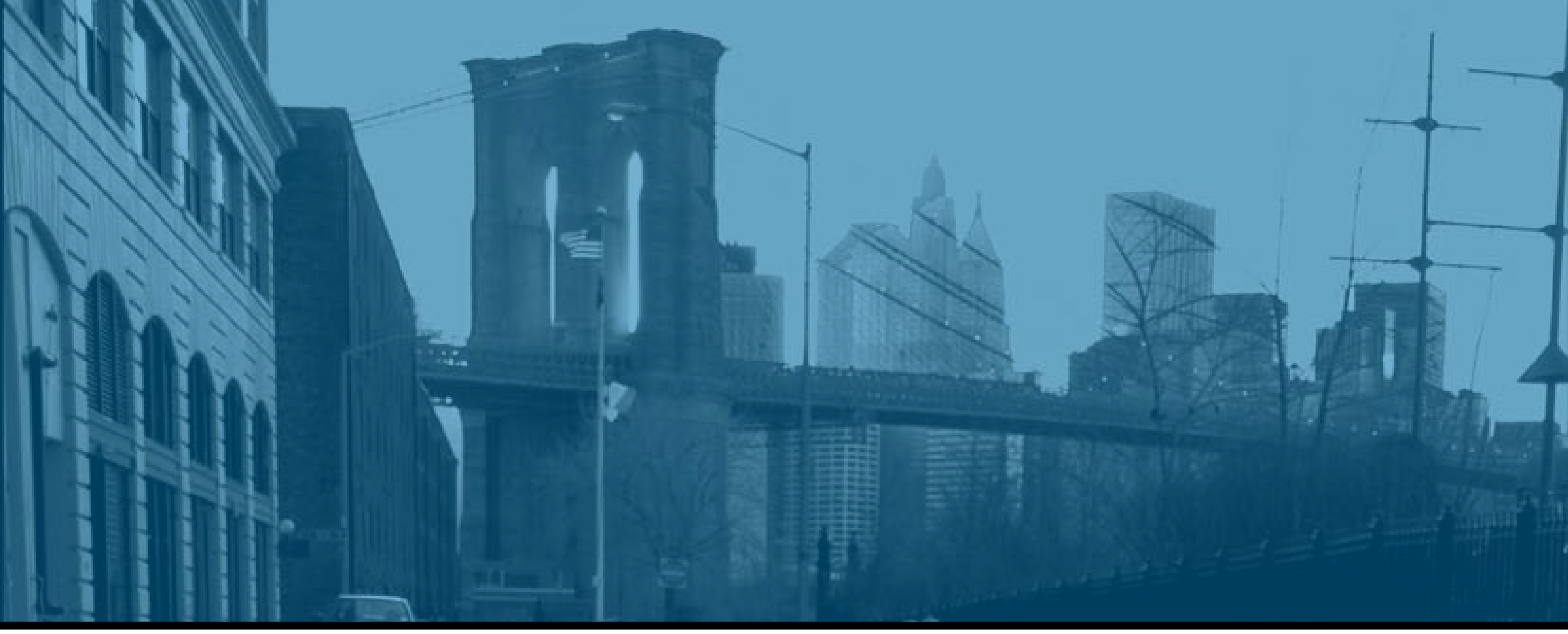

A New Approach to Asset Management for Sewer Networks

Master Thesis Report
G.W. van der Hoop
December 10th, 2010

Master Thesis report
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Cover: Brooklyn sewer stories,New York City, 2007. Made by aaalanaa.
http://aaalanaaa.deviantart.com/art/Brooklyn-Sewer-Stories-55337311

Preface

It is with great pride and satisfaction that I present this report that describes the process and results of my master thesis research: *A New Approach to Asset Management for Sewer Networks.* This research was carried out for the Chair of Design and Construction Processes and marks the end of my Civil Engineering study at Delft University of Technology.

This research was initiated during a discussion at the Chair of Underground Space Technology. The underground space in the Netherlands is becoming increasingly crowded with small subsurface infrastructure networks (e.g. sewers, water supply, cables). Especially in dense urban environments these networks are difficult to manage and optimise because of large external costs that are created during repair, renovation and replacement activities. Sewer networks were chosen as focus of this research because these are vital for public health, but show large variations in age and deterioration level. For municipalities it is becoming more difficult to efficiently maintain their deteriorating sewer networks with limited budgets.

The development of trenchless technologies during the last century has provided sewer network managers with techniques that allow for less disturbance during works. Deciding which technique is most suitable for a specific project proves to be very difficult due to the amount of available techniques, lack of insight into characteristics of various techniques and uncertainty regarding external effects. Because of the great importance of sewers as part of the public health system it is absolutely necessary to perform more research in this field. This will result in better understanding of the various aspects that play a role in the decision making process, which allows for optimisation. I hope this research can be a useful contribution to this.

Performing this research was a long journey, but when looking back I am very satisfied with the experience and insight gained into this topic. Sometimes it was difficult to resist the temptation to include more aspects in the research, but in the end I am pleased with the obtained results. Discussions with my supervisors have given me much insight and were always fruitful and enjoyable.

I would like to thank the members of my graduation committee for their supervision and contributions to this research: Professor De Ridder for his never ending enthusiasm and process knowledge; Professor Bosch for his insight into projects in urban environments and keeping everything in perspective; Dr. Broere for this technical knowledge and daily supervision; Ing. Jutte for providing insight into the contractor’s point of view and his practical knowledge; Ing. Staverman for providing insight into the network manager’s point of view and his practical insight. The various backgrounds of the committee members and the interesting mix of theory and practice has been very helpful to me throughout my research.

Finally, I would like thank my father, mother, sister and friends for supporting me throughout my research and providing distraction at times when I needed it most.

Gerard van der Hoop,
Delft, December 2010

Summary

The underground space in the Netherlands contains a large number of infrastructure networks. The sewer network, which plays a vital role in our public health system, is one of these. Sewer networks in the Netherlands have different ages and show different levels of deterioration. The various components of sewer networks will have to be repaired, renovated or replaced at some point in their lifetime in order to restore their condition.

During the last years there have been many developments in this field and nowadays there are many techniques available for repair, renovation and replacement of sewer pipes. Repair techniques treat defects in certain pipe sections that are deteriorated or damaged. Renovation (or rehabilitation) techniques increase the lifespan of the existing pipe by applying a new liner within the existing pipe. Finally, replacement techniques replace the old pipe completely by a new pipe. Within these three categories there are many techniques available. These techniques differ greatly in required level of investment, nuisance to the surroundings, risks and so forth.

The question which technique is most suitable for a certain component at a certaint time is essential for sewer asset managers. There is however insufficient knowledge available in the local governmental organisations that are responsible for sewer maintenance, which results in sub-optimal decisions being made. Budget for operation and maintenance activities of sewer systems is limited, therefore it is essential that the decision making process is optimised and the available public money is spent in the best possible way.

This research has looked into the question how asset management of sewer networks in the Netherlands can be optimised. This was done by first looking at the current state of decision making and the limitations it has. There are many tools available in different countries that are aimed at sewer networks. A number of these supports the decision making process regarding choice of techniques for sewer pipes. These support tools are often aimed at only very few aspects of the overall decision making process or they are based on local data and thus not usable for other locations. In the Netherlands there is no general tool available that can support the sewer asset managers. The tools that were investigated are too limited to use as a basis for an integral tool for the Dutch situation. The most ideal solution would be to develop a new tool from scratch that includes all important aspects and insights.

In order to construct such an integrated tool it is vital to understand which aspects should be taken into account and what the relations between these aspects are. This report offers an extensive overview of all these aspects and how these should be implemented in a decision support tool. During the course of this research these insights were integrated into a new decision support tool.

As said before, there are many different techniques available for repair, renovation and replacement of sewer pipes. Techniques that are available in the Netherlands have been investigated and their characteristics have been collected. In total 17 techniques are included in this research; this includes five repair techniques, nine renovation techniques and three replacement techniques (including open-cut replacement). Available techniques for manholes and house connections are also shortly discussed, but sewer pipes are the focus of this research.

In order to make an objective comparison between various possible solutions for a sewer project, it is important that all costs and values that are generated by the various solutions are included. Decisions are often based on the lowest direct costs since these can be quantified and have a direct effect on the expenses that municipalities face. This traditional approach has a major flaw; the external costs that are generated by sewer works are not taken into account. Especially in dense urban environments these external costs can far outweigh the direct costs.

Public organisations should thus be aware of these costs and use a sustainable approach when deciding which solution is most suitable for a certain project. This means that there should always be a balance between economic, social and environmental interests. An overview of external cost categories was created, which shows the various effects that should be taken into account. External effects are difficult to express in costs, but this does not mean that they should be ignored! For a number of external effects there are already values or calculation methods available, other effects will need to be researched.

Not only various types of costs are required for a good comparison, but added value should also be taken into account. Some techniques may offer added value compared to other techniques, which can distinguish them in the decision making process. A number of above ground and subsurface added value items has been included in the decision support tool.

Only when all these costs and values are included it is possible to the determine the real costs of various alternatives. The decision can then be made based on the lowest real costs.

Every project is unique and has specific local conditions that should be considered when looking at which solution is most suitable. The developed decision support tool should be able to take these conditions into account when deciding which costs are generated and which techniques are possible. Specific project can be easily entered into the developed model. An effort has been made to construct an overview of the most important considerations that should be included in the decision making process. These considerations have been linked to cost components (both direct and external) that are generated when the considerations are answered in certain ways. The idea is that when the sewer asset manager uses these considerations as a check list, it is no longer possible to forget important items and he is able to get a complete overview of relevant cost components. The considerations have been divided into nine categories, which are combinations of three decision levels (strategic, tactical and operational) and three aspects (economic, environmental, social).

In order to look at long-term investment strategies, the user should have more information than only the previously mentioned overview of cost factors for a single repair, renovation or replacement. In order to determine at what time in the future which technique should be applied, it is necessary to know the condition of the considered asset at every point in time. Futhermore a calculation method should be used to take future cash flows into account. Both these items were added to the tool as a preliminary module.

Condition prediction of sewer pipes is very difficult since the deterioration depends on local conditions. The achieved lifespans of sewer pipes vary greatly, making it unrealistic to use a single life expectancy for all sewer pipes. In order to be able to investigate long-term behaviour of various alternatives in the model, it was necessary to include some sort of condition prediction. Therefore a second degree curve was assumed to approximate deterioration behaviour.

The condition prediction component was constructed with this theoretical curve and based on a number of assumptions regarding the effect of techniques on the condition of sewer pipes. The user can fill in a number of variables, for example the condition level at which techniques should be applied. The program determines the change in condition for every year, subsequently it calculates in which years repairs, renovations or replacement activities are required.

Now that the program knows in which years certain activities take place, it can compare cash flows by using a Life Cycle Costing approach. The cash flows of all alternatives are placed at a point in time and discounted to determine the Net Present Values. Note that his includes the external costs that were entered into the model. The solution with the lowest NPV is the solution with the lowest overall costs and should be chosen.

In order to make sure that no vital aspects were forgotten, a case study was performed. This case study included two streets in a residential area of Amsterdam. These streets have various sewer pipelines in the underground with various characteristics. There were a number of errors and missing items found, which were improved or added afterwards. The case study showed that the tool covers the most relevant aspects. As long as the user understands the assumptions that were made and the limitations that exist, this tool can offer useful support to the decision making process.

One of the biggest strengths of the developed tool is that it has a flexible design. Many parameters can be easily adjusted according to new insights and it is easy to add new components to the tool. This will prove invaluable when new research results become available.

Concluding, this research presents a first step towards a fully integrated decision support tool for sewer networks. There are however still many topics in this broad field of knowledge that require more research. There is still a long way to go, but it is clear where the challenges can be found. Condition assessment and prediction are unreliable and should be thoroughly investigated. Future research will hopefully provide more accurate data, since there is little known about these processes at the moment. Furthermore it is important to look into cost figures for both direct and external costs. Once all external effects can be given cost values it is possible to determine the real costs of all alternatives for a project and the most optimal decision can be made. Sewer networks can be managed more efficiently when this tool is implemented and further improved. Large overall cost reductions can be expected, which will greatly benefit society and the environment.

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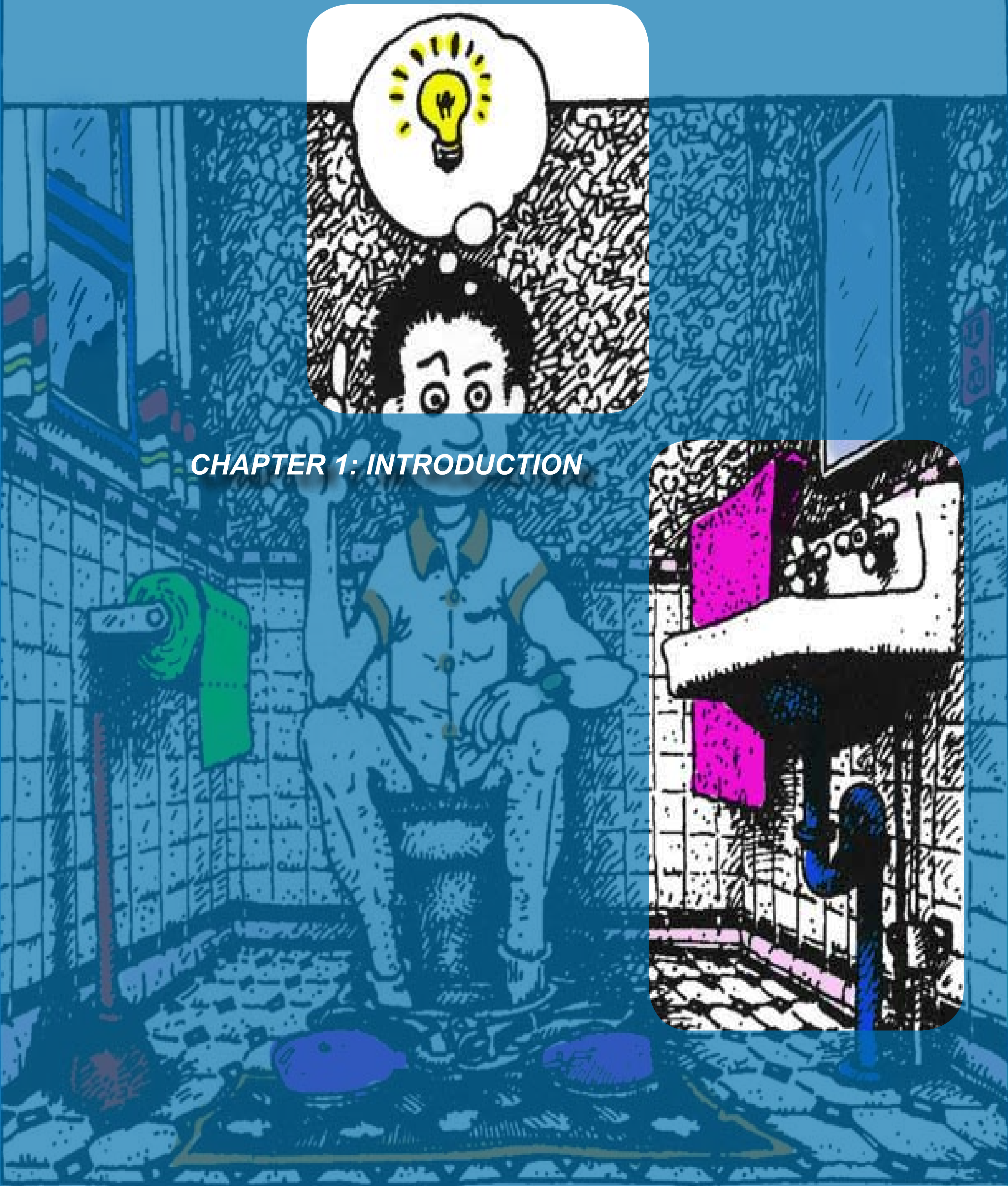
We do it every day, but do we ever *think* about it?



CHAPTER 1: INTRODUCTION

Chapter 1: Introduction

Sewer networks are subsurface infrastructure networks that are often taken for granted in developed countries. Sewers collect waste water and foul sewage before transporting these to a sewage treatment plant or other place of disposal.

Existing sewer networks that are located underneath our towns and cities have only been developed during the last two centuries. Prior to this the sanitary conditions were appalling everywhere. Especially in urban environments the lack of sewer systems resulted in large health risks and it is no surprise that outbreaks of disease were quite common. Strangely, the concept of sewers is not something of the last two centuries. The earliest discovered sewers were already constructed around 2500 BC by various civilizations. The Romans gained much experience with both water supply systems and sewer systems. They introduced the necessary techniques throughout their empire, and thus also in the Netherlands.

The fall of the Roman Empire resulted in the deterioration of existing sewers and loss of gained knowledge regarding sewers. Proper sanitation as we know it today did not start to develop until the beginning of the 19th century.

Nowadays all developed countries have extensive sewer networks located in their subsurface. The treatment of collected sewage has also developed rapidly, reducing the pollution from discharge to the environment. Large parts of sewer networks have already been replaced by newer materials, but in some cities there are still parts of the 19th century sewer in use. In the Netherlands most of the existing network was built in the second part of the 20th century.

Parts of sewer networks used to be replaced by digging a trench, this was only done when a component failed. Fortunately the development of inspection techniques and trenchless technologies has resulted in improved approaches to sewer network management. A reactive approach (taking action only after failure occurs) is no longer considered acceptable. There are many parts of sewer networks that have deteriorated, these will need to be replaced, repaired or renovated in order to garantuee their required performance and to avoid unacceptable risks because of possibility of failure.

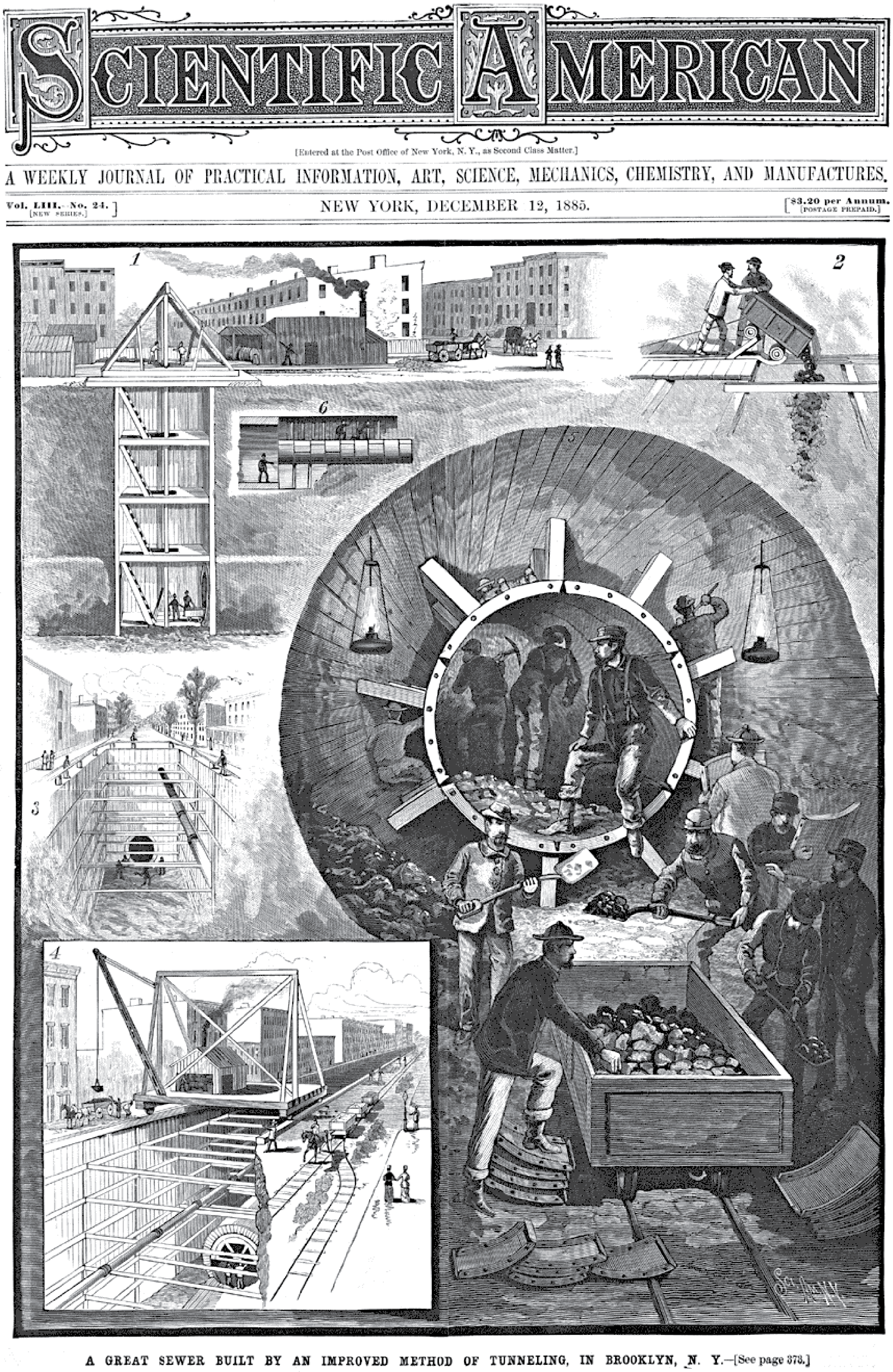
Figure 1:Victorian sewer underneath London (http://www.flickr.com/photos/jondoe_264)

The developed techniques in the field of trenchless technologies provide a solution to this problem of network deterioration. However, these techniques differ greatly in required level of investment, nuisance to the surroundings, risks and so forth. Unfortunately there is very limited knowledge about these effects, making it difficult for network managers to optimize investment strategies. Operation and maintenance activities of sewer networks are usually pressured by limited budgets, this means the available funds should be optimally allocated.

Besides financial considerations there is also need for research into external costs of the considered trenchless techniques. In order to make an optimal choice when choosing techniques for maintenance activities, the actual costs should be evaluated instead of only engineering costs (as is usually done).

Research into this field can result in a new approach to asset management of sewer networks. This will lead to savings in terms of investments and reduction in terms of pollution and material use.

Figure 2:(right) Sewer construction in the USA in 1885 ("The Knickerbocker Avenue Extension Sewer, Brooklyn, N.Y.," Scientific American, Volume LIII, No. 24 (12 December 1885), cover. Collection of Jon C. Schladweiler, Pima County Wastewater Management Department)



SCIENTIFIC AMERICAN

[Entered at the Post Office of New York, N. Y., as Second Class Matter.]

A WEEKLY JOURNAL OF PRACTICAL INFORMATION, ART, SCIENCE, MECHANICS, CHEMISTRY, AND MANUFACTURES.

Vol. LIII.—No. 24. [NEW SERIES.] NEW YORK, DECEMBER 12, 1885. [$3.20 per Annum. [POSTAGE PREPAID.]

A GREAT SEWER BUILT BY AN IMPROVED METHOD OF TUNNELING, IN BROOKLYN, N. Y.—[See page 373.]

CHAPTER 2: PROBLEM ANALYSIS

Chapter 2: Problem Analysis

2.1 Problem description

The underground space in the Netherlands contains a large number of cables and pipes. The sewer network is an import part of this. There are many parts of the sewer network that have deteriorated. These will need to be replaced, repaired or renovated in order to guarantee their required performance and to avoid unacceptable risks because of possibility of failure.

During the last years there have been many developments in this field and nowadays there are many techniques available for repair, renovation and replacement of sewer pipes. Repair techniques treat defects in certain pipe sections that are deteriorated or damaged. Renovation (or rehabilitation) techniques increase the lifespan of the existing pipe by applying a new liner within the existing pipe. Finally, replacement techniques replace the old pipe completely by a new pipe. Within these three categories there are many techniques available. These techniques differ greatly in required level of investment, nuisance to the surroundings, risks and so forth.

In general, repair techniques are considered to be applicable when the component has slightly deteriorated or is damaged in small sections. At a certain deterioration level the option of rehabilitation becomes more interesting. Correct application of renovation techniques to existing sewer pipes, already before the functionality has deteriorated, could possibly significantly improve the total lifespan and capacity.
When the component is at the end of its useful life, replacement should be considered. However, at which point which technique becomes economically attractive is unclear.

Local governments that maintain sewer networks usually do not have sufficient knowledge about these specialised techniques. There is very limited knowledge about the effects of the techniques on the lifespan of the existing sewer pipes for example, which is vital in order to optimise investment strategies.

Determining the most suitable technique for a certain pipe at a certain time is essential for the sewer network manager.

The budget for operation and maintenance activities is limited, which means the available funds should be wisely allocated. The maximum cost effective life span can only be obtained when life cycle management is applied to sewer networks.

Furthermore, not only direct costs should be included in the overall cost evaluation, but external costs also. The actual costs for construction activities can be tenfold of the direct (visible) costs. At the moment only direct costs are considered when deciding which technique to apply. Reduction of material use is another important value that should be taken into account. Sustainability will become even more important in the future due to increased scarcity of resources. Public organisations should have a leading role in these changing conditions and set the right example. The public sewer networks are large infrastructure systems that offer many possibilities for improvement.

By optimising maintenance strategies it is possible to decrease total investment costs, nuisance to the surroundings and damage to the environment.

2.2 Goal

The goal of this master thesis is:

To research how currently available repair, renovation and replacement techniques for sewer networks can be applied in order to optimise asset management strategies for sewer networks in the Netherlands.

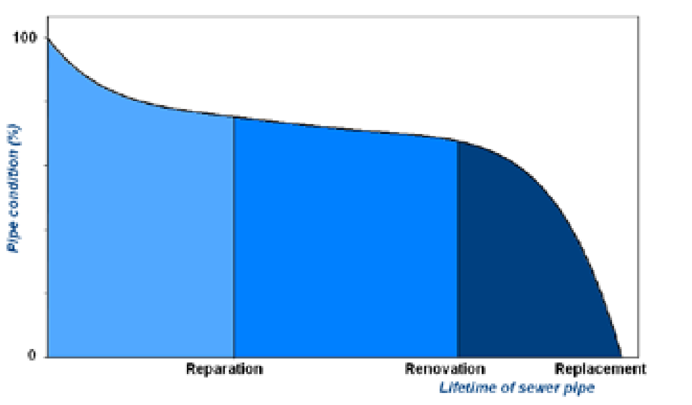


Figure 3:General overview of when which type of technique becomes suitable during the lifetime of a sewer pipe

2.3 Research questions

The following research questions were formulated for this master thesis. The answers on the following research questions will be discussed in this report.

Main question:

How can trenchless technologies be used to develop a new approach to asset management for sewer networks?

Sub-questions:

1. Which techniques for repair, renovation and replacement of sewer networks are currently available in the Netherlands and abroad?

2. Which tools for management of sewer networks are known in the Netherlands and abroad?

3. What are the characteristics of the existing Dutch sewer network?

4. Which costs have to be considered when managing sewer networks?

5. Which investment patterns are possible when considering various techniques?

6. Which externalities have to be considered for the different techniques?

7. How can asset management strategies for sewer networks be optimised?

2.4 Scope

The focus area of this research is quite large and unfortunately not all aspects regarding this topic can be investigated within the limited amount of time. It is important to clearly define the scope of this research in order to prevent any vagueness or omissions.

The following aspects will be considered in this research:

- All available repair, renovation and replacement techniques for sewer systems in the Netherlands
- Available inspection methods
- Sewer networks, which means not only sewer pipes but also the other components of networks, such as manholes and pumps
- Factors that should be included in the overall cost picture
- Not only direct costs, but also external costs such as nuisance and pollution

The following aspects are outside the scope of this research and thus will not be discussed in this report:

- The process of deterioration of components
- The effect of various soil conditions on the life expectancy of sewer pipes, for example chemical and biological conditions. The effect of settlements will be within the scope however.
- Prediction models for sewer failure and their application
- Cost figures for specific techniques and conditions

CHAPTER 3: RESEARCH PLAN

Chapter 3: Research Plan

Before any work is carried out, a research plan was developed that can be used as a framework for the research process.

This thesis is carried out in the overlapping area of two fields of expertise. On one side there is the technical aspect that contains various techniques and the physical assets. The other side consists of the asset management field of expertise, which considers the non-physical processes and economic point of view.

First of all, a literature study will be carried out regarding the available techniques for sewer maintenance, repair, renovation and replacement. Besides this the characteristics and history of the Dutch sewer network will be researched.

The next step is to determine costs and benefits that are associated with various techniques. Not only economic costs will be considered but also external costs (social, environmental). Furthermore possible methods for expressing these external costs in monetary values will be looked into.

At the same time there will be a seperate literature study done regarding the asset management component of the thesis. Insight has to be gained into asset management and how this can be applied to sewer networks. Information about asset management tools that are used abroad will be gathered. These tools will then be evaluated to see if they (or their components) can be useful for the Dutch situation.

These two seperate research paths will then connect and the technical path will be combined with the asset management path. The results from both paths will be used to develop a tool that can support the decision making process that sewer asset managers face.

This tool is then tested by applying it to a case study. This results in a number of solutions and attention points. These findings will then be discussed with experts in phase five. The experts can indicate whether or not the results are realistic and sufficiently complete.

The feedback from these sessions will then be used to improve the tool and the recommended strategies. This can be done a number of times until the desired accuracy is achieved.

The final phase will consist of constructing a clear overview of the achieved results, from which conclusions will be drawn. Furthermore recommendations will be formulated for asset management of sewer networks in the Netherlands.

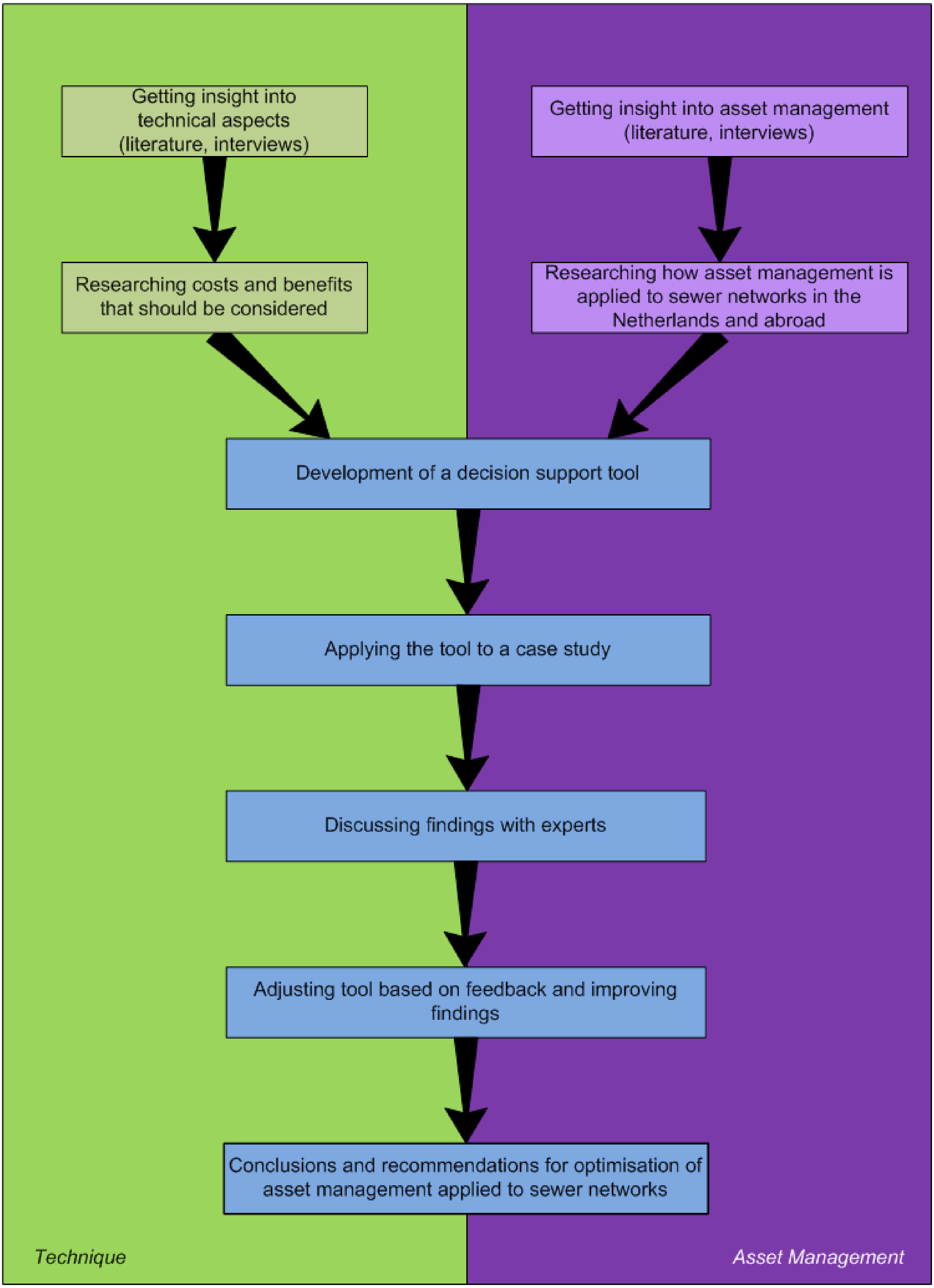


Figure 4:Overview of research plan

CHAPTER 4: SEWER NETWORKS IN THE NETHERLANDS

Chapter 4: Sewer Networks in the Netherlands

4.1 History

In early times there was no need for a sewer system. People simply crouched down behind a bush or a tree for their daily business. Once people began living in tents and houses such habits would quickly pollute the area around their home.
Deep cesspits were dug to collect the human excrement. Once the cesspit was full, it was covered with soil. Household waste was also disposed of in these ditches.

The earliest sewers that are discovered were constructed around 2500 BC. In the Indus valley (now western Pakistan) there were towns where every house had a latrine, some houses had bathrooms and there was even a public bath. In the Netherlands the sewers were introduced by the Romans. In Rome and other Roman cities there were numerous public toilets which had flowing water. Rome was the first city to have a complete sewer system, called *Cloaca Maxima*.

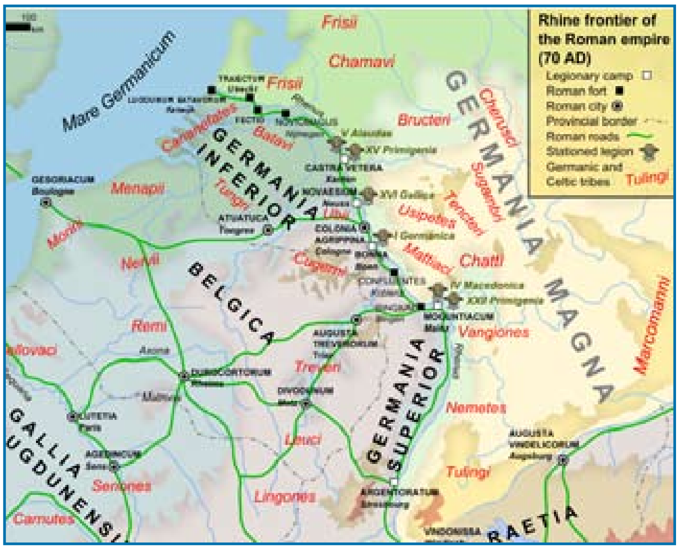


Figure 5: Frontier of the Roman Empire in The Netherlands (http://nl.wikipedia.org/wiki/Limes)

The *limes* (border of the Roman Empire) in the Netherlands was located along the Rhine (between what nowadays is Katwijk and the German border near Arnhem). Most of the fortresses along the *limes* where equipped with toilets which could be used by twenty soldiers at the same time. These toilets were connected to a sewer system.

Following the collapse of the Roman Empire, the toilets disappeared along with the Romans. Cesspits were being dug again or sometimes an outhouse was built above the water (a wooden privy). In some cities the human excrement was collected in barrels underneath the toilet. These barrels were then emptied into canals or picked up by a gong farmer. In some areas of the Netherlands this was still common practice about 50 years ago.

During the Middle Ages the level of sanitation was especially appalling in the cities. Sewage was thrown in city canals or out on the street (and then often ended up in the city canals). There were however many crafts which required the water from the canals for their production process. Soon the local governments imposed rules which forbade the population to throw their sewage in the canals. This often resulted in the use of small side streets for disposal of sewage. This did not solve the problem obviously, sewage still infiltrated into the soil and flowed into the canals.

Due to the Industrial Revolution the population of the Netherlands began to increase rapidly during the 19th century. Besides the stench this also resulted in cholera epidemics, which eventually pressured local governments into constructing drinking water networks and sewer networks. The first sewer network was constructed in 1851 in the city of Maastricht. Not all cities reacted this quickly; some only started looking into developing a complete sewer system during the first years of the 20th century.

An interesting example of developments in the field of sewer technology in the 19th century is the work of engineer Charles T. Leirnur. He developed a pneumatic sewer system that was constructed in Leiden, Amsterdam, Dordrecht, Prague and St. Petersburg. He designed his system as a separate system, with sewage and rainwater disposed of by separated systems. The idea was to collect excrement and urine, which could then be sold as fertilizer. In a number of cities this system was profitably exploited for some years. Eventually, the invention of the flushing toilet resulted in amounts of waste water that were too large for this system. This in combination with the invention of artificial fertilizer proved to be the end for the Liernur system.

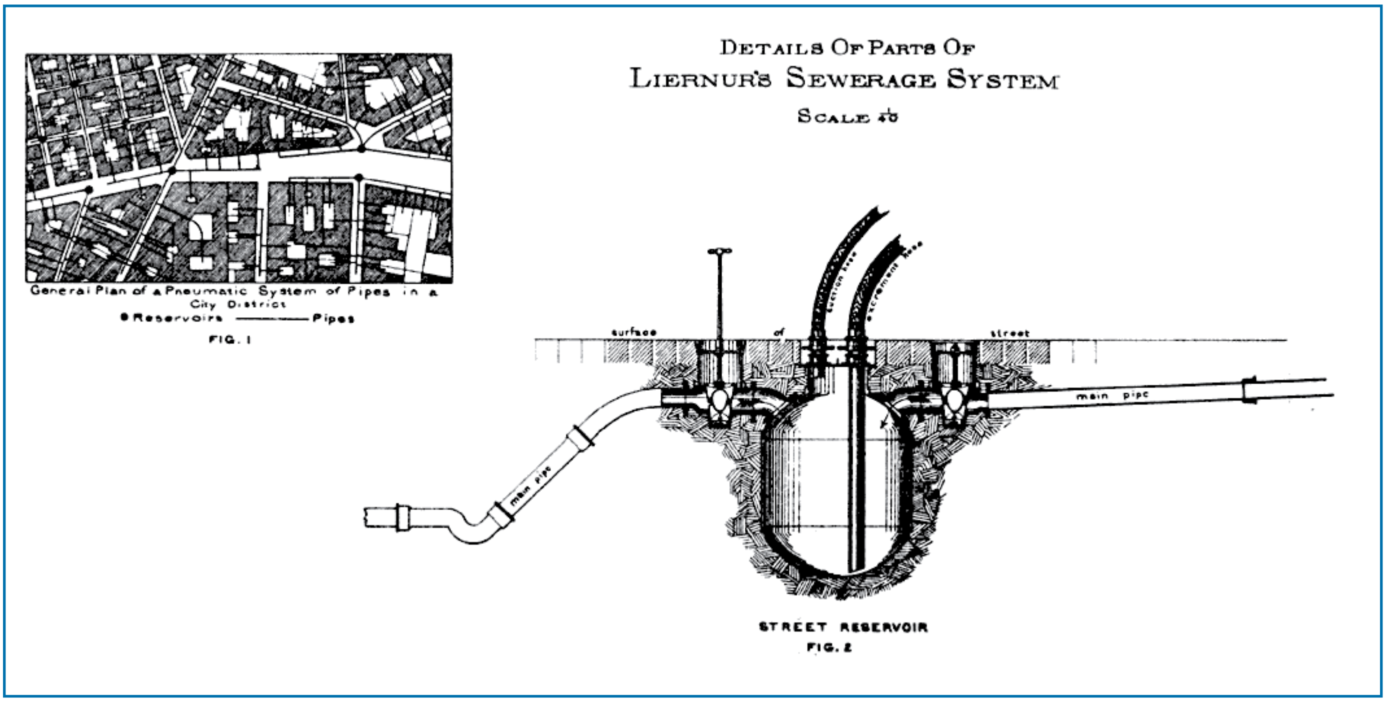


Figure 6:Liernur's Pneumatic Sewerage System, circa 1884.
(Samuel M. Gray, Proposed Plan for a Sewerage System, and for the Disposal of the Sewage of the City of Providence (Providence: Providence Press Company, Printers to the City, 1884), Plate 5, opposite page 22)

The Liernur system collected sewage, but the majority of first sewer networks were only used to transport sewage to the river. Soon it became clear that the resulting water pollution was not acceptable. Sewage treatment technologies started to develop in order to reduce pollution. Nowadays all sewer networks are connected to treatment plants and there are many treatment methods available.

Currently 99,6 percent of the Dutch population is connected to a sewer network. The remaining 0,4 percent makes use of a so called IBA-system (*Individuele Behandeling van Afvalwater* = Individual Treatment of Wastewater). These systems are required when there is no sewer network available to connect a property to (this only happens in the most rural areas). Some 65.000 people make use of a IBA-system in the Netherlands (Stichting RIONED, 2009).

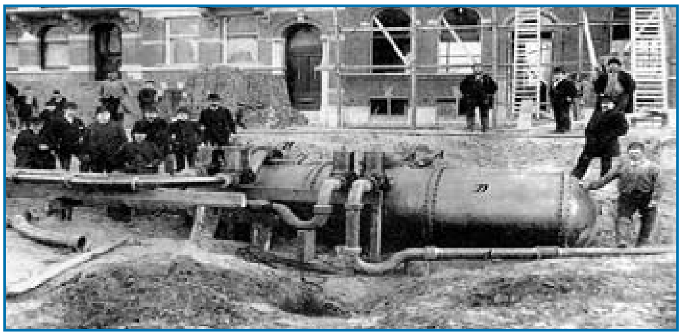


Figure 7:Construction of a Liernur system

4.2 Characteristics

There are many characteristics of sewer networks that can be considered. Fortunately a lot of data has been gathered and the characteristics of the existing Dutch sewer networks are well-known. As can be seen in table 1, sewer networks in the Netherlands have been constructed and expanded over a period of many decades. Many of the oldest sewers have been replaced or renovated, but this has sometimes happened already some decades ago. The existing sewer networks have a large spread in age and thus also in level of deterioration, materials used and types of sewer system.

Year of construction	Length (km)	Percentage of total
Before 1950	4.100	5
1950-1959	6.000	7
1960-1969	12.500	14
1970-1979	18.500	21
1980-1989	16.000	18
1990-1999	15.000	17
2000-2008	14.500	17

Table 1:Age of existing sewer networks in the Netherlands (Data: Stichting RIONED,2009)

4.2.1 System types

There are different types of sewer systems in use in the Netherlands. Large parts of the existing networks are so called combined systems. A combined system is a system which collects both sanitary water and storm water runoff into a single pipe system. When there are large variations in precipitation there is a risk of surface water pollution due to overflow of the sewer. Most of the early sewers were constructed as combined systems because local governments thought this would be cheaper. Most cities also did not have a sewage treatment plant, therefore there was no clear advantage to public health when the system would be separated. This perception changed when sewage treatment plants became more common and health risks were better understood.

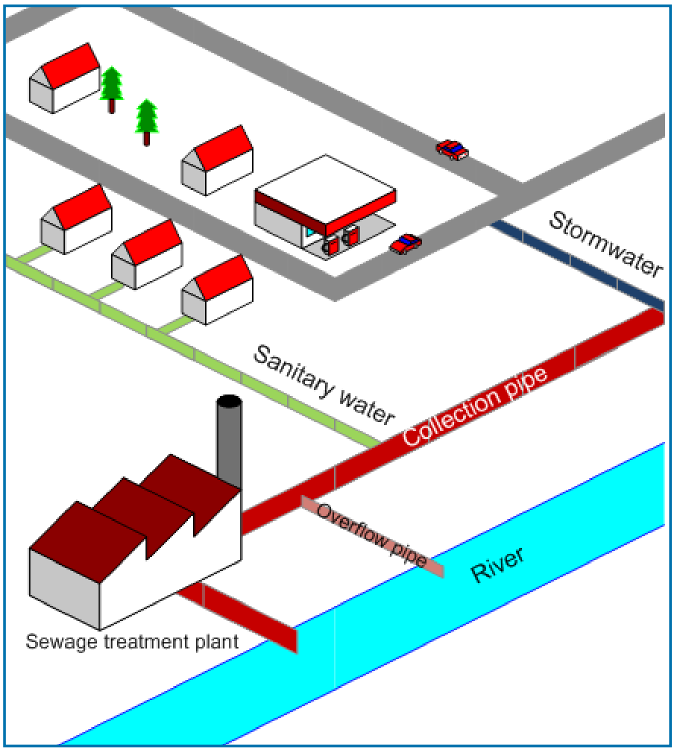


Figure 8:Impression of a combined sewer system

Nowadays all new sewers are constructed as separated or improved separated systems. As the name suggests, separated sewer systems do not collect sanitary water and storm water runoff into a single pipe system, but separate these flows. Sanitary water is collected and transported to a sewage treatment plant, while storm water runoff is collected in a separate pipe and directly transported to a surface water body. The sewage treatment plant does not have to handle the storm water and there is no risk of sewer overflow.

Even though there is no more risk of overflow, there will still be some surface water pollution. Especially during the beginning of rain showers there will be a lot of dirt from the streets transported into the storm water sewer pipes. This dirt will be transported with the storm water and thus will also end up in the surface water.

This problem was solved by developing an improved separated sewer system. This means the storm water pipes are connected to the sanitary pipes at certain locations. One-way valves or overflow constructions are used to prevent sanitary water from entering the storm water sewer pipes. Because the first part of a rain shower will flow into the sanitary sewer pipes, the dirt will not end up in surface water but in the sewage treatment plant instead. A large part of yearly storm water runoff is transported to the treatment plant when this system is used, but the peak load on the treatment plant is lower than when a combined sewer system is used.

Combined sewers have been partly converted to separated sewers, but this is only financially attractive when the road has to be dug up for maintenance anyway. The largest problem with conversion however is caused by the combined house connections. When a combined sewer has to be separated, the house connections will also need to be separated. There is always the risk of wrong connections being made and thus of sewage ending up in the rainwater pipes. The risk of contamination of the discharged rainwater due to connection mistakes can be reason for municipalities and water boards not to entirely separate the system.

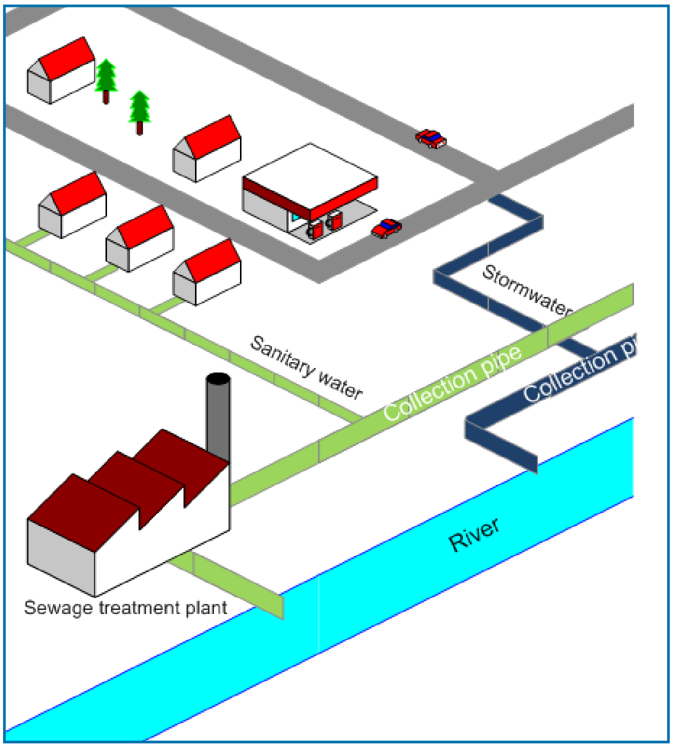


Figure 9: Impression of a separated sewer system

Instead of converting a combined system, it is also possible to reduce the risk of surface water pollution by upgrading a combined system to an improved combined system. This involves the construction of settlement tanks, which can retain large amounts of water. During heavy rainfall these tanks act as buffers, thereby reducing the amount of unwanted overflows. Since the wastewater in the tanks is flowing very slowly the sewage can sink to the bottom. This results in an improved water quality.

The mentioned sewer systems are gravity sewer systems, which means that they rely on gravity to transport sewage. Most of the sewer networks in the Netherlands belong to a gravity sewer system. The advantage of these systems is that there is no need for a large number of pumps. The disadvantage is the necessity to place the sewer pipes at a deeper level because of the necessary inclination.

Another possibility is the pressure sewer system, which uses pressure instead of gravity to transport sewage. This system is usually found in rural areas, where it connects scattered plots (often farms) to the sewage treatment plant. Note that pressure sewer systems do not transport storm water runoff since their capacity is limited. Gravitational methods are usually preferred because of their lower costs and greater reliability, but in rural areas this is often not economical. Pressure systems can use either overpressure or underpressure to transport sewage.

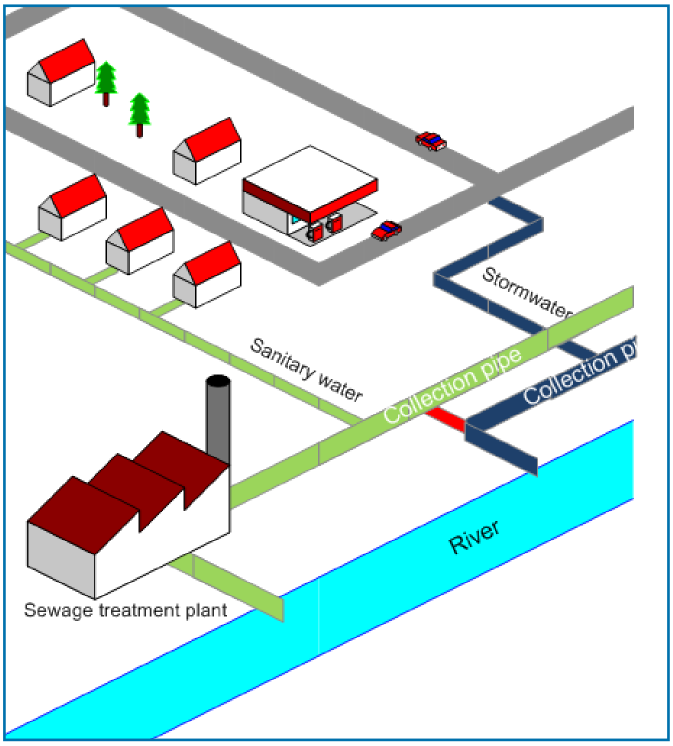


Figure 10: Impression of an improved separated system. Note the (red-coloured) connection pipe between the collection pipes. This is where a one-way valve is situated to prevent sanitary water entering the storm water pipe.

In an ideal situation the sewage treatment plant is located at the lowest point of a sewer network, thereby allowing for all sewage to flow to that point by gravity. This is unfortunately almost never the case, which means that the sewage has to be pumped from collection points to the desired elevation. These large diameter pipes are called rising mains, table 2 shows that the combined length of these mains in the Netherlands is 5.500 kilometer (Stichting RIONED, 2009).

As can be seen in table 2, the value of all existing sewer pipes in the Netherlands is 62 billion Euro, a staggering number. Combined sewer systems are the largest group with regard to both total length and value. The percentage of sewer networks that is constructed as a separated or improved separated system will continue to grow in the future (Stichting RIONED, 2009).

Sewer system type	Length (km)	Value (10^9 €)
Combined	48.500	38
Separated - Sanitary	12.000	6,9
Separated - Storm water	15.500	8,9
Improved separated - Sanitary	5.000	2,9
Improved separated - Storm water	5,600	3,3
Total gravity sewer systems	***86.600***	***60***
Pressure sewer systems	15.000	1,5
Rising mains municipalities	5.500	0,7
Total sewer systems municipalities	***101.000***	***62***

Table 2: Overview of types of sewer systems and their value (Data: Stichting RIONED,2009)

4.2.2 Network layout

Sewer networks consist of a large number of components, most of which are sewer pipes. In the Netherlands households, industries and businesses are connected to sewer pipes that run underneath streets. These pipes then discharge the sewage to larger transport pipes. Different levels of these transport pipes can be present, depending on the size and complexity of the network. The diameter distribution for the combined Dutch gravity networks can be found in table 3. The majority of pipes has a small diameter, as would be expected. Property owners and users are responsible for transport of their sewage to their property boundary. In the most ideal situation the connection point to the public sewer network would be located on the property boundary, this is however not always the case. Often the connection point is found beneath the adjacent public road, which means that the lateral pipe is divided into two parts: one part is the responsibility of the property owner/user, the other part is the responsibility of the municipality.

Sewer networks have a number of branches that service different areas and are divided into different levels of sewer pipes, as can be seen in figure 11. The branches consist of line elements, the smallest element is actually connected to individual properties. Designing such a network is not an easy task; one must also consider possibilities for expansions of the network in the future.

Diameter (mm)	Length (m)	Percentage
250 and below	19.500	24
300	28.000	35
400	13.500	17
500	8.000	10
600	4.000	5
700	1.700	2
800	2.000	3
900	900	1
1000	1.200	2
1100 and above	1.300	2

Table 3: Pipe diameter distribution of gravity sewer networks (Data: Stichting RIONED,2009)

There are two common types of network layouts in the Netherlands. A branch network (figure 11 left) consists of sewer pipes that form branches; sewage is transported to the sewage treatment plant by following a single branch. There is only one possible route for the sewage to take. A mesh network (figure 11 right) is characterised by pipes underneath streets that are connected to a larger collection pipe on both sides. This means the wastewater can be discharged in two directions, this is very useful during heavy rainfall when the capacity of parts of the sewer is insufficient. Combined sewers usually have a mesh layout, as well as rainwater pipes of a separated system. Wastewater pipes of a separated system are usually found in a branch configuration.

Four levels of service pipes can be distinguished and are shown in figure 11:

1 *Lateral sewer: a sewer which collects sanitary water or storm water runoff from domestic, commercial or industrial buildings.*

2 *Collection sewer: a sewer which collects sewage from two or more lateral sewers.*

3 *Main sewer: important sewer which collects sewage from two or more collection sewers.*

4 *Intercepting sewer: a sewer that collects sewage from a number of separated main sewers or collection sewers and transports this to a sewage treatment plant.*

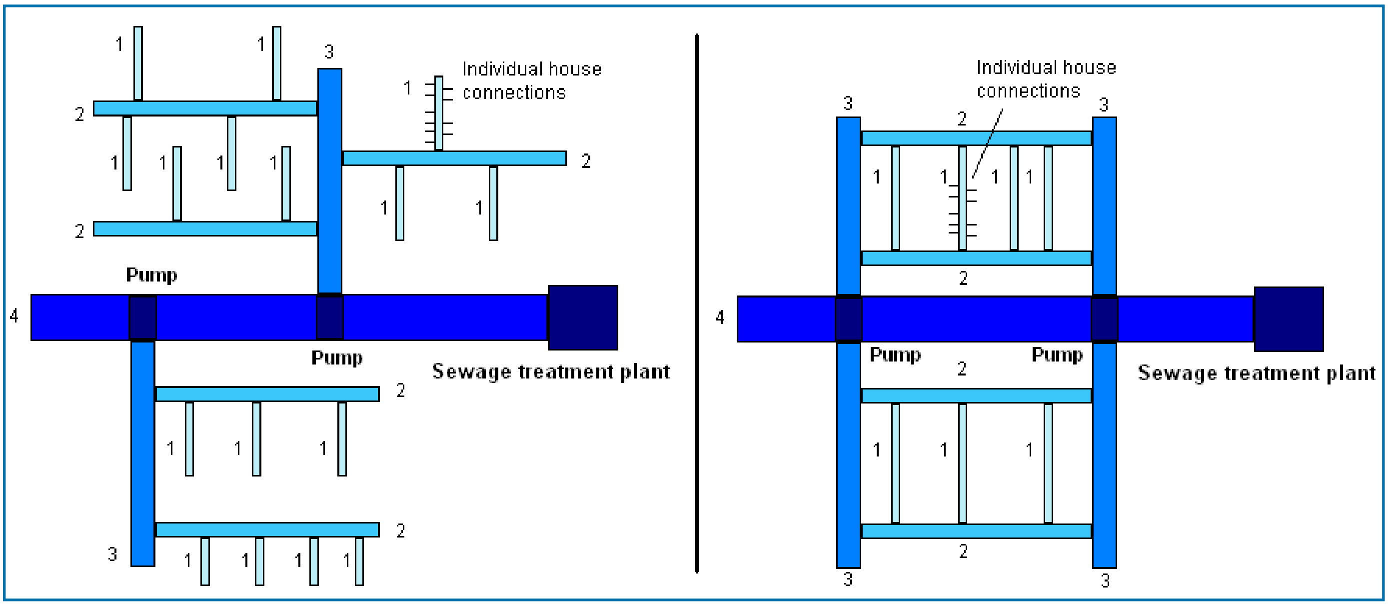


Figure 11: Sewer network layouts: branch network (left) versus mesh network

Note that not all municipalities will have all the mentioned levels of collection pipes; networks of smaller municipalities are usually less complex.
The distinction between the above mentioned pipes is important since these components have different characteristics. Large main sewer pipes for example will have only a small number of connections that come from collection sewers, whereas a sewer pipe beneath a street will have many service connections. An overview of a basic comparison can be found in table 4.
Some pipes in the network may be better suitable for certain maintenance techniques than others, these considerations will be discussed in chapter 6.

Type	Length	Connections	Diameter
Lateral	short	many	small
Collection	medium	average	medium
Main	long	few	large
Intercepting	very long	very few	large

Table 4: Characteristics of different levels of pipes in the network

The only components of the sewer network that are seen by the general public are manholes. These inspection shafts are very important for sewer operation and maintenance. Manholes allow for entry of personnel to inspect and clean the network of pipes that is hidden in the subsurface. The development of trenchless technologies has resulted in the use of manholes for repair, replacement and renovation of adjacent sewer pipes.
Manholes are generally located at intervals of 50 to 100 meters in the Netherlands, this distance is determined by the maximum distance that is possible for inspection and cleaning (Stichting RIONED, 2008). When house connections are directly connected to manholes this distance is usually shorter than when the house connections are connected to sewer pipes. Manholes are also installed whenever there is a corner, a change of pipe diameter, or when there are multiple pipes that intersect.
The manholes used to be constructed from bricks, but nowadays prefabricated concrete or plastics are mostly used. Access can be gained by removing the circular manhole cover, which is usually made from cast iron. In the past there were also square manhole covers installed, but since these can fall down into the manhole (when placed diagonally) they are no longer used. The circular manholes have a diameter of about 600 mm.

Combined sewer systems have the possibility of sewer overflow during heavy rainfall. Stricter rules regarding the surface water quality have forced many network owners

Figure 12: Prefabricated concrete manholes. As can be seen, this type is made out of two prefab elements (http://nl.wikipedia.org/wiki/Rioolput)

to invest in system conversion (to a separate system) or construction of settlement tanks. System conversion however poses a risk since mistakes can be made when separating house connections, resulting in contamination of discharged rainwater. Settlement tanks can retain large amounts of water and act as buffers. During heavy rainfall the tanks can store the additional water load, afterwards they can be emptied by pumps. Table 5 shows the large amount of additional buffer capacity that has been created for combined systems during the last years. Smaller municipalities create relatively more buffer capacity when looking at the buffer per household value.

Municipality size (inhabitants)	Created until 2004 (m^3)	Created 2005 - 2008 (m^3)	Buffer per household (liters)
0-10.000	39.000	25.000	450
10.000-20.000	190.000	110.000	440
20.000-50.000	430.000	230.000	400
50.000-100.000	130.000	150.000	360
>100.000	190.000	100.000	190
Netherlands	970.000	620.000	320

Table 5: Buffers created by municipalities to retain water over the last years (Data: Stichting RIONED, 2009)

Pumping stations are used to transport sewage over longer distances and to a higher elevation. There are currently 13.300 municipal pumping stations in the Netherlands. Pressure sewer systems use smaller pumps to transport sewage throughout the network. These pumping units are numerous; about 115.000 can be found, mostly in rural areas (Stichting RIONED, 2009).

4.2.3 Materials

Most of the sewer networks in the Netherlands are constructed with concrete or synthetic materials, as can be seen in figure 13. Plastics commonly used for sewer pipes are polyvinyl chloride (PVC), polyethylene (PE) or glass-reinforced plastic (GRP).

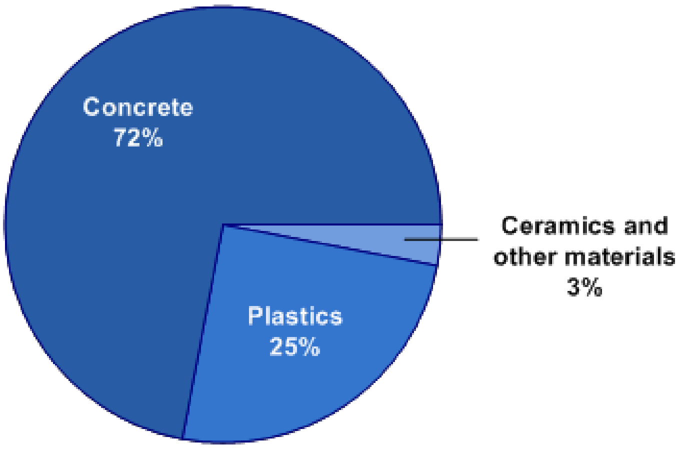


Figure 13: Type of materials that can be found in the existing pipe network (Data: Stichting RIONED)

Besides concrete and plastics, parts of certain networks have been constructed with asbestos cement, ceramics or steel. Health hazards are an important consideration when replacing pipe sections that consist of asbestos cement . Cast iron pipes are sometimes found underneath old buildings, these are usually in poor shape and much in need of replacement. These pipes that consist of polluting materials should not be fractured but should be safely removed.

The type of sewer system has influence on material choice possibilities. Pressure sewer systems require sewer pipes that can withstand pressure and preferably do not have a large number of joints with regard to risk of pressure loss due to leaks. Pressure systems often consist of plastic pipes, which have the additional benefit of being light-weight and thus easy to transport.

Figure 14: Hand-made glazed clay sewer pipe. Found on a plantation in Georgia. Estimated date: mid-1800s (Source: Jon Schladweiler, Historian, Arizona Water Association)

4.3 Responsibilities

In the Netherlands, sewer networks are constructed and maintained by municipalities. At the moment there are 431 municipalities (January 1st, 2010). The so called "*Wet milieubeheer*" (law regarding environmental management) states that municipalities are responsible for "functional collection and transport of wastewater". To make this happen, every municipality has to formulate a "*Gemeentelijk Rioleringsplan*" (Municipal Sewer Plan) periodically, for example every four years. This defines the goals of the overall sewer policy and lists the activities required to reach these goals. Another important component of the "*Gemeentelijk Rioleringsplan*" is the coverage of costs.

Costs that are necessary for maintenance and improvement of sewer systems are paid with municipal taxes, the so called "*rioolheffingen*" (sewage charges). Every year about 1,2 billion Euro is spent by municipalities on sewer maintenance.

While the municipalities are responsible for sewage collection and transport, sewage treatment plants and most of the larger pressurised transport pipelines are responsibilities of district water boards. The district water boards are governmental organisations which are responsible for water management of certain regions. At the moment there are 27 water boards in the Netherlands. An unique organisation in this context is Waternet, which is a joint effort between the municipality of Amsterdam and the district water board Amstel, Gooi and Vecht.

The water boards are responsible for 600 kilometer of gravity sewer pipes and 8.000 kilometer of pressure pipes. These pipelines transport the collected sewage of the municipalities to the sewage treatment plants or they transport the treated water to surface water bodies. Furthermore the water boards operate 2.000 pumping stations throughout the country (Stichting RIONED, 2009).

European regulations are increasingly important for member states, this trend can also be seen in the field of water management. An important directive is the Water Framework Directive of 2000. The aim of this directive is to achieve a good water quality for all waters across the

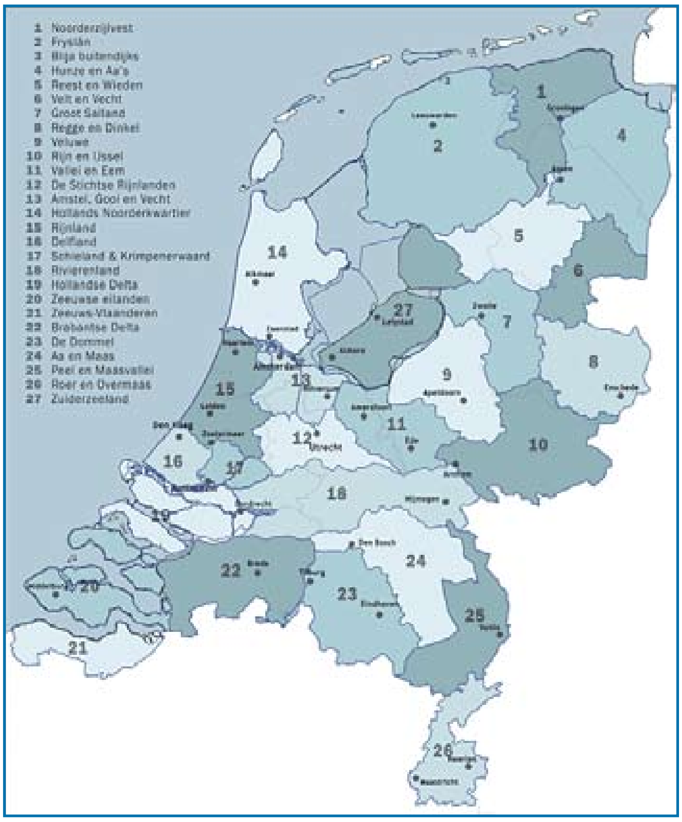


Figure 15: Overview of the 27 district water boards in the Netherlands (Unie van Waterschappen, 2010)

European Union by 2015. This directive obliges member states to improve water quality to an acceptable level. In the Netherlands there already had been an effort to improve water quality with regard to combined systems by implementing the so called "*Basisinspanning*". This policy was aimed at reducing sewage overflows by 50 percent between 1995 and 2005. In order to reach this goal, additional buffer capacity has been constructed for combined sewer systems. This trend contributes to the efforts towards achieving the aim of the Water Framework Directive.

In order to prevent deterioration of water quality, municipalities could be facing increased costs in the near future. Water boards are also affected; additional requirements will be imposed upon sewage treatment. Use of polluting materials by businesses will also be stricter regulated. The Water Framework Directive thus has large consequences for many parties, this will often result in increased costs in order to fulfill requirements.

4.4 Typical difficulties in the Dutch situation

The Netherlands have specific geologic conditions that can sometimes be challenging for construction of all kinds of structures, but also pipelines such as sewer pipes. Part of the country is located beneath sea level, and high groundwater tables are quite common. These specific Dutch difficulties are important to remember when looking at any type of infrastructure system.

4.4.1 Soil conditions

The Netherlands have a varied geological profile, as can be clearly seen in figure 16. This can be challenging when constructing subsurface constructions. The eastern part of the country is located above sea level and has mostly sandy soils. Structures can usually be placed on shallow foundations in this part of the country.

The western part however is located beneath sea level and has many peaty soils. This results in large settlements in this part of the country, many structures therefore have a pile foundation. Subsurface networks such as sewers are obviously also influenced by these settlements. Settlements can greatly reduce the lifespan of components of sewer networks. Large transport pipes and manholes often have a pile foundation to prevent unacceptable settlements, for many sewer pipes however this is not done. It is therefore not uncommon that sewer pipes in certain areas already have to be replaced after 20 years because their discharge capacity is not sufficient anymore because of damage due to settlements.

In order to prevent undesirable leaks or urban flooding because of settlements, municipalities sometimes measure settlements of sewers at regular time intervals (e.g. every 5 years).

Nowadays most new pipes are made out of plastics, which offer better chemical resistance than concrete. These low-weight pipes have another advantage: they incur less settlement than heavy concrete pipes. They should however not be placed too shallow in an area with a high groundwater table; in case of a limited sewage flow this may result in the pipe floating upwards. Design guidelines help to prevent this problem: at the moment a minimum coverage of 1,10 meter is recommended (Stichting RIONED, 2008).

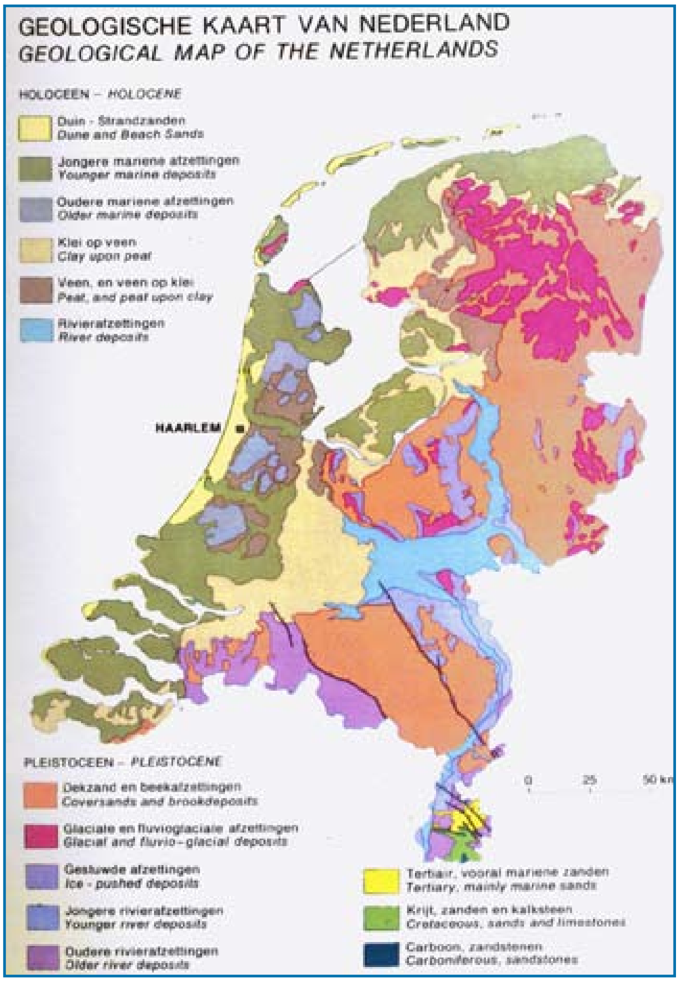


Figure 16: Geological map of the Netherlands (Rijks Geologische Dienst)

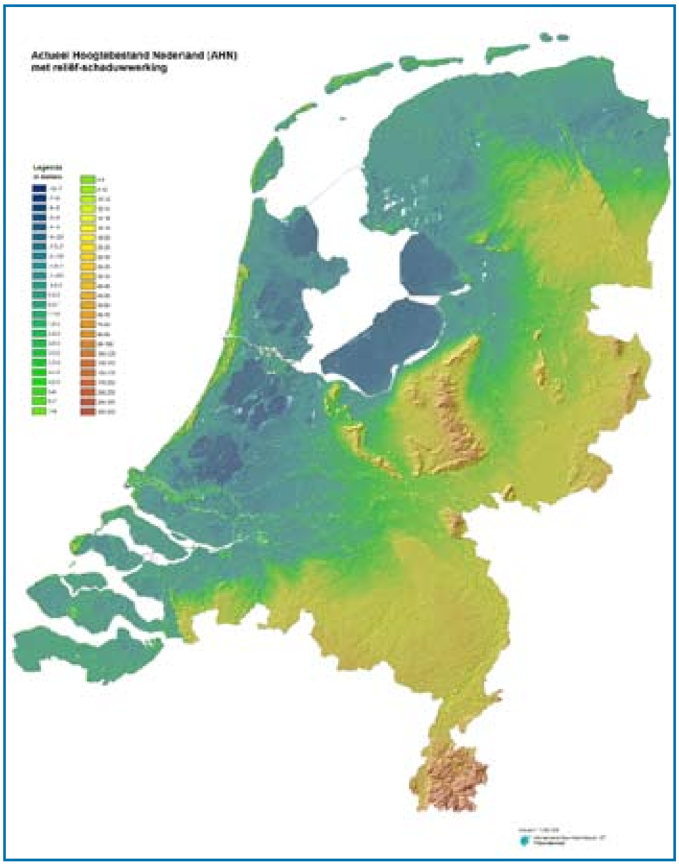


Figure 17: Map showing the height difference in the Netherlands (Adviesdienst Geo-informatie en CT Rijkswaterstaat)

4.4.2 Groundwater table

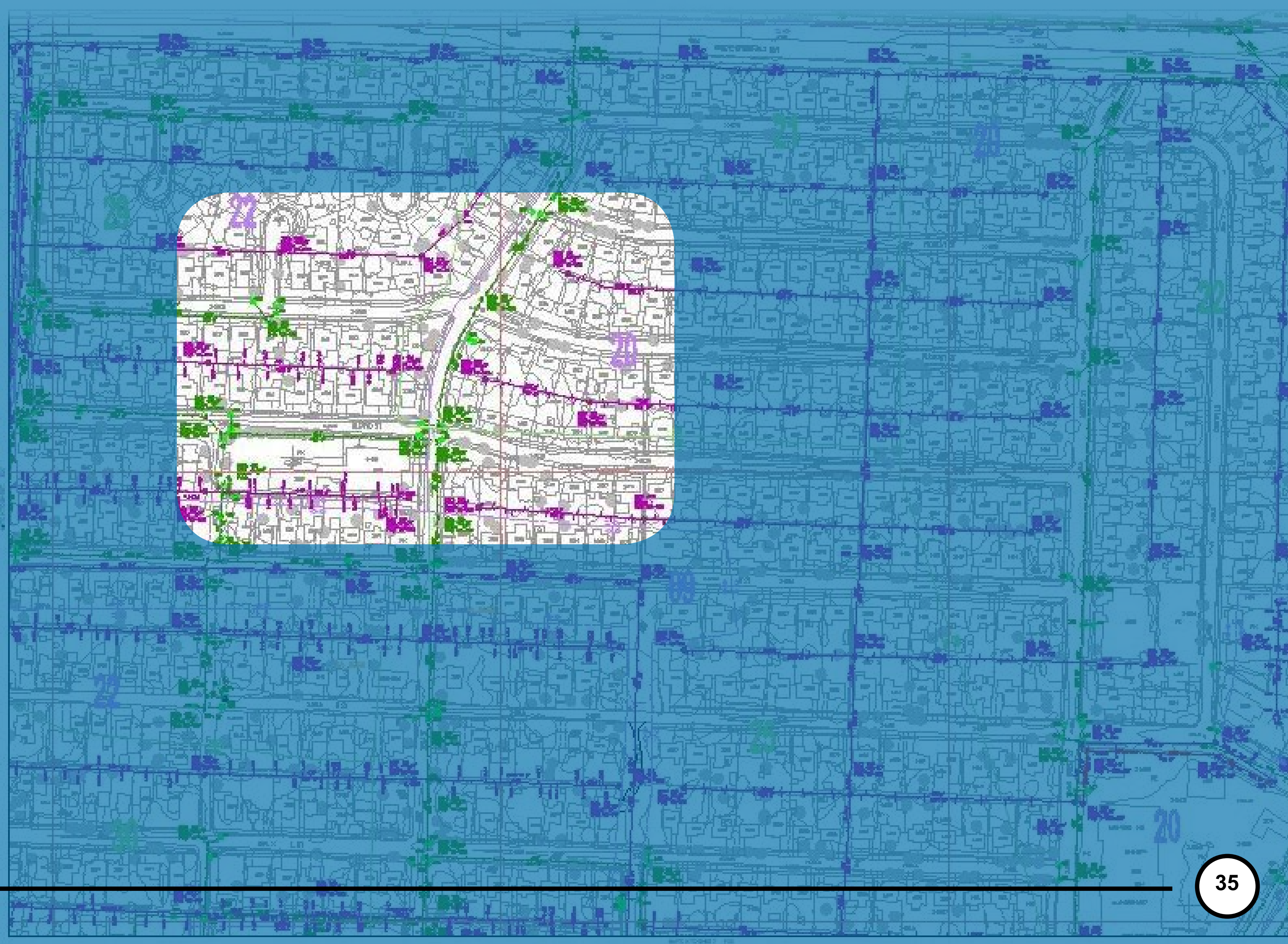
The depth of the groundwater table is an important consideration when working on components of a sewer network. In the eastern part of the Netherlands, the groundwater table is sometimes located at tens of meter beneath the surface level. The western part of the Netherlands shows a very different picture: it is not uncommon to find groundwater only several decimeters beneath the surface. This has great implications for construction activities in the subsurface.

Figure 18: Lowering the groundwater table can result in foundation settlements, resulting in damage (http://www.profoundprofessionals.com)

Large upwards pressures can be an issue when pipes and structures do not have a lot of weight. Furthermore, a high groundwater table poses risks of leakages when digging trenches and shafts. Even though trenchless technologies remove the necessity of digging trenches, sometimes it is still necessary to dig start and exit shafts. These should be able to resist large groundwater pressure and they should be watertight.

Groundwater that leaks into shafts or trenches can result in lowering of the groundwater table. This can result in large settlements, which can heavily damage adjacent buildings and road surfaces. In dense urban environments this can become a large risk when insufficient precautions are taken.

CHAPTER 5: ASSET MANAGEMENT FOR SEWER NETWORKS



Chapter 5: Asset management for sewer networks

5.1 Introduction

Asset management has been increasingly applied to various business sectors. In a number of sectors there is already much experience regarding this topic. Application of asset management to above ground infrastructure is becoming quite well-known. Underground infrastructure has not received this amount of attention, even though an enormous amount of money is needed for expansion and maintenance of this “hidden” infrastructure.

Even though the condition of the Dutch sewer network is not as bad as those in other countries, e.g. The United Kingdom (Read,2004), large problems can be expected in the future if the current approach is not drastically changed. Allocated funds for sewer maintenance and operation are limited and not sufficient to keep the system in good condition.

Therefore a new approach to asset management for sewer networks needs to be developed, taking into account newly developed techniques for repair, renovation and replacement, as well as external costs associated with various activities. Performance and efficiency of the sewer infrastructure could be increased significantly when this development is realised.

5.2 What is asset management?

5.2.1 Assets

Asset management is an expression which is often used in different types of industries. Different definitions can be found, not all of these cover the same aspects. Before asset management of sewer networks is discussed, it is important to explain the term asset management and the definition that is chosen for the purpose of this research. But, first of all, what is an asset (Investopedia, 2010)?

> ***An asset is a resource with economic value that an individual or corporation owns or controls with the expectation that it will provide future benefit.***

Assets can be a great number of things and they can be divided into current assets and fixed assets. When looking at a balance sheet of a company this distinction can always be clearly seen.

Current assets are assets are expected to be sold or otherwise used up in the near future. The near future in this case is usually one year, or one business cycle. The following current assets are usually found on a balance sheet of a company (Wikipedia, 2010):

1. Cash and cash equivalents - these are the most liquid assets. Cash equivalents are assets that can quickly be converted into cash, e.g. bonds, treasury bills.
2. Inventories - goods and materials that are held in stock
3. Accounts receivable - money owed to the company by entities outside the company
4. Prepaid expenses - expenses for future services

Fixed assets can not be easily converted into cash, they are bought by a company in order to be used over an extended period of time. Fixed assets can be of the following types:

1. Property, plant and equipment - for example machinery, vehicles, computers
2. Investment property - for example real estate that is held for investment purposes
3. Intangible assets - assets that cannot be seen, touched or physically measured that are created through time and/or effort. This can be for example copyrights, patents, trademarks or specific know-how.
4. Financial assets - this are financial assets excluding the ones mentioned before (accounts receivable, cash and cash equivalents).
5. Biological assets - living plants and animals

5.2.2 Asset management

Asset management involves handling and optimising the previously mentioned assets and is actually about the central purpose of an organisation. Asset management considers and optimises conflicting priorities upon which an organisation has to make decisions. These conflicts arise between short-term performance opportunities and long-term sustainability, asset utilisation and asset care, capital investments and operating costs (British Standards Institute, 2008b). Asset management considers life cycle costs instead of only optimising costs during a specific phase (e.g. initial costs or maintenance costs).

There are many definitions available for the term asset management. The definition which is used by the Federal Highway Administration (FHWA, part of the U.S. Department of Transportation) is thought to be most suitable for this research (FHWA, 1999):

Asset management is a systematic process of effectively maintaining, upgrading and operating assets, combining engineering principles with sound business practice and economic rationale, and providing the tools to facilitate a more organized and flexible approach to making decisions necessary to achieve the public's expectations

This definition shows the different aspects that are covered by asset management; asset management is located in the area where the technical, economic and process points of view overlap. Asset management strategies help businesses in staying competitive by allowing them to efficiently, effectively and comprehensibly manage their assets. The public sector has started to use and develop asset management strategies as well, this is necessary because nowadays the governmental agencies are forced to be more fiscally responsible than before. Different approaches to asset management have been implemented over the years:

1. Operative based asset management

The most basic approach is operative, which means that operation and maintenance logs are recorded. Failures in the system are fixed and recorded. The failed element can be either replaced or rehabilitated. This method is not always a good choice; significant damage to property or risk to human health care is possible when failures occur. Financially this approach can be inefficient since sometimes it is more expensive to fix something after failure than to repair it prior to failure. The advantage of this approach is the fact that it does not require expensive software tools and a lot of manpower. This approach is probably best suitable for parts of the network that are of relatively low importance (when they fail the effects will be small).

2. Inspection based asset management

The next step is asset management based on inspection. Periodic inspection of the assets provide information about the condition of the assets. This is then used to decide which parts of the system are rehabilitated, replaced or repaired. Assets in the worst condition are fixed first.
At the moment this type of approach is most widely employed by local governments for managing their assets. Available funding is used for the assets which have the worst condition, this is however not the most optimal way of managing assets in the long run. Instead of allowing the assets to deteriorate to a bad condition before action is taken (with a chance that they will fail before they can be rehabilitated/replaced), it may be better to prevent assets from deteriorating to a certain level.

3. Preventative based asset management

This approach relies on the organisation's past experiences and history. These are used to determine fixed intervals for maintenance and rehabilitation/replacement. This approach keeps the assets in much better shape and considerably reduces the chances of failure. It is however important to remember that this approach requires larger investments than the previously mentioned approaches. This investment should not exceed the benefits gained by using this approach.

4. Predictive based asset management

Reliability and performance of the organisation's assets at the lowest possible cost is the key principle in a predictive approach. This approach encourages a better understanding of the system in order to reduce costs. Resource allocation, rehabilitation and replacement planning, and failure prediction have to be optimised and integrated. Therefore this approach is most desirable when looking at overall efficiency. This is the most expensive type of approach however and thus not always the most suitable approach (depending on the possible benefits that can be gained by it).

These four approaches to asset management can be applied to sewer networks, but the question is which approach gives the best results in a certain situation. Predictive based asset management will give most insight and allows for large optimisations. However, this type of approach requires most manpower and the most complex tools, which may undo the cost reductions that are achieved. The most optimal approach depends on the component or part of the network that is considered, the risks involved and the complexity of the network. For a small network it may be completely unnecessary to invest in a predictive based system. A large, complex network may benefit greatly from an expensive predictive based system for its most important pipelines. Relatively unimportant parts of the network (which have low risks attached to them) may be approached by a simpler, less expensive system.
The most suitable approach thus depends on the situation; always a balance has to be found between amount of

money invested in an asset management system and the expected benefits from implementing this system. Risk analysis plays an important role in this as it can identify critical components/areas of the system.

5.2.3 Asset management system

Asset management is applied to an organisation and its activities by making use of an asset management system. This is a framework which provides the organisation with integrated asset management tools that support the decision making process. These tools can be very different from each other and numerous, depending on the type and size of the organisation.

In order for an asset management system to be effective a number of components need to be included (Mehle, 2001):

- An inventory of assets
- A method for assessing the condition of the assets
- Ability to predict the future condition of the assets
- A resource allocation model
- The ability to assign monetary value to assets

It is obvious that a total asset management system can be quite complex; all the components need to be integrated in order to obtain the best possible results. The most complex system is not always the most suitable for every organisation. Complex systems usually require vast amounts of input data in order to generate output. This is not always desirable, especially when a decision has to be quickly made and there is no time for extensive data collection and calculations. Some situations may require "light versions" of an asset management system, which negate some factors but provide a sufficiently accurate result to base decisions on.

5.3 Asset management applied to sewer networks

5.3.1 General

Sewer networks can potentially be very suitable for the application of asset management. Budget for sewer operation and maintenance is limited and in order to optimise the reliability and performance under these constraints the use of asset management is vital.

Existing sewer systems have been expanded and upgraded during many decades. These systems will remain in use for many more decades to come and thus will require many more repair, renovation and replacement activities. Improved decision making can lead to enormous reductions in costs and negative effects when applied during these many years. Furthermore population increase will put even more pressure on these vital systems in the future, thereby increasing the need for efficient management of sewer assets. Population increase may also result in a denser urban environment, which increases the external costs generated by sewer works carried out in urban environments.

Chapter 4 showed the various elements out of which a sewer network consists:

- Sewer pipes
- Manholes
- Pumps
- Settlement tanks

Note that when assets are mentioned, functional components are meant. This means that during the lifetime of an asset, the element that fulfills its function can be replaced numerous times. For example, an asset is a sewer pipe connecting A to B. When this sewer pipe fails and is subsequently replaced by a new pipe, the asset continues to exist (the new pipe is not a new asset). The asset lifetime is thus much longer than the lifetime of a single component. The asset lifetime ends when a sewer section is no longer in use (e.g. because of redevelopment) or when the asset is replaced by another asset that fulfills a different function.

In order to manage these assets as efficient as possible it is important that they are considered as part of the sewer system (instead of stand-alone components). Looking at the relations between various assets allows for more insight into system behaviour and results in optimised decision making.

5.3.2 Components of a sewer asset management system

The previous section has listed the various components of a total asset management system. When we apply this to sewer networks and the assets out of which they consist, this results in the following specific desired components:

1. Asset inventory

The most fundamental component of any asset management system is an inventory that consists of all assets and their characteristics and conditions. This

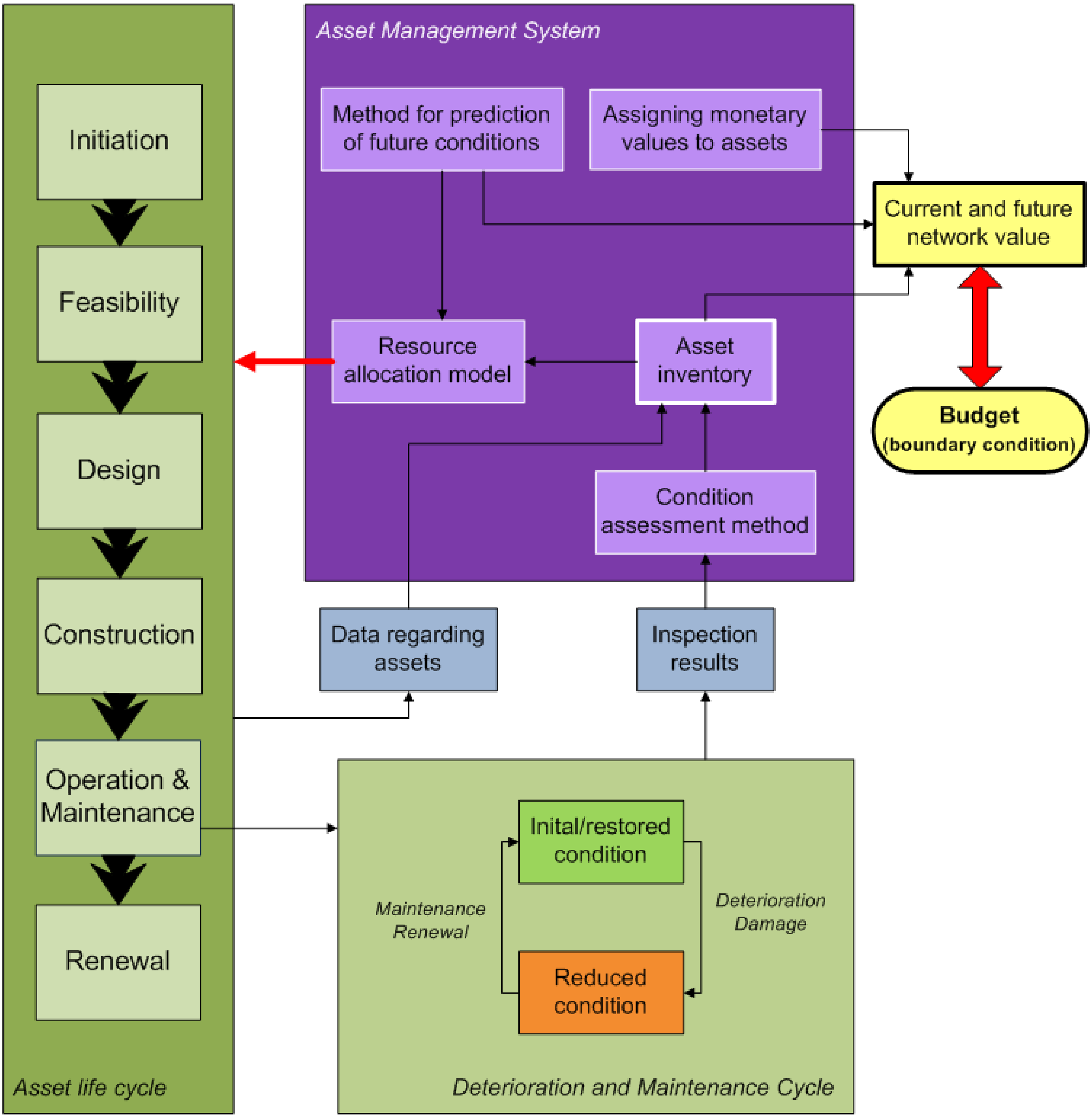


Figure 19:Overview of components of an asset management system and their relations

means dimensions, used materials, inspection dates, maintenance dates et cetera of pipes, manholes, chambers and pumps. A greater number of recorded characteristics will result in a larger, more complex database. Important is that this database is easy to use and to update. A complex system with too much data may result in reduced use of the database. The amount of resources spent on the asset database should not outweigh the added value of the database.

2. Condition assessment method

The scale on which asset conditions are rated should be defined by the responsible agency. A method for determining this condition has to be adopted and used for all the assets in the network. Sewer elements can then be given a condition after inspection results have been analysed by this method. These conditions are used to decide upon future maintenance activities.

3. Prediction of the future condition of assets

In order to optimise future asset maintenance, the sewer network manager should be able to predict the future condition of pipes, manholes et cetera. Future conditions allow for an estimation of future costs and necessary resources. This is a difficult challenge, but over the years a number of models has been developed for this purpose. The problem however is that these are all approximations of the expected lifetime of sewer components. Many factors influence the deterioration process, which makes the actual lifetime very hard to predict.

4. Resource allocation model

When the conditions of assets in the network have been predicted, it is possible to analyse the network to determine necessary activities and funding. This can be done with the help of specialised software. Either the amount of available funding or a minimal level of performance is used as boundary condition. By applying a good resource allocation strategy, costs can be significantly reduced and performance can be greatly optimised.

5. Assigning monetary value to assets

The future condition of the assets can be used to determine the total future value of the sewer network. This allows the manager to see whether value is lost, gained, or stays the same. This can be a basis for determining future budgets.

5.3.3 Focus of this research

As stated before, a complete asset management system is very complex and involves different specialisations. The aim of this research is to look into a specific part of an overall asset management system. Component four, resource allocation, is the key interest of this research. Optimising the decision making process regarding resource allocation to be more precisely.

This research focuses mainly on the managing of physical assets within overall asset management. The public organisations which are responsible for the operation and maintenance of sewer networks receive funds from other public organs, usually local governments. The optimisation and analysis of these cash inflows is outside the scope of this research. For the overall asset management of the organisation these cash flows are ofcourse important boundary conditions, but the focus of this report is on the assets and not on the organisation that maintains and operates them.
The decision making process that is part of asset management of a sewer network consists of many decisions of various complexities and scope sizes. One of the main goals of this research is to identify these decisions and their effects, these findings can then be used to develop a decision support tool.

5.3.4 Decision making levels

Three levels of decision making can be distinguished when looking at an organisation. Getting the right balance between these three levels is essential for optimising overall business efficiency. The three levels of decision making are:

- Strategic
- Tactical
- Operational

Balancing these three levels will help the sewer asset manager to manage his system more proactively.

Strategic decisions

The strategic level deals with the big picture of the organisation. Strategic decisions are aimed at long-term planning and future objectives. The direction in which the organisation is going in the long-term is determined by strategic decisions. Strategic decisions influence the sewer at system level, for example future extensions of the system or relocation of sewer treatment plants. These decisions require large investments that are spent during a number of years.

Tactical decisions

The tactical level consists of decisions on how to achieve the strategic objectives. When the strategic level is explained as “what do we want to achieve?”, The tactical level can be explained as “how do we achieve this?”.
Tactical decisions are aimed at objectives in a shorter time frame than the strategic decisions, usually up to one to three years. In a sewer system the tactical level can be translated to the physical world as being the network level of a sewer system. This means the functional level of a system is usually considered when making tactical decisions. An example of a tactical decision is the upgrade of a large transport pipeline, thereby allowing for increased discharge capacity for a large area.

Operational decisions

The operational level is the micro level; it consists of decisions regarding day-to-day activities. While the tactical level decides how to achieve a certain objective in a general way, the operational level further details this into short-term activities. For example, on the tactical level it has been decided that a new neighborhood will be connected to the existing sewer system. On the operational level this is further divided and detailed, for example: how to construct sewer pipes, which type of manholes will be installed, how houses will be connected in a certain street, et cetera. The operational level thus involves decisions regarding the object level of the physical sewer system.

Figure 20 shows the relation between the previously mentioned decision levels and the physical levels of a sewer system. When making decisions it is important to realise on which level the decision is taken. The possible effect on a higher level of the system should also be known; e.g. when it is decided to replace a number of objects (object level), what effect does this have on the functional (network) level?

Also, when problems are encountered in the sewer system, at which level should this be solved? Instead of replacing or upgrading certain objects, it might be better to make a tactical decision at network level to upgrade or change a part of the network in order to get additional capacity for the future and spend money more efficiently in the long run. Planned system alterations in the near future may solve the problems that are encountered, in which case it may be more economical to not make any investments until these alterations are done.

Insight into various relations between the three decision making levels it thus essential; when the sewer asset manager thoroughly understands this complex web of relations he can greatly improve the quality of decision making.

5.4 Available tools for sewer networks

It was not until the 1980's that researchers started developing decision support tools that were focused on sewer networks. Since then, a number of tools has been developed that support the decision making process of sewer asset management. These tools vary greatly in scope and focus and can entail anything from simple algorithms to complete infrastructure asset management systems. The problem is that especially the more complex tools are rarely used by municipalities, this is probably because of the technical requirements and necessary investments for using these tools.

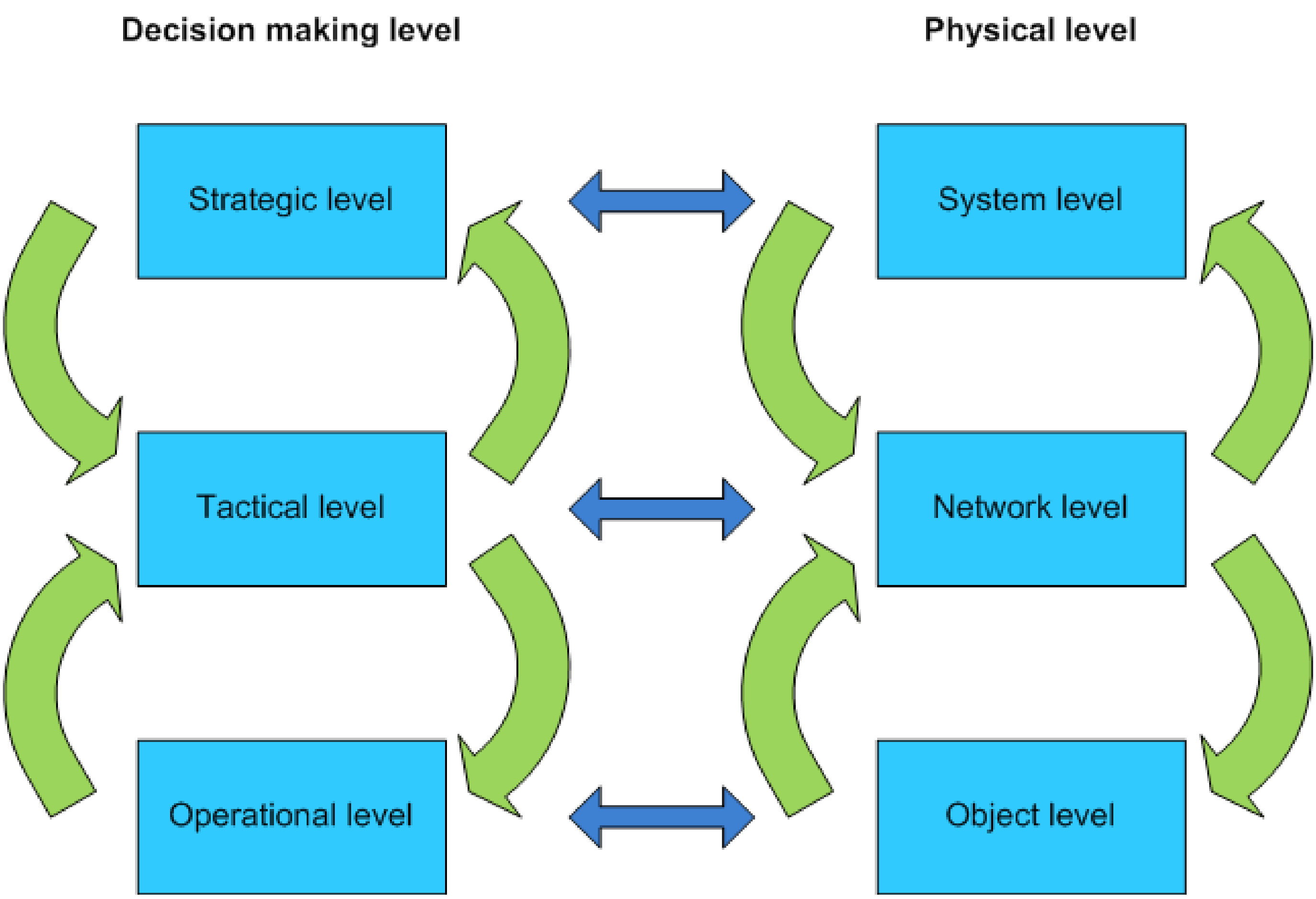


Figure 20: The three levels of decision making with their relation to the physical levels of a sewer system

This section will give an overview of a number of available tools for sewer networks. A distinction can be made between decision support models that are focused on selective inspection of sewers, those that are focused on rehabilitation, and those that are focused on cost forecasting.

5.4.1 Models focused on inspection

There are various models available that focus on inspection. A number of these models were looked into for the purpose of this research. Inspection is used to determine the condition of sewer sections, this allows for decisions regarding maintenance. As was discussed before, the actual deteriorating process is outside the scope of this research. Inspection is however included since there are costs associated with inspection activities (both direct and external). These should be taken into account when looking into life cycle costs of sewer networks. Since there are a number of inspection techniques available (see chapter 6.2), information regarding the choice between inspection techniques and associated costs is necessary. Inspection models were researched in order to find out if such information is already used in certain models.

Baik model (USA)
The idea of the Baik model is to predict future conditions of sewers so that sewer network managers can prepare inspections, rehabilitation and replacement activities in a timely and cost-effective manner. The model estimates transition possibilities in Markov chain-based deterioration models for wastewater systems by using a ordered probit model approach (Baik et al., 2006). Inspections are required to provide information about the structural condition of the existing system. Hydraulic assessment is carried out with the help of models. Furthermore infiltration and inflow are investigated. This model is limited to data collection and performance analysis, it uses inspection data to predict future deterioration. This model does not look into the choice of inspection method unfortunately.

Bengassem and Bennis model (Canada)
Structural and hydraulic conditions of a sewer system are evaluated by applying fuzzy theory (Bennis et al., 2003). Once again, the structural condition is determined by inspection and the hydraulic parameters are derived from modeling. Hydraulic and structural evaluation are then combined to determine a global performance index for each pipe section in the network. This model is focused on determination of pipe section performance after inspection and thus does not contain the inspection process itself.

Hasegawa et al. model (Japan)
The degree of necessity for repairs for existing sewer pipes is estimated by the Hasegawa model. Four aspects are considered: decrease in flow capacity, road collapse possibility, sewer overflow and flooding, and increase in treatment costs due to inflow/infiltration. The examined pipes are given ranks in every aspect. Finally these rankings are combined; pipes with the highest combined rank receive the highest repair priority. This information can then be used to plan maintenance activities.

SCRAPS (USA)
Sewer Cataloging, Retrieval and Prioritizing System (SCRAPS) is a decision support system that uses a knowledge base expert system. The expert system was developed by interviewing experts, operators and managers (Hahn et al., 2002). SCRAPS is developed specifically for small to medium sized sewer networks. The idea behind the system is to focus inspection efforts on the most critical sewer sections of a network. SCRAPS focuses on the likelihood and consequences of failure. Impact on the surrounding is taken into account, this is however from the point of view of sewer failure. The impact from inspection activities on the surrounding, which is interesting for this research, is not included.

SPIRIT (Netherlands)
The SPIRIT project was aimed at developing a program that could predict the deterioration of sewer pipelines, depending on local conditions. The project was a collaboration between Stichting RIONED and several municipal sewer organisations. The program contains a database with inspection results and expert opinions (Rabenort, 2008). The last phase of the project was unfortunately not realised because the required data was not consistent and complete enough. Useful data can be retrieved from the program, but this requires manual adjustments and good interpretation. The model is too limited to be applied on a large scale. More insight into deterioration factors and more data is necessary. When this becomes available the SPIRIT model may be refined and extended in the future.

Younis and Knight model (Canada)
One of the latest research projects into prediction of sewer pipeline deterioration was carried out in Canada. An ordinal regression model based on continuation ratio logits was developed, which provides estimates of conditional probabilities for a pipeline to advance beyond a particular internal condition grade (Younis & Knight, 2010). These estimates depend on pipe material and age. Data from

reinforced concrete and vitrified clay pipes from the city of Niagara Falls, Canada was used to validate the model. One of the conclusions of the research is that deterioration of reinforced concrete pipes is age dependent, while deterioration of vitrified clay pipes is not age dependent. The authors claim that the model provides an accurate estimate for the examined pipes in this city. More research is required to determine if this model could also be applied to different locations and if the model is suitable for other pipe materials.

5.4.2 Models focused on rehabilitation

CARE-S (Europe)

Computer Aided REhabilitation of Sewer networks (CARE-S) is a research project supported by the European Commission under the Fifth Framework Programme. Aim of the project is to develop an integrated tool for functional and structural rehabilitation of municipal sewerage systems. CARE-S aims to analyse the structural and functional reliability of wastewater networks at minimum cost and disturbance. The ultimate product will be a decision support system that will enable municipal engineers to establish and maintain effective management of their sewer networks.

This extensive project lasted for three years and has resulted in integrated tools. Figure 21 shows the general architecture of the system. As can be seen, the system considers structural conditions, deteriorations, hydraulics, socio-economic aspects and available technologies. Since the system is quite extensive it demands large amounts of input data, which can be a disadvantage compared to "light" tools that allow for quick decision support. CARE-S is a very detailed asset management system for sewer networks. Note that there were no Dutch research partners involved in this research project and it is thus not clear if these tools are suitable for the situation in the Netherlands. Furthermore it is not clear whether or not this tool has already been tested in practice.

AQUA-Wertmin (Germany)

This tool allows for maintenance planning and prognostic rehabilitation planning according to German guidelines for cost-minimising maintenance of sewers. It creates deterioration forecasts and helps determine the ideal times to invest in rehabilitating the sewer network. This program makes it possible to determine the investments required for the network to reach a certain condition and also simulates changes in the condition over the course of the defined investment. The right time for rehabilitation can be identified by knowing how deterioration will progress. The rehabilitation planning thus makes it possible to plan for the long-term, to coordinate the rehabilitation work with other measures and to give a measure of predictability to the investments.

The program requires the user to provide input data

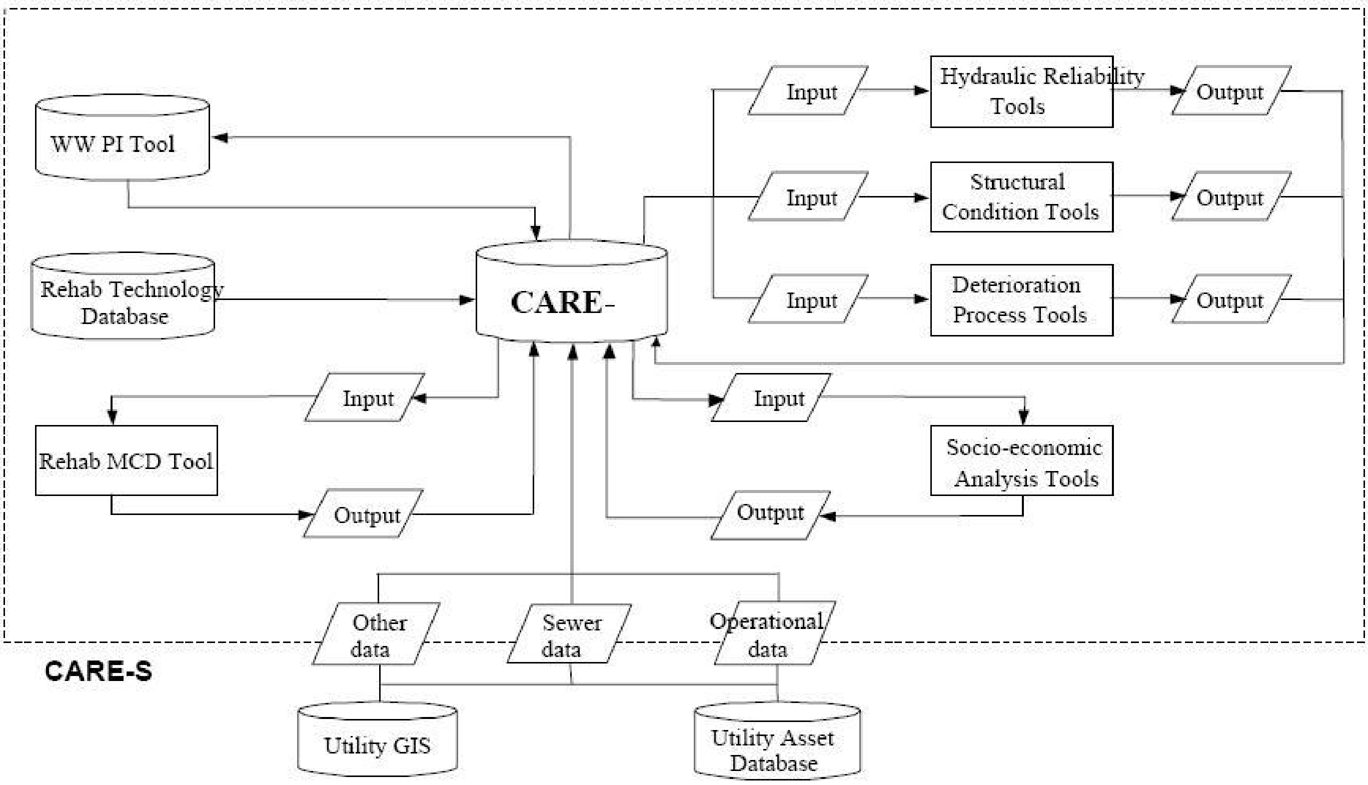


Figure 21:The general architecture of the CARE-S Sewer Rehab Manager (EC Framework Programme 5)

regarding local conditions. This means the network has to be inspected and classified before using this software. Financial parameters regarding techniques and economic conditions are also required. The program does not look into external costs and does not use a database with general cost figures. When it can be accurately customised for a certain municipality it is probably a very useful tool. Disadvantage is the required amount of input data; this means municipalities need to gather a lot of data, which can be costly and time-consuming.

PRISM (Canada)

Proactive Rehabilitative Infrastructure Sewer Management (PRISM) prioritises sewer pipe rehabilitation planning, based on a horizon of budgetary constraints. Pipes are divided into classes, based on certain parameters. A pipe importance factor is then calculated based on type, size and deficiency probability. The program minimises expenditures over a defined planning horizon while utilising all available budget. The pipes with the highest importance factor are first considered for rehabilitation.

APOGEE (France)

This decision support tool uses an expert system to make a diagnosis of the sewer network. Multi-criteria approach is used to define, evaluate and select rehabilitation activities. Technical and environmental criteria are used in this planning process. This tool is already quite old (1989) and is unclear whether this is still used by municipalities.

KureCAD (Finland)

KureCAD uses GIS to manage sewer networks. The tool can store data regarding infrastructure assets, prioritise rehabilitation activities and provide necessary documents for realisation as output. The system is based on a digital map of the network, via which the user can view a wide variety of information. Data from inspections and maintenance are used to give various aspects of pipes a grade from 1 to 4. The program then calculates an overall condition index and shows this on the GIS display. This information can then be used by managers to determine priorities.

HIMA (Canada/USA)

Harfan Infrastructure Management Approach (HIMA) combines a five-step methodology with an integrated decision support system that enhances decision making and provides for asset management by systematic planning, control, expansion, and decommissioning of capital (infrastructure) assets. This method has recently been developed by the Harfan company and can be applied to various types of infrastructure systems.

RIVA (Canada)

RIVA (Real-time Infrastructure Valuation Analysis), developed by Loki Innovations, provides capabilities for long-term asset planning in a 10 to 200 year planning horizon. RIVA is a web-based application that can interface with most common applications. It supports inventory data collection, valuation, determination of deferred maintenance, condition assessment, estimating remaining service life and asset prioritisation. A number of Canadian municipalities is currently using this software.

RioGL (Netherlands)

RioGL is part of the DGDialog software package of the Dutch consultant Grontmij. RioGL is an urban drainage management tool and is currently used by Waternet (Staverman, 2010). The program has a database to in which the entire network can be stored and characteristics can be given to individual components. It supports decision making by linking inspection results to components, thereby giving an overview of the condition of the network.

Three aspects are used to determine whether or not it is necessary to plan maintenance, reparation, renovation or replacement activities. The aspects are watertightness, stability and discharge condition. Each of these aspects receives one of three values based on inspection results: nothing unusual, warning, or immediate action. The program does not give automatic warnings or suggests activities that should be undertaken; it is up to the user to make decisions and check the conditions of parts of the network by using the program. The program can however calculate the flow of water in the entire network by looking at the height values of components. This is useful in order to get a quick impression whether or not the discharge capacity of certain parts of the network or components are sufficient.

5.4.3 Cost estimation models

Burgess (USA)

Markov chain theory has been used by Burgess to probabilistically model the structural condition of sewers. Markov chain theory considers a system which switches among several states, with the next state depending (probabilistically) only on the current state. Burgess evaluated a large number of potential rehabilitation strategies by attempting to minimise a function based on the present value of all sewer condition dependent costs over the planning term. Collapse costs were computed using a failure probability multiplied by the average damage costs associated with observed sewer collapse incidents. A procedure was developed to minimise this cost function. This procedure is repeated iteratively until the range of optimal solutions is reduced to an acceptable size. The model was tested on the City of Hamilton Ohio, which showed that a very aggressive programme of rehabilitation was nearly as costly as the absence of a programme, demonstrating the need to optimise sewer rehabilitation planning. Unfortunately external costs are not taken into account by this method.

Mohanathansan & McDermott (Australia)

Another cost optimisation methodology has been proposed by Sydney Water Corporation. The optimal least cost solution is calculated from a range of sewer rehabilitation and network extension options. The method is designed to compare every combination of sewer rehabilitation in each sub-catchment versus capacity expansion through pipe renewal and treatment plant extension (amplification). Calculation is based upon design flow data, existing sub-catchment data, existing system component's capacity and configuration and cost functions. It does this first using a forward calculation by starting at the upstream end of the system, moving downstream and looking at each possible rehabilitation versus amplification possibility, keeping a memory of the cumulative cost of each possible option combination. Upon reaching the furthest point downstream the option with the lowest cost combination is identified and this is traced back on the decision tree to define the location and extent of the works required. The approach has been designed for planning the wider upgrading of a drainage network based on a consideration of the engineering costs involved. This method allows for testing the cost effectiveness of millions of possible improvements and option combinations. This methodology also does not include external costs, this means the optimal outcome is only based on engineering costs.

El-Assaly & Ariaratnam (Canada)

Deterioration prediction is used by this model to estimate future costs for sewer networks. The City of Edmonton, Canada, was used to implement this model; the local sewer network was divided into groups based on five parameters: age, waste type, material type, diameter and depth. The retrieved data was then used to predict network deterioration. Historical cost data from the city of Edmonton was used as a basis for the forecast of future costs. Note that this model is customised for Edmonton and is thus not applicable to other cities, unless altered by implementing local historical data.

5.4.4 Conclusions

The previously discussed tools differ greatly in scope and amount of input data required. The most complex tool is probably the CARE-S project, which includes a large number of tools for asset management of sewer networks. Unfortunately external costs are not included in most tools, making it impossible to determine the actual cost of projects. Another problem that some tools are customised for a specific location, which prevents the tool from being used in other locations.

For the Dutch situation there is unfortunately no specific decision support tool developed yet. The SPIRIT project was not completed, but may be resumed in the future, thereby providing a tool for predicting conditions. RioGL is used as a tool for storing network data and inspection results. For this purpose it is very useful and it can show many types of data when using different filter settings. However, the user still has to make decisions with regard to required activities. The condition data that RioGL provides is a good starting point for this, the next step in the decision making process is taking into account various considerations regarding possible techniques, specific boundary conditions, available resources et cetera. The aim of this research is to develop such a tool, in order to increase efficiency and get more insight into the large amount of considerations and possibilities that exist. When such a tool would be available, it would be much easier for network managers to make decisions. Another important advantage of such a tool is that it would give a clear overview of all relevant considerations and possibilities. This means that there is no longer any danger of forgetting certain aspects when making decisions (which is possible when there is no methodology used).

Even though the previously discussed tools in this section could possibly be adjusted to fit the Dutch situation, this possibility is not looked into. Creating a new tool from scratch, specifically aimed at the Dutch situation, will probably result in a more accurate and efficient tool. Note that the aim of this research is not to develop a complete asset management system, but to look into the decision support component. This means developing a tool that allows for comparison between various techniques and strategies, depending on the specific situation. External costs will have to be included, thereby allowing for insight into actual costs of activities associated with sewer networks. The required information for the development of a decision support tool will be identified in the chapters hereafter.

CHAPTER 6: TECHNIQUES AVAILABLE FOR SEWER WORKS

Chapter 6: Techniques available for sewer works

6.1 Introduction

Managing a sewer network requires various types of activities. The network has to be able to achieve a certain level of performance. New parts of sewer networks are designed in such a way that they can satisfy performance demands. During the lifetime of the network the various components will start to deteriorate however. This results in reduced performance, which can result in damage to infrastructure, property or public health. In order to prevent these negative effects it is important that the sewer components are kept in good shape, and if necessary, improved.

There are a number of activities that can be undertaken in order to keep the sewer network functional and in good shape. The activities can either be aimed at maintaining the original functionality, or at improving the functionality. The following activities can be distinguished (NEN, 2008):

Maintenance is routine work undertaken to ensure the continuing performance of sewer systems, for example cleaning or inspection. The condition of the component is not altered.

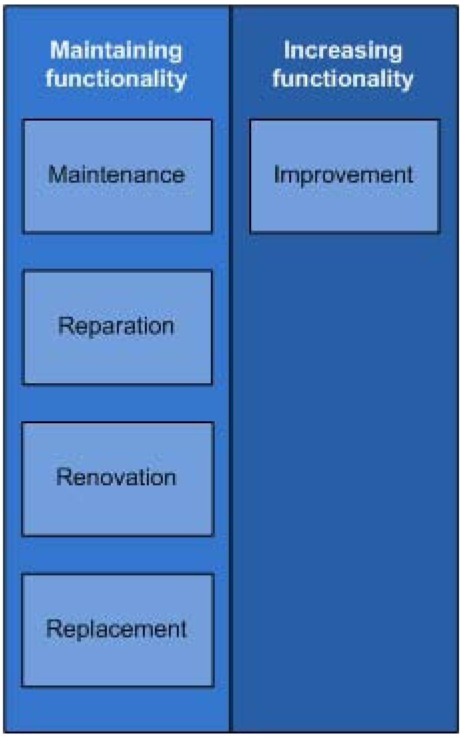


Figure 22: Overview of activity types that are applied when managing a sewer network

Repair involves a small change in condition of a component, this is done in order to repair defects in certain pipe sections.

Renovation (or *rehabilitation*) involves a large change in condition of a component, to a level which equals the condition of a newly constructed component. The lifespan of the existing pipe can be increased by applying renovation techniques.

Replacement involves the removal of the existing component in order to put a similar new component into place.

The previously mentioned activities are aimed at maintaining the original functionality of the component. When the original functionality is insufficient and has to be increased the only possibility is *improvement*. This involves the removal of the existing component, after which an improved component is put into its place. Improvements are meant when looking at large changes that influence parts of the sewer network. Small changes in diameter or hydraulic resistance, which can be achieved by renovation or replacement techniques, are not considered improvements in this context.
Sewer pipes account for the largest physical part of any sewer network. When considering deteriorating sewer pipes, there are a large amount of techniques available with different advantages and disadvantages.

First a number of inspection techniques are discussed in section 6.2. Then repair, renovation and replacement techniques will be addressed. New technologies allow companies to develop even more specialised methods, many of which are patented. The available techniques within these categories are explained in section 6.3.

Besides sewer pipes, one must also consider the activities that are available when considering manholes and house connections. This is important when one wants to look at the entire sewer network. These components will be discussed in sections 6.4 and 6.5. Section 6.6 will make a comparison between the explained techniques for sewer pipes by looking at several characteristics.

6.2 Inspection techniques

Inspection activities are an important part of sewer management. Detecting and classifying defects allows for more focused maintenance efforts and increased efficiency. While many decades ago this was only done manually, nowadays there are different techniques available for sewer inspection. The discussed techniques vary greatly in costs and the type of data they can determine.
Choosing the most suitable technique or combination of techniques is essential when costs have to be minimised and the condition of the network maximised. It is however important to realise that inspection techniques differ greatly with regard to the amount of data they can gather. And how accurate is this data? The exact state of a component can never be determined, inspection techniques can however give a general idea about the current state. Furthermore, how the retrieved data is analysed is just as important for the level of accuracy as the data itself.
The following inspection techniques are currently available:

CCTV inspection

Closed-circuit television (CCTV) systems make use of a television camera which is connected to a video monitor and a recording device. Operators look at the monitor in order to detect defects on the surface of the pipe wall. There are two basic types of CCTV systems: a stationary system which is located inside manholes, or a mobile system.
Stationary CCTV systems look into sewer pipes from manholes, this means that the farther away from a manhole a defect is, the smaller the chance is that it is detected. Defects outside the reach of the camera are missed completely, unless they influence for example the water flow between two manholes.
The mobile system is the most common mean of inspecting a sewer (Makar, 1999). A camera is mounted on a robot which drives through the sewer pipe. The camera generally looks forward while the robot moves through the pipe. Some defects are not detected by this systems, for example defects which are located behind connections or other obstructions. This problem is solved by cameras which can tilt and pan, thus allowing the operator to look behind connections and obstructions. Sometimes ultrasound or sonar modules are attached to the robot, thereby allowing this system to also inspect below the waterline. Another possibility is adding a "light line" attachment, which projects a line of light around the circumference of the pipe. This allows for detection of smaller defects and assessing the shape of the sewer.

Figure 23:CCTV robot with pan-and-tilt possibility (General Utilities Northwest)

The latest development is the use of computer-assisted interpretation in CCTV systems. This reduces operator errors due to fatigue and subjective interpretation.

Laser-based scanning systems

Lasers can be used to determine the shape of the sewer pipe as well as detect defects. This system allows for very accurate inspection of the inner pipe wall. Another advantage is that the gathered data is recorded and analysed by a computer, thus significantly reducing operator errors. Laser-based systems can only inspect above the waterline and require higher initial investment than CCTV. The required inspection time is reduced however, making the operation more economical.

Ultrasonic inspection

Ultrasonic inspection systems make use of high frequency sound waves, which travel into the object being inspected and are reflected when there is a change in density. Cracks can be detected, depending on the size and angle to the incoming sound beam. Cracks which lie parallel to the emitted beam will usually not be detected.
Ultrasonic inspection is also possible for the pipe sections that are below the waterline, the sound waves can however be disrupted or blocked by suspended debris.
While ultrasonic inspection may miss certain cracks and small defects, it is very suitable for quickly detecting deformations, erosion and other problems.

Microdeflections

Pressure is applied to the inside surface of the pipe to slightly deform it. The change in location of the wall compared to the pressure applied can indicate whether there are defects. Care has to be taken when applying pressure to sewer walls which may be below normal strength (even though the pipe is still functioning normally). This technique is restricted in use to rigid pipes where the entire pipe wall will deflect under applied force. Plastic pipes are not suitable since they would deform locally, thereby giving a false positive for defects.

Natural vibrations

This technique involves vibrating the wall at a range of frequencies. This is done in order to determine the frequencies which give the largest vibrations (natural frequencies). Certain pipe sections can be expected to have certain natural frequencies, deviation from these frequencies can indicate defects. The problem is that other effects (e.g. amount of water in the pipe, differences in bedding material/quality) may affect the measurements. More research has to be done into this aspect to determine how these effects can be separated from the effects produced by defects.

Impact echo

A falling weight or a pneumatic hammer is used to make controlled impacts against the inside surface of the sewer pipe. The low frequency surface waves which are produced are detected by geophones, which are also mounted against the inside surface of the sewer pipe. The produced waveforms are then interpreted for possible defects. This manual technique can only be applied to large diameter tunnels that have possibilities for access.

Settlement measurement

GPS is used to measure the height of manholes, this allows for detection of settlements. Uneven settlements of sewer pipes can be detected by comparing settlement values of adjacent manholes.
Uneven settlements cause unwanted stresses in the sewer pipe and possible reduction of the inclination angle. When sewer pipes in gravity systems have their inclination reduced this reduces functionality. Since the GPS measurements are taken on top of the manholes, it is possible to quickly measure many locations in the network without having to enter the pipes.

Spectral Analysis of Surface Waves (SASW)

SASW is similar to impact echo, the difference is that SASW uses more geophones and separates the waves into different frequency components. These components travel at different speeds and penetrate to different depths in the surrounding soil. Thus effects from surrounding soil and effects from pipe defects are easily distinguished, making it a very versatile techniques. Application of SASW is also limited to large diameter tunnels. Future developments are necessary to automate this technique, making it applicable to small diameter tunnels and increasing inspection speed.

Ground Penetrating Radar (GPR)

Radar can be used to detect subsurface voids, rocks and areas of water saturation. Beams of radio waves are emitted, either from surface level or from within the sewer, and are partly reflected when they hit objects with differing conductivity and dielectric constant. This means GPR systems are able to examine the soil behind the pipe wall. Radar can penetrate to great depths in dry sand. The depth of penetration is less when using radar in wet sand or clay.
Ground Penetrating Radar systems generate results which are very dependent on local soil conditions and are not reliable enough. False positives and false negatives occur too often; this will have to improve in order to make these systems eligible for widespread use.

6.3 Techniques for sewer pipes

There are many types of techniques available for sewer pipes. Traditionally sewer pipes could only be replaced by the open-cut method, but during the previous century more options became available due to the development of trenchless technologies. Trenchless technologies were first used in large diameter pipes, in which it was possible for men to enter and repair or renovate them. Long before it was even possible to inspect small diameter pipes with CCTV technology this was happening. Nowadays the available techniques can be applied to various ranges of pipe diameters. Even though the diameter range may be quite large for a certain technique, sometimes they are not economically competitive for larger diameters, mainly because of the large amount of material needed. For example, when cured-in-place techniques (see 6.3.3) are used for large diameter pipes, the required wall thickness results in large quantities of resin needed to produce a structural CIPP liner.
The techniques are divided into three types: repair, replacement and renovation.

6.3.1 Repair techniques

When sewer pipes are only locally deteriorated or damaged it is often most economical to repair the pipes

in these sections. A very general rule states that if less than 25 percent of the sewer length contains structural defects, localised repairs can be economically viable (NSTT, 2001).
Repair techniques can be used as a short term solution but can also repair defects in a structural way. The following repair techniques can be distinguished:

Injection techniques

Leaking joints are sealed by using injection moulds. Two balloons are placed inside the pipeline, on both sides of the leakage. These are inflated and thus prevent fluids and air from entering or leaving. The created chamber is put under pressure, which is higher than the existing ground water table. Either acrylic grout or water-reactive polyurethane is then pumped into this chamber. Water-reactive resin starts a chemical reaction once it comes in contact with ground water. The flexible foam or gel which is created by the reaction fills the gap and infiltrates some distance into the surrounding soil before hardening, thereby sealing the leakage and also enhancing structural stability.

Fill-and-drain techniques

This approach to leak-sealing treats the main sewer, branches and manholes in one operation. The section of the sewer that needs leak-sealing is first isolated from the rest of the network. An environmentally safe chemical solution (usually sodium silicate) is then inserted from a manhole, thereby filling the isolated section. After a predetermined interval, which allows the chemical to permeate through leaking joints and cracks, the chemical is pumped out again. The next step is filling the isolated section with a second chemical solution. This solution reacts with the leftovers from the first solution, thereby forming a waterproof gel. The last step involves pumping out the second solution and cleaning the isolated section.
The advantage of these type of systems is the possibility to treating an entire section of the network in one operation. These systems require a lot of material and plant space on the surface. When there are many leakages present in a certain network section one can imagine that this method can become an economical viable alternative.
One of the most widely used systems was invented in Hungary, however in the Netherlands this technique is not available (Jutte, 2010).

Robot techniques

Remotely controlled robots equipped with cameras can detect cracks and other damages from within the pipe. Robots are mainly used in gravity sewer systems and consist of a grinding module and a filler module.
The grinding module can remove intrusions and encrustations, but also mills out cracks to provide a good surface on which mortar based epoxy can be applied. The robot is controlled from a vehicle on the surface which also contains hose reels, a compressor, a hydraulic power-pack, a hoist for lifting the robot into and out of manholes and other equipment. Nowadays robots can be equipped with different type of tools, making it a versatile system. In order to be economically viable however they need to have regular repair projects; when demand is only sporadic they are usually less interesting. Currently robots can be used in pipes from 200 to 800 mm diameter.

Installation of rings/sealing

Joints are sealed by installing a metal band with an elastomeric material which forms a seal. This repair technique can be applied to both gravity and pressure sewer pipes. The advantage of this technique is that it does not rely on in-situ chemical reactions. Furthermore, there is no curing time, meaning that the seal can be installed quickly without interrupting service for a long time. Material costs are higher than for cured-in-place techniques.
Small diameter gravity pipes (non-man-entry) can be repaired by using mechanical repair units. An inflatable packer is inflated, thereby forcing the ring against the pipe wall. The ring is a scrolled clip which can expand in diameter. The ring is prevented from contracting again by a ratchet mechanism. The outer sleeve is made from rubber and has additional bands of hydrophilic rubber to give a watertight seal. These repair modules are available for pipe diameters from 200 to 600 mm.
Systems are also available for man-entry pressure pipes with diameters from 600 to 3000 mm and up to 20 bar pressure. Besides seals for straight pipe sections, there are also tapered versions available for use between pipes of varying diameter.

Sleeve or patch techniques

Damaged sections of pipeline are covered from the inside with a new lining, which consists of a supporting material impregnated with synthetic resin. A mould construction is used to bring the liner into position. The inner chamber is then pumped up, which results in the liner being fixed to the inside of the pipe. The synthetic resin hardens after a certain time and sometimes a temperature increase is necessary (both thermal-cure and ambient-cure systems are available). These repair techniques are basically short versions of CIPP systems (see section 6.3.3).

After curing the mould is deflated and removed. The new lining is then inspected by CCTV to make sure that the quality meets the requirements. Lateral connections are reopened if necessary.
The used resin can be a polyester resin or an epoxy resin, usually epoxy resin is used since these are not adversely affected by water prior to curing.

6.3.2 Replacement techniques

When using replacement techniques, the existing pipe is removed or destroyed and subsequently replaced by another pipe. There are four types of techniques that fall in this category; three trenchless techniques and the traditional open-cut method.

Open-cut (or trench) method
The oldest method of sewer construction and replacement is the open-cut method. When looking at replacement, this means that the old pipe is dug up and taken out. Subsequently a new pipe is put into place, the trench is backfilled and the road above is repaved. This technique is very straightforward and a new pipe can be placed quite fast, especially when it is placed in a shallow location. Sewers that are placed at a deep level require deep trenches, which means a lot of soil has to removed and backfilled again. Furthermore deep trenches will have the tendency to collapse (there is usually not enough room for a natural slope of the soil), which means additional measures will have to be taken to prevent collapse of the trench. A high groundwater table (which is quite common in the Netherlands) is another problem. One of the largest disadvantages of the traditional open-cut method however is the amount of nuisance caused by it. External costs can be very high when digging a trench in a busy urban environment; trenchless methods are usually preferred here.

Pipe-cracking (or pipe-bursting) method
The pipe-cracking method consists of a cone-shaped head ("crack-head"), which is inserted into an existing pipe and forced through it. Since the crack-head has a larger diameter than the existing pipe, the existing pipe is fractured and its fragments are pushed into the surrounding soil. This technique is aimed at brittle materials such as cast iron, clay ware and unreinforced concrete
Connected to the rear of the crack-head is the new pipe, which immediately replaces the old pipe. The front of the crack-head is connected to a winching cable or a pulling rod assembly. The cable or rod assembly is pulled from the reception pit.

Figure 25: Pipe-cracking, clearly showing the new pipe section attached to the rear of the crack-head (Trenchless Australasia)

Often the front part of the crack-head is slightly smaller than the existing pipe diameter, which means it can be placed within the existing pipe. This is done to maintain alignment and to ensure a uniform burst.
It is possible to add sectional ribs, expanding crushing arms or sharp blades to improve the bursting capability of the head or allow bursting of different materials. When using blades to cut the existing pipe this technique can

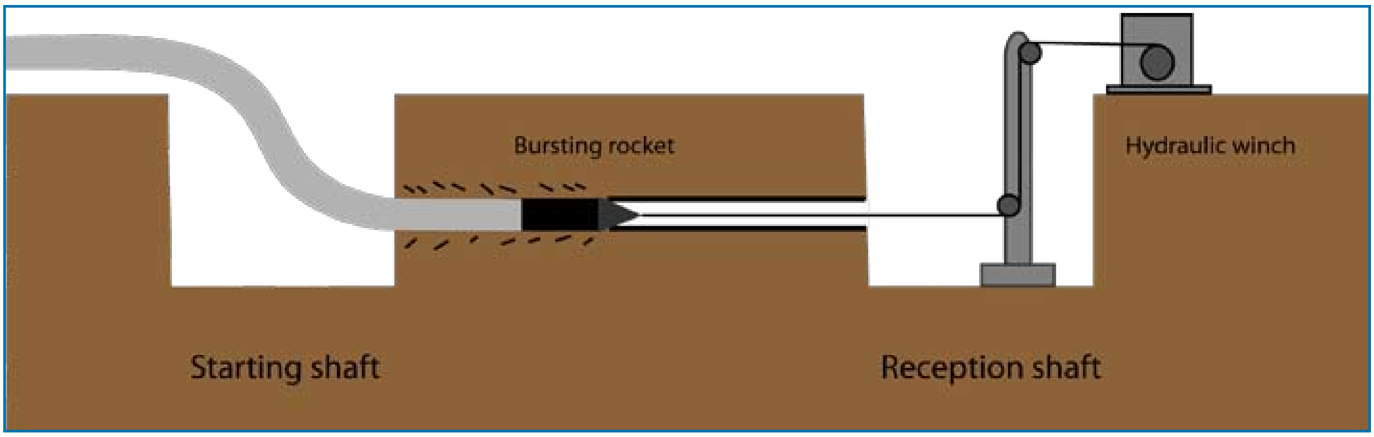


Figure 24:Pipe-cracking method

also be applied to steel, ductile iron, asbestos cement, PVC and polyethylene pipes.

Currently there are three types of pipe-cracking available: pneumatic pipe bursting, hydraulic expansion and static cracking. These are based on the type of bursting head used. Pneumatic pipe-bursting is used in most projects. It relies on a pneumatically driven hammer that repeatedly strikes an anvil at the nose of the bursting tool, causing the crack-head to move forward.

Hydraulic expansion bursters are usually shorter than pneumatic bursters. Sometimes this makes it possible to replace the old pipe from existing chambers, this means there is no need for excavation of start and reception shafts. New short pipes which can easily snap together have been developed for these circumstances.

Pipe-fraising (or pipe-eating) method

Instead of cracking the existing pipe, the pipe is fraised away with a bore head. This is the same technique as used in closed front boring (microtunneling). The rear of the bore head is connected to the new pipe, which is pushed in from behind. The start shaft is equipped with a construction which can withstand the forces which occur during boring.

The boring head is equipped with a "guiding head", which is smaller in diameter and fits within the existing pipe. This guiding head ensures that the new lining will follow the old lining.

The diameter of the new pipe can be the same as the diameter of the old pipe or even larger. In case of a larger diameter, the boring head not only removes the old lining but also some soil (like in microtunneling).

The material which is removed is transported through the new pipeline. When the new pipeline is in place, the bore head can be recovered from the reception shaft.

The latest systems even allow replacement without interrupting the flow of sewage. During installation, the sewage flow is transported through the shield separately from the slurry containing the destroyed pipe and soil.

This method is suitable for replacing clay ware, concrete, asbestos cement, GRP and even reinforced concrete pipelines. When reinforcement is expected the cutterhead is adapted with special cutter teeth.

Pulling and replacing

The existing pipe is dug up at certain locations and uncoupled. From a start shaft a cone is brought into the uncoupled end of the pipe. This cone is connected by a cable which runs through the pipe to the reception shaft. At the rear of the cone a new pipe is connected. Via the steel cable the cone is pulled through the old pipe, which is removed and at the same time replaced by the new pipe. This technique is used for small diameters, e.g. house connections of gas networks, but not for diameters that are common for sewer pipes. This technique is thus not used for the replacement of sewer pipes, at least not in the Netherlands (Jutte, 2010), but perhaps it could be a viable alternative to the previously mentioned replacement techniques once it becomes available for larger diameters.

6.3.3 Renovation techniques

When applying renovation techniques, the old pipe is used and its lifespan is increased. This can be done by either installing a smaller pipe inside or by applying a coating on the inside of the old pipe. There are a large number of renovation techniques available these days, some of which are patented. The following eight techniques will be included in this research:

Plate parts

Pre-formed liners can be made from various materials, either in one piece or in segments. Spacers are used between the liner and the existing pipe to guarantee a correct alignment. The space in between is then filled

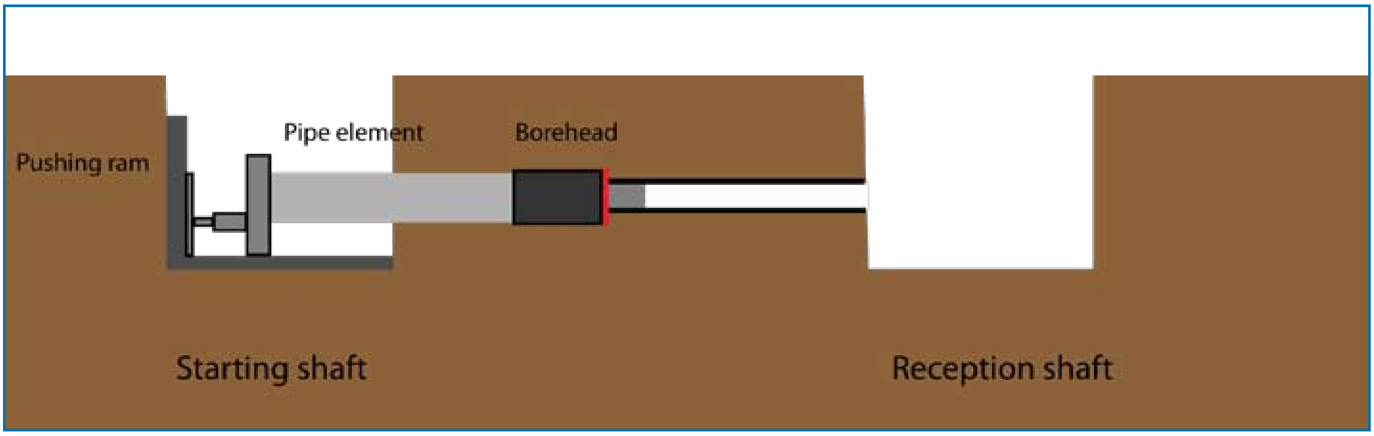


Figure 26:Pipe-fraising method

with grout. The disadvantages of prefabricated liners are the greater reduction in cross-section and less flexibility than in-situ liners. The advantages are high strength and good hydraulic performance. Furthermore pre-formed liners guarantee a certain quality level, whereas the quality of in-situ methods depends often on the quality of execution. Material possibilities include GRP, GRC and ferro-cement.

Glass reinforced plastic (GRP) liners are usually made from glass-fibre strands within a polyester resin matrix. Other types of resin can be used for specific applications. There are systems that incorporate fillers in the matrix, such as sand, to increase stiffness. Any size and shape can be created with GRP. After installation the gap between liner and wall of the existing pipe is filled with grout. Grout can have different functions; in some systems it only holds the liner in place, while in other systems the grout forms a composite structure with the host pipe.The advantages of GRP include light weight and high resistance to most chemicals.

Glass reinforced concrete (GRC) is used for creating structural liners with high compressive, tensile and flexural strength. Liners can be formed from segments or made out of one piece. As with GRP liners, any shape and size is possible. Material costs of GRC liners are lower than of similar GRP liners, they are however heavier. This may result in higher handling and transportation costs. Resistance to certain chemicals is not as high as those of polymeric liners.

Prefabricated liners can also be made from ferro-cement. Prefabricated ferro-cement liners are not widely used at the moment, but it can be seen as a viable alternative to GRC and GRP.

Sliplining

Sliplining involves a prefabricated pipe which is placed inside the old pipe from a start shaft. The old pipe is inspected and thoroughly cleaned, then the new pipe is pulled in with a cable from the reception shaft. The diameter of the new pipe is smaller than the inner diameter of the old pipe. The gap between old and new pipe can be filled with a low-shrinking mortar. Most types of pipes can be pulled (or pushed) into the old pipe, depending on the strength of the joints. The development of polymeric pipes, especially fusion-jointed polyethylene, has increased the popularity of sliplining. Polyethylene is currently the most common choice for sliplining; it offers the advantages of being sufficiently flexible to negotiate minor bends during installation and being abrasion resistant.

A distinction can be made between long and short new pipes. When using short pipes the joints between the pipe sections have to be sealed on site. These joints must be able to withstand the pulling forces during installation. The fusion can take place within the start shaft or on the surface. Fusion on the surface allows for assembly of long pipe strings which can be pulled in quickly to minimise interruption of service. Since the curvature of the pipes is limited this requires a large area, which is not always possible.

Besides fused joints it is also possible to use screw joints and snap-fit joints. Screw joints can be applied to pipes made out of polypropylene and result in a reliable, quickly assembled joint. The disadvantage is the increase in manufacturing costs. Snap-fit joints are usually not able to withstand high tensile forces; when they are used the sewer pipes are pushed in from the start shaft by hydraulic rams instead of being pulled in.

Sliplining allows for relining of both pipes with circular sections and pipes with non-circular sections.

Winding pipe method

The winding pipe method places a new pipe made out of a PVC strip inside the old pipe. The PVC strip is transported to the job site on a coil, where it is fed into a special machine which winds the self interlocking strip into a new pipe. This machine is placed in the start shaft, at the end of the existing pipe. While the PVC strip is winded into a pipe it is pushed inside the existing pipe. When rehabilitating

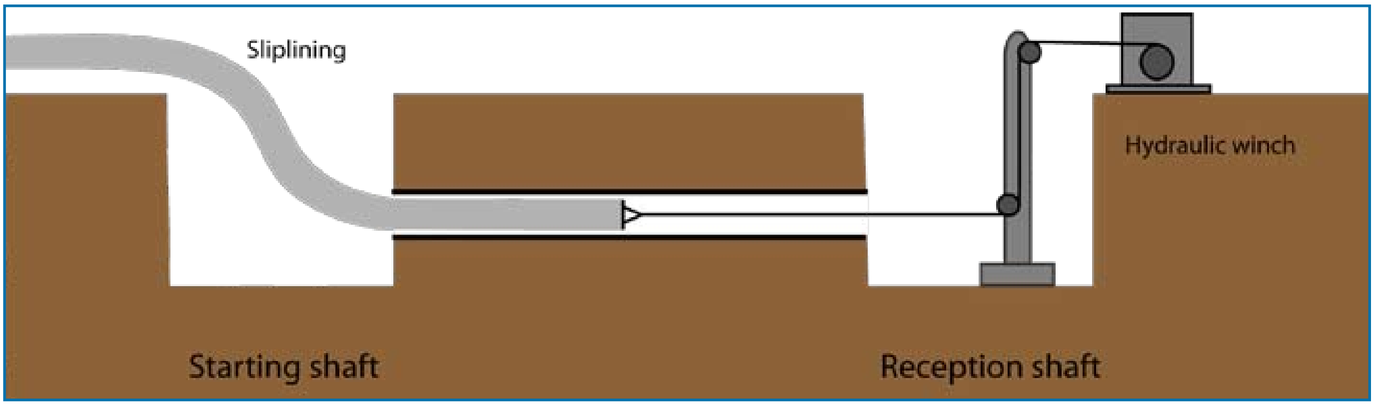


Figure 27:Sliplining method

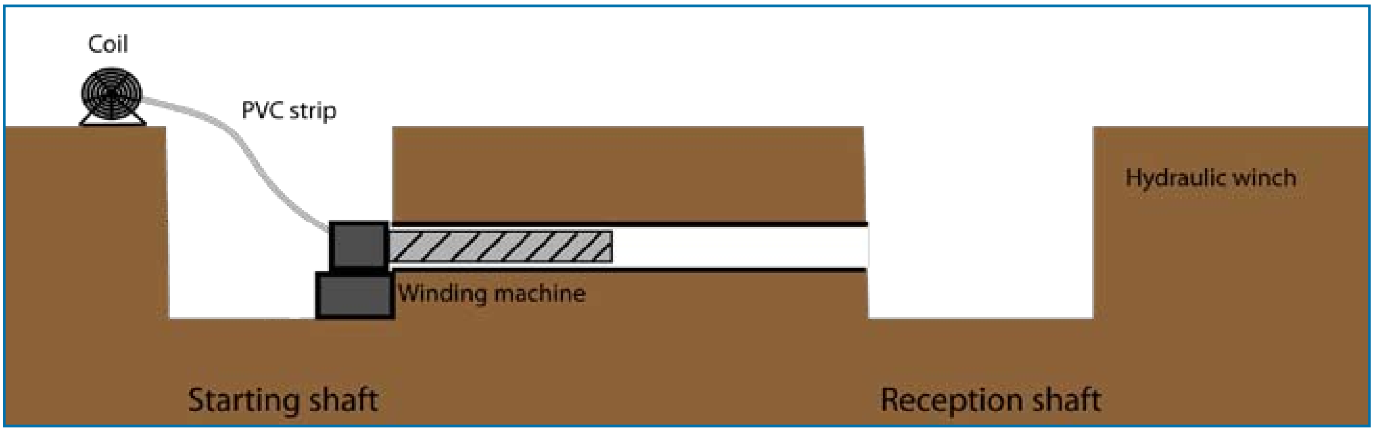


Figure 28:Winding pipe method

large diameter pipes it is also possible to manually wind the pipe into place. The strip has a rubber sealing in the direction of the closing joint of the PVC, which guarantees waterproofness of the new pipe.
After the new pipe has been placed inside the old pipe, the gap between the pipes is filled with grout or mortar. Sometimes this filler is essential for the strength of the composite new pipe.
By changing the dimensions and shape of the guide frame of the winding machine, both circular and non-circular pipes may be renovated. Diameters up to 3000 mm are possible with this technique, furthermore it is possible to install winded pipes in existing pipes that remain in operation (this is only possible with limited sewage flows).

Close-fit method

As the name suggests, the close-fit method places a new pipe within the existing pipe without any space in between. This means the close-fit method reduces the pipe diameter by only the thickness of the new pipe. The close-fit method can be used to install structural or non-structural liners.
Before inserting the new pipe, the existing pipe will be cleaned and inspected thoroughly. The exact inner diameter of the existing pipe is determined during inspection.
It would be impossible to pull the pipe into position when there is no space between the old and the new pipe. There are two options for solving this problem:

1. Mechanical treatment on site of PE pipes; this is done by moving the pipes through moulds. These moulds reduce the diameter of the new pipe, thereby enabling the pipe to fit into the existing pipe. After the pipe is brought into position, bulkheads are placed at both pipe ends. The pipe is then put under pressure by either water or air and sometimes heated. This results in the pipe returning to its original diameter, thereby closely fitting against the inside of the old pipe. Polymeric materials tend to have “memory” and regain the shape and size at which they were extruded. The diameter reduction by using moulds is limited by material properties, which means that this technique is not suitable for sewer pipes that have large dimensional irregularities.

2. Mechanical deformation or folding of PE and PVC material; either in an industrial way or on site.
The new pipe is folded into a U or C shape and can thus be easily installed inside the old pipe. Water or air pressure is used to return the pipe to its original size. Additionally, PVC pipes require heating treatment in order to become flexible, which is necessary to mould to the shape of the host pipe. Groundwater infiltration can be a problem since it can prevent the liner from adapting to the shape of the host pipe.
Pipes which are deformed on site need to be welded, which can be a disadvantage, Factory-folded liners are delivered on coils and do not need welding.

Polyethylene can be used for gravity and pressure pipes, whilst PVC is only suitable for gravity pipes. Currently PE liners are available in diameters up to 450 mm (factory folded) or 1600 mm (folded on site), Folded PVC liners are available for the 100-350 mm diameter range.

Wick-method

Also known as cured-in-place-pipe (CIPP), insitu lining or soft lining. A flexible wick is used as new lining. The wick can be industrial or made on site and is impregnated with an epoxy or polyester resin. The wick is lowered into a manhole and expanded into the existing pipe by using air or water pressure. It is also possible to pull the wick into

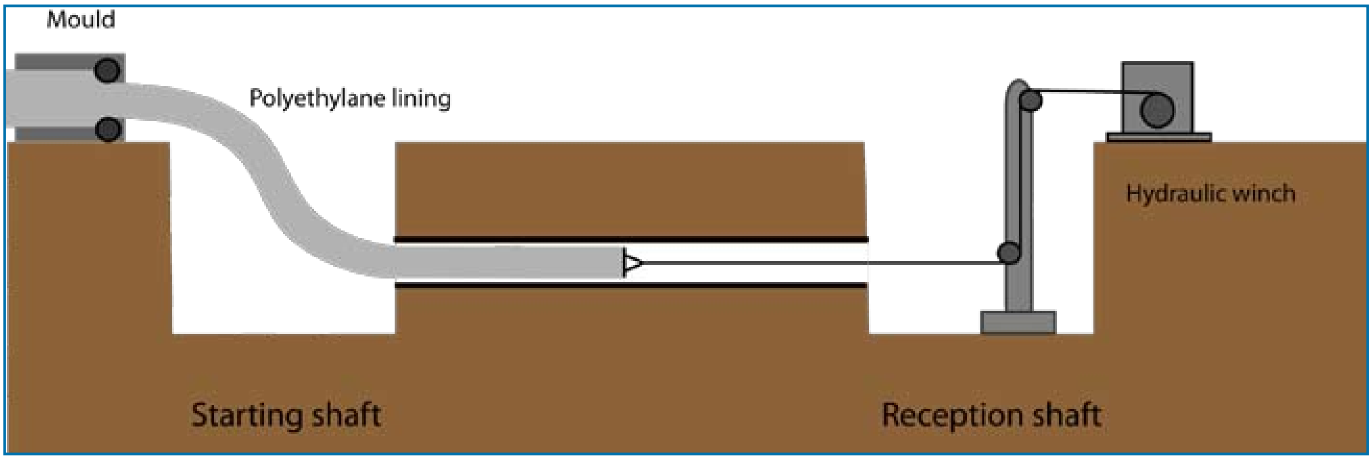


Figure 29:Close-fit method

position. The air or water pressure turns the liner inside out as it travels through the host pipe. The head of water that is necessary is usually obtained by constructing a scaffold tower over the insertion manhole. When relining deep sewers this is not always necessary. The pressure pushes the wick against the inner wall of the existing pipe. Subsequently the water or air is heated and re-circulated to harden the resin, resulting in a plastic pipe. There are systems available that use ultraviolet light instead of water or steam to cure the resin.

The new plastic pipe has some structural strength, depending on the thickness. The host pipe restrains the new pipe, increasing ring-stiffness. Not all systems rely on this connection however.

These systems have the advantage of being able to form to almost any shape. Non-circular cross-sections are no problem if the required dimensions are measured correctly. The limitation of this type of system is the wall thickness which may be required for large pipe diameters or when severe loading conditions are to be expected.

When the main pipe has been relined the lateral connections can be reopened. Nowadays there are also CIPP systems on the market which can reline laterals from within the main pipe.

Polyester resins may be negatively affected by water until they are cured. This can be a problem when there is infiltration or when it is not possible to temporarily stop incoming sewage flows from laterals.

The host pipe needs to be taken out of service during installation and curing of the new liner. In gravity systems it may be possible to temporarily plug certain pipes when there is sufficient storage capacity in the system.

Besides CIPP systems that rely on heating, there are also ambient-cure lining systems that do not need heat sources. Therefore they tend to be less expensive than the thermal-cure systems. Because of the low capital cost of equipment, the ambient-cure lining systems have become popular with many small contractors. The properties of the new liner are usually not equal to those of a thermal-cure liner and there is no external control on the curing cycle. These systems are therefore only suitable for small diameter sewers (<150 mm) and short lengths.

Flexible hose (or hose lining)

This method uses a flexible plastic hose, which is folded before being pulled into the existing pipe. The hose is

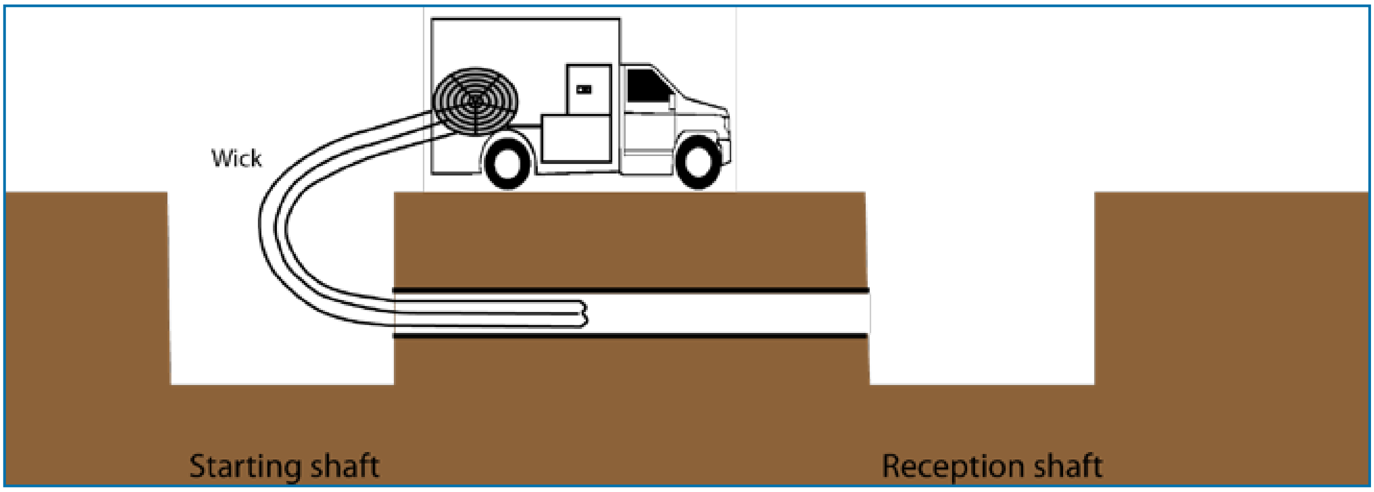


Figure 30:Wick method

connected to the existing sewer system. When the hose is taken in use, the pressure of sewage water running through the hose will unfold it. The hose is then pushed against the inner wall of the existing pipe.
In order to keep the hose in place, some techniques rely on heat to harden the hose while others use stitches to connect the hose to the existing pipe.

Spray lining

Instead of a new pipe which is placed inside the old pipe, spray techniques apply a coating to the inner wall of the existing pipe. This coating can consist of cement, concrete or resin.
Before applying the coating it is important that the pipe is cleaned thoroughly. There are various techniques available for this purpose. When the pipe interior has been cleaned a new layer of coating is applied to the inner pipe wall.
When considering man-entry size pipes, sprayed concrete is often manually applied to old brickwork and masonry pipes. The technique is used to create a new inner skin for the pipe, which enhances strength, prevents loss of mortar and reduces leakages. After application the concrete is trowelled to produce a smooth surface. For non-man-entry size pipes a so called rig is used, which contains a sprayhead that rotates along the inner wall. The rig can apply a coating of either cement or resin.
Cement mortar lining is widely used as a coating material and is relatively inexpensive. Flow characteristics are improved due to the reduced hydraulic roughness of the internal surface. An additional advantage of the use of cement is its alkalinity, which prevents corrosion of iron pipes. The thickness of the coating layer has to be large enough to create an alkaline environment when iron bars are present. Cement mortar coating usually has a thickness of about 3-10 mm.
Epoxy coatings are much thinner than cement mortar coatings and therefore do not cause significant reduction of the inner pipe diameter. Application and curing of the coating also take less time than cement mortar coatings. The disadvantage however is that careful quality control is needed during application and curing in order to prevent defects. The epoxy, unlike cement mortar, does not create an alkaline environment. This means that in case of a defect it is not possible to chemically prevent corrosion. A layer of 0.5-2 mm is usually applied to the host pipe. Such coatings can be applied to steel, concrete and fiberglass.
The entire coating process can be repeated as often as needed, making it a versatile technique. Note that spray lining is however not suitable for pipelines with structural defects or leaks.

Figure 31: A CIPP liner has been inserted from a manhole and is now being cured (AOC Resins)

Reinforced concrete

Reinforcing steel is fixed to the existing sewer wall and lightweight formwork is then placed, usually in sections of two meter wide that are connected with pins. Concrete is pumped behind the formwork, creating a monolithic lining. Lateral connections can be kept intact by using adapted shutters for the formwork. The resulting concrete lining has a smooth finish with low hydraulic roughness.
A similar looking technique uses ferro-cement. Layers of steel mesh are fixed to the existing pipe wall and a mortar is then applied over and through the mesh. The new liner relies on a bond between the old pipe and the applied mortar. The new reinforced lining offers high strength and crack control. Ferro-cement may appear similar to reinforced concrete, but its properties are different. Thanks to the composite action between the steel mesh and the cement matrix, it has higher flexibility and resilience than most concretes. Both reinforced concrete and ferro-cement can only be applied to man-entry size pipes.

Figure 32: Shotcrete (sprayed concrete) lining applied to a corrugated steel sewer pipe in Ottowa, Canada (Environmental Science & Engineering Magazine)

The main advantage of these techniques is the ability to conform to changes in shape or dimensions within any pipe. This minimises the reduction of inner pipe dimensions and amount of grout needed. Liners that are pre-formed have to be able to fit the minimum dimensions of a section and can not conform to every change in shape or dimension.

Both these techniques are however highly dependent on the quality of workmanship within the pipe. Furthermore the structural performance of the new liner may be difficult to assess, especially when renovating pipes with an unusual shape.

6.3.4 Overview

The previously explained techniques are quite different from each other; it is therefore important to understand their advantages as well as their disadvantages before making decisions about which techniques to apply in a certain situation. In order to give a clear overview of the various techniques, their main advantages and disadvantages have been summarised in table 6.

Technique	Advantages	Disadvantages
Injection	• No start shaft necessary • Short interruption of service • Small amount of material needed • Structural stability is enhanced because of some infiltration into surrounding soil	
Fill-and-drain*	• A large network section with many leaks can be treated at once • Main pipes and laterals can be treated at the same time • No start shaft necessary • No need to exactly locate all leaks	• A lot of material is necessary • A lot of plant space is necessary on the surface • Long interruption of service • Many pipes and laterals need to be sealed
Robot	• Can remove intrusions and encrusta-tions • No start shaft necessary	• Robot needs regular repair projects to be economical • A human operator has to constantly control the robot • Repairing many defects can be very time-consuming
Rings/sealing	• No curing time, so short interruption of service • Does not rely on chemical reactions • Joints between pipes of varying diameter can be sealed by tapered seals	• Higher material costs than cured-in-place tech-niques
Sleeve or patch	• Small amount of material necessary • Economical solution	• Laterals are shut off and need to be reopened later
Open-cut	• Easy to execute • Relatively quick method when replacing a shallow pipeline • New pipe can have a larger diameter	• Large amount of soil needs to be removed and backfilled when replacing a deep pipeline • Large area required for trench and machines • High external costs
Pipe cracking	• The parts of the existing pipe are left in the ground and do not have to be removed from the jobsite	• Start shaft necessary • A lot energy may be necessary to crack the existing pipe • Only straight pipe sections can be replaced • Percussive action may cause significant ground movement
Pipe fraising	• Increase in pipe diameter possible • Can be steered and thus can replace curved pipe sections • Can cut through reinforcement • Latest systems allow for some continua-tion of sewage flow	• Human operator has to constantly control and monitor the tunneling machine • Construction that can withstand large forces is necessary in the start shaft • Debris has to be separated and removed from the jobsite (soil and pipe materials)

Technique	Advantages	Disadvantages
Pulling and replacing*	• Short interruption of service • Existing pipe is removed in one piece	• Start shaft necessary • Necessary pulling force may be large for long sections
Plate parts	• New pipe has high structural strength • New pipe has good hydraulic performance	• Reduction of inner pipe diameter • Large volumes of grout are necessary for long pipe sections • Transportation of large segments to and on the jobsite may be costly and difficult • Long interruption of service
Sliplining	• Prefabricated pipe has a high quality • Minor bends can be negotiated	• Start shaft necessary • Reduction of inner pipe diameter • Large area on the surface is necessary for assembly of long pipe sections • Large volumes of grout are necessary for long pipe sections
Winding pipe	• No interruption of service is sometimes possible • Little space on the surface necessary since the strips are transported on coils	• Large volumes of grout are necessary for long pipe sections • Start shaft necessary (but not always)
Close-fit	• Minimal reduction of inner pipe diameter • Can be used for long pipe sections	• Start shaft necessary • Much space is needed on the surface for long pipe sections, moulds to deform the pipes, and other equipment • Groundwater can sometimes be a problem
CIPP	• Minimal reduction of inner pipe diameter • Liner can follow minor irregularities • No start shaft necessary • Little space on the surface necessary since the liner is transported on coils	• Scaffold tower is sometimes necessary to obtain required water head • Polyester resins may be negatively affected by water until they are cured • Long interruption of service • Curing can be difficult for long pipe sections
Hose lining	• Short interruption of service • No start shaft necessary • Little energy needed; sewage water pressure unfolds the new liner	• Liner does not provide structural strength
Spray lining	• No start shaft necessary • Minimal reduction of inner pipe diameter • Process can be repeated as often as needed • Cement coating can prevent corrosion	• Careful quality control is necessary during application and curing • Long interruption of service • Thorough cleaning of the existing pipe is vital
Reinforced concrete	• New liner has high strength and stiffness • Formwork can be costumised for different pipe dimensions and for lateral connections	• Formwork necessary, requires transportation and handling on site • Long interruption of service • Quality of new liner is dependant upon workmanship

*Table 6:Overview of general advantages and disadvantages of various techniques for pipelines, techniques marked with * are not available for sewer pipes in the Netherlands*

6.4 House connections

Laterals connect sanitary fixtures (e.g. toilets, showers) that are located inside buildings to the sewer network. The laterals connect to the collection pipes running underneath streets. Usually a lateral connection is partially located on private property and partially on public property. The part between sewer main and property line is the responsibility of the municipality. The part between property line and building is usually the responsibility of the property owner.

Not all previously mentioned techniques can be applied to rehabilitation, repair or replacement of laterals. Usually the lateral is dug up and replaced. CIPP liners that reline laters from within the main pipe have begun to appear on the market.

An important distinction can be made in the way the laterals are connected to the sewer network. Either the laterals are directly connected to the sewer pipes that run underneath the streets, or the laterals are connected to manholes. When laterals are connected to manholes this results in greater lengths of the laterals (a direct connection to the sewer pipe is shorter). The advantage of connecting laterals to manholes however is that they can be easily reached. Furthermore it becomes easier to rehabilitate sewer pipes, since they do not have laterals that need to be disconnected and reconnected. Furthermore there is no risk of sewage returning to the building during cleaning activities (especially when using high pressure water to clean the pipes).

Trenchless rehabilitation of the collection pipe underneath the street requires lateral shut down for a certain period of time, usually about 24 hours, when the laterals are connected to the pipe . This can be difficult to coordinate with property owners. Unforeseen events can increase this shut down time, creating problems.

The laterals obviously also deteriorate over time and thus also need certain activities. The laterals used to be dug up and replaced. Since they have a small diameter and are in a shallow location this just requires a small trench. This creates disturbance for the surroundings, fortunately a number of trenchless technologies are available that allow for lateral maintenance.
The fill-and-drain concept, as was explained in section 6.3, allows for reparation of cracks and leaks, but is not used in the Netherlands. Trenchless renovation of laterals is only possible with certain CIPP systems. These are usually the somewhat less costly ambient-cure lining systems. It is unclear whether these systems are used in the Netherlands.

In the case of laterals that are connected to the sewer pipes underneath streets, the connection between main pipe and lateral is another important aspect. When a new liner is installed in the main pipe, it is important that there is no possibility for sewage to enter between the old pipe and the new liner. Another problem is the occurance of cracks in the joints between main pipe and lateral due to movements of these pipes relative to each other. These movements can occur because of heavy traffic, difference in settlements or temperature fluctuations.

A solution for this is the use of so called “top hat“ systems. These systems include an impregnated connection piece that is brought to the desired connection by a remote controlled robot. The packer located inside the piece is then inflated, thereby giving the connection piece the shape of the connection between main pipe and lateral. The top hat is pressed against all walls and forms a complete seal. Once the hat is cured (which is often done with UV light, this takes only several minutes) the packer can be deflated, the robot can be removed and the connection is in perfect shape again.

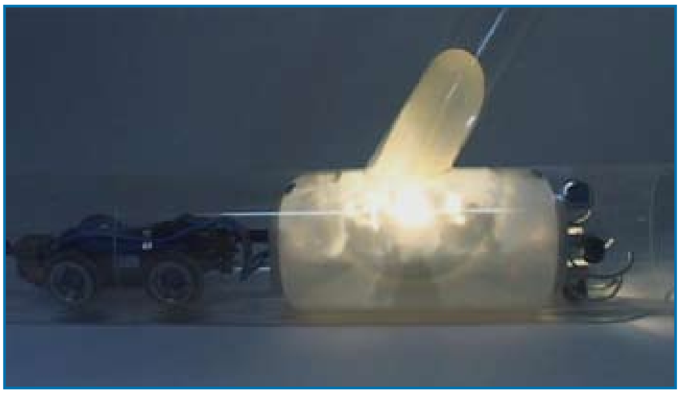


Figure 33: Top hat system, as demonstrated in a transparant tube with lateral connection (Pipe Technologies Limited)

6.5 Manholes

Manholes are an essential part of the sewer network. Even though they do not require as much yearly investment as sewer pipes, they are very important. When manholes are not sufficiently maintained they become the weak link in the network. Infiltration or exfiltration via manholes should be prevented; it is not useful to have all sewer pipes in perfect shape when the manholes in between are leaking!

Manholes that have exit points of pressure pipes inside are more sensitive to detoriation. This is caused by the sewage coming in contact with air within the manhole, thereby causing chemical reactions that negatively affect the material inside of the manhole.
Manholes distinguish themselves from inspection and connection chambers by allowing entry of personnel. European standard EN 476 contains the following requirements for the classification “manhole”:

- inner diameter of 1000 mm of greater, or
- nominal size of rectangular sections of 750 x 1.200 mm or greater, or
- nominal size of elliptical sections of 900 x 1.100 mm or greater

There are two basic methods of manhole rehabilitation. The cracks and joints can be sealed by using resin or grout injection, or an internal liner is installed .

Injection
This is similar to injection techniques for pipes, which usually means the use of polyurethane or acrylic grouts to seal joints and cracks.
Polyurethane grouts react with water and can be directly injected if there is sufficient water surrounding the manhole. The effect of the grout injection is that the soil around the manhole becomes an impermeable mass, which prevents infiltration and exfiltration. The structural strength of the manhole is also increased, allthough this is not quantifiable.
Strong infiltration can wash out the injected grout before it has time to set. This can be solved by using rapid setting hydraulic cements, these sometimes have a setting time of just a few seconds and also expand when setting.

Liner
Just like large diameter pipes, manholes can be given a new liner by using either in-situ methods or by placing a prefabricated liner.
In-situ methods include cementitious products that can be sprayed, trowelled or brushed onto the existing inner wall of the manhole. This results in a waterproof coating. Before applying these materials to the inner wall the surface should be cleaned thoroughly.
A new development in this area is the use of a robot that applies a special mortar to the inner walls of a manhole. This means it is no longer necessary for a worker to enter the (narrow) manhole. This technique can be applied to pre-cast concrete, blockwork or brickwork. When there is a large risk of corrosion it is possible to apply a second layer of coating in the form of an epoxy resin. Uniform coating can be applied with a thickness from 12 to 50 mm.
Cured-in-place systems are also available for manhole rehabilitation. Structural glass-fibre with an impermeable inner membrane is used to fabricate a precisely fitting liner. Epoxy resin is then used to impregnate the liner. An inflation bladder is used to press the new liner against the inner walls of the manhole. Steam heats the liner to 120 degrees Celsius until curing is complete, this usually takes less than two hours. Incoming pipes can then be reopened.
Spirally wounded liners can be used for manhole renovation. This can be done in either rectangular or circular manholes, prefabricated or tailored on site. The in-situ liners can be installed by feeding the PVC strip through the manhole opening. Prefabricated liners usually require removal of the manhole cover slab. The space between liner and existing manhole wall is filled with grout.

6.6 Comparison of characteristics

Many techniques have been discussed so far in this chapter. This section provides a number of overviews in order to see more clearly how these techniques differ from each other. Understanding these differences is vital for the decision making process.

6.6.1 General characteristics

An overview of general characteristics of all the previously discussed techniques for repair, rehabilitation and replacement of sewer pipes can be found in table 7. These characteristics can be considered as clear physical boundary conditions of the techniques. For example, when an existing sewer pipe with a non-circular shape and a certain size has to be relined, this table clearly shows that there are only a limited number of techniques that can be employed. The following characteristics are summarised in table 7:

Entry point
Some techniques can simply be applied to sewers through manhole acces. Others need a start shaft (insertion pit) because more space is necessary. Creating a shaft creates additional costs, e.g. soil removal, nuisance to the surroundings. High groundwater tables may pose a risk when constructing a start shaft (leakages can occur that may result in settlements of nearby foundations).

Corners
Not all techniques are able to follow small bends in the pipe alignment. In some countries this is especially important for smaller collection pipes underneath streets since they tend to follow the bends in the road above. In the Netherlands it is however common practice to place pipes in straight lines between manholes, which means there should not be any bends in the alignment.

Laterals
In most cases the connection between main pipe and lateral has to be reopened after replacement or rehabilitation. This requires additional shutdown time of the main sewer pipe; especially for a pipe with many lateral connections this can result in a shutdown time that is considered too long. Some techniques allow for maintenance of both main pipe and laterals from within the main pipe, which can be a great advantage in certain situations.

Flow interruption
Interruption of service is an important consideration when deciding which technique will be used for maintenance. Long interruption is usually very undesirable and can give lots of problems. In gravity sewer systems with sufficient buffer capacity it may be possible to temporarily put a plug in place. Another possibility is the use of a by-pass pumping system to divert the flow of sewage.

Pipe dimensions
Every technique has a diffent pipe diameter range to which it can be applied. Some can only be applied to man-entry pipes. The definition of ‘man-entry’ varies from country to country, in general it is allowed for men to work inside pipes of 1000 mm diameter and above. Non-circular pipes are usually considered man-entry size when larger than 800 x 1200 mm. Pipe dimensions will usually be considered first in the decision-making process since it immediately excludes a number of techniques. Figure 34 shows clearly which techniques are available for which diameter ranges.

Pipe shape
Not all techniques can handle non-circular pipe shapes. It should however be noted that it is possible to replace a non-circular pipe with a circular pipe with similar hydraulic performance when using certain techniques. Pipe-fraising for example can remove a non-circular pipe and some surrounding soil and replace it with a circular pipe.

Technique	Entry point	Corners	Maintenance laterals	Reopening laterals	Flow interruption	Pipe dimensions	Pipe shape	Reduction of inner diameter	System type (gravity or pressure)
Injection	Manhole	yes	no	no	yes	no restrictions	any	none	G
Fill-and-drain	Manhole	yes	yes	no	yes	no restrictions	any	none	G
Robot	Manhole	yes	no	no	yes	200-800 mm	any[2]	none	G
Rings/sealing	Manhole	yes	no	no	yes	200-3000 mm	circular	minimal	G/P
Sleeve or patch	Manhole	yes	no	yes	yes	200-600 mm	circular	minimal	G
Open-cut	Trench	yes	yes	no	yes	no restrictions	any	*increase*	G/P
Pipe cracking	Shaft/manhole[1]	no	no	yes	yes	50-1000 mm	circular	*increase*	G/P
Pipe fraising	Shaft	yes	no	yes	y/n	>300 mm	circular	*increase*	G/P
Pulling and replacing	Shaft	no	no	yes	yes	unknown	circular	none	G/P
Plate parts	Manhole	yes	no	no	yes	man-entry	any	yes	G
Sliplining	Shaft/manhole	yes	no	yes	yes	200-3500 mm	any	yes	G/P
Winding pipe	Shaft/manhole	no	no	yes	y/n	200-3000 mm	any	yes	G
Close-fit	Shaft	yes	no	yes	yes	75-1600 mm	circular	minimal	G/P
CIPP	Manhole	yes	yes	yes	yes	50-2500 mm	any	minimal	G/P
Hose lining	Manhole	yes	no	yes	yes	up to 300 mm	circular	minimal	G
Spray lining - robot	Manhole	yes	no	no	yes	100-1200 mm	circular	minimal	G/P
- manual	Manhole	yes	no	no	yes	man-entry	any	minimal	G/P
Reinforced concrete	Manhole	yes	no	no	yes	man-entry	any	yes	G/P

Table 7:Overview of general characteristics of techniques for sewer pipes

[1] some hydraulic bursting heads are small enough to be lowered into manholes. Short pipes are necessary then

[2] as long as the robot has a suitable surface to drive through the pipe

Diameter reduction

There are a number of techniques that result in a reduction of the inner diameter of the sewer pipe. When this reduces hydraulic capacity it can be a problem. Often hydraulic performance is increased however, this is the result of reduced friction of the new inside surface of the pipe. Some maintenance techniques result in a much larger reduction in diameter than others because the gap between new liner and old pipe is filled with grout. New liners that are placed against the old pipe without space in between will only reduce the inner pipe diameter by the thickness of the new liner. As can be seen in table 7, there are only two trenchless techniques available that can increase the pipe diameter: pipe-fraising and pipe-cracking.

System type

Many techniques can be applied to both gravity and pressure sewer systems. There are however a number of techniques that are only available for gravity sewer systems. Pressure pipes have to resist larger forces and it is more important that joints are not leaking (pressure loss). Since there are also no manholes present in pressure systems it is much more difficult to reach certain sewer sections from the inside.

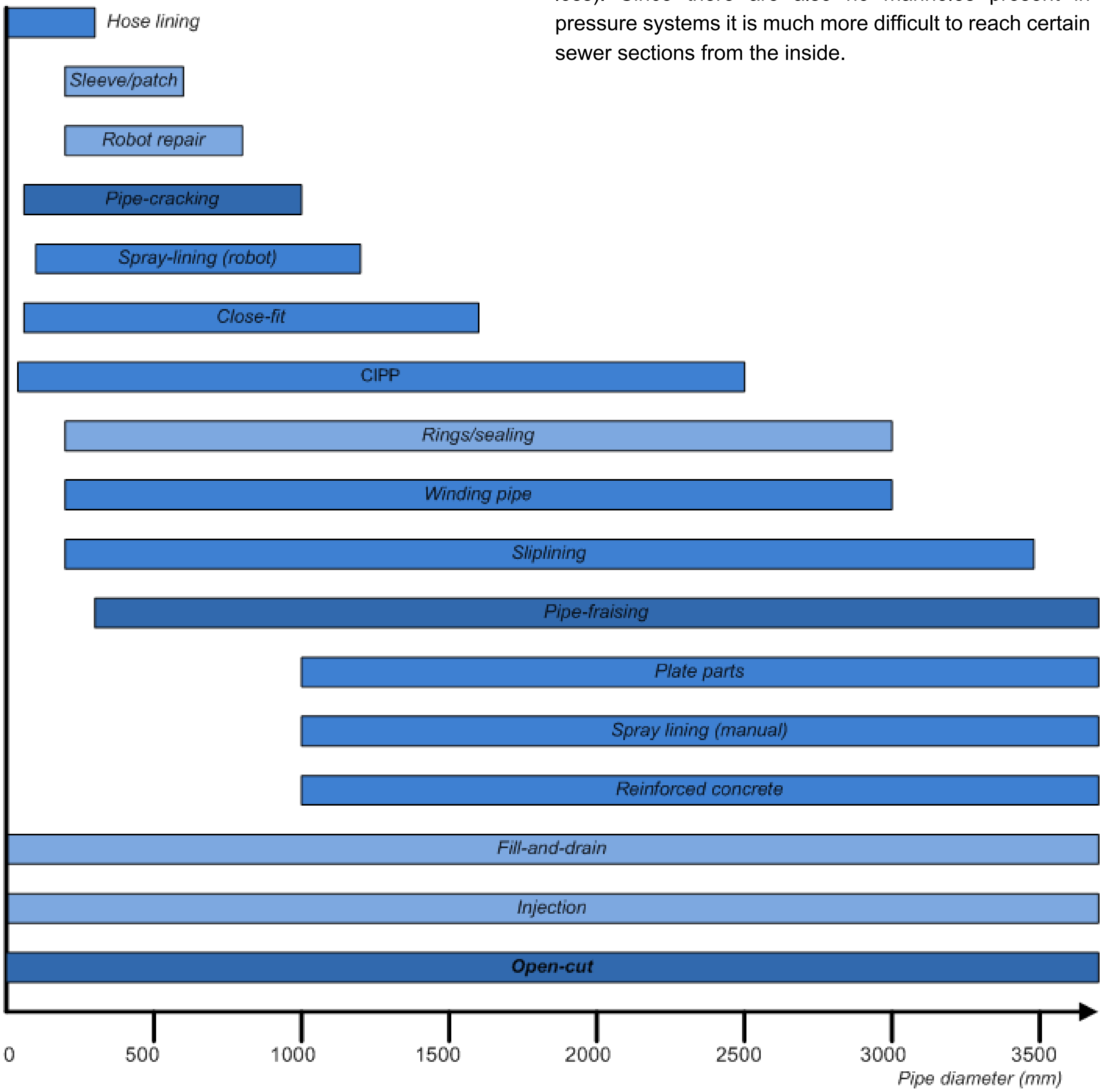


Figure 34: Diameter range for the considered maintenance techniques. Note that light blue is used for reparation techniques, blue for renovation techniques and dark blue for replacement techniques

6.6.2 Other aspects that should be considered when making decisions

The previous section has shown a number of general characteristics. These give insight into the techniques that are within the range of possibilities for a certain project. When there is only one technique suitable for a specific project, the choice is easily made. Usually however more than one technique will be suitable for the project, which means a comparison is necessary on which a decision can be based. The decisive aspect is usually economic cost; the technique which requires the lowest initial investment is chosen.

The first shortcoming of this way of decision making is the fact that costs are only considered in the short term. Costs during the entire lifetime of a sewer pipe should be considered to determine the total economic costs.

Secondly, there are many more aspects to consider besides economic costs. For example, in some cases the speed of construction may be more important than costs (e.g. when maintaining a vital transport pipe). When working in a city center certain external effects may be decisive when determining the most suitable technique. Nowadays there is also an increased interest in sustainability, which clearly shows that reduction of energy use and raw materials use is vital for future generations. Using massive amounts of energy and raw materials for construction activities in order to minimise short-term costs is no longer acceptable and should be further discouraged.

Therefore it is important that the performance of the previously discussed techniques regarding all these apects is researched. This will allow for a more integral approach to decision making that will benefit society as a whole. This section summarises various aspects that affect overall costs and should be included in the decision making process for sewer works. The relative importance of all these aspects is different for every situation; the owner/operator of the sewer system should determine the critical aspects for every project in order to find the most optimal solution.

Construction speed

As mentioned before, construction speed is especially important when an important, high capacity transport pipe receives maintenance. Usually sewer activities require interruption of service, which should be as short as possible. The wastewater has to be diverted for this period of time, this requires additional measures that will increase costs (and when this diversion is placed above ground, nuisance). In gravity systems it might be possible to put a temporary plug in place.

Material use

Material use differs greatly among previously mentioned techniques. While some techniques only involve a new liner, others also require vast amounts of grout to fill the gap between new liner and old pipe. This is important to remember since it affects the material costs that are involved. Besides material costs the comparison between materials required for different techniques gives insight into sustainable performance. Note however that some materials require much more energy to produce or require more non-renewable raw resources than other materials. This is an important consideration when trying to implement a more sustainable approach for construction activities.

Energy use

Heavy machinery and pumps that are deployed do not only contribute to air pollution, but also require diesel to run. When machinery and pumps are in use for many days the amount of burned fuel can be quite large; this means additional depletion of non-renewable resources. Another source of energy use is the delivery of goods; especially large diameter prefabricated liners require many trucks to deliver parts to the jobsite. The diesel necessary to run these trucks should be included in the overall energy picture. Techniques such as CIPP also require energy for the creation of steam, hot water or UV light.

Vibrations

Some techniques will produce vibrations in the subsurface, e.g. pipe-cracking and pipe-fraising. These vibrations may negatively affect foundations of existing buildings. Especially in old city centers the use of such techniques may result in too large risks of damage to adjacent buildings. When this is the case an alternative techniques will need to be chosen for the job. Heavy pumps located near residential buildings may also result in vibration nuisance and complaints.

Noise

The use of heavy machinery will always generate a certain amount of noise. Generators and pumps that are continuously operating will generate noise even during the night, this may require specific sound reducing measures when residential buildings are located nearby. Slow-moving traffic and delivery trucks around the jobsite will increase noise levels. Traffic diversions will increase noise disturbance around the diversion routes.

Required space

The required space for a sewer project consists of two parts. First of all, the actual workplace should be considered, which means an excavation or a manhole that is used as entry point. Secondly, there will often be equipment and material storage necessary on the surface level. The required space for equipment and material is an important aspect to consider since it can be much larger than the space occupied by the excavation. When available road surface is reduced the capacity of the road is also reduced. This may lead to insufficient capacity, thus resulting in congestion. When the level of congestion is unacceptable it may be necessary to create diversion routes. These diversion routes will also create problems of their own, adding up to the total social and environmental costs of the project.

Air pollution

Heavy machinery, generators and slow moving traffic around the jobsite will produce gases that contribute to air pollution. Undesired particles include carbon monoxide, carbon dioxide, hydrocarbons and nitrogen oxides. Another form of air pollution is the disturbance of dust and dirt by the heavy machinery.

Visual intrusion

When working in a residential area the use of large machinery and material storage on the surface level will result in visual intrusion. This means these objects will spoil the view for residents of nearby buildings. Especially high objects that block much of the view can lead to dissatisfied neighbors. Note that there will always be some level of visual intrusion, no matter which technique is chosen. Minimising construction time is a good way of reducing dissatisfaction among neighbors; visual intrusion is usually acceptable if it is for only a short period of time.

Safety

Safety risks should be carefully examinated, regardless of chosen technique. In general, trenchless techniques result in lower safety risks than open trench methods. Open trenching presents a danger not only to the workers that are working in the trenches, but also to the general public that moves near open trenches. These open excavations are greatly reduced by trenchless techniques (some may need a insertion and exit shaft, but this requires less surface space than a trench). Note however that trenchless methods present risks of their own. Moving parts of machinery needed for certain techniques can be a hazard for personnel working on the project. Space that is needed on the surface and for shafts can create traffic disruptions, which may result in an increased number of traffic accidents.

Aspect	Components
Construction speed	• Determined by chosen techniques and local conditions
Material use	• Liner material • Filling material (e.g. grout)
Energy use	• Machinery and pumps • Delivery of goods (trucks)
Vibrations	• Inherent to chosen technique: pipe-cracking, pipe-fraising • Pumps
Noise	• Machinery and pumps • Slow-moving traffic • Delivery of goods (trucks)
Required space	• Start and exit shaft • Manholes used for entry • Equipment and material on surface • Space for vehicles and delivery
Air pollution	• Machinery and pumps • Slow-moving traffic • Dust due to excavation or vibration of machinery
Visual intrusion	• Large machinery/vehicles • Excavation • Material storage on surface
Safety	• Preventive measures • Personal injuries

Table 8:Summary of important aspects and their componnents

CHAPTER 7: VALUES AND COSTS INVOLVED WITH SEWER WORKS

Chapter 7: Values and costs involved with sewer works

7.1 Introduction

In order to make good decisions when operating and maintaining a sewer network it is important to have a clear overview of all costs and values involved. Since budgets for operation and maintenance are limited, minimising costs has become vital for sewer network managers. This has resulted in selection of solutions with the lowest initial costs for sewer projects. This principle is not uncommon; tenders based on lowest capital costs have dominated the entire construction industry for a long time. Fortunately, different selection criteria for tenders have been starting to appear in a number of sectors. It is thought that these developments will result in lower overall costs and higher quality.

When looking at the field of sewer systems, many of these developments still have to take place. Long-term thinking and investments have gained more popularity during the last decades, but unfortunately this is not yet standard practice everywhere.

The developments in the field of trenchless technologies have resulted in the possibility to maintain sewers with a much lower level of undesired effects (such as traffic disruption, pollution et cetera) than open-trench methods. Strangely, these differences are not taken into consideration when selecting techniques for sewer works, even though the financial costs of these effects can be many times larger than the direct costs.

There are a number of cost types that can be identified. When people hear the word "cost" they usually only consider visible direct costs that can be easily given an economic value. As stated before, there are many more costs involved with construction activities; unfortunately these are easily forgotten since they are less visible. Another problem is that some costs are very difficult to translate into actual economic costs (e.g. pollution, nuisance). Even though this poses a challenge, the awareness for the less visible costs has increased in many sectors of industry during the last decade. The following cost types can be identified:

- Direct costs
- Indirect costs
- External costs

Besides costs there can be specific added value that certain alternatives provide. This added value should also be included in order to provide an objective basis for the decision making process.

One of the goals of this research is to identify these effects and the factors that influence them. There are a large number of factors that should be taken into account, identifying these is the first necessary step towards a more integral approach. Ultimately the external effects should be implemented into the decision making process by constructing a model, thereby allowing the owner/operator to compare the "real" costs and benefits of various alternatives to each other.

The items that belong to the mentioned types of costs and added values are explained in the next sections.

7.2 Direct costs

Direct costs are costs that can be directly related to a product or service which is being produced. In this case this means direct costs regarding activities for sewer networks. These costs are often the only costs considered when determining which techniques to employ. In section 7.4 external costs will also be discussed, which should also be included when determining the real total costs.
The following direct costs are present when performing activities on sewer sections (note that this is not a complete list):

Wages for employees
Some techniques require more personnel than others during the construction process. Remote-controlled systems require a certified operator during the entire process. Wage rates increase when working during the night, weekends or holidays.

Material costs
This obviously includes costs for the new pipeline sections or liners, but also grout that is pumped in between the existing pipe and the new liner.

Soil removal and treatment
Excavations remove soil, which has to be transported off site and possibly treated (in case of polluted soil).

Energy costs
Heavy machinery requires large amounts of energy to operate. Some projects may also require pumps that are constantly in operation for a long period of time.

Equipment costs
Running and rental costs for machines that are necessary for certain techniques.

Removal and restoration of top layer
This can be for both open trenches and start/exit shafts.

Removal and restoration of obstructions
Both at surface level (e.g. trees) and in the subsurface (e.g. cables).

Safety measures
Preventive measures to reduce the risk of personal injuries

Subcontractors
Some projects may require the services of specialised subcontractors.

7.3 Indirect costs

Direct costs can be directly linked to a produced product or service, for example a renovated pipeline. Indirect costs do not directly contribute to the production but are necessary to enable the construction activity, for example construction site costs, transportation costs and costs for safety equipment. Some indirect costs can not be linked to a specific project, but are distributed over many projects. Examples of these costs are rent for the office building of an organisation or the salary of the CEO of an organisation; how much value these exactly add to a single pipe renovation project can not be easily said. In order to include these overhead costs in a project, they are defined as a fixed percentage of the total direct costs and added to the cost overview. Profit for the contractor is also included as a fixed percentage of the direct costs.

7.4 External costs

External costs, also known as externalities, are negative effects of production or consumption which are not paid for by the producer but are imposed on other parties. These costs can be divided into social and environmental costs. The problem of external costs is thus that they incur costs

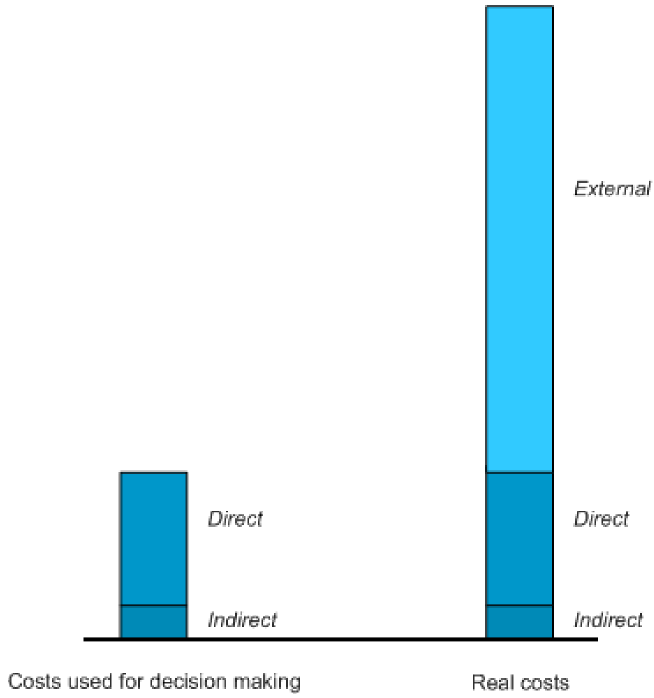


Figure 35:External costs are less visible and often not included in the decision making process, even though they can be much higher than the direct costs

on parties other than the producer, even though these parties are not compensated for this. For example, when a sewer pipe is excavated in an urban environment there is a lot of nuisance for the surroundings; noise, pollution, traffic disruption. Since the producer does not have to bear these costs, it is not in his interest to minimise the external costs (apart from having good public relations). Another reason why external costs are not taken into consideration is the fact that these effects are difficult to measure and to value. The social and environmental costs of a construction activity can far outweigh the visible direct costs, therefore it is vital that these are included when determining the actual costs of a construction activity.

In the last chapter a number of external effects were discussed. In this section the translation from effects to costs will be discussed. Methods for monetarisation the effects will be shown; these can be used to compare different external effects to each other when deciding between various techniques. Figure 36 shows the aspects that were discussed in the previous chapter. On the right side of this figure the various external costs associated with these aspects are shown. The components of these external costs are discussed in this chapter. Note that the aspect “construction time” is not shown since it does not generate unique external costs. Instead, it determines the duration of the other aspects that are shown.

7.4.1 Material use

There are different types of materials that are used by techniques for sewer works. These materials have various characteristics; some are more resistant to certain chemical environments, some have greater structural strength, et cetera. When there are a number of material options for a certain project, usually the cheapest option is chosen. By cheapest option the option with the lowest direct costs is meant. Unfortunately the choice of materials does not only affect direct costs, but also environmental costs. Some materials require much more energy to be produced or deplete more non-renewable resources than other materials. This cost component is often forgotten when chosing materials for a project. The life expectency of a pipe made out of a certain material should be compared to the initial investment costs and the environmental costs.

The Dutch government has the intention of making the acquisition of materials for infrastructure projects fully sustainable from 2010 onwards. In order to achieve this goal, Rijkswaterstaat is developing a tool called Dubocalc, which calculates environmental effects of material and energy use (Rijkswaterstaat, 2010). This tool was expected to be completed in 2010, thereby allowing for environmental comparison of various project alternatives. It is unclear whether this tool can also be applied to sewer systems, but one can imagine that the energy and material data from Dubocalc could be useful and possibly used in a tool for sewer systems.

7.4.2 Energy use

Machinery and vehicles require fuel to run, this obviously results in some degree of air pollution, but the fuel consumption itself also results in an external cost. The fuel requires energy to be produced, furthermore non-renewable resources are depleted. These environmental costs are easily forgotten but should be accounted for when developing a sustainable approach to construction activities. Section 7.4.6 will discuss external cost values for air pollution caused by machinery and traffic.

Table 9 shows the amount of emissions released into the environment during the refinement process and distribution of gasoline and diesel. It is assumed that during the distribution process the amount of hydrocarbon (HC) emissions released in an urban environment consist of 20% of total distribution emissions; the remaining 80% of HC-emissions are released in rural areas (CE, 2001). These emissions are released during refilling of fuel storages and fuel trucks. It is important to make this distinction since the external cost values for HC differ for urban and rural locations.

The depletion of non-renewable resources can not be expressed in monetary values. When similar overall cost figures are obtained for two alternatives this aspect can possibly be used to make a final choice.

	Refinement			Distribution	
	CO_2	NO_x	HC	HC_{rural}	HC_{urban}
Gasoline	407	0,130	0,95	0,028	0,007
Diesel	240	0,074	0,29	0,016	0,004

Table 9:Emission values for refinement and distribution of fuel, in gram per kg fuel (Data: CE, 2001)

7.4.3 Vibrations

Some techniques will produce vibrations in the subsurface. These vibrations may negatively affect foundations of existing buildings in some areas. Especially in old city centers the use of such techniques may result in too large risks of damage to adjacent buildings. When this is the case alternative techniques will need to be chosen for the job. There is no way to easily predict damage caused by vibrations. There are many factors that influence whether or not damage will occur (e.g. soil type, structural details of the adjacent structures). Since it is not logical and possible to calculate the chance and costs of damage to nearby buildings for every project, there are no general cost figures available. For every project where techniques are considered that cause vibrations in the subsurface, the municipality should ask itself: is there a chance that nearby buildings will be damaged? Often the answer to this question will be “no”. In old city centers where activities are planned close to old buildings, this can be a risk that is not acceptable. In this case the techniques that cause vibrations need to removed from the option list. There are two techniques that cause vibrations in the subsurface: pipe-cracking and pipe-fraising.

7.4.4 Visual intrusion

Attributing costs to visual intrusion is very difficult, there is no damage or effect that can be measured. As stated before, minimising construction time is a good way of reducing dissatisfaction among neighbors. Since the project time for sewer activities is usually short (compared to construction time of new structures), the nuisance costs for visual intrusion would be very low. Since there

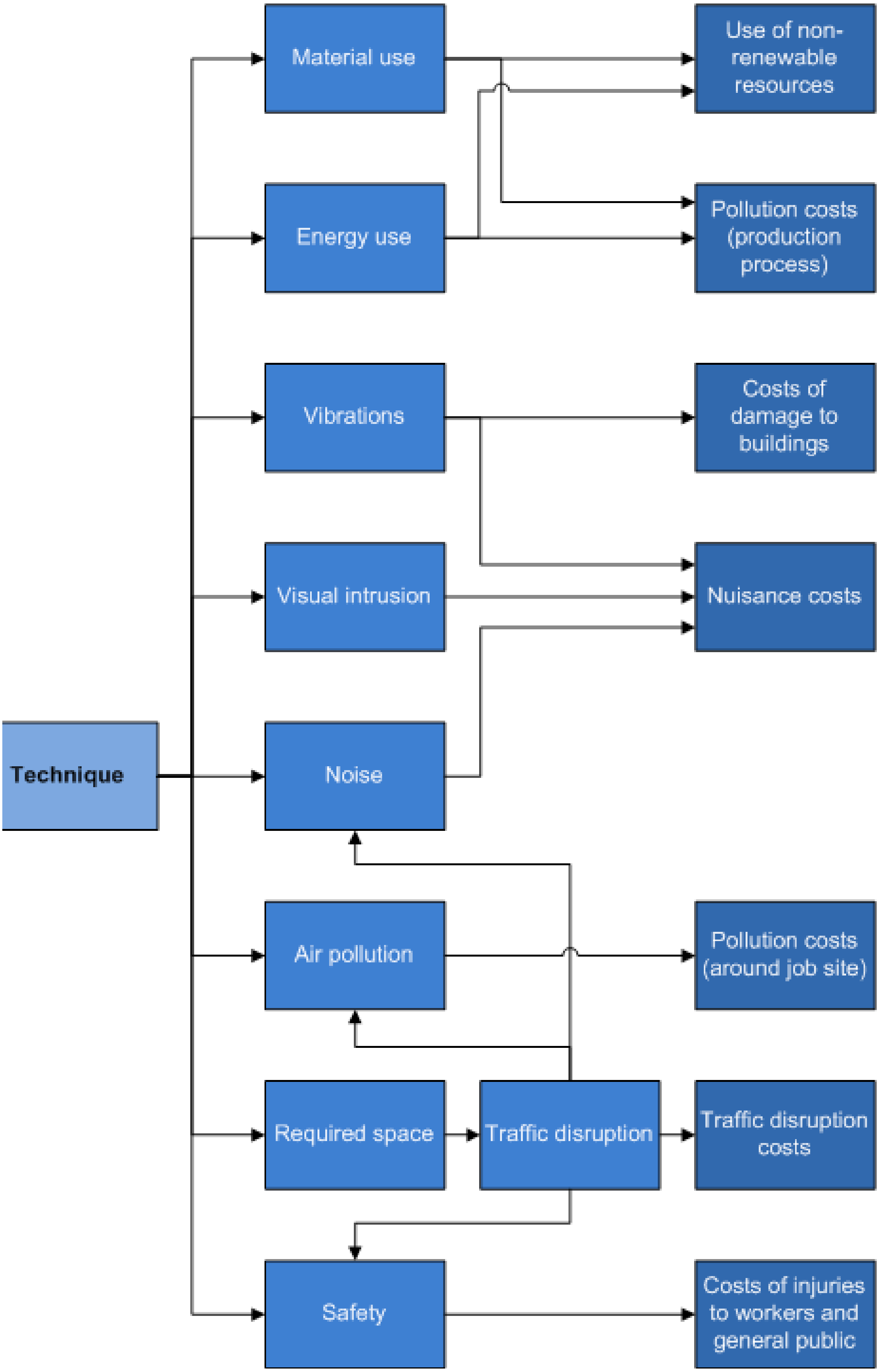


Figure 36:Overview of external effects and the costs associated with them. Note that material use and energy use result in both direct costs and external costs; here only the external cost component is shown.

is no research data available regarding the social costs of visual intrusion, it is impossible to give an estimation for these costs. The willingness-to-pay for reduction of visual intrusion of neighbours could be determined in a survey, but this will probably result in much lower values than for example willingness-to-pay for reduction of noise or vibration effects. One can also wonder whether the costs of such a survey would not outweigh the benefits.

7.4.5 Noise

The use of heavy machinery will always generate a certain amount of noise. Generators and pumps that are continuously operating will generate noise even during the night, this may require specific sound reducing measures when residential buildings are located nearby. Traffic diversions will increase noise disturbance around the diversion routes.

There is a Dutch law that gives noise pollution limits for roads and railroads, there are however no rules included for construction activities. Demands regarding noise emissions of construction machinery can be found in the law ("*Wet Geluidshinder*"), but the noise generated during construction activities are not specified. There are a number of possibilities for specifying allowable sound emissions, usually (Bouwend Nederland, 2007) the so called "*circulaire Bouwlawaai*" is used (Ministerie van VROM, 1991). This states that when construction activities are located near houses, the following rules apply:

- In the evening and at night: no noise generation
- During daytime (7 am until 7 pm): 60 dB(A), or 65 dB(A) when activities are shorter than one month

It is however not clear whether the one month limit applies to one activity or to an entire project. Also, some infrastructure projects are done during night hours. A new version of the circulaire is expected this year that will be more specific and provide more clarity on this topic.

7.4.6 Air pollution

Heavy machinery and slow moving traffic around the jobsite will produce gases that contribute to air pollution. Undesired particles include carbon monoxide, carbon dioxide, hydrocarbons and nitrogen oxides. Another form of air pollution is the disturbance of dust and dirt by the heavy machinery.

Road traffic
Emission values for road traffic are shown in table 10. The Dutch government provides emission values for different types of vehicles and speed levels (Ministerie van VROM, 2009). It is expected that emission levels will decrease during the next years, due to the fact that cars and trucks will become more environmentally friendly. Predictions of emission values until the year 2020 have been made, but it is unclear if these are very accurate. Table 10 only shows the emission values for 2010.

Traffic and speed	PM_{10} (g/km)	NO_x (g/km)	SO_2 (mg/km)	CO_2 (g/km)
Light				
Urban (stagnating)	0,069	0,913	2,67	228
Urban (normal)	0,062	0,578	1,78	228
Urban (flowing)	0,062	0,632	1,58	228
Rural	0,028	0,346	0,98	152
Medium				
Urban (stagnating)	0,569	14,20	7,23	
Urban (normal)	0,357	8,88	7,23	
Urban (flowing)	0,259	6,20	7,23	
Rural	0,189	4,95	4,41	
Heavy				
Urban (stagnating)	0,396	13,01	10,19	
Urban (normal)	0,270	8,13	10,19	
Urban (flowing)	0,209	5,77	10,19	
Rural	0,159	5,76	6,84	

Table 10:Emission values for various vehicle and traffic types (Ministerie van VROM, 2009)

The following vehicle types are distinguished in the table above (Ministerie van VROM, 2009):
- *Light:* Cars, motorcycles
- *Medium:* Trucks below 20 tons GVW (Gross Vehicle Weight), busses
- *Heavy:* Trucks over 20 tons GVW, trailers

The following distinction between speed levels is used:
- *Urban (stagnating):* High degree of congestion, average speed < 15 km/h
- *Urban (normal):* Average degree of congestion, average speed 15 - 30 km/h
- *Urban (flowing):* High degree of free flow, average speed 30 - 45 km/h
- *Rural:* Outside city limits, average speed 60 km/h

Heavy machinery
Heavy machinery produces various gases that contribute to air pollution. The disturbance of dust and dirt is also

considered as a form of air pollution, this is however very hard to quantify.

Cost values

The environmental and social costs of emissions have been researched extensively during the last decades. The effects on the environment and public health have become more clear, this has resulted in more accurate cost figures. The shadow prices of various emissions have been researched for the Ministry of Traffic and Public Works (CE, 2001). This research was aimed at the effects of various fuel types that are used by road traffic; gasoline, diesel and LPG. These values can be used for determining the costs of air pollution by traffic around the worksite, but also for air pollution caused by heavy machinery (which usually runs on diesel).

Emission	Urban	Rural
PM_{10}	300	70
NO_x	12	7
HC	6	3
SO_2	10	4
CO_2	0,03 / 0,05 / 0,10	0,03 / 0,05 / 0,10

Table 11:Shadow prices for various emissions in urban and rural locations, in Euro per kg (Data: CE,2001)

As can be seen in table 11, cost values are different for urban and rural locations. This can be explained by the fact that in an urban environment the population density is higher, which means the negative effects on public health caused by emissions affect more people. The only exception to this is CO_2, which negatively affects the environment and has the same value for both urban and rural locations. The value for CO2 can be chosen from three possible values (CE, 2001). These three values are associated with three packages of CO_2-reducing measures that the Dutch government has developed with regard to the Kyoto Protocol. Depending on the progress towards the agreed climate goals in the Protocol, either one, two or three packages can be installed.

7.4.7 Traffic disruption

Sewer pipes and manholes are usually found beneath roads, which mean that activities will almost always disrupt traffic in one way or the other. Before the development of trenchless technologies, open-trench methods often resulted in heavy traffic problems, especially in dense urban environments. The direct costs of trenching are sometimes lower than no-dig alternatives, but these cost savings are usually exceeded by the reduced economic costs of traffic disruption offered by no-dig methods. In many countries using open-trench methods in city centers is no longer acceptable; Singapore has even introduced a complete ban on open trench activities and in Tokyo open trench methods are only allowed when there are no other options (Read, 2004).

Note however that trenchless techniques do not necessarily mean less traffic problems than open trench methods. When a sewer activity involves using an access shaft near a busy intersection this may result in heavier traffic congestion than a small trench, especially when this access shaft is used for a long period of time.
Social and economic costs can be attributed to the following effects (Read,2004):

- Delays because of reduced road capacity
- Additional travel time and distance because of diversion routes
- Increased number of road accidents because of reduced visibility and reduced traffic flow
- Environmental effects because of additional congestion and unusual traffic on diversion routes
- Damage to roads and underground services on diversion routes which are not suitable for heavy vehicles
- Reduced vehicle access to buildings near the work
- Problems for public transport lines that run nearby: delays, extra travel distance, unreliability of schedules
- Diversion routes that are used for a long period of time may also have a detrimental effect on commercial activities in the area

Not all the above mentioned costs can be easily quantified. Furthermore, even if all these cost components could

Figure 37:Sewer works in dense urban environments can result in heavy traffic disruption

be quantified many of them would be too small to have any effect on the decision making process. It is thought that the delays and additional travel time of diversion routes are one of the largest cost components of external costs caused by traffic disruption. Some of the other costs could be important in very specific situations, but for average maintenance projects it is assumed they can be neglected. It would be impossible to make a general model that can include every unique aspect. This would require an enormous amount of input, which is undesirable and inefficient. More useful is general model which also mentions attention points that should be considered. For example, when a diversion route is planned close to a high school it is quite obvious that this could result in an increased number of road accidents and that this risk should be further looked into. It would be difficult and useless to include the costs of an increased number of road accidents near schools in every project. Instead these potential risks should be considered in a risk analysis.

Costs of additional travel time

In order to calculate the costs of additional travel time caused by sewer works, there are three values required. The additional travel time has to be known, either caused by delays around the jobsite or by diversion routes. Secondly, the number of vehicles that incur this extra travel time has to be determined. Finally, the additional travel time has to be translated to costs by using a certain method.

Determining the additional travel time is difficult; this depends highly on local conditions. The amount of road surface that is occupied by sewer works reduces the road capacity. This may result in delays, depending on the amount of traffic that is present. During rush hours the road capacity may be fully used, while during the night there is almost no traffic and the reduced road capacity is still sufficient.

When the reduced road capacity is not acceptable, a diversion route can be considered. The extra travel time can be easily calculated; the travel time for the original route can be subtracted from the travel time necessary for taking the diversion route.

The number of vehicles using a certain road can be estimated or measured. For important routes this data may even be available in the municipal organisation.

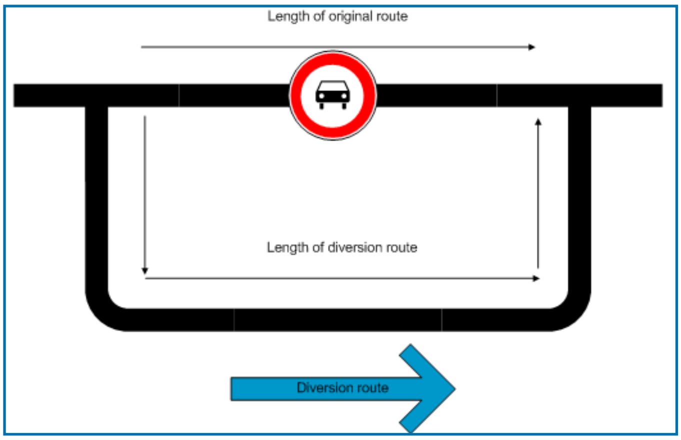


Figure 38:Additional travel time due to diversion routes

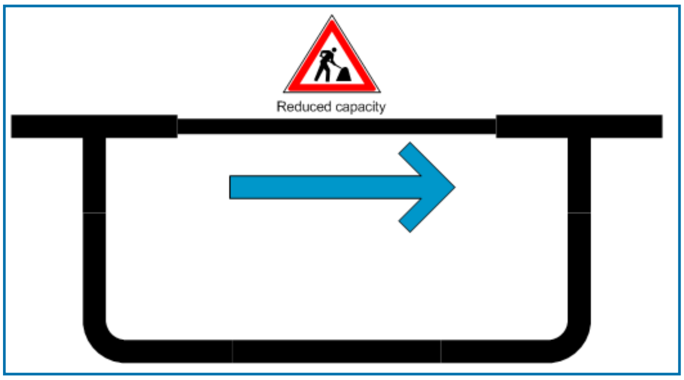


Figure 39:Delays due to reduced capacity

In the Netherlands there are values available for the so called “Value of Time” (VoT). Governmental organizations have been using VoT for years now when assessing effects of infrastructure projects. The Central Planning Bureau (CPB) has calculated four future scenarios for the Netherlands and its economy. The Ministry of Transport and Public Works has used these four scenarios for predictions regarding infrastructure aspects. The development of VoT during the coming decades has been calculated for these four scenarios. These values can be used for the calculation of social costs associated with traffic disruption. Tables 12 and 13 show the lowest and highest VoT values that were found in a report of the Ministry regarding air quality measures (AVV, Ministerie van Verkeer en Waterstaat, 2007). The lowest values are a result of a regional communities scenario, whereas the highest values are a result of a global economy scenario. The previously mentioned report can be consulted for more information regarding these scenarios. Different types of traffic have different VoT values. Additional travel time for commuter traffic is considered less costly than additional travel time for business traffic. The composition of traffic can differ greatly in different locations. Sewer works in a suburban area will only influence commuter traffic, whereas sewer projects in a city center will affect business and freight traffic as well.

Year	Commuter	Business	Other	Freight
2010	8,84	30,63	6,11	43,72
2020	9,58	33,17	6,61	47,34
2040	11,70	40,51	8,08	57,83

Table 12: Value of Time (in Euros) per vehicle per hour for various types of traffic, according to the Regional Communities scenario (Data: Adviesdienst Verkeer en Vervoer, Ministerie van Verkeer en Waterstaat)

Year	Commuter	Business	Other	Freight
2010	9,09	31,47	6,28	45,40
2020	10,44	36,17	7,21	52,17
2040	14,11	48,86	9,47	70,74

Table 13: Value of Time (in Euros) per vehicle per hour for various types of traffic, according to the Global Economy scenario (Data: Adviesdienst Verkeer en Vervoer, Ministerie van Verkeer en Waterstaat)

Reduced access to nearby businesses

When too much space is occupied for sewer works this can have a negative effect on nearby shops. Shops that are difficult to reach will notice a decrease in sales. In busy shopping streets this loss of income can be quite substantial and may result in compensation requests. This economic cost should be considered when deciding how to execute sewer works. Hindrance in commercial areas over a long period of time should obviously be avoided.

7.4.8 Safety

Safety is an important attention point, especially when working in busy urban areas. Safety regulations are quite strict in the Netherlands fortunately, but accidents still occur. Two types of costs can be associated with safety: costs for preventive measures and costs incurred when accidents take place.

When working on sewer systems there are usually a number of safety measures required, which create additional costs. Depending on the chosen technique and local conditions, these costs can be quite substantial but are sometimes easily overlooked in the early stages of a project. Worker safety regulations require certain measures, e.g. protective clothing. On the other hand the safety of the general public has to be guaranteed. Especially open trenches and start/exit shafts can form a risk for the public, these should therefore be not accessible from public areas. Examples of safety measures for the general public include screens, safety nets, signs et cetera. These costs for preventive measures can be considered as direct costs.

Social costs are incurred when accidents happen on a jobsite. When injuries are sustained this results in costs for medical treatment, loss of productivity (when the victim cannot do his/her job for a certain period) and possible lawsuits. Injuries (or even fatalities) are difficult to express in costs, whereas safety measure costs can be accurately estimated. Possibility of injuries occuring should be evaluated in a risk analysis, when there are unacceptable safety risks the sewer network manager can decide to invest additional money in preventive measures. Research into safety hazards of specific techniques is necessary in order to make a good comparison with regard to this aspect. *Syachrani et al*. (2010) have looked into safety hazards and measures for a number of commonly used renovation techniques (slipling, CIPP and spirally wound lining) by using a four-step risk assessment method. More research will hopefully be initiated in order to get more insight into the safety aspect of various trechnless technologies.

7.5 Added value

Sewer works that are carried out in a certain area result in various costs (as shown before), but these sewer works may also add value to the area or sewer network. Techniques for sewer works will obviously improve the condition of an existing asset, but there can be additional value that is generated. The costs of infrastructure projects are often emphasised, while there is little attention for the additional value that is created. Especially from the side of stakeholders the negative side often dominates the discussion, while the benefits that are gained from completing the project are overlooked. The same holds for sewer systems, allthough it is often more difficult to see the added value than when looking at other infrastructure systems. For example, when a road project increases the amount of traffic lanes the average travel time may be reduced. When the diameter of a sewer pipe is increased it is difficult for stakeholders to see how this benefits them (even though if this would not happen there would often be nuisance from overflows).

Value that is added by a sewer project should be included in the overall decision making process. Only then can a sewer asset manager decide whether or not an investment is attractive. An increase in created value may justify larger investments in certain projects. Note that some of these added value items can also be the reason for initiating a project. Some of the discussed items will be applicable to all possible solutions and can be included to justify the overall project. Items that are unique for certain alternatives help the sewer asset manager to make a distinction between techniques. For example, some techniques may result in reduced inspection efforts while others may not. The added value for reduced inspection efforts is thus included in the cost/value overview of certain techniques and excluded for other techniques.

7.5.1 Added above ground value

Sewer works may add value to the above ground area near the pipeline that is repaired,renovated or replaced. The following added value items may be relevant for sewer works:

Overflow reduction (streets)
Overflows that flood streets cause nuisance to traffic and may result in risks to public health (when combined systems are involved). When overflows to the street or sidewalk above a sewer section are common, the sewer asset manager can decide to increase dimensions of the sewer section. This will result in increased discharge capacity that will reduce the number of overflows in the future. This can greatly reduce nuisance and external costs associated with it. The external costs associated with an overflow can be estimated and multiplied by the number of overflows per year. This gives an indication of the yearly cost reduction that could be achieved when overflows no longer occur due to increased discharge capacity.

Figure 40:It is not hard to imagine that prevention of frequent overflows can be seen as value

Overflow reduction (surface water)
Surface water bodies can be polluted due to frequent overflows of combined sewer systems. Reduction of the amount of overflows will result in less pollution and thus lower external costs. When overflows occur frequently this external cost reduction can be substantial when looking at the lifetime of an asset. When the decision is made to increase discharge or buffer capacity in a combined system the external cost reduction in the future should be included in the overall cost/value overview. Once again this value can be determined by looking at the costs per overflow and the change in amount of overflows per year.

Improved quality of road/pavement surface
Sewer works that involve open-cut methods will usually increase the quality of the road or pavement surface. After the sewer section has been replaced, the top layer will be restored. Before the sewer works the top layer may have been damaged or unevenly settled, causing discomfort for users and reduced aesthetic quality. Streets or pavements that are in poor shape could even negatively affect the amount of visitors of nearby shops. While removal and restoration of the top layer for execution of sewer works results in undesirable external costs, it may results in increased visual quality of the area, reduced discomfort for traffic and increased turnover for nearby shops. The quality of the top layer can be increased even further when a new material or colour is applied, which has better characteristics or is more esthetically pleasing.

7.5.2 Added subsurface value

Increased discharge capacity
Sewer works that increase pipe dimensions improve the discharge capacity of the treated sewer section. The activity can even result in increased discharge capacity for (part of) an entire network. This adds value to the network and makes it possible to connect new areas in the future without having to adjust sewer sections. This flexibility also provides buffer capacity for future developments (e.g. increased wastewater production by households). This increase in value of the sewer section (or part of the network) should be included when techniques are used that increase pipe dimensions.

Reduced failures and emergency repairs
Failures can occur to pipelines that are in poor condition, which results in emergency repair costs, nuisance and possibly pollution. Improving the condition of these pipelines reduces the amount of failures (and necessary emergency repairs) and the direct and external costs associated with them. Regular failures can result in high yearly costs that can be prevented by applying repair, renovation or replacement techniques.

Reduced inspection effort
The sewer asset manager can choose to reduce inspection efforts of certain sewer sections that are renovated or replaced and have their condition improved. When a sewer is in bad shape it may receive regular inspection; once its condition is improved it may no longer be necessary to inspect so frequently. This means that the inspection costs occur less frequently, which is beneficial to the overall cost overview. Techniques that significantly improve pipe conditions can offer this additional benefit if the sewer asset manager is willing to increase the interval between inspections.

Pollution reduction (overflows)
Overflows to streets do not only cause nuisance and health risks above ground, but also pollute the subsurface space: soil and groundwater. Reduction of overflows in combined systems thus positively influences groundwater and soil quality. It is possible to give a value to the reduced pollution by determining the external costs that would occur when no action would be taken.

Pollution reduction (leaks)
Leaks in sewer pipelines can result in sewage entering the surrounding soil, which pollutes soil and groundwater. Techniques that seal these leaks thus prevent further pollution and external costs associated with it. This problem does not exist in rainwater pipes and pressure pipelines.

Pollution reduction (materials)
Sewer sections that are made out of polluting materials (e.g. lead or asbestos cement) can become a risk when there has been much damage or deterioration. Polluting parts can enter the surrounding groundwater or pollute the rainwater that flows through the pipe. This pollution can be stopped by replacing the sewer section. The yearly external costs caused by this pollution can be estimated and included in the decision process. This is also possible when there is no pollution yet; experts can estimate future pollution costs and thus the benefit that a replacement technique provides.

7.6 Conclusion

Every sewer project is unique and involves different cost figures. The direct and indirect costs of a project are usually not difficult to estimate and to base a decision on. External costs can far outweigh these costs, but many external costs are very hard to measure and monetarise. Predicting the values for certain external effects is hard since it depends on the specific situation. Besides assigning values to external effects, there has to be a way to convert these values to costs in order to compare them. Certain cost values are already available, e.g. for Value of Time, but many others are still not defined. More research is thus needed in order to better determine the size of certain effects and to convert this to actual costs.

Choice of technique can have a large influence on the total costs, but there are many more factors that influence cost variations. When the owner/operator of a network wants to make the best possible choices when managing his assets it is vital that the factors that influence cost variations are well understood. This means not only looking at a specific maintenance/repair/renovation/replacement project, but also at the sewer system as a whole. Chapter 8 will look further into these considerations and their associated costs.

Besides costs involved with sewer works it is important to also look at the added value that is created. Investments made today can greatly reduce undesirable effects in the future and add value to the network or its surroundings. The sewer asset manager should always look at the value generated by investment alternatives and not only at the cost side of the story. Understanding the values and costs of all possible solutions is a basic requirement for objective comparison and decision making.

CHAPTER 8: DECISION SUPPORT TOOL

Chapter 8: Decision support tool

8.1 Introduction

Efficiently managing a sewer network is a complex task; there are many different aspects involved and it can be difficult to keep a clear overview of them all. In order to make the best possible choices it is vital to understand all the possible techniques and strategies for a certain situation and to understand the impacts that these choices may have on future performance and investments.

The decision support tool that is discussed in this chapter is aimed at helping the sewer network manager to make the best possible decisions. In order to do this it is vital that not only as much useful information as possible is available to him, but also a tool that provides him with a clear overview of all aspects to consider. A standard methodology prevents aspects from being forgotten and can help to improve the quality of decision making.

Figure 42 shows the various steps and components that are necessary to reach an optimal decision. The various components will be discussed in this chapter, thereby explaining how the decision support tool works. The section in which a certain component is discussed can also be found in the overview. The scope of this research is shown in the red box in figure 42; components that are within this scope are integrated into the decision support tool. Besides these components another module has been added to the model; this preliminary module allows the user to investigate long-term investments.

Sewer works are planned and carried out because there is a certain reason for it. Data from the asset database may give reason for action, or events may take place that force the sewer network manager to take action.

The asset database and condition assessment tool are outside the scope of this research, there is however still much uncertainty regarding inspection data that can be found in databases. Since the stored inspection data influences the decision making process it is important to understand these uncertainties. Section 8.2 will shortly discuss this aspect.

In section 8.3 the reasons for deciding to perform activities will be looked into, since each of these has influence on the amount of possible solutions. Some reasons may exclude certain solutions and thus narrow down the search for the optimal solution for a certain project.

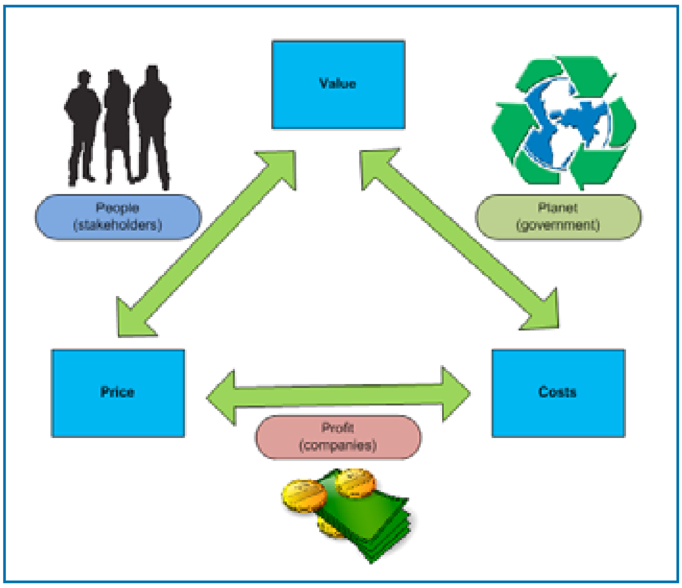


Figure 41:The relation between value, price and costs, and the aspects people, planet and profit

Subsequently a technical decision tree will be discussed (section 8.4) that can be used to narrow down the amount of possible technical solutions, depending on for example the type of sewer system.

Considerations that should be looked at by the sewer asset manager are discussed in this sections 8.5 to 8.7. When the asset manager is aware of all these considerations it will be possible to make the most optimal choices. Forgetting certain considerations can result in a different range of possibilities for a certain sewer project, which can result in choosing a less efficient solution. Integrating all these considerations into a clear decision support tool can greatly benefit asset managers and prevent wrong decisions from being made.

The considerations can be divided into three types: economic (8.5), social (8.6) and environmental (8.7) considerations. These correspond to the elements in the 3P approach: people, planet and profit. Figure 41 shows the business model of the Living Building Concept (De Ridder, 2006), which shows the relation between the three P’s and value, price and costs of a project. People represents the interests area of stakeholders, which can be seen as the difference between price and value of a project. The government is interested in maximising the difference between value and costs, whereas companies strive to maximise profit (which is the difference between price and costs). By balancing these three interests in the decision making process it is possible to develop a

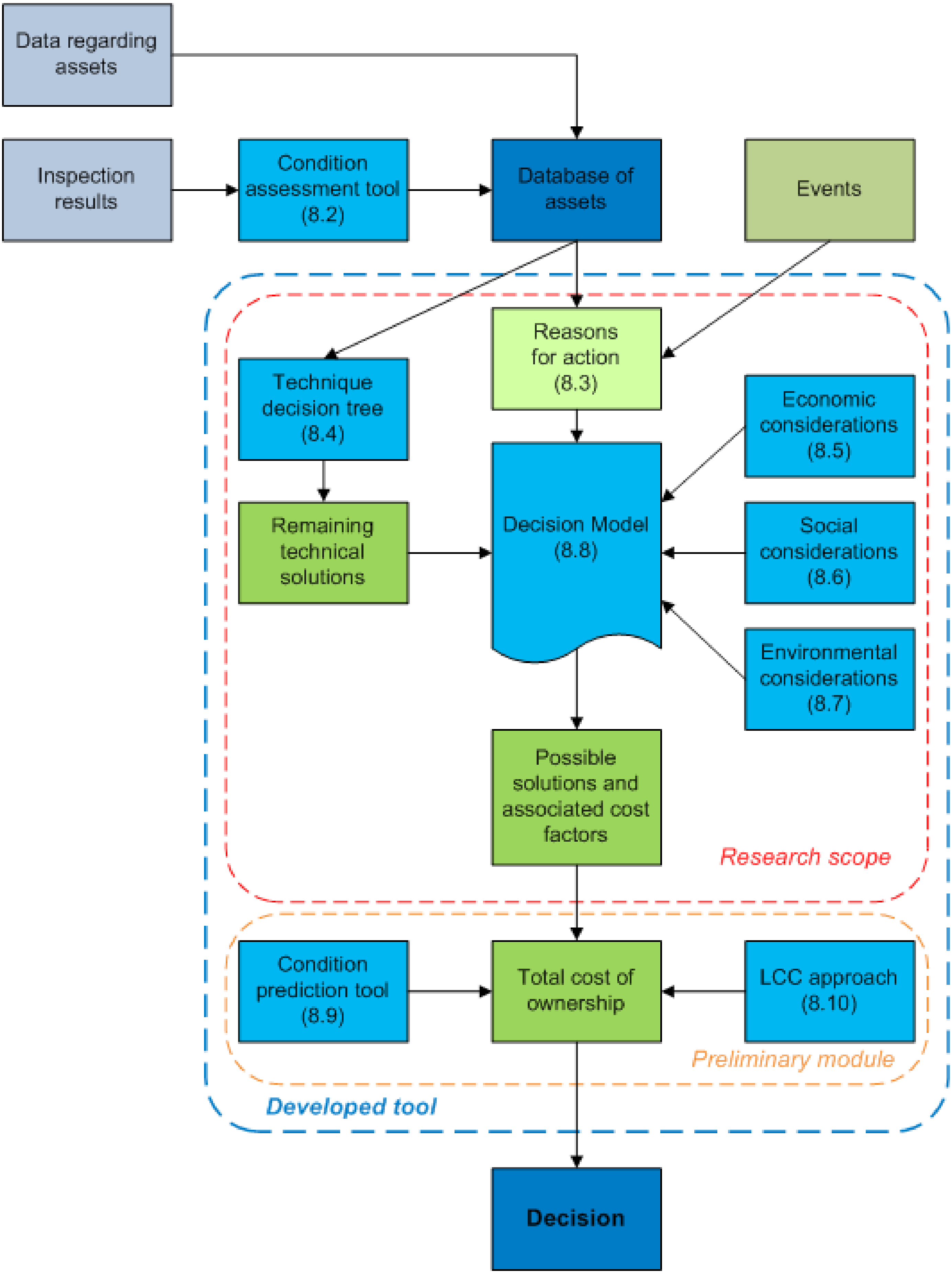


Figure 42:The processes that lead to decision when using the decision support tool; the number shows in which section a certain component is discussed

sustainable approach to asset management of sewer networks that all involved parties support. Decision making based purely on economic motives is no longer acceptable; social and environmental considerations are essential when the sewer network manager wants to determine which solution results in the lowest real costs.

The previously mentioned components were integrated into a decision support model, which was construed with the Excel program. This model can generate possible solutions and associated cost factors for specific situations. The developed model is discussed in section 8.8 of this chapter.

Subsequently the results from the developed model can be used to calculate the total cost of ownership of various alternatives. When these values are known it is easy for the sewer asset manager to compare the remaining solutions and make a decision.

As can be seen in figure 42, two more components are necessary to make this final step. The real costs of a project (economic plus social plus environmental costs) should be considered over the entire lifespan of the components in the project. The network manager should not only look at initial costs, but instead use a Life Cycle Cost (LCC) approach. This basically means that he should look at costs that are made throughout the lifespan of assets. In order to determine these costs it is necessary to predict the deterioration process of objects so the sewer asset manager knows when action is required. General assumptions have been made regarding condition prediction and LCC so that they could be included in the developed tool in the form of a preliminary module. This makes it possible to examine various solutions in the context of long-term strategies. Condition prediction and the LCC approach are discussed in sections 8.9 and 8.10.

Section 8.11 will give an overview of the limitations of the tool and the assumptions that were made. Subsequently the outcomes of a sensitivity analysis will be discussed in in 8.12. Finally section 8.13 will describe which future additions are necessary to further improve the decision support tool and make it more broadly applicable.

8.2 Condition assessment

The sewer asset database that is used by municipalities contains two types of data: general data that is recorded when the sewer section is constructed (system type, location, diameter etc.) and condition data. Inspection results are used to determine asset condition values. The question is whether inspection data can be used to accurately determine the actual condition of an asset.

Research into inspection data of 4 Dutch municipalities has shown that the quality of inspection data is poor and insufficient to base decisions on without adding further information (Dirksen, 2007). Assessment of inspection data is a human process, which means that differences in interpretation can occur and errors can be made. Methods for condition assessment have to be improved in the future in order to garantuee more accurate data to base decisions on.

This research focuses on the decision making process itself and does not look into the question whether or not the database records are correct. The sewer network manager should however realise that the data he receives may not always be accurate. Even though database records may suggest that certain activities are necessary, it would be wise to confirm this by doing a visual inspection (especially when large investments are involved).

8.3 Reasons for reparation/renovation/replacement

There can be a number of reasons for managers of sewer networks to initiate certain activities. It is important to consider these reasons since they affect the available choices when looking into techniques. Some reasons (e.g. damaged components) may require a quick response, while other reasons allow sufficient time for planning and optimisation. The asset manager can decide to repair, renovate or replace certain components or parts of the network because of these reasons. Six main reasons were identified during the research process; some of these reasons are divided into a number of subdivisions.

8.3.1 Performance

During the lifetime of a component its performance will usually slowly decrease. This can be due to material deterioration (which results in more hydraulic resistance) or damage. When the performance has become lower than the minimal required performance, it will be necessary to increase the performance again to satisfy requirements. Height measurements at manholes can give an indication of reduced performance due to settlements when working in soft soil conditions (Staverman, 2010). When this is not possible it is necessary to use flow monitoring instrumentation. Note that settlements can decrease flow capacity, which can result in settlement of waste inside the pipe, thus causing blockage.

Another possibility is that the required minimal performance has increased. This can happen when for example a new housing area has been connected to the existing sewer network and the existing pipes need to discharge a larger amount of wastewater. The existing network may be in good condition, but if the capacity is too low there will be some replacements necessary (e.g. installation of pipes with a larger diameter), or new pipelines have to be constructed. The required minimal performance can also increase because the relevant regulations have been changed. This can have large consequences for the near future as the new requirements will have to be met before a certain date. Even though this deadline can be years away, it can still be a challenge for the sewer network manager since it requires a large amount of changes in the system.

Reason	Specific	Possibilities	Focus points
Performance	Performance has decreased too much	• Reparation • Renovation • Replacement	
	Performance requirements have increased (new areas)	• Renovation • Replacement	• Do more parts of the network need an upgrade?
	Performance requirements have increased (regulations)	• Renovation • Replacement	• Decide at strategic level
Damage	Sewer collapse due to construction activities or heavy traffic loads	• Replacement	• Quick response required • Determine cause and possible measures
Deterioration	Component has reached end of its lifespan	• Renovation • Replacement	• Record lifespan in database for condition prediction
Nuisance	Overflows to street due to insufficient buffer capacity	• Construct additional settlement tanks • Increase discharge capacity (increase pipe diameter)	• Decide at tactical level
Environmental damage	Wastewater is entering surrounding soil because of leaks	• Repair leaks • Renovate or replace entire sewer section	• How much pollution have entered the soil?
	Wastewater is released to surface water during an overflow	• Construct additional settlement tanks • Increase discharge capacity (increase pipe diameter)	• Decide at tactical level • What is the quality of the surface water?
Synchronisation	Nearby infrastructure will be replaced soon, sewer is planned to be replaced in a few years	• Replace sewer at the same time as infrastructure • Extend lifespan of the sewer until the next infrastructure works	
	Sewer has reached expected lifetime, nearby infrastructure will be replaced in a few years	• Extend lifespan of sewer by a few years by reparation/renovation	

Table 14:Summary of possible reasons for taking action

8.3.2 Damage

Sewer sections may be damaged due to nearby construction activities or heavy traffic loads. In the most extreme case this may result in collapse (the road above will also be damaged in this case). This requires immediate replacement in order to restore the destroyed connection and prevent wastewater from polluting surrounding soil and groundwater. Determining the cause of the collapse is also important: can similar collapses be expected in the near future and what measures are possibly necessary to prevent this from happening?

8.3.3 Deterioration

Old parts of the network will have deteriorated considerably. At a certain point these parts will have to be replaced or renovated to prevent components from collapsing or performance from decreasing too much. Sometimes inspection may reveal unacceptable deterioration, other times the manager will decide to take action just because the expected lifetime has been reached. Deterioration speed may vary greatly throughout the system due to differences in materials and soil conditions.

8.3.4 Nuisance

Combined sewer systems have the risk of sewer overflow to the street during or after heavy rainfall. When there is insufficient buffer capacity in the system and sewer overflow to the street happens too often it may be necessary to increase buffer capacity and/or discharge capacity. This means construction of additional settlement tanks in the network or an increase in pipe diameters. Due to climate changes the shower intensities are increasing; old parts of the network may not be calculated for these changes and thus have insufficient capacity. Future climate developments should therefore be recognised when designing new parts of the network.

8.3.5 Environmental damage

Deteriorated sewer pipes and leaking joints may result in wastewater entering the soil. This may result in unacceptable pollution of soil, but more importantly, of groundwater. When pollution is detected the leaks can be plugged with specific techniques, or the owner may decide to renovate or replace the section in which the leaks are located. Especially when the sewer section is planned to be replaced in the near future it may be more economical to replace it immediately.

Another cause of environmental damage are sewer overflows to the surface water. When the capacity of the network is insufficient the abundant wastewater is often released to a body of surface water. This can cause great environmental damage and should therefore be avoided.

8.3.6 Synchronisation with other activities

Sewer works can sometimes be synchronised with other planned activities in order to reduce overall costs and nuisance. A good example of this is road maintenance; roads are designed for a certain lifespan (and also discounted according to this lifespan), after which they need to be replaced.

In an urban environment, most sewer pipes are located beneath public roads. When the municipal infrastructure department has road reconstruction projects planned, it may be very beneficial to combine these projects with sewer projects. Since different organisations are responsible for roads, sewers, cables et cetera there was usually no synchronisation of activities. Nowadays this situation starts to improve, but it is still very common that roads are demolished for sewer projects, just to be reconstructed again a few years later. This results in external and direct costs that are unnecessary. Public money is used to finance these projects, therefore it is vital that this money is spent in the best way possible. Improved communication between various organisations can greatly reduce costs and nuisance. The possibility of synchronisation should always be considered when dealing with infrastructure networks. When it is known that a large road will be replaced soon and the sewer underneath will exceed its lifespan in 5 years, at which time it will be replaced, it would be interesting to consider replacing the sewer now to reduce overall costs and nuisance. The other way around is also possible: if the road will be replaced in 5 years and the sewer underneath is scheduled to be replaced this year, it might be better to wait and replace both in 5 years. Maybe further deterioration can be prevented by slightly renovating or repairing the pipes underneath the road, thereby extending the lifespan of the sewer by 5 more years. The same consideration applies to possible combinations of sewer works and other nearby infrastructure (e.g. gas pipelines, communication and data cables) or public green areas.

Note that when an area is dug up for activities on roads/pipelines/cables/public green areas, trenchless technologies may not be the best choice for sewer replacement. Digging a trench and replacing the sewer

Soil condition	Foundation	System type	Subsystem	Subsystem	Pipe shape	Injection	Robot	Rings/sealing	Sleeve/patch	Open-cut	Pipe-cracking	Pipe-fraising	Plate parts	Sliplining	Winding pipe	Close-fit	CIPP	Hose lining	Spray lining (robot)	Spray lining (manual)	Reinforced concrete
Sandy		Gravity			Circular																
					Non-circular																
		Pressure			Circular																
Peaty	Yes	Gravity			Circular																
					Non-circular																
		Pressure			Circular																
	No	Gravity	Combined		Circular																
					Non-circular																
			Separated	Rainwater	Circular																
				Sewage	Circular																
					Non-circular																
		Pressure			Circular																

Table 15:Decision tree branches, shown in table format

may be more cost efficient in this case (external costs are already created because of the works on other services). For every project the values in this comparison are different, therefore it is important to have a tool to compare alternatives by looking at local conditions and values.

8.4 Technical decision tree

In order to get more insight into viable alternatives for required activities for sewer management, a decision tree was constructed. The decision tree takes into account a number of aspects that are important when looking at sewer networks. By moving from left to right through the decision tree the sewer network manager can quickly see which reparation, renovation and replacement techniques are suitable for a certain project. On the right side of the decision tree the remaining possibilities for a certain combination of aspects can be found. The decision tree is shown in table format, see table 15.

Pipe diameter ranges for all technique have been listed in chapter 6; this is the final aspect that can be used as a filter to determine which of the listed possibilities are available for the pipe diameter(s) found in a specific project. The decision support model allows for input of the existing pipe diameter, this value is then used to exclude techniques that do not support this diameter. If there is a increase of diameter desired, then the desired increase can also be indicated in the tool. The aspects that are used in the decision tree are discussed in the next subsections.

8.4.1 Soil condition

Soil conditions are quite different in different parts of the Netherlands. In general, the eastern part has sandy soils, whereas many areas in the western part of the country consist of peaty, soft soils. Obviously every location has different soil types and combinations, which has certain effects on foundations and structures in the subsurface. Large sewer networks may be constructed in various soil conditions, which means that one part of the network may have larger settlements than the other. In general however the soil conditions in a network can be assumed to be located in roughly the same soil type. For the purpose of this research, the distinction between sandy and peaty soils is made since this makes a large difference in whether or not large settlements can be expected.

Sewers built in sandy soils will not experience significant settlements. This means that many techniques can be chosen by the sewer network manager. Renovation or reparation of old pipelines is a viable alternative when it has deteriorated. The height of components does not change due to settlements, which means there is no risk of changes in pipe inclinations (which can result in discharge problems).

Peaty soils are very common in the western part of the Netherlands. Large settlements can be expected here in sewer networks. Especially sewer pipes are influenced by this; uneven settlements result in damage to pipes and changes in the flow capacity. Sewer pipes are usually given a life expectancy of 60 years (Ministerie van VROM, 2010). While sewer pipes in sandy soils sometimes far exceed their expected technical lifespan, in peaty soils they usually do not reach their technical lifespan. It is not uncommon for sewer pipes to only last 20 to 30 years before they have to be replaced (Staverman, 2010). During this short lifespan the material will not have deteriorated enough to require repair or renovation activities. Technically the same techniques are obviously possible in both sandy and peaty soils, but the sewer asset manager should determine if a sewer section will require complete replacement in order to correct changes in inclination due to settlements. The type of system is an important factor when looking into this aspect; pipes transporting only rainwater do not need an inclination since no sewage can settle inside. Pipes containing sewage flow however will get clogged when they have insufficient inclination.

8.4.2 Foundation

In peaty soils, some components of the network may have foundations underneath in order to prevent significant settlements. Important transport pipes are a good example of this; damage due to settlements is not considered acceptable and thus they have pile foundations. It is assumed that components in peaty soil which have a foundation do not experience large settlements and have a similar life expectancy as components in sandy soils. Note that is a simplification since the mechanical behaviour of pipes that have a pile foundation is different from those that are founded on sand. The pile foundations support pipes at certain intervals, while pipes that are placed on sand are supported along their entire length. Even though this will result in a difference in load transfer and possibly different damages that occur, for now this difference is not taken into consideration.

8.4.3 System type

Gravity systems can make use of all previously discussed techniques. Pressure systems however have a limited amount of techniques available to them. Not all techniques are suitable for pressure systems, this is mainly because pressure systems do not have manholes. Some techniques require manholes for access since they can only be applied to a limited pipeline length. Another factor is the fact that pressure pipes are subjected to different forces than gravity systems.

Futher distinction is made by dividing gravity systems into combined or separated systems. Separated system consists of a rainwater network and a sewage network. These distinctions are only made for gravity networks without foundation in peaty soil condition. The reason for this is that a rainwater network is less sensitive to settlements than a combined or sewage network. When settlements occur in combined systems or in the sewage component of a separated system, the inclinations change and thus also the flow capacity. When it is not possible for sewage to be taken away quickly enough, there is risk of settlement inside pipes or manholes. This results in blockage, which can have very negative consequences for parts of the network. Rainwater networks do not transport sewage and thus do not have this problem. Settlements can be a problem when pipes are damaged severely enough to break. but changes in gradient are not an issue. Water may be stored for some time in the network; the network can be seen as a group of communicating vessels in which the water level is equal, regardless of the lowest point in the network.

8.4.4 Pipe shape

The shape of the cross-section of a sewer pipe is another important aspect. Circular pipes that are in need of repair, renovation or replacement have a larger range of possible techniques than non-circular pipes. Most pipes in the Netherlands have a circular shape, there are however some old sewer sections that contain non-circular pipelines. These are usually part of combined systems and chosen because of flow speed reasons. During rain showers the transported volume is high compared to dry periods. The large pipe dimensions would cause a low speed of sewage transport during dry periods, which can result in clogging. Therefore a different shape is sometimes used, so that the flow speed is always sufficient to prevent sewage from settling inside the pipes.

8.5 Economic considerations

Companies used to make decision primarily from an economic point of view in order to optimise profits. Economic considerations are still important in the decision making process, but the attention for social and environmental considerations has increased over the last decades. Obviously, optimisation of investments in sewer networks still requires a clear insight into economic cost factors. There are a large number of economic considerations that can be relevant for any project; an effort has been made to make the following list as complete as possible. The considerations are assigned to the three levels of decision making as explained in chapter 5.3.4. These three levels (strategic, tactical and operational) can be found in the physical sewer system as three scales. Figure 43 shows these three levels and how they fit in each other. The strategic level signifies the overall system concept, whereas the tactical level covers network functionality. The operational level of decision making is associated with the condition of individual objects in the overall system.

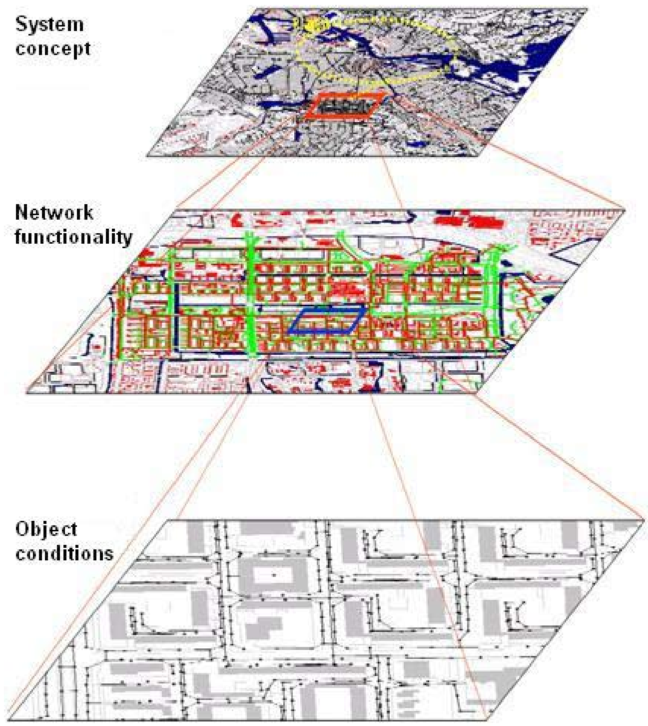


Figure 43:The three physical levels in a sewer system; these signify the strategic, tactical and operational level of decision making (Waternet)

The consequences and limitations related to the mentioned considerations are also listed (in blue), these are integrated into the decision support tool that was developed for the purpose of this thesis.

8.5.1 Strategic

Are there any extensions/upgrades planned for the system in the near future?

Future extensions or upgrades can result in different requirements for parts of the existing system. That is why the strategic level of decision making should never be forgotten in any project. When new areas are connected to the existing network for example this means that a number of existing pipelines will have to discharge larger amounts of sewage in the future. When these pipelines are included in a current project the sewer manager should keep the future extension in mind. Instead of renovating the existing pipelines and extending their lifespan, it may be better to already replace them by pipelines with a greater capacity. When the extension is connected to the existing network it is then no longer necessary to invest money for a second time in order to upgrade the pipelines.

Yes: Determine whether more capacity is required in the future for this sewer section. If this is the case, take into account this increased capacity when planning activities.

Are there plans for relocation of sewer treatment plants?

Relocation of treatment plants will not happen very often, but if it happens it has a large impact on the system. Wastewater may have to be transported in opposite direction all of a sudden, which means that there are large investments required to adjust the entire system. Relocation plans are usually made long before they are carried out, making it possible to prevent large unnecessary investments being made. When a sewer network manager knows that there will be relocation within a number of years, he can chose not to fully replace components that have to be altered anyway in a number of years. Instead of this he can choose to simply repair or renovate these components, extending their lifetime by a number of years.

Yes: Minimise investments in assets that will have to be replaced/altered once the treatment plant is relocated.

What is the expected economic lifespan of the area in which the activity is planned?

The economic lifespan of an area is an important consideration when planning activities for the long term. Redevelopment of a certain neighborhood in the near future makes it likely that the part of the sewer network that services this area will also be altered. This could mean the removal of the old sewer network and the constructing of a new network in this area. Investing a large amount of money at this moment in order to extend the lifespan of this part of the network may be very inefficient. As long as the part of the network remains functional until the redevelopment there is no need for further investments. When renovation or repair activitities are still necessary before this redevelopment it might be possible to use lower grade materials that require less energy and resources during production.

Do other parts of the system also require works because of changing regulations?

Thougher regulations may require many adaptions to the existing sewer system. This requires large investments and therefore it is important to optimise these investments. The sewer asset manager should always keep the required adaptions in his mind, even if they have to be implemented many years from now. Planned replacement activities can be adjusted (e.g. larger pipe dimensions will be installed), so that they immediately fulfill future demands. This is usually much more economical than increasing the capacity once more after a number of years.

Only applies to the reason "Performance requirements have increased (regulations)"

Is there intention to convert to a different system type in the future?

Conversion to a different system type may be planned in the long-term. This has considerable effect on the decision making process throughout many years. Large investments in the current network are unnecessary when their effect will be undone by conversion activities. Upgrading a combined pipeline in order to increase capacity may not be a good idea when the pipeline is expected to be converted in a number of years. The sewer network manager should always keep the long term strategic goals in mind when making decisions at tactical or operational level; this can prevent unnecessary activities being carried out, and thus unnecessary nuisance and costs.

Yes: Do not make large investments in the existing system. Only applies to combined sewer systems.

Will the population composition change in the future?

Sewer networks are designed for a certain area with a certain amount of houses and businesses. Sometimes the population composition will change significantly during a number of decades because of new developments in the area or other parts of the city. The new population composition may result in an increased fresh water demand and thus an increase in the amount of produced wastewater. For example, when more large families are moving into an area that was previously inhabited by young couples, more water will be used and thus more sewage will be created. This can become a problem when the capacity of the existing network is insufficient.

Yes: Determine effect on discharge capacity and take this into account. Does not apply to rainwater pipelines

Will the domestic water usage change in the future?

Changes in domestic water usage can have large effects on the amount of wastewater that needs to be discharged by the sewer system. Between 1995 and 2007 water usage per head of the population dropped by 7 percent, mainly because of technological improvements that reduce water usage of toilets and washing machines. During the last few years however the domestic water usage increased slightly, probably due to an increase in shower usage (Vewin, 2010).

When water usage is expected to increase it would be sensible to take this into account when replacing parts of the network or when expanding the network.

Yes: Determine effect on discharge capacity and take this already into account. Does not apply to rainwater pipelines

8.5.2 Tactical

Are there any sewer sections nearby that also require renovation/replacement/repair?

Instead of simply looking at the object that is in need of a certain activity, the sewer network manager will also have to look at a higher level within the physical system. The network level can give insight into other problems near the object. Instead of replacing one pipe it might be more efficient to replace all the deteriorated pipe sections in a neighborhood. The deployment of equipment and personnel can thus be optimised. Furthermore this may also reduce overall nuisance since the total construction time can be reduced, as well as the number of transport movements necessary to deliver all the materials and equipment (due to optimisation of logistics).

Yes: Combine activities in one area, thereby reducing overall nuisance and costs

What effect on the functionality of the network does activity in this section has?

Most activities require the object to be taken out of commission for a short period of time. This means the flow of water is interrupted, which can result in overflows if there is insufficient buffer capacity in this part of the network. An exception can be made for a mesh network

(for rainwater), since here the water can flow via another route. When part of a branched network is not able to discharge water for a certain period of time it may be necessary to install temporary diversion pipelines and pumps.
Look into the importance of this section/object at functional level, determine whether there is sufficient buffer capacity. When this is not the case, add costs for diversion pipelines and pumps

Is this section the only bottleneck?
When the reason for sewer works is the occurence of too many overlows, it is important to determine if these planned works will fully solve the problem. If the section is the bottleneck of the network that results in overflows, it can simply be upgraded in order to solve the problem. Another possibility is that another section becomes the bottleneck and that the problem is only relocated instead of solved. The sewer asset manager should look at the entire network with regard to other possible bottlenecks. When more sections need to be improved in order to reduce the number of overflows, these can be taken into consideration for other works, thus allowing for optimisation.
No: Adapt the network; determine if optimisations are possible

Are there penalties that have to be paid when overflow to surface water occurs?
Overflows to bodies of surface water result in reduction of water quality. This can be very detrimental for the local environment, therefore the number of overflows should be minimised as much as possible. One method of forcing local governments to pay attention to this is by giving penalties. These additional costs can be seen as compensation for the environmental costs that are created by overflows. It is unclear whether such mechanisms are common in the Netherlands, but it can be an interesting way of including these costs in the decision making process. When there are penalties in place and the amount of overflows per year are known, the sewer asset manager can calculate the amount of money that can be saved by improving discharge capacity.
Yes: Add penalty cost reduction due to improved discharge capacity

8.5.3 Operational

Is the sewer located beneath a road?
In most cases sewer pipes will be located beneath the road structure. When this is not the case the open-cut method may become more favorable compared to trenchless methods, since traffic disruption and restoration of the road surface are no longer an issue. This becomes especially interesting when the pipelines are located at a shallow depth, which means that open-cut methods do not need to remove large amounts of soil.
Yes: include costs for restoration of top layer (when trenches or shafts are required) and traffic disruption.

What type of road surface is present?
When part of the road surface has to be removed for sewer works (either for trenches or start/exit pits) it is important to take the road material into account. Asphalt roads result in higher costs than cobblestone roads.

When will the road be replaced?
As previously discussed in section 8.3, synchronisation of road and sewer works may sometimes result in cost and nuisance reduction. Even when this is not the reason for reparation, renovation or replacement activities this should be taken into account as a consideration. When sewer sections are not in a critical state and the planned activities are not immediately necessary it might be beneficial to look into planned activities for the road above. It might be possible that within a few years the road above the sewer section will be replaced, thereby offering an additional solution for the decision making process: delaying the sewer works until the road will be replaced.
Synchronisation will not be useful in every situation, but especially when parts of the sewer network are planned to be upgraded (e.g. increase of pipe diameters) this can be very beneficial for both the manager and stakeholders.

At what depth is the pipeline located?
An increase in depth means an increase in the amount of excavated material, both for acces shafts and open-cut methods. Open-cut methods will become less economical with increasing depth; trenchless technologies become more interesting at greater depth.

Does the pipeline require a gradient?
Sewer pipes in a combined system that only transport rainwater usually do not have a gradient. This is an advantage when looking at the execution phase, because there it is no longer necessary to make sure that the pipe has the minimal gradient. The pipe can also be laid at a more shallow depth than a pipeline with gradient. In general the costs of placing a pipeline without gradient are lower and it is easier to cross other pipelines and cables since the sewer pipe is always located at the same depth.

Are there house connections present?

When there are house connections present the operation becomes more challenging. When activities are carried out on the sewer pipe underneath the street, it is temporary not possible to discharge wastewater. This means that measures have to be taken for wastewater created during the works.

Yes: Measures have to be taken regarding temporary shutdown of laterals (informing house owners, shutting off water supply)

Are the house connections connected to the pipe?

Another attention point is the reopening of the laterals (since many techniques close off the laterals), which requires additional time and money. An important distinction in this case is whether the laterals are connected to the sewer pipe or to the nearest manhole.

When connected to the pipe: add costs for reopening of house connections (for certain techniques)

Are there any obstacles that would hinder sewer works?

Obstacles can be located either on surface level or in the subsurface. Obstacles in the subsurface are only an issue when shafts have to be excavated, an open-cut method is used, or new pipelines have to be constructed. Trenchless methods that make use of the existing pipe are not affected by obstacles in the surrounding soil, with the exception of start and exit shafts that are necessary for some methods.

On the surface level there can also be obstacles that hinder activities on the sewer network. Access points may be located close to trees, historical buildings, waterways, railtracks, cables or pipelines. This can result in either equipment that can not come close enough to the access point, or lack of space for storage and machines on the job site. Excavation of start and exit shaft may also require the removal of obstacles on surface level. Obstacles like railtracks can obviously not be removed, but may exclude certain techniques (e.g. open-cut methods).

Obstacles that need to removed for access, storage space or trench digging will increase the costs of a project; both in terms of direct costs (additional man-hours and equipment) and social costs (nuisance due to removal). Investigation of the job site location should always be carried out before any decision is made. Some cities already have street view software available to them that can give information about a certain location. The street view software provides a database with photos from every street, allowing for a quick overview of the situation. The city of Amsterdam and Waternet already use such software as support for decision making regarding public works, including sewer works (Staverman, 2010). Another possibility is the use of free online street view software, which can give a good impression the local conditions.

Yes: Add removal costs and external costs for nuisance

Will the municipality receive less income due to the sewer works (e.g. parking fees)?

The sewer works may require space that is normally used for activities that generate money for the municipality (e.g. paid parking or a weekly market). Due to the sewer works these fees are not received by the municipality for a certain amount of time. This loss of income should be taken into account when looking at overall costs for a project.

Yes: Add loss of income as cost factor

Is it possible to use components with a lower technical lifetime?

When a sewer network is located in an area where large settlements occur, the actual lifetime of components may be very short due to damage caused by settlements. In this situation it is not logical to install high quality components that will never reach the lifespan for which they are designed. The sewer manager can decided to use components with a lower life expectancy. These materials may degrade much faster, but if the component will fail after 20 years due to settlements, this may be economically more attractive. Instead of using a component with a lower technical lifespan it might also possible to reduce wall thickness for example. This can save material costs and also results in less emissions during production of the material.

8.6 Social considerations

The social dimension of the decision making process involves considerations regarding labour conditions and interests of the local community. The local community affected by sewer works projects usually consists of the residents of nearby buildings, as well as owners and costumors of nearby businesses. In an dense urban environment this dimension becomes especially important because many residential buildings and businesses are located near the the job site. Social considerations are often decisive when working in these areas and should be carefully examined before taking any decision. Besides the social costs that are generated by projects the public organisation should also take public relations into account. Providing clear information regarding public works can greatly help to reduce opposition and annoyance.

8.6.1 Strategic

Are the risks to public health sufficiently reduced by the sewer system?
The level of public health in a certain area is greatly dependent upon the level of development of the local sewer system. Insufficient service coverage of sewer systems can result in unacceptable risks to public health. In the Netherlands most buildings are connected to sewer systems; if this is not the case the buildings are obliged to have a IBA-system. Service coverage is thus not a problem in the Netherlands, but there is still a risk of insufficient capacity. When the capacity of a system does not increase at the same speed as the amount of wastewater that is produced in a certain area, risks to public health can still occur. Therefore it is important that the sewer asset manager has a long-term strategy for the sewer system that includes future changes in required capacity. Insufficient capacity can result in overflows to streets and surface water bodies, or even sewage that can not be discharged from buildings anymore.
No: Take action as soon as possible by improving the system so that capacity requirements are met. Include this development in current sewer projects: increase capacity requirements for these projects.

8.6.2 Tactical

Can more collapses be expected?
When a sewer section has collapsed, it is important to quickly determine the cause of the collapse. Collapses are fortunately not very common and usually these are isolated incidents, but it may be possible that a serious flaw has caused the collapse. It might be possible that for example errors were made during construction or during traffic load calculations. More sewer sections from the same period may have this problem and thus have an increased chance of collapse. When such a phenomenon is discovered, it is vital that the system is checked for components that may have the same problem.
Yes: Determine which components have priority and which actions have to be taken to prevent future collapses.
Unknown: Research if more collapses can occur. Only applies to reason “Damage (collapse)”.

8.6.3 Operational

Are there any residential buildings close to the job site?
Nearby residential buildings make it more desirable to reduce nuisance caused by noise, vribrations, air pollution and dust. The amount of people that are affected can vary greatly: a street with suburban villas has a much lower population density than a street with skyscrapers on both sides. Open-cut methods become more undesirable as the population density increases due to the disruption of traffic (both motorised and pedestrian) that is usually caused by it.
Yes: Increased external costs for noise, air pollution and vibrations

Are there businesses near the job site?
Access to businesses located close to the job site can be severely reduced because of the sewer works. Especially in busy city streets this effect can be quite large. Reduced access results in reduced turnover for the affected businesses. In busy shopping areas the economic consequences can be substantial, therefore the activities on the sewer network should be done as quickly as possible when they reduce access to premises. Road works and other sewer works in the same area should be planned in such a way that they do not aggravate the situation.
Yes: Reduced turnover for businesses, possible costs for compensations

Are there historical buildings adjacent to the job site?
Historical buildings are a sensitive issue when performing activities in the subsurface. The technical state of these buildings is sometimes poor, making them vulnerable to damage caused by settlements. When working with a high groundwater table, as is often the case in the Netherlands, pumping out water from an excavated trench can be a risk. Leakages in the construction pit can cause groundwater to flow in, thereby lowering the groundwater level in the surrounding area and causing settlements. Trenchless techniques do not have this risk, unless there are start and exit shafts required for the specific technique.
Techniques that create vibrations in the underground should be avoided when working close to historical buildings.
Yes: Increased risk of settlements when using open-cut method or methods that require shafts. Excludes pipe-cracking and pipe-fraising

Is there enough space for the storage of equipment and materials?
Equipment and material can sometimes require a lot of free space, even though this is not always available. When the job site uses part of the public road, sidewalks or parking spaces this creates nuisance. Some premises

may be difficult to reach (see also the previous paragraph) or traffic problems may arise. Therefore it is important to have an overview of the location of planned sewer works in order to see what the consequences will be for the available space.
No: Increased nuisance due to traffic disruption and accessability problems. Possible temporary adjustment of parking rules necessary

What type of road is present?
Some roads have very high amounts of traffic, while others have a very low traffic intensity (e.g. sidestreets in the suburbs). This an important consideration since it gives an idea about the amount of traffic that is negatively affected by planned sewer works. Busy arterial roads that are partly closed for the replacement of a sewer pipe can create a huge traffic problem. Replacing the sewer pipe simultaneously with the road surface is maybe a more suitable solution. Closing off a small road in a low-rise residential area on the other hand should not be a problem.

Will a diversion route be necessary?
By comparing the required space and the available road space the sewer network manager can decide whether or not a diversion route is necessary for the duration of the planned activities. Diversion routes have an effect on the area through which they run. Increased traffic volume results in additional traffic nuisance around the route and can result in traffic jams. Heavy trucks that are diverted can damage road surface along the diversion route (if these roads are normally not used by heavy trucks).
Yes: Increased nuisance around route, risk of damage to road surface, increased risk of accidents around route

Are there any events taking place nearby during the planned sewer works?
Public events that attract large numbers of people should not coincide with activities on roads and sewers in the same area. While in a normal situation a certain activity will not result in any noteworthy nuisance, it may become a problem during large events. Increased traffic volume during an event can already be larger than the capacity of certain access roads; when the municipality decides to execute sewer works at the same time it may be disastrous for the traffic situation.
Yes: Increased traffic disruption, thus increased social and environmental costs

Is it necessary to provide additional safety measures?
Some methods that are used to renovate or replace sewers require the use of cranes. When the job site has limited space available it is possible that certain equipment or materials are hanging from a crane above public areas with traffic. This situation requires additional safety measures in order to protect the public from falling objects.
Yes: Increased costs for preventive safety measures

What is the condition of adjacent manholes?
When sewer pipes are repaired, renovated or replaced it may be more efficient to simultaneously treat adjacent manholes. Instead of doing additional sewer works in a number of years, the activities for manholes and pipes may be combined into a single operation. This could be more economically attractive and furthermore result in lower overall external costs (like nuisance) than when two operations are carried out within a number of years.
When the manholes are in bad condition: determine if it is possible to combine activities for pipes and manholes

What caused the sewer collapse?
Sewer collapse is fortunately not so common in the Netherlands, but it should not be underestimated since the consequences can be grave. Sewer collapse can result in many undesirable effects: interruption of service, pollution of groundwater and surrounding soil, damage to the road surface above, traffic accidents et cetera. Therefore it is very important that collapses that occur are investigated in order to find the cause. This can help to prevent future collapses and thus additional undesirable effects and costs. In the model the user can choose from a number of causes of sewer collapse, these are connected to a number of attention points that are mentioned in the output overview. The user can choose between exceeded lifespan, high traffic loads, nearby works or other.
Only applies to reason “Damage (collapse)”

8.7 Environmental considerations

8.7.1 Strategic

Is it possible to apply secondary and reusable materials?
Public organisations are becoming more aware of the impact of their activities on the environment. The materials that are used for sewer works do not necessarily have to be new. Some materials can be recycled and reused in other sewer projects. Concrete is a good example of this; granulate that is gained from discarded construction

elements can be used again for the production of new concrete elements. Research has shown that the amount of available granulate will double in the coming years, while the demand for granulate for foundations and enbankments will not increase (Rijkswaterstaat, 2006). According to CUR recommendation 112 it is possible to replace up to 50 percent of gravel by granulate without changing the calculation rules (CUR, 2008). This means there are many opportunities for the reuse of concrete granulate, for example in concrete sewer pipes.
Pipes made from plastics can also be reused for the production of new pipe sections. Since 1991 the producers of plastic pipes have a collection system called Buizen Inzamel Systeem. All plastic pipes that become available as waste from various projects are collected and reused in the production process of new pipes (BureauLeiding, 2010). At strategic level the use of secondary and reusable materials should be encouraged as part of a sustainable approach.

Which effect will climate changes have on required sewer capacity?
Sewer systems are designed and constructed for a long period of time; during this time there can be significant climate changes. Intensity of rainshowers will increase in the years to come (Klein Tank, 2009), which means higher peaks of water volume that have to be discharged. In the long-term planning it is important to include expected changes in weather behaviour. When this phenomenon is forgotten there will be more overflows (both to streets and to surface water bodies), which results in increased damage to the environment and nuisance.
Only applies to combined systems and rainwater pipelines: increase discharge and/or buffer requirements

8.7.2 Operational

Are there polluting materials that need to be removed?
There are a small number of old sewer pipes in use that contain polluting materials, e.g. lead or asbestos, that are not used anymore these days. These old pipes will have to replaced and removed eventually. This process involves risks for the enviroment since these polluting materials can end up in the soil or groundwater. This means a careful consideration should be made of how these pipes will be removed. Destroying the pipes in the process is not acceptable since this will result in pollution of the environment. Taking the pipes out intact is mandatory, afterwards they can be brought to a disposal facility. The removal operation requires safety measures and licensed personnel, this will result in additional costs.
Another form of pollution can be polluted soil that is encountered when digging trenches or shafts. The polluted soil will need to be cleaned or removed from the job site.
Yes: exclude techniques that fracture the pipe; include costs for disposal or treatment

Are there environmentally unfriendly residues inside the pipe?
Pipes that have been in use for a long time or have had problems with flow capacity may contain undesirable residues, e.g. oils, minerals or dirt. When the pipe is replaced these residues should not end up in the surrounding soil and groundwater. In some cases it may be preferrable to replace the pipe without fracturing it (as is done with for example pipe-cracking). Another possibility is a thorough cleaning, after which the pipe is relined.
Yes: exclude techniques that fracture the pipe; include costs for pipe disposal OR include costs for cleaning and residue disposal

Is a clean-up operation necessary?
When a sewer section has collapsed or wastewater is entering the surrounding soil because of leaks, the soil and groundwater can become polluted. Small amounts of polluted water will not cause much harm, but large amounts can cause serious pollution. Besides restoring or repairing the leaking or collapsed pipe section it might be necessary to remove the pollution. This results in additional costs, which should be taken into account. Another attention point is the effect of the pollution on groundwater and public health, this can be seen as a risk that should be analysed.
Yes: Add costs for clean-up operation, as well as a possible risk to public health. Unknown: add possible risk to public health and add investigation into size of pollution.
Applies only to reasons “Damage(collapse)” and “Environmental damage(leaks)”.

8.8 Decision support model

The previously discussed components that are within the scope of this research were eventually integrated into a decision support model, which is aimed at improving the decision making process regarding sewer networks. The model generates possible technical solutions and associated cost factors, based upon information entered by the user. These solutions are aimed at a single repair, renovation or replacement project. In order to compare multiple activities over the entire lifetime of an asset, an additional module was later added that determines the total cost of ownership of an asset. The components of this module are discussed in sections 8.9 and 8.10. This section will shortly discuss the developed tool; an extensive explanation of the various components and relations can be found in Appendix A.

8.8.1 Choice of software

The decision support model was constructed with help of the Excel program. The reason for choosing this program is the fact that it is very suitable for designing a tool that relies on many relationships. Furthermore it is easy to add components to the program in a later stage (when more research has been done), allowing for flexibility. Lastly the program is widely available and easy to use, making it easy to implement in various organisations. The tool was constructed in Excel 2007, which has (obviously) more options than its predecessors, for example conditional formatting (which is used extensively for this tool).
It is thus recommended for users to use the 2007 (or newer) version of Excel in order for the tool to fully function.

8.8.2 Layout

The decision support tool consists of a number of worksheets that are connected to each other via various relations. The tool can give the user three levels of solutions, depending on the user's wishes and the complexity of the problem. Figure 44 shows the various steps in the decision support tool; the three moments at which the user can make a decision can be clearly seen.

The first sheet allows the user to select general parameters (system type, pipe diameter, pipe shape, reason for action and local conditions), this immediately shows which techniques are viable solutions. When there only one or two solutions possible this may be sufficient information for the user to make a decision. This is indicated by the first green decision circle in figure 44.

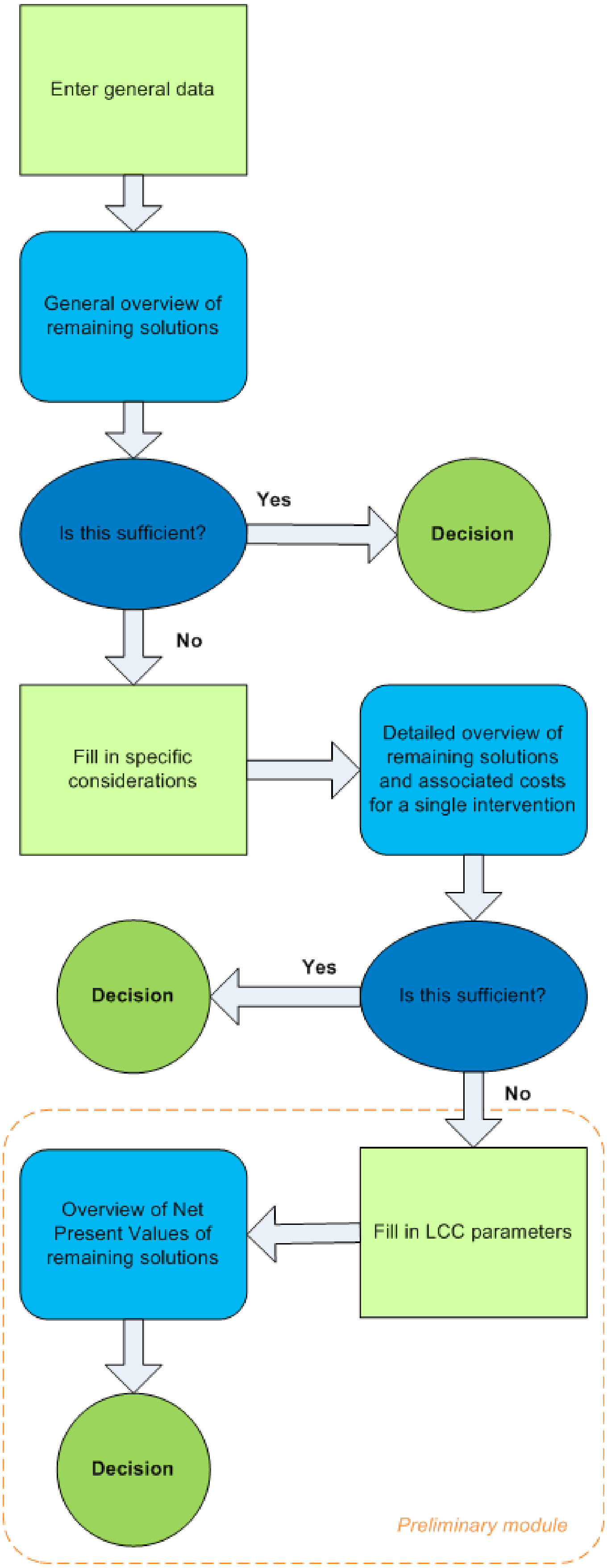


Figure 44:Sequence of steps that illustrate how the excel model works

When there are many solutions remaining the user can proceed to a second sheet in which he can fill in answers to the many considerations that were discussed in sections 8.5 to 8.7. The considerations are divided into nine fields, representing combinations of three decision making levels and three major aspects. The choices that are made by the user are linked to an overview sheet, which generates all remaining techniques, attention points, risks and all related costs that should be taken into account. These generated results provide a valuable overview for a single repair, renovation or replacement activity. The relevant costs can be easily entered into the model by the user in the overview sheet, after which the overall costs of all remaining solutions are calculated. This makes it easy for the user to determine the most suitable solution for this project. At this point the user can make a decision based upon these results, or decide to take one more step to compare the long-term costs of the remaining solutions.

The most extensive level of solutions thus provides information regarding life cycle costs of various alternatives. This last step is possible by a module that takes condition prediction and life cycle costing methods into account. The user should enter a number of variables regarding condition prediction and economic conditions, after which the program can calculate Net Present Values for all alternatives. This is however a preliminary module, based on rough assumptions. While it can provide a useful indication of long-term costs, the user should realise that the generated values are based upon a simple prediction model. More research is necessary to improve condition prediction, which will allow a more accurate prediction model to be developed and implemented. This preliminary module is a first step towards a fully integrated tool that can accurately determine deterioration processes and their effect on investment patterns.

An extensive overview of the associated worksheets and the connections between these sheets can be found in appendix A.

8.9 Condition prediction

Condition prediction is not discussed in detail in this report. As shown in chapter 5, there are a number of prediction tools for sewer components available. Inspection data is often used to calculate future conditions. Just as with condition assessment tools, there is a chance that the used data is not reliable. This will also result in incorrect predictions for future conditions, which is very undesirable.

	Economic	Social	Environmental
Strategic	Strategic economic	Strategic social	Strategic environmental
Tactical	Tactical economic	Tactical social	Tactical environmental
Operational	Operational economic	Operational social	Operational environmental

Figure 45:The various types of considerations that were identified for the purpose of this research. The consideration sheets in the Excel tool have the same layout as shown above.

It may be possible to make a very rough estimation of future conditions, but at this moment there is no possibility of exactly determining and predicting conditions. The sewer asset manager should take this into account when using “rough” predictions in order to determine investment patterns.

8.9.1 The condition curve

The deterioration process of sewer pipes is an important boundary condition when looking at optimisation of investments in sewer networks. The curve that shows the deterioration process can be called the condition curve since it gives insight into the condition of a sewer pipe at a certain moment in time. The deterioration process has been investigated in a number of research projects over the years. The local conditions have a large influence on the curve of a specific pipe. Factors that can have an influence on the process include soil conditions, traffic load, depth, pipe shape, pipe size, and slope of the pipe. There are conflicting research results on which of these effects are most relevant (Ana et. al., 2009; Younis & Knight, 2010). These influences on the deterioration process are however not within the scope of this research and will thus not be addressed any further.

The actual deterioration process can only be found by gathering inspection data throughout the lifetime of an asset. Sewer sections will have different deterioration curves, depending on specific conditions. It is obviously not economical to make a custom curve for every pipeline. General deterioration curves can give an approximation of the expected behaviour. Use of these general curves is necessary since the sewer asset manager requires an assumption on which he can base decisions.

Possible curves

The question is which type of curve is most realistic. Three types of condition curves are known to be used for deterioration of sewer pipes. The first possibility is a linear curve, the most basic type of curve. Linear functions assume a constant deterioration during the lifetime of an asset.

The second possibility is a second-order polynomial, a so called quadratic polynomial. This means an increasing deterioration rate of the asset as its age increases. The last possibility is a third-order polynomial, a cube polynomial. This type of curve has two bends and divides the deterioration process into three parts. The first part of the curve will drop sharply; it is assumed that a new asset will loose condition quite fast in the beginning due to errors made during execution. The middle part of the curve flattens out; the initial degradation is over and the pipe condition will not deteriorate as fast anymore. The last part of the curve shows an increase in deterioration rate; the asset is approaching its technical lifespan. Inspections that are carried out before the assets are delivered to the owner can (partly) remove the first drop in the curve.

Higher order functions can more accurately approximate data curves, there is however no general deterioration process known since it depends highly on local conditions. Higher order functions require more calculation obviously and thus an optimum has to be found between accuracy and complexity. The following arguments can be considered when a prediction of the deterioration process is required:

The linear curve shows a much too negative expectation of the deterioration process. This will result in planned activities being carried out too early, this is very inefficient. Since limited budget is available for sewer works it is important to optimise investment strategies. When a linear curve is adopted this is not possible since the expected condition level is much lower than the actual condition. Figure 47 illustrates this point by showing the difference between a linear and quadratic curve for a renovation that is carried out at the same condition level.

The quadratic curve offers another improvement over the linear curve: the changing deterioration rate is taken into account. This results in improved decision making since a changing rate requires a different investment strategy approach. This is illustrated by figures 47 and 48: because of the changing gradient of the curve there is a chance to optimise the moments at which certain techniques are applied. When action is taken earlier in the lifetime of an asset it takes more time before the same condition level is reached again than when action is taken at a later stage.

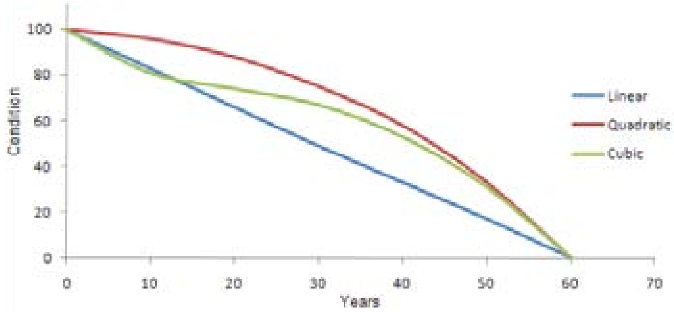


Figure 46:Condition curves of first, second and third degree

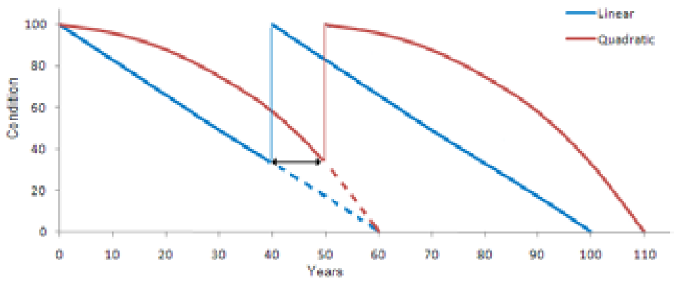


Figure 47:Comparison of linear and quadratic curves when looking at an intervention at the same condition level

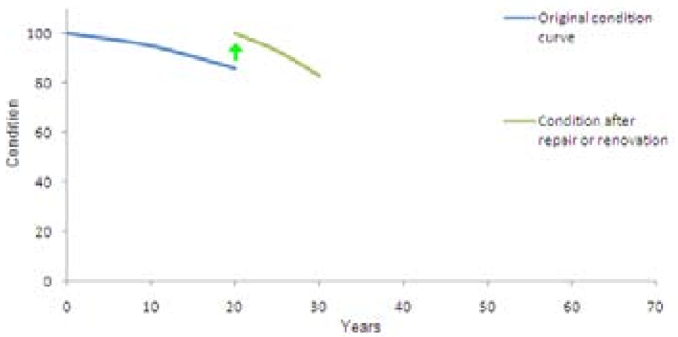


Figure 48:Action taken after 20 years: ten years later the condition has decreased by 20 percent

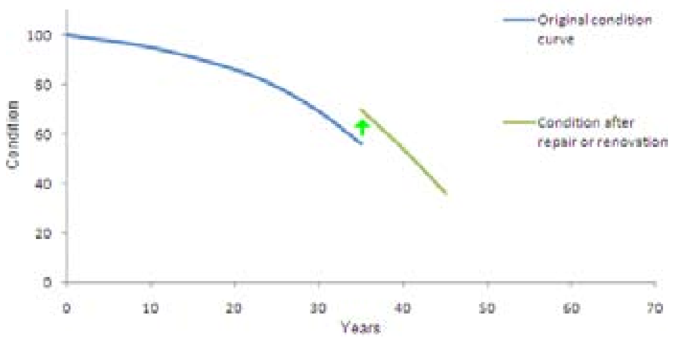


Figure 49:Action taken after 35 years: ten years later the condition has decreased by 34 percent

The cubic curve can give an additional improvement by taking into account the initial degradation due to construction errors. This curve may give a more accurate representation than a quadratic curve, but the question is whether this initial degradation always takes place. Maybe newly constructed pipe sections are delivered in excellent state in certain cities, while errors occur more often in other locations. Since there is no data available regarding this phenomenon, it is impossible to make a statement about which curve should be preferred. One might say that when there are often errors detected when a new sewer section is delivered, a cubic curve may be more suitable. When the contractor delivers quality work without errors, the quadratic curve may be more realistic.

Curve used in the tool

In order to determine costs throughout the lifetime of an asset in the decision support tool, an assumption has been made regarding the deterioration of assets. A theoretical deterioration curve has been chosen and integrated into the Excel model. Since there is no knowledge about the actual deterioration curve of sewer pipes, a simple second order formula has been chosen to approximate the actual deterioration process. The question whether or not this theoretical curve is realistic is not relevant for this research and thus not investigated; this curve merely offers a basis for calculation in the tool. Note that this theoretical curve does not provide any information regarding loss of functionality, diameter reduction or damage. A general dimensionless condition is shown that only indicates at which point the asset will fail (when the condition reaches zero). The formula that was chosen for this research has the following shape:

$$C = 100 - yt^2$$

where

C = condition of the asset at time t (in percents)

y = constant

t = time (in years)

The expected lifetime of an object is chosen to be an input variable and the curve should be able to adjust to this value. The y-value should thus depend upon the expected lifetime that is entered into the model. When t is equal to this value the condition of the asset should be zero. This requirement results in the following formula for y:

$$y = 100 / (t_e^2)$$

where t_e is the expected lifetime of the asset

The maximum value for t_e has been set at 120 years, which is thought to be a realistic upper boundary. An upper boundary is necessary in the model to prevent datasets from becoming unnecessarily large.

8.9.2 Effect of various techniques

There are many techniques for repair, renovation and replacement discussed in this report. The various techniques are used to improve the condition of sewer pipes, the question however is what the effects of this improvement actually are. In order to optimise investments over the entire life cycle of a pipeline it is important to know the effect of different alternatives on the asset condition. There is little data available about this topic unfortunately. Manufacturers of relining methods usually state that their technique will increase the expected lifetime by a certain number of years. This is however a very rough indication and it does not provide any clue on how the asset deterioration curve is altered. Another problem is the fact that most techniques are relatively new and there is no long-term data available regarding their actual performance. More insight into the effects of specific techniques is required so that the sewer network manager knows which condition value an asset has at a certain moment in time.

As discussed before, the deterioration of an asset can be visualised by looking at the condition curve. In order to make a good decision regarding choice of technique it is important to know the effect of the possible techniques on this condition curve. The question thus is: What happens to the condition curve when technique Y is applied at a certain moment? The application of a certain technique will increase the condition of the asset. The question is whether this effect always has the same value, no matter at which point in the life cycle it takes place. It might be possible that techniques have different effects, depending on the amount of deterioration that has already occured. This point of view is illustrated by figure 50, which shows

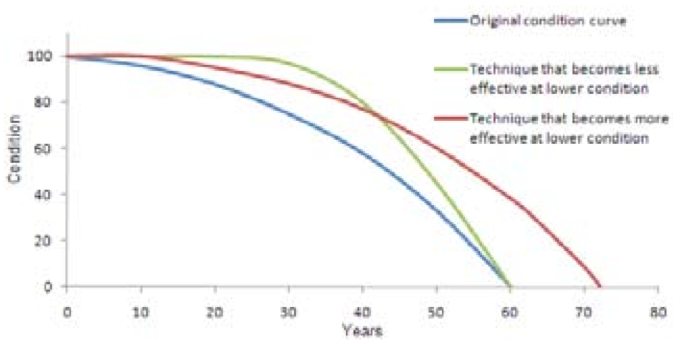


Figure 50: Condition increase that is dependent upon previous deterioration

a condition increase that depends on the deterioration that has occured. Some techniques may become more effective when a large amount of deterioration has occured, while others are more efficient when applied in the early stage of the lifetime of a component.

Note that the angle of the curve is not altered by the activity at time t in figures 47 and 48; it is assumed that after the condition level is increased the curve has the same gradient as before at this condition level. It is unknown whether this assumption is valid; the curve gradient might as well be altered by application of a certain technique. This alteration in itself may also be dependent upon the previous deterioration of the component. Figure 51 illustrates the effect that a possible change of gradient can have; when the curve is “flattened” by the applied technique, the life expectancy may be significantly altered.

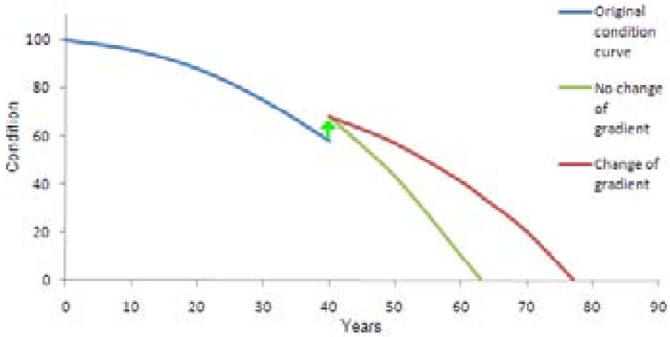


Figure 51: Effect of alteration of the gradient of the deterioration curve

Another difficulty is the fact that not all techniques are able of fully restoring the condition of the asset (back to 100%). Replacement techniques are able of doing this since they replace the old liner by a new pipe, thus putting new material into place. Repair and renovation techniques will not always be able to fully restore the pipe since it has been damaged and deteriorated over a number of years. This distinction should be taken into account when developing a condition prediction tool.

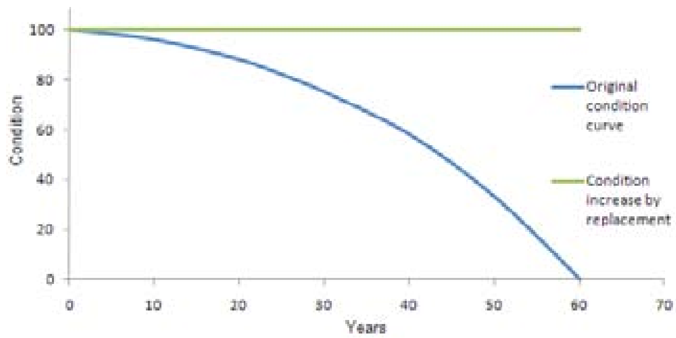


Figure 52:The effect of application of a replacement technique: full restoration of the asset’s condition

Since there is no data available to analyse the previously mentioned phenomena, the most simple assumption would be that the condition increase is always the same. This means that the application of a certain technique always has the same effect and is thus not dependent on the previous deterioration. When choosing a technique this will result in a fixed percentage being added to the condition curve. Figure 53 shows the fixed percentage increase (P_f) that occurs when a certain technique is applied at time t. An additional parameter can be created that takes the inability of certain techniques to fully restore a component into account. The maximum percentage to which a technique can restore the asset is described with the parameter P_m.

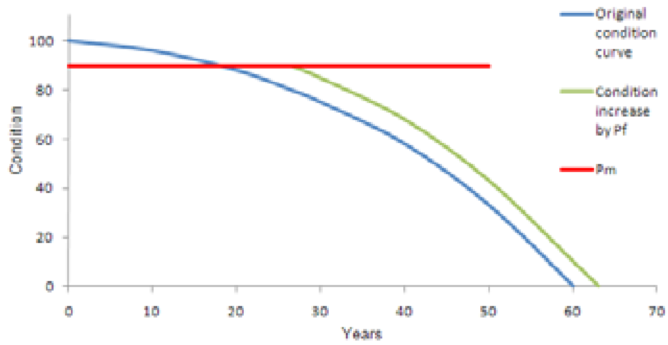


Figure 53:The upper boundary P_m and the increase P_f

Assigning values for P_f and P_m to the various techniques that are included in this research is difficult. There is no data available for these parameter, therefore a rough estimate has to be chosen until more accurate data is available. The estimates can be based on discussions with experts. There are techniques that would have similar values for P_f and P_m. Also, there may be more products available for a certain technique with varying characteristics. Therefore it is not possible to make a realistic estimation of the P_f and P_m values until detailed, reliable data is available. In order to be able to make a comparison in the decision making process, the first step could be to assign these techniques to a general category. An example of such a rough division and the associated values is shown below (the shown values are not based on any research).

Repair techniques
Repair will result in a small increase in the condition of the sewer pipe
P_m=80%
P_f=20%

Renovation techniques
These techniques have a much larger effect than reparation techniques and will result in a substantial increase in condition.
P_m=90%
P_f=60%

Replacement techniques
When a sewer pipe is replaced this will result in full restoration, this means that the condition level is restored to 100%.
P_m and P_f = 100%

It is possible to make a general comparison between various types of techniques by talking to experts. Even though this does not give accurate values, it allows for a general comparison and the possibility to examine developed models. For now the values that are shown above can be found in the model. These values are however placed as initial values in an input field, it is thus possible for the user of the tool to simply alter these values for every technique.

All the previously mentioned uncertainties and possible relations between parameters clearly show that condition prediction is a difficult task. More research is required to increase the understanding of the deterioration process and the effects of repair, renovation and replacement techniques on it. This will hopefully lead to the possibility of accurate condition prediction for sewer assets. The following specific effect will have to be researched:

- *Value of condition increase by application of certain techniques throughout the asset's lifetime*
- *Alteration of deterioration curve gradient when certain techniques are applied*
- *Limitations of certain techniques with regard to condition increase (e.g. upper boundaries as P_m)*

Perhaps a number of curves can be developed that cover the most common situations (combinations of soil type and pipe materials/pipe dimensions for example). This will probably require extensive research, but it is absolutely necessary since the actual deterioration process varies greatly and a general curve is thus often very inaccurate. When the actual deterioration process of a network component can be predicted with sufficient accuracy, budget can be more efficiently allocated. The risk that sewer works are carried out too early (which is financially inefficient) or too late (e.g. after collapse) can be significantly reduced in this way.

8.10 Life Cycle Costing (LCC)

As explained before, there is still much uncertainty regarding condition prediction. More accurate prediction of future conditions will allow for optimisation of investment strategies. Life Cycle Costing, also known as Whole Life Costing, is a technique to determine the total cost of ownership of a certain product or service. The LCC approach addresses all the costs that are expected to occur during the anticipated lifespan of a product or service. Instead of just looking at the initial investment costs the LCC approach thus also includes the costs that are incurred throughout the lifespan of a product or service, which are components of a sewer network in this case. Operational costs (costs incurred during the operational life) and end life costs (costs associated with the disposal or termination of the asset) can be major components of the total costs, therefore it is essential that these are included in the decision making process.

The LCC approach prevents sewer asset managers from simply choosing the solution with the lowest capital costs (which might have much higher operational or end life costs than other options). Application of LCC means that a number of important concepts should be taken into account (Office of Government Commerce, 2010):

Cost Breakdown Structure (CBS)
This identifies all the relevant cost elements that used in the LCC. Chapter 7 has already given insight into various cost types created by sewer works.

Cost estimating
The values for the cost elements that are mentioned in the CBS are either obtained from available data, derived from historical or empirical data or assumed from expert opinion.

Discounting
Discounting techniques are used to compare costs and benefits that occur in different time periods. See the next section for further information.

Inflation
Inflation is usually not included in a LCC analysis, unless different commodities with differing inflation rates are considered. In this research regarding assets of sewer systems this is not the case and therefore inflation can be omitted.

8.10.1 Net Present Value

Present value calculations are widely used in business and economy to provide a means to compare cash flows that occur in different time periods. This method of discounting takes the future cash flows and coverts these to their present value by using discount rates. These present value can then be added up to a Net Present Value and compared in order to see which investment has the highest value (or lowest costs).

The rate used to discount future cash flows is a very important parameter in NPV calculations. Determining the discount rate can be difficult and depends on the type of organisation. Municipalities that invest in sewer networks are public organizations. Public organisations do not have profit-driven goals like private companies. Their goal is to provide public services to the population in the best way possible. This is why environmental and social effects play a more important role for public organisations, since these effects result in costs that are incurred by the population. These costs should thus also be included as cash flows in NPV calculations. Public organisations also do not have shareholders that expect certain returns on their investments, unlike private companies. So which discount rate should be chosen?

In the Netherlands the government prescribes a real discount rate of 2,5 percent. The real discount rate does not include the inflation rate. Municipalities are allowed to add a risk percentage up to a maximum 3 percent. This risk percentage can be added when it is possible that benefits are lower than expected due to economic uncertainties (Ministerie van VROM, 2007). In practice the discount rate thus varies between 2,5 and 5,5 percent. Since uncertainties regarding expected future benefits are not an issue when looking at sewer systems there is no need to add the risk percentage.

8.10.2 Investment scenarios

Different investment patterns are possible when considering asset management of sewer networks. Different techniques result in different life expectancies for components. The question is when which techniques should be applied to reduce costs and nuisance over the entire lifetime of an asset. Various investments are done throughout the lifetime of an asset, which also result in external costs being created. All these costs are included in the Life Cycle Costing approach. The costs should be converted to present values using the PV approach; the results from various scenarios can thus be compared.

In chapter 7 three types of costs were distinguished (direct, indirect, external). These costs should be considered for every activity that is planned. When looking from a LCC point of view, it is possible to divide the lifetime of an asset into three phases in which distinctive activities take place:

Initial phase: Planning and construction of sewer assets, until the point of the asset being in operational use.

Operational phase: Maintenance, repair, renovation, replacement and improvement activities aimed at maintaining or improving the condition of existing assets.

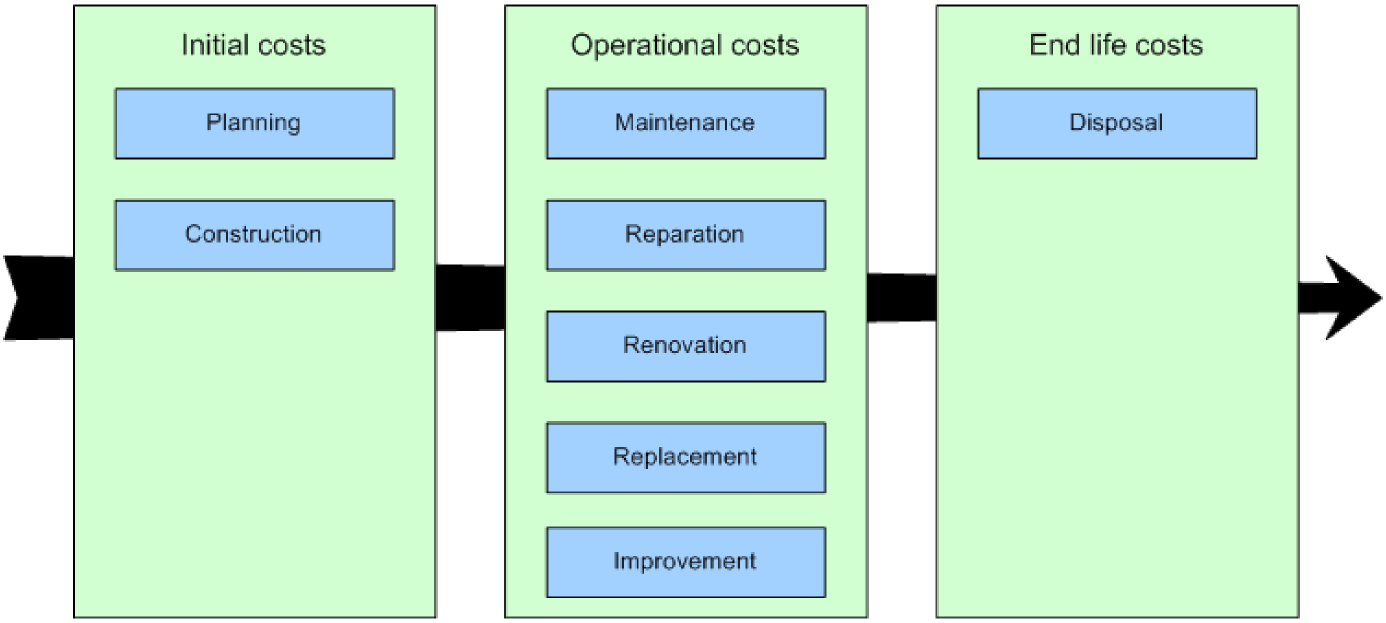


Figure 54:Three distincitve phases in an assets' life, with associated costs

End life phase: Disposal of the asset when it has become obsolete. This can happen when an area is redeveloped and does not need certain sewer sections anymore. Another possibility for the future is that the current method of wastewater collection will be replaced by a completely different system (e.g. decentralised collection of wastewater). At this moment it is however very unlikely that there will be a new collection method implemented.

The activities that take place in these three phases will all generate direct and external costs. When these costs can be identified and converted to monetary values it is possible to make an integral comparison between various solutions.

Many scenarios can be thought of when making a long-term planning for an asset. The condition of an asset will continuously deteriorate until, unless activities are carried out, it will reach zero percent. Three general scenarios can be identified when looking at how to manage a sewer asset, these will be discussed in the following paragraphs.

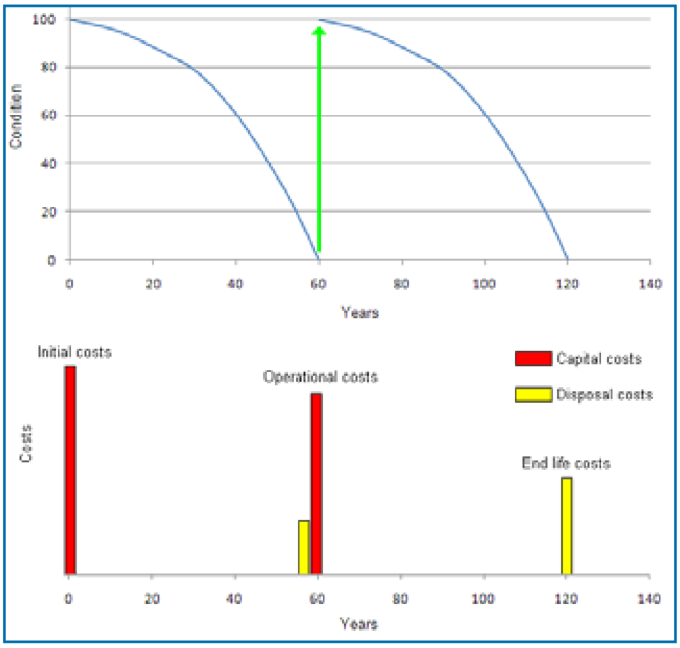


Figure 55: Condition of an asset and investments during its lifetime when investments are delayed until the component (almost) fails and open-trench techniques are used (scenario 1)

Scenario 1

The sewer asset manager may decide to delay investments until the component almost collapses (zero percent). For important sewer sections (large transport pipelines for example) this approach is usually not acceptable since a collapse would have large consequences (pollution, interruption of service).

The traditional solution for this situation is digging a trench, removing the deteriorated or collapsed component, and subsequently placing a new component. After this operation the trench is backfilled and the top surface is restored. As can be seen in figure 55, this results in both capital costs (for the construction of the new component) and disposal costs (for the removal of the old sewer pipe). External costs are not shown since the relative value of these costs is unknown. One can however imagine that the external costs for open trench replacement are high, especially in dense urban areas.

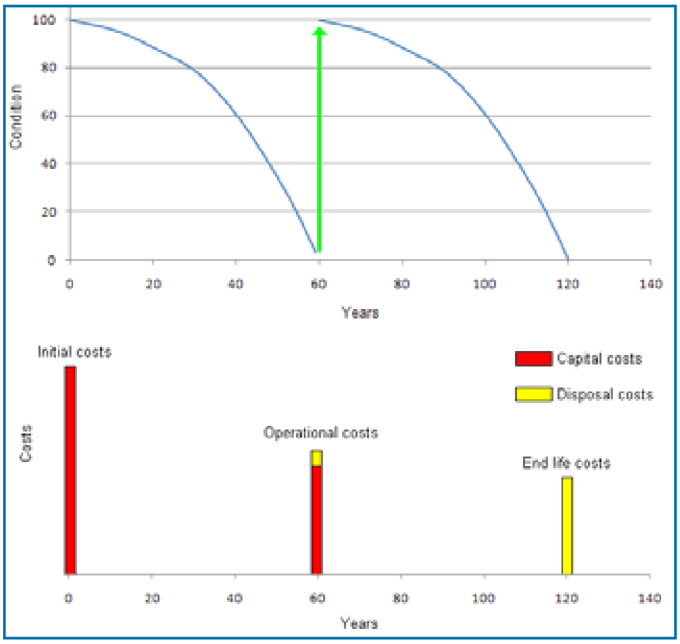


Figure 56: Condition of an asset and investments during its lifetime when investments are delayed until the component almost fails and trenchless techniques are used (scenario 2)

Scenario 2

Trenchless technologies allow the sewer asset manager to replace or renovate (when the component has not collapsed yet) the component without digging a trench. Replacement by applying the pipe-fraising technique will result in some disposal cost since the old liner is eaten and the debris is removed, but these will be lower than when digging a trench (see figure 56). When choosing a different trenchless renovation or replacement technique there are no disposal costs at all. Besides this advantage the trenchless alternative will result in much lower external costs in most cases.

Scenario 3

Another possibility is that the condition of an asset is maintained above a certain value (figure 57). This lower boundary signifies the minimum percentage that an asset is allowed to have; from now on this percentage is called P_l. Whenever the asset reaches this value, repair or renovation activities are carried out in order to increase the condition. This means more frequent activities than the when the asset is allowed to deteriorate until it collapses. The question is which costs can be exptected at the moment that activities take place. More frequent activities do not necessarily mean more overall costs; the direct and external costs may be much lower for small repairs and renovation than for full replacement. In theory, this strategy can be used to keep the asset in shape indefinitely. Disposal costs only occur at the end of the lifetime of an asset. Another advantage of this approach is that there is no chance of collapse due to deterioration or much loss of functionality; the asset can be kept in good shape.

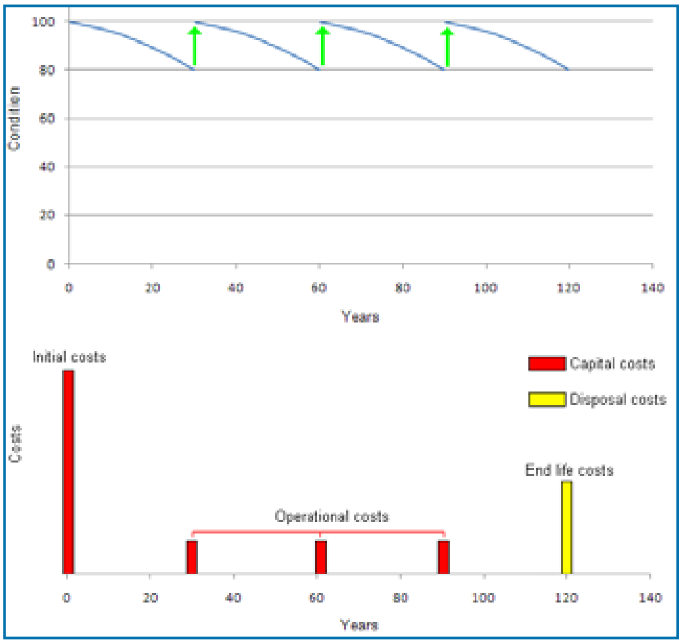


Figure 57:Condition of an asset and investments during its lifetime when the condition is maintained above 80 percent by using small repairs/renovations (scenario 3)

8.10.3 LCC integration into the tool

The LCC approach has been included in the decision support tool in order to allow the user to investigate long-term strategies. The tool should be able to calculate the different investment scenarios that were described in the previous section for various techniques. Since there are a number of uncertainties regarding deterioration processes and effects of techniques on the life expectancy of an asset, various variables have been constructed in the tool. These variables allow for a wide range of possibilities to be investigated and provide flexibility for adjusting the tool to results of future research.

Extensive datasheets have been added to the decision tool to be able to compare many techniques with different characteristics for a specific project. The LCC approach is combined with condition prediction, which was discussed in section 8.9. The effects of considered techniques on the deterioration process are described by P_m and P_f; values for these variables are given in the model but can be altered for every technique. The following variables that are also required for the LCC calculations have been introduced into the decision support tool:

Life expectancy of asset

The chosen life expectancy value is used to construct a value for constant y (see 8.9) in the assumed deterioration formula. With the resulting formula it is possible to construct a deterioration curve for the given situation. The condition of the asset is calculated for every year by using this formula; every year is a data point in the Excel model.

Starting condition of the asset

The value at which the condition curve starts at t=0. This variable was introduced in order to make the tool applicable at any point in the assets' life. This allows the user to investigate long-term solutions for assets that have not fully deteriorated (or assets that have just been constructed and still have maximum condition).

Lower condition boundary (P_l)

This value sets a lower boundary for the condition level that an asset can achieve. The tool compares the yearly condition values to P_l; when the condition drops below this value action is taken. Repair, renovation or replacement activities are initiated the year before the condition drops below P_l; the condition is improved by the technique and a new deterioration cycle starts. If no such boundary is desired then the value can simply be set at zero.

Should the technique be applied at t=0?

Instead of applying repair, renovation or replacement techniques immediately, the user can also choose to wait until the asset reaches a certain condition level. When "yes" is chosen, the tool adds up the starting condition and the condition improvement for every technique. Furthermore it generates all costs produced by an activity at t=0. When "no" is chosen, the starting condition of the asset is used as start value and no costs are generated until the next intervention. Sometimes it may be benificial to wait a number of years before performing an activity. For example, when the condition is 30 percent it may be economically more attractive to wait until the condition is zero percent before using a replacement technique.

Desired time horizon

When the function of an asset does not change, the repair/renovation/replacement cycle can theoretically be continued for an indefinite amount of time. The responsible organisation should therefore determine a time horizon that is used for life cycle calculations, depending on their strategic goals or policies.

The repair, renovation or replacement cycle is repeated until the time horizon is reached, after which the calculation is stopped. Note that the model supports up to twenty cycles, which should be sufficient for every realistic situation.

Discount rate

In order to calculate the Net Present Values of all possible alternatives, a discount rate is necessary. The discount rate converts future cash flows to present day values, thereby allowing for comparison between different cash flow structures. Higher rates will decrease the contribution of future cash flows to Net Present Values. Unrealistic values for the discount rate will result in unreliable long-term cost values.

These variables allow the tool to relate costs that are associated with the remaining technical solutions to specific points in time throughout the lifespan of an asset. This means that the model knows exactly which costs occur at which moments. The cost values are entered manually or selected from a cost database module (once this is researched and developed in the future). The tool makes a distinction between yearly costs and costs that only occur during repair, renovation or replacement activities. The program now has a complete overview of all cost values and their place in time, subsequently the total costs of the different combinations of techniques and scenarios can be calculated. The total costs are a combination of the following components:

- Direct costs
- External costs
- Risk costs
- Added value

Besides the total discounted costs the tool also shows how many times repairs,renovations or replacements are necessary for every alternative in the given time frame. The LCC analysis sheet shows in which years actions take place and the corresponding discount rate. The discounted total costs of every alternative is given a rank based on the lowest costs. The user can thus immediately see which alternative is preferred.

A more detailed description and overview of the relevant datasheets can be found in appendix A.

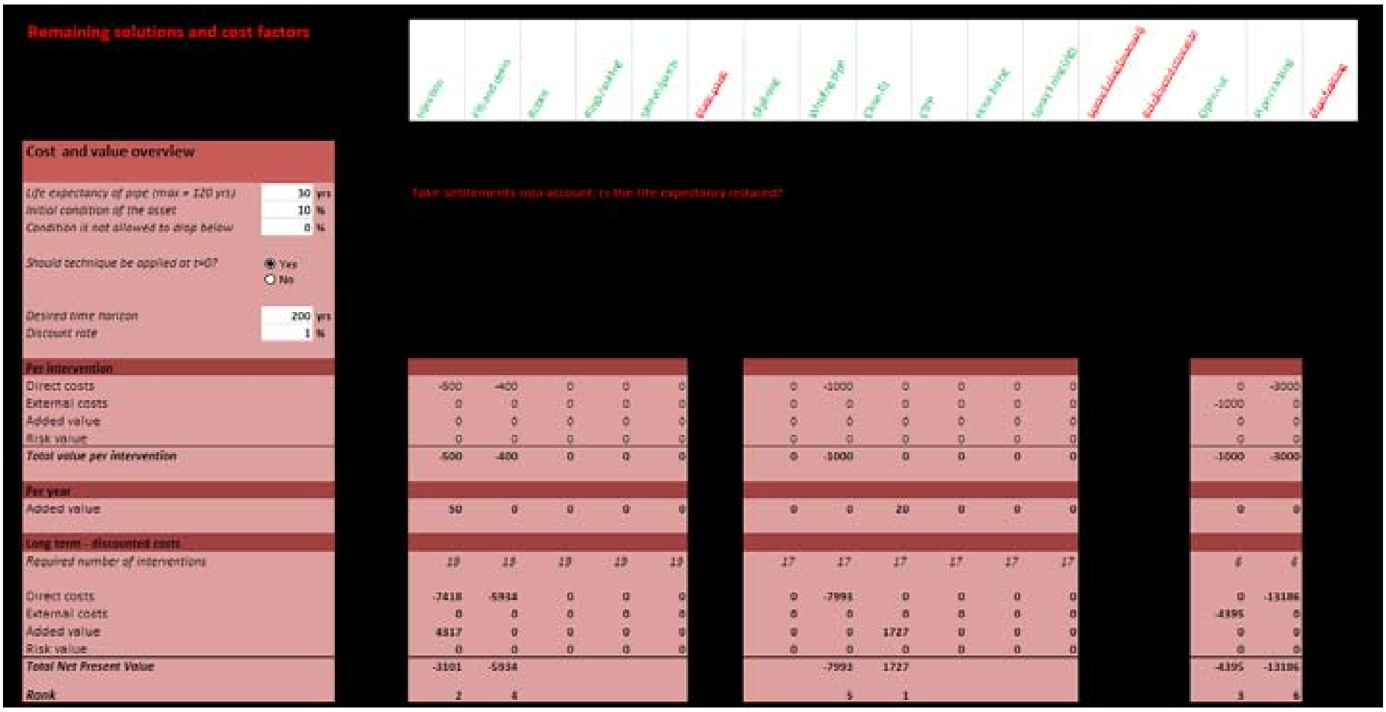


Figure 58:Cost overview module of the decision support tool. Distinction is made between value per activity, specific values that occur every year and total net present value for all possible techniques. Shown numbers are not realistic.

8.11 Assumptions and limitations

As stated before, the aim of this research is not to develop an integral asset management tool for sewer networks. This research is a first step towards such an integral tool however. The developed decision support tool gives a broad overview of possible solutions, associated costs and risks that should be calculated, attention points and opportunities. There are however a number of assumptions and simplifications made because some data does not exist yet. Additional components will have to be developed in the future, when more research data is available.

This section will list all assumptions that are made in the developed decision support tool, as well as its limitations. This identifies which data or components need more attention in future research. Furthermore it makes the user of the tool aware of its possibilities. As long as the user understands the limitations of the tool he knows where uncertainties may exist and he is able to use the tool to his advantage.

The following assumptions were made during the development of the model:

- The deterioration curve of all pipes can be approximated by a formula of the second order with shape $C = 100\text{-}yt^2$. The curve that is generated by this formula merely shows when the asset will fail and does not give any information about other aspects.
- Techniques that are applied to a sewer pipe do not change the behaviour of the curve.
- The condition increase by a certain technique has a fixed value and does not depend on the previous amount of deterioration.
- There is a upper condition boundary for every technique (maximum is 100 percent), which has a fixed value and does not depend on previous deterioration.
- Repair, renovation and replacement cycles for an asset can be repeated indefinitely.
- Sewer pipes in soft soils that have a pile foundations have the same behaviour and repair, renovation and replacement options as sewer pipes in sandy soils.
- The discount rate stays constant throughout the lifetime of an asset.
- Money flows always take place at the beginning of the year.
- Inspection costs throughout the assets' lifetime are identical for all possible techniques. Techniques that lead to reduced inspection effort can be given an added value item in the cost sheet. This added value is the yearly saving because of reduced inspection effort compared to the "standard" inspection policy of an organisation.

The developed decision support tool has the following limitations:

- Only one pipeline can be entered into the model, so there is no possibility to examine multiple pipelines at the same time.
- The model does not make a distinction between different pipe materials and their deterioration curves. The user should fill in a life expectancy, which is used to draw a general curve based on a simple quadratric formula.
- It is not possible to look at combinations of different techniques throughout the lifetime of an asset.
- The tool is aimed only at sewer pipes for the moment and not at other components of a network. Additional modules should be developed for this.
- Inspection techniques and their effects on various costs are not included yet.
- The tool can calculate up to 20 cycles of repair, renovation or replacement for every technique. This should be more than enough to investigate realistic investment patterns in the long-term. More cycles would not be useful and would simply increase the dataset size.
- The life expectancy value can be set up to 120 years. This was thought to be sufficient (in general sewer pipes are designed for 60 years in the Netherlands) and limits the amount of data that has to be generated.

8.12 Sensitivity analysis

In order to get more insight into the effect of variations in the previously mentioned variables on the outcomes of the tool, a sensitivity analysis was performed. Multiple combinations of variables were investigated by applying them to the decision support tool. By performing a sensitivity analysis it is possible to identify which variables would probably have the largest effect on total costs. This can give insight into which alternatives perform better in certain situations. Furthermore it allows for a certain degree of validation because it shows if the model behaves as should be expected for certain parameter variations.

8.12.1 Number of interventions

The number of times that an activity (repair, renovation or replacement) is necessary in a certain period of time can give an idea about the performance of certain solutions. Every time an activity is carried out, direct and external costs are generated. So, the more times an intervention is necessary, the more times costs are generated. The costs that are generated will obviously differ for every technique, which means that the solution with the lowest number of interventions does not always result in the lowest overall costs. The number of required interventions for certain parameter combinations can however give an idea about the effectiveness of these combinations and the behaviour of the tool.

First the effectiveness of combinations of lower condition boundary (P_l) and improvement percentage (P_f) were investigated. Different values for both P_l and P_f were entered into the model in order to determine how many times an intervention was necessary in a period of 200 years. No upper boundary (P_m) has been set, meaning that the condition can always be restored to 100 percent.

Tables 16 to 19 show the number of times an intervention is necessary for various combinations. For example, when looking at table 16, the top left field shows that a combination of P_l = 80 and P_f = 20 results in 15 required interventions. The asset is thus allowed to deteriorate to a condition level of 80 percent, at which point an improvement of 20 percent is made. This has to be done 15 times in a time frame of 200 years in order to keep the condition above 80 percent. When the asset is however allowed to deteriorate to a condition of 50 percent condition before the same improvement is made, the amount of interventions increases to 33. This combination of variables is thus much less effective in the long run.

The four tables correspond to four different life expectancies for the asset: 30, 60, 90 and 120 years. This makes it possible to investigate the effect of variations in the life expectancy value. Values that are marked with * are solutions that are not efficient (e.g. applying a 100% improvement technique at 80% condition of the asset).

When looking at the data, there are a number of things that stand out. Reduction of P_l will increase the number of necessary interventions, which is logical since the speed of deterioration is higher at lower conditions. Higher P_f (improvement) values will reduce the number of interventions. This is also no surprise since more improvement means that it will take more time before the asset deteriorates to the same value again.

	Improvement by technique			
P_l	20	50	80	100
80	15	15*	15*	15*
50	33	9	9*	9*
20	41	17	7	7*
0	45	19	10	6

Table 16:Number of interventions necessary for assets with a life expectancy of 30 years over a period of 200 years

	Improvement by technique			
P_l	20	50	80	100
80	7	7*	7*	7*
50	17	4	4*	4*
20	20	7	3	3*
0	22	8	5	3

Table 17:Number of interventions necessary for assets with a life expectancy of 60 years over a period of 200 years

	Improvement by technique			
P_l	20	50	80	100
80	4	4*	4*	4*
50	10	3	3*	3*
20	12	4	2	2*
0	12	5	3	2

Table 18:Number of interventions necessary for assets with a life expectancy of 90 years over a period of 200 years

	Improvement by technique			
P_l	20	50	80	100
80	3	3*	3*	3*
50	6	2	2*	2*
20	7	3	1	1*
0	7	3	2	1

Table 19:Number of interventions necessary for assets with a life expectancy of 120 years over a period of 200 years

More interesting is the relative difference between various combinations. The largest possible reductions in the number of interventions can be found in the upper part of the condition curve, by increasing the P_l (lower boundary) value from 50 to 80 percent. This is especially true for lower life expectancies. For lower P_l values there is little or no difference (e.g. increasing P_l from 0 to 20 percent).

Figures 59 to 61 show the same data, but this time the data is grouped together for a fixed improvement percentage (P_f). These figures gives a visual impression about in which part of condition curves certain techniques are more effective.

Figure 59 shows that a 20 percent improvement gives the best result when applied at a condition level of 80 percent. Especially for assets with a short lifespan (30 years) there is a large difference between P_l values 50 and 80 percent. Since the same technique (fixed improvement value) is considered the number of interventions is related to the overall costs. Note that this is not a strict linear relation since cash flows in different years are differently affected by the discount rate. It is however safe to say that application of a 20 percent improvement technique at condition levels lower than 80 percent will result in higher costs and is thus less desirable. The same conclusion can be drawn when looking at P_l values 50 and 80 percent, see figures 60 and 61. The most optimal point in time to apply a technique is at the point where it improves the condition level to exactly 100 percent. This is a predictable conclusion since a quadratic curve is considered, which means the curve is least steep at a condition of 100 percent. It does however show that the model works as should be expected and gives insight into the amount of repairs, renovations or replacements that can be expected for certain conditions.

When looking at improvement value P_f the opposite is true: increases in the lower range of P_f have most effect. For example, when an asset has a life expectancy of 60 years and receives a 20 percent improvement when the condition reaches 20 percent this results in 20 actions in 200 years. When instead a technique is applied that improves the assets' condition by 50 percent there are only 7 actions required; a large reduction. An improvement of 80 percent further reduces the required action to 3; this reduction is however relatively smaller than the difference between a 20 and 50 percent improvement. One can imagine the interesting optimisation puzzle that is formed by these variables.

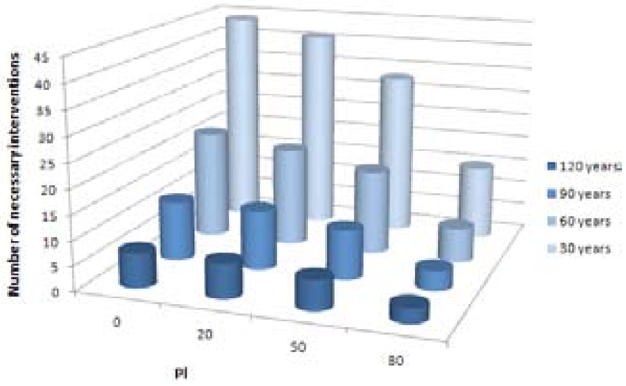


Figure 59:Number of interventions necessary when applying a technique with improvement P_f = 20 percent in a time frame of 200 years

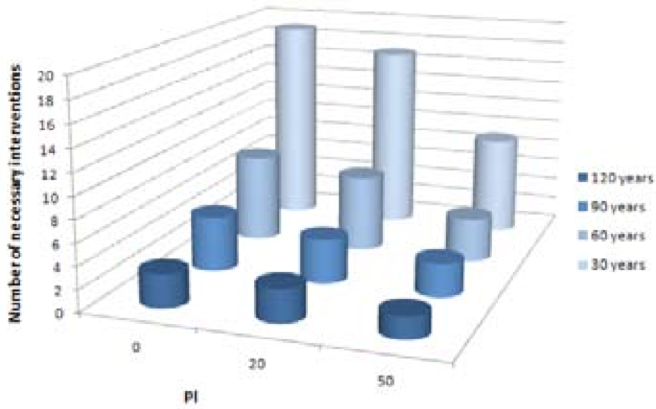


Figure 60:Number of interventions necessary when applying a technique with improvement P_f = 50 percent in a time frame of 200 years

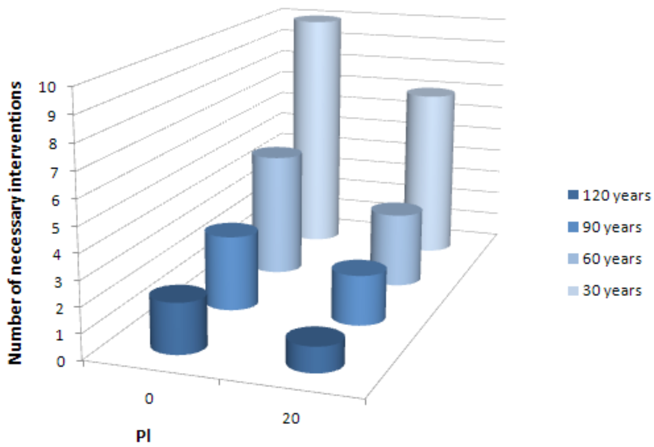


Figure 61:Number of interventions necessary when applying a technique with improvement P_f = 80 percent in a time frame of 200 years

Replacement technique (P_f =100%) do not always result in a lower number of required actions. Curves for all combinations of P_m and P_f can be found in figure 62, where they are compared to the life expectancy of the asset.The number of replacements that are required when applied at zero percent condition are represented by the black curve. The alternative with P_m = 20% and P_f = 80% requires the same amount of actions as replacement when looking

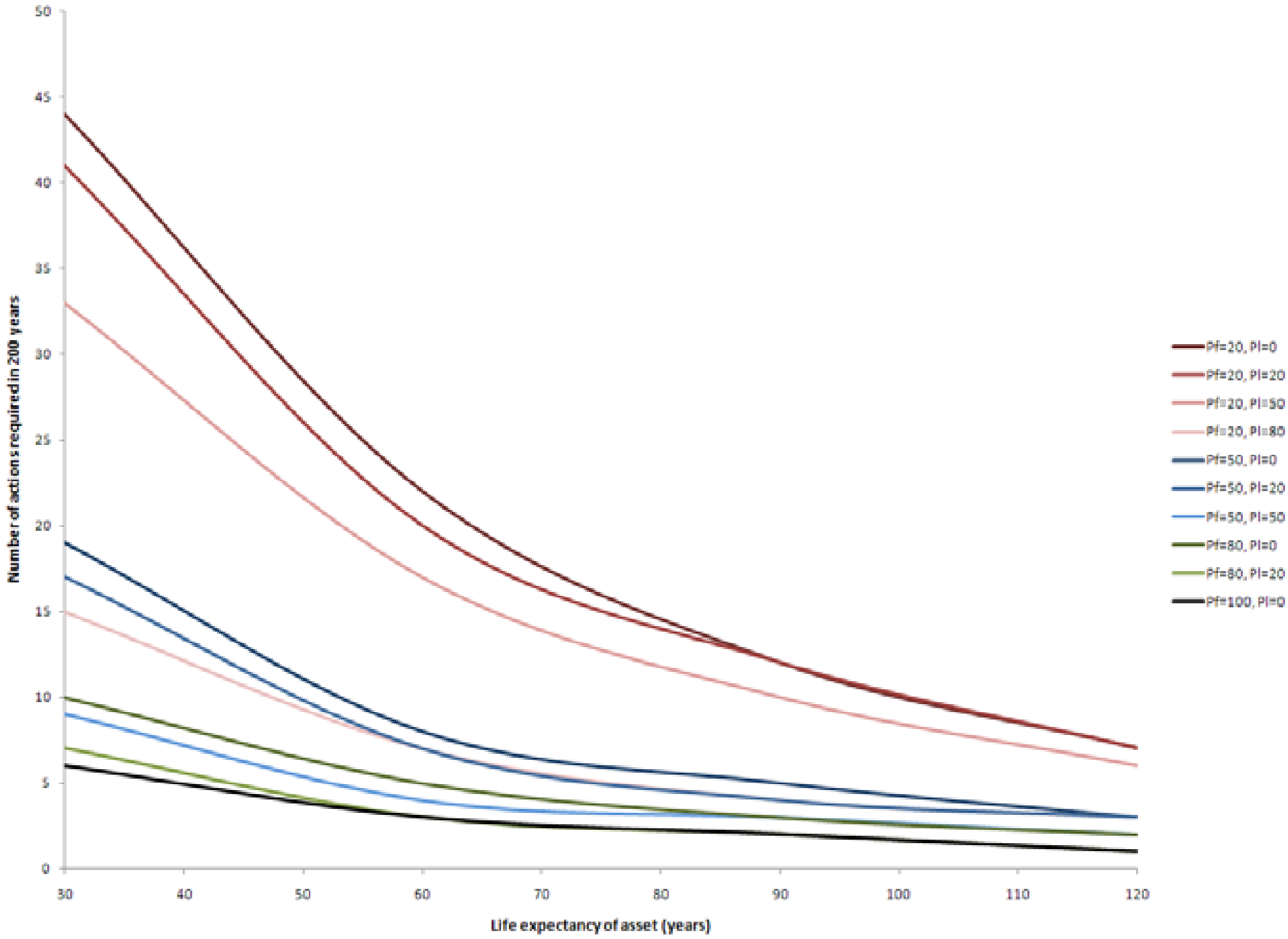


Figure 62:Graphs of the number of required actions for varying life expectancies, for all combinations of P_m and P_f that were researched. This is done for a time frame of 200 years.

at assets with a life expectancy above 60 years. While renovation techniques may have higher capital costs than replacement techniques (in some cases), it is not difficult to imagine that the external costs may be much lower! The total costs may thus be similar or even lower for a renovation alternative. Combinations of P_f and P_l like 50/50 and 20/80 are efficient and also score well when just looking at the number of actions. In some projects these combinations may result in much lower total costs than replacement alternatives. Since there is no cost data available it is unfortunately not possible to make general statements about this.

What can be said is that increased life expectancy greatly reduces the spread in amount of interventions. The various alternatives lie closer together when just looking at number of interventions. When looking at the ratios between amount of interventions for various curves, there is no trend visible. All curves have about the same shape and show the same behaviour for varying life expectancies. One can however say that some alternatives are not competitive for short lifespans due to the many times that they should be applied. Improving a sewer pipe every few years is not very convenient in terms of planning and the use of personnel and equipment.

8.12.2 Upper boundary value (P_m)

Section 8.9 has discussed condition prediction of sewer pipes and the effects that various techniques can have on the condition curve. One of the concepts that was discussed there was the existence of an upper boundary for certain techniques. It is likely that not all techniques can improve the condition of an asset back to its full potential (100 percent in this case). Whether or not such a boundary value can be established is unsure, there is no data available on this topic. The developed tool can however be used to investigate the effects of the existence of such an upper boundary value. An upper boundary can be a disadvantage for repair or renovation techniques, since it can prevent them of fully using their potential. The amount of required interventions and thus the long-term costs of a technique may be increased considerably. In order to determine whether or not an upper boundary would have much effect on the competitiveness of certain techniques, various combinations of parameters were investigated.

Two datasets were generated in order to determine the upper boundary effect. A technique with an improvement value (P_f) of 80, applied when the condition of the asset

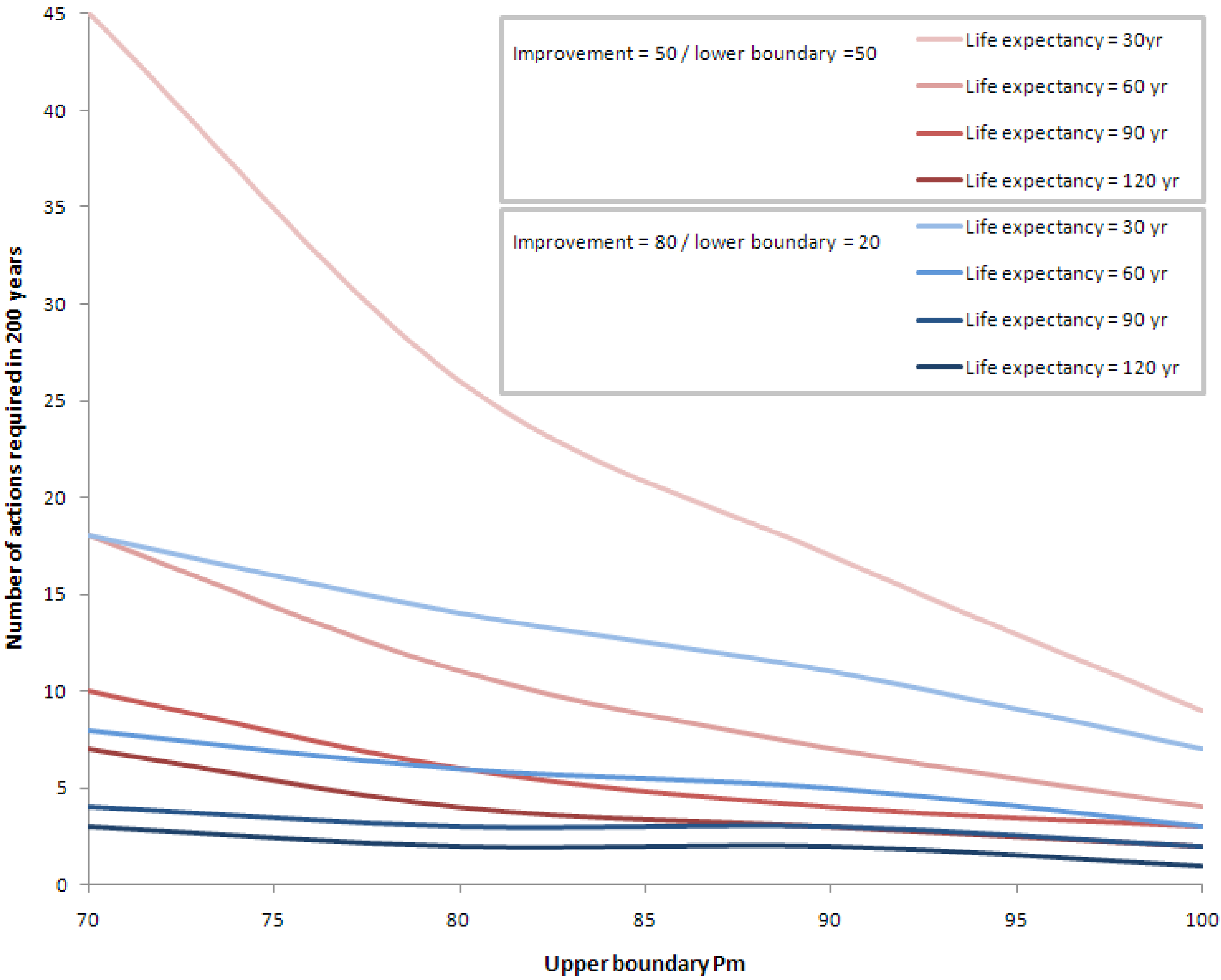


Figure 63:Graphs that show how different upper boundary values influence the amount of required interventions for a number of parameter combinations

reaches 20 percent (P_l=20). The second dataset was constructed by looking at a technique with an improvement value of 50 that is applied at a condition of 50 percent. The number of required interventions over a period of 200 years were again taken as benchmark. Four life expectancies were tested and plotted as curves for both situations. The overview of all eight curves can be seen in figure 63.

The graphs show an interesting change in amount of required interventions as the upper boundary is changed. There can be large differences in the amount of actions for a certain situation, depending on the choice of upper boundary value. Especially when there is a low life expectancy, a change in P_m can result in a large difference. Since more actions equal more times that costs are generated, it is not hard to realise that lowering of the upper boundary value can result in a large long-term cost increase. Some graphs are much more affected at lower values for P_m, where they are more steep. This is not strange since this means the asset is forced to stay in a steeper section of the general condition curve.

It seems that for renovation technique with high P_f values that are applied to assets with a high life expectancy, the effect of an upper boundary is small. The range of upper boundary values (70 to 100 percent) is thought to be realistic for actual repair and renovation techniques. Unfortunately there is no research done yet about upper boundaries and no data that shows that they exist. If they do exist they can be easily entered into the model. The effects on the total costs of alternatives can be large, as can be seen in figure 63, therefore it is important that research is performed in this field so that more insight is gained.

8.12.3 Open-cut versus trenchless

In order to get insight into the competitiveness of trenchless techniques compared to open-cut methods, a simulation was run with the decision support tool. The aim was to get insight into cost ratios between various alternatives. Trenchless techniques can require higher capital costs than open-cut methods, the general assumption however is that the external costs are usually significantly lower (especially in urban environments).

In the tool that is proposed in this research, future cash flows are discounted in order to calculate Net Present Values of various alternatives. One of the general choices that a sewer asset manager faces is whether or not to use traditional open-cut methods or to opt for trenchless technologies (which may require higher initial investments). The cost figures depend highly on local conditions, making it impossible to make a general statement about which technique should be preferred. This is why the sewer asset manager should calculate the overall costs for every project in order to make the best decision and use his budget most wisely.

Open-cut methods have a certain advantage with regard to NPV in the calculation method compared to trenchless technologies. The multiplication factor in the *LCC* sheet, which consists of all discount factors of generated cash flows for a specific technique, will always be lower than those of renovation or repair techniques. This is because of the following two reasons:

- Open-cut methods replace the asset and are therefore often applied when the asset reaches the end of its lifespan (condition=0%). This means they are always applied at the last moment and use the entire lifespan of an asset. Repair and replacement techniques are usually applied at an earlier stage; the investments thus take place earlier and receive less discounting.
- Open-cut methods use the entire condition curve when applied at 0% and result in the lowest number of interventions of all alternatives. Efficient application of renovation techniques may result in the same amount of required interventions, but there are no techniques that require less interventions than the open-cut alternative.

Cost figures are not included in this research, but it is possible to look at ratios to get more insight into the cost mechanism. Application of an open-cut method at

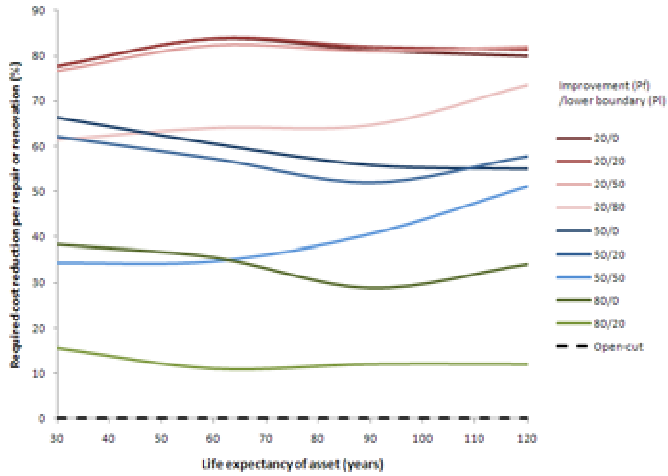


Figure 64: Required cost reduction per intervention, compared to the costs of an open-cut alternative over a period of 200 years and with a discount rate of 1%

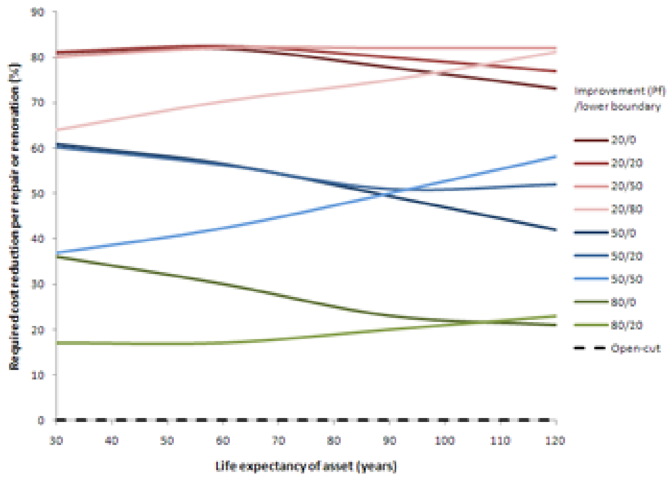


Figure 65: Required cost reduction per intervention, compared to the costs of an open-cut alternative over a period of 200 years and with a discount rate of 2%

zero percent condition has been set as a reference for comparison. The open-cut method has been given a fixed costs per intervention (this would represent the total cost per replacement, so the sum of direct and external costs). Over a period of 200 years the Net Present Value is calculated for this alternative. The trenchless alternatives, which are represented by various combinarions of P_f and P_m, are now investigated for comparison. The value per action that results in the same NPV as the open-cut method is calculated. Subsequently these values are used to calculate the required cost reduction (as a percentage) that would be necessary in order to achieve the same NPV as open-cut. For example, a value of 50 percent means that the total costs (direct and external) of a single renovation or repair should be 50 percent lower than the total cost for a single open-cut replacement in order to be competitive. The data that was obtained was used to construct figures 64 and 65. As can be seen, the required cost reduction per intervention (one repair or renovation) varies greatly; between 10 and 85 percent.

Some techniques will have to generate significantly lower overall costs to be competitive. This is not strange since they have to be applied more often or must be applied earlier than an open-cut solution.

Some combinations are very interesting, for example an improvement of 80 percent that is applied at 20 percent condition (the lowest green line). This combination shows a required overall cost reduction of 10 to 20 percent, which is very low. In general trenchless alternatives will generate less external costs, especially in urban environments. The total costs are expected to be significantly lower than those for open-cut methods. If this is true than it is obvious that trenchless technologies are very competitive when looking at figures 64 and 65.

Even the combinations that have high values can provide a good alternative solution to open-cut. The red lines represent a technique that improves the asset's condition by 20 percent, this can be a small repair technique. When it shows a 80 percent required reduction this seems a lot. The technique thus has to generate five times less overall costs than open-cut. However, one has to realise that it is a repair technique that will probably require a small investment and cause very little external costs since it can be performed via manhole access.

The two figures show the results for two different discount rates. The reason for varying discount rates is to see whether or not this has effect on the overall feasibility of certain alternatives. Various discount rates were tested to see if any general trends can be discovered regarding the effect of a varying discount rate. The results did not show any trend however; there are fluctuations in the cost ratios between open-cut and trenchless alternatives, but these do not show any pattern. Only two graphs are shown here to indicate that there are small fluctuations caused by the discount rate, but no visible trends.

8.12.4 Conclusions

The sensitivity analysis has shown the effect that a number of variables can have on the number of repairs, renovations or replacements that are necessary for an asset. The cost ratios between open-cut and trenchless alternatives that result in the same Net Present Values have also been investigated. The conclusions that were obtained are shortly summarised below.

- Changes in the lower condition boundary (P_l) are more effective at higher values. For example, an increase from 20 to 30 percent has much less effect than an increase from 70 to 80 percent. Increase of this value results in reduction of the number of required interventions in a certain time period.
- Changes in the improvement value for a technique (Pf) are more effective at lower values. For example, increasing the value from 20 to 50 percent has more effect than an increase from 50 to 80 percent.
- The most effective time to apply a technique is when it increases the condition level to 100 percent.
- The existence of an upper boundary can have large consequences for the amount of required interventions, and thus the long-term costs. Especially for low life expectancies this effect is important.
- The total costs per activity of repair and renovation techniques always has to be lower than the costs per replacement technique in order to achieve competitive Net Present Values.
- The required cost reduction for renovation and repair techniques, compared to open-cut replacement, varies between 10 and 85 percent. However, the total costs of trenchless techniques can be significantly lower due to external cost components.

This analysis has produced a number of results that are not only meant to draw general conclusions. The model has also been validated by varying a number of variables. The results show that the model works as can be expected; no unexplainable results were generated that would indicate errors.

Secondly, the analyis has given a sense of scale to a number of items, e.g. the number of interventions that is required for certain combinations of parameters or cost ratios between various combinations of variables. This gives more insight into the values that can be expected and how small (or large) some differences can be.

It is important to keep in mind that the actual combinations for certain techniques are unknown. The P_f and P_m values are theoretical values, which show what would happen if techniques were to have these characteristics. The exact effects of various techniques on the deterioration process will hopefully be researched in future projects.

8.13 Future additions to the tool

The decision support tool provides a powerful framework that gives an overview of all relevant costs throughout the lifetime of an asset. There are however some limitations to the tool and there were a number of assumptions made thoughout the design process. In order to make efficient and optimal decisions more research is needed into various aspects of sewer asset management.

By constructing the decision support tool in the Excel environment it is relatively easy to add more modules in the future. More insight from research projects will hopefully enable the development of an integrated asset management tool for the Dutch situation. Future additions to the tool are discussed in the following subsections.

8.13.1 Cost figures

The values of all listed costs still have to be filled in by the user. Direct costs can usually be estimated by looking at previous projects or by requesting a project price from a contractor, even though eventually it would be desirable to have a number of general cost figures regarding specific techniques. This reduces the amount of project-specific values that the user has to enter.

External effects and their associated costs are more difficult to estimate. A number of possible valuation methods were described in chapter 7, these can be used to calculate certain costs. Many cost figures are however unknown and it is impossible to make an accurate estimate for them. The amount of Euros associated with external effects should be calculated by the tool by using conversion factors and formulas. When looking at air pollution caused by machinery for example, the user should merely select the type of machine used and the amount of time that it is in operation. The tool should be able to calculate the amount of Euros of air pollution for this specific component by retrieving conversion factors from its database and applying these to the entered values.

It is recommended to set up a research project that will try to determine all external cost figures, as well as make an overview of general direct cost figures (which can possibly be obtained by gathering data from many previous sewer projects). Once these cost figures are determined they can be added to the decision support tool in a cost module This will allow the user to quickly get overall cost values (direct and external) to base his decision on.

8.13.2 Condition prediction

At this moment a simplified general formula is used to predict conditions. The actual deterioration process is however much more complex and depends on many variables. The large differences in lifespans of sewer pipes that have been seen in practice emphasise that more research is needed. This will hopefully result in accurate deterioration curves for various combinations of parameters (e.g. soil type, pipe material). Furthermore it is vital to get insight into the effects of various techniques on the condition of assets. Thorough understanding of the actual deterioration and improvement processes will require extensive research but is absolutely necessary in order to develop a reliable integrated decision support tool.

8.13.3 Other additions

There are obviously more aspects that can be added in order to construct an integrated tool. As stated before, there are many more areas in the field of sewer asset management that need to be researched before these components can be developed. Removing the limitations of this model can be a first step. This can be done by adding options for calculating combinations of techniques, different materials and multiple assets.

Instead of focusing on the end of the decision process, e.g. the components for condition prediction and LCC, there is also much work to be done in the first part of the asset management process. Condition assessment is still far from perfect and needs to be improved in order to have a better basis for decision making. Improvements in this field should however first be integrated with an asset database before it is combined with (the components of) this tool. A fully integrated tool could include all components that were identified in this report, but constructing such a tool would only be possible when all areas have been researched. Constructing a fully integrated tool would be challenging and require a substantial amount of funding and manpower.

This research has made a first step by creating an overview of necessary components for an integral tool and researching one part of the overall asset management process. More research projects will hopefully continue where this master thesis research ends, thereby advancing towards the ultimate goal of an accurate, integrated tool that will fully optimise sewer asset management.

CHAPTER 9: CASE STUDY

Chapter 9: Case study

9.1 Introduction

The previous chapters have discussed difficulties in the decision making process that sewer asset managers face and how this process could be optimised. Furthermore a decision support tool was discussed, which can hopefully help sewer asset managers to improve their decision making process. So far the chapters have discussed the topic in a theoretical way; the decision support tool lacks validation from practice. Therefore it was decided to perform a case study in order to investigate the relation between the theoretical framework that has been discussed so far and reality. The case study allows for a certain degree of validation; it might show errors in the developed tool or provide new insights. Note that the goal of the case study is thus not to validate the assumptions used in the model, but the completeness of the model.

An additional benefit of the case study research is that it shows the reader (and researcher) what a typical sewer project can look like. It gives insight into the considerations and difficulties that sewer asset managers face for a specific project, at a specific scale. This makes the research less abstract and better to comprehend.

The case study involves a sewer section beneath two streets in a residential area in the city of Amsterdam. This sewer section consists of parts with very different characteristics and requires sewer works in the near future. Data that was required to perform this case study was provided by Waternet.

First the location and specific characteristics of the case study site will be discussed. After this a number of possible scenarios and relevant considerations will be shown. These will be inserted into the decision support tool, this will result in a number of possible solutions and associated cost factors, risks and attention points. Finally conclusions will be drawn regarding the process and outcomes of the case study.

9.2 Description of the case study

9.2.1 Reasons for site choice

The city of Amsterdam has an extensive sewer system with varying characteristics. Different parts of the system were constructed in different periods, this has resulted in a variety of system types and applied materials. Certain parts have already been replaced since then, which means that plastic sewer pipes can also be found throughout the city. There are many locations that would be interesting for a case study; eventually this specific location was chosen because of the following reasons:

Figure 66:Location of the case study

- Sewer pipes of various ages and conditions are present
- Different pipe materials are present
- Both circular and non-circular pipes are present
- Besides collection pipes there is also a larger transport pipeline present, which requires a different approach than small collection pipes

The case study site thus shows variety in a number of important parameters. This allows for a case study that covers different situations and associated considerations.

9.2.2 Site description

The case study was performed for a residential area in the southern part of Amsterdam (see figure 66), near the end of motorway A2. Two streets were chosen that show a variety of sewer pipes: *Boterdiepstraat* and *Eemsstraat*. These are purely residential streets that distribute traffic in this residential area; they do not provide a connection to arterial roads or a shotcut to adjacent neighbourhoods. The *Boterdiepstraat* and *Eemsstraat* can be found close to the office of Waternet, just on the other side of the river Amstel (see figure 67).

There are a number of old sewer pipes in these streets that have deteriorated considerably. Recently all rainwater and wastewater pipes in both streets have been inspected (2006 and 2007) by a stationary CCTV system. Since condition assessment is outside the scope of this research these inspections will not be discussed here. The pipes are thought to be at the end of their lifetime and in need of renovation or replacement. The reason for the sewer asset manager to plan sewer works here is thus deterioration.

Data regarding previous sewer works and inspections in these streets was available in the RioGL database of Waternet. *Boterdiepstraat* and the sewer pipeline underneath have a length of 225 meters; the sewer underneath the *Eemsstraat* measures 250 meters in length. The surface level of both streets is at height of +0,30 to +0,55 meters NAP.

Subsurface

Figure 68 shows the sewer network layout in this part of the city. There are a number of different pipelines types that are distinguished by different colours:

Orange	- Wastewater pipelines
Blue	- Rainwater pipelines
Green	- Large pressurized transport pipelines
Red	- Large gravity transport pipelines for sewage

The case study area has a seperated sewer system. Furthermore there are many streets that have two collection pipes for rainwater (both sides of the street have a collection pipe); this is also true for the *Eemsstraat* and *Boterdiepstraat*. When these sewer sections were constructed (1930's) there was appearantly a policy to place two rainwater pipes in a street. This reduces the length of house connections, but it also means that two collection pipes have to be maintained. The rainwater pipes are located underneath sidewalks and parking spaces in both streets. The sewage network is located underneath the road surface in both streets and has been replaced in the 1970's. Note that the sewage network flows to the large gravity transport pipeline (shown in red), which transports the sewage of this area towards the west. The rainwater flows are going in southern direction, where there is an outlet to the river Amstel.

There are thus three parallel pipelines that run through the *Eemsstraat* and *Boterdiepstraat*. The sewer sections underneath these streets are not identical however, as can be seen in figure 69. The *Eemsstraat* has the following pipelines in its subsurface:

Figure 67:Case study area, also showing the river Amstel and location of the Waternet office

Figure 68:Overview of sewer network layout in the case study area

- Rainwater pipeline, made out of concrete and constructed in 1934. This circular pipeline has a diameter of 250 mm and is located at a depth of -1,15 to -0,95 meters NAP.
- Rainwater pipeline, made out of concrete and stoneware (alternating sections) and constructed in 1934 and 1948. This circular pipeline also has a diameter of 250 mm and is located at the same depth.
- Wastewater pipeline, made out of PVC and placed in 1989. The diameter of this circular pipe is 235 mm and it is located between -0,69 and -0,90 meters NAP.

The *Boterdiepstraat* has a different set of sewer pipes, the most important difference is the presence of a large transport pipe for rainwater. This pipe transports rainwater of a large area to the river Amstel; this can be clearly seen in figure 68. The following data is available:

- Rainwater pipeline, made out of stoneware and constructed in 1934. This circular pipeline has a diameter of 250 mm and is located between -2,20 and -1,85 meters NAP.
- Rainwater transport pipeline, made out of concrete

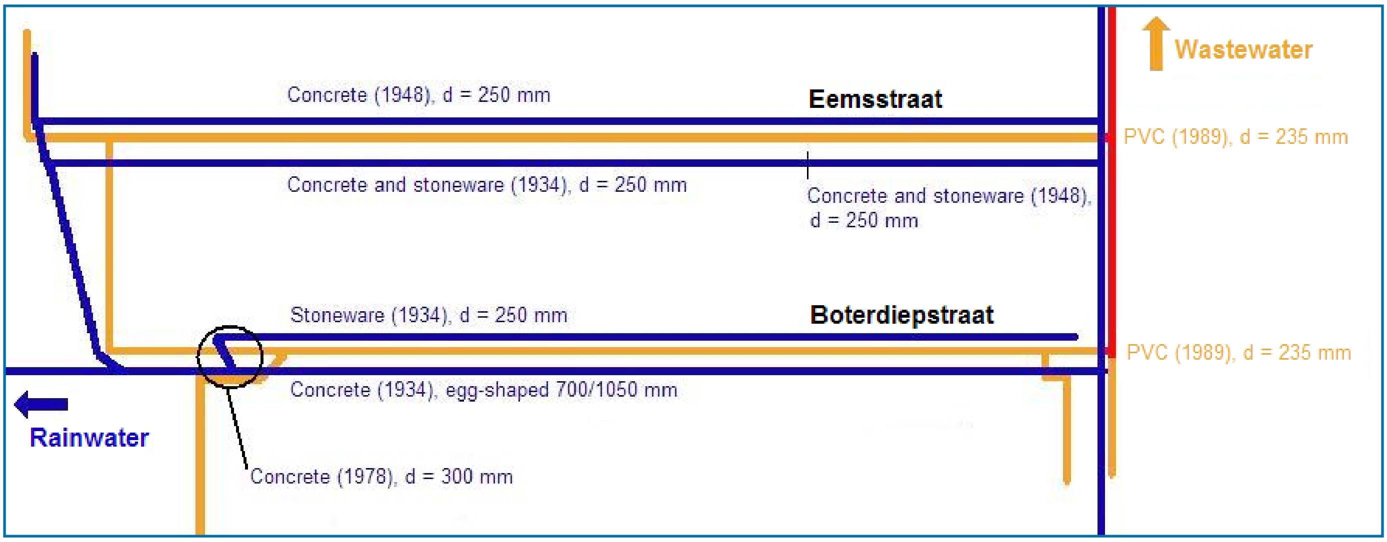


Figure 69:Overview of sewer pipes in the Eemsstraat and Boterdiepstraat

and constructed in 1934. This egg-shaped pipe has dimensions 700/1050 mm and can be found at a depth of -1,60 to -1,15 meters NAP.

- Connection pipe between the rainwater pipelines, made out of concrete and placed in 1978. The diameter of this pipe is 300 mm.
- Wastewater pipeline, made out of PVC and placed in 1989. The diameter of the pipe is 235 mm and it is located at a depth of -0,69 to -0,90 meters NAP.

The underground space in these streets is thus filled with different pipelines. This is very interesting for the purpose of this case study because these pipelines may have different solutions available to them. Investigating possible combinations of solutions provides more insight into the decision making process than a case study with just a single pipeline.

The manholes in both streets are made out of bricks and were constructed in 1934 (rainwater) and 1990 (wastewater). The old manholes have not undergone renovation or replacement and some are in poor condition. The recently constructed manholes in the wastewater network are in good condition.

The groundwater table is located at a depth of -0,54 meters NAP at the southern end of the *Eemsstraat*. In the middle of the *Boterdiepstraat* the groundwater table can be found at -0,36 meters NAP. These values are averages over the last 5 years. When comparing these values to the previously mentioned depths of the various pipelines in both streets, it is clear that all pipelines are located beneath the groundwater table.

Surface level

The situation at surface level should always be investigated in order to get a complete overview of possible difficulties, cost factors and opportunities. The amount of available space is especially important to consider since a lack of space can exclude certain techniques from the list of possible solutions.

The surface level situation in both *Eemsstraat* and *Boterdiepstraat* were investigated by consulting Google Street View software. This can be an inexpensive but effective tool for sewer asset managers to get a quick overview of the situation. The city of Amsterdam has a similar program for street views that can be accessed by its employees.

Screenshots were made at various places in both streets, these can be seen in figures 70 to 79. The locations and directions of all screenshots can be found in the overview map in figure 80. The subsurface sewer layout has been used as basis for this map, making it easy to see which sewer sections can be found in which screenshot. The last two screenshots show the perpendicular streets to which both streets connect. This can give insight into access routes and available space that is located nearby.
The following useful information can be found when looking at the surface level situation in both streets:

Traffic - Most traffic will be generated by residents and people that visit the residents. The streets will thus not have large volumes of traffic. The *Eemsstraat* and *Boterdiepstraat* are one-way streets with parking on both sides. There is only one lane for traffic and it is thus not possible to go around stationary vehicles or obstructions.


Figure 70:Screenshot A


Figure 71:Screenshot B


Figure 72:Screenshot C


Figure 73:Screenshot D


Figure 74:Screenshot E


Figure 75:Screenshot F


Figure 76:Screenshot G


Figure 77:Screenshot H


Figure 78:Screenshot I


Figure 79:Screenshot J

All images were retrieved from Google Street View

Figure 80:Map showing the locations of screenshots that are shown on the left page

Even sewer works that use small amounts of space can already block the road and cause traffic disruption.

Available space - As mentioned before, the available road surface is limited. The parking spaces offer additional space when there are no cars parked. One side of the streets has a narrow sidewalk, but the sidewalk on the other side offers more additional free space. In some parts of the streets there are combinations of green strips and pavement in this sidewalk area.

Nearby houses - The houses are located close to the road, there is only a distance of 17 meters between facades. Sewer works will always be located very close to these houses, which means nuisance can become a problem. Historical buildings or businesses can not be found in these streets.

Location of sewers - The street view software gives clear insight into the location of sewers since the manholes are easily recognisable in the screenshots. The wastewater pipelines are underneath the traffic lane. The rainwater pipelines are placed at a few meters distance from the residential buildings. On the narrow side of the street, the pipeline can be found at the edge of parking spaces, adjacent to the curb. The broader sidewalk has the rainwater pipelines underneath the pavement.

Obstructions - There is a row of trees in both street, on the side with the broad sidewalk. These are located directly next to the parking spaces. This is also true for a number of light posts; these can be found on both sides of the street. The parts of the streets with green strips have metal fences that are placed between green strip and pavement (see figure 72).

Nearby space - Screenshots I and J have been made in order to gain insight into the characteristics of adjacent streets. These streets may offer space for storage of materials and equipment during planned sewer works. Screenshot I shows that the perpendicular street has two lanes and a broad parking area on the side. This space could be used during sewer works in either *Boterdiepstraat* or *Eemstraat*, thereby reducing the amount of required space in these streets. Screenshot J shows that the perpendicular street at the south side of the area offers additional space as well. Here there are parking areas on both sides, but these have less width than the street shown in screenshot I (because the parking spaces are placed parallel to the road instead of at an angle).

9.2.3 Assumptions

The following assumptions were made while performing this case study:

- The pipelines from 1934 have deteriorated so much that their condition can be assumed to be almost zero percent.
- The pipelines from 1948 have deteriorated considerably, but will be able to function for some more years.
- The PVC sewage pipelines are still in good shape and have deteriorated very little.
- The entire pipeline in a street is treated as one object; this means there are three objects per street. This is done instead of treating every pipe between two manholes as one object.
- The case study area can be easily reached by supply vehicles and there is thus no limitation due to height or width restrictions on acces roads.
- When the transport pipeline in the Boterdiepstraat is temporary out of operation, a diversion pipeline has to be placed for rainwater transport.
- Road works take place every 25 years.

9.3 Examined scenarios

There were two scenarios created to examine the situation and the decision support tool. These scenarios allow for research into different boundary conditions, this allows for a broader insight into application of the tool. The following scenarios were investigated:

- Road surface will be replaced within a few years
- Road surface will not be replaced soon

These scenarios and the associated effects will be discussed in the next subsections. The scenarios were used as input for the decision support tool. First every pipeline is considered seperately, subsequently the possible combinations of solutions are discussed. The validity of the generated results from the tool will also be discussed.

Note that the goal of this case study is not to find the most suitable solution for this problem by looking at lowest total costs. This is due to the fact that there are no cost figures available. The preliminary module for Life Cycle Costing is thus also not discussed since there are no costs to make calculations with. This case study shows the decision process and the considerations that play a role in that process. By using the developed tool to do this, it is possible to determine if the tool covers most aspects of the decision making process. The case study thus allows for validation and optimisation of the tool.

9.3.1 Road surface will be replaced within a few years

The infrastructure department of the municipality plans to replace the road surface in both streets in 5 years. This means the entire street, including parking area, will be dug up and a new cobblestone surface will be created. The surface above the sewage pipeline and one of the rainwater pipelines will thus be replaced. The other rainwater pipeline is located underneath the sidewalk (in the *Boterdiepstraat* this is the large transport pipeline).

It could be interesting to improve all pipelines at the same time since the road will be replaced. The sewage pipelines were however constructed in 1989 and are still in good shape. Therefore it is probably not efficient to make investments in these assets at this moment. In 30 years the road will be replaced again; at this time the sewage pipelines will be 50 years old and probably more suitable for renovation or replacement.

In order to get an overview of possible solutions and combinations of solutions, every pipeline will be entered seperately into the decision support tool (note that entering multiple pipelines is not (yet) possible).

Possible solutions: Eemsstraat

Two pipelines can be found that are part of the rainwater network (d= 250 mm). These are made out of concrete and stoneware and constructed in 1934 and 1948. The pipesections are in poor condition and require attention. When entering the characteristics in the decision support tool the following techniques are possible:

- Sliplining
- Winding pipe
- Close-fit
- CIPP
- Hose lining
- Spray lining (rig)
- Open-cut
- Pipe-cracking

For the wastewater pipeline (d=235 mm) the same results are obtained from the decision support tool, which means is it possible to use a single technique to treat all pipes in the *Eemsstraat*.

Possible solutions: Boterdiepstraat

The rainwater pipeline that has a diameter of 250 mm has the following possibilities with regard to renovation or replacement:

- Sliplining
- Winding pipe
- Close-fit
- CIPP
- Hose lining
- Spray lining (rig)
- Open-cut
- Pipe-cracking

	Eemsstraat			Boterdiepstraat		
Technique	1	2	3	1	2	3
Slipling	√	√	√	√	√	√
Winding pipe	√	√	√	√	√	√
Close-fit	√	√	√	√	x	√
CIPP	√	√	√	√	√	√
Hose lining	√	√	√	√	x	√
Spray lining (rig)	√	√	√	√	x	√
Open-cut	√	√	√	√	√	√
Pipe-cracking	√	√	√	√	x	√

Table 20:Overview of possible techniques for all pipelines in Eemsstraat and Boterdiepstraat

The egg-shaped rainwater transport pipeline forms an exception to all other pipes in this case study due to its dimensions and function. When entering this pipeline into the tool it was unclear which pipe diameter to use as input value. While it is possible to select non-circular pipe shape, the question is which diameter to enter for an egg-shaped pipe. The distinctive dimensions are 1050 mm and 700 mm for this rainwater pipe. When entering 1050 mm the tool will recognise this as a pipe that allows personnel to enter. This pipe ratio is however too small for a worker to enter work in, therefore 700 mm was selected. This immediately excludes techniques that require man-entry dimensions. This vagueness with regard to non-circular pipes has to be removed from the tool so that no mistakes can be made when entering data. When using 700 mm as the decisive dimension these techniques remain possible:

- Slipling
- Winding pipe
- CIPP
- Open-cut

The wastewater pipeline can be renovated or replaced by the same techniques as the small rainwater pipeline (see the list at the top of this page).

Attention points and opportunities

The six pipelines have been entered independently into the model, resulting in six overviews with various aspects that should be taken into account. Since the assets are located in two similar streets in the same area, many results are similar and therefore discussed only one time.

The attention points that are generated by the tool are:

- Increased future capacity due to climate changes (rain showers with higher intensity are expected in the future).
- Record the achieved lifespan of the assets that have reached the end of their lifetime in order to improve future condition prediction.
- Arrange for temporary shutdown of water supply and inform residents of affected houses (only applies to wastewater pipelines).

These attention points are applicable to this situation; points that were not mentioned are also not relevant to this case study. Taking increased future demand due to climate changes into account is only possible by increasing the pipe diameter. The 250 mm rainwater pipes only serve one street and will not encounter large additional amounts of water. The transport pipeline however services a large area, which means it may need a much higher capacity in the future. This can only be achieved by using open-cut methods when looking at the remaining possibilities.

The following opportunities are mentioned:

- Determine if sewer works can be combined with nearby sewer works.
- Look into the possibility of performing works on adjacent manholes at the same time in order to reduce overall nuisance.

These point make perfect sense in this situation. There are more pipelines in nearby streets that can use renovation or replacement. By integrating these works into one project it may be possible to optimise costs and nuisance.
The manholes of the rainwater network are very old and in bad shape. It is not expected that they will fail in the near future, but it might be useful to improve their condition in order to prevent future risks. This can be done by either replacement or renovation.

Decision

The tool has so far generated an extensive overview of remaining solutions and associated costs, but this is insufficient to take a decision. The costs thave to be entered by the user to get insight into the total costs of the various alternatives. Since the direct and external cost figures are not available it is not possible to determine the most suitable solution. It is however possible to look at the overview that was generated to get a general impression about which techniques are most viable.

There are a number of techniques that will require start and exit shafts during execution: slipling, winding pipe, close-fit and pipe-cracking. CIPP, hose lining and spray lining only require manholes as access points. Open-cut obviously requires a trench for every pipeline that is replaced and thus results in the highest amount of soil removal.

Rainwater pipelines underneath road surface

Since the road surface will be replaced in 5 years, it is not efficient to use techniques that require shafts. This would result in soil excavation at the present moment and part of the road surface that needs to be restored. The shafts have to be made watertight since the pipes are located beneath the groundwater table, which means there is a risk of leakage and settlements (as the tool indicates). In 5 years the entire street will be dug up and restored, so why would the asset manager decide to excavate shafts at this moment? This means that the sewer asset manager should choose between three renovation techniques or open-cut. When opting for open-cut it should be obvious that the sewer will be replaced at the same time as the road. In this case the road works will already cause external costs and the sewer works will generate little additional external costs.

The renovation methods may not improve the condition of the pipeline as much as replacement techniques if the original pipe is in bad shape. This is an assumption since there is not sufficient knowledge regarding condition improvement by renovation (see 8.9 for a detailed discussion). Since the pipelines from 1934 are in bad condition it makes sense to replace them entirely by new pipes in 5 years; this can be either concrete or plastic. At the same time the manholes (which are in bad shape) and house connections can be replaced.

Wastewater pipelines underneath road surface

The wastewater pipelines in both streets are still in good shape and do not require any repair or renovation. Replacement can also be done in 5 years, at the same time as the road surface, but this would mean removing pipes that are in good shape and do not show any defects. The PVC pipes are expected to remain in reasonable shape and have sufficient functionality until the next road works, which will be 30 years from now. At that moment the pipes will be 50 years old, at which point they will probably not show much signs of deterioration. For these wastewater pipes the decisive reason for improving them will probably be loss of functionality due to settlements.

The manholes in the wastewater network are also quite new and do not need improvement or replacement any time soon.

Rainwater pipeline underneath pavement (Eemsstraat)

This small pipeline is located underneath the pavement and can thus not be combined with the road works in 5 years. As can be seen in various screenshots, the pavement is till in good shape and does not necessarily require improvement. Once again there are various possible solutions. The sewer asset manager can choose to wait 5 years and use open-cut to replace the pipeline. This means both the street and pavement (or green area in some places) will be dug up. This will only add to the nuisance that residents will receive in 5 years. Furthermore the open-cut method will probably result in uneven settlements of the pavement due to loads from digging machinery. Open-cut does allow to replace the manholes and house connections, thereby preventing future problems due to their bad condition.

Renovation techniques that use start and exit shafts are possible, but will require excavation of pavement areas. There is space available for this since the pavements are quite wide. There would still be sufficient space for pedestrians next to the shafts. Techniques like CIPP and hose lining allow for renovation from manholes, which can be an interesting solution here because of the small amount of disturbance. It also does not give any difficulties with regard to groundwater, as can be the case when excavating shafts. The manholes can be relined, which means no excavation is necessary. The house connections can not be replaced in this situation, but maybe they can be relined from within the rainwater pipe with a robot (but it is unclear if this technique can be applied here).

It may be best to treat this pipeline now and leave the pavement intact during the road works, this free space gives more possibilities for both storage and pedestrian movements in 5 years. Access to the pavement will also be a difficulty in 5 years since the road is not usable due to road works.

Transport pipeline underneath pavement

The rainwater pipe that is located in the *Boterdiepstraat* has deteriorated considerably and requires attention. Because of its transport function this pipeline has an important role in the network and should thus be in good condition. The pipe has a (nowadays less common) egg-shape and was constructed in 1934. As shown before, there are a number of possible renovation or replacement techniques. However, since rain showers are expected to have higher intensities in the future the required capacity will increase. The pipe was constructed in 1934 and since then the amount of rainwater that has to be discharged through this pipe has also increased. It would be good to increase the capacity of this transport pipe in order to gain some flexibility with regard to future developments. The pipe can be replaced by a new egg-shaped pipe or a circular tube. Note that increased capacity can be seen as added value to the system, which can be included by assigning a value to this item in the Excel overview.

The only suitable option is thus the open-cut method, which means the pavement will have to be removed and restored later. The question is whether or not to do this now or at the same time as the road works. Replacement at this moment will mean that there is a single trench in the pavement area and the road will be unaffected. In 5 years the trench will increase external costs caused by road works. Which alternative will generate the least total costs can not be predicted; for this cost figures have to obtained and entered into the model.

Another important attention point that is mentioned by the decision tool is the placement of a diversion pipeline during execution. Since this is a transport pipeline that connects the network to an overlflow at the river Amstel, it should remain functional at all times. During replacement this is obviously not possible, which means a diversion pipeline should be installed. This will also require pumps and thus result in additional air pollution, noise and vibrations (as is clearly indicated by the external cost overview that was generated).

Combining rainwater pipes

The Eemsstraat offers an additional solution for this project; the two rainwater pipelines could be replaced by one larger pipeline. As can be seen in figure 68, there are more streets nearby that only have one rainwater pipe. The road has to be replaced in 5 years, which means that there is an opportunity to make changes to the pipeline layout

Solution	Advantages	Disadvantages
• Rainwater pipes underneath street and pavement are replaced in 5 years, as well as their manholes and house connections	• Synchronised with road works to reduce overall external costs • All assets are in good shape afterwards; no weak links	• Street and sidewalks are excavated at the same time; limited free space and increased nuisance
• Rainwater pipes and manholes underneath street are replaced in 5 years, pipeline and manholes underneath pavement are renovated now (Eemsstraat)	• Synchronised with road works to reduce overall external costs • Sidewalks will be available for storage and pedestrians in 5 years and will remain intact	• Renovation will reduce the free space inside pipes and manholes • It is unclear if the house connections can be relined; if not these are still old and could start leaking or fail
• All rainwater pipes and manholes are renovated now (Eemsstraat)	• Limited external costs • No need to transport new pipe sections and manholes to the site	• Renovation will reduce the free space inside pipes and manholes • It is unclear if the house connections can be relined; if not these are still old and could start leaking or fail
• Rainwater pipes are replaced by a single pipe in 5 years (Eemsstraat)	• Less inspection and maintenance in future • All assets are in good shape afterwards	• Longer house connections necessary • Wastewater pipeline also has to be removed/replaced
• Transport pipeline and its manholes and house connections are replaced now, the rainwater pipe underneath the street is replaced in 5 years (Boterdiepstraat)	• Sidewalks will be available for storage and pedestrians in 5 years • All assets will be replaced and in good shape afterwards	• Residents will be facing excavation twice, allthough the first time this is only part of the sidewalk

Table 21:Summary of solutions when the road surface will be replaced soon

in the street without excavating the entire street only for sewer works. The house connection can be replaced by new pipes that connect to the new pipe. This will ofcourse increase nuisance since the sidewalks also have to be dug up in some places for the house connections, but afterwards the rainwater network in this street will be in perfect shape again. The advantage of one rainwater pipe is that it requires less inspection and maintenance than two pipes, which could be financially attractive in the long run. The disadvantage is that the house connections are longer since the distances between collection pipe and houses are longer. The wastewater pipeline will also have to be removed since the rainwater pipeline is located at a greater depth and the house connections will cross the path of the wastewater pipeline.

9.3.2 Road surface will not be replaced soon

The road surface in the *Boterdiepstraat* and *Eemsstraat* will not be replaced in the coming decade. This means there is no opportunity to synchronise construction activities on both road and sewer. The sewer can obviously still be replaced with the open-cut method, but this means residents of nearby houses will have to incur the generated nuisance twice (sewer works and later road works). The possible technical solutions are identical to the previous scenario and can thus be found in table 20. The situation is however quite different because there is no possibility to synchronise sewer works with road works.

The overview that is generated by the decision support tool is similar to the overview of the previously discussed scenario. The cost values that should be entered for certain alternatives are different since no road works take place. This means that the open-cut alternative is now much less interesting because unique external costs are generated. The external costs for digging up and restoring the road surface have to be added to the cost overview of the open-cut alternative. These costs are not generated when chosing other alternatives and may prove to be decisive for the outcome of total cost comparison. For the transport pipeline the only remaining solution will be open-cut when a capacity increase is necessary, as is assumed for now. The possibilities for the various pipes will be shortly discussed again in the next paragraphs.

Rainwater pipelines underneath road surface

Since the road will not be replaced soon, there is no possibility of synchronise and thus external cost reduction when looking at open-cut methods. Once again both open-cut and renovation are possible, but this time the open-cut method will probably generate more external costs. The street has a small amount of traffic however, and there are not a large amount of people that would be affected by works (besides the residents). Which alternative would thus result in the lowest total costs can not be estimated, since it depends on differences in external costs and direct costs associated with the various techniques.

Solution	Advantages	Disadvantages
• Rainwater pipes underneath street and pavement are replaced, as well as their manholes and house connections	• All assets are in good shape afterwards; no weak links	• Amount of external costs that are generated can be significant
• All rainwater pipes and manholes are renovated (Eemsstraat)	• Limited external costs • No need to transport new pipe sections and manholes to the site	• Renovation will reduce the free space inside pipes and manholes • It is unclear if the house connections can be relined; if not these are still old and could start leaking or fail
• Rainwater pipes are replaced by a single pipeline (Eemsstraat)	• Less inspection and maintenance in future • All assets are in good shape afterwards	• High external costs • Longer house connections necessary • Wastewater pipeline also has to be removed/replaced
• Transport pipeline and its manholes and house connections are replaced, the rainwater pipe underneath the street is renovated (Boterdiepstraat)	• Less external costs than when using open-cut for both pipelines	• Renovation will reduce the free space inside pipes and manholes of the small pipeline • It is unclear if the house connections can be relined; if not these are still old and could start leaking or fail

Table 22:Summary of solutions when the road surface will not be replaced soon

Wastewater pipelines underneath road surface

The thought process is the same as in the previous scenario: wastewater pipelines in both streets are still in good shape and do not require any attention at this moment.

Rainwater pipeline underneath pavement (Eemsstraat)

Since the pipeline does not require capacity increase there are a number of techniques available, both renovation and open-cut. When cost figures are known it would be possible to determine which solution is most suitable.

Transport pipeline underneath pavement

As said before, it is assumed that the transport pipeline has insufficient capacity for the future and should be enlarged. Open-cut is thus the only possibility. The only choice that can be made here is whether or not works on this pipeline should be done at the same time as works on the smaller rainwater pipeline in this street.

In this scenario the Eemsstraat can also be excavated and the two rainwater pipelines can be replaced by a single pipeline. This would however cause large external costs and is much less attractive than when the road would already be replaced.

9.4 Example of cost factor

So far the case study has shown the possible solutions that the decision support tool generates for this project and which considerations play a role in the decision making process. Unfortunately it is not possible to calculate total costs and decide which alternative is most suitable since cost figures are unknown. This case study does however help to test the tool and detect omissions in the program, so that it can be improved. Costs and added values can be entered in the *Solutions and cost factors* sheet in the tool. To give an impression of how such values can de determined, a very basic example is shortly discussed below.

When looking at open-cut versus trenchless methods, removal and restoration of the road surface can be a big part of both direct and external costs. External costs have various components, such as noise, dust, obstructions. Determining these external costs is difficult since there are no methods or conversion factors available for most external costs (see chapter 7 for an overview). Direct costs can usually be estimated based on previous experiences or by contacting contractors. Previous experience in Amsterdam has shown that removal and restoration of the cobblestone top layer has a direct cost of about 30 Euros per square meter (Staverman, 2010). When alternatives have to be compared, this cost component can thus be easily determined.

- Start and exit shafts require a certain excavation area. This area can be multiplied by the cost per square meter and the number of shafts to estimate the road restoration costs for a technique that uses shafts.
- Techniques that only need manhole access do not have this cost component, and for these techniques this cost factor is also greyed out in the model.
- Open-cut methods require large road surface or pavement areas to be removed and restored. When replacing one of the pipelines underneath the road surface this means a trench of 225 m (*Boterdiepstraat*) or 250 m (*Eemsstraat*) length. The trench may not be very wide, but the road surface that needs to be removed and restored will be wider, for example 2 meters. When taking the Eemsstraat as example, this means a direct cost of 250 x 2 x 30 = 15.000 Euros. This value can simply be entered into the relevant cost factor field in the Excel model.

This is just a simple example, but it shows how a single cost component can be quickly determined and included in the calculation. Future research may result in a cost database that can be combined with the decision support tool. Ideally the user should just enter a few basic parameters, after which the tool automatically calculates certain values (such as excavated volume, removed surface). Specific equipment data should also be included in the database in order to get insight into variations in direct and external costs (e.g. air pollution values for various types of equipment).

9.5 Tool validation

The case study was performed in order to get more insight into the model and whether or not it can generate realistic results. Furthermore the case study allowed for detection of components that are not yet in the model but should be. The result of the case study is thus that the model can be optimised and “finished” for the goals set in this research. Obviously there are always more improvements and expansions possible, but this requires more additional research, which will hopefully be performed in the coming years.

This section will discuss the most important errors or unclear items that were discovered while performing the case study. There were also many small issues found, but it is not interesting or useful to mention these all here. It suffices to say that the architecture, formulas and relations have been optimised by applying this case study to the model; at this moment the model works as it was intended and errors have been removed. Assumptions and limitations that were found have also been added to section 8.11, wich now provides a complete overview of these items.The most important points that were found are:

- Non-circular pipes have multiple dimension values, while circular diameters can be described by just its diameter. Since there is only one entry field for diameter in the *General data* sheet, this can be unclear. As seen in the case study, egg-shaped pipes can be defined by two values and it is unclear which one to enter. The value that is entered is compared to data for circular pipes in order to decide which techniques are excluded. The data sheet for techniques should be expanded by adding data regarding the type and sizes of non-circular pipes in relation to available techniques.
- Combinations of techniques for pipes and manholes cannot be examined by the model. The model does suggest optimising the project by also looking at adjacent manholes, but does not make a distinction between relining or replacing manholes. This is no surprise since the research has mainly focused on sewer pipes, but it would be good to add manhole techniques in the future.
- Synchronisation of sewer works and other infrastructure works can be selected as a reason, but when another reason is selected this consideration is not very visible. It is possible to enter the years until road works are performed, but this was not linked to any effect or warning. Reduced external costs thanks to synchronisation has been added as a attention point. When the years until road works are lower than 10, the program shows a warning in the *cost overview* page.
- The (preliminary) LCC module of the tool assumes an initial condition of 100 percent (so fully improved) for the asset, but it would be desirable to make the initial condition and improvement variable, so the user can also investigate solutions for assets that are partly deteriorated but have not reached the end of their technical lifespan. Variables for initial condition and whether or not improvement is immediately desired have later been included in the model. This has greatly increased versatility of the tool.
- The tool can generate Net Present Values of various alternatives, but it does not show which technique is most suitable. A ranking system has been introduced that compares all outcomes and lists the techniques from lowest to highest NPV.

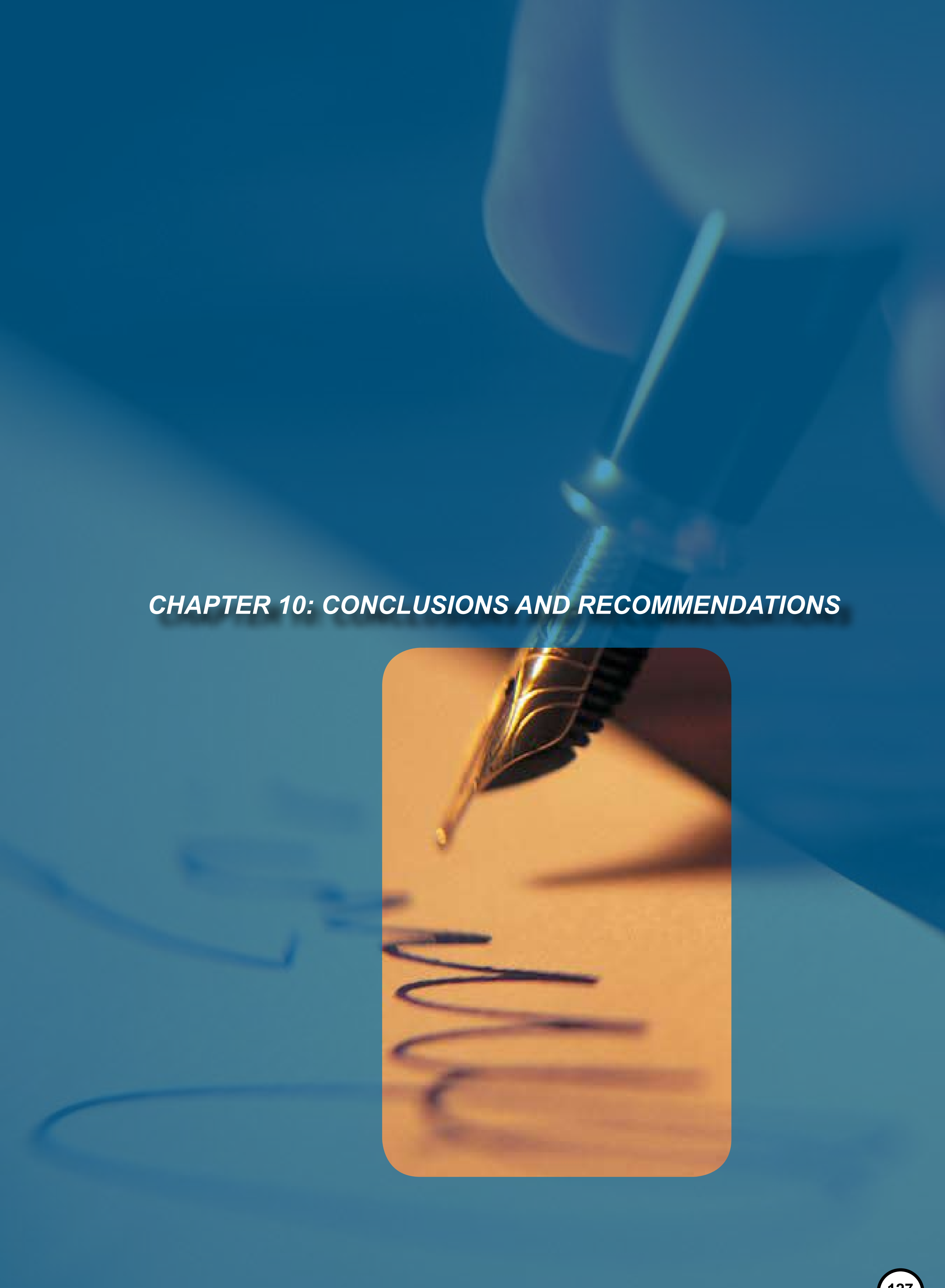
9.6 Conclusions

The case study has given a useful insight into applicability and quality of the decision support tool that was developed for the purpose of this research. The completeness of the tool has been validated by this case study; no important items appear to be missing. Unfortunately it was not possible to calculate which solutions would be best suitable for the two discussed scenarios due to the fact that cost data is absent. Even though cost figures are not within the scope of this research it would have been nice to calculate all costs and make a decision based on this.

The two scenarios were investigated by entering available data into the tool. Data or considerations that could not be entered into the tool were listed and examined. Afterwards the most critical flaws or omissions were fixed or added to the tool. While performing the case study it became clear that it is very challenging to include all considerations, parameters and combinations of these into the model. This general tool will never be able to fully model every unique situation and all its characteristics, but by including the most important components it can still offer very useful support to sewer asset managers and a large improvement over the existing situation.

At this moment the tool includes the most important aspects and factors in the decision making process. Limitations have been clearly identified so that it is possible to fully inform the user about the possibilities of this tool. Furthermore the tool has been designed as flexible as possible, thereby allowing for future additions and improvements. New insights into considerations, technique characteristics, cost factors or life cycle parameters can be easily added to the tool. This is one of the most important strengths of this tool and this will enable the tool to remain up to date and functional for future use. The existence of this tool will also increase incentive for further research since it is possible to improve and expand the tool by adding new research results.

CHAPTER 10: CONCLUSIONS AND RECOMMENDATIONS



Chapter 10: Conclusions and recommendations

10.1 General remarks

Sewers form the backbone of our public health system, but these vital networks are often inefficiently managed because of lack of knowledge or traditional ways of thinking. A new approach to asset management of these underground systems is necessary in order to keep them in good condition while minimising overall costs. This means broadening the decision making process by including social and environmental aspects. Especially in dense urban environments, where social and environmental costs can far outweigh direct costs, such a new approach could greatly reduce overall costs.

Trenchless technologies that have started to appear on the market during the last decades offer an alternative to traditional open-cut methods with less hindrance and nuisance. Depending on project characteristics, application of these techniques can greatly reduce total costs. These different techniques can only be compared to each other and to open-cut methods when external costs are also included in the decision making process.

This research has attempted to look into the items that are necessary for a such a new approach and how these can be obtained or developed. This has resulted in an overview of components and relations that should be present in the decision making process when an integrated approach is desired. First existing methods were examined, most of which were very limited or not suitable for the Dutch situation. The decision was thus made to develop a tool from scratch, which can take all new insights into account and which can be customised for the Dutch situation. This has resulted in a decision support tool that was built throughout this research, which will hopefully help sewer asset managers to optimise their decision making process and thus reduce overall costs and nuisance. Additionally, the gathered information in this report can serve as a manual, providing an overview of the items that should be taken into account when making decisions.

The developed decision tool is not yet complete since there are a number of components that still need to be further developed. This tool does however sets the first step towards such an integrated decision tool. As long as the user understands its limitations and the assumptions that were made, it can already greatly improve decision making. The great strength of the developed tool is that it has a flexible design and allows for future adjustments and additions.

10.2 Conclusions

This research has been looking into various aspects regarding asset management of sewer networks. This has resulted in a number of conclusions, which are listed below.

General conclusions

1. External costs are often not taken into account when making decisions about which technique to choose for a sewer work. This means that decisions are often based on direct costs, which can result in higher overall costs. Many external costs can also not be quantified; more research is needed to determine cost figures for external effects.

2. Added values are not yet taken into account when making a decision, but can be decisive when comparing techniques. They also can be used for justification of the overall project.

3. The curves that are used for condition prediction are based on theoretical models and differ greatly. The real deterioration process is still unclear and more research is required to improve the accuracy of predictions and the effect of local conditions on this.

4. The assumed condition curve has a large influence on the behaviour of solutions and the decision making process. The change from a linear to a second degree curve is probably the most fundamental since the deterioration rate is no longer constant and the optimisation process significantly changes.

5. Results obtained from sewer inspections are unreliable and should be sceptically looked at. Since condition assessment is the basis on which decision making is based, accuracy should be improved to optimise overall decision making.

6. The tool that was developed for the purpose of this research includes the most important items that should be taken into account when making decisions regarding asset management of sewer systems. Furthermore it offers flexibility for future adjustments and additions, which will increase incentive for future research. The assumptions and limitations of this tool are clearly explained in section 8.11.

7. The developed tool integrates maintenance strategies, physical and decision making levels, external effects and trenchless technologies. A proper asset management strategy including these effects can lead to huge savings in the future, both in direct and external costs. Savings of 20 percent or more are deemed possible, even if external or indirect benefits are not included; for the Dutch situation (yearly sewer maintenance costs of 1,2 billion Euros) this would translate to a yearly cost reduction of 240 million Euros. When external effects and indirect costs are included the savings would be even larger.

Conclusions obtained from the sensitivity analysis

8. Short life expectancies greatly increase the frequency of repairs or renovations that offer small condition improvements. This makes them not competitive in these situations since very frequent activities of many assets require a lot of available equipment and manpower.

9. Changes in the improvement value for a technique (Pf) are more effective at lower values. For example, increasing the value from 20 to 50 percent has more effect than an increase from 50 to 80 percent.

10. The most effective time to apply a technique is when it increases the condition level to 100 percent.

11. The existence of an upper boundary can have large consequences for the amount of required interventions, and thus the long-term costs. Especially for low life expectancies this effect is important.

12. The total costs per activity of repair and renovation techniques always have to be lower than the costs per replacement technique in order to achieve competitive Net Present Values.

13. The required cost reduction for renovation and repair techniques, compared to open-cut replacement, varies between 10 and 85 percent. The external cost component of trenchless techniques will usually be significantly lower than open-cut replacement however. This means trenchless techniques will usually result in much lower overall costs.

10.3 Recommendations

The performed research has clearly shown in which areas improvements or changes are necessary. There are still many topics that can be researched in the broad field of sewer asset management.

This research has resulted in the following recommendations:

1. Public organisations should be made more aware of trenchless techniques. In some municipalities there is experience with trenchless techniques that are applied for sewer works, but organisations with little or no experience are often unwilling to use new technologies. A better understanding of the characteristics and associated costs of various techniques will result in objective decision making that does not rule out any technique in advance.

2. It is vital for municipalities to understand the physical levels in their network and the relations that exist between them. When planning sewer works the responsible organisation should always look at both operational, tactical and strategic considerations and effects. This is absolutely vital for optimal asset management.

3. Synchronisation of sewer works and activities on other infrastructure or green zones should always be considered. When works on different systems are synchronised it is possible to greatly reduce costs and nuisance. Organisations that manage assets that are close to other networks should always inform the other party about planned activities. Another option is the use of legislation to force parties to synchronise. A good example of this is Amsterdam; when a road surface is dug up for works, it is forbidden to dig up the road surface within the next five years. This prevents roads from being dug up every year by different organisations.

4. Municipalities should always collect data regarding achieved lifespans of assets, observed deterioration and performance of techniques in different conditions. This will result in more insight into relevant physical processes and allow for more accurate parameters that can be used in the tool.

5. Direct costs should be investigated so that general figures can be included in the decision support tool. General direct cost figures can be obtained from previous experiences, this would allow the user to quickly get insight into direct costs that can be expected. Since there are no general figures at the moment, the user has to fill in all cost figures in the model.

6. External costs should always be included in the decision making process. In order to have a sustainable approach it is vital to include social and environmental costs. These can be substantial when working in heavily populated areas. Some external costs can already be calculated by using certain methods or conversion factors. External effects that cannot be expressed in monetary values should be researched so that their costs can be estimated.

7. Condition prediction needs to be improved and not merely based on theoretical models. Deterioration data has to be gathered in order to determine the the influences of local conditions on the life expectancy of assets. Instead of having a general deterioration curve for all situations, it would be better to have multiple curves that represent a limited number of situations (e.g. combinations of soil conditions and pipe materials).

8. The effect of existing repair and renovation techniques on the condition and deterioration process of assets should be researched. At this moment there is no data available about this topic.

9. Condition assessment by using inspection data should be improved. The results are unreliable, as was shown by research. The question is whether only inspection data should be used for assessment or if there are also other possibilities (e.g. measuring the settlements of pipes as basis for condition assessment).

10. More case studies should be performed in order to further refine the decision support tool and obtain condition data for improved condition prediction.

11. The tool should be improved by making it possible to add multiple pipelines that can be found in one street.

12. Combinations of different techniques as an alternative should be added as possible technical solutions in the tool.

13. Other objects that are part of sewer systems should eventually also be included in the tool (e.g. manholes, pumps, settlement tanks).

14. Non-circular pipes should be further divided into various types and size ranges. This allows for more customisation of which techniques can be applied to it. At the moment the only variables that can be entered are pipe diameter and desired increase in diameter. For non-circular pipes it is unclear which values should be entered.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APPENDICES

Appendix A: Explanation of the decision support tool

A.1 General

This appendix will explain the decision support tool that has been developed for the purpose of this master thesis. The decision support tool was created in the Excel program, it is recommended that users use version 2007 or later.

The tool is able to generate possible technical solutions for specific situations that a sewer asset manager can encounter. The costs that are associated with these technical solutions are also listed, this ensures that the user of the program has a clear overview of all relevant costs. Finally the tool is able to perform life cycle costing calculations for the possible solutions, by making use of a preliminary module that was added during the last part of the research.

This tool is the first step towards an integral decision support tool that can generate all possible combinations of technical solutions and investment strategies. Additionaly this tool should be able to calculate all direct, social and environmental costs throughout the entire lifetime of an asset for these combinations. The final result will be a comparison of total costs for all alternatives that can be used to make a decision. Before such a tool can be developed, a number of additional modules needs to be developed. This however requires more research into certain aspects, see chapter 8 for a discussion regarding future additions to the tool.

A.2 Layout of the model

The decision support tool consists of a number of worksheets that are connected to each other via various relations. Some of these sheets are used for data entry, while others are only used to show results. The following worksheets can be found in the decision model:

- *General data*
- *R1 to R6*
- *Diameter ranges*
- *Solutions and cost factors*
- *LCC analysis*
- *C1 to C17 (hidden)*

The first sheet (*General data*) allows the user to select general parameters, this immediately shows which techniques are viable solutions and the most important attention points.

When there are many solutions remaining the user can proceed to a second sheet (*R1* to *R6)* in which he can fill in the many considerations that were discussed in sections 8.5 to 8.7. The choices that are made by the user are linked to the sheet *Solutions and cost factors*, which gives an overview of all remaining techniques and all related costs (both direct and external) that should be taken into account when one wants to compare these techniques to each other. The cost components that are mentioned can be given values, these are then added up so the cost per repair, renovation or replacement activity can be compared. At this moment the user can make a decision based on this overview.

Instead of comparing all costs for a single intervention (repair, renovation or replacement) the user can also choose to investigate the behaviour of various solutions over the lifetime of an asset. This means he takes multiple interventions into account that occur during many decades. During the last phase of this research a preliminary module was added to the tool. This module contains a framework for condition prediction and Life Cycle Costing (LCC). This allows the user to specify a number of variables related to life expectancy, time and economic conditions. This module then calculates the number of required interventions and the discounted total costs and values over a specified time frame. The result is the Net Present Value of all possible solutions, which allows the user to make the most integral decision. Note that this last module is preliminary and based on a number of assumptions (see chapter 8).

Figure 81 shows the actions that are required to generate results at various points in the overall process. As can be clearly seen, there are three moments at which a decision can be made. The last part of the sequence is part of the preliminary module. The next subsections will explain the various Excel worksheets in detail.

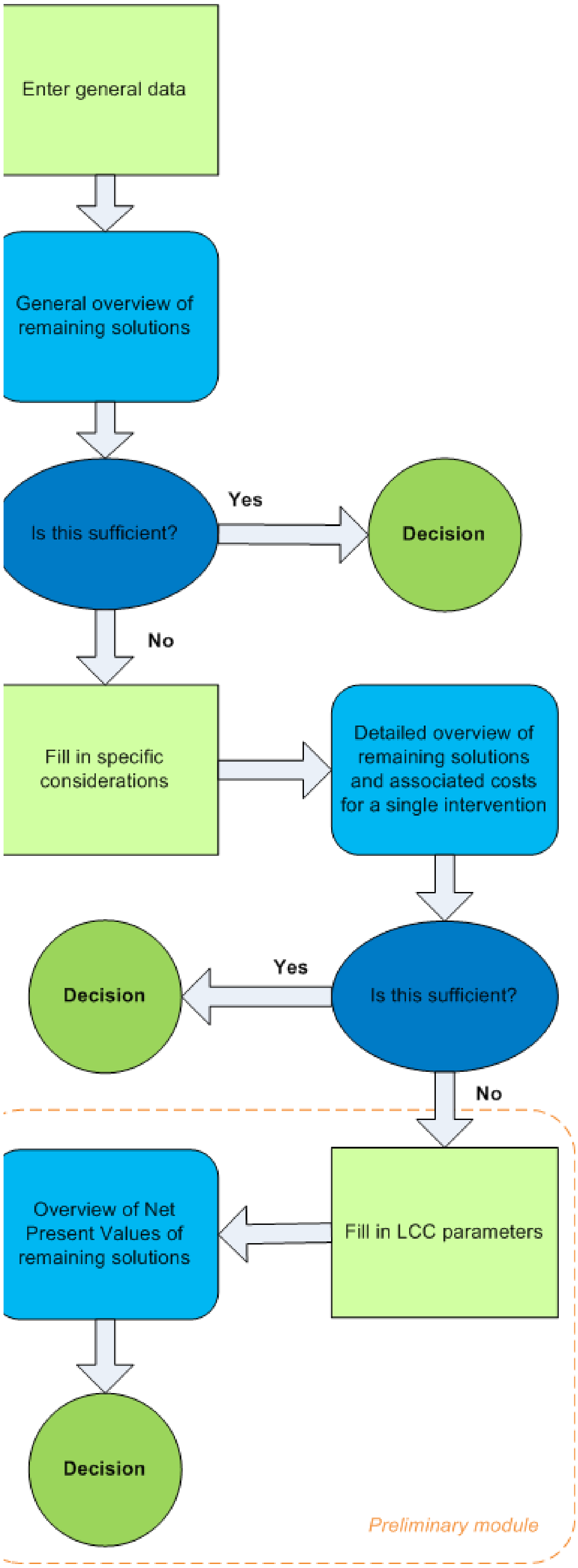


Figure 81:Sequence of steps that illustrate how the excel model works

General data

The first sheet that a user encounters is the *General data* sheet. This sheet allows the user to select a number of characteristics, which are then used to narrow down the amount of available technical solutions. The following characteristics can be entered:

System type - allows the user to select the type of sewer system in which there is a problem. The user can choose between combined gravity, seperated gravity (rainwater), seperated gravity (wastewater) and pressure.

Pipe shape - allows the user to choose between a circular or non-circular profile. As discussed in chapter 6, some techniques are only suitable for circular pipes.

Sewer is below groundwater level - allows the user to indicate if the considered sewer section is below the groundwater level. This is important since trenches or shafts that are below groundwater level have a risk of leakage, which can affect the local groundwater table and cause undesirable settlements to nearby buildings. Furthermore pumps may be necessary to keep shafts and trenches from flooding, which results in additional costs that should be included in the overall costs.

Risk of settlements (soil conditions) - allows the user to indicate if the area has soft soils that have large settlements or sandy soils that have risk of settlements. Settlements can drastically reduce the lifespan of sewer pipes. Wastewater pipes that have their inclination reduced due to uneven settlements can have greatly reduced funtionality. Especially in the western part of the Netherlands this is a big problem.

Sewer has a pile foundation - this means the sewer is not sensitive for settlements in soft soil conditions. This is usually only done for large transport pipelines and not for small collection pipes.

Pipe diameter - the diameter of the existing pipe can be entered into the first field. This field is directly linked to a overview of diameter ranges for all techniques that are included in this research. This overview can be found in the sheet *Diameter ranges*. When the entered diameter is higher than the maximum diameter or lower than the minimum diameter of a specific technique, the technique is excluded from the solutions.
The second field allows the user to enter the desired increase in diameter, if this is applicable. When there

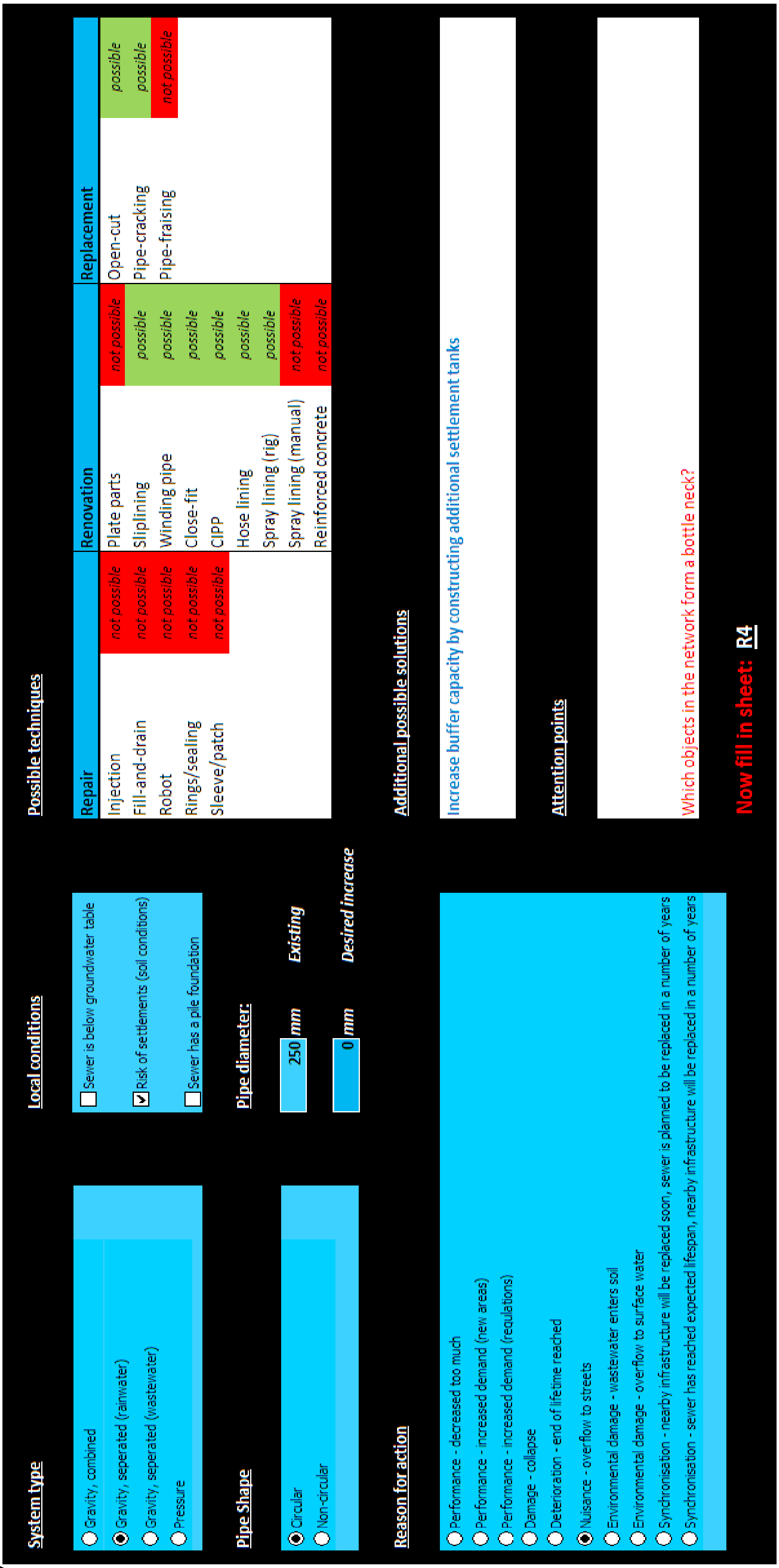


Figure 82:Screenshot of the General data sheet of the Excel model

is no desire for increase, the value should be set at zero. Values higher than zero will exclude all repair and renovation techniques. For replacement techniques this value is compared to a value from the *Diameter ranges* sheet that represents the maximum diameter increase that a technique can achieve. The open-cut method has no maximum diameter increase.

Reason for action - the sewer project has been initiated for a certain reason. In chapter 8 the various possible reasons were discussed; these can be found in the option list that is shown for this aspect. Some reasons will exclude certain techniques or aspects, for example when a sewer section is collapsed the only remaining solutions are replacement techniques. The ten identified reasons are divided into six main categories and summarised in table 23.

The entered data is used to determine which techniques are possible for this project. The fields on the right side of the worksheet display the following information:

Possible techniques - gives an overview of all possible techniques (in green). Techniques that are not possible for this project are shown in red.

Additional possible solutions - shows which other solutions are possible besides applying repair/renovation/replacement techniques to the considered sewer section. At the moment the only solution that is listed here is “construct additional settlement tanks”, which becomes visible when the selected reason for action is *nuisance (overflow)* or *environmental damage (overflow).*

Attention points - shows to which aspects the user should pay attention for this project. This is only based on the data entered in this worksheet and therefore limited. A detailed overview of attention points can be found in the final worksheet, but this requires the user to fill in more detailed information in an intermediate sheet (see next section).

The program indicates to which sheet the user should continue in the bottom right of the worksheet. This depends on the reason that was chosen and this sheet will allow the user to fill in detailed information.

Main reason	Sub-reason	Assigned sheet
Performance	Decrease	R1
	New areas	R1
	Regulations	R1
Damage	Collapse	R2
Deterioration	End of lifetime	R3
Nuisance	Overflow street	R4
Environmental damage	Leaks	R5
	Overflow surface	R5
Synchronisation	Nearby infra will be replaced soon	R6
	Sewer will be replaced soon	R6

Table 23: Summary of reasons and the worksheet to which they relate

Considerations (R1 to R6)

When the *General data* sheet generates a large number of possible solutions it is unclear which solution is most suitable for this project. In order to get an overview of specific cost items, risks and attention points for all these solutions, the user should fill in one of the sheets that contain considerations.

In chapter 8.5 to 8.7, many considerations were discussed that should be taken into account when planning a sewer project. Table 23 already showed which consideration sheet is associated with which specific reason for action.

Different sheets were created because this allows for more customised considerations to be listed and shown to the user. Not all considerations are always relevant; some are only interesting in specific cases. The user should only provide information that is necessary for a specific case and not face questions that are of no importance.

Different sheets for different reasons also allow for easy future adaptations of the model. When more specific considerations emerge these can easily be added to the relevant sheets without cluttering the sheets in the model.

The sheets provide an overview of all relevant considerations and are divided into nine sections. These nine sections represent combinations of the three levels of decision making (see chapter 5) and the three types of considerations that are required for a sustainable approach (see chapter 8). Figure 83 shows the matrix with all possible combinations; the same layout can be found in all consideration sheets.

Considerations are shown as questions that the user should answer. Most considerations can be answered by selecting either “yes” or “no”. Some considerations have more options to choose from or they can be answered by activating checkboxes (in which case more answers are possible). The choices that the user makes have a direct effect on the final sheet of the decision support model, which shows all possible solutions and associated costs. For example, when the user indicates that there is a road present above the sewer section, the model adds costs for restoration of the road surface to techniques that require trenches or shafts.

	Economic	Social	Environmental
Strategic	Strategic economic	Strategic social	Strategic environmental
Tactical	Tactical economic	Tactical social	Tactical environmental
Operational	Operational economic	Operational social	Operational environmental

Figure 83: Matrix of all available combinations of decision making levels and type of consideration

Certain choices in the *General data* sheet or in the consideration sheet itself can make certain considerations not relevant anymore. Considerations regarding rain water for example or not interesting when looking at a pressure system, since this does not transport rain water. These considerations are visually marked to indicate that they are not relevant and should not be answered. This makes sure that the user does not have to face questions that are useless for his project, thus improving efficiency and preventing possible annoyance.
Questions that are not relevant are marked with a red X on the right side and the box containing the question is darkened. This gives a clear signal to users to skip this question.

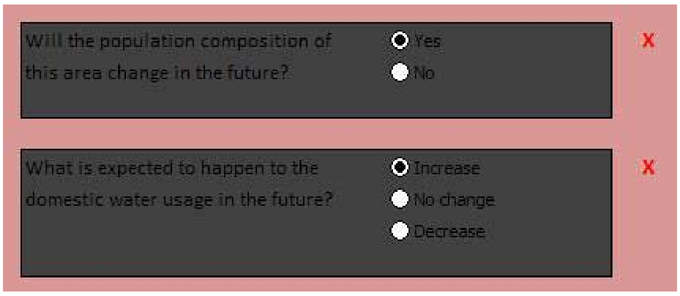


Figure 84: Example of how questions are excluded. Because a rainwater network of a seperated system was selected, these questions regarding sewage water are excluded.

Diameter ranges

The *diameter ranges* sheet contains an overview of parameters for diameter ranges, these are directly linked to the “pipe diameter” field in the *General data* sheet. The parameters were obtained from literature research and talks with experts throughout the research process. New developments can result in a larger application range for certain techniques, in this case this sheet allows for alterations of ranges. The user should however always verify changes in available diameters with manufacturers. By seperating this data from other sheets the risk of accidental alteration of these values is greatly reduced. There are three parameters that can be altered in this sheet.

Minimum diameter and Maximum diameter - determines the lower and upper boundary of pipe diameters that a certain technique can repair/renovate/replace.

Possible increase - gives the maximum diameter increase that is possible when using the considered technique. All repair and renovation techniques do not have a value for this parameter since they cannot increase the diameter of a pipe. Open-cut can increase the diameter of a pipe, but does not have a upper boundary for this. There are thus only two techniques that have a value for this parameter: pipe-cracking and pipe-fraising.

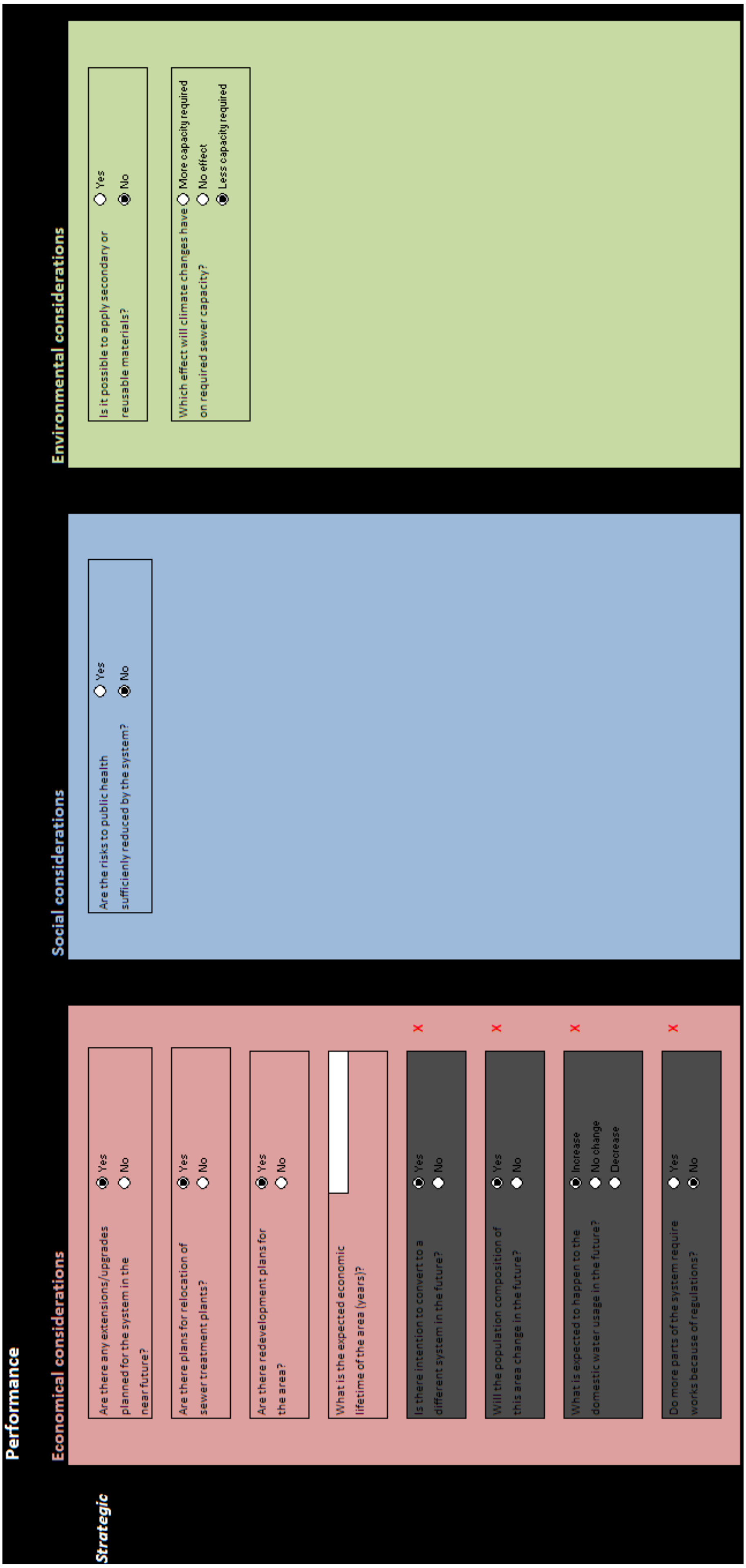


Figure 85:Screenshot of R-type sheet, showing the top part of the sheet

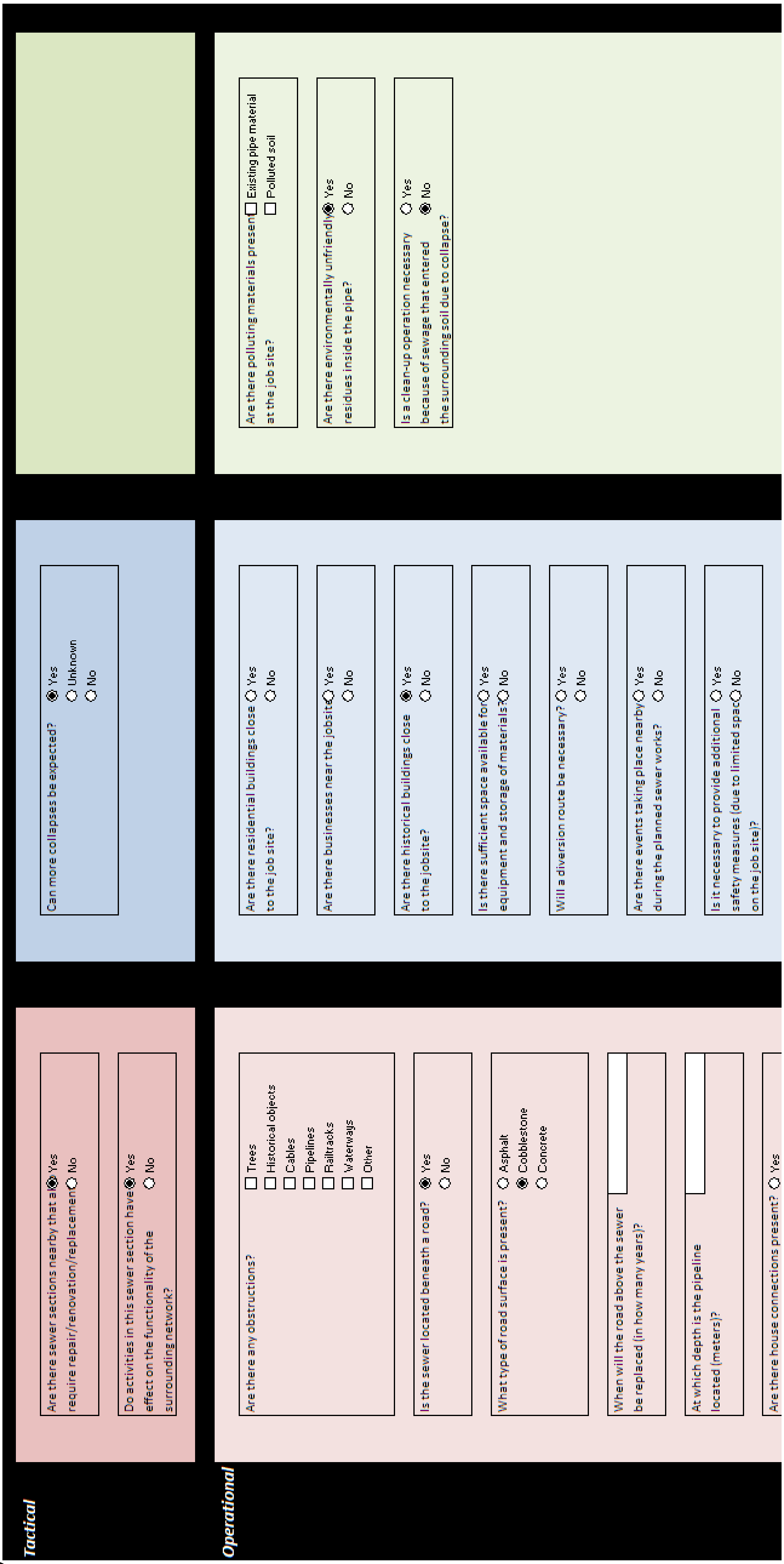


Figure 86: Screenshot of a R-type sheet, showing the bottom part of the sheet

Diameter ranges for the included techniques

Note: only edit these values if the available diameter ranges for certain techniques change (check with manufacturer)

	Technique	*Minimum diameter*	*Maximum diameter*	*Possible increase*
Repair	Injection	0	100000	
	Fill-and-drain	0	100000	
	Robot	200	800	
	Rings/sealing	200	3000	
	Sleeve/patch	200	600	
Renovation	Plate parts	1000	100000	
	Sliplining	200	3500	
	Winding pipe	200	3000	
	Close-fit	75	1600	
	CIPP	50	2500	
	Hose lining	0	300	
	Spray lining (rig)	100	1200	
	Spray lining (manual)	1000	1000000	
	Reinforced concrete	1000	1000000	
Replacement	Open-cut	0	1000000	
	Pipe-cracking	50	1000	100
	Pipe-fraising	300	1000000	500

All diameters in mm

Techniques with unlimited range have their maximum diameter set at 1000000 mm

Figure 87:Screenshot of the diameter ranges sheet, which allows the user to alter minimum and maximum diameters of all included techniques

Solutions and cost factors

This extensive and important worksheet in the decision support model contains various results that can help the sewer asset manager to make better decisions. The worksheet shows all generated results from the various components and acts as an entry sheet for cost and LCC data.

The worksheet lists many possible costs, values, risks, attention points and opportunities. A visual overview of the entire sheet can be found in figures 88 to 93. Not all relationswill be individually explained here since this would only result in an enormous amount of text, while it would not have much additional value. The general categories and their components in the sheet will be discussed in this section. This should provide sufficient insight to understand the layout and functionality of the tool.

The sheet shows a large amount of combinations between possible techniques on the horizontal axis and specific associated items on the vertical axis. All items that are relevant and should thus be assigned a value are shown as white boxes. Items that are not relevant for a technique and should thus be ignored have a grey box assigned to them. Sometimes items are not relevant for any technique, in this case the item itself (in the menu on the left) will be grey and crossed out. There are a limited number of fields with a orange colour; these fields indicate items that are possibly relevant. This only occurs with certain items that are related to the existence of start and exit shafts; some techniques do not always require such provisions. When looking closely at figures 88 to 93, the following components can be seen:

Overview of possible techniques - shows all techniques that are included in this research and whether or not they are possible as a solution for this project. The techniques are horizontally listed in the top of the sheet. The techniques that are possible have a green colour, while techniques that are not possible for the entered situation receive a red colour and are crossed out. The model is constructed in such a way that the entire column of an impossible technique becomes black. This hides all data fields from sight, thus only showing fields of techniques that are possible. This gives a clear overview of all items that should be considered and given a value.

Direct costs - list all direct cost items that should be taken into account when comparing alternatives. A distinction is made between costs that occur during design or preparation and costs that are generated during execution. The execution phase costs are divided into the following aspects, each of which consists of multiple items:

- General
- Preventive safety measures
- Soil removal
- Disposal/treatment of polluting materials
- Removal and restoration of top layer
- Removal of obstructions
- Temporary diversion of sewage flow

External costs - list all external cost items that should be taken into account when comparing alternatives. This includes many social and environmental costs for which there is not yet a calculation method available. The numerous items are listed under the following categories:

Environmental
- Air pollution
- Depletion of non-renewable resources

Social
- Nuisance
- Damage
- Traffic disruption
- Safety

Added value - shows the items that have a positive value, which partly compensate for costs. The added value items are divided in above ground and subsurface added value. Some of these can be entered as yearly “income”, while others add value just one time. The items that offer a yearly benefit are included in the life cycle costing calculations for the various solutions. The added value items were discussed in more detail in chapter 7.

Above ground
- Overflow reduction (surface water) - per year
- Overflow reduction (streets) - per year
- Improved quality of top layer

Subsurface
- Increased discharge capacity
- Pollution reduction (leaks) - per year
- Pollution reduction (overflows to streets) - per year
- Pollution reduction (pipe materials)- per year
- Reduced failures and emergency repairs - per year
- Reduced inspection effort - per year

Specific risks - lists specific risks that should be taken into account when using a specific technique or that are typical for this project in general. Risks that are unique for certain techniques can be used for comparing techniques. At this moment there are only four risks listed, but this list can probably be expanded in the future.

- Damage to nearby building because of settlements
- Damage to historical buildings
- Railroad obstruction
- Waterway obstruction

Characteristics of techniques - lists two variables that are important for LCC calculations. These can be changed for every technique seperately, but this is only useful when these values can be accurately estimated. For now a rough assumption has been made so that it is possible to perform calculations. The entry fields for P_f and P_m have been placed on this page so the user can directly see the effects of alteration of these values on the cost and value overview, which is shown just below this component.

Cost and value overview - shows the total costs of all possible technical solutions and offers entry fields for LCC and condition variables. This is the place where the user should eventually look to see which solution is most suitable for his project. Figure 92 offers a clear overview of the layout of this component. The top part consists of fields that should be assigned a value by the user.

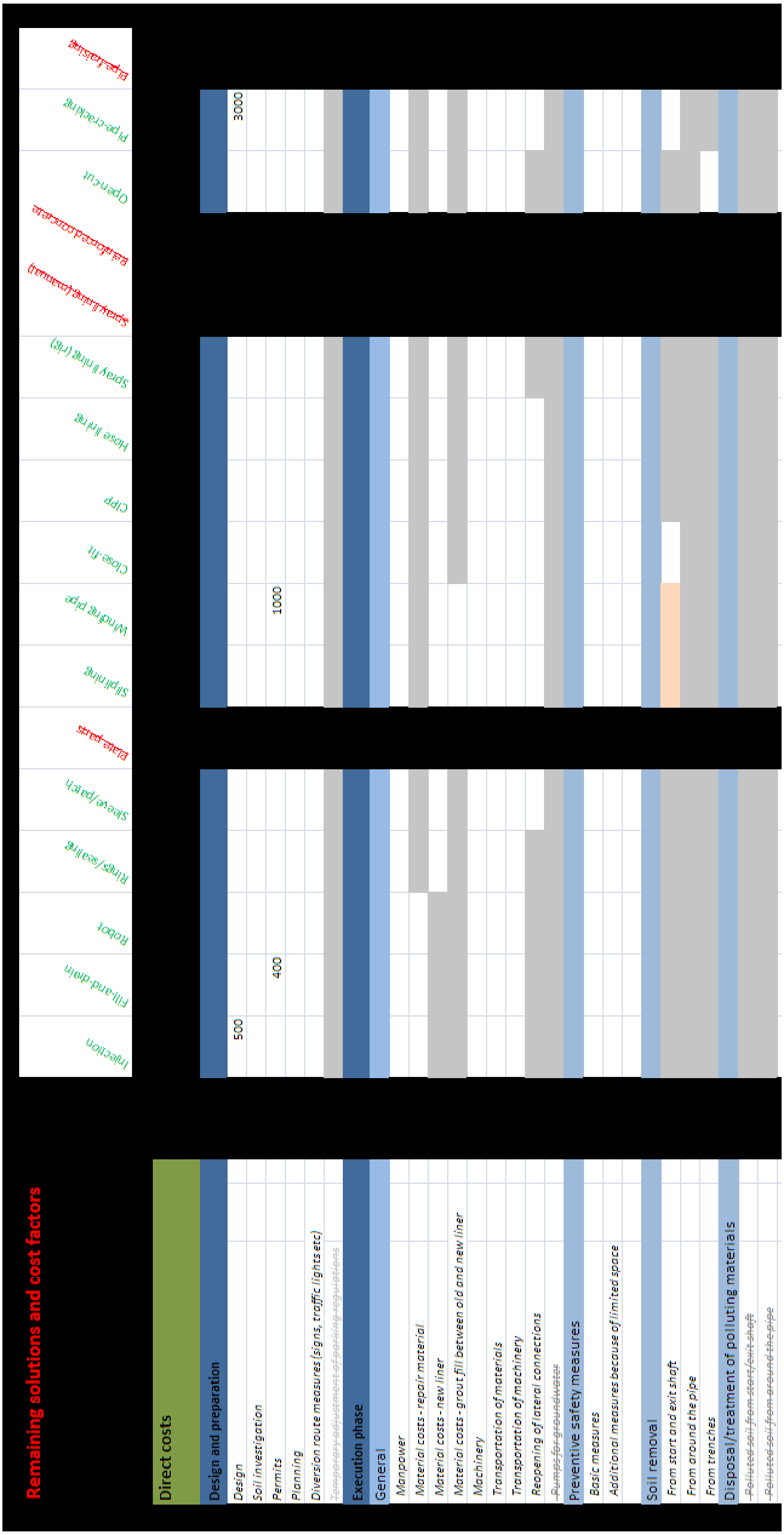


Figure 88:Screenshot solutions and cost factors sheet, part 1

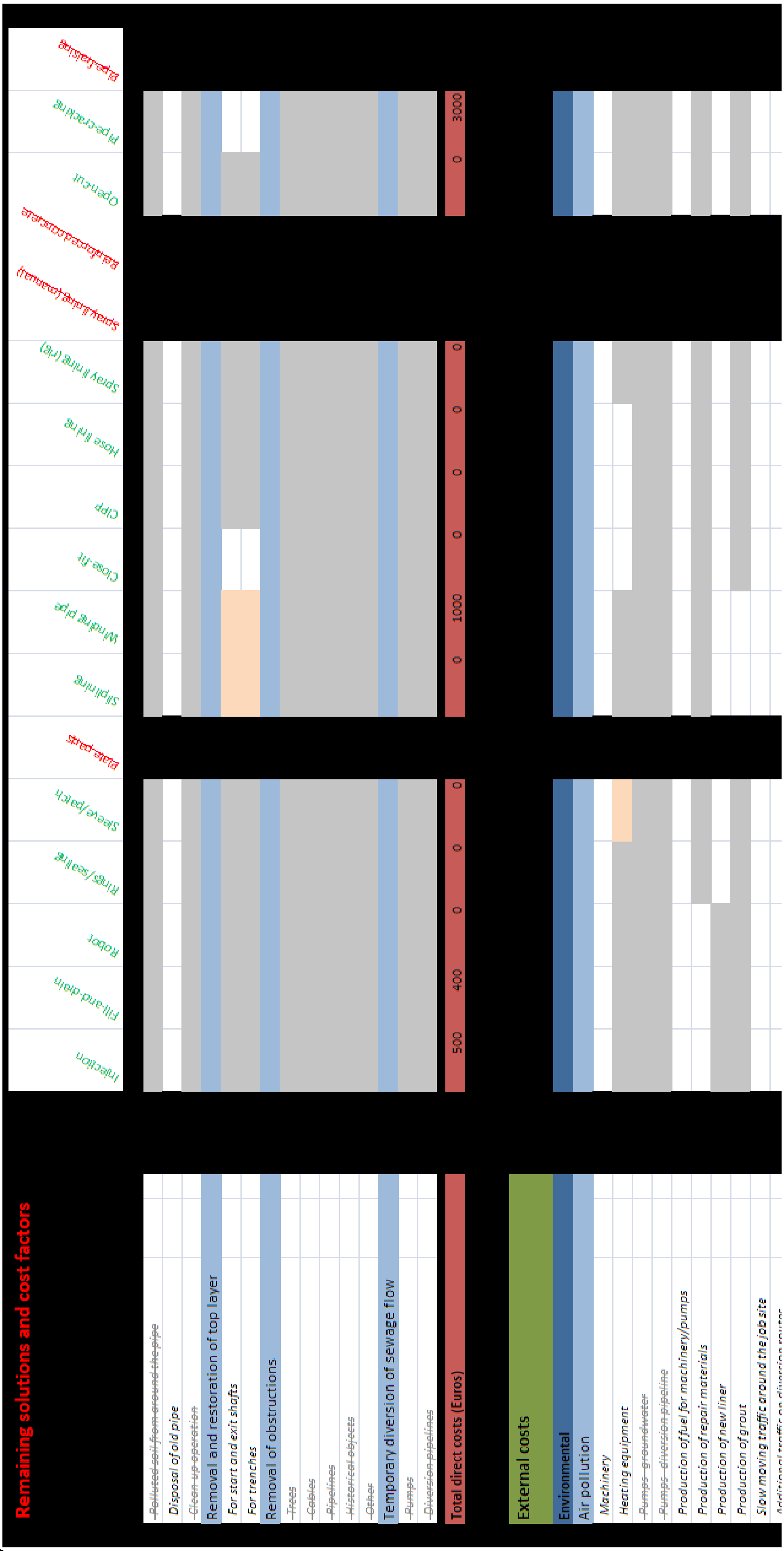


Figure 89:Screenshot solutions and cost factors sheet, part 2

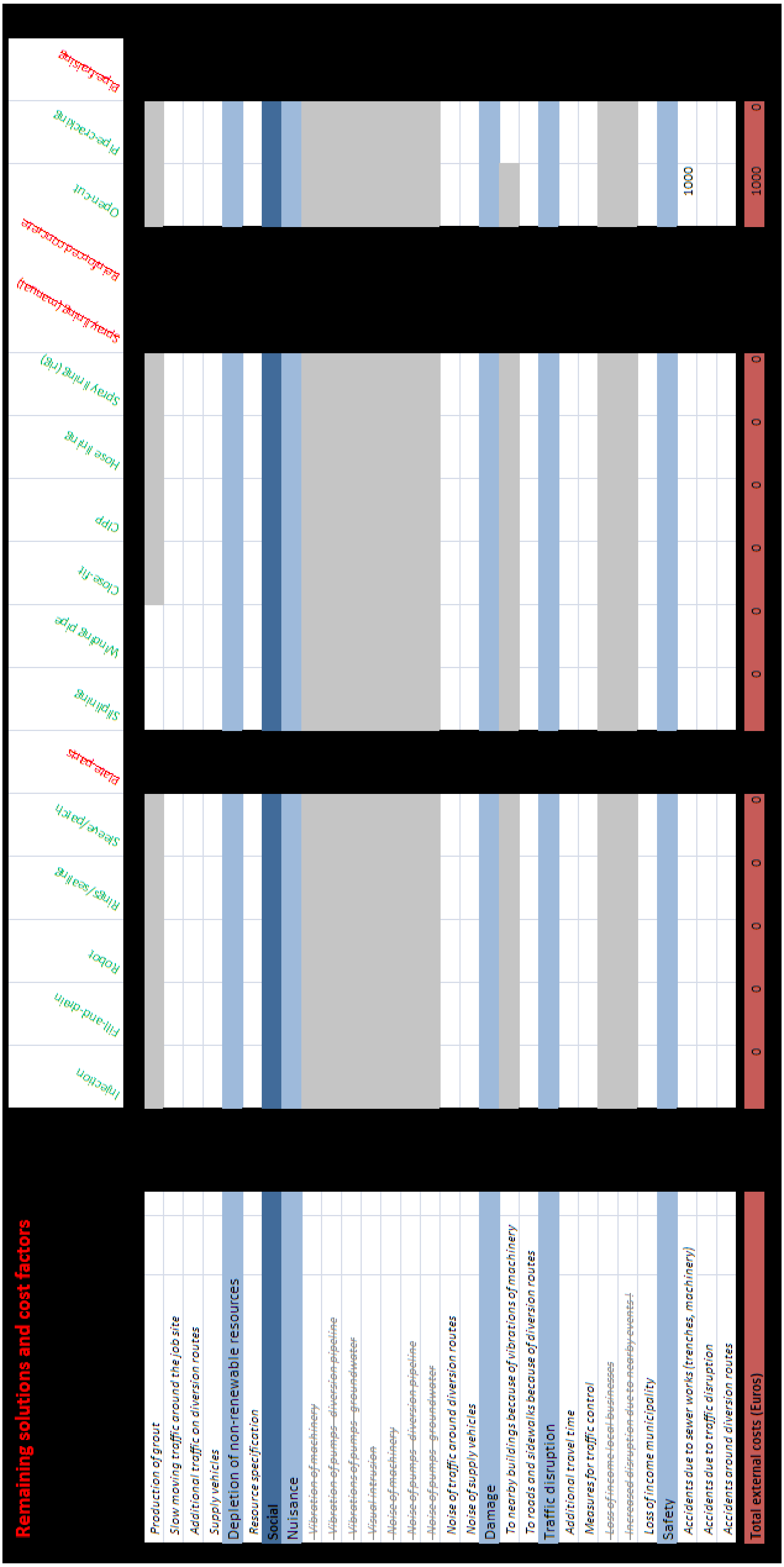
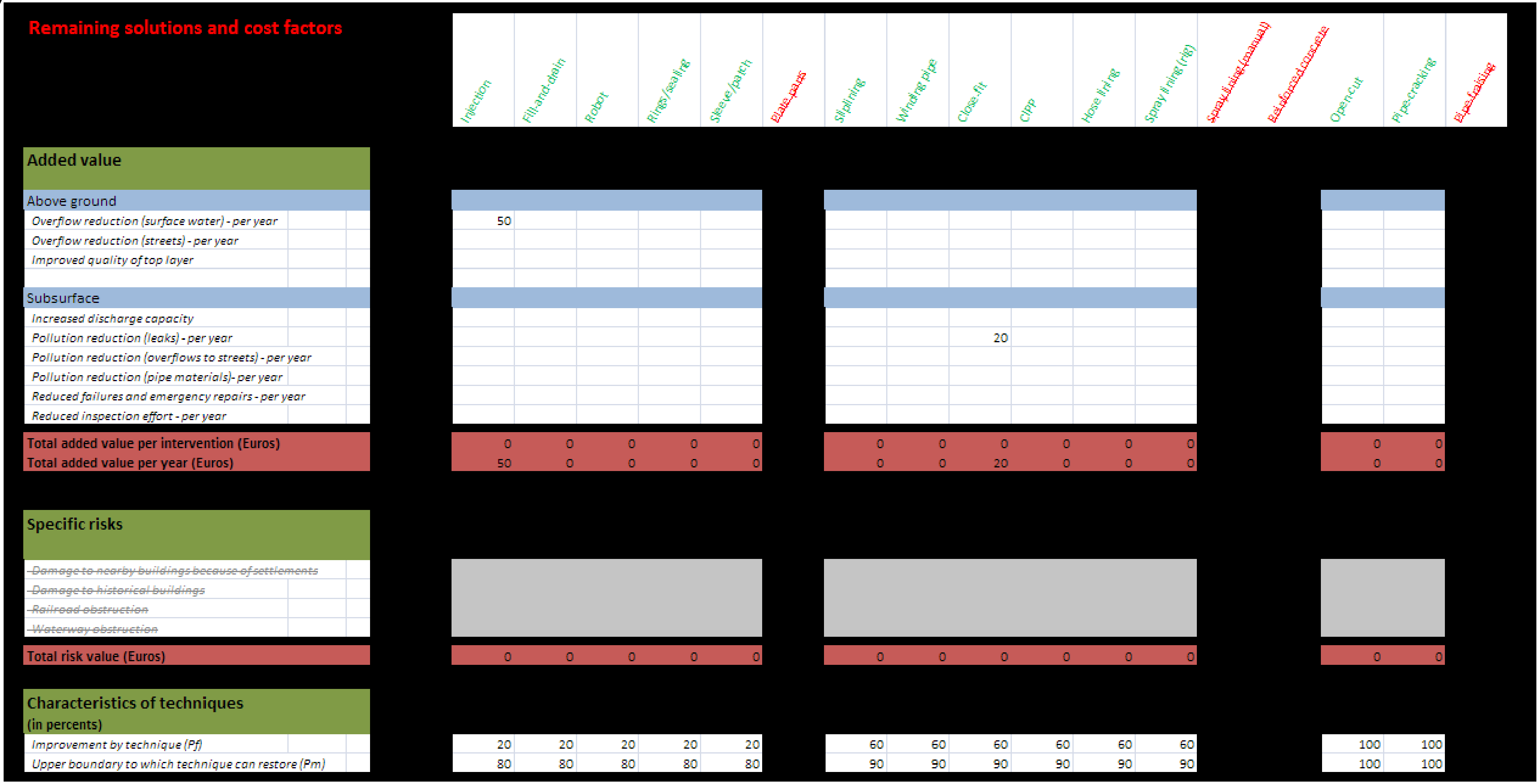
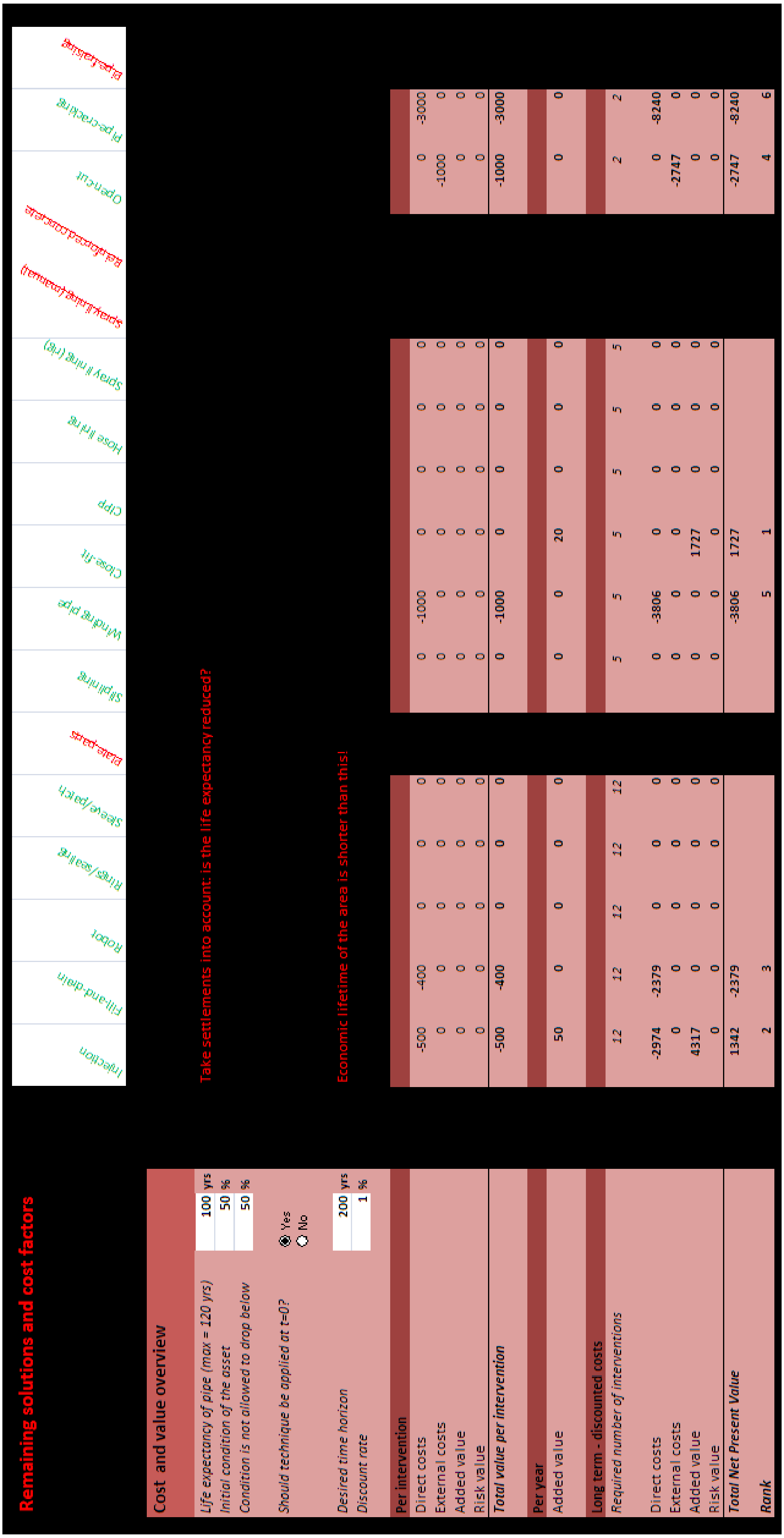


Figure 90:Screenshot solutions and cost factors sheet, part 3



Remaining solutions and cost factors	Injection	Fill-and-drain	Robot	Rings/sealing	Sleeve/patch	~~Blade pairs~~	Slip lining	Winding pipe	Close-fit	CIPP	Hose lining	Spray lining (rig)	~~Spray lining (manual)~~	~~Reinforced concrete~~	Open-cut	Pipe-cracking	~~Pipe-raising~~
Added value																	
Above ground																	
Overflow reduction (surface water) - per year	50																
Overflow reduction (streets) - per year																	
Improved quality of top layer																	
Subsurface																	
Increased discharge capacity																	
Pollution reduction (leaks) - per year									20								
Pollution reduction (overflows to streets) - per year																	
Pollution reduction (pipe materials)- per year																	
Reduced failures and emergency repairs - per year																	
Reduced inspection effort - per year																	
Total added value per intervention (Euros)	0	0	0	0	0		0	0	0	0	0	0			0	0	
Total added value per year (Euros)	50	0	0	0	0		0	0	20	0	0	0			0	0	
Specific risks																	
~~*Damage to nearby buildings because of settlements*~~																	
~~*Damage to historical buildings*~~																	
~~*Railroad obstruction*~~																	
~~*Waterway obstruction*~~																	
Total risk value (Euros)	0	0	0	0	0		0	0	0	0	0	0			0	0	
Characteristics of techniques (in percents)																	
Improvement by technique (Pf)	20	20	20	20	20		60	60	60	60	60	60			100	100	
Upper boundary to which technique can restore (Pm)	80	80	80	80	80		90	90	90	90	90	90			100	100	

Figure 91:Screenshot solutions and cost factors sheet, part 4



Remaining solutions and cost factors

Cost and value overview

Life expectancy of pipe (max = 120 yrs) 100 yrs
Initial condition of the asset 50 %
Condition is not allowed to drop below 50 %

Take settlements into account: is the life expectancy reduced?

Should technique be applied at t=0? (•) Yes ( ) No

Desired time horizon 200 yrs
Discount rate 1 %

Economic lifetime of the area is shorter than this!

	Injection	Fill-and-drain	Robot	Rings/sealing	Sleeve/patch	Blade pads	Slip lining	Winding pipe	Close-fit	CIPP	Hose lining	Spray lining (rig)	Spray lining (manual)	Reinforced concrete	Open-cut	Pipe-cracking	Pipe-raising
Per intervention																	
Direct costs	-500	-400	0	0	0		0	-1000	0	0	0	0			0	-3000	
External costs	0	0	0	0	0		0	0	0	0	0	0			-1000	0	
Added value	0	0	0	0	0		0	0	0	0	0	0			0	0	
Risk value	0	0	0	0	0		0	0	0	0	0	0			0	0	
Total value per intervention	-500	-400	0	0	0		0	-1000	0	0	0	0			-1000	-3000	
Per year																	
Added value	50	0	0	0	0		0	0	20	0	0	0			0	0	
Long term - discounted costs																	
Required number of interventions	12	12	12	12	12		5	5	5	5	5	5			2	2	
Direct costs	-2974	-2379	0	0	0		0	-3806	0	0	0	0			0	-8240	
External costs	0	0	0	0	0		0	0	0	0	0	0			-2747	0	
Added value	4317	0	0	0	0		0	0	1727	0	0	0			0	0	
Risk value	0	0	0	0	0		0	0	0	0	0	0			0	0	
Total Net Present Value	1342	-2379						-3806	1727						-2747	-8240	
Rank	2	3						5	1						4	6	

Figure 92:Screenshot solutions and cost factors sheet, part 5

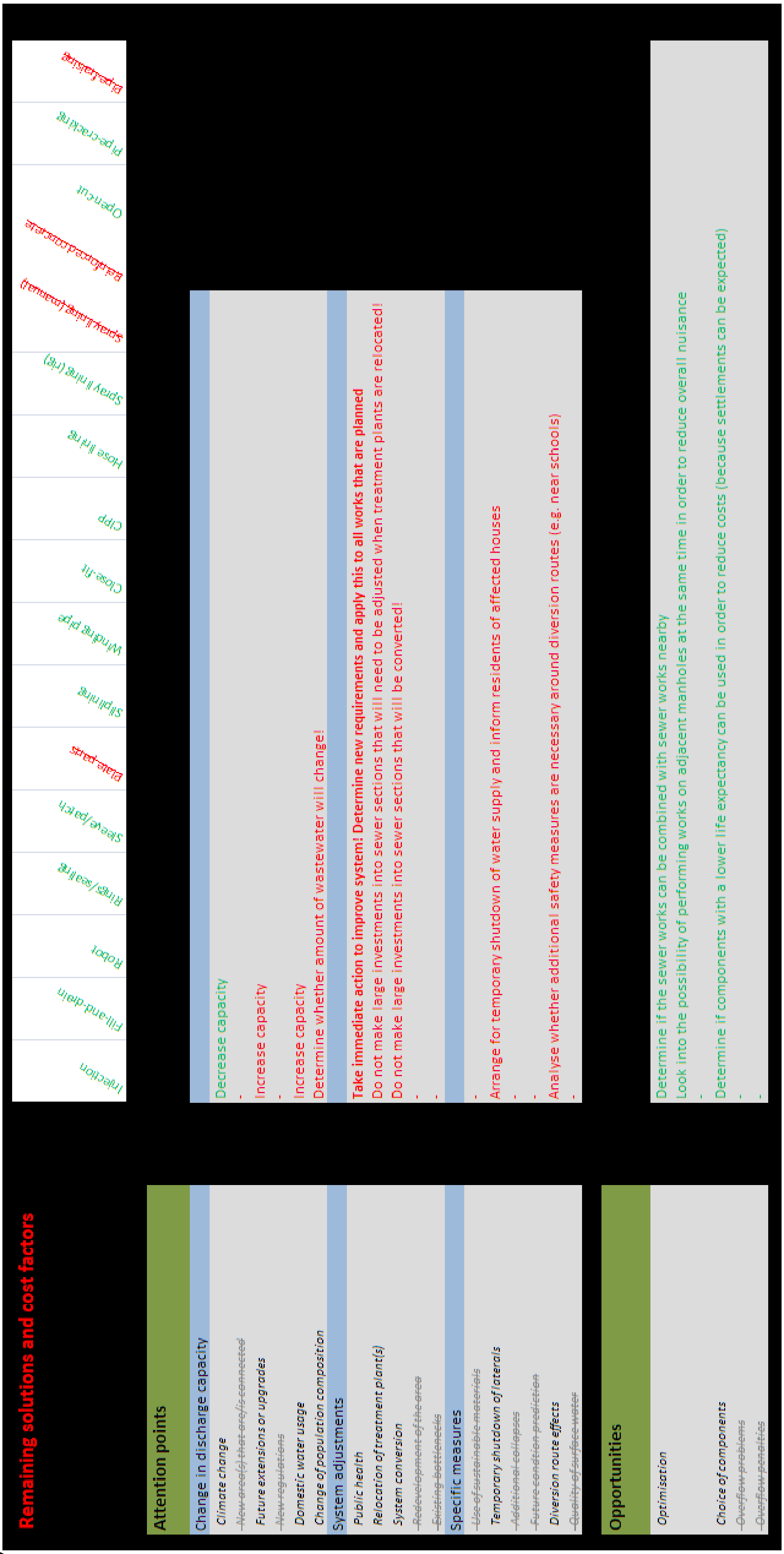


Figure 93:Screenshot solutions and cost factors sheet, part 6

The following values are used to perform LCC calculations for this specific situation. See chapter 8 for a detailed explanation of the condition prediction and LCC module.

- Life expectancy of pipe (max = 120 yrs)
- Initial condition of the asset
- Condition is not allowed to drop below
- Should technique be applied at t=0? (yes or no)
- Desired time horizon
- Discount rate

The lower part of the cost and value overview shows the combined costs and values that have been entered by the user. A distinction has been made between direct costs, external costs, risks and added value. This is done so it easy to compare one aspect for various techniques, for example external costs. First all costs and values per intervention are shown and added up for a total cost figure.

Next there is a section for values that occur every year and are thus not part of a single intervention. A good example of this is the reduction of overflows. Reduction of the amount of overflows means that there is less damage and nuisance, which can be awarded with a value per year.

The last part consists of an overview of costs and values for a specified time period, e.g. 200 years. The tool is able to calculate the number of interventions and the discounted costs over this period of time for all alternatives. This results in the Net Present Values of all possibilities, which shows which alternative has the lowest overall costs in the long-term. These values are ranked by the program, so it is immediately clear for the user which technique should be preferred.

Effect of technique on pipe diameter - shows if the remaining solutions affect the pipe diameter. This provides the user with a quick overview of whether techniques have no effect, a small reduction effect, a reduction effect or if they can increase the diameter.

Attention points - indicates to which points the user should pay attention. This is not only for the considered sewer section, but for the entire network. It provides a clear list with attention points that should not be forgotten. This is not specific for techniques but these are general attention points to support to sewer asset manager. Certain choices in the consideration sheet or combinations of input data can reveal an action point. When an attention point is relevant it is explained in red (or green if it is positive) on the right side. Attention points that are not relevant for this situation are not shown, this is done to prevent misunderstandings. The following topics have been listed so far:

Change in discharge capacity
- Climate change
- New area(s) that are/is connected
- Future extensions or upgrades
- New regulations
- Domestic water usage
- Change of population composition

System adjustments
- Public health
- Relocation of treatment plant(s)
- System conversion
- Redevelopment of the area
- Existing bottlenecks

Specific measures
- Use of sustainable materials
- Temporary shutdown of laterals
- Additional collapses
- Future condition prediction
- Diversion route effects
- Quality of surface water

Opportunities - lists if there are opportunities for the sewer asset manager that can create additional value or reduce costs, for example by optimisation of sewer works on a higher level (tactical or strategic). The opportunities are not assigned to specific techniques but are for the general decision making process. The following aspects are mentioned:

- Optimisation
- Choice of components
- Overflow problems
- Overflow penalties
- Road lifetime
- Economic lifetime of the area

LCC analysis

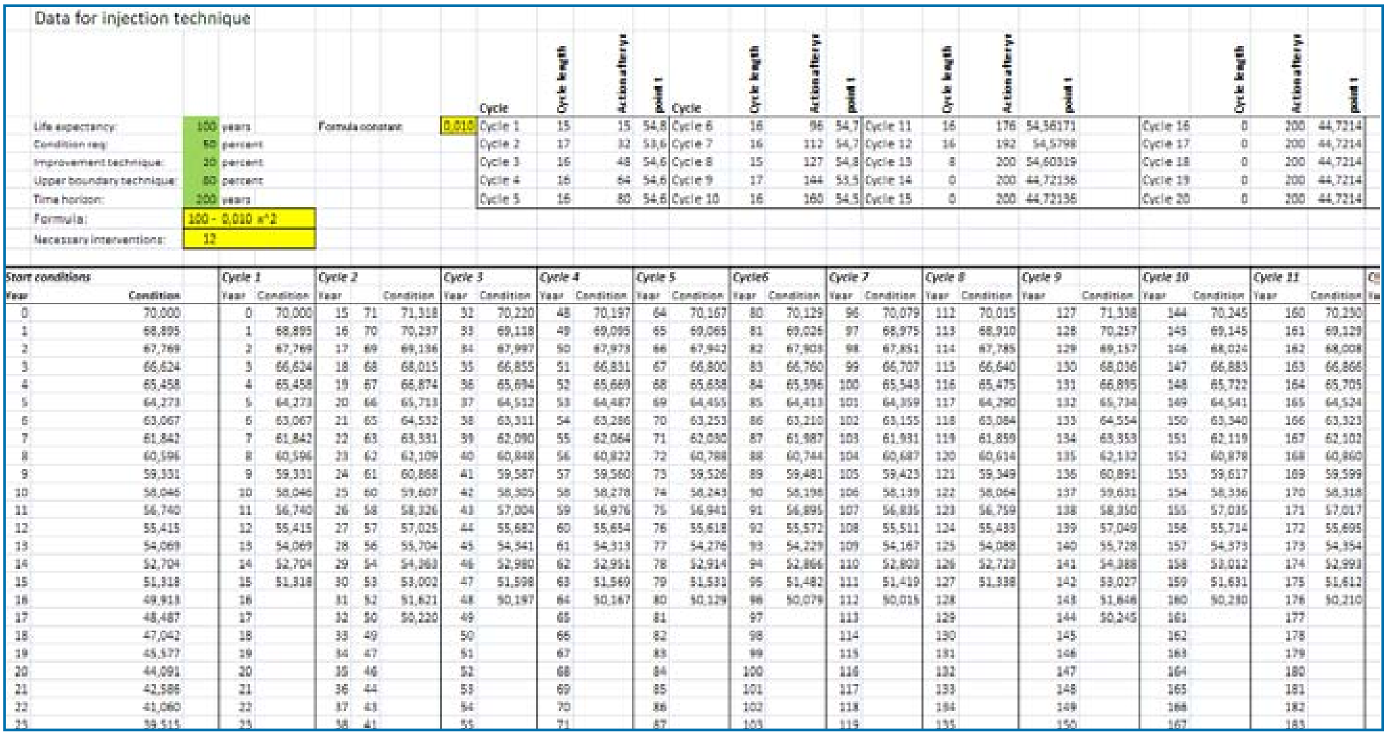
The *LCC analysis* sheet forms the connection between the solution page that shows the results of LCC calculations, and the hidden sheets that calculate condition predictions for all alternatives. The *LCC analysis* page basically gathers the most important data from sheets *C1* to *C17*. It offers an overview of the moments in time that repairs, renovations or replacements are executed. The condition prediction parameters that can be specified in the cost overview component are used to calculate when which techniques should be applied to fulfill these values. Every time a technique is applied to an asset, the condition is improved and a new “cycle” in the overall lifespan starts. The lengths of these cycles and the years in wich they end are shown in this sheet. The moments in time (years from t=0) and the specified discount rate determine the discount factors for the interventions. These discount factors can then be used to calculate the present values of the interventions. The value difference of cash flows at different points in time is thus taken into account (“a dollar today is worth more than a dollar tomorrow”). The shown multiplication factors are the result of adding up all factors and are used for calculation the NPV’s in the *Solutions and cost factors* sheet.

C1 to C17 (hidden)

The last worksheets of the decision support tool are numbered C1 to C17. Every technique that is included in this research has a seperate sheet for condition calculations. These sheets contain datasets that are used to determine at which points in time the specific technique has to be applied. This can be either because the asset has reached the end of its lifespan, or because a lower boundary has been set. For example. when the user enters a lower boundary of 70 percent, the datasheet will perform calculations and comparisons to make sure that the condition never drops below 70 percent. Just before this will happen, the technique will be applied and the condition is improved by a chosen percentage.

As can be seen, the dataset has many cycles with condition values. As said before in this report, the maximum number of cycles has been set at 20 for every technique. This was necessary to limit the amount of data and it was thought to be unlikely to need more cycles than 20.
The sheet thus calculates all necessary cycles for the given project and determines the length and starting point of every cycle. This information is then transfered to the LCC analysis sheet, which combines it with the LCC approach to determine discount factors. Eventually this leads to Net Present Values for all possible solutions.

These last 17 sheets are hidden because they do not contain any data entry fields and it is not necessary for the user to see them (or alter them).



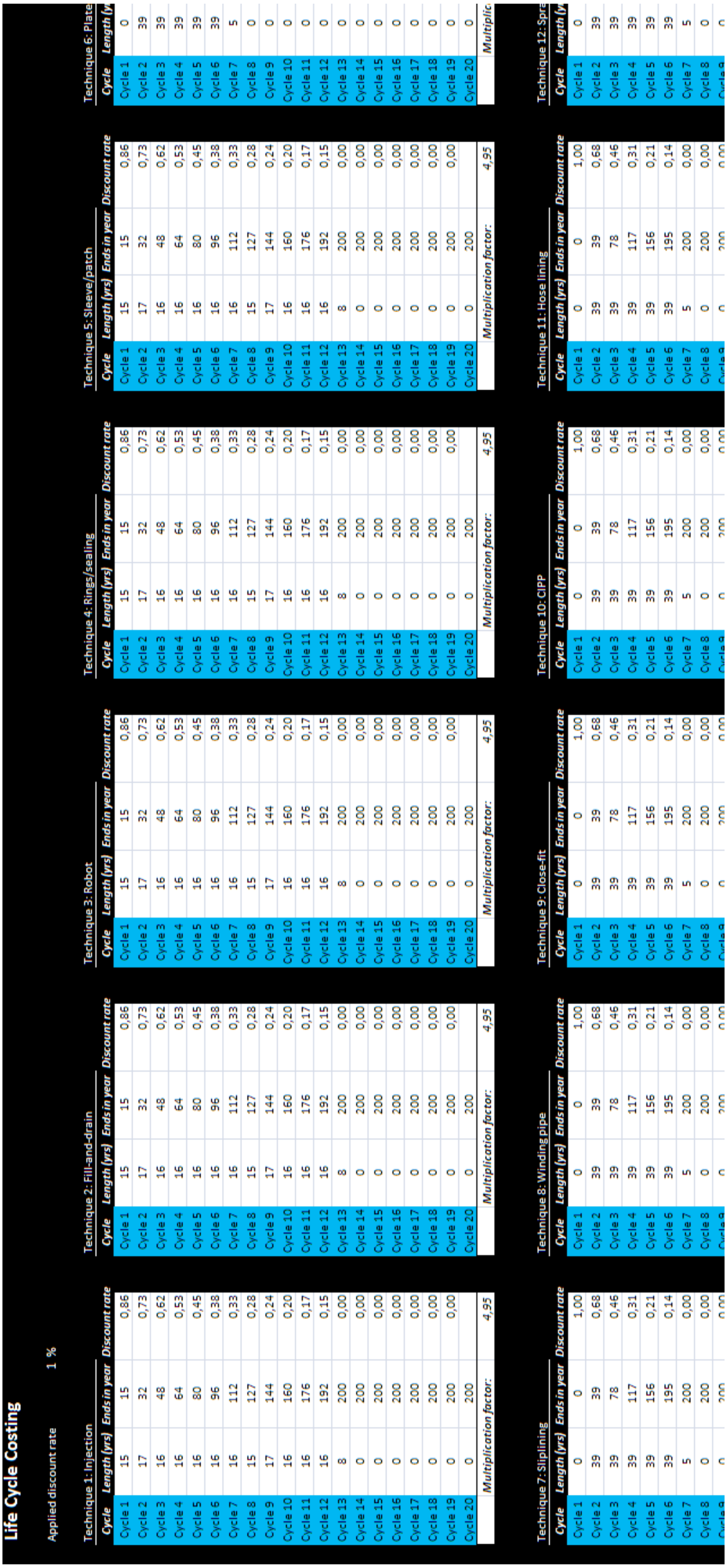
Data for injection technique

Life expectancy:	100	years	Formula constant:	0,010
Condition req:	50	percent		
Improvement technique:	20	percent		
Upper boundary technique:	80	percent		
Time horizon:	200	years		
Formula:	100 - 0,010 x^2			
Necessary interventions:	12			

Cycle	Cycle length	Actionafteryr	point 1	Cycle	Cycle length	Actionafteryr	point 1	Cycle	Cycle length	Actionafteryr	point 1	Cycle	Cycle length	Actionafteryr	point 1
Cycle 1	15	15	54,8	Cycle 6	16	96	54,7	Cycle 11	16	176	54,56171	Cycle 16	0	200	44,7214
Cycle 2	17	32	53,6	Cycle 7	16	112	54,7	Cycle 12	16	192	54,5798	Cycle 17	0	200	44,7214
Cycle 3	16	48	54,6	Cycle 8	15	127	54,8	Cycle 13	8	200	54,60319	Cycle 18	0	200	44,7214
Cycle 4	16	64	54,6	Cycle 9	17	144	53,5	Cycle 14	0	200	44,72136	Cycle 19	0	200	44,7214
Cycle 5	16	80	54,6	Cycle 10	16	160	54,5	Cycle 15	0	200	44,72136	Cycle 20	0	200	44,7214

Start conditions		Cycle 1		Cycle 2			Cycle 3		Cycle 4		Cycle 5		Cycle6		Cycle 7		Cycle 8		Cycle 9		Cycle 10		Cycle 11	
Year	Condition	Year	Condition	Year		Condition	Year	Condition	Year	Condition	Year	Condition	Year	Condition	Year	Condition	Year	Condition	Year	Condition	Year	Condition	Year	Condition
0	70,000	0	70,000	15	71	71,318	32	70,220	48	70,197	64	70,167	80	70,129	96	70,079	112	70,015	127	71,338	144	70,245	160	70,230
1	68,895	1	68,895	16	70	70,237	33	69,118	49	69,095	65	69,065	81	69,026	97	68,975	113	68,910	128	70,257	145	69,145	161	69,129
2	67,769	2	67,769	17	69	69,136	34	67,997	50	67,973	66	67,942	82	67,903	98	67,851	114	67,785	129	69,157	146	68,024	162	68,008
3	66,624	3	66,624	18	68	68,015	35	66,855	51	66,831	67	66,800	83	66,760	99	66,707	115	66,640	130	68,036	147	66,883	163	66,866
4	65,458	4	65,458	19	67	66,874	36	65,694	52	65,669	68	65,638	84	65,596	100	65,543	116	65,475	131	66,895	148	65,722	164	65,705
5	64,273	5	64,273	20	66	65,713	37	64,512	53	64,487	69	64,455	85	64,413	101	64,359	117	64,290	132	65,734	149	64,541	165	64,524
6	63,067	6	63,067	21	65	64,532	38	63,311	54	63,286	70	63,253	86	63,210	102	63,155	118	63,084	133	64,554	150	63,340	166	63,323
7	61,842	7	61,842	22	63	63,331	39	62,090	55	62,064	71	62,030	87	61,987	103	61,931	119	61,859	134	63,353	151	62,119	167	62,102
8	60,596	8	60,596	23	62	62,109	40	60,848	56	60,822	72	60,788	88	60,744	104	60,687	120	60,614	135	62,132	152	60,878	168	60,860
9	59,331	9	59,331	24	61	60,868	41	59,587	57	59,560	73	59,526	89	59,481	105	59,423	121	59,349	136	60,891	153	59,617	169	59,599
10	58,046	10	58,046	25	60	59,607	42	58,305	58	58,278	74	58,243	90	58,198	106	58,139	122	58,064	137	59,631	154	58,336	170	58,318
11	56,740	11	56,740	26	58	58,326	43	57,004	59	56,976	75	56,941	91	56,895	107	56,835	123	56,759	138	58,350	155	57,035	171	57,017
12	55,415	12	55,415	27	57	57,025	44	55,682	60	55,654	76	55,618	92	55,572	108	55,511	124	55,433	139	57,049	156	55,714	172	55,695
13	54,069	13	54,069	28	56	55,704	45	54,341	61	54,313	77	54,276	93	54,229	109	54,167	125	54,088	140	55,728	157	54,373	173	54,354
14	52,704	14	52,704	29	54	54,363	46	52,980	62	52,951	78	52,914	94	52,866	110	52,803	126	52,723	141	54,388	158	53,012	174	52,993
15	51,318	15	51,318	30	53	53,002	47	51,598	63	51,569	79	51,531	95	51,482	111	51,419	127	51,338	142	53,027	159	51,631	175	51,612
16	49,913	16		31	52	51,621	48	50,197	64	50,167	80	50,129	96	50,079	112	50,015	128		143	51,646	160	50,230	176	50,210
17	48,487	17		32	50	50,220	49		65		81		97		113		129		144	50,245	161		177	
18	47,042	18		33	49		50		66		82		98		114		130		145		162		178	
19	45,577	19		34	47		51		67		83		99		115		131		146		163		179	
20	44,091	20		35	46		52		68		84		100		116		132		147		164		180	
21	42,586	21		36	44		53		69		85		101		117		133		148		165		181	
22	41,060	22		37	43		54		70		86		102		118		134		149		166		182	
23	39,515	23		38	41		55		71		87		103		119		135		150		167		183	

Figure 94:Screenshot of a C-type sheet with condition calculations



Life Cycle Costing

Applied discount rate 1 %

Technique 1: Injection

Cycle	Length (yrs)	Ends in year	Discount rate
Cycle 1	15	15	0,86
Cycle 2	17	32	0,73
Cycle 3	16	48	0,62
Cycle 4	16	64	0,53
Cycle 5	16	80	0,45
Cycle 6	16	96	0,38
Cycle 7	16	112	0,33
Cycle 8	15	127	0,28
Cycle 9	17	144	0,24
Cycle 10	16	160	0,20
Cycle 11	16	176	0,17
Cycle 12	16	192	0,15
Cycle 13	8	200	0,00
Cycle 14	0	200	0,00
Cycle 15	0	200	0,00
Cycle 16	0	200	0,00
Cycle 17	0	200	0,00
Cycle 18	0	200	0,00
Cycle 19	0	200	0,00
Cycle 20	0	200	
	Multiplication factor:		4,95

Technique 2: Fill-and-drain

Cycle	Length (yrs)	Ends in year	Discount rate
Cycle 1	15	15	0,86
Cycle 2	17	32	0,73
Cycle 3	16	48	0,62
Cycle 4	16	64	0,53
Cycle 5	16	80	0,45
Cycle 6	16	96	0,38
Cycle 7	16	112	0,33
Cycle 8	15	127	0,28
Cycle 9	17	144	0,24
Cycle 10	16	160	0,20
Cycle 11	16	176	0,17
Cycle 12	16	192	0,15
Cycle 13	8	200	0,00
Cycle 14	0	200	0,00
Cycle 15	0	200	0,00
Cycle 16	0	200	0,00
Cycle 17	0	200	0,00
Cycle 18	0	200	0,00
Cycle 19	0	200	0,00
Cycle 20	0	200	
	Multiplication factor:		4,95

Technique 3: Robot

Cycle	Length (yrs)	Ends in year	Discount rate
Cycle 1	15	15	0,86
Cycle 2	17	32	0,73
Cycle 3	16	48	0,62
Cycle 4	16	64	0,53
Cycle 5	16	80	0,45
Cycle 6	16	96	0,38
Cycle 7	16	112	0,33
Cycle 8	15	127	0,28
Cycle 9	17	144	0,24
Cycle 10	16	160	0,20
Cycle 11	16	176	0,17
Cycle 12	16	192	0,15
Cycle 13	8	200	0,00
Cycle 14	0	200	0,00
Cycle 15	0	200	0,00
Cycle 16	0	200	0,00
Cycle 17	0	200	0,00
Cycle 18	0	200	0,00
Cycle 19	0	200	0,00
Cycle 20	0	200	
	Multiplication factor:		4,95

Technique 4: Rings/sealing

Cycle	Length (yrs)	Ends in year	Discount rate
Cycle 1	15	15	0,86
Cycle 2	17	32	0,73
Cycle 3	16	48	0,62
Cycle 4	16	64	0,53
Cycle 5	16	80	0,45
Cycle 6	16	96	0,38
Cycle 7	16	112	0,33
Cycle 8	15	127	0,28
Cycle 9	17	144	0,24
Cycle 10	16	160	0,20
Cycle 11	16	176	0,17
Cycle 12	16	192	0,15
Cycle 13	8	200	0,00
Cycle 14	0	200	0,00
Cycle 15	0	200	0,00
Cycle 16	0	200	0,00
Cycle 17	0	200	0,00
Cycle 18	0	200	0,00
Cycle 19	0	200	0,00
Cycle 20	0	200	
	Multiplication factor:		4,95

Technique 5: Sleeve/patch

Cycle	Length (yrs)	Ends in year	Discount rate
Cycle 1	15	15	0,86
Cycle 2	17	32	0,73
Cycle 3	16	48	0,62
Cycle 4	16	64	0,53
Cycle 5	16	80	0,45
Cycle 6	16	96	0,38
Cycle 7	16	112	0,33
Cycle 8	15	127	0,28
Cycle 9	17	144	0,24
Cycle 10	16	160	0,20
Cycle 11	16	176	0,17
Cycle 12	16	192	0,15
Cycle 13	8	200	0,00
Cycle 14	0	200	0,00
Cycle 15	0	200	0,00
Cycle 16	0	200	0,00
Cycle 17	0	200	0,00
Cycle 18	0	200	0,00
Cycle 19	0	200	0,00
Cycle 20	0	200	
	Multiplication factor:		4,95

Technique 6: Plate

Cycle	Length (y
Cycle 1	0
Cycle 2	39
Cycle 3	39
Cycle 4	39
Cycle 5	39
Cycle 6	39
Cycle 7	5
Cycle 8	0
Cycle 9	0
Cycle 10	0
Cycle 11	0
Cycle 12	0
Cycle 13	0
Cycle 14	0
Cycle 15	0
Cycle 16	0
Cycle 17	0
Cycle 18	0
Cycle 19	0
Cycle 20	0
	Multiplic

Technique 7: Sliplining

Cycle	Length (yrs)	Ends in year	Discount rate
Cycle 1	0	0	1,00
Cycle 2	39	39	0,68
Cycle 3	39	78	0,46
Cycle 4	39	117	0,31
Cycle 5	39	156	0,21
Cycle 6	39	195	0,14
Cycle 7	5	200	0,00
Cycle 8	0	200	0,00
Cycle 9	0	200	0,00

Technique 8: Winding pipe

Cycle	Length (yrs)	Ends in year	Discount rate
Cycle 1	0	0	1,00
Cycle 2	39	39	0,68
Cycle 3	39	78	0,46
Cycle 4	39	117	0,31
Cycle 5	39	156	0,21
Cycle 6	39	195	0,14
Cycle 7	5	200	0,00
Cycle 8	0	200	0,00
Cycle 9	0	200	0,00

Technique 9: Close-fit

Cycle	Length (yrs)	Ends in year	Discount rate
Cycle 1	0	0	1,00
Cycle 2	39	39	0,68
Cycle 3	39	78	0,46
Cycle 4	39	117	0,31
Cycle 5	39	156	0,21
Cycle 6	39	195	0,14
Cycle 7	5	200	0,00
Cycle 8	0	200	0,00
Cycle 9	0	200	0,00

Technique 10: CIPP

Cycle	Length (yrs)	Ends in year	Discount rate
Cycle 1	0	0	1,00
Cycle 2	39	39	0,68
Cycle 3	39	78	0,46
Cycle 4	39	117	0,31
Cycle 5	39	156	0,21
Cycle 6	39	195	0,14
Cycle 7	5	200	0,00
Cycle 8	0	200	0,00
Cycle 9	0	200	0,00

Technique 11: Hose lining

Cycle	Length (yrs)	Ends in year	Discount rate
Cycle 1	0	0	1,00
Cycle 2	39	39	0,68
Cycle 3	39	78	0,46
Cycle 4	39	117	0,31
Cycle 5	39	156	0,21
Cycle 6	39	195	0,14
Cycle 7	5	200	0,00
Cycle 8	0	200	0,00
Cycle 9	0	200	0,00

Technique 12: Spra

Cycle	Length (y
Cycle 1	0
Cycle 2	39
Cycle 3	39
Cycle 4	39
Cycle 5	39
Cycle 6	39
Cycle 7	5
Cycle 8	0
Cycle 9	0

Figure 95:Screenshot of the LCC analysis worksheet

Appendix B: Company Profiles

Company Profile: Nelis Infra bv

Nelis Infra is a specialised company within the Royal BAM Group as part of the Infrastructure division (as can be seen in the diagram below).

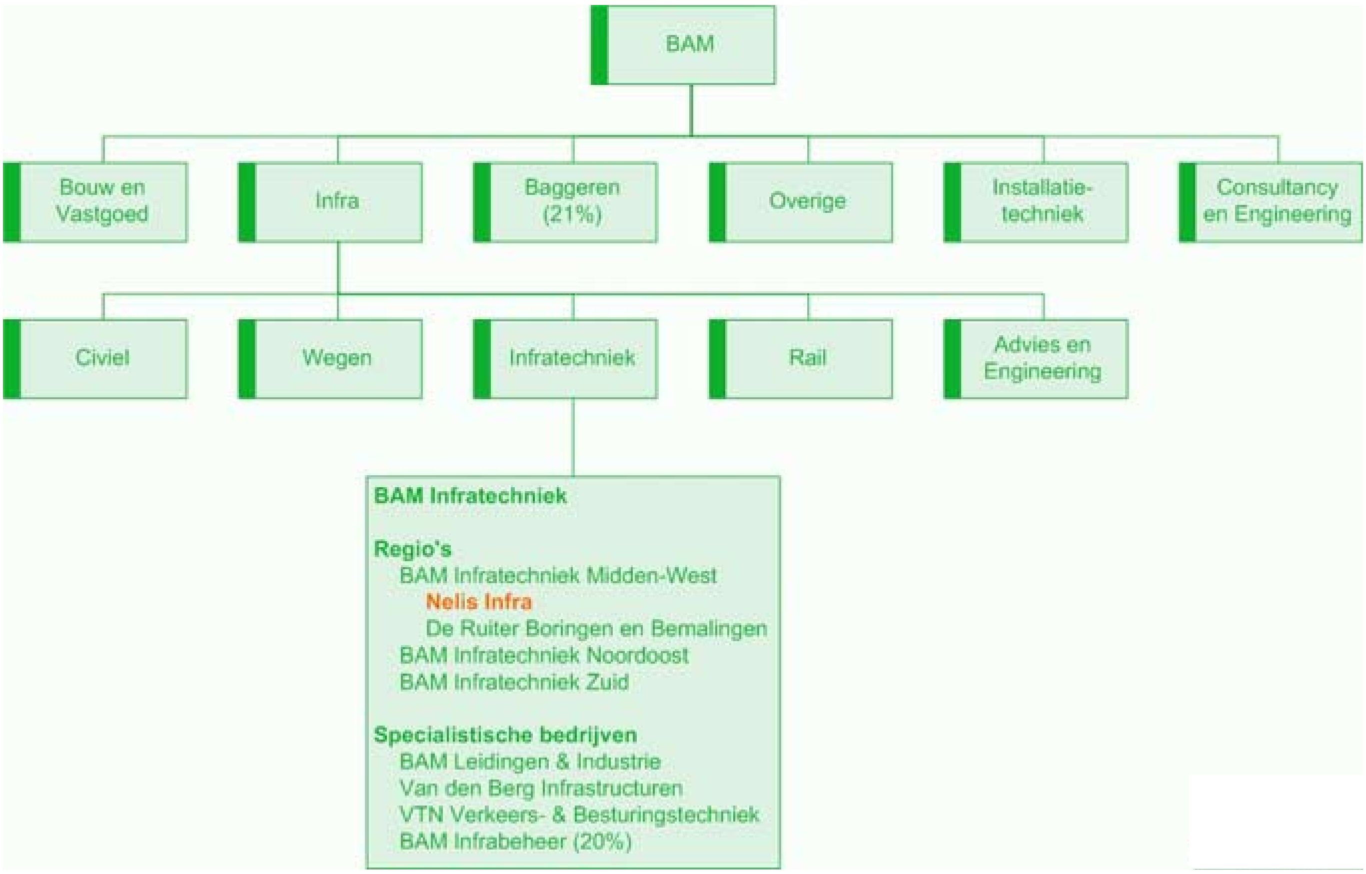
The company is specialised in trenchless pipe renovation and has many years of experience in this area. Design, construction and maintenance phases can all be handled by Nelis Infra.

Project are undertaken on behalf of the Ministry of Waterways and Public Works, municipalities, utility companies, industrial companies and individual citizens. Projects can be executed independently or as a collaboration together with sister companies of the Royal BAM Group.

Early 2009 the company started a joint venture with the Danish company Aarsleff Pipe Technologies. The joint venture has specialised itself in the renovation of pipelines by using the cured-in-place pipe lining (CIPP lining) method.

At the moment Nelis Infra has around 100 employees, all located in the Netherlands.

More information can be found on *www.nelisinfra.nl*.



Company Profile: Waternet

Waternet is the first company in the Netherlands that combines all water services under one roof. Waternet is responsible for drinking water, waste water, surface water and safety behind the dykes. Waternet works in the Amsterdam area, but also in parts of the provinces of Utrecht and Noord-Holland. In this area approximately 1,2 million people live and work. The total length of sewer pipes in this area is about 4000 km.

Waternet helps with sustainable improvement of drinking and waste water facilities all around the globe, for example in Suriname, Egypt, Indonesia, Latvia, Aruba and Palestina. In these international projects Waternet collaborates with organisations such as the Ministry of Foreign Affairs and the province of Noord-Holland.

Waternet is a collaboration between the Municipality of Amsterdam and the Water Board of Amstel, Gooi and Vecht. Plans regarding water services that are created by either the municipality or the water board are prepared and executed by Waternet.

More information can be found on *www.waternet.nl*.