinery used, pipeline diameter, method and the preparatory work. The installation length covered per day does not change much if a project is executed in the open field or in the inner city. On the other hand, open trench projects duration is led by the speed of the excavator and is more location dependent.

Different execution rates were given during the interviews and therefore it is hard to offer a reliable prediction for the duration or productivity of open trench and trenchless projects. Besides, the dependency on the pipeline diameter and the depth of installation stated by contractors hinder the estimation of general figures. However, the interviewees have affirmed that duration can be estimated based on their databases and previous projects, which are more reliable than general values. The different project durations provided during the interviews reiterates the dependency between project duration and other factors:

- “From previous projects we estimate that trenchless projects are 40% faster than open trench.”
- “In one or two days 500 meters of pipeline can be placed using trenchless renovation techniques. Open trench work speed is estimated in 5-10 meters of pipeline per day.”
- “In the countryside where less barriers exist, it is possible to achieve 300 meters of executed pipeline per day if the conditions are favorable (e. g no need of supporting walls) using excavation. If the same project is executed in the inner city, it would take 6 times more and a benchmark of 50 meters/day is expected.”
- “Trenchless techniques installation varies from 100 to 200 meter per day which depends on the pipeline diameter.”

❖ *Traffic delay*

Traffic delay was one of the most mentioned social costs due to both the nuisance caused to the population and the economic aspects involved. However, the opinions about traffic interference in open trench and trenchless renovation projects are diverse. Most of the interviewees mentioned that (a) depending on the factors such as pipeline position, lane width or traffic flow, among others it might be necessary to close a lane and detour the traffic even in trenchless projects; while a minority stated that (b) trenchless methods interfere minimally on traffic and does not require lane closure.

Based on the interviews it can be concluded that open trench projects usually cause more traffic nuisance and trenchless methods might also cause traffic delays when lane closure is required and traffic is impacted. For instance, liner installation trucks might be placed in the middle of a road if the existing pipeline is located there and might block a whole narrow street forcing traffic detour. Therefore, each case has to be analysed separately and general conclusions cannot be drawn without knowing the project specificities. All experts agreed that nuisances are higher for longer project durations and in areas with a more intense flow of vehicles.

In open trench projects, the lane where the pipeline has to be replaced usually has to be closed due to excavation and in these cases traffic detours and delays are more likely to happen. It was possible to conclude that in some cases the project duration is the parameter that has the most influence on traffic delay costs when comparing open trench and trenchless projects. Regarding the traffic related information necessary for the valuation equations, a traffic specialist was interviewed and provided some insights about the parameters necessary to quantify the traffic delay through the valuation equations. This information is summarized in Table 21.

Table 21: Description of parameters involved in the valuation of traffic delay costs

Parameter	Data description
Average number of persons per vehicle (ANP)	ANP will be different depending on the purpose of the trip but usually an average value is used for estimations. The suggested source for ANP values can be found in section 2.4.3.2 and under the references chapter (Otten, 't Hoen, & den Boer, 2015).
Value of time (VOT)	VOT differs during the period of the day (e.g. in the morning there are more business or commuting trips and evening is more for free time), on the month, etc. Usually an average value is used for estimations.
Number of vehicles per day (NVD)	An equipment (traffic loop) which is located every few hundreds of meters along the roads counts the number of passing cars. The equipment belongs to the highway authority, municipality or province and the data generated is open source. Some detectors can also identify the type of vehicle crossing the street, but this information is too detailed. For rough estimations, usually no distinction is made between vehicle types. Information about NVD can be found on the National Data Warehouse for Traffic Information website (NDW, 2017). For getting data access for a project or for traffic information purposes it is necessary to send a request to NDW.
Delay time	There are traffic models to quantify traffic delay but they are more accurate in highways than in the inner city. This happens because in highways it is easier to predict the behaviour of the vehicles and the impacts on the surrounding streets. Consequently, quantification of lost time due to delay can also be conducted in the inner city even though less reliably.

As noticed from Table 21 the modelling of traffic delay might not be accurate in the inner city because it is harder to predict traffic behaviour and the impacts of traffic interference (e.g. a lane closure) in these areas. For this reason, in this research it was suggested to limit the traffic delay only to the vehicles that would be crossing the work zone. The delays of the other vehicles that would not be crossing the work zone are disregarded of the quantification.

Another option would be to consider that the number of vehicles crossing the work zone would be increased using a coefficient. This coefficient would be used to calculate the total number of affected vehicles (crossing and non-crossing vehicles) and could lead to more realistic results. This percentage or coefficient however would have to be developed and adapted to each project and traffic situation.

- *Air pollution*

In order to quantify air pollution, questions about fuel consumption, machinery and equipment used in pipelines projects were asked. This approach sounded more comprehensible than asking information about pollutant and CO_2 emissions. The interviewees could not give exact information about fuel consumption because of the high dependency on the project, but the contractors interviewed estimated the number and type of equipment used.

As a standard requirement, an open trench project would need an excavator/backhoe; two to four trucks for soil transportation and machines for pavement reconstruction and a crane (if applicable). Trucks might be necessary depending on the distance of transportation to the dumping site and the volume of soil. Transportation is mainly needed when the excavated soil is contaminated or when it cannot be compacted again (e. g. clay soil). Besides, pumping machines might be necessary depending on the groundwater level.

For a trenchless renovation project, it is usually necessary to have a truck for cleaning the existent pipeline; one for transporting and installing the liner and opening the connections; and a smaller vehicle for inspecting the work afterwards. Besides, another truck is needed for curing the pipeline depending on the method used (e. g. CIPP needs curing by UV, steam or water). It is also possible that one single truck carries the liner and the curing unit. In trenchless projects, even though different vehicles are used for each activity, it could be estimated that they work in sequence and only one vehicle will be present on site at time. This implies that the noise and air pollution generated due to trenchless renovation comes from one source only.

The machinery/equipment estimations provided in the previous paragraphs are suggested for trenchless and open trench projects respectively. However, since each project has its own characteristics, this general rule of thumb might not be realistic for some cases case. In those cases it might be best to use own project information for guaranteeing more reliable results. Otherwise, experts' opinion can be used.

- *Noise*

For the valuation of noise pollution costs, the interviewees were asked to compare the noise intensity generated by open trench and trenchless methods. It was suggested to correlate the noise level and the number of equipment used during the project because both contribute to the levels of noise. Even though usually no compensation is given for the noise pollution in temporary projects, there might be a significant noise difference when comparing trenchless and open trench methods.

According to some experts, the main differences in noise pollution costs between a trenchless and an open trench project can be noticed in the following aspects:

- Open trench projects durations usually are longer than trenchless projects; therefore the noise pollution/nuisance will be present for a longer time in the construction site and the surroundings.
- Open trench projects require more equipment and machinery, consequently leading to more noise sources and higher noise intensity compared to trenchless projects.

❖ *Dust pollution*

Dust pollution might be present when soil is excavated. Consequently, trenchless renovation technologies, which generate minimum amounts of dust, have little or no impacts related to dust pollution. At the same time, not necessarily an open trench project will produce dust and if this is the case, measures can be taken to minimize these negative effects (e.g. water spraying to settle dust).

❖ *Lifetime expectancy of pipelines*

For making a fair comparison between both methods in terms of the project lifetime expectancy, it was asked about approximate lifetime of a replaced pipelines using open trench and a renovated pipelines using trenchless technologies. It was concluded that the lifetime expectancy does not depend on the execution technique but on the pipeline material. In practice, different factors influence the lifetime expectancy such as the presence and composition of groundwater, pipeline material, depth, load, fluid composition. Those factors imply that a pipeline can either last longer or less than the expected lifetime. In the case of trenchless technologies, the hardening of the line is very important to guarantee its quality over the years.

It was mentioned that a CIPP renovation is usually designed for 50 to 100 years, while a traditional open trench is designed for 70 years. However, in practice the CIPP line lasts longer and its lifetime can be comparable to a pipeline placed using excavation methods. The following estimations were given regarding lifetime expectancy:

- The lifetime expectancy would be 100 years for both open trench and trenchless methods (structural renovation)
- Cast iron: 100 years (Liander)
- Concrete pipe: 80 to 100 years (Den Haag)
- PE piping: 100 years (Liander).

Risks of accidents and damage:

During the interviews, the risks of accidents and damage were investigated. It was asked whether risks are considered in pipelines (renovation) projects and if the costs, probability and severity related to these risks are taken into account. The mentioned risks were basically associated to the damage of infrastructures and accidents involving users and workers. There was no clear answer about monetizing the risks or about the probability and severity of accidents and damage because risks are very project specific. Therefore, the interviewees did not use a general way of monetizing accidents and damage beforehand.

The general approach regarding risk-related social costs is that companies manage risks by doing risk management. These risks are considered in both trenchless and open trench projects and if high risks are present, the project owner would have to manage or mitigate them before starting the project.

Some mentioned that trenchless technologies are new compared to open trench, which requires more safety measures in place. Besides, trenchless does not allow visualizing what is happening underground and this becomes an extra challenge for workers and increases the risk. On the other hand, open trench methods are well-known so even though there are also risks involved (e.g. related to trench stability), safety measures are present to guarantee a safe work environment. The same applies to trenchless projects regarding safety measures.

The interviews also revealed the existence of a relationship between risks and project duration, excavation, work zone size and machines/vehicles. For instance, the longer the project, the more the risk of damage and accidents. Table 22 compares risks between open trench and trenchless renovation projects according to interviewees.

Table 22: Risk comparison between open trench and trenchless (renovation) technologies

Social costs (risks)	Open trench (excavation)	Trenchless Technologies (renovation)
Accidental injury or death (workers)	Open trench requires more workers and machinery. Thus, the likelihood of accidents involving workers is higher because projects are longer, workspace is limited (complete trench) and contact between machines and workers are more likely to happen.	Trenchless uses less machinery, workspace is limited to the manhole and project durations are shorter. Consequently the likelihood of accidents is lower based on these factors.
Increase in traffic accidents (users)	Opinion 1: Open trench involves less risk of traffic accidents because the road where the project takes place is blocked and no traffic is allowed in the area. Opinion 2: the risks are higher because transport (of soil) from the construction site to the soil dump/collection site increases the chance of accident on the way.	Opinion 1: Trenchless projects allow traffic flow on the street where the project will take place because the equipment used is placed around the manholes. Trenchless involve at least 2 workspaces (2 manholes) and around that area there might be flow of pedestrians, vehicles and bicycles. This would increase the chances of accidents involving users. Opinion 2: accident risks are less because fewer machines are used and less transportation of material is needed.
Damage to infrastructure/ property	Transportation of material and heavy loads can cause damage not only in the work zone but also on the trajectory to the work zone. Besides, vibrations due to equipment (e.g. sheet piling for soil stability) can also cause damage to foundations and sensitive structures.	Trenchless uses less equipment than open trench which reduces risk of damage.
Damage to existing pipelines	Risk of clashes with existing pipelines is due to digging. Besides, the subsurface utilities mapping might be inaccurate (e.g. due to subsidence in peat soils) which may also contribute to clashes.	There are no risks of clashes with existing pipelines in renovation techniques because the relining takes place inside the existing pipe. However, other types of trenchless technologies that cause pressure in the subsoil might cause damage (e. g. replacement, new installations).

As it can be noticed, the opinions regarding risks sometimes differ when comparing open trench and trenchless renovation. Safety depends on external factors that are hard to predict beforehand because accidents and damage can be unpredictable. Examples are human mistake or reliance on the contractors' expertise. Besides, the interviewees did not monetize risks and instead had a risk management approach for their specific projects. Consequently, it was not possible to propose a way to predict the costs associated with the risks in advance. These factors led to adopting a qualitative approach towards risks as will be described in Chapter 4.

*3.2.2. **Surveys***

The surveys were replied by four respondents who gave their opinions about the scales and factors affecting risks. The goals of the surveys were (1) to define scales to be used in the risk analysis and (2) to define the factors affecting the risk types (sub criteria). The results of the part 1 survey are the input data scales (scale for the factors affecting risks). These scales are used for scoring the input data, resulting in a final score for each risk type. The scoring is based on an ordinal 5-point scale where number 1 represents the input data that affects the probability of a risk event the least; and number 5 affects it the most.

Considering that risk is given by the *impact* of an event times *likelihood*, an important assumption on this research is that the impact is considered equal for open trench and trenchless alternatives. However, the likelihood of occurrence of damage and accidents is different for both methods, and this difference is analysed in the model using the scales. To exemplify, if an accident involving users (vehicles) happens, the impact of the accident (e. g. on health, material losses) would be the same for the open trench and trenchless projects. As a consequence, risks would only depend on the likelihood of occurrence.

Table 23 presents the input data, scales and descriptions based on the interviews and survey responses. The description of input data was based on the responses from the interviews and explains how the different factors affect the risks of accidents and damage. The input data on the table are classified as *project specific* and *location specific*.

The project specific input data are intrinsic to the project while location specific input data do not depend on the project characteristics but on the project location/surroundings. As a consequence, the scores given to the location specific input data in the model will be the same for both open trench and trenchless alternatives as they do not depend on the execution methods.

The scales have been defined based on the responses to the survey. However, the scales for the input data *size of work zone, transportation of material and naturalness of area* could not be unified into a single scale and are shown as "context dependent". This is due to the fact that when comparing the answers of the respondents, the values proposed were either inexistent or very discrepant. As a consequence, the risk scales proposed on this research cannot be seen as absolute and should be adapted according to the project situation.

Table 23: Input data scales for assessing risks sub criteria

Project specific			
Input data	**Scales**		**Description**
Project duration	1 - very short	<=1 week	Project duration influences risk in the sense that the longer the project takes, the higher the risks of damage and accidents might be. This is applicable to workers that will be exposed to different risky situations in the construction site and the users crossing the area. Besides, a new construction site placed in an area might require extra attention from the drivers, cyclists and pedestrians. If the site is present for a longer period, these users might get used to it and pay less attention to the safety measures, increasing the risks of accidents.
	2 - short	1 - 2 weeks	
	3 - medium	>= 2 weeks	
	4- long	>= 4 weeks	
	5- very long	>= 3 months	
Number of machines on site	1 - very low	1	Machinery size and number affect the risks of accidents and damage as a higher number of machines and bigger machines result in more risks to workers that have to operate them and circulate in the working zone.
	2 - low	2	
	3 - medium	3	
	4- high	4	
	5- very high	> 5	
Excavation volume	1- very low	< 10 m^3	Excavation can increase the risks of damage due to higher chances of clashes with existing utilities or foundation for example. Besides, the presence of trenches causes a higher risk for the workers on site due to fall hazards.
	2- low	10-50 m^3	
	3- medium	50-100 m^3	
	4- high	100-200 m^3	
	5- very high	>200 m^3	
Size of work zone	1- very small	Context dependent	Work zone size has an influence on risks because the more workers present in the workspace, the higher the amount of people vulnerable to accidents. Larger workspaces usually involve a higher number of workers, increasing the risks of accident because more people and machinery are interacting and circulating in the area.
	2- small		
	3- medium		
	4- large		
	5- very large		
Transportation of material (offsite)	1- very low	Context dependent	When constant transportation is needed to and from the construction site there is an extra risk of accidents/damage on the trajectory involving property and infrastructure damage and accidents involving users.
	2- low		
	3- medium		
	4- high		
	5- very high		

Location specific			
Input data	**Scales**		**Description**
Area density (Development above ground)	1 - very low density	natural area	The density of an area (given by the presence of buildings, infrastructure or facilities above ground) can affect the risk of damage due to movements of machine, equipment, vibrations, foundations damage and higher chance of clashes. It is expected that the higher the area density, the higher will be the chance of damage due to clashes.
	2 - low density	low density residential area	
	3 - medium density	high density residential area, schools, shops	
	4- high density	industrial/business area, schools, shops	
	5- very high density	city centre, shopping centres, skyscraper buildings	
Traffic density	1 - very low density	< 1000/day	Traffic density influences the risks of accidents nearby the construction site. More intense vehicle flows can lead to stop and go situations and cause more traffic jams, increasing the risks of accidents involving users.
	2 - low density	1000-5000/day,	
	3 - medium density	5.000 - 15.000/day, busses and/or trams	
	4- high density	15.000 - 40.000, busses and/or trams	
	5- very high density	> 40.000, busses, trams	
Pedestrian flow (incl. bikes)	1- very low flow	< 10 pedestrians/day	The presence of pedestrians and cyclists increases the chances of contact with machines and vehicles and consequently the risk of accidents.
	2- low flow	10 - 250 pedestrians/day	
	3- medium flow	250 - 1000 pedestrians/day	
	4- high flow	1000 - 3000 pedestrians/day	
	5- very high flow	3000 - 5000 pedestrians/day	
Density of buried pipelines	1 - very low density	only the pipeline under renovation	A higher density of buried utilities contributes to damage because the chances of clash during project execution increase. Factors such as poor subsurface mapping or subsidence of pipelines in clay soil can also affect damage to utilities.
	2 - low density	only regular distribution pipelines	
	3 - medium density	regular distribution pipelines plus warm water distribution	
	4- high density	regular distribution pipelines, warm water distribution plus transport (high voltage, high pressure, big diameter)	
	5- very high density	main pipeline corridor (e.g. in harbour area)	
Naturalness of area	1- very urbanized area	Context dependent	Damage to nature, specifically vegetation, is more evident in natural areas or in areas with presence of many trees. Projects can damage roots or require cutting down trees and thus damaging the local vegetation.
	2- urbanized area		
	3-medium urbanized area		
	4- natural area		
	5- very natural area		

The survey Part 2 revealed which factors affect the probability of each risk type to happen based on experts opinion. It was noticed that most of the answers of the survey are similar to the opinions obtained during the interviews. However, the survey was more structured and allowed the development of the framework present in Figure 13. The last column shows the factors affecting risks sub criteria according to the respondents.

The opinions about the factors affecting risks were also diverse but more homogeneous than the survey part 1, since the respondents had only pre-defined options to choose from. Only the factors with more than half of the votes (at least 2 votes) were selected so on average from 5 to 6 factors out of 10 were selected for each risk sub criteria. In the exceptional case of the sub criteria *Property damage*, the factor *Pedestrian flow* was left out of consideration even though it received 2 votes because based on previous research this factor did not seem to influence the risks of property damage. The framework presented in Figure 13 is a basis for the risk analysis described in Section 4.2.

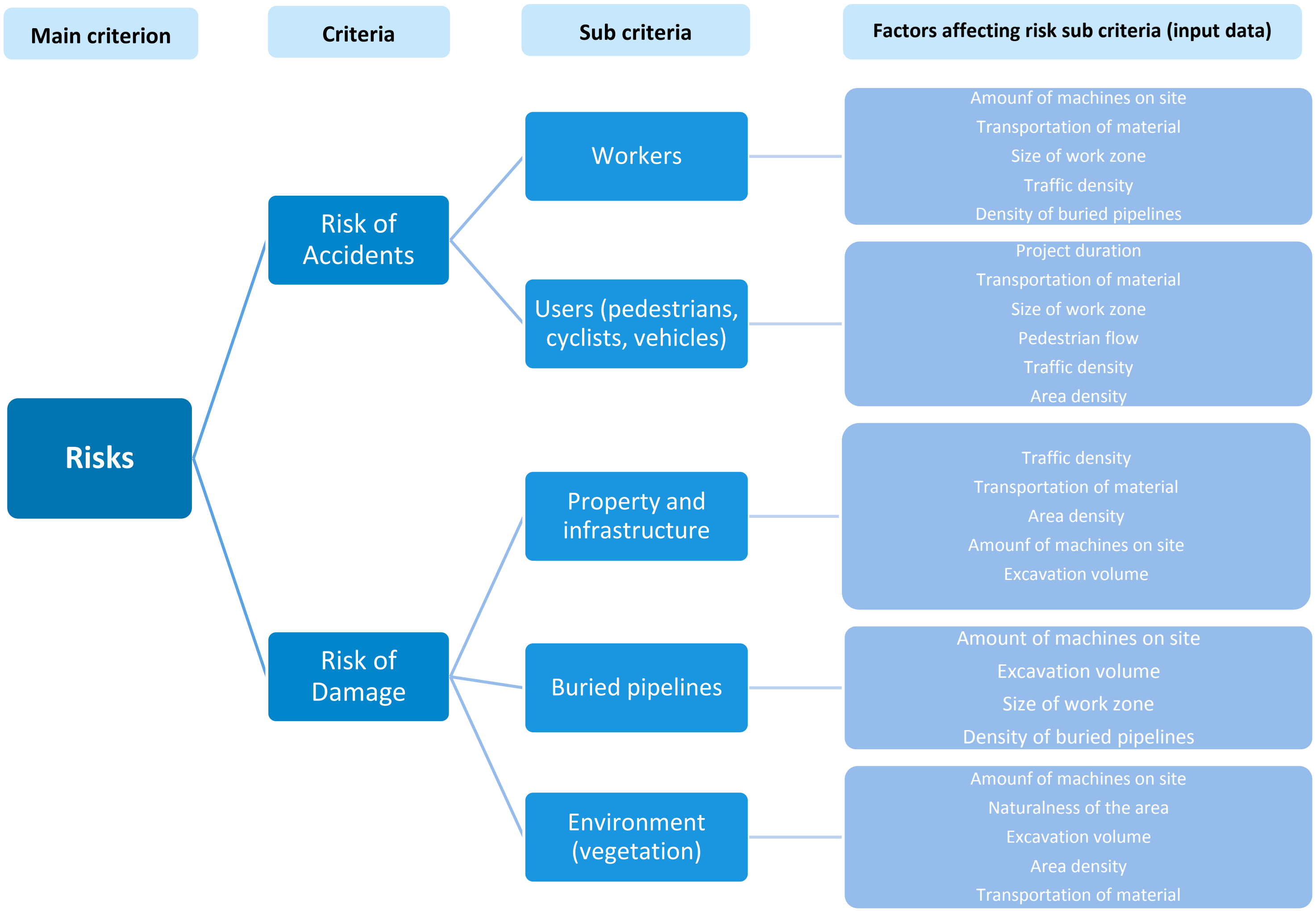


Figure 13: Risks criteria, sub criteria and affecting factors used in the risk analysis

3.2.3. Conclusion

The literature review as part of the data collection methods was used for providing a general overview about social costs and valuation methods included in the model. Based on this information, the interviews were developed and used for providing a practical view about social costs, for choosing the most pertinent social costs in pipelines projects, and to opt for a qualitative approach towards risks after realizing that it was hard to implement a general valuation method for the risk related social costs. It can be concluded that the interviews corroborated most of the facts about trenchless and open trench projects found during the literature review.

The experts' surveys were used to develop the risk approach for the social costs that could not easily be monetized. As a result, a scoring/scaling method is proposed based on the survey results in order to incorporate risks in the decision making. The approach towards risk is qualitative and dependent on experts' opinion, which makes the risks model subjective. Therefore, it might be that the scales defined using the survey would have been different if other respondents were chosen. As such, the risk approach is an added value to the fixed social costs calculator since it was not possible to quantitatively and objectively assess risks in this research.

Chapter 4 presents the steps involved in the model development based on the information presented in this chapter.

4. Model development

This chapter explains the model proposed for the risks and cost analysis, developed based on the outputs form the data collection explained in Chapter 3. The model, developed in the form of an Excel matrix/table, has the goal to integrate total project costs and risks for supporting decision-making. In the model, the total costs are divided into direct/indirect and fixed social costs; while the risk related social costs are divided into risks of damage and accidents.

Figure 14 represents the costs and risks types involved in the decision making regarding pipelines projects. The approach provided in the figure highlights that not only direct and indirect costs are important during the decision making process, but other criteria should also be involved in the choice such as social costs and risks.

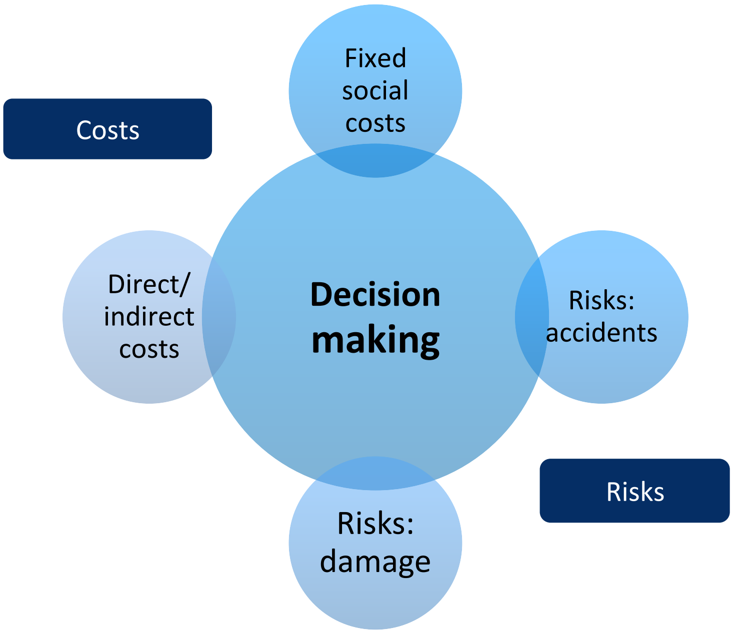


Figure 14: Decision making criteria and sub criteria in the model

The next sections describe the model development: first, the costs category is described together with the valuation equations, input data and key figures used. Second, the Risk category is presented with the necessary input data, scales and an example. Third, an explanation on how to use the model/matrix is presented. Fourth, the assumptions made during the model development are listed. Fifth, the validity of the proposed key figures and scales is discussed. Finally, the model is validated by experts.

4.1 Costs category

The total project cost is one of the criteria in the decision making and can be directly expressed in monetary units. Inside this criterion, two sub criteria are identified: direct/indirect costs and social costs. This division is important for identifying the contribution of each cost type in the total project costs and also for comparing direct/indirect costs to social costs in each project alternative.

4.1.1 *Valuation equations and input data*

The total project costs are given by the sum of direct/indirect costs and social costs. Direct and indirect costs are usually provided by the project owner, while the total social costs are given by the sum of (fixed) social costs calculated through the valuation equations. Table 24 reviews the valuation equations necessary for quantifying each cost component used in the model.

Table 24: Costs criteria, sub criteria and valuation equations

Criteria/ Sub criteria		Equations		
1	**Total costs**	$\sum 1.1 + 1.2$		
1.1	Direct and indirect costs	$\sum \text{direct costs} + \text{indirect costs}$		
1.2	Social costs	$\sum \text{Equations } 3, 6, 7, 8, 9, 12, 13, 16, 17, 18$		
		Increased vehicle operating costs	$\mathrm{IVOC\ Total} = \mathrm{IVOC\ 1} + \mathrm{IVOC\ 2}$	Eq. 3
		Traffic delay	$\mathrm{TDC} = \mathrm{CD} \times \mathrm{NVD} \times \mathrm{D}$	Eq. 6
		Pedestrian delay	$\mathrm{PDC} = \mathrm{AT_P} \times (0{,}5 \times \mathrm{HR_P}) \times \mathrm{P} \times \mathrm{D}$	Eq. 7
		Loss of parking space	$\mathrm{LPm} = \mathrm{PM} \times \mathrm{R} \times \mathrm{Ho} \times \mathrm{O} \times \mathrm{D}$ $\mathrm{LPt} = \mathrm{PM} \times \mathrm{F} \times \mathrm{FT} \times \mathrm{D}$	Eq. 8 Eq. 9
		Pavement service life reduction	$\mathrm{PSL} = \mathrm{PDF} \times \mathrm{Excavated\ Area}$	Eq. 12
		Air pollution	$\mathrm{APC} = \sum_{i=0}^{i} \mathrm{V_i} \times \mathrm{C_i}$	Eq. 13
		Noise pollution	$\mathrm{NPC} = \mathrm{N_H} \times \mathrm{C_n} \times (\mathrm{N_c} - \mathrm{N_n}) \times \mathrm{D} \div 365\ \mathrm{days}$	Eq. 16
		Dust pollution	$\mathrm{DPC} = \mathrm{AC} \times \mathrm{HR_p} \times \mathrm{D}$	Eq. 17
		Business revenue loss	$\mathrm{BRL} = \mathrm{U} \times \mathrm{ADI} \times \mathrm{D} \times \mathrm{P}$	Eq. 18

The list of all input data necessary for quantifying the social costs through the valuation equations are incorporated into the Excel model and summarized in Table 25. Table 26 summarizes only the input data to be provided by the users and their respective units grouped according to the social cost type.

Using the valuation equations, key figures and input data provided it is possible to calculate each social cost indicator and the total social costs. When a social cost (indicator) is considered irrelevant and/or when not enough data can be provided by the user, the input data field in the model can be left blank. Consequently, the calculation of that specific indicator will amount zero and not influence the total costs results. Afterwards, the comparison between open trench and trenchless renovation can take place based on total costs, direct/indirect costs and social costs.

Table 25: List of input data used in the model for the valuation of social costs

Project characteristics data	• Duration; Pipeline length; Execution speed; Pipeline diameter; Direct costs
Traffic data	• Street type; Traffic control plan; Number of vehicles per day
Vehicle operating costs data	• Additional travel distance
Traffic delay data	• Delay time or: • Length of work zone including detours; Speed through work zone; Length of work zone normal situation; Normal speed
Pedestrian delay data	• Additional distance to cross the work zone; Number of pedestrians affected or: • Number of domiciles in the area
Loss of parking space data	• Number of parking meters/spaces; Meter daily operational hours; Occupancy; Amount of one fine; Frequency of fines; Duration of parking obstruction; Meter rate price
Pavement service life reduction data	• Excavation area; Road classification; Pavement age
Air pollution data	• Number of machines; Daily distance driven by transportation trucks; Number of transport vehicles
Noise pollution data	• Number of disturbed domiciles; Noise during construction(all equipment)
Dust pollution data	• Additional cleaning time
Business revenue loss data	• Area of affected business units (food); Area of affected business units (non-food); Percentage of business loss during construction

Table 26: List of users input data and units per social cost type

User input data and units			
General		**Loss of parking space**	
Duration	days	Number of parking meters/spaces	spaces
Pipeline length	m	Meter daily operational hours	hours
Execution speed	m/day	Occupancy	%
Pipeline diameter	mm	Amount of one fine	€
Method	-	Frequency of fines	fines/space*day
		Duration of parking obstruction	days
		Meter rate price	€/hour
Traffic data		**Pavement service life reduction**	
Street type	-	Excavation area	m2
Traffic control plan	-	Road classification	Arterial/Collector/ Local
Number of vehicles per day	vehicles/day	Pavement age	years
Traffic delay		**Business revenue loss**	
Length of work zone including detours	km	Area of affected business units (food)	m^2
Speed through work zone	km/h	Area of affected business units (non-food)	m^2
Length of work zone normal situation	km	Percentage of business loss during construction	%
Normal speed	km/h	N of affected units (food)	n
Or: Delay time	h	N of affected units (non-food)	n
Pedestrian delay		**Air pollution**	
Additional distance to cross the work zone	km	Number of machines	n
Number of pedestrians affect	pedestrian/day	Daily distance driven by transportation trucks	km
Or N of domiciles in the area	domiciles	Number of transport vehicles	n
Noise pollution		**Dust Pollution**	
Number of disturbed domiciles	n	Additional cleaning time	hours
Noise during construction (all equipment)	dBA		
VOC			
Additional travel distance	km		

4.1.2 *Key figures for valuation equations*

As mentioned throughout this report, the key figures proposed were retrieved from official Dutch reports. Therefore, they are applicable to the Dutch context and might not be appropriate to other countries. The valuation equations, however, were based on international literature and therefore should be valid in different contexts.

The key figures proposed are used in the valuation equations to reduce the amount of input data requested from the users. These key figures are divided into general and specific to differentiate those that are used in several equations and those that are only used for a specific social cost calculation, respectively.

The key figures are incorporated in the Excel model and do not need to be changed by the users, unless if they opt to provide their own values. Tables 27 and 28 summarize the general and specific key figures respectively, the units and the values used in the model for the Netherlands.

Table 27: General key figures for the calculation of fixed social costs

General Key figures	Unit	Open trench	Trenchless	Source
Value of time (road user)	€/person	11.83	11.83	RIGO, 2012
Value of time (pedestrian)	€/person	14.40	14.40	Loonwijzer, 2017
Vehicle operating costs	€/veh. kilometer	0.13	0.13	RIGO, 2012
Wage rate cleaning personnel	€/hour	14.4	14.4	Loonwijzer, 2017
Average number of persons per vehicle	persons/vehicle	1.39	1.39	Otten, 't Hoen & den Boer, 2015

Table 28: Specific key figures for the calculation of fixed social costs

Specific Key figures	Unit	Open trench	Trenchless	Source
Pedestrian delay				
Pedestrian average speed	km/h	5	5	Interviews
Average inhabitants/domicile		2.2	2.2	CBS, 2015
Pavement service life reduction				
Pavement depreciation due to excavation	€/m^2	See Table 12	See Table 12	Karim et al, 2014
Air pollution				
CO_2 cost of emission	€/ton	40	40	RIGO, 2012
CO_2 emission (middle car)	Ton/km	0.000133	0.000133	BOVAG-RAI, 2015
CO_2 emission (urban normal/medium duty, 2015)	Ton/km	0.000783	0.000783	Ligterink, van Zyl & Heijne, 2016
Emissions machinery	Kg CO_2/liter of diesel	2.7	2.7	Rehan & Knight, 2007
Fuel consumption machinery	Liter diesel/hour	9.1	9.1	Rehan & Knight, 2007
Noise pollution				
Cost per increase in 1dBA	€/dBA	49	49	RIGO, 2012
Normal level of noise	dBA	65	65	Vermeulen et al, 2004
Business revenue loss				
Daily income per business (food, 2017)	€/m^2/day	30.70	30.70	Detail Handel, 2017
Daily income per business (non-food, 2017)	€/m^2/day	5.90	5.90	Detail Handel, 2017

4.2 Risk category

As previously mentioned, the risk related social costs are qualitatively assessed in the model. Basically, the risk analysis is conducted using the predefined factors affecting risks and the predefined scales based on the survey results. Using this background information, the risk analysis can be conducted in the model. Figure 15 summarizes the factors affecting risks and Table 29 presents the input data scales used in the model.

Accidents workers	Accidents users	Damage to property/ infrastructure	Damage to buried pipelines	Damage to environment
•Amount of machines on site •Transportation of material •Size of work zone •Traffic density •Density of buried pipelines	•Project duration •Transportation of material •Size of work zone •Pedestrian flow •Traffic density •Area density	•Traffic density •Transportation of material •Area density •Amounf of machines on site •Excavation volume	•Amount of machines on site •Excavation volume •Size of work zone •Density of buried pipelines	•Amount of machines on site •Naturalness of the area •Excavation volume •Area density •Transportation of material

Figure 15: Risks sub criteria and factors affecting risks (input data)

Table 29: Input data scales for assessing risks sub criteria

Project specific			Location specific		
Input data	**Scales**		**Input data**	**Scales**	
Project duration	1 - very short	<=1 week	**Area density (Development above ground)**	1 - very low density	natural area
	2 - short	1-2 weeks		2 - low density	low density residential area
	3 - medium	>= 2 weeks		3 - medium density	high density residential area, schools, shops
	4- long	>= 4 weeks		4- high density	industrial/business area, schools, shops
	5- very long	>= 3 months		5- very high density	city centre, shopping centres, skyscraper buildings
Amount of machines on site	1 - very low	1	**Traffic density**	1 - very low density	<= 1000/day
	2 - low	2		2 - low density	1000-5000/day,
	3 - medium	3		3 - medium density	5.000 - 15.000/day, busses and/or trams
	4- high	4		4- high density	15.000 - 40.000, busses and/or trams
	5- very high	< 5		5- very high density	>= 40.000, busses, trams
Excavation volume	1- very low	< 10 m^3	**Pedestrian flow (incl. bikes)**	1- very low flow	< 10 pedestrians/day
	2- low	10-50 m^3		2- low flow	10 -250 pedestrians/day
	3- medium	50-100 m^3		3- medium flow	250-1000 pedestrians/day
	4- high	100-200 m^3		4- high flow	1000-3000 pedestrians/day
	5- very high	> 200 m^3		5- very high flow	3000 - 5000 pedestrians/day
Size of work zone	1- very small	<=300 m^2	**Density of buried pipelines**	1 - very low density	only the pipeline under renovation
	2- small	300 - 600 m^2		2 - low density	only regular distribution pipelines
	3- medium	600 - 1200 m^2		3 - medium density	regular distribution pipelines plus warm water distribution
	4- large	1200 - 2400 m^2		4- high density	regular distribution pipelines, warm water distribution plus transport (high voltage, high pressure, big diameter)
	5- very large	>= 2400 m^2		5- very high density	main pipeline corridor (e.g. in harbour area)
Transportation of material (offsite)	1- very low	**Context dependent**	***Naturalness of area***	1- Very urbanized area	0.005 trees/m^2
	2- low			-	0.01 trees/m^2
	3- medium			3-medium urbanized area	0.1 trees/m^2
	4- high			4- natural area	0.5 trees/m^2
	5- very high			5- very natural area	1 trees/m^2

Table 29 was adapted from Table 22 to be used in the projects provided by Experts in the model validation phase. Therefore, the *excavation volume, size of the work zone* and *naturalness of the area* scales were based on the opinion of a single expert since there was no convergence in the scales for these particular input data.

Another scale used in the model is the risk criteria and risk sub criteria scales. Similarly to the input data scales, 1 represents the best performance and 5 the worst performance in the risk (sub) criteria scale. A colour scale is combined with this 5-point scale, where green is equivalent to number 1 and red is equivalent to number 5.

To exemplify, suppose that after scoring the project alternatives for each risk sub criteria based on the input data scales, project A scores 4 in the sub criteria *accidents workers* and project B scores 2. Besides, the overall Risk score (considering the average of the scores of each sub criteria) for project A is 3 and for project B is 2. As a conclusion, the likelihood of accidents involving workers and the overall risk will be higher for project A compared to project B: the higher the score, the higher is the likelihood of a risk event happening.

Table 30 presents the scales for the main risk criterion and the risk sub criteria. The scales vary from very unlikely to very likely to happen, indicating how high the chances are that accidents or damage take place in the project.

Table 30: Scales for risk main criterion and sub criteria

Risk main criterion	Scale	Likelihood
• **Risks**	1	Very unlikely to happen
	2	Unlikely to happen
	3	Possible to happen
	4	Likely to happen
	5	Very likely to happen
Risk sub criteria	**Scale**	**Likelihood**
• Accidents: workers	1	Very unlikely to happen
• Accidents: users	2	Unlikely to happen
	3	Possible to happen
	4	Likely to happen
	5	Very likely to happen
Risk sub criteria	**Scale**	**Likelihood**
• Damage: Property/infrastructure	1	Very unlikely to happen
• Damage: buried pipelines	2	Unlikely to happen
• Damage: environment	3	Possible to happen
	4	Likely to happen
	5	Very likely to happen

4.2.1 *Risks analysis*

This section explains how the risk analysis is conducted based on the scales previously described. In the risk analysis, the risk scores for each alternative are calculated and a comparison is made based on these results. In Table 31, a risk assessment matrix is proposed to illustrate the model. In order to understand the matrix, the following considerations are made:

- Rows represent input data that affect the sub criteria under analysis
- Columns represent the alternatives under evaluation (open trench versus trenchless technologies)
- Cells represent the performance of a given alternative in terms of an input data for a given sub criteria. The performance is measured through the 5-point input data scales proposed in section 4.2.

Table 31: Example of risk sub criteria assessment - sub criteria, input data and scoring of alternatives

Criteria/Sub criteria	Input data	Score (1-5)	
		Alternative 1	**Alternative 2**
1 Risks	*Input data 1*	S_{11}	S_{12}
1.1 Sub criteria X	*Input data 2*	S_{21}	S_{22}
	Input data 3	S_{31}	S_{32}
	Input data n	S_{n1}	S_{n2}
Sub criteria score (Sub criteria X, Alternative 1,2)		Score Alt. 1	Score Alt. 2

In Table 30 each risk sub criterion is independently evaluated based on the respective affecting input data. For each alternative and input data, a score is given ranging from 1 to 5. The sub criteria scores have to be calculated separately for each of the five sub criteria.

Each sub criteria score is given by the arithmetic average of the input data scores (Equation 24). The arithmetic average was chosen instead of weighed average because after consultation with experts, it was concluded that it would be difficult to give weights to each input data and express their contribution to a certain sub criteria. Besides, the weights would have been dependent on the expert experience and the project itself, making them context and project dependent.

$$\text{Score (Sub criteria X,} \quad \text{Alternative 1)} = \frac{S_{11} + \cdots + S_{n1}}{n} \qquad \text{Eq. 24}$$

The *overall risk score* is given by the arithmetic average of the sub criteria scores, for each alternative under evaluation as exemplified in Table 32. The *overall risk score* represents the final result which is used for comparing the open trench and trenchless renovation alternatives in terms of risks. The interpretation of the overall risk score is based on the 5-point scale/colour scale explained in Section 4.2.

Table 32: Example of risk assessment - Overall Risk score

Criteria/Sub criteria	Score (1-5)	
	Alternative 1	**Alternative 2**
1 Risks		
1.1 Accidents with workers	2.9	1.5
1.2 Accidents with users	2.6	1.6
1.3 Damage to Property/infrastructure	2.8	2.0
1.4 Damage to buried pipelines	2.6	1.2
1.5 Damage to the environment	3.4	2.4
Overall Risk Score	**3**	**2**

The choice of arithmetic average for calculating the Overall risk score presents limitation regarding the importance of different risk sub criteria to the final results. This approach considers that each risk type has the same importance for the project and project owner, which might not always be the case. If one wants to highlight a risk type compared to the other, weighed average could be an option. Besides, the scales from Table 32 are given in decimal numbers for informative purposes. Rounding the scores to the closest integer does not affect the overall risk score much neither the likelihood.

4.3 How to use the model

This section explains how to use the Excel model for assessing the fixed social costs and risks. The model consists of five different types of calculation sheets and the contents of each sheet and how to use it are detailed in this section.

i. Input data sheet
ii. Social costs calculation sheets
iii. Risks sub criteria analysis sheets
iv. Risk analysis sheet
v. Final results sheet

i. Input data sheet

The input data sheet lists all the general data necessary for quantifying social costs and risks in open trench and trenchless project alternatives. The data is divided into (1) key figures previously defined and (2) project data to be provided by the user. The information should be provided for both open trench and trenchless renovation methods if a comparison between the options is envisaged. Even though it is not the main objective, the model can also be used to calculate the social costs for only one of the options.

In the excel model, the *input data table* assembles the input data by social cost indicator. Therefore, under each social cost indicator table, the user can fill in the information needed for the calculation of that specific social cost.

The necessary data to evaluate risks are aggregated in a separate table and classified into project specific and location specific data. This table should be filled by the users as scores based on the 5-point scales presented in Section 4.2. Using the scales, the user can indicate the scores for each input data and each alternative.

ii. Social costs calculation sheets

In the social costs calculation sheets the actual calculation of (fixed) social costs is performed. There are nine (fixed) social costs calculation sheets which are used to separately calculate each social cost in the model. Some social costs sheets contain key figures retrieved from literature that are pertinent to a certain social cost and therefore were not added to the input data sheet.

The calculation sheets make use of the valuation equations, the input data sheet information and key figures to calculate social costs. These sheets do not have to be filled in or modified by the user. They are only used for calculation purposes and can be useful if one wants to check where the results of the Final results sheet come from; and for checking the equations and specific key figures used. However, if the user has a different key figure, s/he can make a modification in these sheets to generate different results.

iii. Risks sub criteria analysis sheets

The risks sub criteria analysis sheets are used to score the risks sub criteria. There are five sheets in the excel model, one for each risk sub criteria. The information in these sheets consist of the risk sub criterion under analysis, the alternatives compared, the input data relative to the sub criterion, the scores for each input data retrieved from the input data sheet and the overall score/performance for each alternative in a 5-point scale and colour scale.

These sheets are used for calculating the scores for each sub criteria/alternative. The results from the five sheets are summarized in the *Risk analysis sheet*. The user does not have to add any data or information to these sheets.

iv. Risk analysis sheet

This sheet summarizes the final scores of the different risks sub criteria calculated in (iii). Besides, it is used to calculate the overall score for the Risk main criterion for each alternative under comparison. No input data from the user is needed in this sheet.

v. Final results sheet

The final results sheet summarizes the main results calculated in the model and does not require the users input. In this sheet, the user can compare the alternatives based on the final results obtained throughout the model in terms of costs and risks. The information presented in this sheet consists of the (a) direct costs; (b) total social costs and social costs indicators/components; (c) total project costs and (d) risk scores for open trench and trenchless alternatives.

4.4 Assumptions

The development of the social costs model for comparing open trench and trenchless renovation technologies involved some assumptions. These assumptions are necessary due to the limitations regarding the scope, the model and data availability. Some of these are based on the research from Alkema (2015) due to similar research contexts:

- The alternatives/methods under comparison are limited to open trench and trenchless *renovation* technologies.
- No distinction is made between the different trenchless renovation methods in terms of social costs calculations. Therefore, it is assumed that the social costs will be similar for any renovation method analysed.
- The social costs and risks comparison considers that the project would be executed in the same location and under the same conditions in both open trench and trenchless methods. Consequently, location-related characteristics (e.g. traffic density, developments above ground) should be independent of the method.
- General project characteristics such as pipeline length or diameter should be similar for both options so that the social costs comparison is fair.
- The user can provide information about direct costs for both options beforehand. If not, some equations are provided for calculating the direct costs but the reliability of the results cannot be guaranteed.
- The project duration, project location and length of the installations are estimated beforehand and can be provided by the user.

- The technical feasibility of the alternatives under comparison is guaranteed by the user, since only technically feasible options should be tested against social costs.
- The user should provide information about (traffic) delay times related to each project alternative for more reliable end results. If this information is not available, s/he can provide other information so that the model would estimate the traffic delay with less reliability.
- In the risk analysis, it is assumed that the input data (factors affecting risks) have the same impact/weight on the risk criteria. Besides, it is assumed that there is an equal impact of the risk criteria on the overall risk.

4.5 Validity of key figures and scales

During the model development, key figures and scales have been developed to allow the calculation and analysis of social costs and risks. These values were based on literature, reports and experts interviews and their validity is discussed on Table 33.

Table 33: Validity of key figures and scales

Aspects	Comments about validity
Increased vehicle operating costs	• There is a general key figure for the VOC where no distinction is made between vehicle types crossing the work zone.
Traffic delay	• No distinction is made between the types of vehicles crossing the work zone. Consequently a general *value of time* is used; • The estimation of time delay using the alternative equations does not consider the impacts of the project on the surrounding traffic. Only the vehicles crossing the work zone are considered, which consequently might not fully represent the real situation (especially in very busy areas where a lane closure can impact a large radius).
Pedestrian delay	• An approximate calculation is proposed for the affected pedestrians in the project area because it might be hard to have real data measured on the source.
Air pollution	• Only CO_2 is considered in the equations and other pollutants are excluded for simplifying the calculations; • No distinction is made between the types of vehicles generating pollution.
Noise pollution	• The population disturbed by noise is based on the number of houses nearby the construction site.
Dust pollution	• Dust pollution calculation needs information about the number of cleaning hours, which might not be available at the project early stages.
Business revenue loss	• The percentage of revenue loss will depend on the project. Therefore the user can either use their own values or literature references (from 10% to 50% loss).
Risks	• The scales are based on interviews, literature and survey with experts. Therefore they are subjective and subject to change depending on the project context; • The scales for risk criteria are general and are mostly used to compare the open trench and trenchless alternatives. The results should not be interpreted as a thorough risk analysis.

4.6 Model validation

The method proposed to validate the model is by Expert intuition, where an expert who has knowledge about the system evaluates the model outputs and behaviour. The first step of the validation was to collect data of a project to be used in the model. Since it was not possible to find data of a real project, experts have made “educated guess” and suggested figures for two fictitious projects in the city of Rotterdam. The next step was to validate the results of the model by experts, based on their experience. The details of the projects used for the Excel model validation, the input data and the results are presented in Appendix H.

Project 1: Nieuwe Binnenweg

The project 1 is located in a shopping/residential street in the region of Delfshaven in Rotterdam consisting of around 500 domiciles. The street is two-way and allows the flow of cars and tramways. The pipeline that needs rehabilitation is located under the sidewalk and consequently no road closure is needed for the open trench or trenchless methods. It is assumed that most of the parking spaces in the area are under subscription for residents and only 10% of them are open for the public. From those, half of the parking spaces are unavailable during open trench execution. Besides, the open trench option causes a pedestrian sideway closure. The trenchless option does not affect the parking availability or pedestrian flow. It is supposed that the loss of parking space and pedestrian walkway closure will impact business revenue by 10% for the open trench option. Regarding the reduction of pavement service life, the pavement degradation fee of 25€/m^2 is adopted for sideway concrete tiles.

Figure 16: Nieuwe binnenweg in Rotterdam. Source: Google Maps , 2017

Project 2: Volmarijnstraat

The project 2 is located in a residential street in the region of Delfshaven in Rotterdam. There are approximately 200 domiciles located there. The street is one-way and does not allow tramway transit. The pipeline that needs rehabilitation is located under the road in the middle of the street and therefore a complete road closure is needed in the open trench option. For the trenchless option, only around the manholes will be blocked and therefore partial closure is needed. The pedestrians will not be affected in any case and therefore no pedestrian delay is predicted. All the parking spaces are *reserved for residents with a subscription and therefore it is assumed that the hourly rate is much lower than a normal parking place. Regarding pavement service life reduction, the degradation fee adopted is 32€/m² for non-asphalt roads.*

Figure 17: Volmarijnstraat in Rotterdam. Source: Google Maps , 2017

This project information was used as input data for filling in the Excel model and calculating the social costs and risks. Once the results for the projects were generated, two experts from Rotterdam Municipality were consulted to validate the results and the model. At this point, the experts compared the outputs of the model with values/forecasts they would have expect based on their experience.

The results obtained for both projects are consistent with what would be expected in reality. The (fixed) social costs are higher for the open trench options in both cases. For instance, the pavement service life reduction is higher in the open trench options due to a larger volume of excavation. The noise pollution is also higher due to a longer project duration and a higher number of affected domiciles when open trench is used. The trenchless option also generates noise, but fewer domiciles are affected since the machines are located in specific areas on the site instead of throughout the whole street like in the excavation.

In project 1, no road closure is needed and therefore no traffic delay is expected. However, in many cases the pipeline is located under the road pavement which might require a total or partial lane closure. This situation would lead to detours and most probably traffic delays, especially in open trench projects. Some pedestrian delay is also expected in project 1 for both methods; however the longer project duration for the open trench option will lead to higher pedestrian delay costs.

In project 2, the open trench and trenchless methods will require complete and partial lane closure, respectively. Consequently, there will be some delay time and traffic delay costs. These delay costs are higher for the open trench option due to the longer project duration and the traffic management plan. The traffic delay costs are not very significant in project 2 because the traffic flow, the delay time and duration of street obstruction are low. In large projects, traffic delay costs can amount more than 50% of the total social costs (Matthews and Allouche, 2010).

The social costs of project 1 are much higher compared to project 2 because the former is located in a shopping street. Consequently, some loss of business revenue is expected during the project 1 execution due to the loss of accessibility to customers. Higher losses would be likely if the street was completely closed during a longer period of time.

Concerning risks, in project 1 the five risks criteria (risk of accidents workers; accidents users; damage to property/infrastructure; damage to buried pipelines; damage to environment) scored higher for the open trench option. Consequently, the overall risk score was also higher for the open trench compared to trenchless option (overall score 3 against 2). The same situation happened in project 2, where the overall score for open trench was 2 and for trenchless 1.

The results indicate that the risks related to the five risk types are higher for open trench considering the factors affecting risks described in this research. These results do not represent a risk assessment, but just an indication of which option is risker in terms of likelihood.

When comparing the overall risk scores of the projects, project 1 which is located in a shopping/residential area presented a higher score for both methods in comparison to project 2. This result is expected based on literature and experts consultations: busier areas tend to present more risks due to the higher flow of pedestrians, traffic, presence of buildings and so on. In these situations, the likelihood of accidents and damage are higher especially if the projects last long and many machines are on site.

In the fictitious projects described above, the main social costs relate to loss of business revenue, pavement service life reduction, noise pollution and loss of parking space. The data used came from educated guess made by experts, and therefore other values could have been suggested leading to different results. The particularities of the projects under analysis are reflected on the social costs results for both open trench and trenchless methods.

The validation conducted in this research aimed at verifying (1) which social costs and parameters should be included in the model and (2) whether the model satisfies the objectives defined at the start of this research, mainly to quantify/monetize social costs. The outputs obtained from the model, based on the two project cases, were realistic according to the experts.

Another validation comparing the model outputs and real/standard values could not be performed. Even though there are many social cost models proposed in literature, there is not much standardization among them and as a consequence the parameters used in the equations are not compatible. Therefore, the validation performed was subjective in the sense that it was only based on the opinions of experts.

5. Discussion and Conclusion

5.1 Discussion

The framework used in this research follows other research lines that identify the social costs related to construction projects and proposes valuation equations. From a theoretical point of view, the model provides a base for decision makers to recognize which social costs and risks might be present in their projects, where these social costs come from and which parameters influence these social costs and risks. Besides, it allows comparing social costs quantitatively and qualitatively between open trench and trenchless renovation methods in smaller projects.

The next paragraphs discuss the choices made during the research and the limitations encountered especially regarding the model development, validity and data availability. The discussion is divided into improving model validity and practical issues to differentiate theoretical and practical aspects.

Improving model validity

The scope of this research was drafted in a general way so that the social costs quantification could be applied to different renovation methods. Besides, the idea was to provide a general social costs list that is pertinent to different types of projects and not only to pipelines projects. In such a way, the social costs and valuation equations would remain valid for different cases, making the theoretical model more general and applicable to different contexts where social costs are considered.

Even though a general theoretical model is used, the scope only considers social costs related to trenchless renovation technologies and excludes new installations, repair and replacement. Besides, in terms of social costs calculations, no distinction is made between the trenchless renovation methods since these differences are assumed to be insignificant. The choices were based on the fact that trenchless renovation is the most used rehabilitation method for sewages and is related to life time extension by preserving the existing pipeline.

Furthermore, the project scope in this report is limited to the project execution phase and excludes the social costs incurred during design, maintenance and operation phases. This decision was based on the assumption that most of the social costs are usually incurred (or are more intense) during project execution and less during other project stages.

No Life Cycle Analysis (LCA) is considered in the social costs calculations, which might make a difference on the total social costs (e.g. impacts of pipelines material on the environment during its life cycle). Besides, some social cost indicators that could not be quantified through valuation equations were not included in the model, but the ones most relevant retrieved from literature and interviews were added.

A general approach for monetizing risks is not proposed because risks are project specific and each company predicts and manages risks in their own way. To tackle this issue, a scoring approach was proposed for qualitatively assessing risks. However, defining the scales and the factors affecting risks is a subjective task since they are based on experts' opinions and might differ depending on the respondent background.

Another comment regards the clear separation between open trench and trenchless projects during the analysis using the model. Experts stated that they usually try to combine works and in (many) cases they use both methods in the same project. In such situation, it would be hard to predict the shares of social costs related to each method. Even though the goal of the model is to compare these options, it might be useful to verify the outcomes of a project that combines both methods.

Finally, the model validation was only performed by the experts who provided the "educated guess" projects. This validation could have been conducted using more projects and consulting more experts from different perspectives to express their view about the validity of the outputs of the model.

Practical issues

Some practical limitations regarding the model use were encountered when discussing with experts as presented in the next paragraphs.

When it comes to the social costs valuation, the idea was to propose simple equations that require the least data from the users for running the model because it was expected that information was limited. However, it was noticed that even when the information is existent, it might be spread among different parties and it becomes a challenge to collect this data.

Experts stated that the way the Excel model is organized is valid, however the information required is not easy to be collected because it is too time and effort demanding to be gathered. Therefore, even though the necessary data is existent, assembling it is one of the challenges for the users because they are not used (or did not have the need) to gather this type of data beforehand for other purposes.

Besides, usually there are not data for both the open trench and trenchless options under comparison, but mainly for the chosen option that will be executed. This can partially be explained by the fact that usually the comparison in terms of social costs is not conducted by decision makers and therefore there is not much need to generate this project information beforehand. Consequently, a comparison is hindered due to the lack of data for one of the methods under analysis.

5.2 Conclusions

The main objective of this research was to develop a model that incorporates social costs in the evaluation of open trench and trenchless renovation methods for pipelines projects. The goal of the model was to compare these methods in terms of social costs as an added value for the decision making within municipalities. Like that, decision makers could make more informed decisions regarding pipelines projects based on total project costs, which includes the costs to society and environment. The model developed makes use of valuation equations and a scoring system to calculate social costs and evaluate risks, respectively.

Concerning practical issues, social costs are not systematically included in the decision making and this research tried to fill in this gap. However, during the research development, it was found that the information needed to valuate social costs is not always available or that it is spread among different parties, which became the biggest limitation of the model. A change in the way information is organized and communicated should help with filling this gap. Besides, the development of a common database with project information could be created and be used for social costs estimation in future projects.

Another observation lays on the fact that technical and economic aspects are actually very important in the decision making. This means that first of all the options under analysis have to be technically feasible. Afterwards, direct and indirect costs would play a role as other criteria for decision making between the project options.

It was also found that the incorporation of social costs would not always be used or influence the decision making and in these cases a social costs model would not add much value. This might happen in projects where the direct/indirect costs are very discrepant (here the choice might tend to the cheapest option to the project owner) or when the decision maker opts for the cheapest direct/indirect costs instead of Most Economic Advantageous Tender (MEAT) bid.

On the other hand, social costs can be very important and make a difference when the project owner wishes to reduce the nuisances to the society generated by a project. Here, the direct/indirect costs might not be the most important criteria (e.g. not the lowest price would be chosen). In these types of projects, the consideration of social costs can make a difference in the decision making and result in projects with the lowest cost to society and the environment.

The choice about incorporating social costs in the decision can be of great added value to the society and an opportunity for governmental agencies to provide a better environment to their citizens even during a project execution phase. Nevertheless, the way projects are actually chosen should be revisited and improved. A social costs model that is able to support the comparison of project nuisances generated to society and the environment is a first step to call the attention of how great theses negative externalities can be and the benefits of considering social costs in construction projects.

Finally, this research is concluded by answering the research questions presented in the start of this report.

How can the social costs be considered in the selection of (re-)construction methods in pipelines renovation projects? How can the social costs be integrated in a calculation tool?

After researching into social costs it was concluded that the best option was to split social costs into fixed social costs and risk related social costs. The fixed social costs can be monetized in euros and be directly compared with total project costs and direct/indirect costs between the alternatives. The risk related social costs could not be monetized because there was no simple way of providing a "general calculation tool". This is due to the fact that risks of damage and accidents are intrinsic to the project and the location and therefore the valuation would have to consider the particularities of each project.

As an alternative, the risks are not monetized but scored and compared between the alternatives. For that, risks have been divided into five risks sub criteria (risks of accidents users; accidents workers; damage to property/infrastructure; damage to subsurface utilities; damage to environment) and ten factors affecting risks have been listed. A combination of factors is proposed for each sub criteria and by using scales for each factor it is possible to have a score for each risk sub criteria and a final risk score (based on all the sub criteria scores), for open trench and trenchless alternatives. Finally, the comparison in terms of risks is made based on this final risk score.

The integration of social costs and risks resulted in an Excel model composed five types of worksheets for calculating fixed social costs and estimating risks. With the model, the user can estimate social costs and risks involved in pipelines projects and compare the alternatives not only based on direct costs but also considering social costs. As such, the model is an added value to the traditional selection of projects only based on direct/indirect costs.

What are the impacts of subsurface utility projects on society, economy and environment?

The impacts of subsurface utilities projects vary in intensity and severity depending on the project characteristics and on the surrounding environment conditions. These impacts have been researched in literature and described in sections 2.3 and 2.4. There are four main impact areas where the negative effects of pipelines projects can be noticed: traffic, pollution, damage to environment and health, and economy.

Which social costs are the most relevant for renovation projects using trenchless technologies and open excavation? Which costs indicators are relevant to the model?

Many social costs were found on literature and suggested by experts'. A list with the most relevant ones was proposed to compose the model. The social costs were divided into fixed social costs and risk related social costs. The difference is basically related to the ease of monetizing the social costs and the dependency (or not) on likelihood vs. impact. The fixed social costs consist of: Increased vehicle operating costs, traffic delay, pedestrian delay, loss of parking space, pavement service life reduction, air pollution, noise pollution, dust pollution and business revenue loss. The risk related social costs are increased accidents rate (users and workers) and damage (property, subsurface utilities and infrastructure).

Which valuation methods are the most relevant to quantify the impacts of open trench and trenchless projects based on the selected cost indicators and data available?

The valuation methods are equations used for quantifying and monetizing social costs. Different valuation methods have been found on literature and were detailed in the Section 2.4 of this research.

Which input data is necessary to calculate social costs through valuation methods? Are the required input data available to calculate social costs through valuation methods?

The valuation equations require different input data in order to calculate each social cost. Some key figures or general values have been found on literature and official Dutch websites and reports and are used as input data for the equations. This approach requires less effort from the user in providing data, besides making the model more standardized by the use of official key figures.

The necessary input data list has been presented to experts during interviews in order to investigate data availability. It was concluded that the needed data is diffused between different stakeholders and not all information necessary is available when the model is to be used. Therefore, the choice of the valuation equations aimed at requiring simple input data. Besides, the users have the option to disregard a social cost indicator that seems irrelevant; or when not enough information can be provided.

5.3 Recommendations

Based on the limitations encountered during this research, some recommendations are given for further research and practitioners.

First, further research could include other trenchless methods (a) to evaluate if there are differences regarding social costs between trenchless renovation and the other trenchless methods; and (b) to confirm or deny the hypothesis that the social costs are similar within trenchless renovation methods. It is expected that the same social costs list or theoretical model can be used for different execution methods, since the valuation of social costs does not necessarily depends on the method used but on other project related parameters.

Second, other project phases such as maintenance could be included in the social costs calculations for verifying whether they are significant or not in the total social costs. Besides, further research could comprise a life cycle analysis and/or other social costs such as waste management costs, soil pollution and accessibility to ambulances/fire brigade/police vehicles.

Third, the risks assessment could be further developed by improving the scales or by recommending a method to monetize risks taking into account data limitations and projects specificities. Moreover, investigations regarding risk quantification and monetization of risks at early project stages would be of great added value to the model since in this research only a qualitative analysis was proposed. In this sense, gathering data regarding likelihood and impact of accidents and damage related to pipelines projects could help monetizing risks.

It is recommended that more research is done regarding the social costs related to pipelines projects and about the reliability of key figures used. Besides, more research can be done regarding the key figures and data used in the model. For instance, for quantifying economic impacts through business revenue loss percentages.

It is also suggested that users change the way they organize and communicate project information for the social costs valuation, so that data can be easily gathered and applied in such a model. Since social costs can impact different areas and involve different areas of expertise, it is necessary that practitioners work towards integrated projects from the early project stages. For instance, if there is a common database for sharing project social costs information it would be easier to retrieve the necessary data and apply a calculation model.

Once the social costs are quantified or compared in a reliable way between open trench and trenchless projects, it will be possible to obtain a maximum welfare from these projects in a societal point of view. Such approach would benefit the society in the sense that projects causing less nuisance could be easier supported based on social costs and having higher chances to be selected in a bid.

Therefore, it is proposed that practitioners change their mindset if social costs are to be included in the decision making. At the moment, this decision is subjective and based on experience or past projects but as an improvement it could become more systematic and objective. Parties should work together from the early project stages to gather and exchange the necessary information for quantifying social costs. Once this becomes a practice within the practitioners and organizations, the quantification of social costs can become more structured and be incorporated in the decision making process in a reliable way.

6. References

Alkema, S. (2015). *Externe kosten bij leidingrenovatie: onderzoek naar de projecteiden kosten van open sleuf en sleufloze renovatie.*

Amsterdam. (2017). Retrieved June 2017 from: *https://www.amsterdam.nl/bestuur-organisatie/organisaties/organisaties/schadeloket-algemene/*

Bickel, P., Friedrich, R., Burgess, A., Fagiani, P., Hunt, A., De Jong, G., ... Tavasszy, L. (2006). *Developing Harmonised European Approaches for Transport Costing and Project Assessment*.

BOVAG-RAI. (2015). *Mobiliteit in Cijfers Auto's: 2014/2015.* Amsterdam: Stichting BOVAG-RAI Mobiliteit.

CBS. (2015). *Demografish kerncijfers per gemeente 2015.* Den Haag: Centraal Bureau voor de Statistiek.

Conway, W. M. (2008). *An investigation of trenchless technologies and their interaction with native Iowa soils* (Master thesis).

Council, F. o. (2003). *Selection of Technologies for Sewer Rehabilitation and Replacement.*

Decisio. (2016). Retrieved March 2017 from Decisio: http://decisio.nl/en/research/social-cost-benefit-analysis/

Department of Labour. (1995). *Guidelines for the management and removal of asbestos.* New Zealand: Occupational Safety and Health Service.

Detail Handel. (2016). Retrieved March 2017, from http://detailhandel.info/index.cfm/retail/non-food/

Geneletti, D. (2013). *Spatial Multicriteria Analysis for environmental Decision-making*. Trento, Italy.

Gilchrist, A., & Allouche, E. N. (2005). *Quantification of social costs associated with construction projects: state-of-the-art review.* Tunnelling and Underground Space Technology, 89–104.

Gillespie, J. S. (1998). *Estimating User Costs as a Basis for Incentive/Discentive Amounts in*

Google Maps. (2017). Retrieved July 2017 from Google Maps: www.maps.google.com

Hillston, J. (2013). *Model verification and validation.* Retrieved from http://www.inf.ed.ac.uk/teaching/courses/ms/notes/note14.pdf

International Society of Trenchless Technologies. (2017). Retrieved April 2017, from ISTT: www.istt.com

International Society of Trenchless Technologies. (2017). Retrieved April 2017, from ISST: www.istt.com

Iseley, T., & Gokhale, S. B. (1997). *Trenchless Installation of conduits beneath roadways.* Washington: National Academy press.

Jain, T. R., Khanna, O. P., & Sen, V. (2010). *Development and environmental economics and international trade.* Delhi: V. K. Publications.

Janssen, R. (2001). *On the Use of Multi-Criteria Analysis in Environmental Impact Assessment in The Netherlands* . Journal of Multi-Criteria Decision Analysis, 201-109.

Jung, Y. J., & Sinha, S. K. (2007*). Evaluation of trenchless construction methods for municipal infrastructure system.* Journal of Infrastructure Systems, 144-156.

Karim, M.M.A.; Rizvi, R.B.A.; Henderson, V.; Uzarowski, L.; Chyc-Cies, J. (2014). *Effect of Utility Cuts on Serviceability of Pavement Assets – A Case Study from the City of Calgary.* Annual Conference of the Transportation Association of Canada. Montreal, Quebec

KiM - Kennisinstituut voor Mobiliteitsbeleid. (2013*). The social value of shorter and more reliable travel times.* Retrieved from: https://www.rwseconomie.nl/kengetallen/documenten/publicaties/2016/2016/bereikbaarheid/kengetallen-bereikbaarheid

Kramer, S.R., & Gauthier, S.W. (1995). *Trenchless rehabilitation: Which choice for gas distribution pipe replacement?* Pipeline and Gas Journal, 222(1).

Lakkavalli, V., Poon, B., & Dhanoa, S. (2015). *Challenges in Utility Coordination and Implementation of Pavement Degradation.* Charlottetown.

Ligterink, N. E., van Zyl, P., & Heijne, V. (2016). *Dutch CO_2 emission factors for road vehicles.* Utrecht.

Linde, G. v., & Donkelaar, J. v. (2012). *Veiligheid in Maatschappelijke Kosten-Baten Analyse.* Delft: Rekafa drukkers bv.

Loonwijzer. (2017, April). Retrieved April 2017, from Loonwijzer: https://www.loonwijzer.nl/home/nieuws/loonwijzer-nieuws/nederland-voor-tweede-jaar-op-rij-stabiel-uurloon-07-04-2016

Mallela, J., & Sadasivam, S. (2011). *Work zone road user costs concepts and applications.* Washington.

Matthews, J. C., & Allouche, E. N. (2010). *A social cost calculator for utility construction projects.* North American Society for Trenchless technologies (NAST).

Matthews, J. C., Allouche , E. N., & Sterling, R. L. (2015). *Social cost impact assessment of pipeline infrastructure projects*. Environmental Impact Assessment Review, 196–202.

Mendoza, G., & Martins, H. (2006). *Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms*. Forest Ecology and Management, 1-22.

Michigan Department of Transport . (2017). Retrieved from http://mdotjboss.state.mi.us/webforms/GetDocument.htm?fileName=3701.pdf

Mind Tools. (2017). Retrieved May 2017, from Mind Tools: https://www.mindtools.com/pages/article/newPPM_78.htm

Nadeelcompensatie.net. (2017). Retrieved March 2017, from http://www.nadeelcompensatie.net/ontwikkelingen-15-omzetdrempel.html

Najafi, M., & Kim, K. O. (2004). *Life-Cycle-Cost Comparison of Trenchless and Conventional Open-Cut Pipeline Construction Projects*. Pipeline Engineering and Construction, 635-640.

NCSU. (2017). Retrieved May 2, 2017, from Natural Resources Leadership Institute: https://www.ncsu.edu/nrli/decision-making/MCDA.php

NDW. (2017, May). Retrieved from National Data Warehouse for Traffic Information: http://www.ndw.nu/pagina/en/78/database/81/historical_data/

NSTT (2010). *Groot hinderonderzoek: inzicht in ervaringen van consumenten en detaillisten met hinder.*

Ormsby, C. (2009). *A framework for estimating the total cost: a case study in Montreal.* Montreal.

Otten, M., 't Hoen, M., & den Boer, L. (2015). *STREAM Personenvervoer 2014: Studie naar TRansportEmissies van alle modaliteiten Emissiekentallen 2011.* Delft: CE Delft.

PBL Netherlands Environmental. (2016, December 12). Retrieved February 2017, from http://www.pbl.nl/en/news/newsitems/2016/subsidence-of-peatlands-leads-to-high-costs

Piehl, R. (2005*). Summary of trenchless technologies for use with USDA forest service culverts*. Eugene, Oregon.

Rahman, S., Vanier, D. J. and Newton, L. (2005). *MIIP Report: Social Cost Considerations for Municipal Infrastructure Management*. National Research Council Canada

Rehan, R., & Knight, M. (2007). *Do Trenchless Pipeline Construction Methods Reduce Greenhouse Gas Emissions?* Ontario.

RIGO Research en Advies BV. (2012). *Omgevingskwaliteiten bij MIRT-projecten: overzicht van methoden voor het meten en waarderen van welvaartseffecten in een MKBA.*

RWS. (2016). Waardering van verkeersveiligheid. Retrieved from https://www.rwseconomie.nl/kengetallen

SWOV (2010). *Roadworks and road safety*. SWOV Fact sheet, July 2010, The Hague.

SWOV (2014). *Road crash costs*. SWOV Fact sheet, March 2014, The Hague.

SZW. (2014). *Sectorraportage Grong, Weg en Waterbouw.*

Tighe, S., Knight, M., Papoutsis, D., Rodriguez, V. and Walker, C. (2002). *User cost savings in eliminating pavement excavations through employing trenchless technologies*. Canadian Journal of Civil Engineering, 29(5), 751-761.

Vermeulen, J.P.L.; Boon, B.H.; van Essen, H.P.; den Boer, L.C., Dings, J.M.W.; Bruinsma, F.R.; Koetse, M.J. (2004). *The price of transport - Overview of the social costs of transport*. Delft.

Welling, S. M., & Sinha, S. K. (2013). Practice Review of the Cost of Condition Assessment and Renewal. *Pipelines 2013*, 627-635.

WHO. (2016). Retrieved from World Health Organization: http://www.who.int/mediacentre/factsheets/fs313/en/

Woodroffe, N. J., & Ariaratnam, S. T. (2009). *Contractor Perspective on Factors for Evaluating Installation Options for Small-Diameter Utilities*. Journal of Construction Management and Engineering, 75–87.

Xueqing, W., Bingsheng, L., Allouche, E. N., & Xiaoyan, L. (2008). *A practical bid evaluation method considering social costs in urban infrastructure projects*. Proceedings of the 2008 IEEE ICMIT.

Yu, W.-D.; Lo, S.-S. (2005). *Time-dependent construction social costs model*. Construction Management and Economics, 327–337.

Appendix A: Trenchless renovation technologies description

Trenchless renovation technologies can be classified into *plastic-based, spay on method and cured in place method* according to the installation process and types of material used. This classification is briefly explained as follows:

Plastic-based methods

The plastic-based method has structural function and uses material such as Polyvinyl Chloride (PVC), Polyethylene (PE) and Glass-fiber Reinforced Plastics (GRP). The trenchless technologies in this category include sliplining, close-fit lining and spirally wound lining.

- ***Sliplining***

Sliplining is a simple and traditional trenchless technology that consists of inserting a new pipe into the existing one. The new pipeline diameter has to be smaller than the diameter of the existing pipe so that the new pipe can be pulled inside the other one. Sliplining is more suitable for existing pipelines with no deformations, curvature, and angles (ISTT, 2016). The annular space between the old and new pipe is grouted to restrain the new pipe and transfer load from the existing pipe. The most common material used in this technique is PE, PVC, and GRP. A disadvantage of slip lining is the decrease of the internal pipeline diameter, which is a main concern for small diameter existent pipelines (Syachrani et al. 2010). A representation of sliplining is shown in Figure 16.

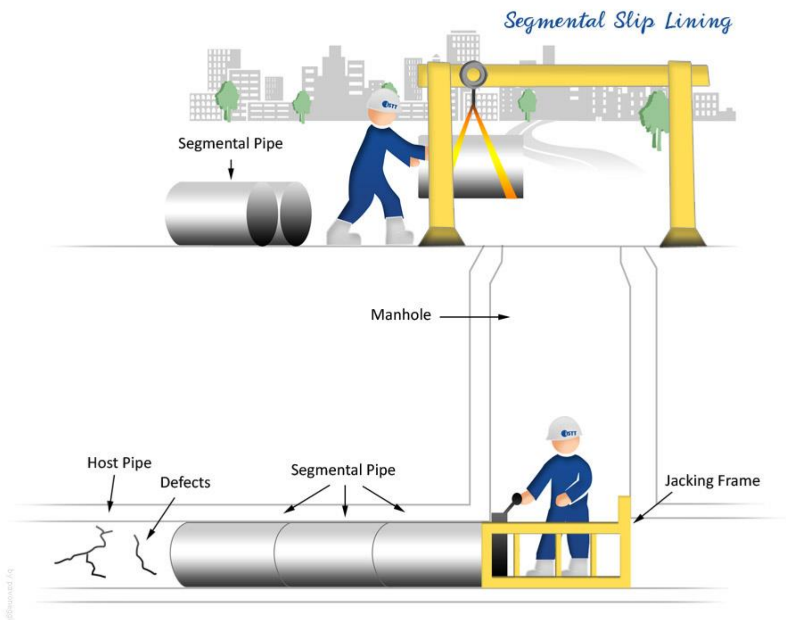


Figure 18: Execution of Slipling trenchless technology (ISTT, 2016)

- ***Close fit sliplining***

Close fit sliplining uses similar principles to sliplining, but here the outside diameter of the new pipe is in close fit with the diameter of the existing pipe (ISTT, 2016). In this way, the loss of internal diameter is lower compared to sliplining and grouting is not necessary. This technique is more suitable for pressure pipes that are relatively straight. In this technique, the new pipeline made of thermoplastic material has its diameter slightly reduced in order to fit inside the old pipe and be close fit to it. After insertion, the new pipeline will be pressurized and/or heat to shape it closely fit to the existing pipe (Syachrani et al. 2010). Figure 17 shows a pipeline renovation executed by close fit sliplining technique. It is possible to notice from the schematic the difference in diameters between the new pipeline and the existing pipeline during installation.

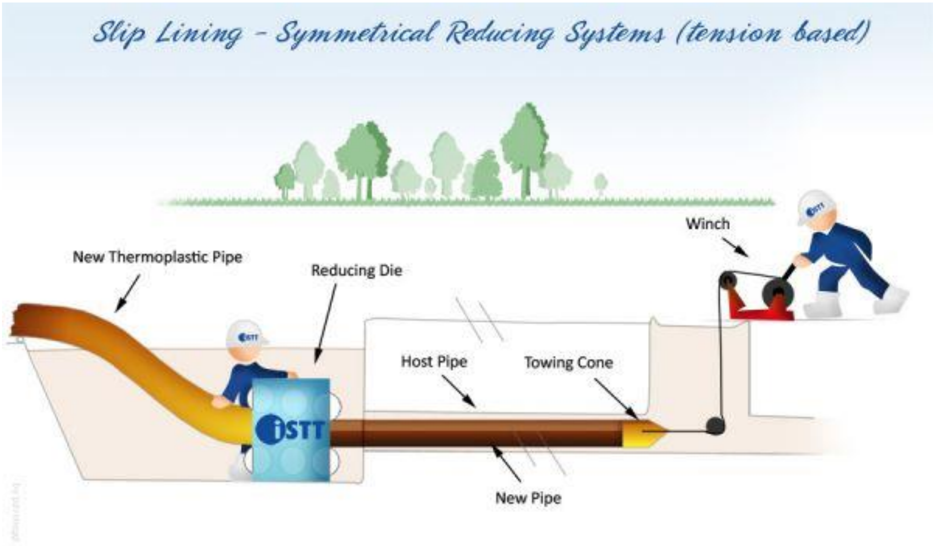


Figure 19: Execution of close fit slipling (ISTT, 2016).

- ***Spiral wound line***

The spiral wound line technique is more suitable for renovation of gravity pipelines (e.g. storm sewers, sanitary sewers, conduits, culverts and process pipes) and has structural function. In this method strips of PVC, steel reinforced PVC or High Density Polyethylene (HDPE) are wound to form a continuous pipe and then installed in the pipeline to be renovated. This strip is fed through a winding machine which locks the edges of the strip together to form a water tight continuous lining and advances the liner through the existing pipe. Grouting may be necessary to make the new pipe a close fit to the existing pipe and that loads will be transferred to the old pipe (Syachrani et al. 2010; ISTT, 2016). A schematic representation of spiral wound lining is shown in Figure 18.

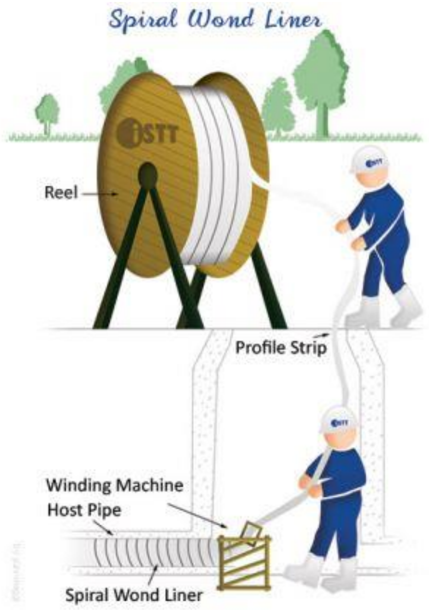


Figure 20: Pipeline renovation by spiral wound linin (ISTT, 2016)

Spray on methods

Spray on methods do not have structural function and mostly aim at protecting the pipeline from corrosion and small repairs. Their execution is done by applying cementitious or resin-based material through the existing pipe using a robotic spraying machine with a rotating head (Syachrani et al. 2010). Examples are cement mortar lining, epoxy lining and polyurethane lining (Figure 19).

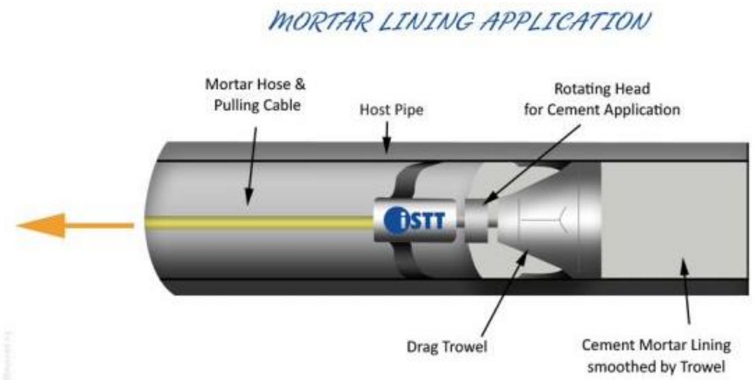


Figure 21: Pipeline renovation by spray on method: cement mortar lining (ISTT, 2016)

Cured in place method (CIPP lining)

Cured in place lining is the most used trenchless method for sewer pipelines rehabilitation in The Netherlands. CIPP has structural function and has flexible uses in sanitary sewers, storm drains and pressure pipelines for water, gas and process effluents. The technique requires prior cleaning of the existing pipelines to remove debris and detritus.

CIPP lining consists of inserting a tube made of flexible polymer or glass-fiber with thermos set resin and inflating it inside the host pipeline before curing the resin (Figure 20). The cure happens at ambient temperature, with hot water or steam circulation or using ultraviolet light. The installation uses an inversion method which employs a scaffold tower or pressure vessel to apply air or water pressure to turn the liner inside out and push it along the host pipe (Syachrani et al. 2010; ISTT, 2016).

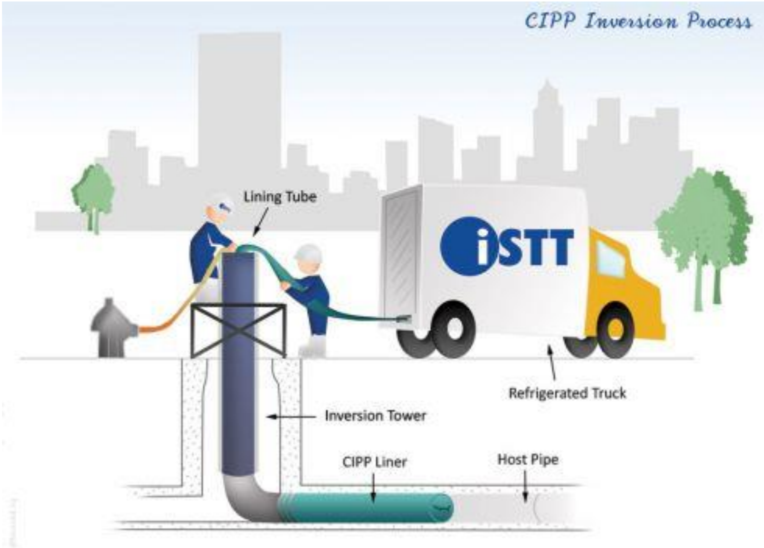


Figure 22: Pipeline renovation by CIPP lining (ISTT, 2016)

Appendix B: Air pollution detailed valuation

Air pollution can be generated by the following sources of pollutant during a construction project:

- Vehicles extra fuel consumption due to detours and stop and go situations;
- Equipment/machinery used in the construction zone during the project;
- Transport of materials to and from the site.

The total emitted volume of pollutant is the sum of the emissions of each source during the whole project duration.

$$V = V_F + V_D + V_M + V_T \quad \text{Eq. 24}$$

Where:
V_F = Volume of pollutant due to vehicles extra fuel consumption
V_D= Volume of pollutant due to extra travel distance
V_M = Volume of pollutant due to equipment/machinery
V_T= Volume of pollutant due to transport of materials to and from the site

The following items present the equations, key figures and assumptions to quantify the volumes of pollutant emitted from different sources during a construction project

i. Vehicles extra fuel consumption due to stop and go situations and detours

Tighe et al. (1999) proposed three typical traffic control plans that can be implemented on two lane highways and will be used as possible scenarios for traffic intervention (Figure 21).

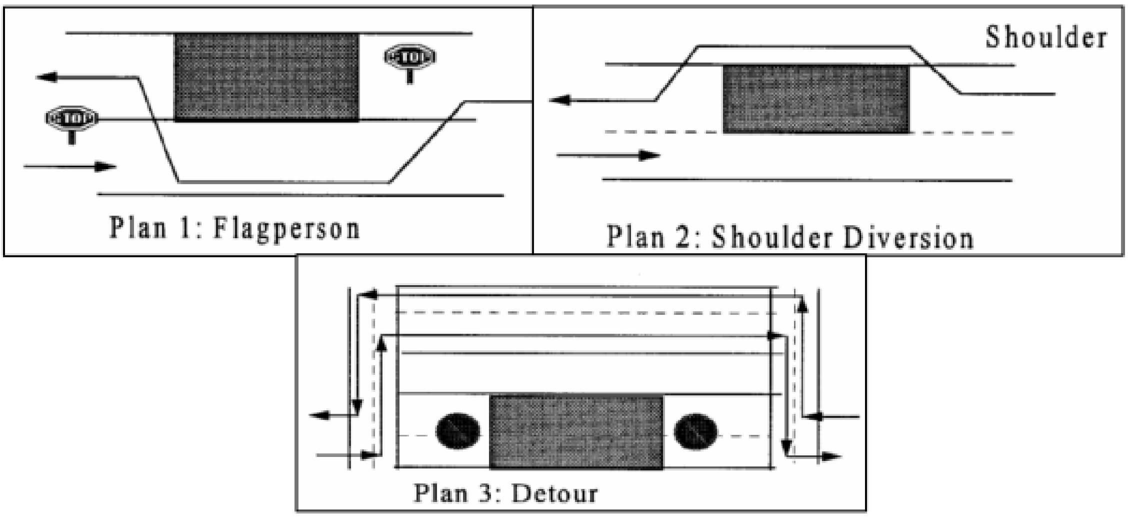


Figure 23: Traffic control plans (Tighe et al, 1999)

Each of the control plans will result in different fuel consumptions and consequently in different volumes of pollutant emissions. In Plan 1, one lane is blocked and traffic of both ways has to be deviated to one of the lanes with help of a flag person. In Plan 2, a lane is blocked but the shoulder width is enough to allow traffic to flow through it. Consequently, traffic can flow on both ways, but with limited speed on the shoulder of lane that is blocked. In Plan 3, both lanes are blocked and traffic has to be detoured through a nearby road. Plan 3 could be used when a pipeline has to be constructed across the road width (Rehan and Knight, 2007).

A relation between fuel consumption and speed is given by Davis and Diegel (2007, cited by Rehan and Knight, 2007). In Equation 25, the speed is measured in kilometre per hour, while the fuel consumption is given in gallons of gasoline per kilometre (1 US gallon ≈ 3,78 liters). Once the fuel consumption (in gallons of gasoline) is known, it can be translated into a volume of CO_2 emission per vehicle (in tons) (EPA, 2005 cited by Rehan and Knight, 2007).

$$\text{Fuel consumption} = (3 \times 10^{-6} \times \text{speed}^2 - 0{,}0004 \times \text{speed} + 0{,}0319) \qquad \text{Eq. 25}$$

$$\text{Volume of } CO_2 \text{ emission} = 0{,}0088 \times \text{fuel consumption} \qquad \text{Eq. 26}$$

The fuel consumptions for the three traffic control plans use Equation 25 and are described as follows (Rehan and Knight, 2007):

- In traffic control Plan 1, the total fuel consumption is given by the sum of fuel consumed due to change in vehicle speed and idling time. The fuel consumption due to change in vehicle speed is given by the difference in the fuel consumed in normal speed situation and the fuel consumed in the controlled traffic situation throughout the construction zone. Rehan and Knight (2007) also proposed that an idling vehicle would consume half gallon (1,9 liter) of gasoline per hour.
- In control Plan 2, there is no idle time and the extra fuel consumption due to change in vehicle speed is calculated as in traffic control Plan 1.
- In control Plan 3, the speeds of diverted traffic and traffic of the detour road have to be determined and then converted into fuel consumed. For the diverted traffic, the emissions related to the extra travel distance are also considered (Table 34). The extra travel distance has to be known beforehand.

Table 34: CO2 emissions in grams/kilometre for passenger vehicles (RAI, 2014)

Category	CO_2 emission (g/km)
Car (small)	109
Car (middle class)	133
Car (big)	169

For the equations cited above, it is very important to consider the number of vehicles crossing the work zone per day (NVD) and the project duration in order to valuate the total Air pollution costs.

ii. Equipment/machinery used in the construction zone during the project;

There are different construction machinery and equipment involved in the execution of pipelines projects such as excavators, backhoes, loaders, and hauling trucks, etc. According to Rehan and Knight (2007), the CO_2 emissions due to construction equipment depends on information about the operation duration and fuel consumption.

The authors used a general conservative fuel consumption of 2,4 gallons (approximately 9 liters) of diesel per hour. For converting fuel consumption into CO_2 emissions, they used the value of 10.1 kg of CO2 for each a gallon of diesel fuel based on EPA (2005). By converting into liters, there would be an emission of approximately 2,67 kilos of CO_2 per liter of diesel. *Considering that one equipment functions 8 hours/day, it would emit approximately 0,2 tons of CO_2 per day.* This estimated value can be used when no specific figure is available related to fuel consumption of each equipment used in the project.

ii. Transport of materials to and from construction site

In some cases it might be necessary to transport material to and from the construction site, which will contribute to pollutant emissions. For instance, if open trench excavation is executed in contaminated soils, this cannot be used as a backfill and will have to be discharged for treatment. It is responsibility of the contractors to transport the soil, while its treatment would be responsibility of (the municipality).

Trenchless technologies involve minimal or no excavation, thus emissions due to transport of material to the dump site will not be considered for trenchless. However as explained above, this travel might be needed in open trench projects depending on the situation and if it is known beforehand that transport of material will be necessary. For means of simplification, the travel of equipment/machinery to the construction site will be considered equal to both trenchless and open trench projects and will not contribute to CO_2 emissions.

The volume of CO_2 emissions can be estimated based on the distance travelled by the vehicle and the CO_2 emission rates in grams per kilometre. The travel distance parameter has to be known by the project owner. The CO_2 emission factors can be retrieved from Table 35 for heavy duty vehicles (Ligterink, van Zyl and Heijne, 2016). If the road type is unknown, it is suggested to use the "urban normal" situation.

Table 35: The real-world CO2 emission factors for 2015-2030 (Ligterink, van Zyl and Heijne, 2016)

CO_2 [g/km]	**Jaar**	**2015**	**2020**	**2030**
Road type	**Vehicle classe**			
urban congestion	Light-duty	350	313	275
	Busses	1013	998	989
	Medium duty [10-20 ton]	1138	1128	1097
	Heavy duty	2356	2441	2440
urban normal	Light-duty	232	212	189
	Busses	1013	998	989
	Medium duty [10-20 ton]	783	728	690
	Heavy duty	1542	1540	1527
urban free flow	Light-duty	223	201	179
	Busses	1013	998	989
	Medium duty [10-20 ton]	611	535	493
	Heavy duty	1149	1105	1086
Rural	Light-duty	142	137	127
	Busses	664	624	602
	Medium duty [10-20 ton]	520	507	504
	Heavy duty	994	1028	1038
Motorway average	Light-duty	183	168	156
	Busses	563	508	478
	Medium duty [10-20 ton]	451	431	420
	Heavy duty	768	787	792

Appendix C: Noise pollution parameters

The noise intensity due to different sources together is given by Equation 27. The noise emission levels due to construction equipment in dBA for different source distances are presented in app 36.

$$L = 10\ \mathrm{Log}_{10}\left(\sum_{i=1}^{n} 10^{Li/10}\right) \qquad \text{Eq. 27}$$

Where:

Li = noise intensity of equipment i

Table 36: Maximum equivalent noise levels associated with construction equipment (Gillchrist and Allouche, 2005)

Maximum equivalent noise level, L_{eq} (dBA)						
	15m	**30m**	**45m**	**60m**	**90m**	**120m**
Equipment						
Backhoe	85	79	75	72	68	65
Compactor	82	71	67	64	61	57
Concrete mixer	85	69	65	62	59	56
Concrete vibrator	78	54	51	49	47	44
Dozer	85	78	76	71	67	64
Excavator	83	77	73	70	66	63
Jack hammer	88	79	74	72	69	65
Roller	86	70	66	64	61	58
Activities						
Handling formwork	90	52	50	48	46	44
Truck discharge	90	46	44	42	41	39

Appendix D: Business revenue loss key figures

Detail Handel (2017) provides current facts and figures about the retail sector and the underlying sectors in The Netherlands. Their data were used by Alkema (2015) to provide an estimate of revenues in food and non-food businesses and as an input for quantifying business revenue loss due to pipelines projects. Because it is hard to estimate revenue loss before the project taking place, the same approach is proposed in this research. Tables 37 and 38 present average values of yearly business revenue per store or per square meter.

Table 37: Revenue key figures for food business (Detail Handel, 2017)

Food								
Period	**2014**		**2015**		**2016**		**2017***	
Unit	€/year	€/day	€/year	€/day	€/year	€/day	€/year	**€/day**
Revenue per store	2.396.000	6.564	2.379.000	6.518	2.395.000	6.562	2.411.000	**6.605**
Revenue per m2	11.800	32,3	11.530	31,6	11.360	31,1	11.190	**30,7**

** Interpolated value for year 2017*

Table 38: Revenue key figures for non-food business (Detail Handel, 2017)

Non-Food								
Period	**2014**		**2015**		**2016**		**2017***	
Unit	€/year	€/day	€/year	€/day	€/year	€/day	€/year	**€/day**
Revenue per store	604.000	1.655	625.000	1.712	642.000	1.759	659.000	**1.805**
Revenue per m2	2.033	5,6	2.063	5,7	2.117	5,8	2.171	**5,9**

** Interpolated value for year 2017*

Using the Tables 37 and 38 it is possible to estimate revenue based on (a) the revenue per store if the type and number of affected businesses is known, or based on (b) the revenue per square meter if the type and area of the affected businesses is known. For instance, Google Maps can be used to identify the area and types of business in a certain location.

Anco (2014 cited by Alkema, 2015) has estimated a 30% reduction in revenue loss due to construction activities. Even though this value will not lead to accurate results, the use of data from previous similar projects from a certain company can help achieving a more customized percentage of revenue loss reduction.

In 2010, NSTT (2010) has conducted a research about the nuisance caused by excavation works in public spaces and its impacts on human behaviour and economy in the Netherlands. As part of their research, a survey was conducted among 1056 inhabitants/costumers and 546 retailers/shops. The conclusion was that 72% of the interviewed retailers has experienced nuisance in the past five years due to excavation activities. From those, 19% had frequent or regular nuisance; 54% experienced nuisance sometimes; and 27% never. The interviews revealed that accessibility issues impact business revenues: 91% of businesses think that costumers avoid frequenting shops that are difficult to access and 72% think that there is a *revenue loss of 10%.*

According to NSTT (2010), there is a drop in revenue of *40 to 50%* due to excavation activities because of all the negative effects cited above. The survey also concluded that few retailers take action about the situation due to unfamiliarity with claims procedure. In the Netherlands, a request for financial compensation due to temporary construction works has to be conducted within the municipality and the application procedure costs 300 euros for the applicant. Besides, different factors are examined during the process to prove that the business loss is indeed due to the construction works (Amsterdam, 2015).

Rijkswaterstaat has established eligibility criteria for businesses that are entitled to compensation for revenue loss due to temporary infrastructure works. In order to be entitled to compensation, businesses have to prove a revenue loss higher than 15% of the standard annual revenue or the standard cost per year. This threshold can be different for each governmental body and most municipalities do not have a specific compensation standard value. The municipalities of Amsterdam, Groningen, Vaals, Rotterdam (minus a discount of 25%) and Eindhoven adopted a lower value of 8% over which business losses can be compensated. The municipalities of Amersfoort, Breda, The Hague and Utrecht use the same threshold as RWS (Nadeelcompensatie, 2017).

Appendix E: Survey questionnaire

- **Part 1**

First of all, thank you for participating in my survey. Your feedback is very important!
This survey relates to my Master Thesis project: Development of a decision making model for the social costs of pipelines renovation projects. This is a project between Deltares, University of Twente and NSTT.

<u>Questions</u>
In this survey part 1, you will be asked to help developing 5-point scales for qualitatively assess risks of accidents and damage in pipelines projects. More specifically, the risks of accidents involve workers and users (pedestrians, cyclists, vehicles, etc.) and the risks of damage involve damage to property/infrastructure, existing buried pipelines and environment (vegetation). Therefore, you will help translating the 5-point scales into actual figures or numbers based on previous experience for each of the 10 factors affecting risks listed below. Some examples for the scales are proposed but you are free to suggest any other figures or indicators for representing the 5-point scale numbers.

<u>My research</u>
My research aims at quantifying in monetary units the social costs related to pipelines renovation projects. The social costs comparison is made between open trench and trenchless renovation projects. Besides, I try to assess risks of accidents and damages related to these projects. For doing so, I need to define which factors affect the risks related to pipelines renovation projects and open trench excavation and to define scales for "measuring" these risks. My research scope is mainly related to gravity pipes such as sewage.
First of all, I divided risks related to pipelines projects into (1) risks of accidents involving workers; (2) risks of accidents involving users - pedestrians, drivers, cyclists; (3) risks of damage to property/infrastructure; (4) risk of damage to buried pipelines; and (5) risks of damage to environment - vegetation.
The second step was to define which factors affect/influence the probability of risks of accidents and damage in general. Therefore,10 factors are proposed: project duration; amount of machines on site; excavation volume; size of work zone; transportation of material (offsite); area density (developments above ground); traffic density; pedestrian flow (incl. cyclists); density of buried pipelines underground; and naturalness of area.
I proposed a 5-point scale for each of these factors, where number in 1 the scale represents the best performance (situation that would contribute to risks the least); and number 5 represents the worst performance (situation that contributes to risks the most).

If needed, comments can be sent to my email at camila.nunesvasconcelos@deltares.nl

1. Please fill in the the number of days that corresponds to each of the values in the 5-point scale for the factor *Project duration (e.g. use below/above/between N days)*. For instance, you may suggest that "1-very short" project duration is less than X days, a "5- very long" project duration is higher than Y days and so on.

1 - very short	
2 - short	
3 - medium	
4- long	
5- very long	

2. Please fill in the number of machines that corresponds to each of the values in the 5-point scale for the factor *Amount of machines on site*. For instance, you may suggest that "1-very low" amount of machines on site is less than X machines; a "2- low" amount of machines is between X and Z machines and so on.

1 - very low	
2 - low	
3 - medium	
4- high	
5- very high	

3. Please fill in the excavation volumes that corresponds to each of the values in the 5-point scale for the factor *Excavation volume*. For instance, you may suggest that "1-very low" excavation volume is less than X m3; a "2- low" volume is between X and Z m3 and so on.

1 - very low	
2 - low	
3 - medium	
4- high	
5- very high	

4. Please fill in the size of work zone that corresponds to each of the values in the 5-point scale for the factor *Size of work zone (e.g. m2)*. For instance, you may suggest that a "1-very small" work zone would have less than X m2; a "2- small" work zone would have between X and Z m2 and so on.

1 - very small	
2 - small	
3 - medium	
4- large	
5- very large	

5. Please fill in the transportation of material offsite that corresponds to each of the values in the 5-point scale for the factor *Transportation of material offsite*. For instance, you may suggest that "1-very low" transportation would be less than X m3 of material; a "2- low" transportation is between X and Z m3 of material and so on.

1 - very low	
2 - low	
3 - medium	
4- high	
5- very high	

6. Please fill in the developments above ground that corresponds to each of the values in the 5-point scale for the factor *Area density (e.g. residential area, scenic area, large business area. etc)*. For instance, you may suggest that "1-very low density" would correspond to less than X houses/km2 or to a countryside area; a "2- low density area" would have between X and Z houses per km2 and so on.

1 - very low density	
2 - low density	
3 - medium density	
4- high density	
5- very high density	

7. Please fill in the traffic density that corresponds to each of the values in the 5-point scale for the factor *Traffic density (e.g. ><= N vehicles/day)*. For instance, you may suggest that "1-very low density" would correspond to less than X vehicles/day; a "2- low density" traffic would be between X and Z vehicles/day and so on.

1 - very low density	
2 - low density	
3 - medium density	
4- high density	
5- very high density	

8. Please fill in the pedestrian and cyclist flow that corresponds to each of the values in the 5-point scale for the factor *Pedestrian flow(e.g. ><= N pedestrians-cyclists/day)*. For instance, you may suggest that "1-very low density" would correspond to less than X pedestrians/day; a "2- low density" pedestrian flow would be between X and Z pedestrians/day and so on.

1 - very low flow	
2 - low flow	
3 - medium flow	
4- high flow	
5- very high flow	

9. Please fill in the density of buried pipelines that corresponds to each of the values in the 5-point scale for the factor *Density of buried pipelines in the subsoil (e.g. meters of pipeline/m2; volume pipeline/m2)*. For instance, you may suggest that "1-very low density" would correspond to less than X meters of pipeline/m2; a "2- low density" pipelines density would be between X and Z meters of pipeline/m2 and so on.

1 - very low density	
2 - low density	
3 - medium density	
4- high density	
5- very high density	

10. Please fill in the naturalness of the area that you think corresponds to each of the values in the 5-point scale for the factor *Naturalness of area (e.g. n of buildings/ per km2; N of trees per km2; area of asphalt/km2; etc.)*. For instance, you may suggest that "1-very urbanized area" would correspond to less than X trees/m2; a "5- very natural area" would have more that X trees/m2 and so on.

1 - very urbanized area	
2 -	
3 - medium urbanized area	
4-	
5- very natural area	

- **Part 2**

First of all, thank you for participating in my survey. Your feedback is very important!
This survey relates to my Master Thesis project: Development of a decision making model for the social costs of pipelines renovation projects. This is a project between Deltares, University of Twente and NSTT.

Questions
In this survey part 2, you will be asked to give your opinion about the factors that affect/impact risks of accidents and damage in open trench and trenchless (renovation) pipelines projects. The questions then ask you to correlate each risk type with the factors that influence/affects/impacts the probability of that risk to happen. For instance, when assessing risks of accidents to workers, you might reflect if e.g. pedestrian flow would have any influence on the probability of accidents involving workers happen, and so on.

My research
My research aims at quantifying in monetary units the social costs related to pipelines renovation projects. The social costs comparison is made between open trench and trenchless renovation projects. Besides, I try to assess risks of accidents and damages related to these projects. For doing so, I need to define which factors affect the risks related to pipelines renovation projects and open trench excavation and to define scales for "measuring" these risks. My research scope is mainly related to gravity pipes such as sewage.
First of all, I divided risks related to pipelines projects into (1) risks of accidents involving workers; (2) risks of accidents involving users - pedestrians, drivers, cyclists; (3) risks of damage to property/infrastructure; (4) risk of damage to buried pipelines; and (5) risks of damage to environment - vegetation.
The second step was to define which factors affect/influence the probability of risks of accidents and damage in general. Therefore,10 factors are proposed: project duration; amount of machines on site; excavation volume; size of work zone; transportation of material (offsite); area density (developments above ground); traffic density; pedestrian flow (incl. cyclists); density of buried pipelines underground; and naturalness of area.
I proposed a 5-point scale for each of these factors, where number in 1 the scale represents the best performance (situation that would contribute to risks the least); and number 5 represents the worst performance (situation that contributes to risks the most).
Based on the research background you are asked to answer the questions presented next.
If needed, comments can be done in the comment button in the end of this survey or sent to my email at camila.nunesvasconcelos@deltares.nl

1. Which factors affect **risks of accidents involving workers**? Here, you are asked to predict which from the factors below have an influence/impact on the probability of accidents involving workers. In other words, if the factor varies from e.g. from low to high, would it contribute to increasing/decreasing the risks of accidents with workers?

you can select more than one answer

- [ ] Project duration
- [ ] Amount of machines on site
- [ ] Excavation volume
- [ ] Size of work zone
- [ ] Transportation of material (offsite)
- [ ] Area density (developments above ground
- [ ] Traffic density
- [ ] Pedestrian flow (Incl. bikes)
- [ ] Density of buried pipelines
- [ ] Naturalness of the area
- [ ] Other (please specify)

2. Which factors affect **risks of accidents involving users (vehicles, pedestrians, cyclists, etc)**? Here, you are asked to predict which from the factors below have an influence/impact on the probability of accidents involving users. In other words, if a factor varies from e.g. from low to high, would it contribute to increasing/decreasing the risks of accidents with users?

you can select more than one answer

- [ ] Project duration
- [ ] Amount of machines on site
- [ ] Excavation volume
- [ ] Size of work zone
- [ ] Transportation of material (offsite)
- [ ] Area density (developments above ground
- [ ] Traffic density
- [ ] Pedestrian flow (Incl. bikes)
- [ ] Density of buried pipelines
- [ ] Naturalness of the area
- [ ] Other (please specify)

3. Which factors affect **risks of damage to property/infrastructure?** Here, you are asked to predict which from the factors below have an influence/impact on the probability of damage to property/infrastructure. In other words, if a factor varies from e.g. from low to high, would it contribute to increasing/decreasing the risks of damage to property/infrastructure?

you can select more than one answer

- [ ] Project duration
- [ ] Amount of machines on site
- [ ] Excavation volume
- [ ] Size of work zone
- [ ] Transportation of material (offsite)
- [ ] Area density (developments above ground
- [ ] Traffic density
- [ ] Pedestrian flow (Incl. bikes)
- [ ] Density of buried pipelines
- [ ] Naturalness of the area
- [ ] Other (please specify)

4. Which factors affect **risks of damage buried pipelines utilities?** Here, you are asked to predict which from the factors below have an influence/impact on the probability of damage to buried pipelines. In other words, if a factor varies from e.g. from low to high, would it contribute to increasing/decreasing the risks of damage to buried pipelines?

you can select more than one answer

- [ ] Project duration
- [ ] Amount of machines on site
- [ ] Excavation volume
- [ ] Size of work zone
- [ ] Transportation of material (offsite)
- [ ] Area density (developments above ground
- [ ] Traffic density
- [ ] Pedestrian flow (Incl. bikes)
- [ ] Density of buried pipelines
- [ ] Naturalness of the area
- [ ] Other (please specify)

5. Which factors affect **risks of damage to the environment (trees, vegetation)**? Here, you are asked to predict which from the factors below have an influence/impact on the probability of damage to the environment (vegetation). In other words, if a factor varies from e.g. from low to high, would it contribute to increasing/decreasing the risks of damage to vegetation?

you can select more than one answer

- [ ] Project duration
- [ ] Amount of machines on site
- [ ] Excavation volume
- [ ] Size of work zone
- [ ] Transportation of material (offsite)
- [ ] Area density (developments above ground
- [ ] Traffic density
- [ ] Pedestrian flow (Incl. bikes)
- [ ] Density of buried pipelines
- [ ] Naturalness of the area
- [ ] Other (please specify)

6. Please indicate whether you would like to be informed about the outcome of the surveys.

- ◯ Yes, I would like to.
- ◯ No, thank you.

7. Please indicate whether you would like to receive the final master thesis report.

- ◯ Yes, I would like to.
- ◯ No, thank you.

8. Please leave your contact information. **Not mandatory**

Name	
Company	
Email Address	

9. You can leave your comments here.

Appendix F: Interview responses compilation

1. **Can you mention social costs/impacts related to TT renovation projects?**
2. **How do TT pipelines renovation projects affect traffic? (e.g. lane closure, traffic delays, detours)? What have you noticed in practice?**
3. **How do TT pipelines renovation projects affect pavement service life? What have you noticed in practice? (heave, subsidence, frac-out, and collision with underground obstacles)**

There are not many specific social costs and impacts exclusively related to trenchless renovation technologies. One interviewee mentioned the smell of the pipeline material used in a certain renovation technique could bother the people nearby.

The advantages of trenchless mentioned are related to:

- Shorter project durations and consequently less duration of nuisance to the population and environment. This implies in better acceptance of the residents as well.
- Even though trenchless may also interfere on traffic with detours or blocking streets, the impact on traffic is less compared to open trench due to shorter project durations.
- Residents of a street will be less hindered if a trenchless project takes place in their street because some accessibility may be guaranteed. If open trench is used, it might be necessary to use planks to guarantee their access home and mainly disabled and elderly people will be affected.
- Renovation does not affect pavement service life because it requires minimal or no excavation. The damage would be limited to the small portion of pavement that has been excavated.
- In most cases, the equipment used in open trench is heavier than that used in trenchless renovation which can contribute to pavement damage.
- Equipment used in open trench may cause vibrations that might be felt by residents especially in peat soil. Vibrations can be associated with damage and complaints from the population.
- Service unavailability is shorter with trenchless than open trench projects.

4. **Which social costs from the table do you consider in your OT and TT projects? Please add other social costs that you think relevant.**

The conclusion is that social costs are not quantified even though the interviewees are aware that they are existent. Interviewees agreed with the social costs presented, except for the loss of property value. The short project durations do not influence the property values and they mentioned that a positive effect of the project might be noticed in the end since the utilities or even the pavement will be new. The social costs that were not mentioned in the table are related to smell (trenchless renovation material) and pollutant emissions due to transport of exceeding soil or dust usually produced in open trench excavation.

In order to reduce social costs and impacts, they mentioned that combining works with other companies is the ideal situation. In this case, open trench would be used and different utility companies would perform their work and share the costs related to pavement restoration and traffic control. Another ideal situation is to conduct open trench when the pavement is already in the end of its life cycle and has to be replaced anyway. The companies can use this opportunity to reduce their project costs and the population will have impacts only at once.

5. **Are social costs passed to the contractor/client? Do they usually have to compensate for damages/nuisance? Is there a project budget for these unforeseen damages (% of direct costs)? What kind of damage is compensated?**

The companies usually do not compensate the population for the negative impacts of their projects. They have mentioned that it is impossible to conduct works without nuisance so social costs will always be present and the society has to deal with it. The most important point is to communicate well with the affected stakeholders so they will know beforehand about the negative effects of a project.

The cases where they have to compensate is when the project caused damage and when they block parking spaces that a resident had paid for it before. In this case they have to find a solution or compensate the affected party. The compensation of business loss compensation is not common to happen.

To protect themselves against complaints, before the project starts the companies have to write a report with the actual situation of the infrastructure in the project zone such as houses and buildings. They can make use of equipment to measure deformations or photos registering. In case a complaint is place in the future, they should be able to distinguish if the damage was caused by the project or if it was an existing problem.

Social costs risks

6. **Which risks do you consider in pipelines (renovation) projects executed by OT and TT? Do you quantify them? Do you know the costs, probability and severity related to these risks?**

The approach regarding the risk-related social costs such as accidents and damage is that they always manage risks in all cases by doing risk management. A project may not start if these risks are present, or will only start after these risks are not existent or managed. Damage or accidents are not common to happen but it is not possible to assure that they will not happen with 100% certainty.

The interviewees mentioned that trenchless technologies are new compared to open trench, which requires more safety measures in place. Another point is that with trenchless it is not possible to see what is happening underground which becomes an extra challenge for workers and increases risks. Open trench methods are well-known so even though there are also risks involved (e. g. related to trench stability), the safety measures are present to guarantee work safety. The same applies to trenchless projects, but in this case more safety measures might be necessary.

Risks are considered in both trenchless and open trench projects but none of them is risk free for the infrastructure, workers and society.

Some interviewees mentioned a relationship between risks and project duration. The longer the project takes, the more will be the risk of damage and accidents. Looking into this perspective, open trench projects will result in higher risks of accidents and damage because they are longer than open trenchless projects. A summary of the risk comparison between open trench and trenchless renovation projects is presented in the below.

Social costs (risks)	Cost, Probability, Severity	
	Open trench	**Trenchless Technologies-renovation**
Accidental injury or death (workers)	Open trench has more workers and uses more machinery. The probability of accidents involving workers is higher because projects are longer and workspace is limited (complete trench)	Trenchless uses less machinery (4 to 5 times less) and the workspace is limited to the manhole. Project durations are much shorter; consequently the probability of accidents is lower.
Increase in traffic accidents (users)	Open trench involves less risk of traffic accidents because the road where the project takes place is blocked and no traffic is allowed in the area. Road is blocked at the beginning and end of the road. There is no traffic. OT is only	Trenchless projects allow traffic flow on the road where the project will take place because the equipment used is placed around the manholes. Trenchless involve at least 2 workspaces (2 manholes) and around that area there

	one work space with barriers	will be flow of pedestrians, vehicles and bicycles which increases the chances of accidents.
Damage to facilities/ infrastructure/property	Transportation of material and heavy loads can cause damage not only on the work zone but also on the trajectory to the work zone. Vibrations due to equipment (e.g. sheet piling for soil stability) can also cause damage to foundations and sensitive structures.	Trenchless uses less equipment. For smaller pipelines diameters, only one truck with the pipeline and a crane is used. For bigger diameters a truck with the liner and a crane to put the liner in the old pipeline is necessary. The need of less machinery means less damage.
Damage to underground infrastructure	Risk is higher since one has to dig and this involves risks of touching a pipeline.	There are no risks to underground infrastructures with renovation techniques because the relining takes place inside the old pipe.

Data availability

7. **Are the project direct costs usually available in the early stages when a choice has to be made between trenchless and open trench (budget estimation)?**

In the decision making phase, companies can estimate the direct costs of a trenchless technique and open trench, besides having an idea of the project durations and the surroundings buildings.

8. **How faster is a project executed by TT compared to OT? Can you provide productivity rates for OT and TT renovation projects? (e.g. m3/h; m/h of renewed/renovated pipe)?**

The comments about the speed of project execution through trenchless technologies and open trench vary per company. This is probably due to the fact that they have different areas of expertise and have projects in several regions in the country.

Liander: From previous projects they estimate that trenchless projects are 40% faster than open trench

Den Haag: It is possible to execute long extensions of pipeline renovation using trenchless methods. For instance, in 1 or 2 days 500 meters can be placed. Open trench are more dependent on soil conditions, water level or depth so this will influence the work speed which is estimated in 5 to 10 meter of pipeline per day.

Waternet: Trenchless projects speeds are dependent on the limits of the machinery used and the pipeline section involved. The speed is function of the method used and the pre-works preparation. The length covered per day does not change much if a project is executed in the open field or in the inner city. Open trench projects speed are led by the speed of the excavator and are more dependent on the project location. In the countryside where less barrier exist, it is possible to achieve 300 meters of executed pipeline per day if the conditions are favourable (e. g no need of supporting walls). If the same project is executed in the inner city, it would take 6 times more and a benchmark of 50 meters/day is expected.

9. **Can you give an average direct cost per unit (euros/m3 or euro/m) of pipelines renovation projects executed by OT and TT?**

Check Appendix I.

10. **Do you know the average fuel consumption (or CO2/pollutant emission) of vehicle/equipment used for OT and TT renovation projects? Is there an average number of vehicles/equipment used (e. g. N equipment per m3 of open trench; N equipment per m of renovated pipeline TT)?**

Open trench requires a minimum of 1 crane, 1 shellfoll and 2 to 4 trucks to transport soil depending on the distance of transportation and their activities happen in parallel. Besides, pumping might be necessary if the groundwater level is high. (Ane Jutte)

Trenchless renovation projects requires one trucks for cleaning the old pipeline, installing the liner, open the connections and inspect the work afterwards. Even though different vehicles are used for each activity, it can be assumed that they work in sequence and only one vehicle will be present on site at time. This implies that the noise generated due to trenchless renovation comes from one source only (Antoine Steentjes).

Most of the time only one truck to transport and install the liner is needed and no transport to dump site is necessary. For bigger diameters, one truck a one crane working in parallel might be necessary. (Ane Jutte)

11. Is the noise intensity generated by TT and OT equipment similar?

It is suggested to consider that the level is proportional to the number of equipment used during the project. There is a limit of 85 dBA within one meter of the building on the daytime. (Kragten)

Open trench requires a minimum of 1 crane, 1 shellfoll and 2 to 4 trucks to transport soil depending on the distance of transportation and their activities happen in parallel. Besides, pumping might be necessary if the groundwater level is high. (Ane Jutte)

Trenchless renovation projects requires one trucks for cleaning the old pipeline, installing the liner, open the connections and inspect the work afterwards. Even though different vehicles are used for each activity, it can be assumed that they work in sequence and only one vehicle will be present on site at time. This implies that the noise generated due to trenchless renovation comes from one source only (Antoine Steentjes).

Most of the time only one truck to transport and install the liner is needed and no transport to dump site is necessary. For bigger diameters, one truck a one crane working in parallel might be necessary. (Ane Jutte)

12. Can you provide approximate values of lifetime expectancy of new installed pipeline executed by OT excavation and renovated pipeline using TT? Or can you give a ratio of the lifetime expectancy between a new installed pipeline and a renovated pipeline?

The lifetime expectancy of a trenchless or open trench project is not dependent on the execution technique but on the pipeline material. The lifetime of pipelines are dependent on different factors such as the presence and composition of groundwater, pipeline material, depth, load, fluid composition etc. In the case of trenchless technologies, the hardening or the line is very important to guarantee its quality over the years. The following estimations were given regarding lifetime expectancy:

- Cast iron: 100 years (Liander)
- Concrete pipes: 80-100 years (Den Haag)
- Renovation techniques: 50 years (Den Haag)
- PE piping: 100 years (Liander).
- Most of open trench projects use PP, concrete and GVC glass (??)
- CIPP designed for 50 years (Kragten)
- Traditional methods designed for 70 years (Kragten)
- In reality the CIPP last longer so the 50 years predicted are going to be 70 in the end (Kragten)

It can be concluded that social costs related to open trench and trenchless renovation projects can be compared over its life cycle considering the frequency of intervention. For instance, if both pipeline materials have the same lifetime expectancy, the next intervention should happen at the same time and the social costs would happen only once considering a lifetime period.

13. **Before deciding between OT and TT, do you know what will the impact of the project on traffic be? Do you have this information based on previous projects? (e.g. the street will be closed and there will be a detour of X meters, causing traffic delays of X minutes).**

The traffic management is usually dealt by the municipality once the project owner has paid some costs. For instance, in Amsterdam these costs are included in the BLVC (bereikbaarheid, leefbaarheid en veiligheid).

14. **Do you estimate business losses due to open trench or trenchless projects? How? Do you use any rule of thumb for percentage of business losses (e.g. due to road closure, you expect a business loss of 10% per day)?**

They do not estimate this social cost.

Choice between open trench and trenchless technologies

15. **How is the choice made between open trench and trenchless technologies? What is taken into account during the decision making? (Costs, technical feasibility, contractor expertise, location….?)**

The choice between open trench and trenchless technologies is based on factors such as technical feasibility, (direct/indirect) costs and social impacts. Regarding social impacts, companies look into aspects like project location (e. g. business area, residential, old city centers), traffic disturbances and presence of trees in the area. Projects in old cities with expensive pavement restoration costs give advantages to using trenchless and reduce this cost. An interviewee mentioned that they are working on an economic model to identify which technology to choose for each project based on the different aspects as cited above.

The lifetime of the pipeline is also an important factor when selecting the technologies. For instance, if two methods have comparable benefits but the lifetimes are too different, then the highest lifetime might have advantage of the lowest one.

The condition and remaining lifetime of the pavement and the infrastructure above ground are also considered when a choice has to be made between trenchless and open trench methods. If the conditions above ground are not good and the remaining pavement lifetime is short (has to be replaced soon), then opting for open trench is more realistic because the pavement restoration can be done only once. Both pipeline renewal and pavement restoration projects would be combined so that costs could be shared and nuisances minimized.

On the other hand, when the conditions of the above ground infrastructure and pavement are good, trenchless become an option to avoid damages to pavement and restoration costs, besides minimizing social costs. In this case, the choice between open trench and trenchless is relevant and social costs can make a difference in the method selection. (Kragten)

In the cases cited above, the choice between open trench and trenchless technologies regarding social costs is based on experience and "feeling" because social costs are not calculated or translated into monetary units. Political factors also play a role in the selection of a project over another. (Kragten)

16. **In which situations is the choice between OT and TT renovation relevant? When would social costs make a difference in choosing TT instead of OT even if the direct costs of OT are higher?**

The most common method and the most used by the companies is open trench. This is the case because open trench is the traditional method with which people are used to work. Therefore, the first condition to be fulfilled before having a choice between open trench and trenchless methods is that trenchless renovation technologies are technically feasible in the specific project. Once this condition is satisfied, one can look into social costs. For instance, the following (technical) aspects would unable the use of trenchless renovation:

- If the host pipeline is too damaged over its length
- If the capacity is fully used or if more capacity is needed in the near future

- If the grading is not enough (sewage)

A situation where the choice between open trench and trenchless is at stake is related to projects in complex environments or with big impacts in the surroundings. In this case, the choice for traditional open trench is less obvious because the project owner has to try to minimize as much as possible the negative effects of the project. Consequently, the technical feasibility, costs and more important the social costs will play a role in the decision making.

Another situation relates to the number of pipeline utilities that need rehabilitation. If different utilities need rehabilitation, then open trench might be an option to have a single intervention with different companies to share restoration costs and have a single intervention. If only one type of utility needs renovation, then trenchless becomes an option to minimize nuisance and avoid restoration costs.

When direct costs are similar for open trench and trenchless methods, social costs can make a difference in the final selection.

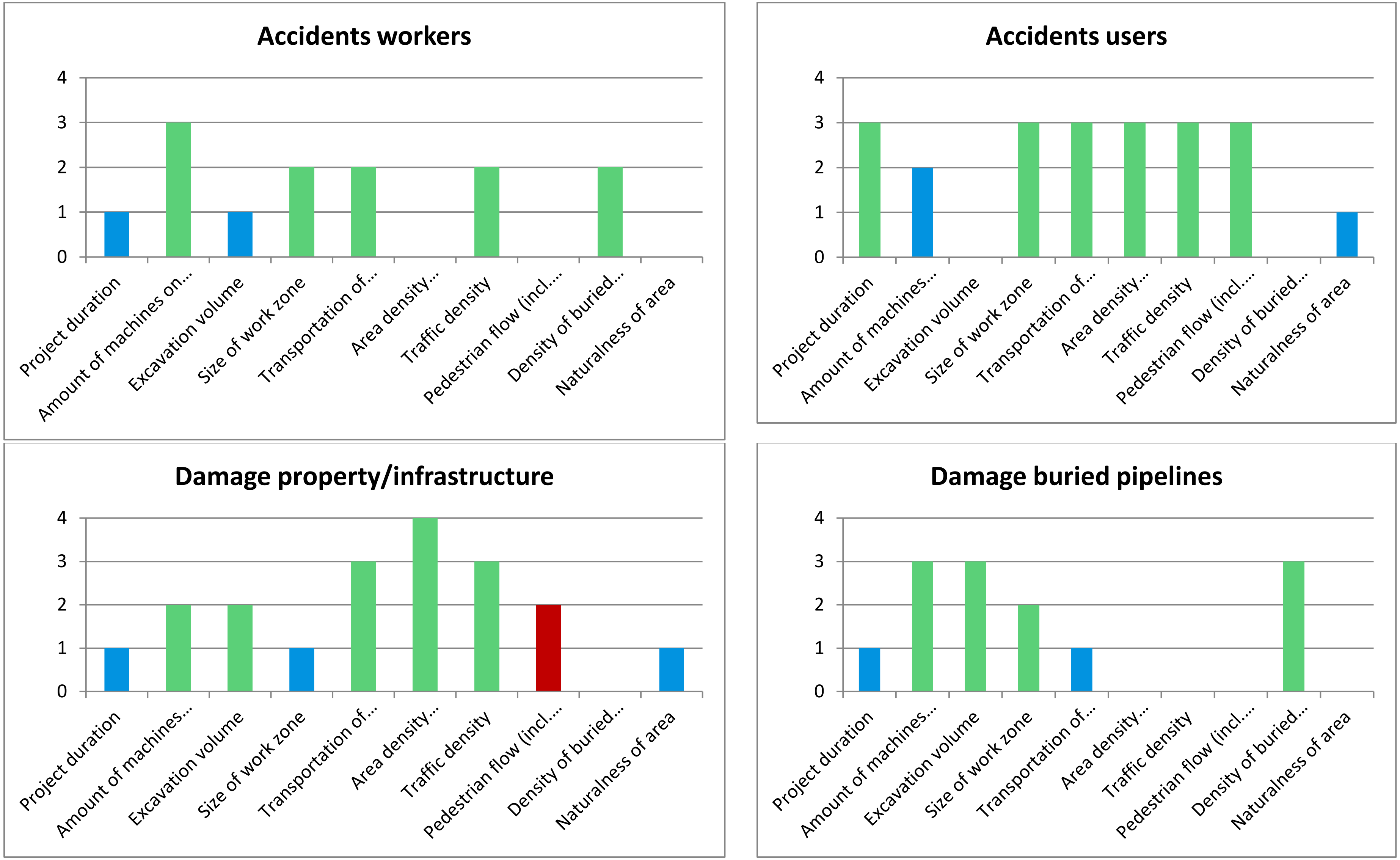
Appendix G: Survey results

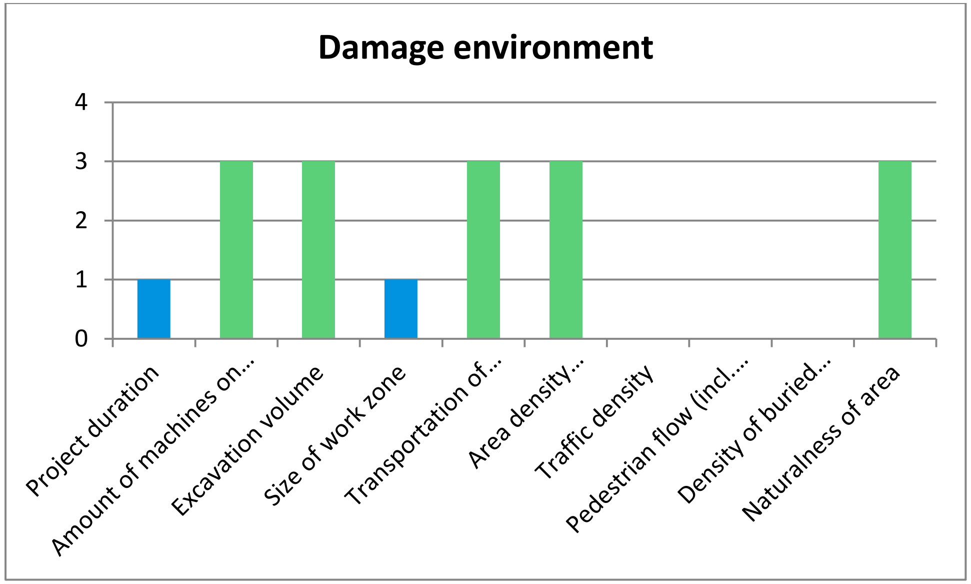
Table 39: Results of survey part 1

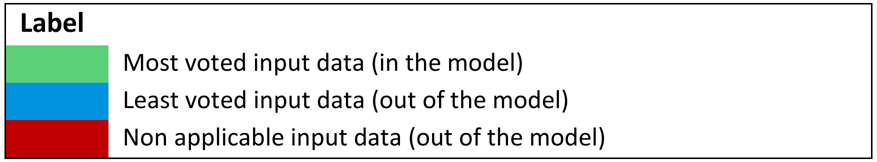
Project specific			Respondent 1	Respondent 2	Respondent 3	Respondent 4
Question	**Input data**	**Scales**	**Values**	**Values**	**Values**	**Values**
1	Project duration	1 - very short	<=1 week	10 weeks	1	2
		2 - short	1-2 weeks	23 weeks	10	5
		3 - medium	>= 2 weeks	23-52 weeks	30	10
		4- long	>= 4 weeks	1,5 years	45	15
		5- very long	>= 3 months	2+ years	60	25
2	Amount of machines on site	1 - very low	0	3	1	1
		2 - low	1	3	3	2
		3 - medium	2 to 3	3	5	3
		4- high	4	6	7	5
		5- very high	5	9	10	10
3	Excavation volume	1- very low	-	20m3	1	2
		2- low		20m3	250	10
		3- medium		40m3	1000	50
		4- high		80m3	2500	100
		5- very high		120m3	5000	200
4	Size of work zone	1- very small	-	300m2	50	5
		2- small		600m2	750	10
		3- medium		1200m2	5000	30
		4- large		2400m2	7500	60
		5- very large		3600m2	10000	100
5	Transportation of material (offsite)	1- very low	-	250m3	5	10
		2- low		500m3	500	20
		3- medium		1000m3	2000	30
		4- high		2000m3	5000	40
		5- very high		5000m3	10000	50

Location specific			Respondent 1	Respondent 2	Respondent 3	Respondent 4
Question	Input data	Scales	Values	Values	Values	Values
6	Area density (Development above ground)	1 - very low density	natural area	-	10	100
		2 - low density	low density residential area		100	2000
		3 - medium density	high density residential area, schools, shops		250	8000
		4- high density	industrial/business area, schools, shops		400	20000
		5- very high density	city center, shopping centers, skyscrapers buildings		500	40000
7	Traffic density	1 - very low density	< 1000/day	-	50	10
		2 - low density	1000-5000/day		300	100
		3 - medium density	5.000 - 15.000/day, busses and/or trams		750	300
		4- high density	15.000 - 40.000, busses and/or trams		1250	800
		5- very high density	> 40.000, busses, trams		2000	1500
8	Pedestrian flow (incl. bikes)	1- very low flow	-	-	50	10
		2- low flow			250	250
		3- medium flow			1000	1000
		4- high flow			2500	3000
		5- very high flow			5000	5000
9	Density of buried utilities in the subsoil	1 - very low density	only the pipeline under renovation	-	0	0.1
		2 - low density	only regular distribution pipelines		305	0.5
		3 - medium density	regular distribution pipelines plus warm water distribution		15	1
		4- high density	also transport (high voltage, high pressure, big diameter		25	3
		5- very high density	main pipeline corridor (e.g. in harbour area),			5
10	Naturalness of area	1- Very urbanized area	-	-	0.0001	0.005
					0.0005	0.01
		3-medium urbanized area			0.001	0.1
		4- natural area			0.002	0.5
		5- very natural area			0.05	1

Table 40: Results of survey Part 2: Number of input data votes for each risk sub criteria and chosen input data (green colour)




Damage environment
4
3
2
1
0
Project duration
Amount of machines on...
Excavation volume
Size of work zone
Transportation of...
Area density...
Traffic density
Pedestrian flow (incl....
Density of buried...
Naturalness of area


Label
Most voted input data (in the model)
Least voted input data (out of the model)
Non applicable input data (out of the model)

Appendix H: Model validation input data

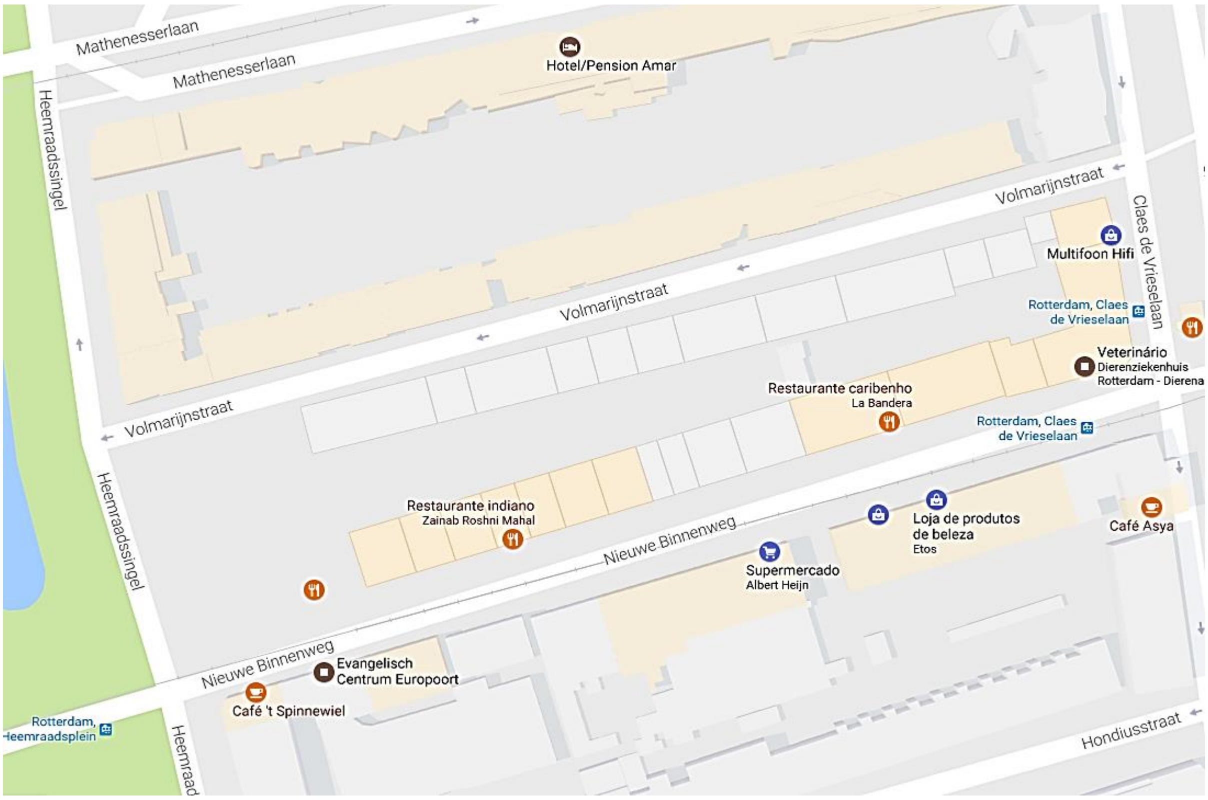


Figure 24: Projects locations. Google Maps (2017).

Table 41: Projects input data

		Project 1: Nieuwe Binnenweg		Project 2: Volmarijnstraat	
		Location: Delfshaven, Rotterdam		Location: Delfshaven, Rotterdam	
Key figures (from literature)	**Unit**	**Open trench**	**Trenchless renovation**	**Open trench**	**Trenchless renovation**
Value of time/road user	euro/person	11.83	11.83	11.83	11.83
Value of time/pedestrian	euro/person	14.4	14.4	14.4	14.4
Vehicle operating costs	euro/veh.kilometer	0.13	0.13	0.13	0.13
Wage rate cleaning personnel	euro/hour	14.4	14.4	14.4	14.4
ANP	persons/vehicle	1.39	1.39	1.39	1.39
Users input data					
Project characteristics					
	Unit	**Open trench**	**Trenchless renovation**	**Open trench**	**Trenchless renovation**
Duration	days	12	5	12	5
Pipeline length	m	250	250	250	250
Execution speed	m/day	21	50	21	50
Pipeline diameter	mm	300	300	300	300
Method	-	excavation	CIPP	excavation	CIPP
Direct costs		200,000	50,000	200,000	25,000
Traffic data					
Street type	-	urban street two-way	urban street two-way	urban street-one way	urban street-one way
Traffic control plan	-	no road closure	no road closure	complete road closure	partial road closure
Number of vehicles per day	vehicles/day	5000	5000	500	500
VOC					
Additional travel distance	km	0	0	0	0
Traffic delay					
Length of work zone including detours	km	0	0	0.367	0.367
Speed through work zone	km/h	0	0	25	25
Length of work zone normal situation	km	0	0	0.25	0.25
Normal speed	km/h	0	0	25	25
Or: Delay time	h	0	0	-	-

Key figures (from literature)	Unit	Open trench	Trenchless renovation	Open trench	Trenchless renovation
Pedestrian delay					
Additional distance to cross the work zone	km	0.05	0.05	0	0
Number of pedestrians affect	pedestrian/day	2500	2500	0	0
Or N of domiciles in the area	domiciles				
Loss of parking space					
Number of parking meters/spaces	spaces	50	50	100	0
Meter daily operational hours	hours	12	12	12	0
Occupancy	%	0.050	0.1	0.1	0.0
Amount of one fine	€	0	0	0	0
Frequency of fines	fines/space*day	0	0	0	0
Duration of parking obstruction	days	12	5	12	0
Meter rate price	€/hour	4	4	4	4
Pavement service life reduction					
Excavation area	m2	750	10	750	10
Road classification	Arterial/Collector /Local	Local	Local	Local	Local
Pavement age	0 to 70 years	10	10	10	10
Air pollution					
Number of machines	n	1	1	1	1
Daily distance driven by transportation trucks	km	0	0	0	0
Number of transport vehicles	n	1	0	1	1
Noise pollution					
Number of disturbed domiciles	n	500	50	200	20
Noise during construction(all equipment)	dBA	85	85	85	85
Dust Pollution					
Additional cleaning time	hours	0	0	0	0

Key figures (from literature)	Unit	Open trench	Trenchless renovation	Open trench	Trenchless renovation
Business revenue loss					
Area of affected business units (food)	m2	0	0	0	0
Area of affected business units (non-food)	m2	0	0	0	0
Percentage of business loss during construction	%	0.08	0.10	0	0
N of affected units (food)	n	13	0	0	0
N of affected units (non-food)	n	15	1	0	0
Risks					
Project specific inputs					
Project duration	scale (1-5)	2	1	2	1
Amount of machines on site	scale (1-5)	1	1	1	1
Excavation volume	scale (1-5)	3	1	3	1
Size of work zone	scale (1-5)	3	1	3	1
Transportation of material (offsite)	scale (1-5)	2	1	2	1
Location specific inputs					
Area density - Development above ground	scale (1-5)	3	3	3	3
Traffic density	scale (1-5)	3	3	1	1
Pedestrian flow (incl. bikes)	scale (1-5)	3	3	2	2
Buried utilities density	scale (1-5)	4	4	3	3
Naturalness of area	scale (1-5)	1	1	1	1

Table 42: Model validation final results

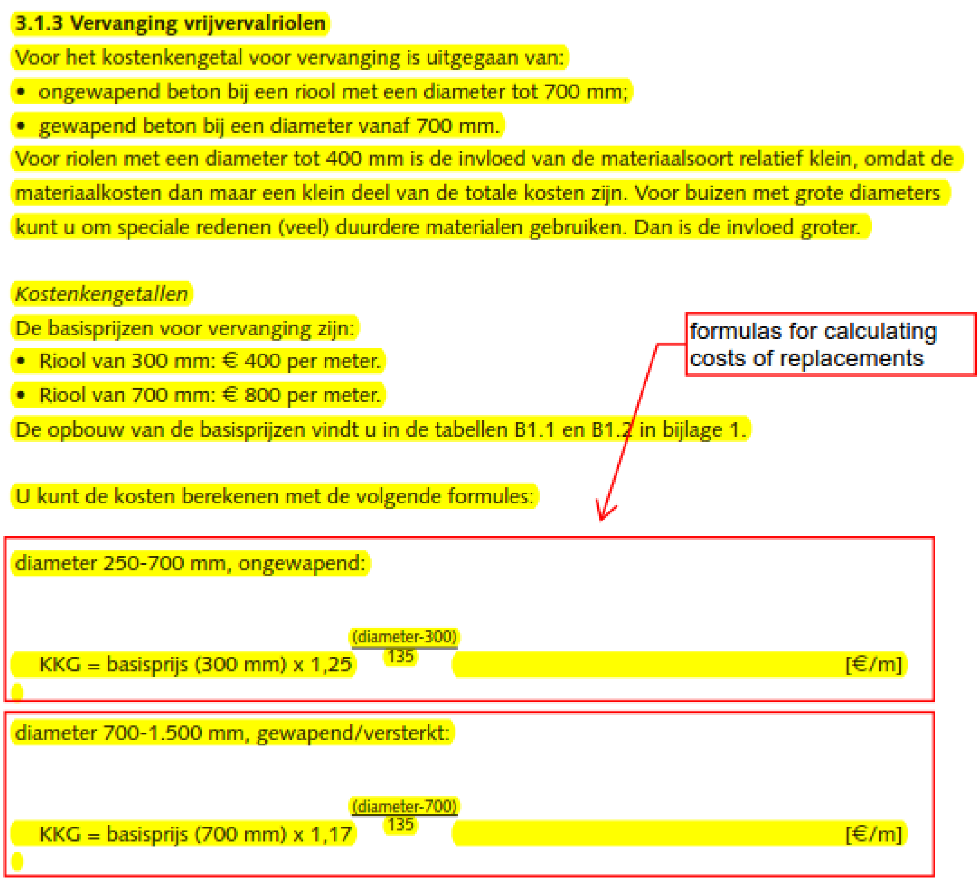
Final results					
		Project 1: Nieuwe Binnenweg		**Project 2: Volmarijnstraat**	
	Unit	**Open trench**	**Trenchless renovation**	**Open trench**	**Trenchless renovation**
Direct/indirect costs	**euro**	**200,000**	**50,000**	**200,000**	**25,000**
Total Social costs	**euro**	**146,975**	**3,963**	**36,762**	**821**
VOC	*€*	*0*	*0*	*0*	*0*
Traffic delay	*€*	*0*	*0*	*462*	*192*
Pedestrian delay	*€*	*2,160*	*900*	*0*	*0*
Loss of parking space	*€*	*1,440*	*1,200*	*5,760*	*0*
pavement service reduction	*€*	*18,750*	*250*	*24,000*	*320*
Air pollution	*€*	*93*	*39*	*97*	*40*
Noise pollution	*€*	*16,110*	*671*	*6,444*	*268*
Dust pollution	*€*	*0*	*0*	*0*	*0*
Business revenue loss	*€*	*108,422*	*903*	*0*	*0*
% of direct costs	*%*	*73%*	*8%*	*18%*	*3%*
Total project costs	**euro**	**346,975**	**53,963**	**236,762**	**25,821**
Costs/meter placed pipe	*€/meter*	*1,388*	*214*	*947*	*103*
Overall risk score	**Scale (1-5)**	**2.5**	**1.8**	**2.1**	**1.4**
Accidents workers	*Scale (1-5)*	*2.6*	*2.0*	*2.0*	*1.4*
Accidents users	*Scale (1-5)*	*2.7*	*2.0*	*2.2*	*1.5*
Damage to property/ infrastructure	*Scale (1-5)*	*2.4*	*1.8*	*2.0*	*1.4*
Damage buried pipelines	*Scale (1-5)*	*2.8*	*1.8*	*2.5*	*1.5*
Damage to environment	*Scale (1-5)*	*2*	*1.4*	*2*	*1.4*

Appendix I: Direct cost estimation

In the decision making phase, companies affirmed that it is possible to estimate the direct costs of both trenchless technologies and open trench. They can also estimate project durations and the type of surroundings infrastructure. These finds are similar to Alkema (2015) who also investigated social costs in pipelines renovation projects. Information about direct costs and project duration are necessary for correlating social cost and direct costs and having an idea of how great the social costs are compared to the project direct costs for both methods.

In some cases, unitary costs (e.g. euro/m^2; euro/m^3) can be used for quick costs estimation. The costs per unit estimations for open trench and trenchless project depends on different factors such as pipeline material, diameter and depth of installation. Consequently, unitary costs are rather indicative and are more used for a quick scan of the direct costs.

One of the companies provided estimative equations for unitary costs related to CIPP and open trench projects. For CIPP lining the cost per meter is between half and one third of the diameter. For example, a CIPP lining with 300 mm diameter would cost between 100 and 150 euros per meter. For open trench replacement they provided a cost estimation equation based on the pipeline diameter (Figure 25). Even though their estimation can be used, it is expected that the user of the tool will provide this cost information based on their cost compositions.



3.1.3 Vervanging vrijvervalriolen

Voor het kostenkengetal voor vervanging is uitgegaan van:

- ongewapend beton bij een riool met een diameter tot 700 mm;
- gewapend beton bij een diameter vanaf 700 mm.

Voor riolen met een diameter tot 400 mm is de invloed van de materiaalsoort relatief klein, omdat de materiaalkosten dan maar een klein deel van de totale kosten zijn. Voor buizen met grote diameters kunt u om speciale redenen (veel) duurdere materialen gebruiken. Dan is de invloed groter.

Kostenkengetallen

De basisprijzen voor vervanging zijn:

- Riool van 300 mm: € 400 per meter.
- Riool van 700 mm: € 800 per meter.

De opbouw van de basisprijzen vindt u in de tabellen B1.1 en B1.2 in bijlage 1.

U kunt de kosten berekenen met de volgende formules:

diameter 250-700 mm, ongewapend:

$$KKG = \text{basisprijs (300 mm)} \times 1{,}25^{\frac{(\text{diameter}-300)}{135}} \quad [€/m]$$

diameter 700-1.500 mm, gewapend/versterkt:

$$KKG = \text{basisprijs (700 mm)} \times 1{,}17^{\frac{(\text{diameter}-700)}{135}} \quad [€/m]$$

Figure 25: Estimation of direct costs based on pipeline diameter

Appendix J: Risk of accidents key figures

According to Linde and Donkelaar (2012) there are three methods for retrieving the costs per accident type. The first one is the use of key figures for fatalities, injuries and material damage (Table 42). The second is a “rule of thumb for overall road safety based on traffic fatalities and serious road injuries, assuming a fixed relationship between serious traffic injuries, slight injuries and material damage”. RIGO (2012) has estimated the costs of € 2,89 million per fatality and € 0,61 million per serious road injuries. The third one is a rule of thumb based on traffic fatalities, assuming a fixed ratio of fatalities, injuries and material damage, where the value of € 16,3 million is estimated (RIGO, 2012).

The cost of accident per victim and per casualty in The Netherlands is presented in Table 43, while the average costs of collisions in euros per vehicles-kilometre is presented in Tables 44.

Table 43: Cost of traffic accidents per victim, casualty and property damage (in euros year 2011) (RIGO, 2012)

Accident type	Cost per victim (€)	Cost per casualty (€)
Fatality	2.836.626	3.101.758
Serious injury	291.632	372.822
Emergency aid required injury	9.245	11.498
Slight injury	5.398	6.970
Damage-only accidents	-	4.479

Table 44: Social costs of road traffic accidents inside and outside urban areas for year 2011 (RIGO, 2012)

Vehicle type	Inside urban areas (€/vehicle-km)	Outside urban areas (€/vehicle-km)
Car	0,063	0,025
Bus	0,150	0,087
Motorbike	0,063	0,107

UNIVERSITY OF TWENTE.

Faculty of Engineering and Technology

User Guide

Based on the master thesis project: "Development of a decision support model for the social costs of pipelines renovation projects".

Author: Camila Nunes Vasconcelos

August 2017

Supervisors:
Dr. S. H. (Saad). Al-Jibouri
Dr. Faridaddin Vahdatikhaki
Drs. C.C.D.F. (Derk) van Ree

Faculty of Engineering and Technology
Department of Construction Management & Engineering
University of Twente
P.O. Box 217
7500 AE Enschede

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1. Introduction

This User Guide is based on the master thesis project “Development of a decision support model for the social costs of pipelines renovation projects” (Vasconcelos, 2017). The research was conducted under supervision of University of Twente and Deltares, with cooperation of NSTT (The Dutch Society of Trenchless Technologies) during the months November 2016 and August 2017.

The research project is a continuation of the research efforts conducted by TU Delft and NSTT for having a model that gives insights into the social and environmental costs related to renovation of pipelines in The Netherlands.

This model should be used to assist decision-makers to consider the magnitude of social costs and hence helping them in taking more informed decisions as to the most appropriate choice of the method to be used. The research problem that gave meaning to the development of the master thesis and the model can be stated as follows:

“There is a need for Dutch companies and governmental agencies to assess their utilities projects based on total project costs, which include the costs to the society and environment.”

The objective and outcome of the research were to develop a method that incorporates social costs in the evaluation of construction methods for pipelines renovation projects. As such, the model proposed uses valuation equations and a scoring system to calculate social costs and assess risks, respectively. The model is presented in the form of an Excel file that can be used to compare open trench and trenchless based on inputs from the users.

From a theoretical point of view, the model provides a base for decision makers to recognize which social costs and risks might be present in their projects, where these social costs come from and which parameters influence these social costs and risks. The model supports decision-makers to assess the social costs related to pipelines projects at an early stage. With this information, a decision-maker could improve decision-making and make a more informed choice between two techniques.

Research scope

The model focuses on social costs related to open trench and trenchless renovation projects for sewage systems (relining). Besides, only trenchless renovation methods are part of the scope and new installations, repair or replacement are not considered. The focus is on the early stages where the strategic decision on the application of open trench or trenchless technologies needs to be made.

In the scope of this research, a monetary quantification of risks did not take place because it was not possible to build a model to quantify and monetize risks in a general way. However, a qualitative risk analysis was proposed aiming at incorporating risks into the decision-making and comparing open trench and trenchless alternatives.

The envisaged users of the proposed model are the decision-makers from municipalities who are responsible to make a choice about which method to use when a pipeline has to be rehabilitated, usually by the end of its life cycle. In this research, the choice was restricted to open trench excavation and trenchless renovation methods in accordance with the research scope.

2. Model description

The model, developed in the form of an Excel matrix/table, has the goal to integrate total project costs and risks for supporting decision-making. In the model, the total costs are divided into direct/indirect and fixed social costs; while the risk related social costs are divided into risks of damage and accidents. Figure 1 represents the costs and risks types involved in the decision making regarding pipelines projects. The approach provided in the figure highlights that not only direct and indirect costs are important during the decision making process, but other criteria should also be involved in the choice such as social costs and risks.

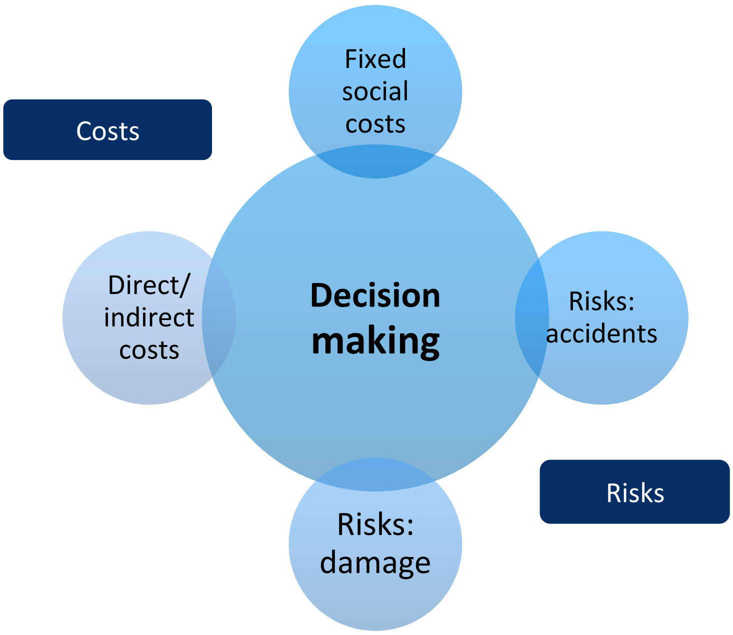

Figure 1: Decision making criteria and sub criteria in the model

The next sections describe the model development: first, the costs category is described together with the valuation equations, input data and key figures used. Second, the Risk category is presented with the necessary input data, scales and an example. Third, an explanation on how to use the model/matrix is presented. Fourth, the assumptions made during the model development are listed. Fifth, the validity of the proposed key figures and scales is discussed. Finally, the model is validated by experts.

2.1 Costs category

The total project cost is one of the criteria in the decision making and can be directly expressed in monetary units. Inside this criterion, two sub criteria are identified: direct/indirect costs and social costs. This division is important for identifying the contribution of each cost type in the total project costs and also for comparing direct/indirect costs to social costs in each project alternative.

2.1.1 Valuation equations and input data

The total project costs are given by the sum of direct/indirect costs and social costs. Direct and indirect costs are usually provided by the project owner, while the total social costs are given by the sum of (fixed) social costs calculated through the valuation equations. Table 23 reviews the valuation equations necessary for quantifying each cost component used in the model.

Table 1: Costs criteria, sub criteria and valuation equations

Criteria/ Sub criteria		Equations		
1	**Total costs**	$\sum 1.1 + 1.2$		
1.1	Direct and indirect costs	$\sum \text{direct costs} + \text{indirect costs}$		
1.2	Social costs	$\sum \text{Equations } 3, 6, 7, 8, 9, 12, 13, 16, 17, 18$		
		Increased vehicle operating costs	$\text{IVOC Total} = \text{IVOC 1} + \text{IVOC 2}$	Eq. 3
		Traffic delay	$\text{TDC} = \text{CD} \times \text{NVD} \times \text{D}$	Eq. 6
		Pedestrian delay	$\text{PDC} = \text{AT}_\text{P} \times (0{,}5 \times \text{HR}_\text{P}) \times \text{P} \times \text{D}$	Eq. 7
		Loss of parking space	$\text{LPm} = \text{PM} \times \text{R} \times \text{Ho} \times \text{O} \times \text{D}$ $\text{LPt} = \text{PM} \times \text{F} \times \text{FT} \times \text{D}$	Eq. 8 Eq. 9
		Pavement service life reduction	$\text{PSL} = \text{PDF} \times \text{Excavated Area}$	Eq. 12
		Air pollution	$\text{APC} = \sum_{i=0}^{i} \text{V}_\text{i} \times \text{C}_\text{i}$	Eq. 13
		Noise pollution	$\text{NPC} = \text{N}_\text{H} \times \text{C}_\text{n} \times (\text{N}_\text{c} - \text{N}_\text{n}) \times \text{D} \div 365 \text{ days}$	Eq. 16
		Dust pollution	$\text{DPC} = \text{AC} \times \text{HR}_\text{p} \times \text{D}$	Eq. 17
		Business revenue loss	$\text{BRL} = \text{U} \times \text{ADI} \times \text{D} \times \text{P}$	Eq. 18

The list of all input data necessary for quantifying the social costs through the valuation equations are incorporated into the Excel model and summarized in Table 2. Table 3 summarizes only the input data to be provided by the users and their respective units grouped according to the social cost type.

Using the valuation equations, key figures and input data provided it is possible to calculate each social cost indicator and the total social costs. When a social cost (indicator) is considered irrelevant and/or when not enough data can be provided by the user, the input data field in the model can be left blank. Consequently, the calculation of that specific indicator will amount zero and not influence the total costs results. Afterwards, the comparison between open trench and trenchless renovation can take place based on total costs, direct/indirect costs and social costs.

Table 2: List of input data used in the model for the valuation of social costs

Project characteristics data	• Duration; Pipeline length; Execution speed; Pipeline diameter; Direct costs
Traffic data	• Street type; Traffic control plan; Number of vehicles per day
Vehicle operating costs data	• Additional travel distance
Traffic delay data	• Delay time or: • Length of work zone including detours; Speed through work zone; Length of work zone normal situation; Normal speed
Pedestrian delay data	• Additional distance to cross the work zone; Number of pedestrians affected or: • Number of domiciles in the area
Loss of parking space data	• Number of parking meters/spaces; Meter daily operational hours; Occupancy; Amount of one fine; Frequency of fines; Duration of parking obstruction; Meter rate price
Pavement service life reduction data	• Excavation area; Road classification; Pavement age
Air pollution data	• Number of machines; Daily distance driven by transportation trucks; Number of transport vehicles
Noise pollution data	• Number of disturbed domiciles; Noise during construction(all equipment)
Dust pollution data	• Additional cleaning time
Business revenue loss data	• Area of affected business units (food); Area of affected business units (non-food); Percentage of business loss during construction

Table 3: List of users input data and units per social cost type

User input data and units			
General		**Loss of parking space**	
Duration	days	Number of parking meters/spaces	spaces
Pipeline length	m	Meter daily operational hours	hours
Execution speed	m/day	Occupancy	%
Pipeline diameter	mm	Amount of one fine	€
Method	-	Frequency of fines	fines/space*day
		Duration of parking obstruction	days
		Meter rate price	€/hour
Traffic data		**Pavement service life reduction**	
Street type	-	Excavation area	m2
Traffic control plan	-	Road classification	Arterial/Collector/Local
Number of vehicles per day	vehicles/day	Pavement age	years
Traffic delay		**Business revenue loss**	
Length of work zone including detours	km	Area of affected business units (food)	m^2
Speed through work zone	km/h	Area of affected business units (non-food)	m^2
Length of work zone normal situation	km	Percentage of business loss during construction	%
Normal speed	km/h	N of affected units (food)	n
Or: Delay time	h	N of affected units (non-food)	n

Pedestrian delay		Air pollution	
Additional distance to cross the work zone	km	Number of machines	n
Number of pedestrians affect	pedestrian/day	Daily distance driven by transportation trucks	km
Or N of domiciles in the area	domiciles	Number of transport vehicles	n
Noise pollution		**Dust Pollution**	
Number of disturbed domiciles	n	Additional cleaning time	hours
Noise during construction (all equipment)	dBA		
VOC			
Additional travel distance	km		

2.1.2 Key figures for valuation equations

The key figures proposed were retrieved from official Dutch reports. Therefore, they are applicable to the Dutch context and might not be appropriate to other countries. The valuation equations, however, were based on international literature and therefore should be valid in different contexts.

The key figures proposed are used in the valuation equations to reduce the amount of input data requested from the users. These key figures are divided into general and specific to differentiate those that are used in several equations and those that are only used for a specific social cost calculation, respectively.

The key figures are incorporated in the Excel model and do not need to be changed by the users, unless if they opt to provide their own values. Tables 4 and 5 summarize the general and specific key figures respectively, the units and the values used in the model for the Netherlands.

Table 4: General key figures for the calculation of fixed social costs

General Key figures	Unit	Open trench	Trenchless	Source
Value of time (road user)	€/person	11.83	11.83	RIGO, 2012
Value of time (pedestrian)	€/person	14.40	14.40	Loonwijzer, 2017
Vehicle operating costs	€/veh.kilometer	0.13	0.13	RIGO, 2012
Wage rate cleaning personnel	€/hour	14.4	14.4	Loonwijzer, 2017
Average number of persons per vehicle	persons/vehicle	1.39	1.39	Otten,’t Hoen and den Boer, 2015

Table 5: Specific key figures for the calculation of fixed social costs

Specific Key figures	Unit	Open trench	Trenchless	Source
Pedestrian delay				
Pedestrian average speed	km/h	5	5	Interviews
Average inhabitants/domicile		2.2	2.2	CBS, 2015
Pavement service life reduction				
Pavement depreciation due to excavation	€/m^2	See Table 12	See Table 12	Karim et al, 2014
Air pollution				
CO_2 cost of emission	€/ton	40	40	RIGO, 2012

CO_2 emission (middle car)	Ton/km	0.000133	0.000133	BOVAG-RAI, 2015
CO_2 emission (urban normal/medium duty, 2015)	Ton/km	0.000783	0.000783	Ligterink, van Zyl and Heijne, 2016
Emissions machinery	Kg CO_2/liter of diesel	2.7	2.7	Rehan and Knight, 2007
Fuel consumption machinery	Liter diesel/hour	9.1	9.1	Rehan and Knight, 2007
Noise pollution				
Cost per increase in 1dBA	€/dBA	49	49	RIGO, 2012
Normal level of noise	dBA	65	65	Vermeulen et al, 2004
Business revenue loss				
Daily income per business (food, 2017)	€/m^2/day	30.70	30.70	Detail Handel, 2017
Daily income per business (non-food, 2017)	€/m^2/day	5.90	5.90	Detail Handel, 2017

2.2 Risk category

The risk related social costs are qualitatively assessed in the model. Basically, the risk analysis is conducted using the predefined factors affecting risks and the predefined scales based on the survey results. Using this background information, the risk analysis can be conducted in the model. Table 6 summarizes the factors affecting risks and Table 7 presents the input data scales used in the model.

Accidents workers	Accidents users	Damage to property/ infrastructure	Damage to buried pipelines	Damage to environment
• Amount of machines on site • Transportation of material • Size of work zone • Traffic density • Density of buried pipelines	• Project duration • Transportation of material • Size of work zone • Pedestrian flow • Traffic density • Area density	• Traffic density • Transportation of material • Area density • Amounf of machines on site • Excavation volume	• Amount of machines on site • Excavation volume • Size of work zone • Density of buried pipelines	• Amount of machines on site • Naturalness of the area • Excavation volume • Area density • Transportation of material

Table 6: Risks sub criteria and factors affecting risks (input data)

Table 7: Input data scales for assessing risks sub criteria

Project specific			Location specific		
Input data	**Scales**		**Input data**	**Scales**	
Project duration	1 - very short	<=1 week	**Area density (Development above ground)**	1 - very low density	natural area
	2 - short	1-2 weeks		2 - low density	low density residential area
	3 - medium	>= 2 weeks		3 - medium density	high density residential area, schools, shops
	4- long	>= 4 weeks		4- high density	industrial/business area, schools, shops
	5- very long	>= 3 months		5- very high density	city centre, shopping centres, skyscraper buildings
Amount of machines on site	1 - very low	1	**Traffic density**	1 - very low density	<= 1000/day
	2 - low	2		2 - low density	1000-5000/day,
	3 - medium	3		3 - medium density	5.000 - 15.000/day, busses and/or trams
	4- high	4		4- high density	15.000 - 40.000, busses and/or trams
	5- very high	< 5		5- very high density	>= 40.000, busses, trams
Excavation volume	1- very low	< 10 m^3	**Pedestrian flow (incl. bikes)**	1- very low flow	< 10 pedestrians/day
	2- low	10-50 m^3		2- low flow	10 -250 pedestrians/day
	3- medium	50-100 m^3		3- medium flow	250-1000 pedestrians/day
	4- high	100-200 m^3		4- high flow	1000-3000 pedestrians/day
	5- very high	> 200 m^3		5- very high flow	3000 - 5000 pedestrians/day
Size of work zone	1- very small	<=300 m^2	**Density of buried pipelines**	1 - very low density	only the pipeline under renovation
	2- small	300 - 600 m^2		2 - low density	only regular distribution pipelines
	3- medium	600 - 1200 m^2		3 - medium density	regular distribution pipelines plus warm water distribution
	4- large	1200 - 2400 m^2		4- high density	regular distribution pipelines, warm water distribution plus transport (high voltage, high pressure, big diameter)
	5- very large	>= 2400 m^2		5- very high density	main pipeline corridor (e.g. in harbour area)
Transportation of material (offsite)	1- very low	**Context dependent**	***Naturalness of area***	1- Very urbanized area	0.005 trees/m^2
	2- low			-	0.01 trees/m^2
	3- medium			3-medium urbanized area	0.1 trees/m^2
	4- high			4- natural area	0.5 trees/m^2
	5- very high			5- very natural area	1 trees/m^2

Table 7 was adapted from Table 22 (See thesis report) to be used in the projects provided by Experts in the model validation phase. Therefore, the *excavation volume, size of the work zone* and *naturalness of the area* scales were based on the opinion of a single expert since there was no convergence in the scales for these particular input data.

Another scale used in the model is the risk criteria and risk sub criteria scales. Similarly to the input data scales, 1 represents the best performance and 5 the worst performance in the risk (sub) criteria scale. A colour scale is combined with this 5-point scale, where green is equivalent to number 1 and red is equivalent to number 5.

To exemplify, suppose that after scoring the project alternatives for each risk sub criteria based on the input data scales, project A scores 4 in the sub criteria *accidents workers* and project B scores 2. Besides, the overall Risk score (considering the average of the scores of each sub criteria) for project A is 3 and for project B is 2. As a conclusion, the likelihood of accidents involving workers and the overall risk will be higher for project A compared to project B: the higher the score, the higher is the likelihood of a risk event happening.

Table 8 presents the scales for the main risk criterion and the risk sub criteria. The scales vary from very unlikely to very likely to happen, indicating how high the chances are that accidents or damage take place in the project.

Table 8: Scales for risk main criterion and sub criteria

Risk main criterion	Scale	Likelihood
• **Risks**	1	Very unlikely to happen
	2	Unlikely to happen
	3	Possible to happen
	4	Likely to happen
	5	Very likely to happen
Risk sub criteria	**Scale**	**Likelihood**
• Accidents: workers • Accidents: users	1	Very unlikely to happen
	2	Unlikely to happen
	3	Possible to happen
	4	Likely to happen
	5	Very likely to happen
Risk sub criteria	**Scale**	**Likelihood**
• Damage: Property/infrastructure • Damage: buried pipelines • Damage: environment	1	Very unlikely to happen
	2	Unlikely to happen
	3	Possible to happen
	4	Likely to happen
	5	Very likely to happen

2.2.1 Risks analysis

This section explains how the risk analysis is conducted based on the scales previously described. In the risk analysis, the risk scores for each alternative are calculated and a comparison is made based on these results. In Table 9, a risk assessment matrix is proposed to illustrate the model. In order to understand the matrix, the following considerations are made:

- Rows represent input data that affect the sub criteria under analysis
- Columns represent the alternatives under evaluation (open trench versus trenchless technologies)
- Cells represent the performance of a given alternative in terms of an input data for a given sub criteria. The performance is measured through the 5-point input data scales.

Table 9: Example of risk sub criteria assessment - sub criteria, input data and scoring of alternatives

Criteria/Sub criteria	Input data	Score (1-5)	
		Alternative 1	Alternative 2
1 Risks **1.1 Sub criteria X**	*Input data 1*	S_{11}	S_{12}
	Input data 2	S_{21}	S_{22}
	Input data 3	S_{31}	S_{32}
	Input data n	S_{n1}	S_{n2}
Sub criteria score (Sub criteria X, Alternative 1,2)		Score Alt. 1	Score Alt. 2

In Table 9 each risk sub criterion is independently evaluated based on the respective affecting input data. For each alternative and input data, a score is given ranging from 1 to 5. The sub criteria scores have to be calculated separately for each of the five sub criteria.

Each sub criteria score is given by the arithmetic average of the input data scores (Equation 24). The arithmetic average was chosen instead of weighed average because after consultation with experts, it was concluded that it would be difficult to give weights to each input data and express their contribution to a certain sub criteria. Besides, the weights would have been dependent on the expert experience and the project itself, making them context and project dependent.

$$\text{Score (Sub criteria X,} \quad \text{Alternative 1)} = \frac{S_{11} + \cdots + S_{n1}}{n} \qquad \text{Eq. 24}$$

The *overall risk score* is given by the arithmetic average of the sub criteria scores, for each alternative under evaluation as exemplified in Table 10. The *overall risk score* represents the final result which is used for comparing the open trench and trenchless renovation alternatives in terms of risks.

Table 10: Example of risk assessment - Overall Risk score

Criteria/Sub criteria		Score (1-5)	
		Alternative 1	Alternative 2
1	**Risks**		
1.1	*Accidents with workers*	2.9	1.5
1.2	*Accidents with users*	2.6	1.6
1.3	*Damage to Property/infrastructure*	2.8	2.0
1.4	*Damage to buried pipelines*	2.6	1.2
1.5	*Damage to the environment*	3.4	2.4
	Overall Risk Score	**3**	**2**

The choice of arithmetic average for calculating the Overall risk score presents limitation regarding the importance of different risk sub criteria to the final results. This approach considers that each risk type has the same importance for the project and project owner, which might not always be the case. If one wants to highlight a risk type compared to the other, weighed average could be an option. Besides, the scales from Table 10 are given in decimal numbers for informative purposes.

Rounding the scores to the closest integer does not affect the overall risk score much neither the likelihood.

2.3 How to use the model

This section explains how to use the Excel model for assessing the fixed social costs and risks. The model consists of five different types of calculation sheets and the contents of each sheet and how to use it are detailed in this section.

i. Input data sheet
ii. Social costs calculation sheets
iii. Risks sub criteria analysis sheets
iv. Risk analysis sheet
v. Final results sheet

i. Input data sheet

The input data sheet lists all the general data necessary for quantifying social costs and risks in open trench and trenchless project alternatives. The data is divided into (1) key figures previously defined and (2) project data to be provided by the user. The information should be provided for both open trench and trenchless renovation methods if a comparison between the options is envisaged. Even though it is not the main objective, the model can also be used to calculate the social costs for only one of the options.

In the excel model, the *input data table* assembles the input data by social cost indicator. Therefore, under each social cost indicator table, the user can fill in the information needed for the calculation of that specific social cost.

The necessary data to evaluate risks are aggregated in a separate table and classified into project specific and location specific data. This table should be filled by the users as scores based on the 5-point scales presented in Section 4.2. Using the scales, the user can indicate the scores for each input data and each alternative.

ii. Social costs calculation sheets

In the social costs calculation sheets the actual calculation of (fixed) social costs is performed. There are nine (fixed) social costs calculation sheets which are used to separately calculate each social cost in the model. Some social costs sheets contain key figures retrieved from literature that are pertinent to a certain social cost and therefore were not added to the input data sheet.

The calculation sheets make use of the valuation equations, the input data sheet information and key figures to calculate social costs (Figure 2). These sheets do not have to be filled in or modified by the user. They are only used for calculation purposes and can be useful if one wants to check where the results of the Final results sheet come from; and for checking the equations and specific key figures used. However, if the user has a different key figure, s/he can make a modification in these sheets to generate different results.

Open trench			
Parameter	**Symbol**	**amount**	**unit**
Number of parking meters/spaces	PM	50	spaces
Meter operational hours**	Ho	12	hour
Occupancy	O	0.1	%
Duration of parking obstruction	D	12	days
Amount of fine	F	0	€
Frequency of fines	FT	0	fines/space*day
Meter rate price*	R	4	euro/hour
Valuation (€)			
Loss of parking space		**2,880**	

Trenchless renovation			
Parameter	**Symbol**	**amount**	**unit**
Number of parking meters/spaces	PM	50	spaces
Meter operational hours	Ho	12	hour
Occupancy	O	0.1	%
Duration of parking obstruction	D	5	days
Amount of fine	F	0	€
Frequency of fines	FT	0	fines/space*day
Meter rate price	R	4	euro/hour
Valuation (€)			
Loss of parking space		**1,200**	

Figure 2: Example of social costs calculation sheets – Loss of parking space

iii. Risks sub criteria analysis sheets

The risks sub criteria analysis sheets are used to score the risks sub criteria (Figure 3). There are five sheets in the excel model, one for each risk sub criteria. The information in these sheets consist of the risk sub criterion under analysis, the alternatives compared, the input data relative to the sub criterion, the scores for each input data retrieved from the input data sheet and the overall score/performance for each alternative in a 5-point scale and colour scale.

These sheets are used for calculating the scores for each sub criteria/alternative. The results from the five sheets are summarized in the *Risk analysis sheet*. The user does not have to add any data or information to these sheets.

2.1: Risk accidents workers				
Criteria/Subcriteria		**Input data**	**Score (1-5)**	
			Open trench	**Trenchless renovation**
2	**Risks**	*Amount of machines on site*	*1*	*1*
2.1	*Accidents workers*	*Transportation of material (offsite)*	*2*	*1*
		Size of work zone	*3*	*1*
		Traffic density	1	1
		Density of buried pipelines	3	3
		Performance SC 2.1	*2.0*	*1.4*

Figure 3: Example of risks sub criteria analysis sheets

iv. Risk analysis sheet

This sheet summarizes the final scores of the different risks sub criteria calculated in (iii). Besides, it is used to calculate the overall score for the Risk main criterion for each alternative under comparison (Figure 4). No input data from the user is needed in this sheet.

Risk Analysis			
Criteria/Sub criteria		Score (1-5)	
		Alternative 1	Alternative 2
2	**Risks**		
2.1	*Accidents workers*	*2.2*	*1.4*
2.2	*Accidents users*	*2.6*	*1.8*
2.3	*Damage to property/ infrastructure*	*2.5*	*1.5*
2.4	*Damage buried pipelines*	*3.3*	*2.0*
2.5	*Damage to environment*	*2.0*	*1.0*
	Risk Score	***2.5***	***1.5***

Figure 4: Example of risk analysis sheet

v. Final results sheet

The final results sheet summarizes the main results calculated in the model and does not require the users input. In this sheet, the user can compare the alternatives based on the final results obtained throughout the model in terms of costs and risks. The information presented in this sheet consists of the (a) direct costs; (b) total social costs and social costs indicators/components; (c) total project costs and (d) risk scores for open trench and trenchless alternatives.

2.4 Assumptions

The development of the social costs model for comparing open trench and trenchless renovation technologies involved some assumptions. These assumptions are necessary due to the limitations regarding the scope, the model and data availability. Some of these are based on the research from Alkema (2015) due to similar research contexts:

- The alternatives/methods under comparison are limited to open trench and trenchless *renovation* technologies.
- No distinction is made between the different trenchless renovation methods in terms of social costs calculations. Therefore, it is assumed that the social costs will be similar for any renovation method analysed.
- The social costs and risks comparison considers that the project would be executed in the same location and under the same conditions in both open trench and trenchless methods. Consequently, location-related characteristics (e.g. traffic density, developments above ground) should be independent of the method.
- General project characteristics such as pipeline length or diameter should be similar for both options so that the social costs comparison is fair.
- The user can provide information about direct costs for both options beforehand. If not, some equations are provided for calculating the direct costs but the reliability of the results cannot be guaranteed.
- The project duration, project location and length of the installations are estimated beforehand and can be provided by the user.

- The technical feasibility of the alternatives under comparison is guaranteed by the user, since only technically feasible options should be tested against social costs.
- The user should provide information about (traffic) delay times related to each project alternative for more reliable end results. If this information is not available, s/he can provide other information so that the model would estimate the traffic delay with less reliability.
- In the risk analysis, it is assumed that the input data (factors affecting risks) have the same impact/weight on the risk criteria. Besides, it is assumed that there is an equal impact of the risk criteria on the overall risk.

2.5 Validity of key figures and scales

During the model development, key figures and scales have been developed to allow the calculation and analysis of social costs and risks. These values were based on literature, reports and experts interviews and their validity is discussed on Table 11.

Table 11: Validity of key figures and scales

Aspects	Comments about validity
Increased vehicle operating costs	• There is a general key figure for the VOC where no distinction is made between vehicle types crossing the work zone.
Traffic delay	• No distinction is made between the types of vehicles crossing the work zone. Consequently a general *value of time* is used; • The estimation of time delay using the alternative equations does not consider the impacts of the project on the surrounding traffic. Only the vehicles crossing the work zone are considered, which consequently might not fully represent the real situation (especially in very busy areas where a lane closure can impact a large radius).
Pedestrian delay	• An approximate calculation is proposed for the affected pedestrians in the project area because it might be hard to have real data measured on the source.
Air pollution	• Only CO_2 is considered in the equations and other pollutants are excluded for simplifying the calculations; • No distinction is made between the types of vehicles generating pollution.
Noise pollution	• The population disturbed by noise is based on the number of houses nearby the construction site.
Dust pollution	• Dust pollution calculation needs information about the number of cleaning hours, which might not be available at the project early stages.
Business revenue loss	• The percentage of revenue loss will depend on the project. Therefore the user can either use their own values or literature references (from 10 to 50% of loss).
Risks	• The scales are based on interviews, literature and survey with experts. Therefore they are subjective and subject to change depending on the project context; • The scales for risk criteria are general and are mostly used to compare the open trench and trenchless alternatives. The results should not be interpreted as a thorough risk analysis.

2.6 Project cases

The projects proposed in this section were used to validate the model and were provided by "educated guess" from experts. Therefore, all the information described in the cases is based on previous experiences and knowledge about the area and the projects are fictitious. Still, the numbers and results are important for giving an idea about how the model works and whether the results are reasonable based on the input data provided.

Project 1: Nieuwe Binnenweg

The project 1 is located in a shopping/residential street in the region of Delfshaven in Rotterdam consisting of around 500 domiciles. The street is two-way and allows the flow of cars and tramways (Figure 5). The pipeline that needs rehabilitation is located under the sidewalk and consequently no road closure is needed for the open trench or trenchless methods. It is assumed that most of the parking spaces in the area are under subscription for residents and only 10% of them are open for the public. From those, half of the parking spaces are unavailable during open trench execution. Besides, the open trench option causes a pedestrian sideway closure. The trenchless option does not affect the parking availability or pedestrian flow. It is supposed that the loss of parking space and pedestrian walkway closure will impact business revenue by 10% for the open trench option. Regarding the reduction of pavement service life, the pavement degradation fee of 25€/m^2 is adopted for sideway concrete tiles.

Figure 5: Nieuwe Binnenweg street. Source: Google Maps, 2017

Project 2: Volmarijnstraat

The project 2 is located in a residential street in the region of Delfshaven in Rotterdam (Figure 6). There are approximately 200 domiciles located there. The street is one-way and does not allow tramway transit. The pipeline that needs rehabilitation is located under the road in the middle of the street and therefore a complete road closure is needed in the open trench option. For the trenchless option, only around the manholes will be blocked and therefore partial closure is needed. The pedestrians will not be affected in any case and therefore no pedestrian delay is predicted. All the parking spaces are reserved for residents with a subscription and therefore it is assumed that the *hourly rate is much lower than a normal parking place. Regarding pavement service life reduction, the degradation fee adopted is 32€/m^2 for non-asphalt roads.*

Figure 6: Volmarijnstraat. Source: Google Maps, 2017

This project information was used as input data for filling in the Excel model Input data sheet and calculating the social costs and risks (Table 12). Once the results for the projects were generated, experts were consulted to validate the results and the model. The results obtained for both projects are consistent with what would be expected in reality.

Table 12: Input data sheet

		Project 1: Nieuwe Binnenweg		Project 2: Volmarijnstraat	
		Location: Delfshaven, Rotterdam		Location: Delfshaven, Rotterdam	
Key figures (from literature)	**Unit**	**Open trench**	**Trenchless renovation**	**Open trench**	**Trenchless renovation**
Value of time/road user	euro/person	11.83	11.83	11.83	11.83
Value of time/pedestrian	euro/person	14.4	14.4	14.4	14.4
Vehicle operating costs	euro/veh.kilometer	0.13	0.13	0.13	0.13
Wage rate cleaning personnel	euro/hour	14.4	14.4	14.4	14.4
ANP	persons/vehicle	1.39	1.39	1.39	1.39
Users input data					
Project characteristics					
	Unit	**Open trench**	**Trenchless renovation**	**Open trench**	**Trenchless renovation**
Duration	days	12	5	12	5
Pipeline length	m	250	250	250	250
Execution speed	m/day	21	50	21	50
Pipeline diameter	mm	300	300	300	300
Method	-	excavation	CIPP	excavation	CIPP
Direct costs		200,000	50,000	200,000	25,000
Traffic data					
Street type	-	urban street two-way	urban street two-way	urban street-one way	urban street-one way
Traffic control plan	-	no road closure	no road closure	complete road closure	partial road closure
Number of vehicles per day	vehicles/day	5000	5000	500	500
VOC					
Additional travel distance	km	0	0	0	0
Traffic delay					
Length of work zone including detours	km	0	0	0.367	0.367
Speed through work zone	km/h	0	0	25	25
Length of work zone normal situation	km	0	0	0.25	0.25
Normal speed	km/h	0	0	25	25
Or: Delay time	h	0	0	-	-

Key figures (from literature)	Unit	Open trench	Trenchless renovation	Open trench	Trenchless renovation
Pedestrian delay					
Additional distance to cross the work zone	km	0.05	0.05	0	0
Number of pedestrians affect	pedestrian/day	2500	2500	0	0
Or N of domiciles in the area	domiciles				
Loss of parking space					
Number of parking meters/spaces	spaces	50	50	100	0
Meter daily operational hours	hours	12	12	12	0
Occupancy	%	0.050	0.1	0.1	0.0
Amount of one fine	€	0	0	0	0
Frequency of fines	fines/space*day	0	0	0	0
Duration of parking obstruction	days	12	5	12	0
Meter rate price	€/hour	4	4	4	4
Pavement service life reduction					
Excavation area	m2	750	10	750	10
Road classification	Arterial/Collector /Local	Local	Local	Local	Local
Pavement age	0 to 70 years	10	10	10	10
Air pollution					
Number of machines	n	1	1	1	1
Daily distance driven by transportation trucks	km	0	0	0	0
Number of transport vehicles	n	1	0	1	1
Noise pollution					
Number of disturbed domiciles	n	500	50	200	20
Noise during construction(all equipment)	dBA	85	85	85	85
Dust Pollution					
Additional cleaning time	hours	0	0	0	0

Key figures (from literature)	Unit	Open trench	Trenchless renovation	Open trench	Trenchless renovation
Business revenue loss					
Area of affected business units (food)	m2	0	0	0	0
Area of affected business units (non-food)	m2	0	0	0	0
Percentage of business loss during construction	%	0.08	0.10	0	0
N of affected units (food)	n	13	0	0	0
N of affected units (non-food)	n	15	1	0	0
Risks					
Project specific inputs					
Project duration	scale (1-5)	2	1	2	1
Amount of machines on site	scale (1-5)	1	1	1	1
Excavation volume	scale (1-5)	3	1	3	1
Size of work zone	scale (1-5)	3	1	3	1
Transportation of material (offsite)	scale (1-5)	2	1	2	1
Location specific inputs					
Area density - Development above ground	scale (1-5)	3	3	3	3
Traffic density	scale (1-5)	3	3	1	1
Pedestrian flow (incl. bikes)	scale (1-5)	3	3	2	2
Buried utilities density	scale (1-5)	4	4	3	3
Naturalness of area	scale (1-5)	1	1	1	1

Table 13: Model validation final results

Final results					
		Project 1: Nieuwe Binnenweg		**Project 2: Volmarijnstraat**	
	Unit	**Open trench**	**Trenchless renovation**	**Open trench**	**Trenchless renovation**
Direct/indirect costs	**euro**	**200,000**	**50,000**	**200,000**	**25,000**
Total Social costs	**euro**	**146,975**	**3,963**	**36,762**	**821**
VOC	*€*	*0*	*0*	*0*	*0*
Traffic delay	*€*	*0*	*0*	*462*	*192*
Pedestrian delay	*€*	*2,160*	*900*	*0*	*0*
Loss of parking space	*€*	*1,440*	*1,200*	*5,760*	*0*
pavement service reduction	*€*	*18,750*	*250*	*24,000*	*320*
Air pollution	*€*	*93*	*39*	*97*	*40*
Noise pollution	*€*	*16,110*	*671*	*6,444*	*268*
Dust pollution	*€*	*0*	*0*	*0*	*0*
Business revenue loss	*€*	*108,422*	*903*	*0*	*0*
% of direct costs	*%*	*73%*	*8%*	*18%*	*3%*
Total project costs	**euro**	**346,975**	**53,963**	**236,762**	**25,821**
Costs/meter placed pipe	*€/meter*	*1,388*	*214*	*947*	*103*
Overall risk score	**Scale (1-5)**	**2.5**	**1.8**	**2.1**	**1.4**
Accidents workers	*Scale (1-5)*	*2.6*	*2.0*	*2.0*	*1.4*
Accidents users	*Scale (1-5)*	*2.7*	*2.0*	*2.2*	*1.5*
Damage to property/ infrastructure	*Scale (1-5)*	*2.4*	*1.8*	*2.0*	*1.4*
Damage buried pipelines	*Scale (1-5)*	*2.8*	*1.8*	*2.5*	*1.5*
Damage to environment	*Scale (1-5)*	*2*	*1.4*	*2*	*1.4*

As it can be noticed in Table 13, the (fixed) social costs are higher for the open trench options in both cases. For instance, the pavement service life reduction is higher in the open trench options due to a larger volume of excavation. The noise pollution is also higher due to a longer project duration and a higher number of affected domiciles when open trench is used. The trenchless option also generates noise, but fewer domiciles are affected since the machines are located in specific areas on the site instead of throughout the whole street like in the excavation.

In project 1, no road closure is needed and therefore no traffic delay is expected. In project 2, the open trench and trenchless methods will require complete and partial lane closure, respectively. Consequently, there will be some delay time and traffic delay costs. These delay costs are higher for the open trench option due to the longer project duration and the traffic management plan.

The social costs of project 1 are much higher compared to project 2 because the former is located in a shopping street. Consequently, some loss of business revenue is expected during the project 1 execution due to the loss of accessibility to customers. Higher losses would be likely if the street was completely closed during a longer period of time.

Concerning risks, in project 1 the five risks criteria scored higher for the open trench option. Consequently, the overall risk score was also higher for the open trench compared to trenchless option (overall approximate score 3 against 2). The same situation happened in project 2, where the overall approximate score for open trench was 2 and for trenchless 1.

In the fictitious projects described above, the main social costs relate to loss of business revenue, pavement service life reduction, noise pollution and loss of parking space. The data used came from educated guess made by experts, and therefore other values could have been suggested leading to different results. The particularities of the projects under analysis are reflected on the social costs results for both open trench and trenchless methods. More detailed comments about model validation can be found in Section 4.6 of the thesis report.

3. Limitations and recommendations

The main objective of the research was to develop a model that incorporates social costs in the evaluation of open trench and trenchless renovation methods for pipelines projects. The goal of the model was to compare these methods in terms of social costs as an added value for the decision making within municipalities. Like that, decision makers could make more informed decisions regarding pipelines projects based on total project costs, which includes the costs to society and environment.

In practice, social costs are not systematically included in the decision making and this research tried to fill in this gap. However, during the research development, it was found that the information needed to valuate social costs is not always available or spread among different parties, which became the biggest limitation of the model. A change in the way information is organized and communicated should help with filling this gap. Besides, the development of a common database with project information could be created for social costs estimation in future projects.

Experts stated that the way the Excel model is organized is valid, however the information required is not easy to be collected because it is time and effort demanding to be gathered. Therefore, even though the necessary data is existent, assembling it is one of the challenges for the users because they are not used (or did not have the need) to gather this type of data beforehand for other purposes. Besides, usually there are not data for both the open trench and trenchless options under comparison, but mainly for the chosen option that will be executed.

It is suggested that decision makers change the way they organize and communicate project information so that the necessary input data can be easily gathered and applied in a social costs model. Since social costs can impact different areas and involve different areas of expertise, it is necessary that practitioners work towards integrated projects from the early project stages. For instance, if there is a common database for sharing project information about social costs it would be easier to use it in a calculation model.

At the moment, the social costs quantification is subjective and based on experience or past projects but as an improvement it could become more systematic and objective. For that to happen, it would be necessary to identify the social costs involved in the project and the parties responsible for providing the necessary data to the model.

Once the social costs are quantified or compared in a reliable way between open trench and trenchless projects, it will be possible to obtain a maximum welfare from these projects from a societal point of view. Such approach would benefit the society in the sense that projects causing less nuisance could be easier supported based on social costs and having higher chances to be selected in a bid.