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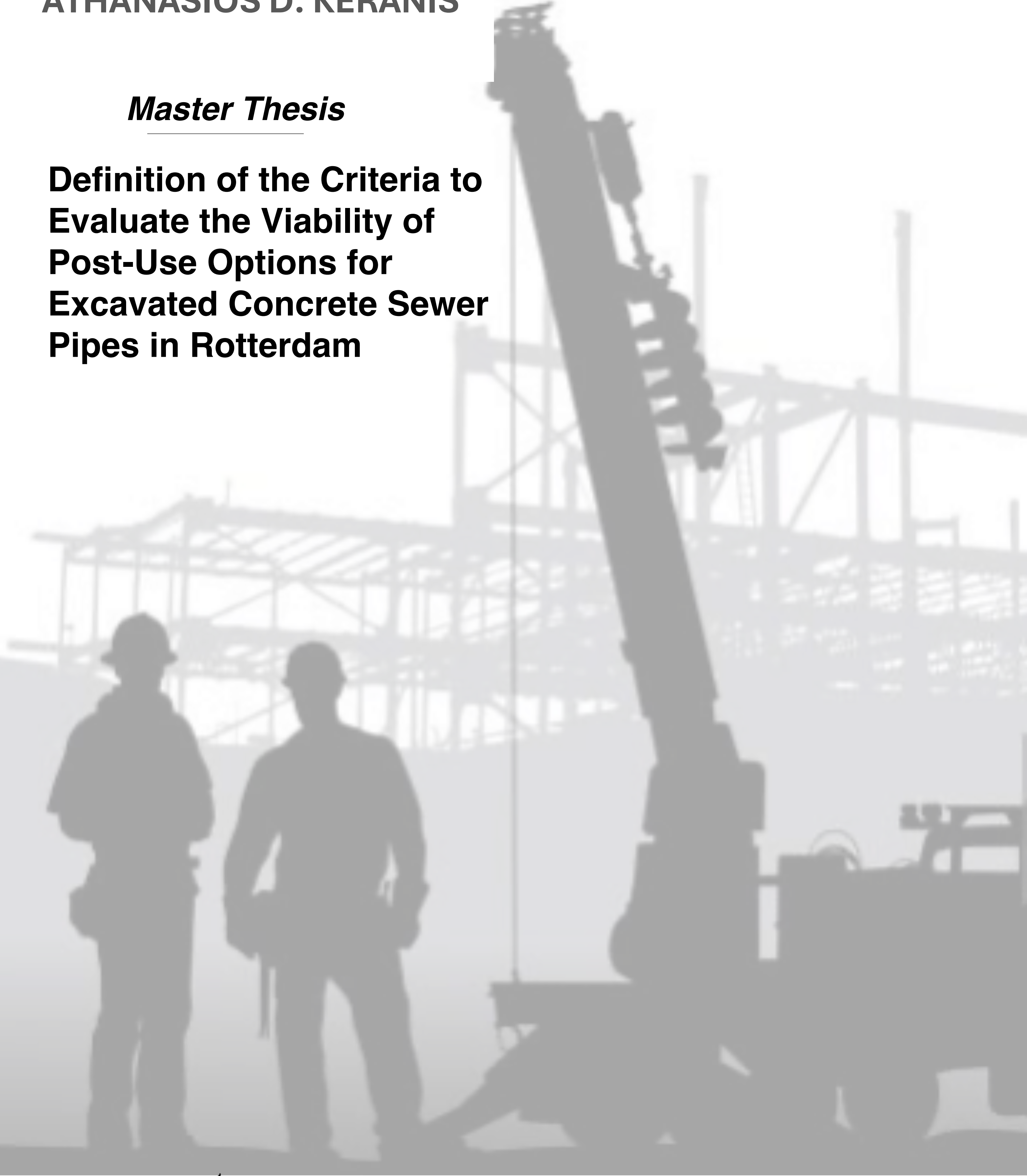
Master Thesis

Definition of the Criteria to Evaluate the Viability of Post-Use Options for Excavated Concrete Sewer Pipes in Rotterdam



TU Delft

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Master Thesis

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Summary

This study aimed to define and evaluate the viability of post-use options for excavated concrete sewer pipes. The research was conducted with a combination of literature review and expert interviews with professionals from the Municipality of Rotterdam. The process involved several key steps. The goal was to create a conceptual framework that can evaluate the viability of post-use options for excavated concrete sewer pipes.

This study was influenced by the significant environmental challenges posed by rising global temperatures and greenhouse gas emissions. International agreements, such as the Paris Agreement, aim to limit global warming and reduce emissions. The European Union's Green Deal and various national strategies, including the Dutch Climate Act and the Rotterdam Climate Agreement, try to mitigate these issues. The construction industry, responsible for a substantial portion of waste and emissions, is a primary focus of these strategies, emphasizing the need for sustainable and circular economy practices. The specific problem of managing the waste generated by the regular replacement of concrete sewer pipes in Rotterdam, where approximately 40 kilometers of concrete sewer pipes are replaced annually. The study aims to align with municipal and national circular economy initiatives, proposing a qualitative analysis through literature review and expert interviews.

Initially, the study identified two existing circular economy theories from which four circular strategies were adopted. The potential post-use options for the excavated sewer pipes, were developed based on those strategies such as reuse, repurpose, refurbish, and recycle. The potential post-use options were identified through literature review. Following this, viability criteria were developed from academic literature and expert interviews. These criteria were categorized into general criteria, which must be met by all post-use options, and specific criteria specified to each circular strategy.

A conceptual framework was established using the identified viability criteria, designed to evaluate the practical feasibility of post-use options for concrete sewer pipes. This framework was then applied to a test case involving excavated concrete sewer pipes in Rotterdam, serving as a prototype application to test its practical applicability. Seven potential post-use options were evaluated using the framework. From those seven, only two options were considered viable for the test case of Rotterdam. These were, repurposing the pipes for breakwater construction and recycling them using a conservative breaking installation. Other options were rejected due to factors such as insufficient remaining lifetime, lack of structural integrity, and inefficiency.

The study concluded by answering the main research question, demonstrating the practical application of leading criteria to evaluate post-use options. It also provided insights into the limitations of the study and suggested areas for future research, particularly in improving data accuracy and expanding the applicability of the criteria. However, the study faced some limitations. Some academic criteria were too generalized and not directly applicable to the specific context of concrete sewer pipes. The study heavily relied on expert opinions from the Municipality of Rotterdam, which may introduce bias or limit the perspective to that specific locality. Lastly, changes in environmental regulations and the constant development of technology could impact the viability of the proposed post-use options over time.

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Chapter 1: Introduction

1.1 Introduction

The mean terrestrial surface temperature has been observed to be increasing over the past half-century (GESTEMP Team, 2023). In fact, the combined air and water temperature is nowadays approximately 1 °C higher in comparison to the 1951-1980 climatological mean (Figure 1). This phenomenon poses a formidable natural, societal, economic, and territorial threat (European Commission, n.d.) which the world has collectively agreed to battle on a global, regional, and local scale, as implied by the noticeable trend break in temperature anomaly fluctuations during 2015-2023 period.

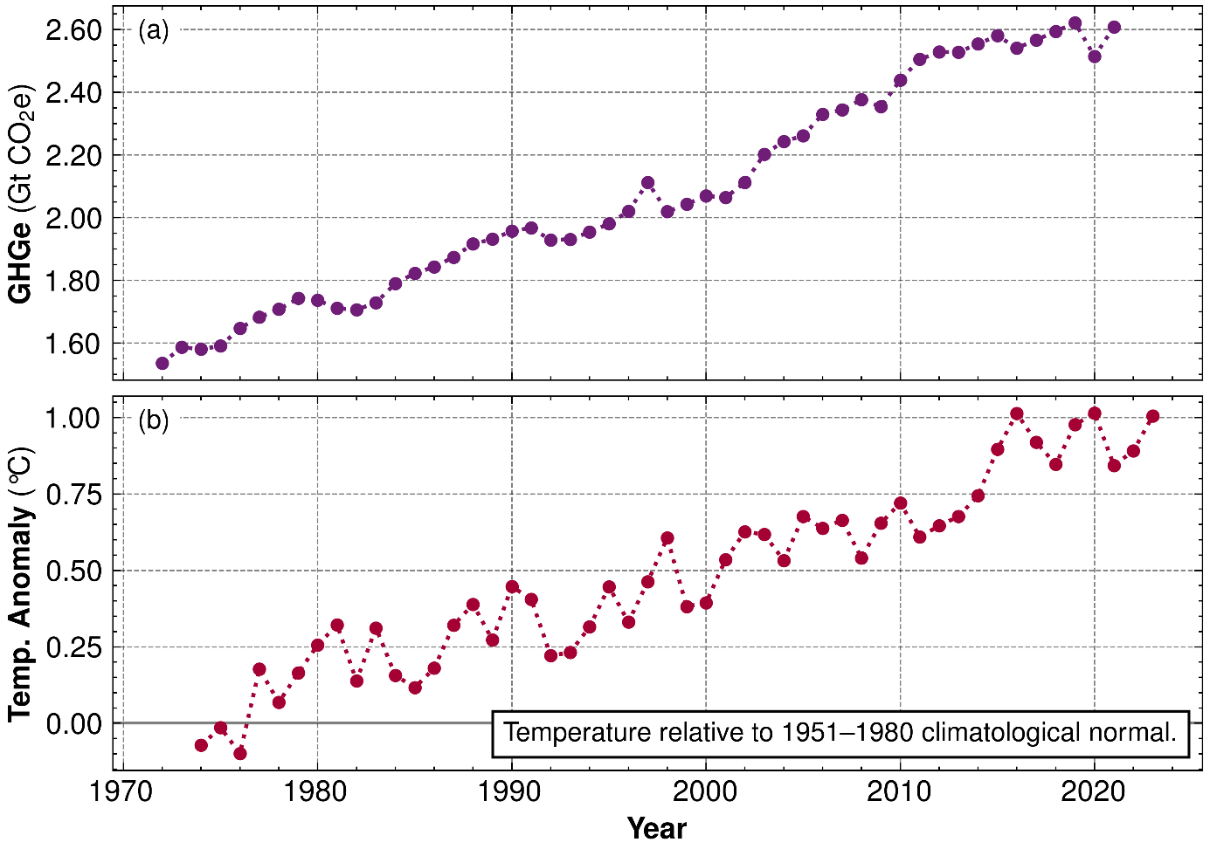

Figure 1: *Annual global greenhouse gas emissions (GHGe) from all sources, including agriculture and land use change (a), and combined land-surface air and sea-surface water temperature anomaly (b). Adapted from Ritchie, Roser, & Rosado, 2020.*

Most of the current climate change mitigation policies and strategies have been drafted in the context the Paris Agreement (2016), a legally binding treaty originally signed by 196 nations who pledged to limit global warming at least 2 – ideally 1.5 °C above pre-industrial levels by 2100 (United Nations Framework Convention on Climate Change, 2018). As climate change is predominantly attributed to similarly rising GHGe (Lindsey & Dahlman, 2023), this goal is equivalent to them peaking before 2025 and declining by at least 43% by 2030 (United Nations Framework Convention on Climate Change, 2023).

Overdelivering on this promise, the European Union (EU) countries have agreed to the European Green Deal (2020), a set of legally binding regulations designed to reduce the union's GHGe by at least 55% compared to 1990 levels within the same time frame, with the ambition to achieve carbon neutrality by 2050 (European Commission, 2023). Since the construction industry is responsible for approximately 33-35% of all waste generation in the EU (Ragonnaud, 2022; Council of the EU, 2023), a subset of said proposals comprise the Strategy for a Sustainable Built Environment (2022) which aims to facilitate the integration of circular economy practices into the construction industry (Ragonnaud, 2022). In particular, a recently adopted negotiating position of the European Council outlines the introduction of digitalized, resilient, repairable, and recyclable construction products. This is in accordance with both the European Green Deal and the related Circular Economy Action Plan (2020) (Council of the EU, 2023).

On a national level, the Dutch government has integrated the propositions of the above-mentioned regulations into the Dutch Climate Act (2019) which encompasses the Dutch Climate Agreement (2019) and – most importantly – the 2021-2023 Dutch Climate Plan (2020), a ten-year strategy for various sectors, such as construction which is responsible for 66% of all waste generation in the Netherlands ("OECD Environmental Performance Reviews: The Netherlands 2015," 2015). In this context the use of environmentally impactful construction materials is discouraged through the integration of environmental performance and cost indicators into the state permit and tendering processes in the form of minimum or maximum limit values, depending on the situation (Ministry of Infrastructure and Water Management, 2016). Furthermore, the Dutch Circular Economy Program (2016) also advocates circular design and construction (Ministry of Infrastructure and Water Management, 2016). This was followed up by a relevant transition agenda under the Circular Economy Program and the Raw Materials Agreement (2017) which prescribes the development of novel building techniques such that even individual load-bearing elements would be detachable, interchangeable, and reusable after the end of their technical lifespan (Ministerie van Infrastructuur en Waterstaat, 2018). At this point it should be noted that these proposals were recently re-adopted by the 2023-2030 Circular Economy Implementation Program (Ministry of Infrastructure and Water Management, 2023).

Conforming to the above-mentioned policies and strategies, the Municipality of Rotterdam, which is solely responsible for approximately 20% of the national GHGe a big part of them is caused by the construction industry (Glatek, et al., 2019), has formulated a local climate strategy in conjunction with the relevant global, union, and state goals. This is expressed in the form of the Rotterdam Climate Agreement (2019), a joint venture amongst local companies, institutions, and governmental bodies which aims to guide the city towards a downward GHGe trend by 2023, a minimum decrease of 49.6% compared to 1990 levels by 2030, and climate neutrality by 2050 (Municipality of Rotterdam, 2023). At this point it should be noted that both the second and third said goals are stricter than their national equivalents. Moreover, the Municipality has prepared its own circular economy program based on a relevant study conducted by an external research consortium on its behalf (Municipality of Rotterdam, 2019). This study conducted a material flow analysis in four sectors, namely agriculture, construction, consumer goods, and healthcare, identified their most environmentally impactful shortcomings, and proposed pertinent intervention measures (Glatek, et al., 2019). In this context, the 2019-2023 Rotterdam Circularity Program (2019) aims to decrease its primary raw material use by at least 50% by 2030, with the ambition to achieve complete circularity by 2050 by sensitizing the public and integrating circularity into its economy. At this point it should be noted that such a transition in the local construction industry is of critical importance since it is one of the least efficient in terms of waste generation in the municipality (Municipality of Rotterdam, 2019). Hence, it is an integral part of the Rotterdam Circularity Program. In this context the extension of the technical lifespan of existing assets, the prioritization of their eventual dismantling instead of demolition, and the effective reuse of construction products are encouraged.

1.2 Problem & Research Objectives

The Municipality of Rotterdam is replacing on a regular basis the concrete pipes of its sewer system. Every year in Rotterdam around 40 km of concrete sewer pipes are replaced which creates a steady and significant waste per year (Bleijenberg, 2021). This creates an increased need for managing the concrete waste from the excavated concrete sewer pipes. Furthermore, according to a senior asset manager that was interviewed, the pipes that replace the old ones are all new, which means that currently there is a form of linear economy on the renewal of the sewer system. In the Netherlands and the city of Rotterdam aim to increase programs and actions that promote circularity in the construction industry (Glatek, et al., 2019). That means that some viable post-use options for excavated concrete sewer pipes, to be in accordance with the new regulations and strategies that are established at a municipal and national level.

As it was described in the introduction of this research proposal the Municipality of Rotterdam takes several circular initiatives in order to reduce its construction waste. As a result of that the Municipality aims to find post-use options of their excavated concrete sewer pipes. Based on that, the primary objective of this master thesis will be the determination of potential post-use options of excavated concrete sewer pipes reaching end-of-life. After that a qualitative analysis of data that were obtained through literature review and expert interviews in order to form criteria to assess the viability of the post-use options. Once they have been determined the criteria will be used for the case of the city of Rotterdam. It must be noted that in the context of this master thesis, the concrete sewer pipes that this research will evaluate, are used concrete sewer pipes which have been already excavated from the ground.

Firstly, the next lifecycle uses of concrete sewer pipes must be analyzed. The alternatives will be based on the 10 R circular strategies that guide how circular design and manufacturing can keep resources in use and waste out of the environment in combination with the circular value hill model. Those concepts are explained in detail on chapter 2, together with the selection of suitable next lifecycle steps.

The necessary information for the analysis of this research is going to be obtained by literature review and analysis, and by conducting interviews to some experts on circular economy and asset managers in the Municipality of Rotterdam. The validation of the framework will be achieved with the help of managers in the construction sector from the Municipality of Rotterdam.

1.3 Research Questions

The significant carbon emissions which are caused by the construction industry in Rotterdam and the upgoing prices of the raw materials (Mike, 2023) are the key variables that magnify the need to increase the use of circular materials. The Municipality of Rotterdam has identified this problem, and it is a pioneer in circular initiatives especially by the adoption of the Rotterdam circularity Program. Every year in the city of Rotterdam around 40km of concrete sewer pipes are being replaced and around 1.6 billion Euros were spent in 2019 for sewerage projects in the Netherlands (Bleijenberg, 2021).

Based on the research that has been conducted, there has not been an existing framework for the definition of the post-use options of an excavated concrete sewer pipe. Therefore, it is important to identify the post-use option for a concrete sewer pipe and define viability criteria to identify if those options can be realized. As a result of that the main research question, that will be analyzed in this report, will be the following:

How to use criteria to evaluate the viability of post-use options for excavated concrete sewer pipes?

During the research to tackle the main problem of this master thesis, four sub-questions would have to be answered. Those questions are the following:

1. Which post-use options can be applied on an excavated concrete sewer pipe according to existing circular economy strategies according to academic literature?
2. What are the criteria to evaluate the viability of post-use options of concrete sewer pipes?
3. How can the criteria which evaluate the viability of post-use options for excavated concrete sewer pipes be applied in practice?
4. Which potential post-use options are considered viable for the test case of excavated concrete sewer pipes in Rotterdam?

By addressing these sub-questions, critical information will be gained which will play a major role in the determination of the validation criteria for post use options for the concrete sewer pipes. The objective is to identify and develop post-use options for the excavated concrete sewer pipes and a conceptual framework based on the viability criteria, to evaluate the options.

1.4 Scientific Knowledge Gap

Circular economy strategies and practices are rapidly evolving in the recent year as they are strongly supported by the European Union and by the Netherlands (Ghisellini et al., 2016). However, this is a new economic approach and plenty of its aspects have not been yet properly addressed. One of them is to determine the viability criteria for post-use options of excavated concrete sewer pipes due to the lack of comprehensive and standardized assessment frameworks.

Currently, decision makers are unable to take evaluated decisions because there is no robust methodology that integrates environmental, economic, social, and technical factors to evaluate the various post-use options for concrete materials reaching end-of-life (Alamerew et al., 2019a). Decision makers are mainly interested in understanding the viability and feasibility of the potential post-use options (Alamerew et al., 2020b). An evaluation framework of post-use options for concrete sewer pipes should consider their viability. This would increase the adoption of circular strategies which is currently quite limited due to the lack of criteria which could evaluate their viability.

Another critical point that must be mentioned, is the limited understanding of the material quality and properties of excavated concrete from sewer pipes and how these factors influence its suitability for post-use based on the current legislations. A study conducted by Alamerew and Brissaud (2019) explained that factors such as legislative pressure and customer demand should not be neglected from evaluating methods. For that reason, there is a need for detailed investigations into the characteristics of the concrete, as its degradation over time could affect its potential applications which would determine if their recycled concrete products could be used for the production of circular concrete.

Apart from the viability criteria, it also necessary to address the factors that influence the viability of post-use options for excavated concrete sewer pipes. Another study which presented the factors that affect the extraction of in-situ materials from buildings, contributed to the development of methodologies and frameworks of other researchers who investigated recover resources at the built environment of materials reaching end-of-life (Mollaei et al., 2023). Similarly, the determination of factors that influence the viability of post-use options, which have not been addressed, can contribute to other studies which investigate post-use options of concrete sewer pipes or concrete materials.

1.5 Practical Knowledge Gap

This research takes into account the test case of the post-use options of excavated sewer pipes in Rotterdam. As a result, the outcome of this study addresses not only an academic research gap but also a practical knowledge gap. More specifically, there is a lack of practical, field-tested methodologies for evaluating the condition and usability of excavated sewer pipes in a municipal setting. Their application in the specific context of Rotterdam, with its unique infrastructure and environmental conditions, has not been thoroughly explored. This gap highlights the need for developing practical assessment techniques that can be easily adopted by municipal authorities to evaluate the viability of various post-use options.

Furthermore, there is insufficient practical guidance on integrating post-use options into existing municipal waste management and construction practices. The Municipality of Rotterdam may face challenges in terms of logistics, regulatory compliance, and cost-effectiveness when attempting to put into effect post-use options for the excavated concrete sewer pipes. Practical solutions and strategies are needed to overcome these challenges, ensuring that post-use options can be implemented within the municipality's operational framework. This includes creating a conceptual framework that is applicable to the specific needs and constraints of urban environments like Rotterdam.

1.6 Thesis Outline

A description of the structure of the chapters is presented.

Chapter 1: Introduction

In this chapter an introduction to the circularity initiatives of the last years, the scope of the research, the research questions and an outline of the master thesis will be presented.

Chapter 2: Theoretical Framework and Problem Analysis

In this chapter a theoretical framework will be developed which will explore details for the next lifecycle alternatives of an excavated concrete sewer pipe and circular economy theories related with this research will be analyzed. The need for circular concrete in the Netherlands is going to be presented in this chapter and existing viability criteria for the post-use of concrete materials developed by academics.

Chapter 3: Research Methodology

In this chapter the qualitative analysis and the development method of viability criteria will be explained. Lastly, the research methodologies that will be used for the development of this master thesis will be analyzed in this chapter.

Chapter 4: Results

In this chapter the development of the viability criteria will be explained. Later on, the criteria that emerged from the literature analysis and the interviews are presented which are all combined, in order to form the final viability criteria. In the last part of chapter 4 the application of the viability criteria to the excavated concrete sewer pipes is presented.

Chapter 5: Discussion

The outcomes of this research will be highlighted in this chapter. Furthermore, the limitations of the research and recommendations for future research are going to be presented in chapter 5.

Chapter 6: Conclusion

In this chapter an overview of the answers the research questions will be presented. Moreover, all conclusions which were derived during the realization of this master thesis will be mentioned.

Chapter 2: Theoretical Framework

On chapter 2 the is going to be explained what circular economy is. Furthermore, the theories of 10Rs of circularity and circular value hill model are going to be analyzed in chapters 2.2 and 2.3. From those theories the next lifecycle alternatives will be determined and a detail analysis for all of them will take place on chapter 2.4. Another critical aspect that will be discussed on chapter 2.5 is the increasing need for circular concrete in the Netherlands. Chapter will be concluded with section 2.6 where the most important information of this chapter will be summarized and the answer of the first research question will be presented.

2.1 Definition of Circular Economy

For the purpose of this study, it is very important to determine the term of circular economy. The circular economy (CE) is considered as a sustainable economic model that separates economic expansion from resource consumption, by minimizing and recycling natural resources (Corona et al., 2019). In practice CE is a new model of production and consumption which prompts the adoption of post-use options for existing materials and products, such as reuse, refurbish or recycle, in order to increase the life cycle of existing products or materials (Circular Economy | European Parliament, n.d.). This leads to the significant reduction waste of materials and subsequently to a significant decrease of the use of raw materials. The circular economy model is depicted in Figure 2.

Figure 2: *Circular Economy Model (Circular Economy | European Parliament, n.d.)*

Linear Economy which is based on the take – make – dispose approach, which is not suitable for the needs of the 21st century. The reason for this is that linear economies are inherently counter-motivated to consider the efficiency of resource exploitation, they produce a huge quantity of waste (Sariatli, 2017). Furthermore, products in a linear economy model have a short lifetime because they are designed with only a single purpose for their whole lifecycle (Neves & Marques, 2022). As it was explained in chapter 1.1 the need to adopt circular economy strategies is very important. Increased welfare based on restored environmental integrity and preventive and regenerative eco-industrial growth are possible with the help of circular economy, which offers a solid framework for drastically enhancing the current business model (Ghisellini et al., 2016).

2.2 Explanation of the 10R Circular Economy Strategy

The "10 Rs of Circularity" is a framework that emphasizes key principles for sustainable living and resource management. These principles encourage individuals and organizations to rethink their consumption patterns and adopt more sustainable practices. The approach is based on the mindset of minimizing waste production, optimizing material consumption throughout several product lifetimes and extending the use of materials in every cycle (Ong, 2023).

Figure 3: *An Overview of the 10R Strategy (Potting et al., 2017)*

The first three Rs of circularity are referred to as designing or redesigning the ways of consumption (Çimen, 2021; Potting et al., 2017).

- **Refuse:** Suggests refusing or minimizing the use of products that are harmful to the environment or unsustainable.
- **Rethink:** Encourages designers and developers to revaluate their design approach, to consider alternative use options when their product will reach the end-of-life.
- **Reduce:** Focuses on reducing consumption and waste generation, advocating for simpler and more minimalist lifestyles.

The next five Rs of circularity are addressing actions which lengthen the lifecycle of products (Çimen, 2021; Potting et al., 2017).

- **Reuse:** Promotes the reuse of products and materials to extend their lifespan and reduce the need for new resources.
- **Repair:** Encourages repairing items instead of discarding them, thus reducing waste and conserving resources.
- **Refurbish:** Focuses on restoring products to a functional state without completely disassembling them.
- **Remanufacture:** Involves disassembling and refurbishing products to like-new condition, allowing them to reenter the market and extend their lifecycle.
- **Repurpose:** Involves finding new uses for old or discarded items, giving them a second life and reducing the demand for new products.

The last two Rs of circularity are focused on applying usefully the materials gained from used products (Çimen, 2021; Potting et al., 2017).

- **Recycle:** Supports the recycling of materials to recover valuable resources and divert waste from landfills, closing the loop in the production cycle.
- **Recover:** Involves recovering energy or other resources from waste that cannot be recycled, maximizing the value extracted from resources before disposal.

It must be noted that R8–R9 targets do not necessarily promote a CE because recovery and recycling activities end up destroying products and do not help products remain in the economy. Recycle and Recovery offer a few advantages in terms of the (partial) reclamation of materials and energy recovery in comparison with the more powerful CE strategies are R0-R7 targets (Morseletto, 2020).

2.3 Explanation of Value Hill Model Theory

The Value Hill model is a strategy framework that gives companies the concepts they need to place their business, strategy, and value chain in a circular environment (Inachainge, 2023). For the purposes of this study, it is important to be mentioned the differences between the linear economy value hill model and the circular economy value hill model. The linear economy value hill model consists of three phases (Achtenberg et al., 2016), which can be observed in Figure 4.

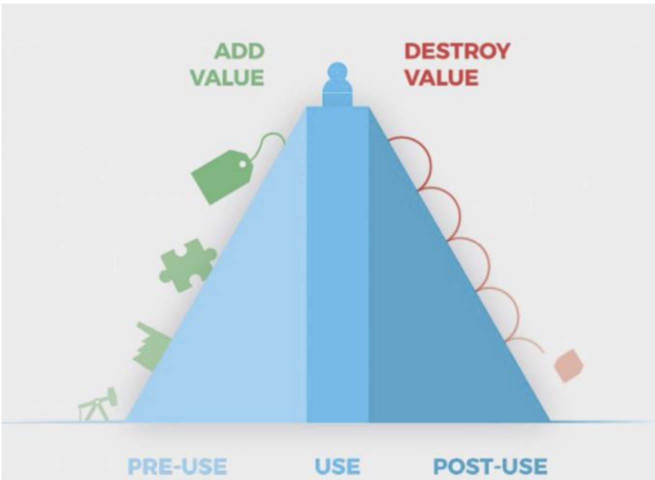

Figure 4: *Value Hill Model of Linear Economy (Achtenberg et al., 2016)*

– Pre-use phase: On this phase the material is climbing the hill. During this phase the commodity is extracted, manufactured, assembled, and value is added on each stage of this phase.
– When a product is bought by a customer and goes into the second part of the pyramid which is the use-phase. Here, the commodity is utilized for its intended purpose.
– After the product is used up completely, it starts to lose value. The product loses value in this post-use phase since the consumer can no longer utilize it.

On the other hand, the circular value hill model employs multiple ways to sustain the product's value by reestablishing it on the post-use phase of the pyramid, in contrast to the linear model where the product's value swiftly drops to zero (Rodrigo-González et al., 2021). In this sense, as the product moves toward the base of the pyramid, the amount it contains reduces. In each phase are different strategies which can be implemented to increase the level of circularity of the business. Those strategies can be observed on Figure 5 and are the following (Achtenberg et al., 2016):

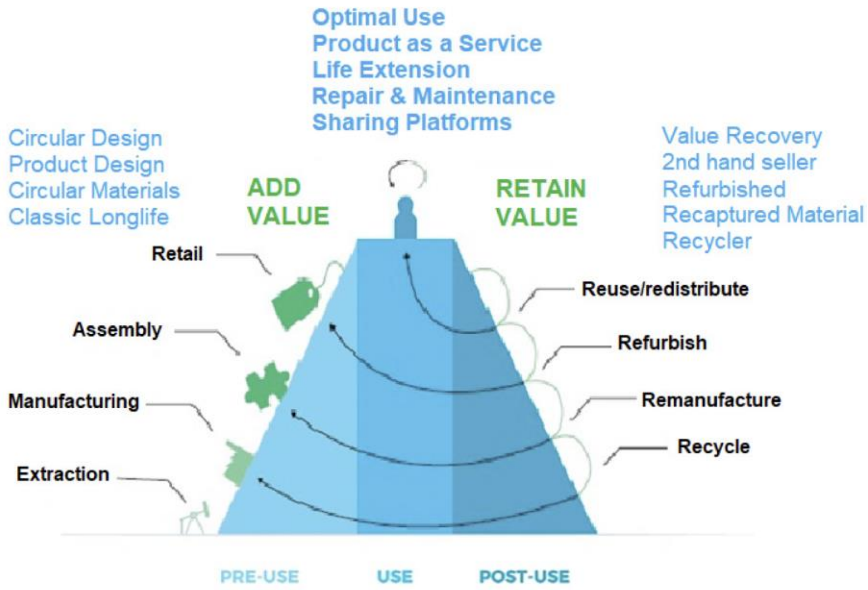

***Figure 5:** Value Hill Model of Circular Economy (Achtenberg et al., 2016)*

– For the **pre-use phase** of product development, circular design strategies are applicable, which enable companies to create products with future use and circular post-use in mind. This includes designing products which can be easily maintained and repaired.
– Optimal Use initiatives are best suited for the material's **use phase**. These initiatives focus on enhancing the product's utilization through additional use options or commodities that help preserve its original value.
– Value Recovery initiatives are suitable for the material's **post-use phase**, aiming to reclaim the utility of commodities which have no longer useful.

The circular economy value hill model could be the base for the next lifecycle steps of the concrete sewer pipes. In chapter 2.3 the selection of the new use option for the excavated concrete sewer pipes are explained in detail.

2.4 Selection & Analysis of the next Lifecycle Alternatives

By implementing the value hill model to the excavated concrete sewer pipes, they are at the end of their use-phase, and they are entering the post-use phase. More specifically, the pipes have been used for several years and then removed from their position on the ground, which means that they have fulfilled their initial purpose. As a result of that they have entered the post-use phase based on the value hill model.

In Figure 5 it can be observed that according to the circular value hill model are four potential next lifecycle steps for a concrete sewer pipe. These are the following:

- **Reuse**: Examine the feasibility and cost-effectiveness of reusing them as pipes in Rotterdam.
- **Repurpose:** The use of old sewer pipes in breakwater construction projects or being used as underground water tanks.
- **Remanufacture:** Involves disassembling and refurbishing products to like-new condition, allowing them to reenter the market and extend their lifecycle.
- **Recycle:** Evaluate the implications of recycling the old sewer concrete pipes to generate aggregates that can be used in the production of new concrete materials which are needed in the construction industry of the city of Rotterdam.

However, a concrete sewer pipe is not possible to be remanufactured. As it explained in the remanufacturing involved disassembling the product which in the case of concrete sewer pipe is to recycle it and then reproduce it. For that reason, remanufacturing will not be selected as a next lifecycle step for a concrete sewer pipe in this study. An option which is suitable based on 10Rs of circularity that can be placed in the post-use phase of a product because it can lengthen the lifetime of a product is the Repurpose target. Repurposing involves finding new uses for old or discarded items, giving them a second life and reducing the demand for new products (Çimen, 2021 & Potting et al. 2017).

The next lifecycle steps of the concrete sewer pipes will be divided into four categories. These different options are to be reused, refurbished, repurposed and recycled. The exact use of the concrete sewer pipes for every alternative is explained in the following chapters. The goal is to be determined which alternative is the most suitable lifecycle step for an excavated concrete sewer pipe.

2.4.1 Strategy A: Reuse

The first R of the post-use phase of the circular value hill model, is the reuse option of a certain product (Achtenberg et al., 2016). Based on that, the first next lifecycle step for the excavated concrete sewer pipes that must be included in the alternatives is to be reused again as a concrete sewer pipe. It should be established when it is possible to for an existing sewer pipe to be placed again in the sewer system and be operational for a certain number of years. For that reason, it must be dictated when a concrete sewer pipe is suitable for reuse in the sewer system.

An important aspect that usually affects the reuse application of a concrete material is its condition (Küpfer et al., 2023). For that reason, it must be clear when and how a material should be reused again. A recent study identified that the loss of healthy wall thickness on a concrete sewer pipe gives the best information in respect with its geometry for the current strength of this material (Stanić et al., 2016). Round sewer pipes and egged shaped sewer pipes which have developed specific types of cracks in four specific locations of their cross section are not suitable for reuse in the public sewer system (Scheperboer et al., 2021). The technical characteristics and the condition of a concrete material can affect its reuse capability and that is a fact that should not be ignored.

Another point that should be considered is whether the concrete corrosion has reached the rebar surface (Song et al., 2020). In that case, the concrete and rebar corrosion are quite extensive, and the micro-cracking is getting faster by the dissolution, diffusion and deposition of Fe at the concrete corrosion front and eventually reduces the strength of the pipes (Song et al., 2020). Yearly a significant number of kilometers of concrete sewer pipes need to be removed earlier than planned in order to be repaired. The reason for that is the severe bacteria-induced corrosion (bio-corrosion) which is caused by the extended exposure of concrete to aggressive environments (Roghanian & Banthia, 2019).

There are several technical characteristics which affect the reusability of a used concrete sewer pipe, but that does not mean that it is not possible to be reused again in the sewer system of a city. If the concrete sewer pipes fulfil some standards which allow their reusability, then it is the benefit of their owner to used them again instead of buying new ones.

2.4.2 Strategy B: Repurpose

The second reuse strategy that is going to be addressed in the current research is called repurpose. According to the 10Rs theory repurposing involves finding new uses for old or discarded items, in order to find them a second life and reduce the demand for new products (Çimen, 2021; Potting et al., 2017). Two future use options are going to be considered in this research which are based on the repurpose strategy. The first is to use the excavated concrete sewer pipes in the breakwater construction. This solution is based on the decision of the Ministry of Infrastructure and Water Management to acquire used concrete sewer pipes in order to use them in the breakwater construction (Municipality of Rotterdam, 2023).

To identify how the pipes can be used in a breakwater, it is important to understand in which parts of the breakwater in is possible to be placed. A breakwater structure's main function is to create shelter to protect vessels or coastal areas against currents, waves, storm surges and tides (Breakwaters for Ports & Harbours, n.d.). The concrete sewer pipes could be used for the armored layer of the breakwater, or the breakwater will be made solely from concrete sewer pipes. The different part of a breakwater construction can be seen on Figure 6.

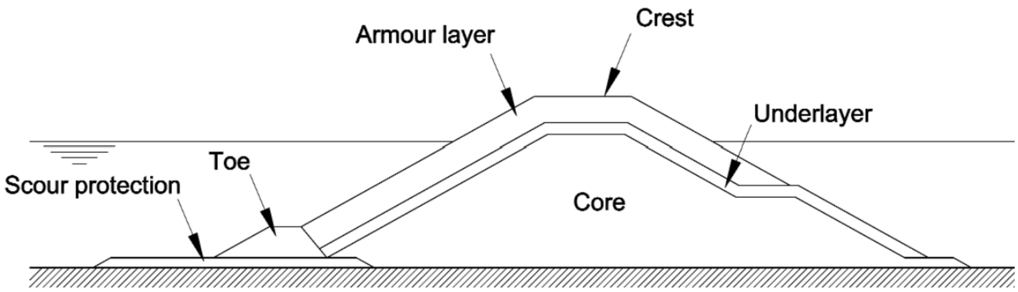

Figure 6: *Cross-section of a typical rubble mounted breakwater (The Rock Manual, 2007).*

In the past natural stones were used as armor units but as the years passed and the marine constructions were being build breakwaters in deeper waters, the requirements for heavy armors increased which led to the development of concrete blocks (Kudale et al., 2021). Another type of a concrete block is the tertapod which height varies from 1.4 to 2.45 meters and weigh up to 7.8 tons (Tetrapod Moulds by Betonblock, n.d.). Furthermore, the accropode type of concrete blocks is worth mentioning. They are also produced in several sizes which vary from a height of 1.43 to 4.35 meters. In a breakwater located in the entrance of the North Sea channel, at Ijmuiden in the Netherlands, the concrete blocks which have been used have a size of 2 by 2 meters (EcoShape, 2020).

It is clear that the concrete blocks which are placed in the armor layer of a breakwater have a relatively big size. As result of that, should be taken into account which size of concrete sewer pipes could be used in an armor layer of a breakwater. Furthermore, the concrete sewer pipes could be broken into smaller pieces or be sent in their original shape and be used for the construction of a breakwater structure.

The second option is to use them as temporary underground water tanks to retain rainwater. This alternative arise from the need to tackle big rainfalls that tend to appear in an increasing pace in the recent years which eventually forced water engineers to develop urban water buffers (KWR Water Research Institute, 2023). One of the measures to create urban buffers was to place pipelines under the surface of highways to retain rainwater in heavy rain showers (Neerslag - Rotterdams Weerwoord, 2023).

As a result the concrete sewer pipes can be repurposed, by using them as underground water tanks, to retain the rainwater. In the Netherlands and especially in the city of Rotterdam a new approach on managing the rainwater to prevent flooding. More specifically the Municipality of Rotterdam develops a system which increases the sponge effect of the city (Neerslag - Rotterdams Weerwoord, 2023). The basic idea of the system is to keep the rainwater in small tanks for a small period of time to prevent flooding during extreme rain showers. The concrete sewer pipes can be used as underground water tanks to retain rainwater for a certain period of time, before the water will be moved to a permanent water tank of the city. It is important to be specified under which conditions a concrete sewer pipe will be capable to be used as an underground water tank.

2.4.3 Strategy C: Refurbish

The third next lifecycle step for concrete sewer pipes that will be considered in this research is the option of refurbishing. As it is explained by the theory of 10Rs of circularity, refurbishing is a method which aims to restore the products to their initial function without disabling them (Çimen, 2021). Refurbishing concrete materials is beneficial for the environment according to a study because the necessary energy and materials to make again a product, from its end of lifecycle to usable condition, are usually minimal compared to those needed for new manufacturing (Cooper & Gutowski, 2015). However, in some products there is a break-even point at which refurbishing a product is not preferable, as it becomes more environmentally desire to discard or recycle the product and replace it with a new one that has a better performance (Ardente et al., 2018).

One method to refurbish the concrete sewer pipes is by using carbon fiber reinforced polymers (CFRP). CFRP is simply attached with epoxy adhesive to the surface of the damaged area which increases the load-carrying capacity and significantly improves the water tightness of the sewer pipe (Karmakar et al., 2021). Another option to refurbish the sewer pipes is called Slip Lining. This method has a technology that covers the deteriorating concrete pipe with a corrosion-resistant liner material which includes a high-density polyethylene (HDPE) (Karmakar et al., 2021). Those methods can be used for refurbishing concrete sewer pipes and convert damaged pipes into a condition which will allow their reuse in the sewer system. Nonetheless, it is important to be established up to which condition of the products is beneficial for the user to refurbish them instead of recycling and using new ones.

2.4.4. Strategy D: Recycle

Recycling concrete is a vital part of the circular economy in the construction industry, aiming to reduce waste, conserve natural resources, and minimize environmental impact. Recycling is one of the 10R targets and the last part of the post-use phase in the circular economy value hill model. It might be the last step on the value hill model, but it is quite important, because concrete recycling is one of the best ways to manage concrete waste as it turns discarded concrete into recyclable aggregates (Badraddin et al., 2021). Furthermore, according to Badraddin, recycling concrete is an essential activity to lessen the environmental impact of concrete debris.

Moreover, recycling concrete debris is the best way to reduce the amount of construction waste produced because it is the main source of construction solid waste, which accounts for roughly 50% of all construction waste (Tam, 2008). In Europe alone around 900 tons of construction waste are produced on a yearly basis (Fischer & Davidsen, 2010). An important point that must be highlighted is that the recycling of concrete will produce used aggregates which can replace new aggregates. According to a study (Abbas et al., 2006), recycling concrete can reduce the greenhouse gas emissions for two main reasons. Firstly, the cement production will be reduced due to the fact that part of the new cement is going to be replaced by used one. The second reason is that the transportation distance of unprocessed rock/stone from quarries to the processing plants will be shortened, because the used aggregates will be reused for the production of circular concrete.

It must be highlighted that using recycled concrete aggregates is also beneficial from an economic point of view. More specifically, manufactured recycled concrete aggregates have become less expensive than using new aggregates due to their reduced transportation costs and the increased cost of construction and demolition landfilling rubble (Meyer, 2009). If there is not a suitable next lifecycle step for the concrete sewer pipes and they are not recycled, then they will end up in a landfill. Recycling concrete sewer pipes and concrete materials in general can reduce the increasing pressure on landfill capacity, because of the concrete waste from the construction industry (Hsiao et al., 2002).

For the purpose of this study two different recycling methods of concrete waste and hence for concrete sewer pipes will be analyzed. Those methods are the Demolition Plant for aggregates and the Smart Crusher. A demolition plant for aggregates processes construction and demolition waste materials to recover and recycle concrete and other materials into usable aggregates (Handbook of Recycled Concrete and Demolition Waste, n.d.). Those facilities reduce the environmental impact associated with waste disposal and producing new construction materials.

The Smart Crusher is an innovative technology designed for the recycling of concrete and the recovery of its original components. The main advantage of this technology is that does not only breaks down used concrete materials but it also separates its materials to sand and stone which can then be reused to create new concrete (SmartCrusher Holland Circular Hotspot, 2022). Furthermore, biggest difference for conservative concrete crushers of this new method is that is capable of removing the cured cement from that sticks gravel and sand together very effectively. More specifically, depending on the type of cement that was used it manages to cure 50% to 70% of it (Smart Crusher Saves Concrete and CO2, 2018). As a result of that, the smart crusher can be considered as a productive method for concrete recycling.

2.5 Criteria to assess the viability of post-use options for concrete Materials

Apart from defining post-use options for the excavated concrete sewer pipes based on circular strategies that ware developed by academics, this project also investigates which viability criteria academics consider for their post-use options. Due to scarcity of information the research was not limited to viability criteria specified only for concrete sewer pipes but it also included criteria for the assessment of concrete materials and some types of construction materials.

A study that was conducted recently, highlights the critical role of the waste hierarchy in managing construction waste in Europe and underscores the need for continuous improvement and adaptation of waste management practices to achieve higher circularity and sustainability in the construction sector (Zhang et al., 2022). As it was described on the same study, circular strategies of reuse, refurbish and repurpose are prioritized compared to recycle because of their environmental impact. However, reuse of entire concrete components is rare due to the complexity of estimating their condition (Purnell and Dunster, 2010). More specifically, concrete elements or components are designed to withstand specific loads for a specific period of time which limits the potential reuse options for them. It also quite challenging to divide cast-in-situ structures without damaging them.

While some companies are implementing circular economy strategies, widespread adoption is lacking due to evaluation method gaps for product-level strategies. A recent research conducted by Alamerew et al. (2020) addresses this gap by proposing a multi-criteria decision-making method for evaluating product-level circularity strategies. The most important criteria that were developed by that study are the following:

End-of-Life Impact Indicator: This indicator measures the environmental impacts specifically associated with the product's end-of-life phase. It assesses how well the product's materials and components can be reused, recycled, or safely disposed of, minimizing environmental harm.

Resources: This criterion focuses on the efficient use of natural resources, evaluating the product's material and energy efficiency, and its contribution to conserving resources.

Life Cycle Costing: This criterion involves calculating the total cost of a product over its entire life cycle, including production, maintenance, and disposal costs. It helps in understanding the economic viability and cost-effectiveness of different circularity strategies.

Disassembly Cost: This indicator evaluates the costs associated with disassembling the product at the end of its life. It considers the labor, time, and financial resources required to dismantle the product for recycling or remanufacturing.

Effect of Legislative Pressure: This criterion evaluates how current and future legislation might impact the adoption of circularity strategies. It includes compliance with environmental regulations, waste management laws, and incentives for sustainable practices.

Technical State: This criterion evaluates the current technical condition and performance of the product. It considers the ease of upgrading, repairing, and maintaining the product to extend its life.

Separability of Materials: This criterion evaluates how easily the product's materials can be separated for recycling or reuse. It considers the design and assembly methods that facilitate material recovery.

Another study that was conducted by Alamerew and Brissaud (2019) presents a comprehensive decision-making methodology to evaluate end-of-life product recovery strategies within the framework of a circular economy. Traditional end-of-life decision-making methods often focus solely on technical and economic factors, neglecting other crucial areas such as legislative pressure and customer demand. However, this research introduces a holistic assessment tool that evaluates end-of-life recovery strategies considering a wide range of factors. From those factors the most influential are following:

Compliance with National & EU Legislation: Ensuring that the recovery strategy complies with existing legislative requirements, including European Union regulations, is vital. This factor evaluates the strategy's adherence to legal standards and its ability to meet regulatory obligations.

Customer Demand: This criterion assesses the market demand for products recovered through the strategy. It considers consumer preferences and trends, evaluating whether there is sufficient demand to justify the recovery process. High market demand indicates a greater likelihood of economic viability.

Level of Customer Satisfaction: Customer satisfaction is crucial for the success of any product recovery strategy. This criterion assesses how well the strategy meets customer expectations and needs, considering factors such as product quality, reliability, and overall user experience.

Return Core Volume: This factor evaluates the volume of products that can be returned and processed through the recovery strategy. A higher return core volume indicates a more substantial potential for resource recovery and reuse, enhancing the strategy's feasibility.

Financial Cost of Operating Product Recovery Business: The overall financial cost associated with operating the product recovery business is a critical economic factor. This criterion evaluates all expenses, including collection, processing, labor, and overhead costs, to determine the strategy's economic viability.

Technical State: The technical condition of products at the end of their life significantly impacts the recovery strategy. This criterion assesses the state of returned products, determining the feasibility of different recovery options such as repair, refurbishment, or recycling.

The necessity of including both the use and end-of-life phases in comprehensive life cycle assessments of concrete, is a factor that must be considered for the post-use evaluation of concrete materials (Wu et al., 2014). The reason for that is that, both phases significantly affect the overall environmental impact, and their exclusion could lead to inaccurate representations of GHG emissions associated with concrete. The recycling of concrete at the end of its life cycle can lead to substantial reductions in GHG emissions. Research shows that up to 75% of precast concrete products can carbonate within five years of demolition, resulting in a reduction of $CO2$ emissions by approximately 25% (Worrell et al., 2001). Efficient management of concrete materials at the end of their life cycle. such as recycling are reuse, is pivotal in minimizing environmental impact and it can be evaluated by a life cycle assessment.

On chapter 4.3 it will be addressed which of the criteria that were developed by academics could be applied to the excavated concrete sewer pipes. Those criteria must be able to assess the viability of the post-use options.

2.6 The influence of the Increased Demand for Circular Concrete in the Netherlands

The construction industry worldwide, a big part of which is related with the concrete production, creates a significant amount of greenhouse gas emissions that are harmful to the environment (Damtoft et al., 2008). In the Netherlands the construction industry is a very pollutant mean, as it is responsible for 66% of all waste generation across the whole country (Organisation for Economic Co-operation and Development (OECD), 2015). At this point, it must be noted that the Municipality of Rotterdam, is solely responsible for approximately 20% of the national GHGe (Glatek, et al., 2019). As it is explained in chapter 1.1, the Dutch government has supported several initiatives to limit the pollution which is caused by the construction industry.

However, the Dutch government has formed an agreement in July of 2018 for the concrete production which is called the concrete agreement or in Dutch Betonakkoord (Het Betonakkoord - Betonakkoord, 2024). This deal aims to manage the concrete production more sustainable by reducing the CO_2 and by promoting circularity. More specifically the first goal is to reduce by 30 percent the CO_2 of the concrete chain by 2030 and the ultimate goal being 49 percent reduction compared with the 1990 standards. Furthermore, the deal promotes the use of circular concrete by enforcing that all waste steams must be used in way that from 2030 100 percent of it will be used permanently in the concrete. It must be highlighted that in 2020 only 10 percent of sand and 50 percent of gravel that was used to produce new concrete came from concrete residual flows.

The fact that all aggregates and sand that will be used for producing new concrete must come from recycled concrete residual flows increases the need for concrete recycling. Despite that, the amount of poorly managed concrete demolition still exceeds recycling, and precast buildings are still mostly limited to pattern uniform housing projects (Xavier et al., 2021). As a result of that, the building industry has opportunity for improvement in this area.

The concrete sewer pipes can be a reliable source of aggregates, sand and cement for new concrete products. As it was mentioned on chapter 1 the Municipality of Rotterdam replaces every year a significant amount of concrete sewer pipes which can be recycled and generate aggregates, sand and cement. The products from the recycling procedure could be used to produce new concrete or new concrete materials. However, it is important to be defined, if the pollution of the concrete sewer pipes can potentially limit the use option of their recycled products.

2.7 Conclusion of the Theoretical Framework

In this subsection the first sub question will be addressed. The response of this question is based on the theoretical framework which is presented on chapter 2.

One of the objectives for the development of the theoretical framework was to address the following research question: “Which post-use options can be applied on an excavated concrete sewer pipe according to existing circular economy strategies according to academic literature?”

The analysis that was conducted on chapter 2 identified several existing circular strategies for construction products like the concrete sewer pipes. The two theories which were explained in detail in chapters 2.1 and 2.2 are the 10Rs of circularity and the circular value hill model. The 10Rs theory is based on ten strategies which can be applied on one of the three phases of the lifecycle of a product. The first three strategies refer to the design phase of a product and aim to change the designing philosophy, the next five can be applied during the lifetime of a product and their goal is to extend it and the last two aim to retrieve materials from products at the end of their lifetime. The circular value hill model is divided also in three phases, the pre-use phase, the use phase and the post-use phase of a product.

As it was mentioned on chapter 2.3 an excavated sewer pipe is entering the post-use phase based on the theory of the circular value hill model. There are four circular strategies which can be followed in the post-use phase of a product which to be either reused, refurbished, remanufactured, or recycled. Out of those four alternatives three are applicable for excavated sewer pipes and one is not. The option which will not be selected is the remanufacturing option, because a product must be disassembled first in order to be able to be remanufactured. In the case of a product such as a concrete sewer pipe this is not realistic because disassembling it, means to recycle it first and then rebuilt it which fall in the category of the recycling option. Therefore, the remanufacturing option is rejected and will not be considered as a next lifecycle alternative for the concrete sewer pipes in this study. From the theory of 10Rs the strategies that lengthen the lifetime of a product can be considered as possible use option for an excavated concrete sewer pipe. From those strategies the only one that is applicable and does not overlap with the selected strategies from the circular value hill model is the repurpose alternative. As a result of that, this circular strategy will be taken into account in this research.

Based on the aforementioned, there four circular strategies that are applicable for a concrete sewer pipe and will be used in this research are the following: Reuse, Repurpose, Remanufacture and Recycle. Based on the literature analysis that has been conducted and is presented on chapter 2 there seven different next lifecycles use option for an excavated concrete sewer pipe. Those options are the following:

- To be used again as concrete sewer pipes in the sewer system of a city which is based on the reuse strategy.
- To be used in the breakwater construction as part of a breakwater, based on the repurpose strategy.
- To be used in as an underground water tank to hold the rainwater for a short period of time, based on the repurpose strategy.
- To be refurbished by using the CFRP method and then used again as concrete sewer pipe, based on the refurbish strategy.
- To be refurbished by using the Slip Lining method and then used again as a concrete sewer pipe, based on the refurbish strategy.
- To be recycled with a smart crusher, based on the recycle strategy.
- To be recycled with a breaking machine, based on the recycle strategy.

These seven post-use options can be applied on an excavated concrete sewer pipe based on the theory of the circular value hill model combined with the 10Rs of circularity. The options that are addressed for the purpose of this master thesis must be fully operational for the case of the Municipality of Rotterdam and not under development. This is a very important step for this research because from these seven different use options will be defined which of them are considered viable for an excavated concrete sewer pipe according to the developed viability criteria that are presented on chapter 4.4.

Chapter 3: Methodology

In chapter 3 are described the methodologies followed for the realization of this master thesis. In chapter 3.1 is explained the research strategy which is the process that is used for the development of this research. In chapter 3.2 the approach that was followed during the research in order to gain all the necessary information for the development of the post-use options and the viability criteria. In chapter 3.3 are presented the research methods that were used. Lastly, in chapter 3.4 is presented data analysis and the approach that was used for the development of the conceptual framework.

3.1 Research Strategy

Exploratory research is defined as research conducted to investigate an issue that is not yet well understood. Its purpose is to gain a deeper insight into the current issue, though it does not aim to produce conclusive results. In such studies, the researcher starts with a broad idea and uses the research process to identify potential research topics (Stebbins, 2012). This study is exploratory because there is limited knowledge about post-use options for excavated concrete sewer pipes and criteria to assess their viability. Consequently, the research methodology is qualitative (Braun, 2012). Qualitative research is recognized for its flexibility, openness, and responsiveness to context (Busetto et al., 2020).

The main research question has been divided to the four sub-questions that are presented on chapter 1.3. To address the first sub-questions, a literature review was conducted to gather the necessary information. For the second sub-question a combination of information for literature review and from expert interviews was used. The third sub-question was addressed by the development of the evaluation framework that is presented on chapter 4.4. Finally, the fourth sub-question was addressed by the results on chapter 4.5 which were developed by the information from the test case the use of the evaluation framework. The research strategy of this study is depicted in figure 10. The answers to all research questions are presented on chapter 6.1.

3.2 Research Approach

The research approach is conducted in four different parts which are illustrated on Figure 7. In the first part of the research a literature review is conducted in order to identify first potential post-use options for the excavated concrete sewer pipes. From the literature review viability criteria that evaluate the post use options of concrete materials which are defined by the academics will be gathered. Once the literature review has been completed, the second part of the research approach will begin. More specifically, the people that must be interviewed have to be identified and schedule the interviews. After that, the structure and the questions for the interviews must be developed, in order to manage getting all necessary information. The second part of the research approach will finish with the realization of all interviews. The third part of the research approach consists of the analysis of the retrieved information from both interviews and literature review. The development of the viability criteria for the evaluation of the excavated sewer pipes will be based on the results of this analysis. The last part of the research approach consists of the test case of Rotterdam, in which the evaluation framework will be applied to evaluate the viability of post-use options. This test case will be the prototype application of the framework.

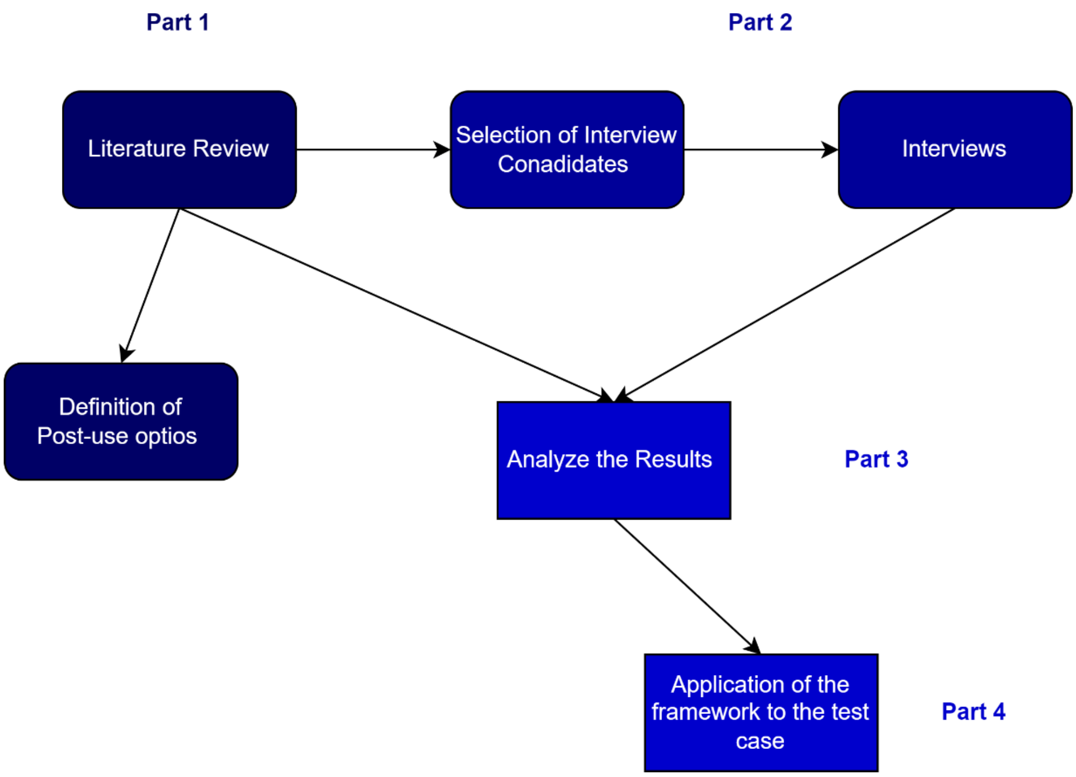

Figure 7: *Research Approach, Own Illustration*

3.3 Research Methods & Methodologies

A qualitative research method was used for the realization of this study. The research methods used are literature review and expert interviews. The approach that was followed in these research methods are described in sections 3.3.1 and 3.3.2.

3.3.1 Literature Review

The first research methodology that is going to be used in this master thesis is the Literature Review. Literature review can provide a comprehensive overview of existing research and findings in the field. It will be used mainly on the initial stages of this master thesis, to identify circular economy strategies on which the post-use options for the concrete sewer pipes was based on. Moreover, the analysis of research articles related with circular economy provided information for the study that helped validating data from the interviews. Lastly, conducting a literature review contributed on identifying a research gap which is addressed in this research study. The literature review is presented on chapter 2.

The literature review was divided into two sections. The first section aimed to identify potential post-use options for the sewer pipes. However, to post-use options are based on circular economy strategies, therefore the first step was to find which circular strategies are suitable for excavated sewer pipes. Once those strategies were selected, the potential post-use options were selected based on information from the literature review. For this part of the literature review a combination of academic and grey literature was used. More information regarding grey literature is presented in the following text.

The second section of the literature review aimed to identify existing criteria that could be used to evaluate the viability of the post-use options for the excavated concrete sewer pipes. As a result, those criteria were gathered and then analyzed in order to assess which of the can be applied on concrete sewer pipes. The selection of the criteria that were retrieved from the literature review for the evaluation framework, is presented on chapter 4.3. For the second section of the literature review was used only academic literature, because that information had to be peer reviewed by experienced academics. This fact, increased the validity of the data.

Developing a comprehensive theoretical framework for a complex and innovative concept which the current research aims to address can be quite challenging. The scarcity of information in this domain created the necessity to combine grey literature with academic literature. For the purpose of this research the term grey literature is defined as open source, publicly accessible, international or domestic data that is typically only accessible through certain channels and may not find its way into the regular publishing, distribution, bibliographic control, or acquisition processes of book retailers or subscription agencies (Benzies et al., 2006).

Using grey literature can be useful in research because reviews that are only focused on systematic research have come under fire for failing to offer insightful analysis of complicated treatments or a national or regional context for variations in their application (Pawson et al., 2005). That means that several information related with technical characteristics need to be gathered which are not necessarily available in academic literature. Moreover, grey literature entails information about interventions which are based on long term practical experience which is often called “clinical wisdom” and are not supported by academic literature (Benzies et al., 2006).

However, the information which are obtained from grey literature must be assessed. A study has developed a checklist which has been adjusted to the needs of this research in order to validate the sources which are considered as grey literature (Garousi et al., 2019). The checklist is presented in the following table 1.

Table 1: *Validation Criteria for Grey Literature (Garousi et al., 2019).*

Validation Criteria for Grey Literature	
Criteria	**Questions**
Authority of the Producer	Is the publishing organization reputable? Is the author associated with a reputable organization? Does the author have expertise in the area?
Methodology	Does the source have a clearly stated aim? Does the source have a methodology? Does the work cover a specific topic? Does the work refer to a certain case of social group?
Objectivity	Is the work presented properly? Are the conclusions supported by data? Are the statements in the sources as objective as possible?
Date	Does the source have clearly stated date?
Novelty	Does the literature provide something unique or entails critical information which are necessary for the research

The information which was obtained from academic and grey literature were used in the analysis of the report. This was the basis for the development of this solution and also helped in structuring the approach that was followed in the approach of the interview participants. Some necessary information, that was not available in both academic and grey literature was obtained from conducting interviews. This research methodology is explained in detail in the following section.

3.3.2 Interviews

The interview method is one of the tools that was used for data gathering and analysis of identifying the key problems and challenges. For the purposes of this master thesis, the interviews had semi-structured format, to gather information regarding the development of viability criteria to evaluate the potential post-use options for excavated concrete sewer pipes. The people who were selected to be interviewed where amongst the following groups of expertise:

- Asset managers from the Municipality of Rotterdam which are involved in projects related to the sewer system of the city. Asset managers were selected because to provide information regarding the sewer renewal, the condition of the old concrete pipes, the reuse aspect of old pipes materials, how the old materials are handled and the recycling of sewer pipes.
- Consultants which are related with circular projects of the Municipality of Rotterdam. These responders were selected in order to give information about the circular materials that are used in construction projects, the recycling of sewer pipes, the reuse aspect of old pipes materials and the need for circular materials in the construction industry.

- Experts in road construction and responsible for the acquisition of construction materials for road construction. The were selected to provide information about the circular materials that are used in the road construction, the recycling of materials and the need for circular materials in the road construction.
- Experts in the reuse of concrete materials and concrete degradation properties. Those experts provided information about the degradation of concrete materials, if the chemical degradation in the sewer system might affect the recycling of sewer pipes.
- An expert in environmental cost indicators. The expert provided insights on how different next lifecycle alternatives can be evaluated from an environmental cost indicator perspective and mentioned the most crucial factors on the analysis.

In total 11 interviews were conducted following a semi-structured approach. More specifically, some fixed questions were addressed to almost all interviewees combined with some random questions that will be based on the expertise of each interviewee and the flow of the conversation. On Appendix B are presented the questions that were addressed to the responders during the interviews and all critical information that were gathered from every interview. However, in some cases due to the specific expertise of some interviewees the fixed questions were adjusted in order to focus on gathering information related to the expertise of the respondent. For example, in the interview with an expert in the reuse of concrete materials the questions were quite different than the standards ones in order to collect information related to concrete degradation from sulfites and concrete recycling methods. Those questions are also presented on Appendix B. As the interviews progressed some adjustments were also made in order to focus on information that were still missing, or factors that played a major role like the pollution by sulfites and the different uses of recycled aggregates.

Table 2: *Codes of the Interview Participants*

List of the Participants of the Expert Interviews		
Code	**Role of the Interviewee**	**Date of the Interview**
Adv1	Advisor in the Municipality for Circular Projects	8/4/2024
PM1	Project Manager	8/4/2024
Eng1	Engineer for Groundwater Projects & Water Quality	11/4/2024
PL1	Project Leader for the development of a Framework	12/4/2024
AM1	Asset Manager	12/4/2024
TM1	Transition Manager	15/4/2024
Adv2	Advisor of Structural Engineering & Expert in Concrete Durability	15/4/2024
Adv3	Advisor of Maintenance & Expert on ECI	18/4/2024
RE1	Road Engineer	22/4/2024
PM2	Project Manager	23/4/2024
AM2	Asset Manager	23/4/2024

The interviews were all conducted online and they were recorded. This helped the researcher to be able to watch again the interviews and collect all critical information accurately. It must be noted that all participant signed a consent form in which they agreed to use the data that they have provided during the interview anonymously. The consent form is presented on Appendix C. All the recordings were deleted after the completion of this research and none of them will be published. All information that is going to be retrieved from the interviews are presented anonymously in this master thesis. However, codes were used in quotations from the interview transcripts. Those codes were developed based on the role of each interview participant and they are presented on table 2.

3.3.2.2 Communication through emails

After the analysis of the interview data some questions were made to participants in order to clarify some of the already obtained information. Furthermore, some additional questions were asked to explain some ambiguities that prompt up during the analysis of the interview data. It must be noted that the researcher attempted to conduct an interview to a breaking installation company manager in order to get more information regarding the recycling process of concrete sewer pipes and about the management of their recycled products. However, this was not possible and some questions were asked to the manager through emails. The answers of the manager were taken into consideration in the evaluation procedure of the next lifecycle use options of the concrete sewer pipes.

3.3.3 Test Case

The test case that are used in this research focuses on the Municipality of Rotterdam, which is used for investigating the applicability of the framework for the evaluation of the potential post-use options for excavated concrete sewer pipes. Rotterdam, renowned for its advanced infrastructure and progressive circular initiatives, as it was described on the introduction, provides a rich context for examining the potential post-use options of decommissioned sewer materials. The city's extensive sewer network, coupled with its commitment to circular economy principles, makes it an ideal candidate for exploring innovative strategies to manage construction and demolition waste, particularly concrete sewer pipes.

Every year in Rotterdam around 35km of sewer pipes are being replaced as part of the renewal of the city's sewer system. As a result, the experience of the employees from the Municipality and the continuous projects in the system gave the opportunity to gather high-quality information. From the interviews key information was gathered about the current management of the excavated concrete sewer pipes and about some previous testing that were conducted from the Municipality.

The test case of the Municipality of Rotterdam was used to evaluate the viability of the seven potential post-use options for the concrete sewer pipes. Specifically, it was evaluated the efficiency of recycling the sewer pipes by using a smart crusher, refurbish them with the slip lining or CFRP method and repurpose the sewer pipes to the breakwater construction. Furthermore, it was tested the recycling of concrete sewer pipes with conservative breaking installation. It was also examined the option to reuse the excavated sewer pipes again in the city's sewer system. Lastly, the option to use the pipes as underground water tanks to retain the sewer water was evaluated. This test case, in combination with the information regarding the condition and the current management of the pipes in Rotterdam contributed to the evaluation of the viability of post-use options for sewer pipes.

The seven potential post-use options that are presented on chapter 2.7 were used in this test case. The process of the development of the conceptual framework is analyzed on chapter 3.4. The use of this test case for the evaluation of the potential post-use options showed that the conceptual framework can also have a practical application. The evaluation process of the potential post-use options is presented on chapter 4.4. The data for the test case were gathered through expert interviews which is explained of the following section.

3.4 Data Analysis

The third phase of the research is the analysis of the collected information. It is a very critical step of the research because all the information will be analyzed, and it will be defined which criteria would be selected for the evaluation of the post-use options. As it was mentioned earlier in chapter 3, there are two approaches for data gathering, interviews and literature review. It is important to compare all information in order to proceed to the development of the viability criteria for the post-use options.

Firstly, the evaluation of the information from the interviews will take place. More specifically, all interviews are going to be recorded and transcribed in order to capture the exact words of the interviewees. This gave the opportunity to watch again the interviews and then remove all information that might reveal the identity of the interviewees. Furthermore, due to the bad quality of the original transcribed document from MS Teams, it was necessary to correct the transcribed text based on the recordings. The final transcribed documents were used for the analysis of the data that was acquired from the interviews.

The interview research method has a final step which plays a crucial role, which is the analysis of the collected data (Weiss, 1995). For the purpose of this research, ATLAS.ti was used, which is a CAQDAS program, for the analysis of the interview data. The use of this software reduced significantly the time for the analysis and improved its accuracy. The method that was followed for the first cycle of the analysis on ATLAS.ti was a combination of structural coding and descriptive coding. Structural coding was selected because it is very suitable method for studies with multiple participants and semi-structured data gathering approaches (Saldaña, 2009). The code will be based on the fixed interview questions that were used in most of the interviews. However, some questions were not standardized and were used only in one interview. As a result, the use of descriptive coding was used in order to analyze the information that were retrieved from those questions. The use of key words was used for this purpose. In total 22 codes were used in the first cycle of the analysis of the data, which are presented on table 11 on Appendix D. After that the second cycle of the analysis took place where the codes were grouped based on the circular strategy that it was referred to, on the increase for circular concrete, on the reasons of the extensive degradation of the pipes and on crucial information for the evaluation of the potential post-use options. The data analysis is illustrated on figure 8. The results of the data analysis are presented on chapter 4.1.

Once the information from the interviews has been analyzed there are two objectives that had to be achieved. The first one is, that certain data that must be cross examined are going to be compared with information from the interviews and the theoretical framework. This fact will ensure the validity of the information and the development of the viability criteria will be based on reliable and realistic information. The second objective is to gain enough and accurate information for the evaluation of the viability of the potential post-use options for the test case of Rotterdam.

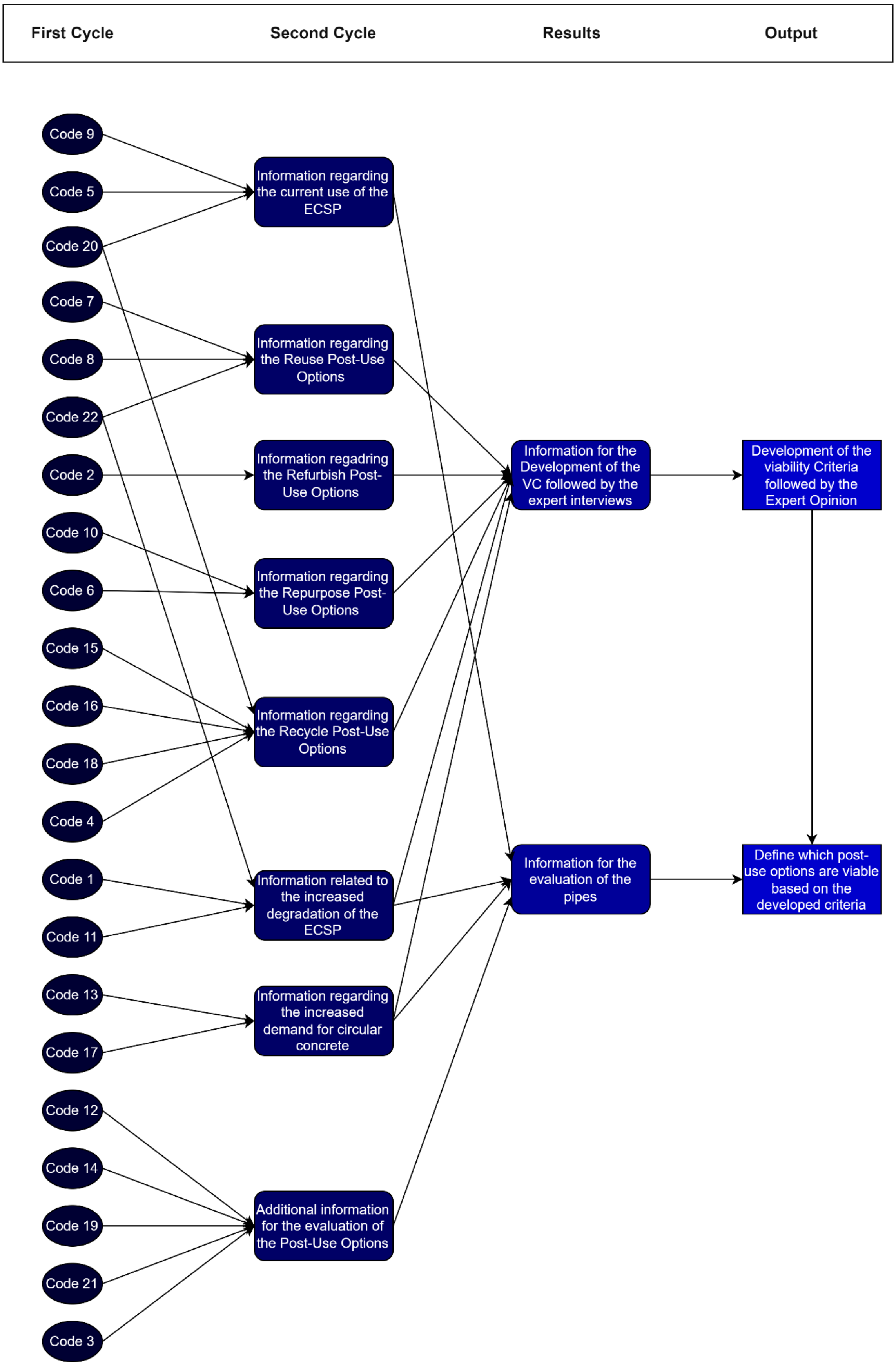

Figure 8: *Procedure of the analysis of the Interview data, Own Illustration.*

The second part is the development of the viability criteria that will evaluate the post-use options for the excavated concrete sewer pipes. In the context of this master thesis, the term of **viability is considered as the practical feasibility of a post-use option.** Those criteria are going to be developed by a combination of the data from the literature review and the analyzed data from the interviews. More specifically, from the literature review were collected criteria that were defined by the academics which evaluated the viability of post-use options of concrete materials. From the interviews some new criteria were developed based on the opinion of the experts. After that all viability criteria from those 2 different categories were grouped in order to identify if there are repetitions or contradictions between them. From this procedure the final viability criteria were developed. The development of the viability criteria for the evaluation of the post-use options for the excavated concrete sewer pipes is presented on Figure 9.

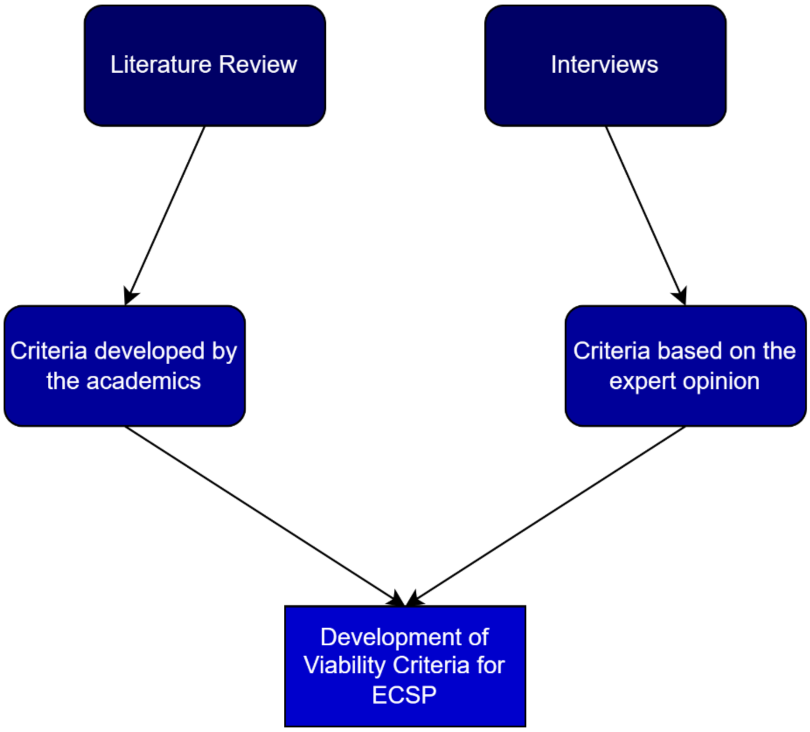

Figure 9: *Strategy of the development for the viability criteria, Own Illustration.*

When the final criteria were developed, are going to be used to evaluate the viability of the criteria for the test case of using the potential post-use options in the city of Rotterdam.

From the evaluation process several conclusions and insights will be gained which are going to be explained. Based on those conclusions, suggestions for further research or improvements will be presented in chapter 5.

An overview of the research strategy and different phases of the master thesis are presented in Figure 10. It can also be observed how the data will be gathered for every section of the master thesis.

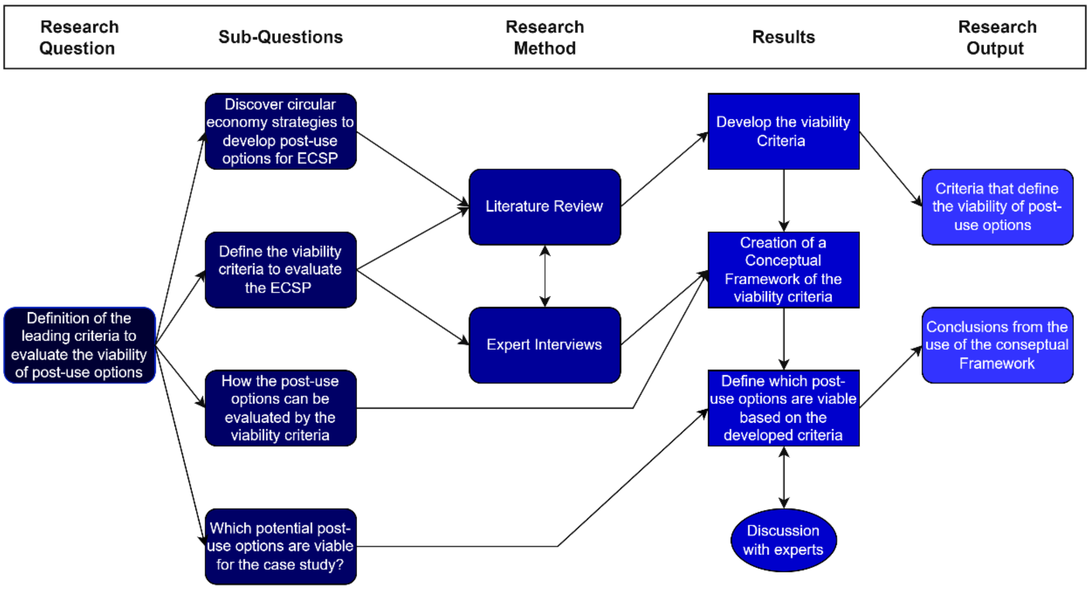

Figure 10: *Overview of the Research Strategy, Own Illustration.*

Chapter 4: Analysis & Results

On Chapter 4 the core part of this master thesis is presented. On section 4.1 are mentioned data that were obtained from the interviews and the viability criteria that were developed based on the expert opinion. On subchapter 4.3 are presented the analysis of the viability criteria that were retrieved by the academics. On chapter 4.4 is presented the development of the conceptual framework for the evaluation of the excavated concrete sewer pipes. Lastly, on section 4.5 are presented the learnings from applying viability criteria to the case of concrete sewer pipes within the municipality of Rotterdam.

4.1 Viability Criteria Followed from Expert Interviews

In the subchapter is presented the development of the viability criteria followed by the expert interviews. The interview results are grouped by the circular strategy that they referred to. The data related to the increased degradation of the sewer pipes and the information regarding the increased demand for circular concrete are also presented in separate sections. This Approach is illustrated in Figure 11. Lastly, information about the concrete sewer pipes in Rotterdam are also provided in this chapter, which was used for the evaluation of the post-use options that is presented on chapter 4.5.

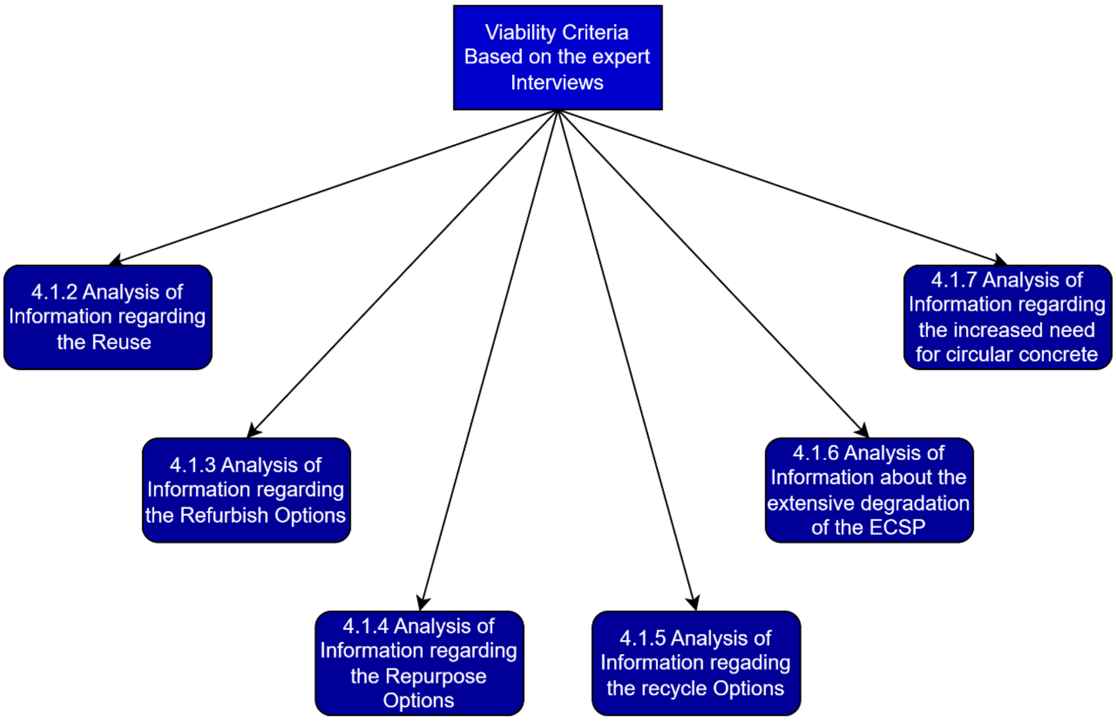

Figure 11: *Virtual Representation of the analysis of the information that were combined for the development of the Viability Criteria followed from Expert Interviews, Own Illustration.*

4.1.1 Current Management of the excavated concrete sewer pipes in Rotterdam

Each year, the city of Rotterdam aims to replace approximately 40 kilometers of aging sewer pipes. However, as Adv1 noted, "They usually replace 32 to 35 kilometers of pipes per year." Currently, the decommissioned sewer pipes are sold to the Ministry of Water Management and Infrastructure for use in breakwater construction or sent to recycling facilities. According to Eng1, due to time constraints, the concrete sewer pipes are often not carefully extracted from the ground, resulting in damage.

Before being sent to the breakwater or recycling installations, a specific cleaning process is adhered to. PL1 explained, "The rings that connect the pipes and all synthetic materials used in the connection must be removed. Additionally, organic materials, rubber, and coatings must be eliminated. Failure to do so would result in the municipality incurring higher costs from the recycling facility. Therefore, thorough cleaning of the concrete sewer pipes is necessary." Adv1 also added, "Before the removal from the ground takes place, the sewer pipes are cleaned from the inside. They also investigate whether the soil surrounding the pipes is polluted." During the cleaning procedure, a machine is used to clean the pipes, by ejecting pressurized water at 2.5 bars to remove dirty materials from their inner part. PL1, PM2 and Adv1 are responsible for managing the concrete sewer pipes after they have been excavated from the ground. As a result, they are also involved with the two post-use options of the sewer pipes that are used currently by the Municipality of Rotterdam. Those are to recycle them in the breaking installation or repurpose them in the breakwater construction.

The replacement of the old sewer pipes is part of Rotterdam's broader initiative to renew and expand its sewer system. The used concrete sewer pipes are currently replaced with either new concrete or PVC pipes. There are two variants of the new concrete sewer pipes: one made entirely of new concrete and another comprising 50% recycled concrete.

4.1.2 Viability Criteria for post-use options based on the Reuse strategy

Most interview participants were asked to provide their experiences on the potential post-use option of reusing concrete sewer pipes within the sewer system. These participants acknowledged that concrete pipes are designed to have a lifespan of 40 to 60 years but are typically replaced around their 40th year. This earlier replacement is due to the accelerated degradation that is detected in the concrete sewer pipes. PM1 remarked, "The conditions within a pipe cause extensive corrosion, which necessitates their replacement every 40 years and also complicates their reuse potential." PM1 added, "It's actually hardly possible to reuse them. The reason for this is that they have reached the end of their lifetime." All participants expressed significant reluctance towards the reuse potential of the excavated concrete sewer pipes due to their advanced degradation. Additionally, PM1, PL1 and Adv3 noted that only new sewer pipes are currently used for the renewal and construction of the sewer system.

Furthermore, Eng1 and PM2 highlighted that sewer projects in large cities like Rotterdam significantly impact the daily lives of local residents. Sewer pipes are typically located beneath roads, which leads to road closures for their replacement. This situation generates additional pressure on site workers to speed up the removal of old pipes, often resulting in further damage. PM2 noted that reusing used sewer pipes with minimal degradation requires detailed investigation and testing, to ensure their structural integrity or to detect any extensive deformation due to the level change. TM1 stated, "The reuse option is not a good option for the sewer pipes because, based on the opinion of the asset managers, the pipes have significant degradation and vary in size, making reuse quite difficult.”

One key consideration mentioned is the depth at which the pipes are to be laid. The deeper the pipes are, the greater the weight above them, and the traffic on the street above also affects the pipe's thickness and durability.

Based on the information provided by the experts regarding the reuse option of the old sewer pipes in the sewer system, two viability criteria that arise. **First, the concrete sewer pipes must have a minimum remaining lifetime of 40 years.** As it was mentioned by several interviewee’s there is no point on reusing a sewer pipe if it cannot last at least 40 years.

Second, **the strength of the used pipes must meet a minimum level that it will ensure that they can withstand the loads that they will be exposed to**, for the next 40 years. No user of the old sewer pipes will be willing to reuse them unless they are confident that their structural capacity can resist the expected loads. This is also related to the depth that the pipes will be placed and the type of road that will be above them, as deeper placements and heavier traffic loads force more pressure on the pipes.

4.1.3 Viability Criteria for post-use options based on the Refurbish Strategy

During the interviews, respondents were asked about the refurbishment options for concrete sewer pipes. Their opinions were predominantly negative for several reasons, many of which were quite similar to the challenges associated with reuse. The primary concern, highlighted by PM1, TM1 and Eng1, was the significant degradation of the old sewer pipes, which makes refurbishment particularly challenging and practically not possible. Eng1 noted, "In Rotterdam, most of the pipes are quite damaged, making it very difficult to reuse them as they are or to repair and reuse them." The extent of corrosion varies due to soil consolidation, which in certain areas of Rotterdam can be as much as 40 cm. Consequently, some sewer pipes may be broken, with inconsistent thickness along their length. This variance occurs because, due to ground settlement, some parts of the inner surface of the pipes are submerged in water, preventing degradation from sulfuric acid, while other parts that are not covered by water are heavily degraded. Thus, these respondents indicated that the concrete sewer pipes are already quite old and damaged, and the cost of repair would be substantial. Additionally, the risk is considerable, as it is difficult to ensure that refurbished sewer pipes could last another 40 years.

Moreover, Adv3 added that this option would only be beneficial if the refurbishment costs are low and if the refurbishment facility is located close to the site where the pipes are removed and replaced. If the facility is not local, the environmental cost would be high, negating any environmental benefits of the process. As a result, it is crucial to be a local procedure. If refurbishment is not local, the environmental costs will rise, and the transportation process will exacerbate traffic problems.

From the information shared by the experts for the refurbish option, two viability criteria must be considered. First the **refurbished concrete sewer pipes must have a minimum lifetime of 40 years.** Second the **refurbish procedure must be conducted locally.** If the last condition cannot be achieved, the environmental cost and financial cost will be very high.

4.1.4 Viability Criteria for post-use options based on the Repurpose Strategy

Currently, some used concrete sewer pipes are sold to the Ministry of Infrastructure and Water Management for use in breakwater construction. Approximately half of the interviewees expressed that this has been a beneficial solution for the city, as it generates revenue from the sale of these pipes. In fact, Adv1 noted, “Rijkswaterstaat gives 10 euros per meter of sewer pipe regardless of its diameter to the Municipality.” The concrete sewer pipes are either broken to form the foundation of the dams or used intact for the upper parts of the dams. There is no limitation on the size of the concrete sewer pipes used for breakwater construction, provided they originate from the municipal wastewater system and not from the industrial sewer system. Last year, approximately 5 kilometers of concrete sewer pipes were sold to Rijkswaterstaat for breakwater construction. The aim is to increase the amount of pipes repurposed to the breakwater construction.

The primary reason for the positive responses of this reuse option among participants was financial. Adv1 mentioned, “Instead of paying money to recycle them, the city earns money by selling them to breakwater construction projects.” However, before being sent to the construction site, the concrete sewer pipes must be cleaned to remove rubber rings, coatings, and all synthetic materials used in the connections.

Given the positive appraisal of this post-use option by experts, the only additional viability criterion is **that the Municipality should be compensated when concrete sewer pipes are repurposed in projects outside of the city**. Otherwise, circular concrete is removed from the city’s construction cycle.

The second repurpose option involves using old sewer pipes as underground water tanks for rainwater. Experts expressed several concerns about this post-use option. The primary issue is the cost of preparing and installing the pipes, which must not exceed the value of the structure, a value depended on the pipes' durability. The uncertain endurance of these pipes characterizes this option as risky. Another significant concern raised by respondents is the potential pollution of the concrete walls of the sewer pipes. These walls might be contaminated by sewer water or iron from groundwater that entered through cracks. Therefore, it is crucial to specify the intended use of the stored rainwater, as environmental quality standards for drinking water are very strict, and any pollution could limit the usability of the rainwater. Eng1 stated, “If you use the old pipes for temporary storage and then disperse the water into the current sewer system, environmental quality might not be a problem.”

Additionally, two other factors contributed to the experts' reluctance regarding this repurpose option: the strength and shape of the used pipes. Typically, pipes are placed beneath highways, necessitating their ability to withstand traffic loads. However, assessing the strength of used sewer pipes is challenging due to their reduced thickness. When placed under roads, these pipes must withstand high traffic loads, and their compromised strength might be insufficient. Furthermore, because of their round or egg shape, placing multiple pipes next to each other for water storage results in significant space taken up by the concrete, reducing the effective storage area. This space inefficiency could be mitigated by using materials with different shapes. Lastly, storing water in used pipes is problematic due to frequent damage to the connections, making it difficult to reconnect them without leaks.

Based on the opinion of the experts some viability criteria that are relevant to the post-use option of the concrete sewer pipes being used as underground water tanks. Firstly, the pipes must be in **a good condition that will allow them to have the strength** to withstand the loads across their lifecycle and to **prevent the rainwater from leaking**. Another important aspect that was addressed by the experts is that the concrete sewer **pipes can only contain rainwater that will be later discharged to the sewer system,** to prevent a potential contamination of the drinking water.

4.1.5 Viability Criteria for post-use options based on the Recycle Strategy

The excavated concrete sewer pipes can be recycled through breaking installations or smart crushers. Currently, the city of Rotterdam employs two breaking installation companies to recycle a portion of their concrete sewer pipes. According to AS2, the Municipality pays 10 Euros for every ton delivered to these facilities. The sewer pipes must be cleaned according to the procedure described in sub-chapter 4.1.1. If the pipes are not properly cleaned, the Municipality is burdened with additional costs. Adv1 explained that if recycled concrete is needed, it must be repurchased from the breaking companies: “The Municipality pays to destroy them and then has to pay again to buy them back if they want circular aggregates or cement.”

A significant finding by the researcher was the strong emphasis by participants on the importance of recycling concrete materials and the increasing demand for circular concrete. PM1 stated, “The aggregates from concrete sewer pipes can be very useful in the production of circular concrete.” Circular cement is necessary for new construction projects and is also used in Repack, a product containing 50% recycled concrete, utilized in road foundations. RE1 elaborated, “The base layer of roads consists of 50% recycled concrete products and 50% materials from recycled masonry parts.”

RE1, Adv2 and Pm2 highlighted the significance of the Beton Akkoord deal, which is related to the recycling prospects of sewer pipes. They noted that this deal has increased the demand for circular concrete in construction projects. Consequently, more clean recycled concrete is being acquired by construction companies for high-quality construction projects, reducing its availability in the Repack mix. As RE1 noted, “Nowadays, the good quality recycled concrete is being removed from Repack because it is needed for new construction projects.”

Adv2 emphasized the importance of recycling concrete by stating, “All waste concrete should return to the concrete cycle. Therefore, the construction industry must be very precise and careful about managing old concrete, including sewer pipes. There is likely a need to develop an optimized method for reusing these old sewer pipes.” Participants generally expressed positive views on recycling concrete sewer pipes, linking this option to the growing demand for circular concrete.

A crucial factor in determining the post-use of recycled concrete is whether it meets environmental standards, to define if it is considered “clean”. For instance, concrete contaminated with oil or other pollutants cannot be used as a foundation for new roads according to environmental laws. Consequently, concrete is classified as either clean or not clean, as described by experts. However, none of the participants could definitively state whether recycled concrete sewer pipes would yield clean concrete.

The experts shared their opinion towards the recycle post-options of the concrete sewer pipes. From the analysis of that information a viability criterion that must be developed is **if the recycled concrete from concrete sewer pipes could be used again.** Despite the anticipated increase in demand for circular concrete, it must be determined if this type of recycled concrete is suitable for use. Another viability factor is **if the post-use option could cause delays to sewer system construction projects**, because those projects have a significant influence on the transportation of the local residents.

To date, smart crushers have not been utilized for recycling sewer pipes, as reported by the interview participants. However, one participant provided information regarding an experiment conducted to determine the amount of clean products that could be generated from recycling a concrete sewer pipe using a smart crusher. Adv2 explained that 40 tons of old sewer pipes were delivered to a recycling company. These pipes were initially crushed in a conventional breaker into pieces of 400 mm. Subsequently, a sieve of 0 to 40 mm was used to remove the smaller pieces from this initial breaking, as contamination tends to be concentrated in these smaller fragments. Adv2 noted, "After this first step, from the original 40 tons, only 24 tons remained, meaning that 16 tons consisted of contaminated material."

In the second step, the smart crusher was used to further break down these smaller pieces. The result was that only 6 tons out of the original 40 remained suitable for reuse. Adv2 that, following this experiment, the recycling company decided not to use the smart crusher for recycling concrete sewer pipes, as the majority of the recycled material could not be reused. This indicates that this recycling method is less efficient compared to conventional breaking installations.

From the experimental use of the smart crusher on recycling concrete sewer pipes a factor regarding the viability of the post use options is derived. More specifically, **a post-use options must be able to maintain the majority of the materials of the excavated concrete sewer pipes.** Otherwise, it will generate a significant amount of waste which is not a desired outcome for a circular post-use option.

4.1.6 Viability Criteria followed by the increased degradation of the sewer pipes

A point of emphasis during the interviews was the determination of the causes behind the advanced degradation of sewer pipes. It was discovered that certain chemical substances in the sewer water are responsible for the degradation of the inner walls of these pipes. PM1 explained, “The chemical degradation caused by H_2SO_4 (sulfuric acid) is harmful to concrete products. This highly aggressive acid, produced in the sewer system, significantly reduces the thickness of pipes. For instance, the thickness of a pipe has been reduced from 7 cm to 2 cm due to this acid, which destroys the concrete. Specifically, the cement is eroded by the acid, causing the aggregates to remain on the wall of the pipe and eventually detach as the cement continues to deteriorate. Thus, when concrete aggregates become visible on the inside walls of a sewer pipe, chemical degradation has already begun.” The degradation from sulfuric acid is usually more pronounced at the upper sections of the sewer pipes, as the acid's density is higher in the air. Sulfites penetrate the concrete, particularly affecting the upper parts of the inner pipe more than the lower parts.

This chemical pollution could impact the post-use options for the excavated concrete sewer pipes. RE1 elaborated, “There might be an issue with using materials from concrete sewer pipes because they contain large amounts of sulfites. When using or reusing broken aggregates from sewage pipes in the base layer of roads, the leaching of sulfur must be assessed.”

Additionally, the high density of aluminum detected in recycled products from concrete sewer pipes poses another problem. Adv2 explained that aluminum is found in the bottom ashes from furnaces and final grades. They noted, “Aluminum in concrete reacts with oxygen, creating light oxygen cells, which reduce the density and ultimately the strength of the concrete.” This could affect the usability of recycled aggregates, as RE1 pointed out, “Breaking companies have certain requirements, and they might not accept materials from household waste. The BRL 2506 standard limits the amount of ashes acceptable in the reuse of recycled aggregates.”

In addition to sulfuric acid, Eng1 and PM2 identified two more significant factors responsible for the advanced degradation of concrete sewer pipes. Time pressure is a critical factor that influence the viability of the post-use options, as the renewal of a city's sewer system causes traffic disruptions. The necessity to quickly replace sewer pipes and reopen roads adds pressure on onsite workers and engineers, leading to less careful removal of old sewer pipes. Consequently, the used pipes are further damaged during their extraction from the ground.

Another factor contributing to the poor condition of used sewer pipes is ground settlement. This phenomenon is influenced by the varying soil types across the city. In some areas, the ground is solid and remains stable over time. However, in other areas with substantial clay layers, the ground settles, causing level drops in the pipelines. These variations in ground levels can break the pipes or their connections and affect the chemical degradation of their inner parts. As described earlier, the inner surface above the sewer water level is more vulnerable to extensive corrosion by sulfuric acid.

Based on the experts’ insights regarding the extensive degradation some viability criteria must be developed. **The potential chemical pollution of the concrete sewer pipes might affect the post-use options** therefore it has to be considered.

Products derived from recycled concrete sewer pipes are highly likely to be incorporated into new circular concrete, but the issue of chemical degradation must be addressed. PM2 and Adv2 explained that the structure of the new sewer system has evolved, with old pipes being replaced by two new ones: one for sewer wastewater and another for rainwater. This change implies an increased concentration of sulfuric acid within the pipes. However, as Adv2 noted, “The specifications for concrete sewer pipes have not changed, even though they will face a more aggressive environment. This increases the need for more resistant concrete to withstand these conditions and allow the pipes to reach their expected lifetime.”

The unchanged standards increase significantly the likelihood that these pipes will need to be replaced earlier than their intended 40-year lifespan. This scenario will further increase the number of concrete sewer pipes replaced annually, consequently raising the volume of old concrete.

4.1.7 Viability Criteria followed by the increased demand for circular concrete

During the interviews, a new factor arise that was not considered in the early stages of the research: the increased demand for circular concrete in Rotterdam and across the Netherlands. This demand is driven by the Beton Akkoord deal, which must be fully implemented by 2030. According to PL1, the Municipality of Rotterdam has a contract with a breaking installation company, which dictates that clean concrete delivered to them must be made available to the city's construction industry. This arrangement means that the Municipality does not necessarily repurchase the recycled concrete; instead, construction companies undertaking projects in Rotterdam have the option to purchase the recycled concrete from the breaking company.

The Municipality of Rotterdam according to PL1, aims to stimulate the market for recycled concrete by offering advantages in tendering procedures to construction companies who use it. For instance, products made of recycled concrete receive extra points in tenders, leading to a virtual discount. Although recycled concrete products may have a higher initial price, this virtual discount allows them to achieve a better score than competitors offering regular concrete. The goal is to encourage the market to develop innovative, environmentally beneficial ideas. Consequently, construction companies would be more willing to buy circular concrete from old sewer pipes. However, they must be assured that the material is clean and suitable for use.

At least half of the respondents mentioned that it is necessary to have several post-use options available because there is a big need for recycled concrete in the industry. They explained that relying on a single option may not always be optimal, and it is crucial to ensure a continuous supply of recycled concrete for the construction industry. Based on the importance of maintaining the availability of circular concrete to the construction industry, a viability criterion that must be mentioned is whether **the post-use option contributes to the demand for circular concrete**. The contribution of circular concrete to the construction industry can be achieved directly, by recycling the sewer pipes and making available their products for reuse, or can be achieved indirectly, when the post-use option reduces the demand for circular concrete. For example, if a sewer pipe is being reused, the circular concrete that would have been used for producing a new sewer pipe can be used elsewhere.

Another crucial factor that has to be considered is the environmental cost indicator. This value can quantify the environmental impact of the post-use option especially when a sewer pipe is refurbished or repurposed. As a result, the viability of a post-use option can be determined by **the evaluation of the environmental cost indicator.**

4.1.8 Summary of Viability Criteria followed by the expert opinion

To summarize the viability criteria for the post-use options of the excavated concrete sewer pipes, they are all presented in table 3. The criteria are divided into 5 categories. The first category is called general. All post-use option must fulfill those criteria to be considered viable. The rest of the categories referred to every circular strategy of the post-use options. Those are the reuse, the repurpose, the refurbish and the recycle strategy. Every post-use option must also fulfill the criteria that are applicable to their category, based on the circular economy strategies. The criteria that are developed based on the expert opinion are called Expert Criteria (ExC).

Table 3: *Viability Criteria based on the expert opinion.*

Viability Criteria Based on the Expert Interviews		
General	ExC1	The post-use option is not affected by a potential chemical pollution of the concrete sewer pipes.
	ExC2	The evaluation of the environmental cost indicator is positive.
	ExC3	The post-use option contributes to the demand for circular concrete.
Reuse	ExC4	The concrete sewer pipes have a minimum remaining lifetime of 40 years.
	ExC5	The strength of the used pipes meets a minimum level that ensures they can withstand the loads that they will be exposed to.
	ExC13	A post-use option does not disturb or cause significant delays to the construction of sewer system.
Repurpose	ExC6	Their strength allows to withstand the loads across their lifecycle and to prevent the rainwater from leaking.
	ExC7	The used sewer pipes can only contain rainwater that will be later discharged to the sewer system.
	ExC8	The Municipality is compensated when concrete sewer pipes are repurposed in projects outside of the city.
	ExC13	A post-use option does not disturb or cause significant delays to the construction of sewer system.
Refurbish	ExC9	The concrete sewer pipes have a minimum remaining lifetime of 40 years.
	ExC10	The strength of the used pipes meets a minimum level that ensures they can withstand the loads that they will be exposed to.
	ExC11	Any refurbish procedure is conducted locally.
	ExC13	A post-use option does not disturb or cause significant delays to the construction of sewer system
Recycle	ExC12	A recycle post-use options maintains most of the materials of the excavated concrete sewer pipes.

4.2 Viability Criteria Followed from the Desktop Research

On chapter 2.5 are presented several criteria that have been developed by the academics to evaluate the viability of post-use options for concrete materials. In this chapter, is explained which of them can be applied to the evaluation process of the excavated concrete sewer pipes. All potential viability criteria are presented on Table 5.

Table 4: *Viability Criteria based on the Academic Literature.*

Viability Criteria Based on the Academics		
AcC1	Waste Hierarchy based on the circular strategies	Rejected
AcC2	Accurate Estimations of the strength and condition of the sewer pipes.	Selected
AcC3	Assessment of the End-of-Life Impact Indicator	Rejected
AcC4	Efficient use of the natural resources of the material	Selected
AcC5	Evaluation of the Life Cycle Costs	Rejected
AcC6	Evaluation of the costs associated with disassembling the product at EoL.	Rejected
AcC7	Compliance with National & EU Legislation	Selected
AcC8	Estimation of the Technical State of the Material	Rejected
AcC9	Estimation of the Separability of Materials	Rejected
AcC10	Assessment of the demand for the post-use option.	Rejected
AcC11	Estimation of the Customer Satisfaction.	Rejected
AcC12	Evaluation of the volume of materials that can be returned and processed by the post-use option.	Selected
AcC13	The overall financial cost of the post-use option.	Rejected

In table 5 is also illustrated which academic criteria (AcC) are selected and which are rejected from the final evaluation process of the excavated concrete sewer pipes. In total 4 are selected and 9 are rejected from the final evaluation process. AcC2 is also selected because the condition of the pipes can play a major role in the viability of the post-use option, a fact that was also highlighted by the experts. AcC4 is selected for the recycle post-use option, to minimize the waste generation from the recycling post-use options. Furthermore, all post-use options must be in accordance with the national and Eu regulations. For that reason, AcC7 is selected for the evaluation process. Lastly, AcC12 is selected because the goal of the post-use options is to maximize the use of materials of the sewer pipe, especially in the recycle post-use options.

From the evaluation criteria that were described in academic literature and are described on chapter 2.5 and are also presented on table XX, some cannot be used for the evaluation of the excavated concrete sewer pipes. Firstly, AcC1 is rejected because a waste management hierarchy will prioritize a potential post-use option compared to another one and will not define its viability. Moreover, AcC3 suggests the evaluation of an indicator that presents the environmental impacts associated with the product's end-of-life phase. A similar estimation will be done by the evaluation of the Environmental Cost Indicator, that is mentioned in criterion ExC2. For the same reason AcC5 is also rejected, and because the only difference between the concrete sewer pipes is their size which will not have a big influence on the estimation of the lifecycle costs before the post-use option. Moreover, an estimation of the lifecycle costs is going to increase significantly the complexity of the evaluation process of the excavated concrete sewer pipes.

The next factor that was rejected is AcC6 that evaluates the disassembly costs of the post-sue option. This could have been a criterion worth considering but in the context of this master thesis only excavated concrete sewer pipes are considered, which means that their disassembly costs must be considered because they have already been removed from the city's sewer system. AcC8 is referred to the evaluation of technical state of the concrete sewer pipe. This is a very important aspect of the evaluation of the post-use option, but this factor is included in AcC2. As a result, AcC8 is rejected. The separability of the materials, which is described by AcC9, is mainly referred to recycle post-use options and is equivalent to AcC12 because if the post-use option cannot divide the materials efficiently, then the recycled volume of materials drops. Criteria AcC10 evaluates the potential demand for the post-use option, but the majority of the options is managed inside the organization, therefore this factor would not be able to be applied in the majority of the post-use options. Therefore, AcC10 is rejected. For the same reason AcC11 is also rejected. The last viability factor that was defined by the academics is AcC13 which is also rejected. The reason for that is, that costs must not be a viability factor in circular use-options because it does not consider the benefits of those options. This fact was also highlighted by the experts.

The viability criteria that were developed by the academics and selected for the evaluation of the excavated sewer pipes and they will be part of the conceptual framework which is developed on Chapter 4.4. The 4 selected criteria are summarized on table 6.

Table 5: *Selected criteria which were developed by the academics.*

Viability Criteria Based on the Academics		
AcC2	Accurate Estimations of the strength and condition of the materials	Selected
AcC4	Efficient use of the natural resources of the material	Selected
AcC7	Compliance with National & EU Legislation	Selected
AcC12	Evaluation of the volume of materials that can be returned and processed by the post-use option.	Selected

4.3 Development of the Conceptual Evaluation Framework

On this chapter the viability criteria that were developed on chapters 4.1, and 4.2 and are presented in table 3, and table 6 respectively, must be combined. The viability criteria will form a conceptual framework that would be used for evaluating the viability of post-use options for excavated concrete sewer pipes. However, before the development of the final viability criteria, the summary the most important factors that were derived from the research and affected the development of the criteria must be presented. Those factors are summarized on table 7.

Table 6: *Summary of the Factors that affect the viability of the post use options*

Factors that affect the viability of the Post-use Options	
Category	**Factors**
Characteristics of the Sewer pipes	Remaining Lifetime.
	Strength of the Sewer Pipes.
	Condition of the Connections.
Operational Factors	Impact on the construction process.
	Limitations from the Chemical Pollution.
Environmental Factors	Environmental Cost Indicator.
	Contribution to the demand for circular concrete.
Policy Factors	Compliance with EU & National Regulations.

The first step for the development of the framework is to identify if some viability criteria that were developed by a different analysis, have an overlap. If there is an overlap, it means that practically the same criterion was developed through different types of analysis (Ex. By academic literature and expert interviews), and it will be considered as a combined viability criterion (CmA). The first criterion that has an overlap with other is AcC2, which is similar to ExC5, ExC6 and ExC10. Those criteria all referred to the strength and technical condition of the pipe and how it can affect the viability of a post-use option, a factor that was highlighted by both academics and experts. As a result, these criteria are combined and form criterion CmC1. The second overlap that was detected is between AcC4, AcC12 and ExC12. Those criteria referred to the efficient use of the materials of the sewer pipe when it is recycled. As a result, those criteria are combined, and they will be considered as CmC2. All viability criteria that will form the basis for the evaluation of the viability of the post-use options are presented on table 8.

__Table 7:__ Viability Criteria for the evaluation of the post-use options.

Selected Viability Criteria		
General	**ExC1**	The post-use option is not affected by a potential chemical pollution of the concrete sewer pipes affects the post-use options.
	ExC2	The evaluation of the environmental cost indicator is positive.
	AcC7	Compliance with National & EU Legislation.
	ExC3	The post-use option contributes to the demand for circular concrete.
Reuse	**ExC4**	The concrete sewer pipes have a minimum remaining lifetime of 40 years.
	CmC1	The strength of the used pipes meets a minimum level that it will ensure that they can withstand the loads that they will be exposed to.
	ExC13	A post-use option does not disturb or cause significant delays to the construction of sewer system.
Repurpose	**CmC1**	Their strength allows to withstand the loads across their lifecycle and to prevent the rainwater from leaking.
	ExC7	The used sewer pipes can only contain rainwater that will be later discharged to the sewer system.
	ExC13	A post-use option must not disturb or cause significant delays to the construction of sewer system.
	ExC8	The Municipality is compensated when concrete sewer pipes are repurposed in projects outside of the city.
Refurbish	**ExC9**	The concrete sewer pipes have a minimum remaining lifetime of 40 years.
	CmC1	The strength of the used pipes meets a minimum level that it will ensure that they can withstand the loads that they will be exposed to.
	ExC13	A post-use option does not disturb or cause significant delays to the construction of sewer system.
	ExC11	Any refurbish procedure is conducted locally.
Recycle	**CmC2**	A recycle post-use options maintains most of the materials of the excavated concrete sewer pipes.

The viability criteria are divided into 5 categories. The first category is called general and all post-use options must fulfill the 5 viability criteria that are in this group. The remaining 4 categories represent the circular economy strategies that can be applied on the excavated sewer pipes and all post-use options that were developed, were based on them. As a result, each post-use option must also fulfill the criteria that belong to the category that is applicable to the post-use option. If the post-use option fulfills the criteria of the general category and those from its circular category then it is considered viable. This procedure is illustrated on Figure 12.

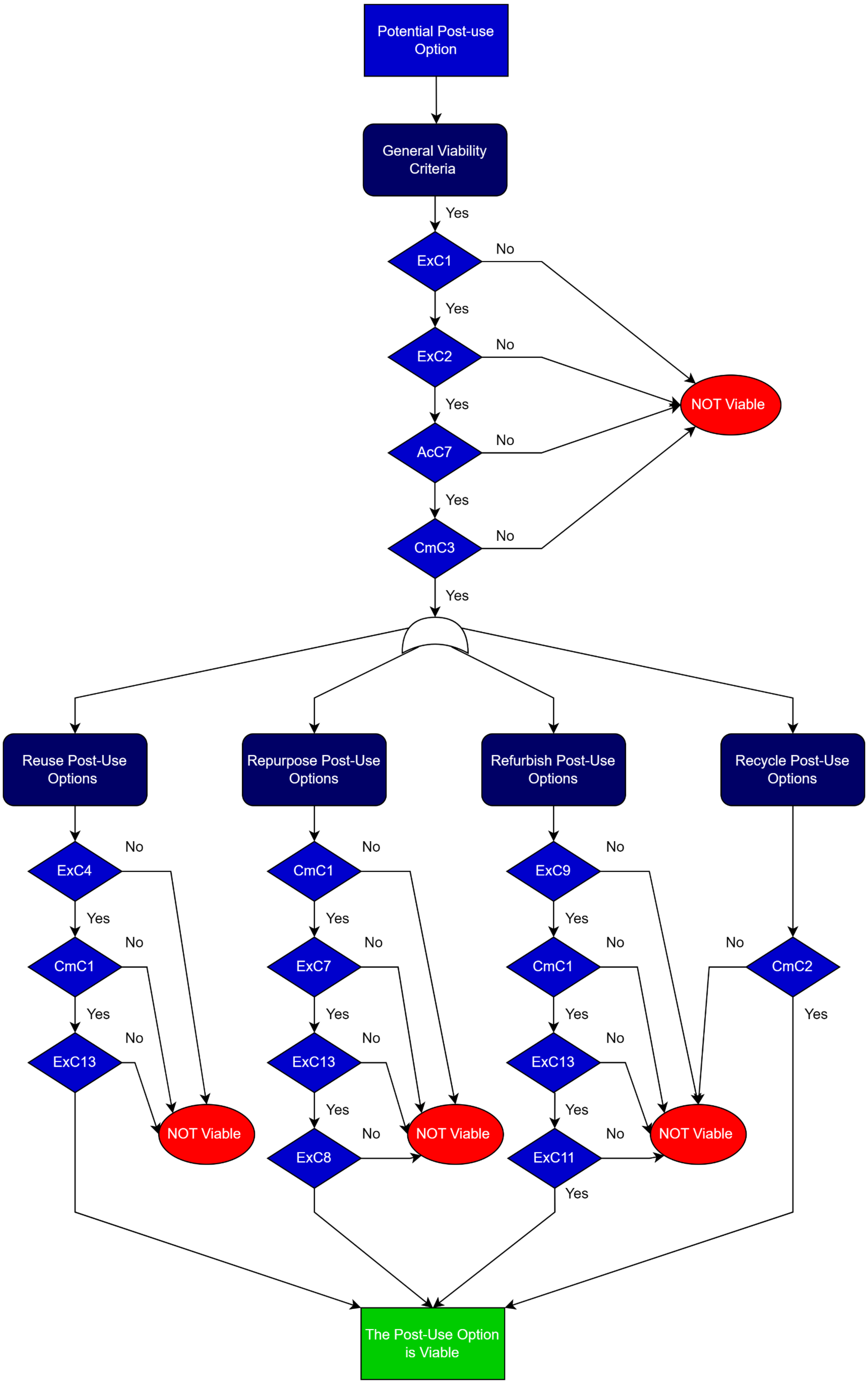

Figure 12: *Conceptual Framework for the Evaluation of the Post-Use Options for Excavated Concrete Sewer Pipes, Own Illustration.*

4.4 Evaluation of the Potential Post-Use Options for the test case of the Municipality of Rotterdam

The evaluation framework was applied to the 7 post-use options that were developed and are presented on Chapter 2.7. The evaluation of the post-use options was based on the information that were gathered from the interviews for the test case of excavated concrete sewer pipes in Rotterdam. The evaluation process and its results are presented on table 9.

On the right side of the table are the post-use options and their evaluation for every viability criterion that is applicable to them. The column with the Reuse is referred to the post-use option which the concrete sewer pipes would be used again as concrete sewer pipes in the sewer system of the city. As refurbish 1 is considered the post-use option that the pipes would be refurbished by using the CFRP method and then used again as concrete sewer pipes. As refurbish 2 is considered the post-use option that the pipes would be refurbished by using the Slip Lining method and then used again as concrete sewer pipe. As repurpose 1 is considered the post-use option which the sewer pipes would be used in the breakwater construction as part of a breakwater construction. As repurpose 2 is considered the post-use options of using the pipes as underground waters tank to retain the rainwater for a short period of time. As Recycle 1 is addressed the post-use option of recycling the concrete sewer pipes by using a conservative breaking installation and as Recycle 2 by using a Smart Crusher.

The use of the term “Pass” is used when the post-use options is considered viable and “FAIL” when it is not considered viable. The term “N/A” is used when the criterion in not applicable to the post-use options and the term “N/D” when there were not enough data to evaluate the option by that specific viability criterion. On the last row of table 9 are presented the results of the evaluation of the viability for every post-use option. It must be noted that, as it was explained on chapter 4.4, a post-use option will be considered viable if it fulfils all viability criteria from general category and from the category that is applicable based on the circular strategy that the post-use options belong to.

According to the results of the evaluation framework, only 2 out of the seven potential post-use options are considered viable for the test case of the Municipality of Rotterdam. Those are to recycle the concrete sewer pipes by used a conservative braking installation and to be repurposed in the breakwater construction. Those results are in accordance with the test case that the Municipality has conducted to repurpose the pipes to the breakwater construction. The results were the desired and this post-use option is slowly adopted by the Municipality of Rotterdam. The 5 remaining post-options did not fulfil all viability requirements based on the framework. However, it must be explained which of the viability requirement these options were not able to meet.

The first post-use option that was evaluated, is the option to reuse the concrete sewer pipes again to the sewer system. According to PM1, PL1 and Adv3 the excavated sewer pipes are in bad condition due to extensive corrosion, and they have reached their 40th year of age. As a result, their remaining lifetime is far less than the minimum of years and it is highly unlikely that their strength is the required level to withstand the loads. Based on these findings this option failed criteria EcC4 and CmC1 and it is not considered viable. Detailed information regarding the reuse potential of the pipes is provided on subchapter 4.1.3.

Table 8: *Evaluation of the potential post-use options for the test case of the Municipality of Rotterdam*

Evaluation of the Potential Post-Use Options									
Viability Criteria			Potential Post-Use Options						
			Reuse	Refurbish 1	Refurbish 2	Repurpose 1	Pepurpose 2	Recycle 1	Recycle 2
General	ExC1	The post-use option is not affected by a potential chemical pollution of the concrete sewer pipes affects the post-use options.	PASS	PASS	PASS	PASS	PASS	PASS	PASS
	ExC2	The evaluation of the environmental cost indicator is positive.	N/A	N/A	N/A	PASS	N/A	N/A	N/A
	AcC7	Compliance with National & EU Legislation.	PASS	PASS	PASS	PASS	PASS	PASS	PASS
	CmC3	The post-use option contributes to the demand for circular concrete.	PASS	FAIL	PASS	PASS	PASS	PASS	PASS
Reuse	ExC4	The concrete sewer pipes have a minimum remaining lifetime of 40 years.	FAIL						
	CmC1	The strength of the used pipes meets a minimum level that ensures that they can withstand the loads that they will be exposed to.	FAIL						
	ExC13	A post-use option does not disturb or cause significant delays to the construction of sewer system.	PASS						
Repurpose	CmC1	They have the strength to withstand the loads across their lifecycle and to prevent the rainwater from leaking.				N/A	FAIL		
	ExC7	The used sewer pipes can only contain rainwater that will be later discharged to the sewer system.				N/A	PASS		
	ExC13	A post-use option does not disturb or cause significant delays to the construction of sewer system				PASS	PASS		
	ExC8	The Municipality is compensated when concrete sewer pipes are repurposed in projects outside of the city.				PASS	N/A		
Refurbish	ExC9	The concrete sewer pipes have a minimum remaining lifetime of 40 years.		FAIL	FAIL				
	CmC1	The strength of the used pipes meets a minimum level that ensures that they can withstand the loads that they will be exposed to.		FAIL	FAIL				
	ExC13	A post-use option does not disturb or cause significant delays to the construction of sewer system.		PASS	PASS				
	ExC11	Any refurbish procedure is conducted locally.		PASS	PASS				
Recycle	CmC2	A recycle post-use options maintains most of the materials of the excavated concrete sewer pipes.						PASS	FAIL
Is the Post-Use Option considered Viable			**FAIL**	**FAIL**	**FAIL**	**PASS**	**FAIL**	**PASS**	**FAIL**

The next two post-use options that were evaluated, are based on the refurbish strategy and the pipes would be refurbished by either using the CFRP or Slip Lining method. These methods are presented on chapter 2.4.3. Then in both options the refurbished excavated concrete sewer pipes would be used again in the sewer system. However, again due to the poor condition of the pipes, it cannot be sure that the refurbished pipes would last at least 40 years and their strength could not meet the bare minimum requirements. Furthermore, the Municipality of Rotterdam tried in the past to refurbish concrete sewer pipes by using the slip lining method. This method failed due to the different thickness of the concrete walls. It also prevented future recycle of the concrete because the materials that were used in the refurbish procedure could not be removed from the concrete which prevents the reuse of the recycled aggregates. As a result, these post-use options could not fulfil criteria ExC9 and CmC1 and are not considered viable.

Furthermore, a post-use option that was classified as not viable, is the option to use the concrete sewer pipes as underground water tanks to retain rainwater. This option did not meet the requirements of CmC1. Specifically, according to Eng1 and Adv1, the connections of the pipes are quite damaged, and their strength has reduced significantly (Detailed analysis is presented on chapter 4.1.4). That means that the pipes would not prevent the water from leaking, and it is quite unsure if they can withstand the traffic loads because they have to be placed underneath the highways.

Lastly, the option fifth post-use option that could not fulfil the requirements of the viability criteria is to recycle the concrete sewer pipes by using a smart crusher. This option did not meet the requirements of CmC2. More specifically, a test case that was conducted, around two years ago by the Municipality of Rotterdam and is described on section 4.1.5, showed that a smart crusher can recycle and generate circular aggregates with an efficiency of 15% of the total amount of concrete pipes that were recycled. As a result, this recycle option cannot maintain the majority of the materials from the used sewer pipes.

Another point that must be considered is the availability of data. The extensive research that was conducted for the purpose of this study, provided enough information to develop the viability criteria and to evaluate the post-use options for the test case of Rotterdam. However, this extensive research did not provide data relating to the Environmental Cost Indicators which means that ExC2 was excluded from the evaluation of the post-use options. The only exemption was in for the post-use options which the pipes are used in the breakwater construction in which Adv3 explained that they have calculated the environmental impact of this post-use options and turned out to be beneficial. Furthermore, the evaluation framework considers the viability of the post-use options and does not evaluate which of the viable post use-options is the better. A way to define the best option could be by calculating the environmental cost indicator of the viable options. Adv3 mentioned that based on the test case of Rotterdam repurposing the pipes to the breakwater construction is better than recycling from an ECI point of view. However, this is out of the scope of this research, therefore it is not analyzed in this project.

Chapter 5: Discussion

On Chapter 5 are presented findings that derived from the realization of this study and should be reflected. On Chapter 5.1 and 5.2 is presented the reflection followed from the literature study and from the test case, respectively. On chapter 5.3 is explained the reflection followed from the application of the conceptual study to the test case of Rotterdam. On Chapters 5.4 and 5.5 is presented the contribution of this study to academic literature and practice, respectively.

5.1 Reflection on post-use options and criteria that followed from literature study

The development of potential post-use options for excavated concrete sewer pipes necessitated the integration of both grey literature and academic sources. This approach was imperative due to the lack of information available on this specific subject. Grey literature, encompassing reports, and industry publications, provided a pragmatic insight that complemented the more theoretical perspectives found in academic literature. This hybrid methodology was essential to construct a comprehensive understanding of viable post-use scenarios.

One significant challenge encountered was the scarcity of accurate estimates concerning the volume of recycled concrete and the demand for circular concrete on a national scale. The need for circular concrete has an indirect relation with the viability of post-use options, because it affects the reuse of circular aggregates coming from recycled concrete sewer pipes. This gap in data presented a considerable obstacle in accurately evaluating the viability of various post-use options. National statistics and industry reports often lacked the granularity needed to make precise evaluations, highlighting a critical area for future research and data collection.

Moreover, the difficulty in obtaining information meant that existing criteria identified by academics primarily focused on the evaluation of post-use options for concrete materials in general, rather than being tailored specifically to concrete sewer pipes. This generality in academic criteria limited their direct applicability to the specific context of sewer pipes. These criteria often encompassed broader material considerations, without addressing the unique characteristics and challenges associated with sewer pipes.

From the academic criteria that were retrieved, a significant portion was considered unsuitable for incorporation into the conceptual framework. This was primarily because many of these criteria were originally developed for multi-criteria analysis (MCA), a methodological approach designed to evaluate options across a broad spectrum of factors (Dean, 2020). While MCA provides a robust tool for decision-making in diverse contexts, the criteria are designed to evaluate the best alternative amongst many for a specific situation. However, he specific needs and requirements of evaluating the viability post-use options for concrete sewer pipes made most of the criteria unfit for the current study.

5.2 Reflection on criteria that followed from the Expert Opinion

The information gathered from the interviews provided a different and enriched perspective to this study, contributing insights that were not captured through the literature review alone. Interviewees highlighted a significant connection between the post-use options for concrete sewer pipes and the rising demand for circular concrete in the construction industry. This relation highlighted the importance of sustainable practices and the recycling of concrete materials within the industry, which should align with broader environmental and economic goals.

A critical finding from the interviews was the extensive corrosion which was detected in concrete sewer pipes, primarily due to sulfuric acid exposure and ground settlements. This discovery significantly impacted the viability of various post-use options. The degradation of the pipes' structural integrity is a substantial challenge for their post-use options. As a result, more sophisticated and innovative interventions have to be developed, to classify them as suitable for post-use applications. The extensive degradation thus emerges as a pivotal factor in evaluating the viability of potential post-use strategies.

Experts interviewed for this study expressed positive attitudes toward the adoption of circular strategies within sewer system projects. Their positive reaction indicates that there is a will to embrace more sustainable practices within the industry. However, they also acknowledged that transitioning from a linear to a circular economy model presents substantial challenges. This transformation is inherently time-consuming and complex, reflecting the scale of change required to adopt circularity comprehensively.

5.3 Reflection on application of the Conceptual Framework on the test case of Rotterdam

The application of the conceptual framework to the test case of Rotterdam was notably straightforward and not time consuming. The thorough research that was conducted provided sufficient data to evaluate accurately all potential post-use options using the framework. However, there was one exception: Criterion ExC2, which addresses the environmental cost indicator of the evaluated post-use options. Unfortunately, the lack of necessary data did not allow the inclusion of this criterion in the evaluation process. highlighting a significant gap that affected the comprehensiveness of the assessment. However, this indicates that in practice it might not be possible to gather all the necessary information to apply all viability criteria. Despite that, the evaluation process was conducted successfully.

The reuse and refurbish options for the excavated concrete sewer pipes were assessed unviable mainly due to uncertainties surrounding the remaining lifetime of the excavated concrete sewer pipes and their compromised structural integrity. The reduced strength of the concrete, due to the extensive exposure to harsh environmental conditions, notably sulfuric acid and ground settlements, undermined confidence in the durability and safety of these post-use options.

Similarly, the reduced strength of the excavated concrete sewer pipes was a critical factor in the rejection of the second repurpose option. The extensive degradation of the sewer pipes significantly reduced their structural capabilities, making them unsuitable for repurposing as underground water tanks to retain the rainwater, because they are placed underneath the roads which requires reliable strength and durability. This extensive issue of material degradation emerged as a decisive factor in the overall evaluation process.

As a result, the extensive degradation of the sewer pipes played a pivotal role in the assessment of the viability of various post-use options. The test case of Rotterdam illustrates the practical challenges and limitations encountered when evaluating post-use options for concrete sewer pipes. Therefore, it must be emphasized the importance of integrating detailed material assessments and environmental considerations to evaluation processes for the post-use options of concrete materials.

5.4 Contribution to academic literature

This study makes several significant contributions to the academic literature in the field of sustainable construction and materials management in the public space. Firstly, it identifies and highlights the most critical factors that affect the viability of post-use options for excavated concrete sewer pipes. By pinpointing these key factors, the study provides a clear basis for the development of evaluation criteria for the viability of post-use options for concrete sewer pipes. An existing study presented factors related factors that affect the extraction of in-situ materials from buildings (Mollaei et al., 2023), which are not specified for concrete sewer pipes. As a result, the development of the specified factors which are presented on table 6 on section 4.4, address a notable gap in the existing literature.

Secondly, this research introduces the first conceptual framework specifically designed to evaluate the viability of post-use options for concrete sewer pipes. Prior to this study, existing evaluation procedures were largely generic, assessing concrete materials in a broad sense without accounting for the unique characteristics and challenges associated with sewer pipes (Alamerew et al., 2019a). Moreover, this study developed criteria, such as ExC3 and AcC7, that consider the current regulations and circular concrete demand. The consideration of factors apart from technical and economic increase the accountability of the developed framework as a study conducted by Alamerew and Brissaud (2019) explained. This specificity of the criteria and represents a significant advancement, as it tailors the evaluation process to the distinct properties and conditions of concrete sewer pipes, thereby improving the accuracy and applicability of the findings.

The development of the viability criteria was based on a combination of information from academic literature and expert interviews. From the academic literature the existing criteria that were retrieved during the research were based on multi criteria analysis. Specifically, a recent study, conducted by Alamerew et al. (2020) addresses this gap by proposing a multi-criteria decision-making method for evaluating product-level circularity strategies. However, most of those criteria were rejected and were not used in the evaluation process. The reason for that is, that their goal is to determine the best option and not to define if an option fulfils some specific requirements. As a result, other academics who aim to develop criteria to evaluate the viability of a post-use option for a concrete material, should develop criteria with a pass or fail form as in this study.

The development the post-use options was based on existing circular strategies. According to this research the circular strategies that could be used for the development of post-use options for concrete sewer pipes are the reuse, refurbish, repurpose and recycle strategy. However, the circular strategies applicable to the post-use phase of a material that are presented in the circular value hill model, are the reuse, refurbish, remanufacture and recycle strategy (Achtenberg et al., 2016). The repurpose strategy is not being addressed by this model and it is not included in the other four strategies that are addressed. Additionally based on the fact that, one of the two viable post-use options in the test case of Rotterdam was developed from the repurpose strategy, this circular strategy is suitable for the development of post-use options. Therefore, it should be added to the post-use phase of the circular value hill model as a fifth circular strategy. The adoption of the repurpose strategy will provide an alternative post-use strategy for material that is not considered in the current form of the circular value hill model.

On the other hand, the 10Rs of circularity model consists of all the circular strategies that were addressed in this study for the development of the post-use options for excavated concrete sewer pipes (Çimen, 2021; Potting et al., 2017). This theory consists of 10 circular strategies which makes it applicable to different cases such as the development of post-use options for concrete sewer pipes. However, for the selection of the circular strategies that can be applied to excavated sewer pipes, both theories were used in order to solidify the applicability of those strategies. Furthermore, this fact encourages the implementation of the two circular theories into new circular initiatives and their close relevance.

Furthermore, the study achieves an innovative integration of academic and practical knowledge. By combining theoretical insights from existing literature with empirical data and practical experiences, the research develops a framework that is both academically rigid and practically applicable. This dual approach ensures that the evaluation framework is grounded in robust academic principles while also being adaptable to real-world scenarios. This hybrid methodology enhances the framework's utility and relevance, making it a valuable tool for practitioners and researchers alike.

5.5 Contribution to practice

The conceptual framework developed in this study was used for the test case of Rotterdam as a prototype application, in which it managed to evaluate successfully the viability of the post-use options for excavated concrete sewer pipes. The success of this test case indicates that the framework could be used as a practical tool for evaluating similar post-use options by other organizations.

The factors that were identified, in which the development of the viability criteria of this framework was based on, highlight the key reasons that influence the viability of post-use options for concrete sewer pipes. These criteria provide a comprehensive understanding of the various aspects that must be considered, from structural integrity and environmental impact to disruptions caused by the construction. As a result, other practitioners can adopt these factors or criteria as a foundational basis for developing evaluation frameworks specified to other types of concrete materials. This adaptability extends the framework's applicability beyond sewer pipes, indicating its relevance and utility across a broader spectrum of concrete-based infrastructure projects.

The results of this study also promote the adoption of circular initiatives within the construction industry. By demonstrating how post-use options for concrete sewer pipes can be evaluated effectively, the study provides a realistic example for implementing circular economy principles in practice. These initiatives have the potential to significantly impact society by promoting sustainable practices, reducing waste, and enhancing resource efficiency. The framework encourages a shift towards more sustainable construction methods, aligning with national and EU efforts to mitigate environmental impacts and foster long-term sustainability.

Chapter 6: Conclusion

In this chapter are presented the conclusions that were derived from the realization of this study. Specifically, on chapter 6.1 are presented the answers to the sub-questions and to the main research question. On chapter 6.2 are explained the limitations of this research and on chapter 6.3 are presented the recommendations for further research.

6.1 Answers to the research questions

Prior to the answer to the main research question, it is necessary to address the four sub-questions in which the answer for the main research question is derived from.

The **first sub-question** is: "Which post-use options can be applied on an excavated concrete sewer pipe according to existing circular economy strategies according to academic literature?"

The definition of the potential post-use options was based on the two theories which were explained in detail in chapters 2.1 and 2.2. These are the 10Rs of circularity and the circular value hill model. Excavated concrete sewer pipes, which are addressed in this study, enter their post-use phase. As a result, only the circular strategies that are applicable for the post-use phase of a product were considered for the sewer pipes. Based on the circular value hill model a potential post-use option can be derived from four strategies which are the Reuse, Refurbish, Remanufacture and Recycle. However, remanufacturing a concrete sewer pipe is not an independent strategy because the product would have to be dissembled first. For the case of concrete sewer pipes, it means that it must be recycled. As a result, there is an overlap between those strategies, therefore the Remanufacturing strategy is rejected.

From the theory of 10Rs, the strategies applicable to the post-use phase of a product are those which lengthen its lifetime. From those strategies the only one that is applicable and does not overlap with the selected strategies from the circular value hill model is the repurpose strategy. As a result of, this circular strategy will be taken into account in this research.

From the analysis of the circular theories, four circular strategies are applicable for the excavated concrete sewer pipes and were used in this research. These are the Reuse, Repurpose, Remanufacture and Recycle strategies. Based on the literature review that was conducted and is presented on chapter 2 there seven different potential post-use options for the excavated concrete sewer pipe.

From the Reuse Strategy one option was suggested which is the reuse of the concrete sewer pipes in the city's sewer system. From the Repurpose strategy two potential options were developed for the sewer pipes, to be either used in the breakwater construction as part of the breakwater, or to be used as underground water tanks to retain the rainwater. Furthermore, two potential post-use options were developed based on the refurbish strategy, which to refurbish the sewer pipes by using the CFRP method or by using the Slip Lining method. Lastly, two potential post-use options were also developed based on the recycle strategy. These are to recycle the concrete sewer pipes by using a breaking installation or by using a smart crusher.

The **second sub-question** is: "What are the criteria to evaluate the viability of post-use options of concrete sewer pipes?"

In the early stages of this research, it was identified that currently there are no specific criteria or factors that could determine the viability of post-use options for concrete sewer pipes. The only existing evaluation frameworks were applicable to concrete materials in general and did not include factors specific for a type of concrete products. As a result, the viability criteria had to be developed from scratch. The approach that was followed in this study for the development of the viability criteria had three pillars.

Firstly, an extensive literature study was conducted to identify criteria that were used to evaluate the viability of post-use options for concrete materials to gather information from those studies. Data were also collected from studies which developed MCDA frameworks for the definition of the best post-use options for concrete materials. That information is presented on Chapter 2.6. However, not all criteria were applicable to evaluate the viability of the post-use options of the concrete sewer pipes. As a result, those data were analyzed on Chapter 4.3 and only 4 criteria were eventually retrieved from the literature study, which are presented on table 6.

For the third part of the development of the criteria, the information that was collected from the expert interviews was used to develop viability criteria. Firstly, the data were analyzed were the most important factors that the experts mentioned were presented. From those factors the viability criteria were developed. From the opinion of the experts, 9 criteria were developed which are presented on table 3. The analysis of the interview data and the development of the viability criteria from them, is presented on chapter 4.1.

The **third sub-question** is: "How can the criteria which evaluate the viability of post-use options for excavated concrete sewer pipes be applied in practice?"

After the development of the viability criteria, it was necessary the development of a procedure that would allow their application in practice. For that reason, a conceptual framework was developed with the viability criteria that are presented on table 8. The viability criteria were divided into 5 different categories. The first one was called general, in which the criteria that were placed did not belong to a specific circular strategy, but they could be applied to every potential post-use option for excavated concrete sewer pipes. The remaining criteria were divided into four groups, one for every circular strategy (Reuse, Refurbish, Repurpose and Recycle).

After that the conceptual framework was formed which is presented on Figure 13. A potential post-use option would be considered viable, when it fulfills all criteria from the general category and all from the circular strategy that it was developed from. All viability criteria are pass or fail which means that a potential post-use option would either fulfill them or fail them. Even if a post-use option does not meet the requirements of one criterion, then it is rejected. However, if a criterion is not applicable to a potential post-use option, then it is excluded from the evaluation process. Furthermore, when there are not enough data to use a specific criterion then it should be excluded from the evaluation of the post-use options. The application of the framework to the test case proved that the exclusion of criterion does not affect the evaluation process. The final formatting of viability criteria and the development of the conceptual framework for the evaluation of the viability of the potential post-use options is presented on Chapter 4.4.

Apart from applying the evaluation framework it has to be established who should be responsible for assessing the viability of the post-use options. Currently in Rotterdam two potential post-use options are used for the sewer pipes. From the information that was retrieved by the interviews PM2, PL1 and Adv1 are responsible for selecting the post-use options for excavated concrete sewer pipes. Based on that and that the complexity and the different criteria which are included in the framework require the availability of multiple data (Alamerew et al., 2020b), the cooperation of employees with different expertise within the organizations in necessary. That group should include experts in calculating environmental cost indicators, the strength of the pipes, the chemical pollution of the concrete and potential implications of the post-use option to the construction of the sewer system. The group of experts have to provide that information to the project managers and project leaders which are responsible for managing the sewer pipes. Those managers already have an opinion about the condition of the pipes and with all the information they are responsible for conducting the evaluation of the post-use options for concrete sewer pipes, by using the framework. Once the evaluation is finished, the project managers or project leaders are able to take accurate decisions regarding the viability of post-use options for excavated concrete sewer pipes.

Notably, applying the conceptual framework to the Rotterdam test case was simple and didn't take much effort. Enough information was gathered from the extensive study to appropriately assess every possible post-use option utilizing the framework. Criterion ExC2, which deals with the environmental cost indication of the assessed post-use options, was the only exception. Regretfully, this criterion could not be included in the review process due to a lack of essential data. pointing up a substantial gap that compromised the assessment's accuracy. This suggests, however, that in reality, it might not be able to obtain all the data required to apply all viability criteria. Despite that the evaluation procedure can be completed.

The extensive degradation of the sewer pipes played a pivotal role in the assessment of the viability of various post-use options. The test case of Rotterdam illustrates the practical challenges and limitations encountered when evaluating post-use options for concrete sewer pipes. Therefore, it must be emphasized the importance of integrating detailed material assessments and environmental considerations to evaluation processes for the post-use options of concrete materials.

All in all, the viability criteria can evaluate the viability of post-use options for excavated concrete sewer pipes by project managers or project leaders of sewer construction projects by the use of the evaluation framework, the application of which is relatively simple.

The **fourth sub-question** is: “Which potential post-use options are considered viable for the test case of excavated concrete sewer pipes in Rotterdam?”

The test case of Rotterdam was used as a prototype application for the conceptual framework that was developed. The viability of the 7 potential post-use options was evaluated from the information that was retrieved by the expert interviews. Out of the 7 potential post-use options, only 2 were considered viable to applied by the Municipality of Rotterdam. Those were to either repurpose the concrete sewer pipes to the breakwater construction or to recycle them by using a conservative breaking installation.

The results of the evaluation of the post-use options for the test case of Rotterdam are presented on table 9. The main reasons that the other 5 post-use options were not considered viable were quite similar. The reuse and refurbish options did not meet the minimum of 40 years of remaining lifetime and their structural integrity raised significant risks. Similarly, the repurpose option of using the sewer pipes as underground water tanks lacked the required strength and was not considered viable. The recycle option by using a smart crusher was quite inefficient, therefore it was rejected by the test case of Rotterdam. The evaluation of the viability of the post-use options for the test case of Rotterdam is presented on Chapter 4.4.

The Main Research question is: **How to use criteria to evaluate the viability of post-use options for excavated concrete sewer pipes?**

The main research question is answered through the four sub-questions, as it is illustrated on Figure 10 in which is depicted the research strategy. This problem was first addressed by the development of potential post-use options for excavated concrete sewer pipes. Then, detailed research was conducted to gather information which led to the development of the viability criteria. The following step was the development of a conceptual framework with the viability criteria, which made possible the evaluation of potential post-use options for excavated concrete sewer pipes. Lastly, the test case of Rotterdam was used as a prototype and the successful implementation of the framework proved that it could have a practical application on the evaluation of post-use options by an organization.

Apart from using the evaluation framework it must be explained who is capable of judging the viability of the post-use options by using the framework. The complexity and the different expertise that is required to use the criteria, necessitate the cooperation of multiple experts within organizations (Alamerew et al., 2020b). As it was discovered in the expert interviews, in Rotterdam Adv1, PM2 and Pl1 are responsible for the selection of the post-use option for concrete sewer pipes. In the current study, the evaluation of the seven post-use options of the excavated concrete sewer pipes was achieved by the test case combined with information from multiple experts. This approach provided the required information to use the evaluation framework. Based on that, project managers and project leaders that are responsible for managing the sewer pipes should also be responsible for the evaluation of their post-use options by using the framework. Despite the fact that they have an extensive knowledge about the condition of the pipes, they must be accompanied by a group of experts who will provide them extra information that they might need for the evaluation.

As a result, the leading criteria that evaluate the viability of post-use options for excavated concrete sewer pipes can be applied by the use of the conceptual framework which is illustrated on Figure 12. The conceptual framework can be used by project managers or project leaders of projects with concrete sewer pipes. The analysis and the results of the whole study is presented in detail on chapter 4.

6.2 Limitations of the study

This thesis has several limitations that should be acknowledged. First, the reliance on grey literature, due to the lack of specific academic sources, may have affected the comprehensiveness and reliability of the data used to develop the conceptual framework. While grey literature provided valuable practical insights, it often lacks the peer review process that ensures the quality and validity of academic publications. This reliance might have introduced biases or gaps in the information that could influence the definition of post-use options for excavated concrete sewer pipes.

Another limitation is the scarcity of precise data regarding the national demand for circular concrete and the availability of recycled concrete. The importance of the increased need for circular concrete has not been quantified, therefore it is very difficult to estimate the minimum volume of the demand for circular concrete. Additionally, it is not yet possible to classify the recycled products from the excavated concrete sewer pipes as clean or dirty concrete. This classification is crucial for understanding the quality and potential uses of the recycled material, and its absence represents a significant limitation in the current evaluation process. Furthermore, the circular transition is very dynamic and innovative, and technologies arise frequently. As a result, the current evaluation of the viability of the post-use option might change in a few years due to those breakthroughs.

Finally, the framework's applicability was tested solely in the context of Rotterdam, which may limit its generalizability to other regions or contexts. The specific conditions, regulatory environments, and infrastructural characteristics of Rotterdam might differ from those in other areas, potentially affecting the framework's effectiveness elsewhere. Furthermore, the selection of experts from the Municipality of Rotterdam might have introduced a bias. Their opinions and experiences may not fully represent broader perspectives, from other organizations. Despite these limitations, the framework represents a significant step forward in evaluating post-use options for concrete sewer pipes, providing a foundation for further research and refinement.

6.3 Future research recommendations

Further research should focus on defining clear criteria for classifying recycled concrete products from excavated sewer pipes as either clean or dirty concrete. Establishing these criteria is essential for understanding the quality and potential applications of the recycled material. A study dedicated to this classification would provide much-needed clarity and standardization, facilitating better utilization of recycled concrete or recycled concrete products in various construction projects.

Additionally, the development of higher quality concrete sewer pipes with improved endurance against sulfuric acid should be prioritized. Increasing the durability of these pipes could extend their lifespan to 60 years or more, significantly reducing the frequency of replacements and the associated environmental impact. Research in this area should explore advanced materials and innovative construction techniques to achieve greater resistance to corrosive conditions but without limiting the recycle of concrete when they reach their post-use phase.

Finally, there is a need for a comprehensive framework to manage circular concrete efficiently at the municipal level. Such a framework would guide municipalities in implementing sustainable practices, optimizing the use of recycled concrete, and integrating circular economy principles into local construction and infrastructure projects. Developing and testing this framework in various municipal contexts would ensure its practicality and effectiveness, promoting widespread adoption of circular concrete management strategies.

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Appendix A

On appendix A is presented the Approval of the Data Management Plan from the TU Delft Ethics Committee.

Date 19-Jul-2024
Correspondence hrec@tudelft.nl

TU Delft Delft University of Technology

Human Research Ethics Committee TU Delft
(http://hrec.tudelft.nl)

Visiting address
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P.O. Box 5015 2600 GA Delft
The Netherlands

Ethics Approval Application: Master Thesis: Development of a Decision-Making Framework for the Reuse of Concrete Sewer Pipes in Rotterdam
Applicant: Keranis, Thanos

Dear Thanos Keranis,

It is a pleasure to inform you that your application mentioned above has been approved.

Thanks very much for your submission to the HREC which has been conditionally approved. Please note that this approval is subject to your ensuring that the following condition/s is/are fulfilled:

1. Make sure to update the Informed Consent form to indicate the involvement of the municipality contact person in recruitment.
2. Make sure to only share pseudonymized transcripts with the wider research team, as per the DMP.

In addition to any specific conditions or notes, the HREC provides the following standard advice to all applicants:
• In light of recent tax changes, we advise that you confirm any proposed remuneration of research subjects with your faculty contract manager before going ahead.
• Please make sure when you carry out your research that you confirm contemporary covid protocols with your faculty HSE advisor, and that ongoing covid risks and precautions are flagged in the informed consent - with particular attention to this where there are physically vulnerable (eg: elderly or with underlying conditions) participants involved.
• Our default advice is not to publish transcripts or transcript summaries, but to retain these privately for specific purposes/checking; and if they are to be made public then only if fully anonymised and the transcript/summary itself approved by participants for specific purpose.
• Where there are collaborating (including funding) partners, appropriate formal agreements including clarity on responsibilities, including data ownership, responsibilities and access, should be in place and that relevant aspects of such agreements (such as access to raw or other data) are clear in the Informed Consent.

Good luck with your research!

Figure 13: *Approved Data Management Plan by the TU Delft Ethics Committee*

Appendix B

On Appendix B are presented the interview questions, the consent form and other important information related to the interview process.

Interview Questions

1) What is your current position and in which projects you are involved which are related to the Municipality of Rotterdam?
2) How many concrete sewer pipes are replaced every year?
3) Do you replace the concrete sewer pipes with new or used ones?
4) Are the any circular strategies which you follow for the excavated concrete sewer pipes?
5) Do you believe that using again the concrete sewer pipes in the sewer system can be practically applied and why?
6) Based on your experience can the old sewer pipes being refurbished and reuse again and why?
7) Do you believe that concrete sewer pipes could be used as underground water tanks to retain rainwater for a short period of time and why?
8) How many sewer pipes are being sold every year to be used in the breakwater construction and what is the details of the deal that you have made?
9) Do you recycle the used sewer pipes?
10) What is the procedure that you follow prior to sending them in order to be recycled?
11) Are the cement and the aggregates affected by chemical pollutants that might limit their future uses?
12) Which criteria would be the most important to identify the optimal next lifecycle alternative of a concrete sewer pipe?

Adjusted Interview Questions for the interview with the expert in concrete recycling.

1) What is your position and what with which projects you are involved?
2) Do you believe that the recycled concrete from sewer might be affected by chemical degradation and how? If yes how this can limit the use of that concrete?
3) How can the recycling of polluted concrete affect the products that will be generated from this procedure?
4) Did the breaking installation produce new sewer pipes with this concrete?
5) Is it possible to produce other products from that concrete?
6) What happened to the contaminated concrete?
7) can we use the aggregates or sand or cement coming from all sewer pipes?
8) Which technical factors should be considered in the decision-making framework for concrete sewer pipes?

Appendix C

On Appendix C is presented the interview consent form.

Interview Consent Form

20/03/2024

You are being invited to participate in a master thesis study titled Development of a Framework for the reuse of concrete sewer pipes in Rotterdam. This study is being done by Athanasios Keranis, TU Delft, and the Municipality of Rotterdam.

The purpose of this research study is to develop a framework that will dictate to the Municipality of Rotterdam which is the next lifecycle step for excavated concrete sewer pipes. The interview will take you approximately 45 minutes to complete. The data will be used for the completion of this project and will not be published. I will be asking you questions about circular designing, concrete sewer pipes, potential future uses of the sewer pipes and assessment criteria for the framework.

As with any online activity the risk of a breach is always possible. To the best of my ability your answers in this study will remain confidential. I will minimize any risks by using a secured, limited-access data storage solution and the recorded interviews will be deleted at 20th of September 2024.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. If you change your mind and disagree with the use of the data provided by your answers, you can inform me before the 20th of June 2024 not to include them in the project.

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated 20/03/2024, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves a sound- or video-recorded interview and myself. I have been informed that in the case the interview is hosted on an online-meeting platform, I can keep my camera turned off during the interview or disable it at any time, without having to give a reason. I consent to the interviewers taking written notes during the interview and that in the case it is video recorded, that the recorded audio will be transcribed automatically using appropriate software. I understand that all collected information will be destroyed on 20/09/2024.	☐	☐
4. I understand that the study will end on 20/09/2024.	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
5. I understand that taking part in the study also involves collecting specific personally identifiable information (PII), such as my full name and position within my organization, and associated personally identifiable research data (PIRD), such as specific information on certain activities and policies within my organisation, with the potential risk of my identity being revealed.	☐	☐
6. I understand that all collected information will be stored using an online, limited-access data storage solution to minimise the threat of a data breach.	☐	☐
7. I understand that personal information collected about me that can identify me, such as my full name and my position within my organisation, will not be shared beyond the study team.	☐	☐
8. I understand that the (identifiable) personal data I provide will be destroyed on 20/09/2024.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
9. I agree that my responses, views, or other input can be quoted anonymously in research outputs.	☐	☐

Appendix D

On appendix D are presented information related to the analysis of the interview data.

Table 9: *Codes Used in the First Cycle of the Interview Data Analysis.*

Codes used in the First Cycle of the Interview Data Analysis	
Code Number	**Code Description**
1	Are the cement and the aggregates affected by chemical pollutants that might limit their future uses?
2	Based on your experience can the old sewer pipes being refurbished and reuse again and why?
3	Breakwater Specs
4	Clean / Dirty Concrete
5	Current Management of the pipes
6	Do you believe that concrete sewer pipes could be used as underground water tanks to retain rainwater for a short period of time and why?
7	Do you believe that using again the concrete sewer pipes in the sewer system can be practically applied and why?
8	Do you replace the concrete sewer pipes with new or used ones?
9	How many are replaced per year
10	How many sewer pipes are being sold every year to be used in the breakwater construction and what is the details of the deal that you have made?
11	Increase in Chemical Pollution
12	Minimum Thickness
13	Need for circular concrete
14	Quantities of concrete demand and need
15	Recycling procedure Info
16	Recycling Products
17	Repack
18	Smart Crusher
19	Technical Improvements
20	What is the procedure that you follow prior to sending them in order to be recycled?
21	Which criteria would be the most important to identify the optimal next lifecycle alternative of a concrete sewer pipe?
22	Why the sewer pipes are heavily degraded?