PAVE the way towards a Circular Economy in the public space

Maintenance plan analysis tool to value the enhancement towards a Circular Economy

Master thesis

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PAVE the way towards a Circular Economy in the public space

Maintenance plan analysis tool to value the enhancement towards a Circular Economy

By

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Abstract

In 2017, the Dutch government has set the goal to achieve a 100% circular economy by 2050 [1]. A transition from the current linear economy towards a circular economy is necessary to reach this goal. In the circular economy, products at end-of-life are no longer seen as waste but will be reused as a secondary product or resource [2].

The general aim of this research is to investigate the implementation of the circular economy concept in the public space. From this study, it became clear that Dutch municipalities are willing to implement circularity for assets released from the public space. However, the municipalities are not aware of the actions which are required to increase the circularity within its maintenance activities. A method is proposed which gives decision makers of a municipality guidelines to justify their decision for a maintenance plan of an urban area. This method includes PAVE (maintenance plan analysis tool to value enhancement of circularity in the public space): a tool which quantifies the environmental and economic impact of maintenance plans. To express the impacts four criteria were selected: the carbon footprint, financial footprint, material loss and monetary value loss. The tool follows a life cycle assessment (LCA) framework.

In this research, the use of PAVE was investigated during the maintenance of a neighbourhood in Almere. It was concluded that to be able to implement PAVE in an effective manner, the asset database of the municipality needs to be updated to fill in the information gap. Part of the case area database was renewed to conduct an inventory of the assets in the selected urban area for this research. In PAVE, the impacts of the selected assets were calculated for both the circular project plan of the contractor and the traditional linear plan. PAVE indicated that using the new project plan for the case area results in approximately 1455 ton less CO_2 emissions and is €4304000 cheaper compared to the traditional linear maintenance plan. Furthermore, PAVE demonstrated that the use of the new plan leads to 238 m^3 and €424.000 less material and monetary value loss, respectively.

In this research, it was evident that to select a maintenance plan among others, the tool should be included in the decision-making scheme of municipalities. By implementing PAVE, decision makers will be able to compare the impacts of different maintenance plans and select the most suitable plan based on environmental and economic considerations. The implementation of the tool can be ensured by making the provided budget dependent on implementation. Finally, the proposed plans of contractors should be evaluated on their circularity. Guidelines have been formulated to support the selection of the maintenance plan for urban areas in the public space.

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Introduction

1 Introduction

Since the beginning of the industrial revolution, the consumption pattern follows a linear take-make-dispose model, which is called the linear economy [2]. The linear economy model along with the fast-growing population and its higher living standards will eventually result in the depletion of the world's resources [3][4]. Moreover, the change in the geopolitical situation and the raw materials dependency on other countries will enhance political tensions, which will eventually result in volatile prices and insecurity of the supply of resources [5]. On the other hand, secure access to resources has become an increasing strategic economic issue, while possible negative social and environmental impacts on third countries constitute an additional concern [6].

The linear economy also indirectly causes health and environmental issues, as it does not support advanced waste management alternatives such as Reduce, Reuse and Recycling. For example, the disposing nature of the linear economy causes the release of waste plastics into the environment. Since plastics have a minimum lifespan of 450 years before they decay, even the contamination of the environment with a small amount of these pollutants is affecting all living species negatively, including humans. In the research of S. A. Mason *et al.* in 2018 [7], it was found that 93% of potable water is contaminated by micro-plastics. This endorses the necessity of improvements in waste management and to move towards an industrial model that decouples economic growth from material input.

A circular economy (CE) is proposed as an alternative to the current linear economy. In the circular economy, products at end-of-life (EOL) are no longer seen as waste but will be reused as a secondary product or resource. As a result of reusing high-value products, the lifespan of these products will be increased and they will not immediately end up in landfills as waste [2].

The general aim of this research is to investigate the implementation of the circular economy concept in public space. Public space refers to areas openly accessible to everyone. Examples of urban public spaces are public parks, squares and roads [8]. Buildings are not part of the public space.

The construction industry already started the transition towards a more circular economy through successful pilot projects. The buildings in such projects are designed to be built from recycled or reused materials. Also, material passports are introduced to document the material composition of assets in new buildings [9]. However, circular initiatives within other sectors, like the infrastructure sector, are rare [10][11]. This stresses the need for a method to improve the circularity in the public space.

1.1 Problem context

In 2017, the Dutch government set a goal to achieve a 100% circular economy by 2050 [1]. To speed up the transition, designated teams per sector defined a transition agenda. One of the focus sectors for this issue is the building industry. The transition agenda for the building industry also applies to the infrastructure sector. The team claims that zero emissions by the building and infrastructure sectors are achievable, which is equal to a reduction of 107 megaton CO_2-eq per year [1]. To achieve this reduction, the government needs to stimulate the transition towards circularity. Both local and national government departments have a pioneering role in exploring options [12][13].

The municipality of Almere is one of the leading municipalities when it comes to implementing CE. For different material streams, improved waste management alternatives are explored and implemented. A plant has been built in Almere to reduce the environmental footprint of the concrete waste stream. Options for similar plants for plastic and wood waste are being explored [14]. The municipality also aims to increase the recycling of household waste to a 100 percent [15]. Furthermore, funds are established to support circular innovations, such as upcycle city where old materials are refurbished [16]. In its ongoing drive to improve circularity, the municipality is now on a quest to improve the reuse of assets in the public space [17]. Assets in the public space are items located in the urban area and decompose into objects, components, materials and resources.

Currently, linear waste management is implemented at municipalities for assets in the public space. This implies the dumping of released objects at a waste management plant and procurement of virgin objects to replace these released objects. In Almere, an ongoing transition towards circular waste management for public space assets is taking place by recycling concrete objects into new materials. However, this focusses only on one material. (Figure 1). Complete circular waste management includes more waste management alternatives (e.g. reuse) and can be applied to more than one material. Ideally, circular waste management modifies the established consumption patterns and value chains, while promoting innovation and new business opportunities at the same time.

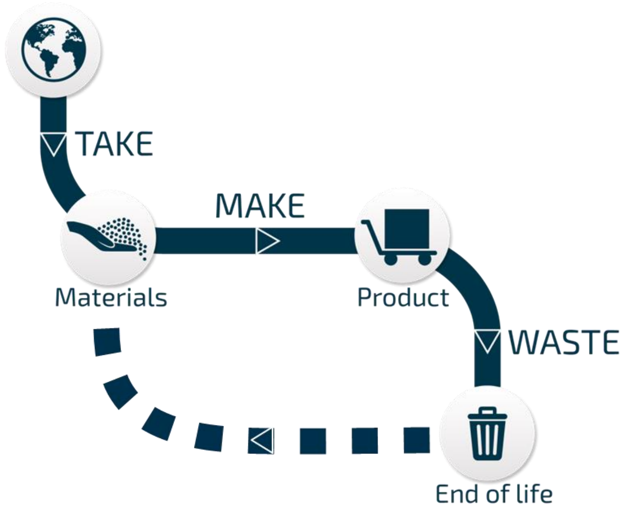


Figure 1. Linear Economy in Almere. "Solid line: classic linear economy. Dashed line: recycling of materials, first step towards circularity." Recovery of materials is implemented, however, still limited to specific material streams. Adjusted from Contraload. [85]

Nationwide problem

From short interviews with representatives of the municipalities Apeldoorn, Haarlem, Haarlemmermeer, Utrecht, Rheden and Venlo (see Appendix A1); it became clear that all these municipalities are also willing to implement circularity for assets released from the public space. However, the municipalities are not aware of the actions that are required to increase the circularity within the maintenance activities in their public space. In the transition plan for the building industry, it is stated that municipalities have until 2021 to find appropriate solutions to accomplish 100% circularity in 2050. In 2030, 50% of the goal should be achieved. [18] As this problem is nationwide, this research aims to find a solution for the problem (Figure 2) which could be implemented by any Dutch municipality.

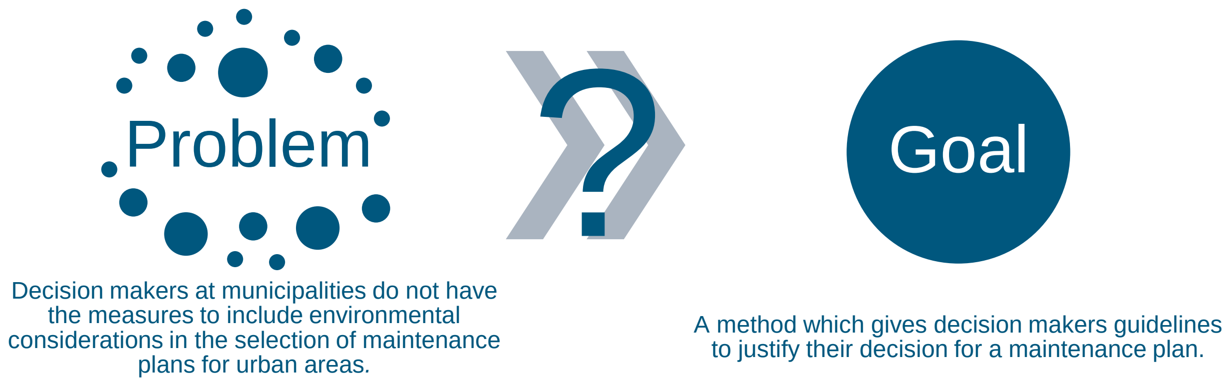


Figure 2. Overview of problem statement and research goal.

1.2 Research gap

Municipalities must come up with strategic plans to implement circularity. It needs to decouple growth from finite resource consumption, which includes designing systems to keep products, components, and materials usable and at their highest value [19]. Several tools aim to increase reuse of assets, for example platforms that connect procurement and supply [16], [20]–[22]; pilot projects; or a life cycle assessment (LCA). This LCA closes the loop for: a material [23], an asset [11][24], a process [25] or an entire building [26]. The Excess Material Exchange tool quantifies the waste management of one product or process. However, this tool is not focussed on assets in the public space [21], thus development of a new tool is desired. The complexity of waste management in urban areas causes the decision makers to act impaired when considering environmental factors in their maintenance planning. Furthermore, the development and use of the new tool give decision makers insight on the data necessary to make an informed decision of their assets in the public space.

1.3 Research objectives

A method is proposed in this thesis, which gives decision makers guidelines to justify their decision for a maintenance plan of an urban area. This method includes PAVE (Maintenance plan analysis tool to value enhancement of circularity in the public space): a tool which quantifies the environmental and economic impact of maintenance plans. By implementation of the tool, decision makers can compare the impacts of different maintenance plans and select the most suitable plan based on environmental and economic considerations. This method is split in three different aspects: the current stock, development of PAVE and implementation in the municipality (Figure 3). These aspects are explained in more detail later in this paragraph. The municipality of Almere is viewed in this thesis as a case study to investigate the different aspects that play a role in successfully using PAVE as a tool towards the goal of achieving a circular economy.

Figure 3. Overview of steps in the method.

Within the case study offered by the municipality of Almere, the aforementioned methodology has been implemented to assess the maintenance plan of the refurbishment of the Regenboogbuurt' area. This urban area was built in the 80's and has circa 5500 inhabitants, which is equivalent to 2200 households. The maintenance project is executed by the contractor Dusseldorp and consists out of four phases. Only phase 1 is further investigated during this research, as data of the other three phases is not yet available. Phase 1 is the red area in Figure 4 and will be referred to as the case area in this research.

Figure 4. Maintenance plan for the neighbourhood 'Regenboogbuurt', Almere. Received from Dusseldorp.

1.3.1 Stock inventory

Before implementing PAVE, a stock inventory should be conducted based on the available information from the asset database of the municipality. However, asset databases of municipalities contain limited information of their available assets, which is an issue in the transition towards a CE. These databases could be used to store a lot of meaningful data about the assets, like maintenance plans, the material composition of the assets and the number of assets of each type. The extent of this lack of data is not known, and therefore a clear overview of the available data is needed. This will give insight in missing data that could be crucial for the implementation of PAVE. An overview of the missing data is made in this research and will be referred to as ‘inventories’. Based on these inventories it will be possible to set up guidelines for improving the usage of the asset database in place. Additionally, the research aims to enrich the database with missing data that is to be collected in the case area, underlying this research. It enables this research to complete the inventories and the prioritization of assets. A complete inventory makes it possible to prioritize assets, which ensures that only assets with a significant contribution are included in PAVE. For the prioritized assets, the environmental and economic impact after EOL will be quantified using PAVE, which is a support tool that helps municipalities to choose the most cost-efficient and environmental-friendly maintenance plan for an urban area.

1.3.2 The tool: PAVE

Different factors influence the municipal assets: maintenance, use and natural factors. This increases the difficulty of determining when assets become ready to be replaced, and thus should be deconstructed. As objects are not released at a uniform pace, the implementation of the tool should be done at the same time as most assets are released, for example during a large neighbourhood maintenance event. Therefore, the tool aims to quantify the impact of these large maintenance events. During the maintenance events, the contractor has the power to decide whether the objects will be disposed. Conventional waste management is still mainly linear, therefore the implemented waste management alternatives after removal of the object are the key to quantify the environmental and economic impact of the maintenance plan. Comparing the alternative implemented by the contractor, with conventional waste management per asset, gives a measure of the environmental and economic benefits of the alternative.

In order to develop a new tool, this research draws inspiration from the Product Structure-Based Integrated Life Cycle Analysis (PSILA), developed by J. Low *et al.* [27]. PSILA is a technique used for carbon footprint modelling, cost modelling and analysis of closed-loop production systems. Although PSILA indicates the economic and environmental burdens of production systems and provides decision support to managers on closed-loop production systems, the aim of this thesis research is different. In this research, the focus lies on the decision makers at the municipality instead of the managers of a closed-loop production system, opposite to the research of J. Low *et al.* Only a part of the PSILA is used in this thesis, because the decision makers are not familiar with the production systems. The part used is LCA, which is an academic framework used to capture the environmental burden [28].

Discounting of values is a method used to model the costs of the LCA in the PSILA. The monetary values of objects can be discounted back to a base period or projected forward based on inflation rates. This results in a time-dependence of the economic value [29]. Instead of including this time-dependence in PAVE, the found economic values should be updated on a yearly basis. This gives a static indication of the value of objects and processes during that year. The difficulty to determine the time-dependence and its reliability results in the exclusion of the time-dependence. PSILA teaches us that values of processes and objects should be evaluated on reliability and used with caution. Applying parts of the PSILA framework to maintenance plans for urban areas forms the base of PAVE and solves the problem of this research.

1.3.3 Implementation in the municipality

Although the use of PAVE by municipalities helps decision makers in the selection of maintenance plans, PAVE is not going to be used if it is not integrated in the conventional decision-making scheme. This is because municipalities have a conservative nature where habits are not easily changed. In this research, the current conventional decision-making scheme is investigated and the best location for the implementation of PAVE is chosen. Furthermore, the execution of plans and projects is dependent on the available budget. This means that making the project budget dependent on the implementation of PAVE, accelerates the use of PAVE by the municipality. To further assist with the implementation of circularity, guidelines are set up to select the maintenance plan with the most comprehensive circular ambitions. These guidelines include PAVE and other measures to incorporate circularity in the maintenance plan. Together with the stock inventory and PAVE, the guidelines lead to achieving the research objectives (Figure 5).

Figure 5. Methodology to solve the problem and achieve the research goals.

1.4 Research questions & scope

The method proposed in the previous paragraph leads to the main research question:

What data should decision makers collect to be able to make an informed decision about retired urban area assets, based on environmental and financial considerations?

An approach for answering this question is described in the previous paragraph. This approach includes three different parts: stock inventory, the tool PAVE and guidelines for implementation at municipalities. To get a complete answer to the main research question, the following aspects are addressed:

1. *What information level of the current stock is necessary to enable the selection of the most promising assets and the use of PAVE?*

For this case study, a comparison is made between the available data at the municipality and the optimal inventory. Thus, the found data gap is case dependent and cannot be generalized for all Dutch municipalities. Still, it can be an example on showing how the municipalities could improve their asset databases.

2. What are the possible waste management alternatives per object?

As stated earlier, assets can be divided into objects, components, materials and resources. The object level is leading in this research, as the material and resource level are not able to represent the higher value of the object.

3. How should the object level related environmental and economic impact be quantified and evaluated?

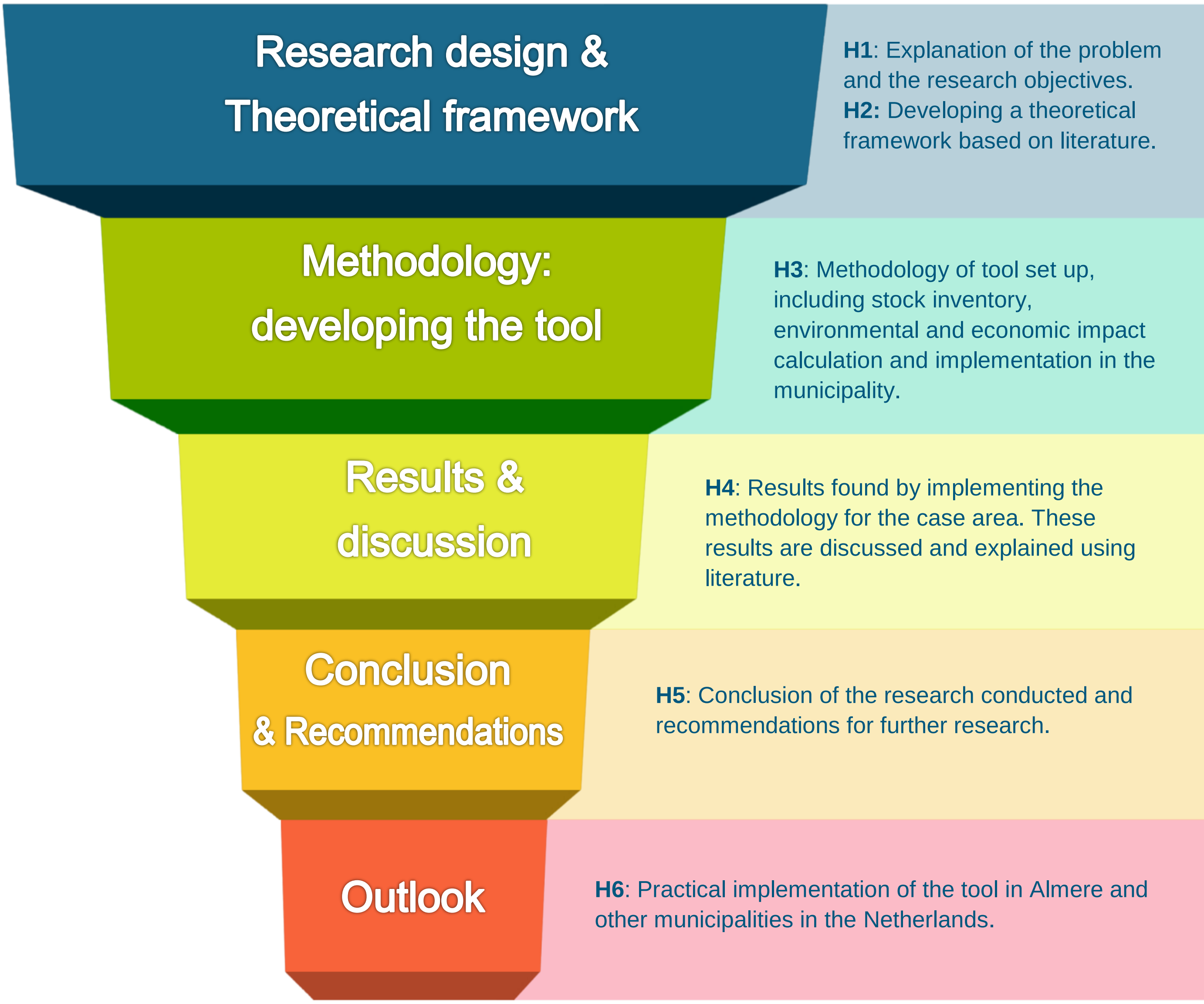
LCAs mainly focus on the environmental impact of processes or products. However, processes and products also have other impacts, such as economic, social, behavioral, technical and governmental [30]. This research only focuses on the environmental and economic impact, as the quantification of other impacts is not feasible with the current research strategy.

4. How should municipalities use PAVE for the best improvement of circularity in the public space?

PAVE is developed to be implemented by Dutch municipalities, thus only Dutch guidelines and regulations are considered.

1.5 Research design

In this first chapter, the problem and goal are set. A research methodology was also defined, which includes three parts: the stock inventory, the tool PAVE and implementation. This research is started off by literature review and setting up a theoretical framework in Chapter 2, aiming to define the boundaries of this research. Within these boundaries the tool is developed and the methodology is explicated in Chapter 3. Subsequently, the results of the research are discussed in Chapter 4. The conclusion and recommendations are given in Chapter 5. Finally, Chapter 6 is dedicated to describing the next steps that must be taken towards implementation, which will be referred to as the Outlook Chapter.



Theoretical framework

2 Theoretical framework

In this chapter, a theoretical framework is established, which substantiates assumptions and decisions to develop and implement the tool PAVE, based on literature. This chapter includes theory on CE and sustainable development, followed by waste management and quantification of impact. A literature review is conducted towards tools which quantify the life cycle of assets. Finally, a summary is given of the necessary elements for the new tool based on the literature review.

2.1 Theory of Circular Economy

As stated by the Ellen MacArthur Foundation (EMF): "A circular economy is an industrial system that is restorative or regenerative by intention and design."[2]. EMF illustrates this vision of circular economy for renewables flow and stock management in one figure, which is included in this report as Figure 6. In this research, only stock management will be considered; renewables flow management falls outside the scope of this research and thus will not be discussed.

In a circular economy, waste does not exist but is seen as a valuable resource. Every asset exiting the production chain re-enters the production chain again after being processed as waste, following one of the four loops presented in Figure 6. A smaller loop indicates a smaller value loss of the asset in the figure. EMF states that improvement of their model results from increased use of the inner circles, improving the life time of assets before entering any circles, and less use of impure materials. Consequently, less asset value is lost and the circularity of product streams is improved [2].

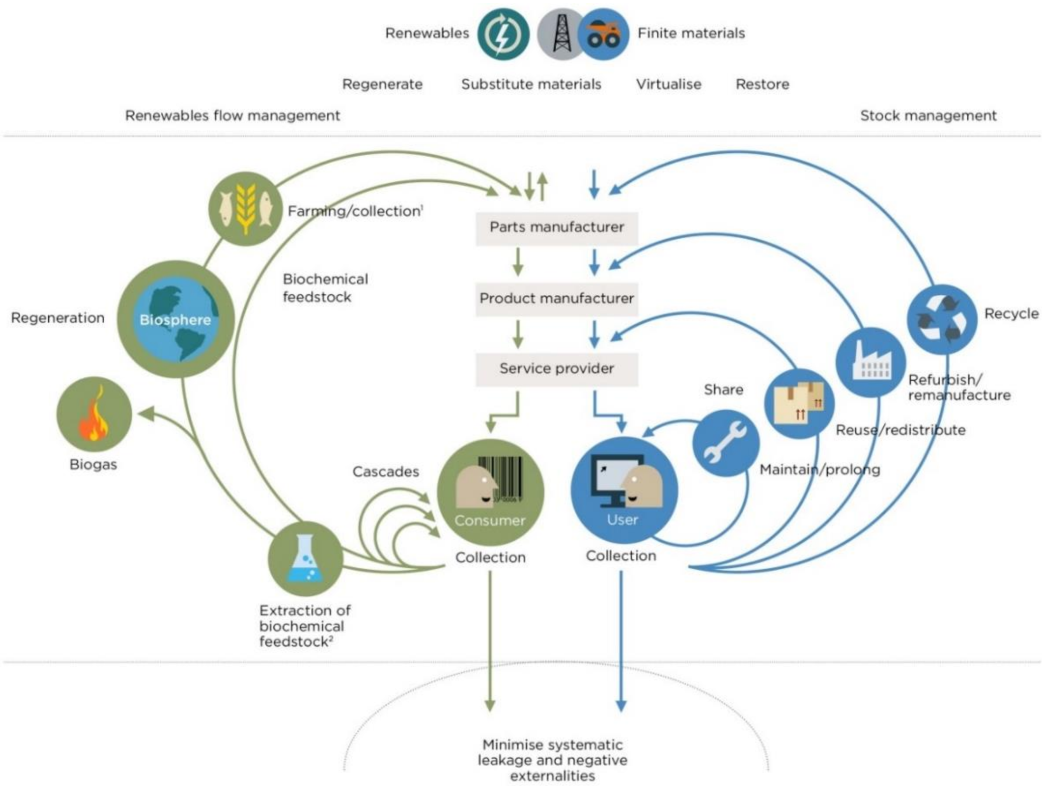


Figure 6. Outline of a Circular Economy, adjusted from Ellen MacArthur Foundation [2].

Improving sustainable development

With the implementation of CE, the government aims to enhance sustainable economic and social development, while still taking into account the protection of the environment [31]. Developed in 1994 by John Elkington, this concept is called the triple bottom line and is also referred to as the 3Ps: people, planet and profit (Figure 7) [32]. Respectively, 3Ps refer to the social, environmental and economic aspects of sustainable development. Formats with five aspects have been cited, which additionally include the technical and institutional aspects of sustainability [33]. CE contributes positively to sustainable development by including all three of the triple bottom line elements. It promotes an environmental friendly use of resources following a new business model and improving the well-being and health of the community [34].

Figure 7. 3Ps of sustainability [86].

This vision on the contribution of CE on sustainable development is expanded by the Dutch company Metabolic and is called the “Seven Pillars of the Circular Economy”. Metabolic states that in the circular economy an infinite cycle of materials should be achieved and aimed for. Material scarcity and toxicity are included as topics to consider. However, it is important to look beyond the materials which can be achieved by considering the seven pillars**.** The seven pillars are: the support of health and well-being of humans, generation of value beyond financial, an adaptable and resilient economic system, cycles of material at a high value, use of renewable energy, enhancement of biodiversity, and preservation of culture and society [35]. While these pillars are comprehensive, including all pillars in projects has the consequence of having a complex framework.

CE in municipalities

In circular cities and municipalities local value loops should be encouraged, which will result in more local reuse [19]. The improvement of waste management after end of life of assets boosts local reuse. For example, innovative projects in Almere promote local reuse by using waste material to manufacture new products, like furniture [16]. Due to the small-scale nature of these projects, this is not a solution for the infrastructure sector. By implementation of CE in the waste management of the infrastructure sector tons of materials could be locally reused, improving the sustainable development of the infrastructure sector.

2.2 Waste Management after End-of-Life of Assets

EOL of a product is the moment when a product is at the end of its useful life or it is no longer supported due to marketing, ending of support or other processes [36]. In this research, the support of assets is not relevant as it relates to the consumer market. An example is the termination of support for software. Reaching the end of an asset’s life in the infrastructure sector could result from several factors: the condition of the asset, malfunction of the product, not fitting the current city plan or its unpleasant outlook. Thus, it is inaccurate to anticipate that the useful EOL is reached when deconstruction occurs [19].

A good example is the reuse of concrete paving bricks. Paving bricks have a life expectancy of more than 100 years [37], however due to subsidence, discolouring or other malfunctions, a street is rebuilt approximately every 25 years [38]. Consequently, a paving brick could be used approximately four times before its useful EOL is reached. A different example are trees, because they are not easily removed from the ground and placed at another spot, as roots make the removal difficult and big trees are adversely affected when moved to another place [39]. Therefore trees reach their EOL when removal occurs and direct reuse is not possible. These examples give an indication of the difference in reuse potential per asset type.

In conclusion, why an asset is removed and if EOL is reached, cannot be easily estimated during the production phase. However, Almere municipality plans the maintenance of their assets for four years beforehand, resulting in the booklet “Meerjarenperspectief Beheer Almere” (MPBA) [38]. Based on the MPBA, the municipality could select areas or assets where circularity should be included during maintenance, making the moment of EOL known.

2.2.1 Waste management alternatives

After EOL, several waste management alternatives can be chosen during maintenance in the infrastructure sector. Waste management hierarchies give an overview of the possible alternatives. Most implemented in the Netherlands is Lansinks Ladder, developed by Ad Lansink in 1979 [40]. The hierarchy contains six waste management alternatives: prevent, reuse, recycle, energy, incineration and landfill. More elaborated hierarchies have been developed after 1979, which include more alternatives, such as refurbish and repurpose [41]. Nevertheless, these elaborated hierarchies are not relevant in this research, as the extra alternatives are not used as a conventional one [42]. In the infrastructure sector, these alternatives are technical innovations and should be indicated as such.

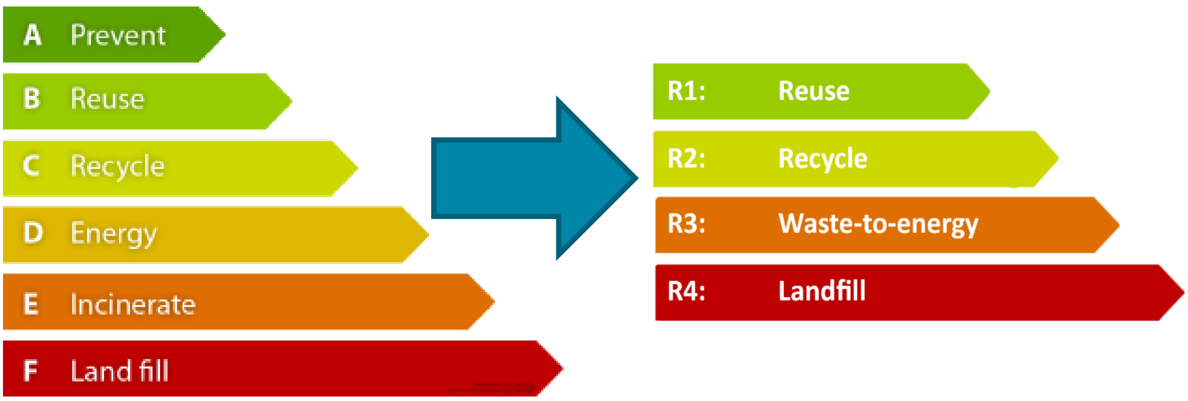


Figure 8. Lansinks ladder (left), retrieved from blog Maurits Korse [43] and adjusted version for this research (right).

From the six waste management alternatives in the Ladder, only four are included in this research (Figure 8). The ‘prevent’ alternative is excluded. It was decided to exclude the alternative ‘prevent’, because assets that are due to be removed have a higher potential in terms of waste management improvement than simply preventing demolition. This is thanks to the related environmental and economic benefits of reuse compared to waste management alternatives lower in the hierarchy [40].

Besides excluding ‘prevent’, two alternatives from Lansinks Ladder will be merged together for the purposes of this research. These alternatives are ‘energy’ and ‘incinerate’. The merged waste alternative is called waste-to-energy. The difference between the two options is that the energy release due to incineration is the aim in the ‘energy’ option, while in the ‘incinerate’ option this is a by-product [40]. However, this difference is not relevant for decision-makers at the municipality. Incineration generates energy, so the output is the same for both strategies [44].

Waste management regulations for specific materials

Regulations for waste management per material type are formulated by the Dutch government and combined in the national waste management plan, LAP3 2017-2029 [45]. Regulating of materials that are relevant to this research is investigated: process-depended industrial waste for production processes, vegetation waste, plastics, metals, stony material, crushed sand, asphalt, wood and soil [46]–[54]. In general, materials are recycled or reused if the cost of the processes is no higher than 205 euro per ton. If the processing cost exceed this amount, incineration or landfilling is allowed. Incineration is often used for vegetation and plastics; however, recycling of the materials is still preferred. Vegetation is recycled to compost or fermented to produce biogas [47]. For plastics, waste separation is necessary to enable reuse or recycling [48].

Pavement materials, such as asphalt, crushed sand and stony material, are divided in two groups. One group can be directly reused and recycled. The other group needs thermal or chemical cleaning before recycling is feasible. The cleaning is necessary due to contamination of the material with toxic pollutants. Contaminated residues go to a landfill after treatment [54].

Wood is separated in three groups: untreated wood, painted or glued wood, and impregnated wood, also referred to as A-, B- and C-wood, respectively. A- and B-wood can be reused or recycled. C-wood is used for fuel. If C-wood contains metals, landfilling is currently the only option [53].

These national regulations also apply in Almere. Almere has even stricter regulations when it comes to concrete materials: they can only be recycled at the concrete recycling factory at the Vijfhoek. At this factory all material is recycled to new concrete. This concrete recycling factory is part of the strategy of Almere to encourage sustainable innovations [14]. Almere is known as a leader when it comes to sustainability; the city council has set the ambitious goal to create a zero-waste city. However, strengthening of the economy has a consequence of stagnation in the decrease of waste, due to the higher consumption rate of the inhabitants. Therefore, the municipality needs to come up with innovations to achieve their goal [55].

2.2.2 Decision-making criteria

Selecting the appropriate waste management alternative depends on the asset's condition and criteria set by the municipality. Multi-criteria decision-making analysis (MCDMA) can help decision-makers selecting the best waste management alternative compromise among alternatives. Also, it can be a powerful tool to convince the public of the quality of the waste management alternative [56]. MCDMA in combination with Life Cycle Analysis (LCA) modelling as a decision-support tool enables the selection of an optimal management plan in waste management problems [57].

Roussat *et al*. used MCDMA to choose between sustainable demolition strategies in the construction sector [58]. First the waste management alternatives are listed, after which selected criteria are evaluated per alternative. The included criteria in this research are the cycle's carbon footprint, financial footprint, material and value loss. To evaluate these criteria, PAVE is developed. This tool follows the LCA framework.

2.3 Life Cycle Assessment

Life Cycle Assessment (LCA) is a framework, which follows the life cycle of a product or process and determines the associated environmental burden [10]. The life cycle comprises all transportation steps and every stage from the extraction of resources to the recycling, recovery, reuse or disposal stage. Other stages included are production, manufacturing, use and maintenance [33]. A well-defined LCA examines all aspects from resource depletion to human health. Based on these aspects and life cycle perspectives, LCAs indicate environmental problems and the shifting of problems between phases or regions [26].

The framework and principles of an LCA are set out by the International Organization for Standardization (ISO) in the ISO 14040 [59]. The ISO defines four phases in an LCA study:

a) The goal and scope definition phase: the system boundaries and level of detail are defined, which result from the goal and intent of the LCA.
b) The inventory analysis phase: also called Life Cycle Inventory (LCI). The input into and output from the system are investigated and determined. It depends on the goal and scope of the LCA, which level of detail is necessary for the inventory.
c) The impact assessment phase: also called Life Cycle Impact Assessment (LCIA). Its purpose is to provide the necessary information to understand and evaluate the magnitude of the environmental burdens based on the LCI data.
d) The interpretation phase: during the other three phases checks can be executed. This is to test whether conclusions are sufficiently supported by the used data.

In Figure 9, an overview of the different phases and the link with different possible applications are given. The LCA framework can be an input for the defined application. Interpretation is linked to all the other phases, where the goal, LCI and LCIA follow each other. The LCIA is used to give relevance to the found results. For instance, greenhouse gas emissions can be expressed in related infrared radiative forcing and its relation to the loss of coral reef [60]. The impact assessment is not executed in this research, as this research focusses on the comparison between different maintenance plans. These plans are evaluated based on their environmental and economic impact, which are directly extracted from the LCI.

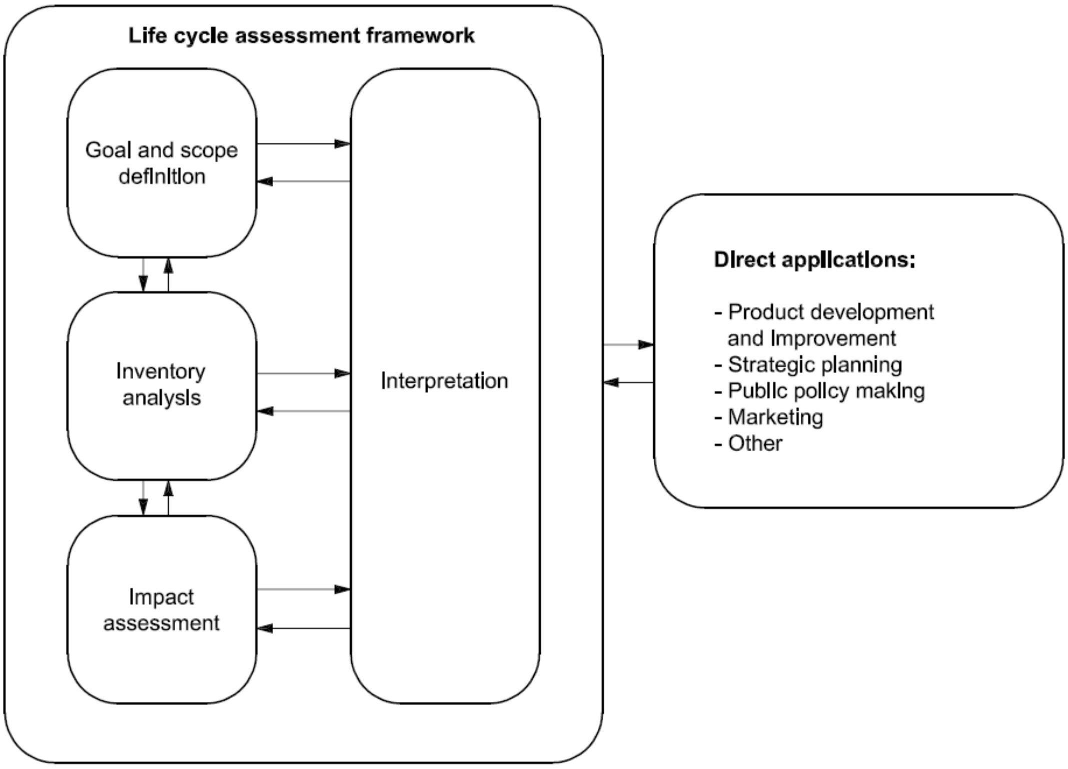


Figure 9. Stages of an LCA (from ISO 14040 [59]).

Although, an LCA seems to be the best framework for this research, it has some important shortcomings when it comes to answering the research questions stated in Chapter 1. Potential weaknesses are the time and resource intensity, the availability of data and the immense quantity of data involved. Moreover, the main limitation arises from the LCI. The LCI has a high degree of uncertainty, which causes large variability in the results [33]. Furthermore, LCAs are used to exclusively capture the environmental burden of a process and not economic aspects related [61], while this research aims to include the economic aspects of a life cycle.

In literature, three types of LCAs are described: process, Input-Output (IO) based and hybrid LCAs. Process LCAs aim to capture all details of a process. In contrast, IO-based LCAs rely on simplified and coarse models. Hybrid LCAs try to combine the two strengths of both, being systematically complete, while retaining process specificity [62]. In literature we find which model is best-implemented based on the scale of the LCA [63]. Product, organizational, city and country scale LCA's are described in Figure 10. Based on the scale a type of model should be selected. Figure 10 shows that hybrid LCA models should be applied for all scales between the product and global scale [63].

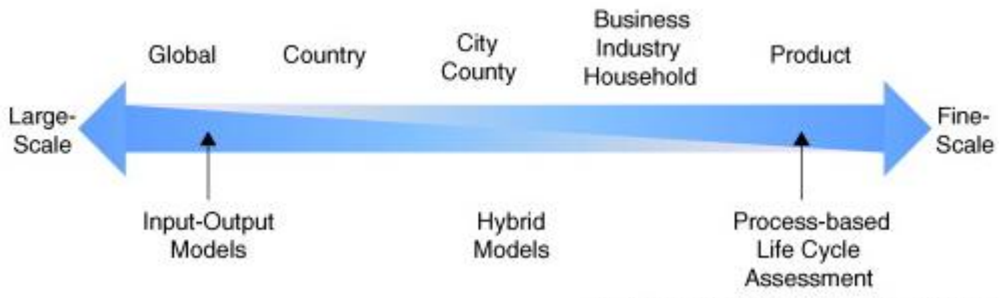


Figure 10. Model related to the scale of the project or process [63].

In this research, the tool is focussed on an area, thus a hybrid model is proposed to analyse the system. In literature, hybrid LCAs mainly analyse a system using static LCI data [62]. Hence, all input data is predetermined.

As to include the product level, J. Low *et al.* developed a product structure-based integrated life cycle analysis (PSILA) [64]. In this technique closed-loop product systems can be broken down into smaller subsystems. This technique could be used to follow a structured path to dissect the available assets in the area. For each of these subsystems the economic performance can be simulated [64] and the related environmental impact can be determined [27]. Municipalities often choose the use of tools for which data is readily available and which suits the ambitions of the municipality [65]. In this research, the adaptability of this strategy to maintenance of urban areas should be investigated and is used as an inspiration to develop a new tool.

2.3.1 Life Cycle Inventory

To capture the performance of the smaller subsystems, an LCI per object system needs to be studied. This results in multifunctional processes, which yield more than one functional flow. More than one product outflow and/or waste flow causes the system to be multi-functional [66]. Multifunctional processes make measuring problematic, as the processes are part of different systems. Therefore, allocation of the calculated impacts to the different systems is necessary [66]. Methods to allocate the impacts are subdivision, system expansion, physical partitioning and economic partitioning [66]. The subdivision method is applied in this research, following the dissecting of assets by J. Low *et al.* to smaller subsystems [64]. This results in mono-functional processes for which four criteria are investigated per subsystem stage [66].

Each LCI of a subsystem captures the different phases of a life cycle. J. Low *et al.* [64] distinguish two main phases: the mainstream production phase and EOL phase. The mainstream production phase consists of the manufacturing, distribution and use or service stage. Where the EOL phase consists of the collection, processing and disposition stage [64]. Each of these stages has an impact on the environmental and economic performance of the life cycle, however they do not contribute equally to the total performance of the subsystem. To be able to calculate the impact of every stage, a flowchart of the product system should be set up, as shown in Figure 11 [59]. As the processes in this project are more complex than the example in the figure, a more elaborated flow chart should be created to be able to understand the process system. Normally, an LCI consists of a detailed compilation of the environmental inputs and outputs at every lifecycle stage. Inputs include material and energy, and outputs can be air emissions, water effluents and solid waste disposal [67]. Due to the less detailed nature of hybrid LCA models and to keep the system comprehensible, not all environmental inputs and outputs are included in the model.

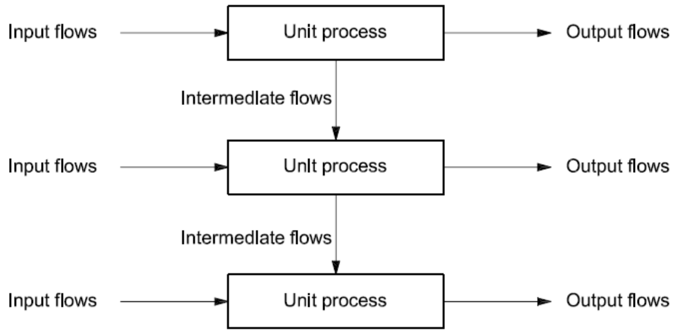


Figure 11. Example of flow chart of a product system. (from ISO 14040 [59])

2.3.1.1 Quantification of impacts

M. Kucukvar and O. Tatari [68] demonstrated that indirect suppliers of the construction sector have the largest impact compared with on-site construction processes. Indirect suppliers are manufactures, which are responsible for processes from resource extraction to product assembling. M. Kucukvar and O. Tatari [68] investigated the contribution of the three different emission scopes. Scope 1 comprises of all direct emissions from a site, including on-site combustion emissions. Scope 2 includes indirect emissions as a consequence of electricity use during construction. Scope 3 refers to all emissions resulting from the upstream and downstream supply chain [68]. M. Kucukvar and O. Tatari [68] cited that scope 3 emissions are responsible for the largest carbon emissions compared to scope 1 and 2, thus the upstream and downstream supply chain cannot be neglected.

In this research, these impacts are included using cradle-to-gate impacts per criteria found in literature. Cradle-to-gate refers to the resource extraction process (cradle) to the sale of the final product (gate) [33]. All three scopes are included in cradle-to-gate impacts. For EOL stages, cradle refers to the collection of waste streams from the construction site. In the EOL stages, the concept cradle-to-grave is also relevant, which refers to the material loss after the linear processes of incineration and landfill. However, if the loop is closed and objects will be reused or recycled, one speaks of cradle-to-cradle [33]. Transportation emissions are calculated to include the impacts related to the exchange of objects between stages. Indirect impacts can be excluded, because they are not directly related to the supply chain. Examples are the change in land use, construction of facilities and the manufacture of equipment [27].

The exclusion of these indirect emissions can be validated, by benchmarking the calculated impact of the project plan with a traditional linear case [27]. In the traditional linear case, new products are bought to replace the removed objects. The removed objects are disposed using the conventional waste management process. The process implemented after EOL depends on the country, object and material. Comparing the calculated impact of the project plan with the impact of a traditional linear case gives insight on the difference in impact of a stage per system. If the difference is negligible the stage can be excluded.

Impacts can be described via several parameters; one of the parameters is a footprint. L. Čuček *et al.* [33] have defined “a footprint as an indicator of how human activities can impose different types of burdens and impacts on global sustainability”. Selection of environmental and economic footprints to include in will be discussed in the next paragraphs.

Environmental impact
The most-known environmental impact indicator is the carbon footprint [33]. Generally, the carbon footprint of a functional unit is the climate change impact that considers all relevant emission sources and sinks within the system boundaries. In academic research, the carbon footprint is used as a transition indicator, translating other environmental indicators (such as NO2-emission) into carbon footprint equivalents [65]. In this research, the embodied carbon footprint is the most relevant environmental impact indicator. The embodied carbon is the emission that occurs along the supply chain of a functional unit. These emissions are released during the supply chain, however, they are physically not part of the object [63].

Using the carbon footprint as a main impact indicator is under discussion, as the climate is also affected by other emission sources. However, the carbon footprint is widely used by policy-makers and industries, making it a widely accepted environmental indicator in the non-academic world [65]. The carbon footprint is an acceptable metric when the environmental impact predominately stems from one process, or processes with a strong covariation, i.e. the combustion of fossil fuel related to the stages in the LCI [65]. In this research, other environmental indicators are included by using carbon footprint equivalents.

While the carbon footprint is an appropriate indicator of the environmental impact of the LCI, it is not used for the resource depletion related with the waste management processes. In CE waste does no longer exists, instead, it is a valuable resource [2]. Evaluation of material loss gives an indication for the amount of replaced primary resources by reused and recycled materials [69].

Economic impact
The monetary value loss is included as an economic indicator. Monetary value loss gives an indication of the value lost due to downcycling of assets. On the other hand, upcycling improves the monetary value of assets. While in both cases materials are not necessary lost, including both material and monetary value loss will encourage high quality reuse [69]. In the rest of this report, monetary value loss of assets will be referred to as value loss.

Footprints which indicate the economic impact of the LCI are the economic footprint and financial footprint. For both footprints, no clear definition is available. However, the total direct and indirect economic impact of the stages in the LCI appear to be presented by the economic footprint [33]. The economic footprint could also be represented by the net present value [64]. Unfortunately, due to limited data on the costs of the different stages in the LCI, calculation of the economic footprint is not feasible in this research. Instead the financial footprint is chosen to represent the economic impact. Expenditures made by a human or company are represented by the financial footprint [33]. Market value prices and the transportation costs are representing the expenditures of the contractor.

2.3.2 Life Cycle Interpretation

As stated in ISO 14044, the life cycle interpretation phase comprises of the identification of significant issues in the results, an evaluation including data quality checks, sensitivity analyses, conclusions, limitations and recommendations [60]. The identification of significant issues is based on the result obtained from the LCI and will contain inventory data and a contribution analysis from life cycle stages, such as individual unit processes or groups of processes, like transportation and energy production.

Three checks are mentioned in the ISO 14044 document, which must be done after the LCI. The completeness check ensures the availability of relevant information and data. If the missing or incomplete data influences the outcome significant and the goal of LCA is not met, revising of the goal or LCI is necessary. If the influence of the missing or incomplete data is rather small, no revision is necessary, however, this should be recorded. The sensitivity check assesses the reliability of the results. The results can be affected by preliminary-made assumptions or data uncertainties. The result of the sensitivity check shows effects on the LCI results. Last, a consistency check ensures assumptions, methods and data to be consistent with the goal and scope of the LCA.

2.4 Guidelines for the new tool

As evident from the literature review in this chapter, calculating the complete environmental and economic impact brings a few challenges to the table. The available tools and methods do not cover the scope that should be investigated for implementation of CE in a municipality. Based on current literature, this thesis aims to develop a new tool for calculating the environmental and economic impact.

The following guidelines for this new tool (PAVE) resulted from the literature review:

1. The tool encourages local waste management, resulting in more local reuse. Improvement of the waste management strategies after EOL of assets should boost the local reuse.

2. The tool enables the selection of an optimal alternative in waste management problems. Waste management alternatives are compared to each other and benchmarked to the traditional linear economy system.

3. The tool respects the rules and regulations of the Dutch government and Almere municipality concerning waste management.

4. Dissecting assets into smaller subsystems results in application of the subdivision allocation method.

5. The tool includes scope 3 emissions from the upstream and downstream supply chain. However, it does not include indirect impacts, which do not directly relate to the supply chain [27].

6. Selected impact criteria are carbon footprint, financial footprint, material and monetary value loss.

7. The interpretation phase of the tool comprises of reporting on the identification of significant issues in the results, an evaluation including completeness, sensitivity and consistency checks, conclusions, limitations and recommendations.

Methodology

3 Methodology

In this chapter the developed method will be discussed. First, an introduction of the method via an overview is given. Next, the several steps of the method will be explained in detail. This results in the subdivision of this chapter in four paragraphs: introduction method, inventory of assets, PAVE and implementation in the current decision-making scheme. In every paragraph, the method and validation steps to justify assumptions and conclusions are explained.

3.1 Introduction method

To improve the available information of assets, inventories of the stock and waste management are composed. The stock inventory of assets is composed based on data of the Almere municipality and in more detail for the case area. This results in an overview of the current available information and optimal information level, which enables the prioritization of assets based on the largest volume and value. The prioritized assets are dissected into objects and materials. The inventory of waste management processes will be composed for prioritized objects.

Next, PAVE is developed. This tool gives an insight on the environmental and economic impact of the maintenance plan of the contractor and compares these to the impacts of conventional waste management. This helps decision makers to support their choice for the maintenance plan (of an urban area) in question. In the case study, the urban area is the studied case area: phase 1 of the neighbourhood ‘Regenboogbuurt’. To ease calculation of the impacts, the system is split in smaller subsystems: the prioritized objects. For every prioritized object, an LCI is conducted. The LCI gives an overview of the possible strategies and related stages, such as transport and demolition. For each stage in the LCI, criteria are quantified to calculate the impact. These criteria are carbon footprint, financial footprint, material and value loss. In this chapter, the equations, framework and validation techniques are discussed.

To have an impact, the tool should be included in the decision-making scheme of municipalities. The current decision-making scheme is investigated and the optimal spot for implementation of the tool is chosen. The different steps in the method are implemented for the case area and the quality of the result is analysed. This method (Figure 12) results in a validated answer to the stated research questions.

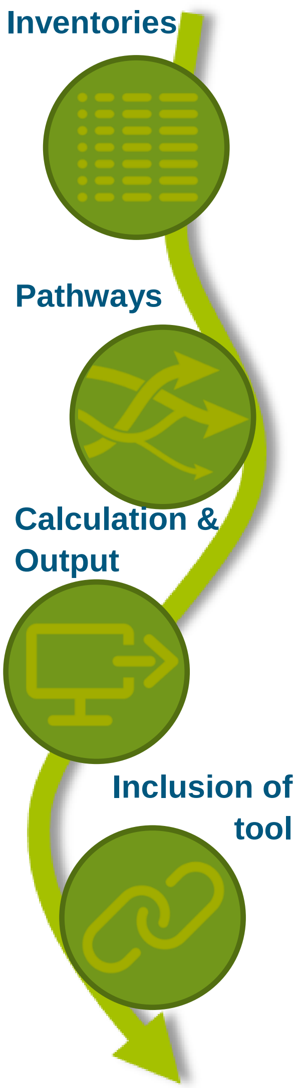


Figure 12. Overview of methodology.

3.2 Inventories

This research consists of several inventories to enable the use of PAVE. First, the method used to conduct a stock inventory is discussed below. A sophisticated selection of objects is made, consisting of the objects with the highest value and largest volume. Afterwards, the developed LCI is discussed.

3.2.1 Stock inventory

Table 1. Overview of node levels.

Levels	Related asset level
Root	Area
First	Object type
Second	Object
Leaves	Material

Based on the asset management system GBI, an overview of the current information per asset will be investigated. In GBI, Almere municipality stores data of their assets, such as their location and size. Following the PSILA methodology, different node levels are distinguished with related asset levels [64]. These levels are displayed in Table 1. The root node level is the area under investigation. All assets are located in the area; thus, the root level is not of relevance. The other node levels are the object type, object and materials. These levels can be pavement, tiles and concrete, respectively.

In the 'Results' section, a comparison is made between the information available in GBI, also referred to as the current information level, the achievable information level and the optimal information level. The achievable information level is based on information available at the municipality, which is collected form outline zoning plans of the case area. The contractor, Dusseldorp, made an inventory of the case area based on field work and expertise. For each node level, the optimal information level is listed and compared with the available information of each of these inventories. The optimal information level is necessary to use PAVE. This shows the currently existing data gap in the asset database of Almere municipality.

The prioritized assets are selected based on the stock inventory of the contractor. Object streams with the highest values and largest volume are selected. The considered object streams should together contain at least 80% of the volume and value in the area. Finally, improvement of the conventional waste plan is investigated. If no or only little improvement is feasible, the implicated object stream is excluded from the priority list.

If the contractor decides to implement the conventional waste plan, the object streams are excluded for the case study. Since this does not result in a change in impact, this assumption is only valid for the case study. Generally, all prioritized object streams should be included to make comparison between maintenance plans feasible.

Unprioritized object streams will be neglected in further inventories. Nonetheless, a complete overview should contain the implemented circular solutions for these streams. This will not result in a change in the calculated impact of the system, but offers extra indicators to select a maintenance plan.

3.2.2 Life Cycle Inventory

For the selected object streams an LCI is conducted. Each object is a unique subsystem, which needs its own LCI. All subsystems together form the system under consideration. In the LCI, the most significant burdens which an object endures during its life cycle are compiled and quantified [70]. The LCI incorporates all possible pathways of the released objects. These pathways consist of different stages. Stages under consideration are demolition, transport, waste management, on-site construction, manufacturing and storage.

A general flow chart is introduced in Figure 13. This is the base LCI and is adjusted per object. This flow chart is an indication of the possible waste management and procurement alternatives per object and considers possible in- and outflows. Starting point of the flows is the area of interest: the urban area where a large maintenance event is planned. Thereafter, the released object can follow different pathways.

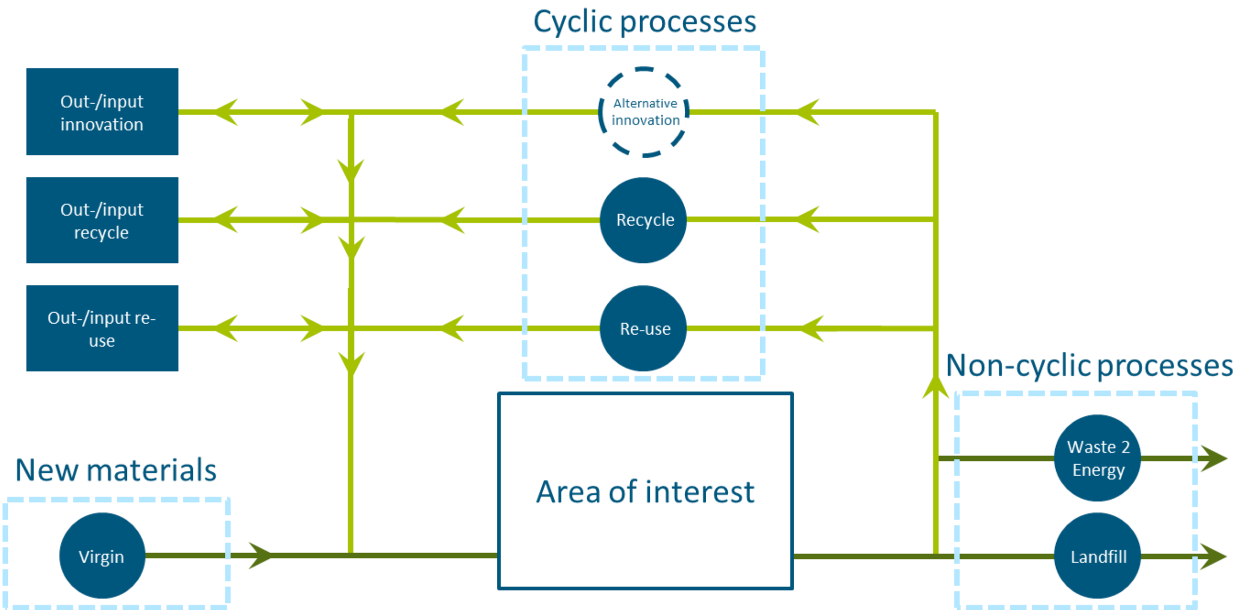


Figure 13. General flow chart of possible waste management and procurement alternatives.

A clear distinction is made in the waste management stage between the non-cyclic and cyclic processes. Non-cyclic processes represent the linear waste management system. These processes result in 100% material loss followed by replacement with virgin material. Cyclic processes are preferred, which are reuse, recycle or an alternative innovation. After a cyclic process, objects or materials can return to the area of interest or exit the cyclic subsystem. Reusable objects are often stored if they exit the subsystem or immediately used at another location. Recyclable objects could be used as an input to produce new objects. These objects could be placed in the area of interest, but also leave the subsystem. To yield a comprehensive tool, all possible pathways of the LCI are included into the tool.

The alternative innovation can be any process where objects are assimilated. The addition of this option enables the inclusion of unconventional processes, which are not considered in the conventional design of the tool. This procedure can be an upcycling or recycling process, but also a reuse process where e.g. the carbon footprint is diminished.

To enable comparison of the implemented waste management plans with the traditional plan, LCIs of both systems are conducted. The traditional plan is referred to as the benchmark system. An overview of necessary information sources for the LCIs and assumptions is given in Table 2.

Table 2. Info sources per situation and the corresponding assumptions.

Necessary info	**Traditional plan**	**Implemented plan**	**Details**
Outflow of objects			
Waste management processes	BRBS recycling	Dusseldorp	Given in percentage of object going to a certain process.
Costs of processes	Market value	Market value	Review of online market prices
Carbon footprint of processes	Ecoinvent & literature review	Ecoinvent & literature review	
Material loss during processes	Dusseldorp	Dusseldorp	Estimation based on experience of contractor
Innovations used	Not relevant	Dusseldorp	
Inflow of objects			
Used manufacturing processes	100% virgin	Dusseldorp	
Costs of processes	Market value	Market value	Review of online market prices
Carbon footprint of processes	Ecoinvent & literature review	Ecoinvent & literature review	
Material loss during processes	Dusseldorp	Dusseldorp	Estimation based on experience of contractor
Innovations used	Not relevant	Dusseldorp	

3.3 The tool: PAVE

PAVE quantifies the impact of plans for large maintenance projects of urban areas. To do so, it is necessary to calculate the different environmental and economic impacts related to chosen maintenance plans. In the next paragraph equations are defined to calculate the impact of selected criteria per stage, followed by the explanation on how to combine the calculated impacts into one output per criteria. Finally, the input and output of the tool are validated by several analysis techniques. The used techniques will be explained in more detail below.

3.3.1 Quantifying impact

The impact is quantified for four different criteria: carbon footprint, financial footprint, material and value loss. These criteria are calculated for each subsystem per one cubic meter of an object, which is the functional unit (Figure 14). The object under consideration changes per subsystem. The related unit per criteria is defined to ensure that one unit per criteria is consistently used (Table 3). The functional unit of both the financial footprint and value loss is euro per cubic meter. While the units are the same, the used values are different. The value loss represents the monetary value loss of the objects, while the financial footprint represents the costs for the contractor. Both are based on the market value of objects. An equation per stage is developed for each selected criterion. Negligible differences between the implemented plan and benchmark system determine whether a stage is included or not.

Table 3. Unit per criteria.

Criteria	unit
Carbon footprint	Kg CO_2/ m^3
Financial footprint	€/ m^3
Material loss	m^3/m^3
Value loss	€/ m^3

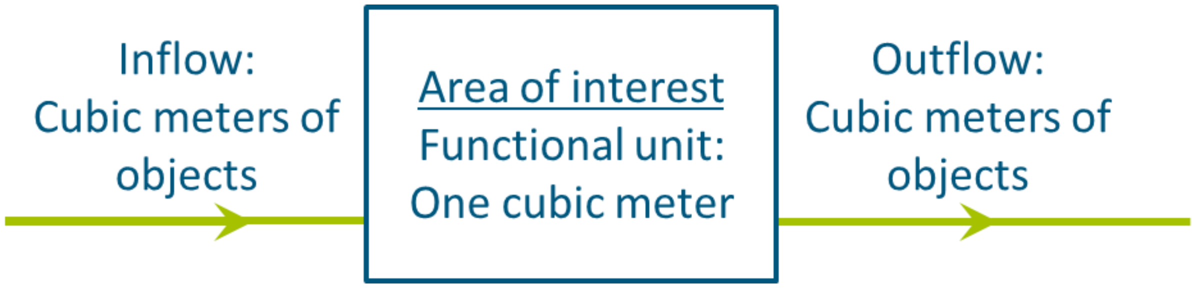


Figure 14. Inflow and outflow from area of interest. The selected fuctional unit is cubic meter of an object.

In Table 4 an overview of the stages in the system is given. For each stage expected differences between the implemented plan and the benchmark system are investigated. The removal stage and on-site construction stage are expected to have a negligible difference in impact with the benchmark system, resulting in the exclusion of these stages from the model.

Table 4. Stages with an environmental and economic impact and differences between the implemented plan and the traditional plan.

Stages with environmental and economic impact	Implemented plan compared to traditional plan	∆ between traditional and implemented plan
Demolition	Demolition footprint is equal	0
Transport	Different process, so different transport	∆
Waste management	Different waste management processes	∆
On-site construction	Same quantity coming in	≈0
Manufacturing	Objects coming in from different processes	∆
Storage	Not used in traditional plan	∆

3.3.1.1 Environmental impact

The carbon footprint and material loss are selected to measure the potential environmental impact. Lower carbon emissions will be a stimulant to select a certain plan, following the ambition to decrease the national carbon footprint [71]. In addition, it is a widely used and understood measure by local governments. Material loss indicates the loss of valuable resources that could be avoided. A mass balance does not easily track this measure, as the release of material from the system without replacement does not necessarily affect the depletion of resources. To include this element, not only the released materials are calculated, also the incoming recycled or reused materials are considered. Thus, it is very important to define the loss of material for every stage in the process.

Carbon footprint equations

For each subsystem, the carbon footprint is calculated per stage, according the equations 1-5.

Transport stage:

$$Transport\ footprint_{A\rightarrow P_{n_i}} = volume\ of\ object \frac{vehicle}{volume} \frac{2\ x\ Distance_n}{vehicle} \frac{L\ Diesel}{Distance} \frac{CO_2}{L\ Diesel} \tag{1}$$

$$Transport\ footprint_{P_n\rightarrow A_i} = volume\ of\ object \frac{vehicle}{volume} \frac{2\ x\ Distance_n}{vehicle} \frac{L\ Diesel}{Distance} \frac{CO_2}{L\ Diesel} \tag{2}$$

Waste management stage:

$$Footprint\ P_{n,out_i} = volume\ object \frac{Carbon\ footprint_n}{volume} \tag{3}$$

Manufacturing stage:

$$Footprint\ P_{n,in_i} = volume\ object\ \frac{Carbon\ footprint_n}{volume} \tag{4}$$

Storage stage:

$$Footprint\ depot_i = volume\ object\ *\ \frac{Carbon\ footprint\ depot}{volume} \tag{5}$$

Where A is the area of interest, P is manufacturing or waste management process, n is the index number used to refer to a certain waste management process and i is the subsystem index number used. Carbon footprints of processes are based on secondary cradle-to-gate data, such as ecoinvent and LCA research. The total carbon footprint of the subsystem is calculated by summing up all the equations:

$$\begin{aligned} CO_2\ footprint_i = & \sum_n Transport\ footprint_{A\rightarrow P_n} + \sum_n Transport\ footprint_{P_n\rightarrow A} \\ & + \sum_n Footprint\ P_{n,out} + \sum_n Footprint\ P_{n,in} + Footprint\ depot \end{aligned} \tag{6}$$

The total carbon footprint of the full system is found by summing up all the subsystems.

Material loss equations

The material loss is calculated by determining the material loss in the downstream supply chain and the material gain in the upstream supply chain. The material gain will be subtracted from the material loss, resulting in the possibility of the total material loss to be negative.

The equation for calculating the downstream supply chain' material loss is:

$$Material\ loss\ P_n = volume\ object * Lost\ fraction\ P_n \tag{7}$$

The material gain in the upstream supply chain is caused by the use of recycled or reused object. The volume gained is calculated with equation 8:

$$P_{r_{new},\,in} = \sum_n Material\ gain\ P_{r,n} \tag{8}$$

The total material loss of a subsystem is simply found by subtracting the material gain from the material loss:

$$Total\ material\ loss_i = \sum_n Material\ loss\ P_n - P_{r_{new},\,in} \tag{9}$$

Where r refers to the use of reused or recycled materials in the process. The total material loss of the system is the sum of the material loss in all subsystems.

3.3.1.2 Economic impact

The costs of the maintenance plans are expressed in euros. As budget is still the main drive in the current decision maker scheme, gaining insight on the financial footprint of the implemented plan will lead to support the selection of the most favourable maintenance plan. Also, the monetary value loss of assets due to downcycling is included in this research as an economic impact indicator. Equations for both the financial footprint and monetary value loss are developed.

Economic costs equations

For the environmental and economic impact, the same stages are included to calculate the impact. Per stage the equations are given.

Transport stage:

$$Transport\ costs_{A\rightarrow P_n} = volume\ object \frac{vehicle}{volume} \frac{2\ x\ Distance_n}{vehicle} \frac{L\ Diesel}{Distance} \frac{costs}{L\ Diesel} \tag{10}$$

$$Transport\ costs_{P_n\rightarrow A} = volme\ object \frac{vehicle}{volume} \frac{2\ x\ Distance_n}{vehicle} \frac{L\ Diesel}{Distance} \frac{costs}{L\ Diesel} \tag{11}$$

Waste management stage:

$$Costs\ P_{n,out} = volume\ object \frac{Dump\ costs_n}{volume\ object} \tag{12}$$

Manufacturing stage:

$$Costs\ P_{n,in} = volume\ object \frac{Procurement\ costs_n}{volume\ object} \tag{13}$$

Storage stage:

$$Costs\ depot = volume\ depot * \frac{Depot\ costs}{volume} \tag{14}$$

The total financial footprint of the subsystem is given by:

$$\begin{aligned} Financial\ footpint_{\ i} = & \sum_n Transport\ \ costs_{A\rightarrow P_n} + \sum_n Transport\ costs_{P_n\rightarrow A} \\ & + \sum_n Costs\ P_{n,out} + \sum_n Costs\ P_{n,in} + Costs\ depot \end{aligned} \tag{15}$$

The total financial footprint of the total system is the sum of the financial footprints of the subsystems.

Monetary value loss equations

The monetary value loss of assets depends on the implemented waste management process. The value loss is expressed as:

$$Value\ loss\ P_{n_i} = (virgin\ market\ price - market\ price\ after\ P_n)_i \quad (16)$$

Where virgin market price refers to the current price paid for objects made from virgin materials.

For each waste management alternative, the calculated values are given in Table 5. Technological innovation has a possible value gain. An increase in the selling price of a product after implementing a certain innovation is referred to as upcycling.

Table 5. Monetary value loss equation per waste management alternative.

Waste management alternative	Monetary value loss
Reuse	0
Recycle	$virgin\ market\ price - market\ price\ after\ P_n$
Waste-to-energy	$virgin\ market\ price$
Landfill	$virgin\ market\ price$
Technological innovation	$virgin\ market\ price - market\ price\ after\ P_n$

The total monetary value loss is simply the sum of all value losses of the different subsystems. Similarly, the value loss of the complete system is the sum of all the subsystems' value loss.

$$Total\ value\ loss_i = \left(\sum_n Value\ loss\ P_n\right)_i \quad (17)$$

3.3.2 Presentation of tool elements

The input values of the equations consist of values based on secondary data for both footprints. A database of these input values is built to congregate all values. To encourage the input of technological innovation data, a technological innovation sheet is developed with guidelines and requirements for the inserted data, enclosed in this report as Appendix A2.

The output of the tool should be comprehensive and coherent. Hence, all inputted information results in only four numbers: the system's carbon footprint, financial footprint, monetary value and material loss (Figure 15). To add more detail, the calculated values for each subsystem can be presented. However, this extra knowledge is only relevant if the decision maker is familiar with the different objects and traditional waste management.

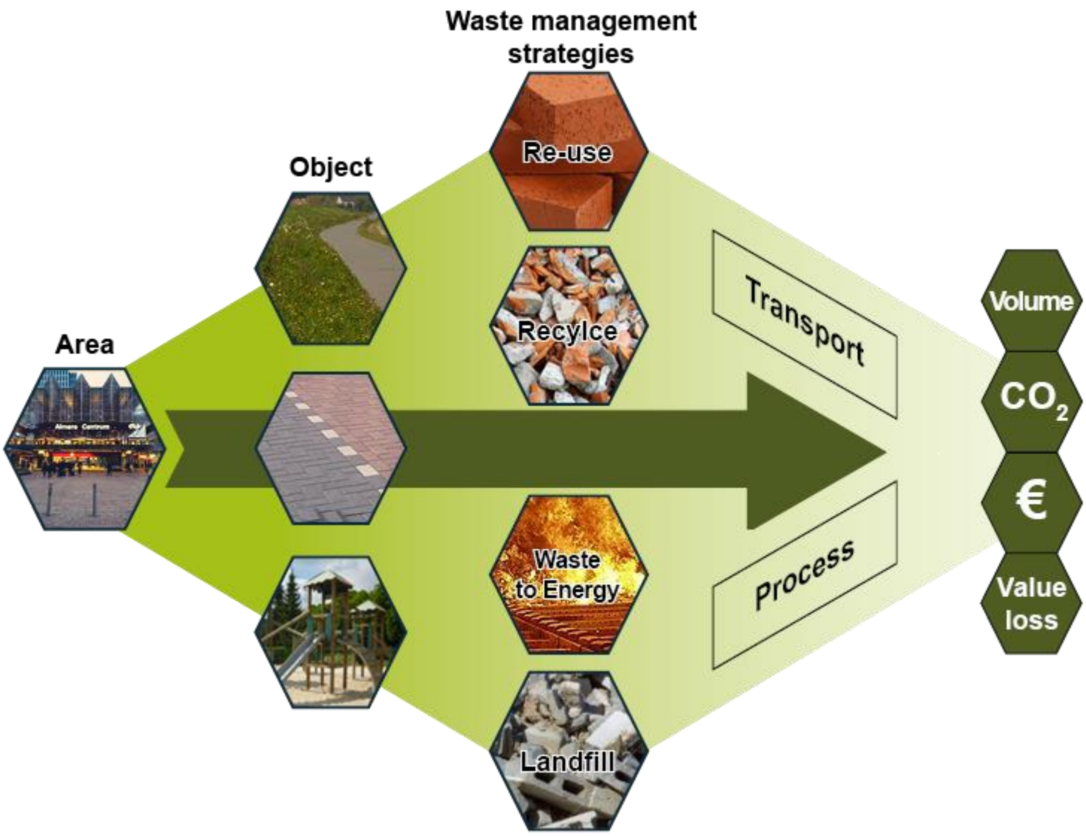


Figure 15. Overview of all elements, which comprises the info for the output values.

3.3.3 Analysis of results

Three types of analysis are conducted: data quality check, contribution analysis and sensitivity analysis. The data quality check investigates the consistency and completeness of the used data. The contribution analysis shows the dominant stage and object. The sensitivity analysis validates the model and checks the two main assumptions made in the model. The two main assumptions are:

1. The transport distance for virgin objects is estimated to be 100 kilometres [72]. This is a rough estimation. The influence of the assumption on the calculated transportation footprint is studied. Also, the influence on the total footprint of the systems is investigated.
2. The selected values for the waste management processes should be representative. However, it is expected that a small change in the footprint of these processes has a big influence on the results. Adjusting the footprints by ten percent and implementing these new values in the tool, provides an insight on the robustness of the tool and its sensitivity to input changes.

3.4 Implementation in decision-making

To include the tool in the conventional decision-making scheme, this scheme should first be known (Figure 16). Based on expert interviews at the municipality of Almere, a better understanding of the conventional scheme is gained. Hereafter the most suitable implementation of the tool is chosen. A trade-off between maximum impact and easy implementation is made to ensure the feasibility of the proposed implementation.

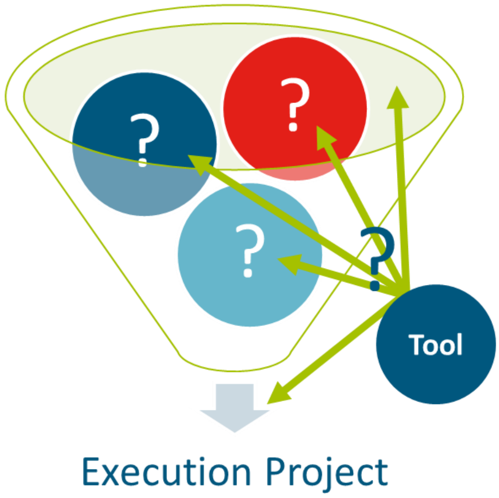


Figure 16. Unknown processes in the conventional decision-making scheme.

The three largest financial banking companies in the Netherlands, ABN AMRO, ING and Rabobank formulated guidelines to fund initiatives which enhance the implementation of CE [73]. In this study, these guidelines are investigated and used as an inspiration to come up with appropriate guidelines selecting the best maintenance plan.

Finally, the decision makers at Almere municipality are consulted to review the tool applicability. Furthermore, it was tested whether the tool satisfies the needs of the municipality. Finally, the usability of the tool is tested by LCA experts at Royal HaskoningDHV, who checked the complexity and reliability of the tool for the application during large maintenance events.

Results & discussion

4 Results & discussion

4.1 Stock inventory results

A complete stock inventory dissects all assets in an urban area into materials and their respective volume, embodied carbon, monetary value and estimated EOL (Figure 17). A complete inventory should contain the material composition as well as the related volume of all assets. The EOL is based on the MPBA of the municipality. Here the municipality of Almere selects areas and assets which will be maintained in the coming four years. Estimations of embodied carbon and monetary value could be added based on the ecoinvent database and an investigation on market value, respectively. The currently available information is inventoried per node level. In Table 6, the optimal information level of object type roads is compared with the available information from different sources. The sources are the asset management system of Almere municipality 'GBI', GBI combined with outline zoning plans of the case area and the contractor's inventory of the case area. The optimal system is not achieved for every node in the subsystem roads. In Appendix 0, a similar comparison table is included for the three remaining object type subsystems: sewage, vegetation and street furniture.

Furthermore, the inventory of the entire municipality is compared with the case area to investigate if the collected values are representative for the municipality. The information level of assets in the entire municipality can be easily improved when the inventories are comparable. This comparison is based on GBI and enclosed in Appendix 0. The case area lacks mechanical pipes and boulevard plants in its GBI inventory. Other assets are found in both or only in the inventory of the case area. The latter is caused by labelling in GBI as there is more than one labelling system, resulting in different inventory outputs. These different labelling systems are redundant. While the inventories are comparable, it is advised to first restructure the current information level in GBI to decrease complexity, before improving the information in the database.

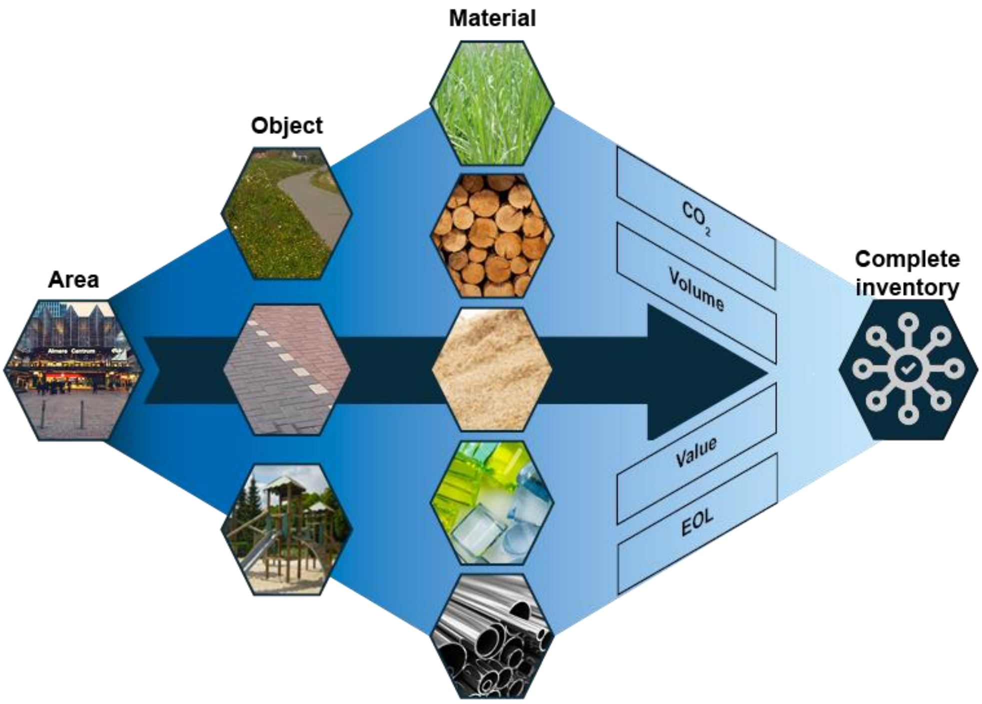


Figure 17. Overview of a complete inventory for an urban area.

Table 6. Required information level for an optimal system and the available information from different sources for object type roads.

Nodes	Optimal system	GBI	GBI + outline zoning plan	Information contractor
Roads	Info about m² per road type, thickness and materials	Only info about m² of available road types	Yes, for available road types	No, info missing about thickness & road base
Paving stones Double	Material, m² & thickness	m²	Yes	Yes, only surface course
Paving stones	Material, m² & thickness	m²	Yes	Yes, only surface course
Paving tiles	Material, m² & thickness	m²	Yes	Yes, only surface course
Gutter	Material, m² & thickness	n.a.	n.a.	Yes, only surface course
Prefab element	Material, m² & thickness	Pieces	Yes	Yes, only surface course
Grass tiles	Material, m² & thickness	m²	Yes	Yes, only surface course
Stairs elements	Material, m² & thickness	n.a.	n.a.	Yes, only surface course
Street kerb	Material, m² & thickness	n.a.	n.a.	Yes, only surface course
Flush kerb	Material, m² & thickness	n.a.	n.a.	Yes, only surface course
Access road bricks	Material, m² & thickness	n.a.	n.a.	Yes, only surface course
Lowered kerb	Material, m² & thickness	n.a.	n.a.	Yes, only surface course
Kerb	Material, m² & thickness	n.a.	n.a.	Yes, only surface course
Concrete	m² & thickness	n.a.	Yes	Yes
Mixed granulate	m² & thickness	n.a.	Yes	n.a.
Sand	m² & thickness	n.a.	Yes	n.a.
Asphalt roads	Material, m² & thickness	m²	Yes	Yes, only surface course
Asphalt	m² & thickness	n.a.	Yes	Yes
Mixed granulate	m² & thickness	n.a.	Yes	n.a.
Sand	m² & thickness	n.a.	Yes	n.a.
Shell path	Material, m² & thickness	m²	Yes[1]	Yes, only surface course
shell/ clay mixture	m² & thickness	n.a.	n.a.	Yes, only surface course
Sand	m² & thickness	n.a.	n.a.	n.a.

[1] *The shell path is specified in outline zoning plan of the municipality of Almere. However, the composition of the upper layer is not well-defined. On the contrary, the contractor gives an estimation of the expected composition.*

4.1.1 Prioritizing assets

The volumes and values per object and material are estimated in order to conduct the prioritization step. These estimations are included in Appendix A3.2 and can be used to select prioritized assets. The included object streams combined should contain at least 80% of the volume and value in the area.

In the case area, the total available volume and value of assets are 25.712 m^3 and € 1.044.978, respectively. The distribution of the total volume and value among object types are displayed in Figure 18. To exceed 80% of the total volume, the road base should be selected with either vegetation or road surface course. In case of the value distribution: road base, road surface course and sewage need to be combined. To exceed 80% for both distributions, the road base, road surface course, and sewage were selected as prioritized object types. Altogether, they comprise 84% of the total volume and 93% of the total value.

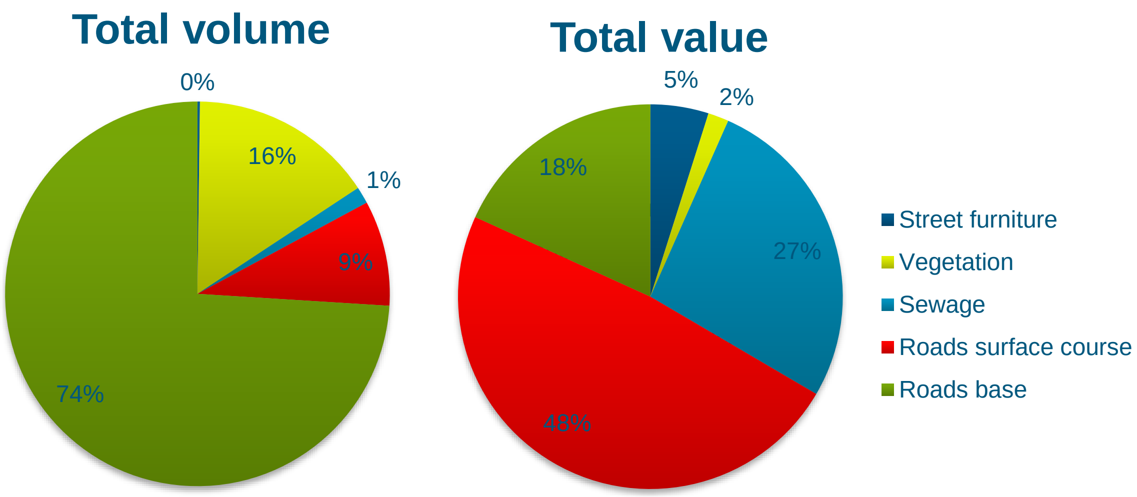


Figure 18. Distribution of volume and value per object type in the case area.

The selected object types consist of different objects. For each object the possibility for improvement is checked. For example, asphalt pavements are currently optimally recycled [70][74]. Therefore an improvement of asphalt recycling is unlikely. If improvement is feasible, the maintenance plan of the contractor is consulted on the implementation of this waste management alternative. The object is excluded from further investigation when the waste management cannot be improved or when the contractor implements the traditional waste management plan. The second selection criterion is only valid for this case study. Inclusion of all objects that are part of the prioritized object types and can potentially improve waste management, is required for a fair comparison between the different maintenance plans.

In Table 7 the selected objects for further investigation are given in bold. Reasons for in- or exclusion are described. Accordingly, the following materials are further investigated: cast iron, concrete, and PVC.

Table 7. Selected objects based on prioritization of object type, waste management opportunity and the contractor's waste management plan.

Objects in prioritized object types	Waste management opportunity?	Opportunity implemented by contractor?	In- or exclude
Concrete bricks	Yes, reuse	Yes	Include
Concrete tiles	Yes, reuse	Yes	Include, excluding 500x500 tiles[2]
Prefab concrete elements	Yes, reuse	No	Exclude
Grass tiles	Yes, reuse	No	Exclude
Asphalt roads	No	-	Exclude
Gravel tracks	No	-	Exclude
Kerbs	Yes, reuse	Yes	Include
Road base	Yes, use of reused materials for inflow	No	Exclude
Road gully	Yes, reuse	Yes, only concrete road gullies	Include
Drainage well	Yes, reuse	Yes, however the position of the well is not changed, which makes reuse the conventional choice	Exclude
Sewage well	Yes, reuse	Yes, however the position of the well is not changed, which makes reuse the conventional choice	Exclude
Sewage pipes	Yes, reuse	Yes	Include

[2] *500x500 tiles are recycled. This is not different from the conventional method.*

4.2 LCI for selected objects

The subsystem 'concrete tiles' is split into 'concrete tiles: general', 'concrete tiles: access road' and 'stair elements'. This results from the large volume of access road tiles and stair elements when compared to general tiles. Also, the kerbs subsystem is split into 'kerbs: general' and 'kerbs: 100/200'. The latter break easily, which decreases their reuse rate. Every subsystem has its own index number. For each of the eight selected subsystems (Table 8), an LCI is set up.

The LCI of concrete bricks is included in this report as Figure 19. For every subsystem, it is inventoried which processes are used and whether any data is available. All found data for the selected subsystems is included in the object database of the tool with a reference source. The data is adjusted to the functional unit of one cubic meter of the object. The object database is added to this report as Appendix A4.4.

Table 8. Subsystems and corresponding index number.

Index number	Subsystem object
1	Concrete bricks
2	Concrete tiles: general
3	Stair elements
4	Concrete tiles: access road
5	Kerbs: general
6	Kerbs: 100/200
7	Road gully: concrete
8	Sewage pipes

In Figure 19, the acronym n/a stands for not available and either indicates that the pathway is not used in this case study or that no data was available. Table 9 presents how waste management alternatives are distributed over the traditional and implemented system. Based on consultation with dr. ir. Peter Fraanje, director of BRBS recycling, the traditional distribution over waste management alternatives per subsystems is explicated. 1% of the concrete material ends up in landfills. However, this option is excluded due to the lack of data. It is assumed that concrete bricks do not contain toxic pollutants, which is the main component of the landfilled concrete [46]. Instead, 100% recycling is applied to the traditional system. The implemented system is based on the maintenance plan of Dusseldorp and one sees that reuse is implemented for 85% of the subsystem.

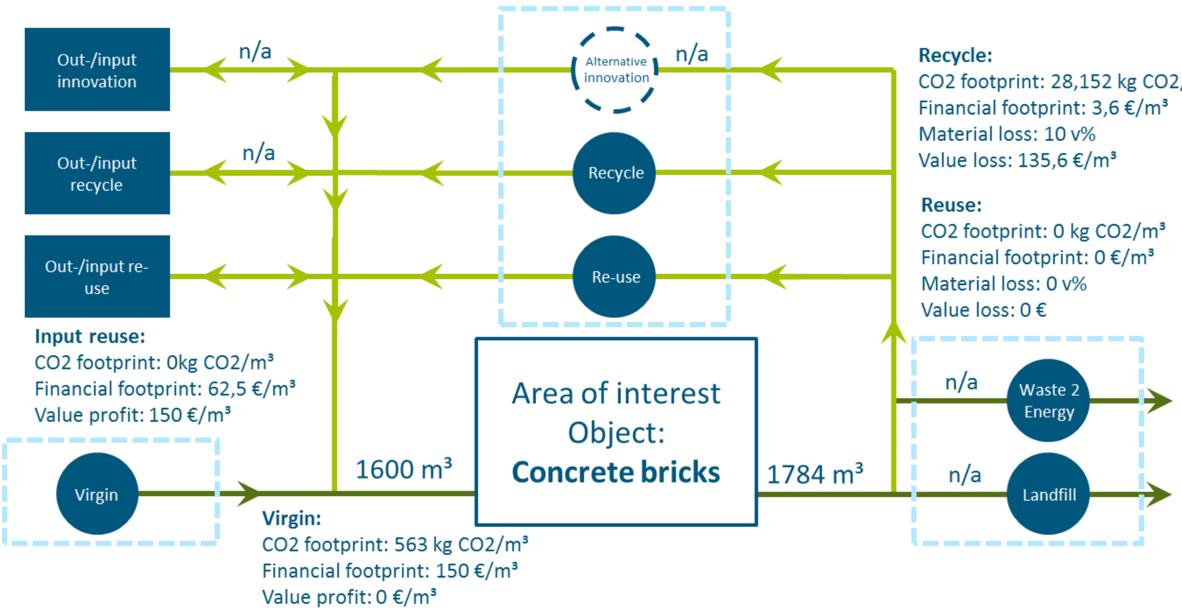


Figure 19. LCI of subsystem concrete bricks.

Table 9. Overview of waste management distribution in the traditional and implemented system.

Waste management alternative	Traditional system (%)	Implemented system (%)
Reuse	0	85
Recycle	99	15
Waste-to-energy	0	0
Landfill	1	0

The collected data combined with calculations for transport and storage (appendix A4.3) allows the calculation of the environmental and economic impact of the subsystem by applying the developed equations discussed in paragraph 3.3.1.

4.3 PAVE

Based on the calculation sheet of concrete bricks (Appendix A4.1), PAVE was used to calculate the total carbon footprint, financial footprint, material and value loss of the subsystem. An overview of the subsystem's results is given in Table 10 which includes the calculated criteria for the traditional and project system. The calculated criteria values for the different systems are subtracted, resulting in the difference between the two systems. This difference indicates the benefits of the implemented project plan. The result of the total urban area system is obtained by combining the results of all the subsystems, which is reported in Table 11. The tool indicates that the project plan emits approximately 1455 ton less CO_2, is 434.000 euro cheaper, and loses 238 m^3 and 424.000 euro less material and monetary value. Further analysis of the contribution of the subsystems and different stages will be conducted in the next paragraphs.

Table 10. Calculated result of the subsystem concrete bricks.

System	Carbon footprint kg CO2	Financial footprint €	Material loss m3	Value loss €
Traditional	986.097,06	256.574,74	176,84	239.795,04
Project	87.225,50	24.211,32	26,53	35.969,26
Δ	898.871,56	232.363,43	150,31	203.825,78

Table 11.Total result of the urban area under investigation.

System	Carbon footprint kg CO2	Financial footprint €	Material loss m3	Value loss €
Traditional	1.707.442,74	558.127,73	282,77	511.368,58
Project	252.243,23	124.264,69	44,39	87.019,44
Δ	1.455.199,51	433.863,04	238,38	424.349,14

4.3.1 Contribution analysis of different objects

The results displayed in Table 10 and Table 11, indicate that the contribution of the subsystem concrete bricks to the total system is large. The contribution of the different subsystems to the decline of the total carbon footprint and the financial footprint is displayed in Figure 20. Together with concrete tiles and sewage pipes, the concrete bricks subsystem is responsible for 82% and 75% of the decrease in carbon and financial footprint respectively. The rest of the decrease is due to the subsystems stair elements, concrete kerbs, concrete kerbs 100/200, tiles: access road and road gully.

The contribution of each subsystem was normalized by dividing each criterion with its corresponding volume, which resulted in a different distribution (Figure 21). The largest carbon footprint contributors in the distribution after normalization are the sewage pipes, road gully, and tiles: access road. The financial footprint is more equally divided with sewage pipes and road gully being the biggest contributors. Striking is the small contribution of concrete bricks to the normalized distribution. It only contributes for 4% and 6% to the carbon and financial footprint distribution respectively. Similar differences are observed for concrete tiles. Thus, the contribution of concrete bricks and concrete tiles to the total impact of the system (Figure 20) is due to the large available volume of these subsystems in the urban area. The six remaining subsystems have a larger or similar normalized contribution.

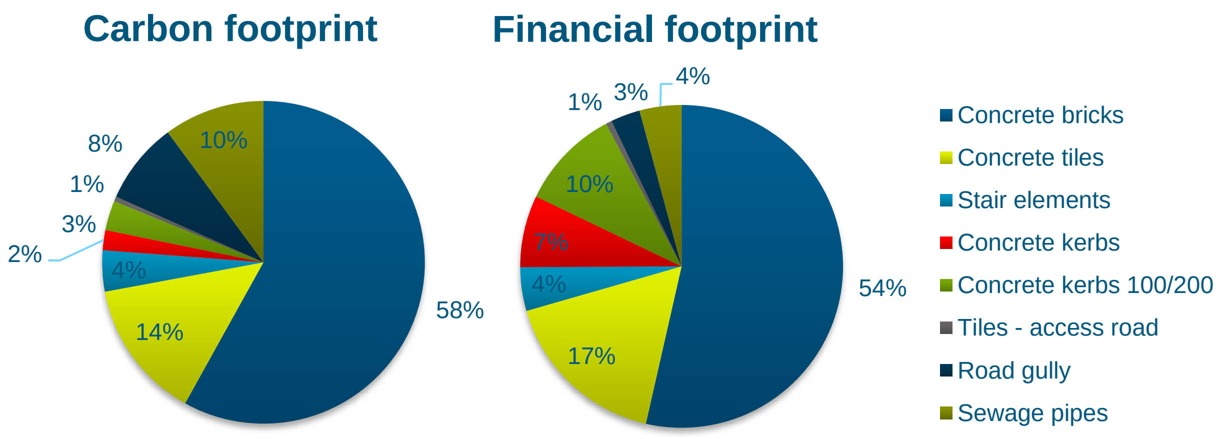


Figure 20.Contribution of subsystems to the total carbon and financial footprint.

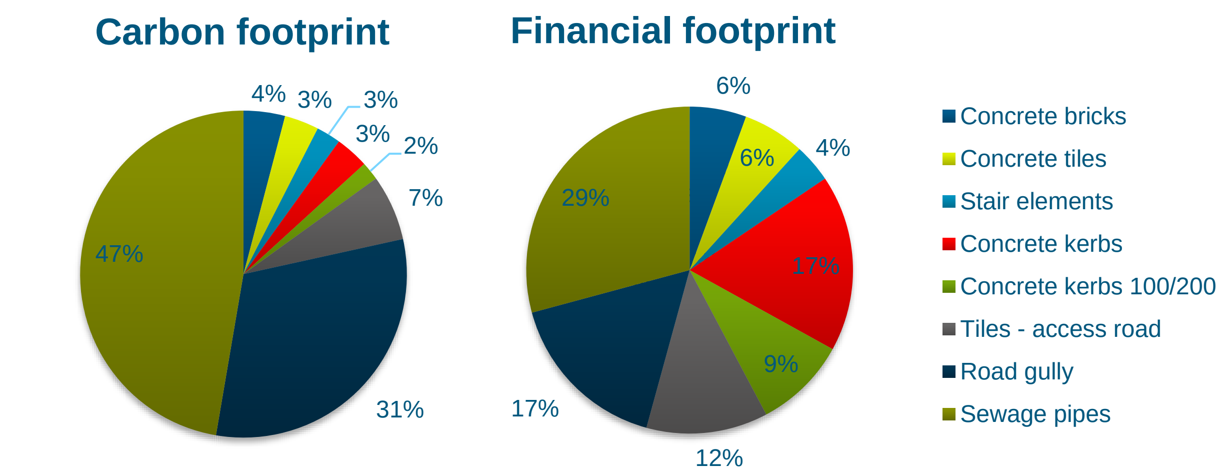


Figure 21. Contribution of subsystems to the carbon and financial footprint per volume.

The ‘concrete bricks’ subsystem is again the dominant subsystem in the decrease of material and value loss (Figure 22). This is caused by the high reuse rate in this subsystem. Compared to the traditional waste management, reuse of road gullies yields the highest material and value profit of approximately 0,019 m^3 and 700 €/m^3 per cubic meter of gully respectively. Concrete bricks have a reuse rate of 85 %, which compensates the relatively low material (0,008 m^3) and monetary value (135 €/m^3) profit per cubic meter of bricks. In conclusion, implementing the reuse waste management alternative results in the highest decrease in material and value loss.

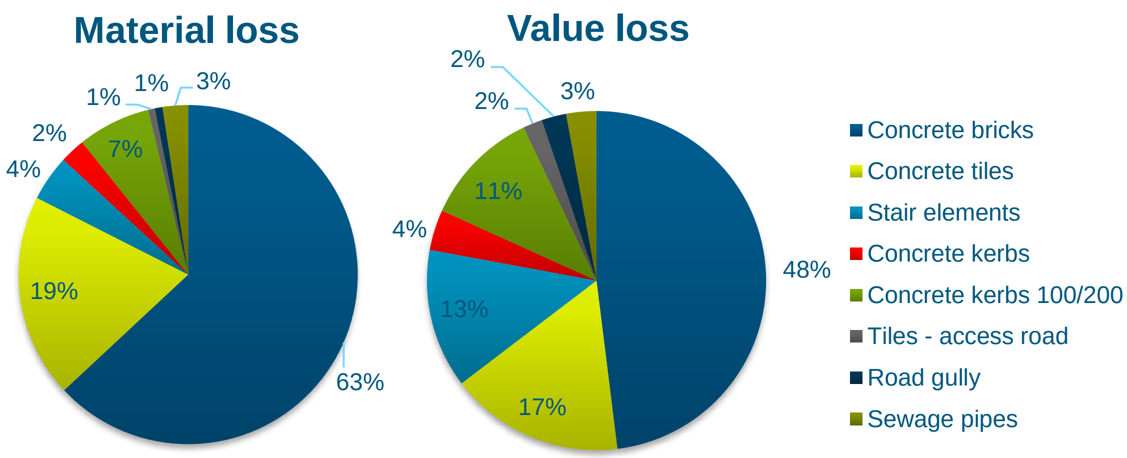


Figure 22. Contribution of the subsystems to the decrease in material and value loss.

4.3.2 Contribution analysis of different stages

To determine the main contributor, the total carbon and financial footprint are split into three different stages: procurement, transport and waste management. The procurement stage is referring to the footprint of the processes related to incoming objects. The waste management stage is referring to the processes located downstream the supply chain. The transport stage only includes the transport between the urban area and the described processes located up- and downstream the supply chain.

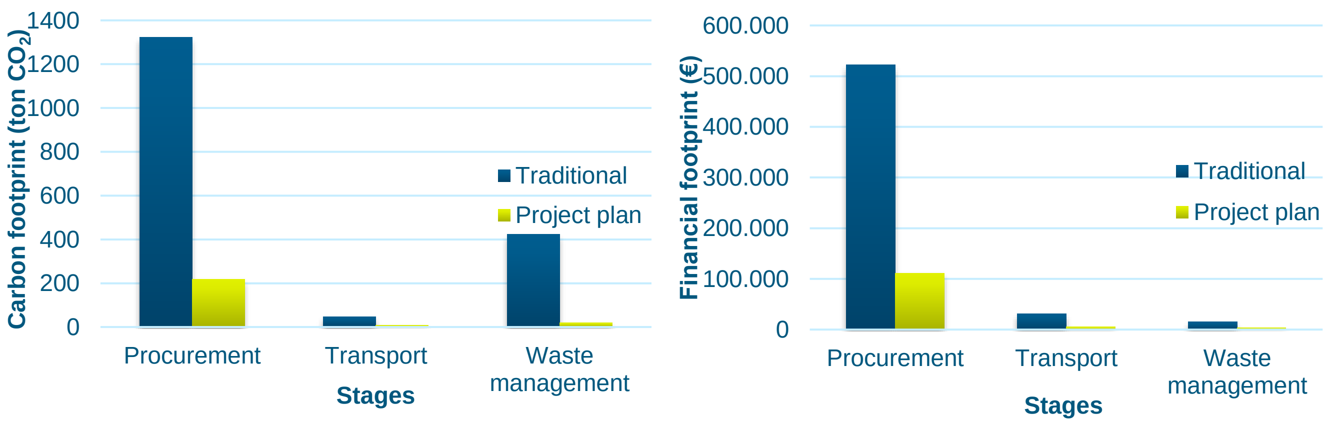


Figure 23. Contribution of different stages to the carbon and financial footprint.

Figure 23 illustrates that the procurement stage is the main contributor in both the traditional system and the contractor's maintenance plan for the carbon and financial footprint. Additionally, in the procurement stage the largest reduction in footprints is achieved by implementing the contractor's maintenance plan. The waste management stage' carbon footprint also shows a decrease. Its financial footprint decrease is smaller. This is due to the definition of financial footprint: expenditures made by a human or company. The price of dumping material at a waste processing plant is low compared to the procurement costs and for some materials even zero due to their high monetary value.

The contribution of the transport stage to both the carbon and financial footprint was expected to be higher, as different studies state that transport is one of the main contributor to the carbon emission [67][68][76][77]. The study by U. Hossain *et al.* [67] stated that 40% of the total energy consumption is due to transport of primary minerals. This indicates that there is a flaw in the tool when it comes to the contribution of transport.

After analyzing the different input values, it was concluded that the transport stage defined here is only a small part of the total transport in the down- and upstream supply chain. For example, for the manufacturing of virgin products, different materials are necessary. These materials comprise different resources. Between the extraction of the resources and selling the product at the gate, many transport movements are required. However, these transport movements are included in the values found for the virgin products. Splitting these transport movements from the process of manufacturing new materials is not possible based on the collected values. A detailed analysis of the upstream supply chain is required to enable this split. This is beyond the scope of this research. To investigate the influence of transport movements in the transport phase, a sensitivity analysis of this stage is conducted. Moreover, the data quality of all stages is checked on completeness and consistency to ensure similar assumptions in the used values per stage.

4.4 Data quality analysis

The quality of the collected data will be discussed per criteria, starting with the carbon footprint. Most of the carbon footprint data is acquired from the ecoinvent 3 database. Ecoinvent 3 is a life cycle inventory database, which consists of LCI datasets for different processes. From this database, carbon footprints are obtained for the manufacturing of virgin materials and products, and the processing of different waste streams. Preferably, the spatial scope of the acquired data is within the Netherlands and includes all stages of the process from cradle-to-gate. Also, the data should be determined before 2015 to be able to represent the current situation. Whether all three restrictions are met, is evaluated for the acquired carbon footprint data.

The spatial scope of the collected values is different. This is based on the RER and ROW acronyms used in the description of the values. RER is assigned to values valid in the European Union and ROW stands for 'Rest Of the World'. This means that these values are valid in the Netherlands. However, no value is found, which is exemplary for the Netherlands. A carbon footprint value with the Netherlands as the spatial scope was only found for plastics. This value is not acquired from ecoinvent, but from a study of Suez. Suez is one of the main waste processing companies in the Netherlands.

The second restriction is met, as all values are cradle-to-gate. However, the temporal scope is not assured. As some data in the econinvent database originates from before 2015, but is still assumed to be valid representation of the current system. Yet, many processes are improved in the last ten years [77][78][79], which weaken the representability of the collected values for the current situation. Moreover, the use of different data sources undermines the comparability of the different values.

The material loss in different stages is based on the expert knowledge of the contractor. On average 10% of the material is lost in recycling processes. The material loss is assumed 0% for reuse, and 100% for energy-to-waste and landfill. These assumptions have a large margin of uncertainty, as material loss is process-depended and could be influenced by many factors, such as the abundant supply of materials and malfunctions in the processing plants. This coarse assumption is applied to all subsystems, enabling the comparability of subsystems. Similar, the material loss of different maintenance plans can be compared based on this coarse assumption. However, the assumption results in an invalid representation of the process itself and the assumed material loss values should not be presented as true. Instead they should only be used to compare the performance of different plans.

The financial footprint and value loss are both based on market prices. Thus, the data quality of both are discussed by examining the quality of the collected market prices. Again, the values were examined on their spatial and temporal scope. Furthermore, fluctuations in these values were explored. Both the spatial and temporal scope are met, as the market price is based on values found online of the Dutch market. Large fluctuations are found in the collected value per object or material, making it difficult to determine the current value of an object. However, the different plans can be compared when this uncertainty is identical for all maintenance plans.

In conclusion, the quality of the collected data is insufficient to analyse the process and the calculated output values for the different criteria cannot be presented as true. However, the quality of the data is sufficient to compare the performance of different maintenance plans. Allowing the use of the tool in a decision-making scheme to select the most environmental-friendly and cost-efficient maintenance plan among other. Thus, the tool should only be used as such.

4.5 Sensitivity analysis

The sensitivity of the tool towards different transport distances and the manufacturing of virgin objects is investigated. As the procurement phase is determined to be the main contributor to the total footprint of the system, a 10% error in the collected values for the manufacturing of virgin object are expected to result in a large error in the total footprints.

The transport distance investigated here is the distance between the supplier of virgin objects and the case area. This transport distance is roughly estimated to be 100 km. However, values ranging from 50 km to 150 km are found in literature [72]. The influence of this deviation on the transport footprint and total footprint is investigated.

Sensitivity analysis: margin of error in transport distance

The minimum and maximum value for the transport distance from the supplier to the construction site are 50 km and 150 km, respectively [72]. The impact of the varying transport distance of virgin products is investigated by filling in the minimum and maximum value in the tool (Figure 24-Figure 25). It is concluded that the error in the transport stage is largely due to the change in transport distance. However, Figure 25 shows that the error is negligible. This is due to the small contribution of the transportation stage to the total system.

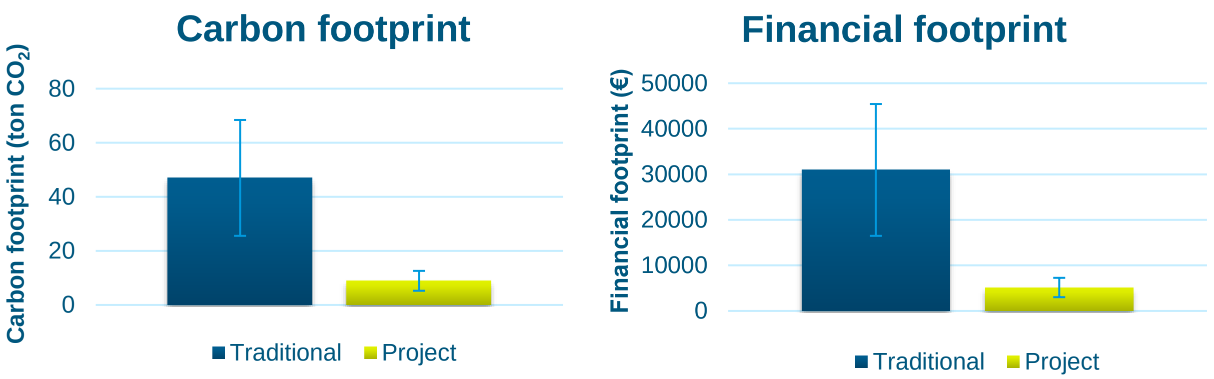


Figure 24. Possible error in the footprints of the transport stage due to a different transport distance for virgin objects.

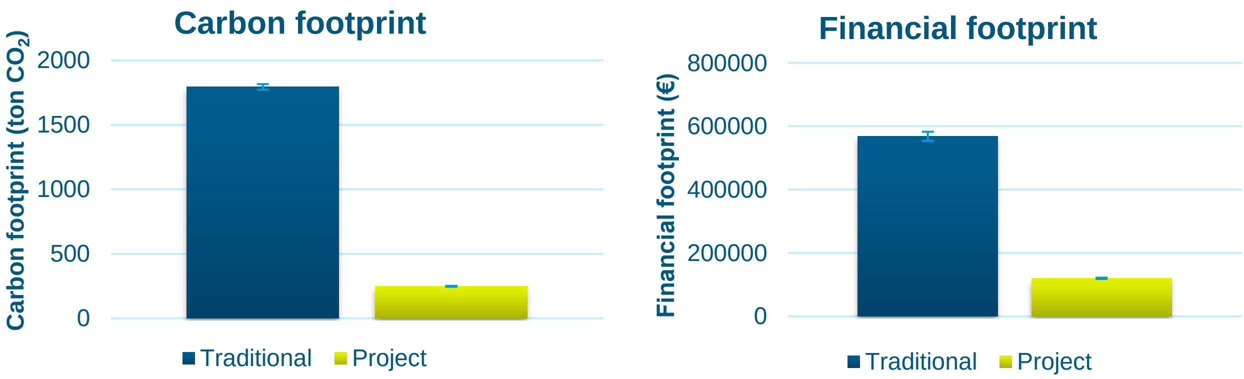


Figure 25. Possible error in the footprints of the total system due to a different transport distance for virgin objects.

Sensitivity analysis: margin of error in dominant stage

For the analysis of the tool's sensitivity towards a margin of error in the dominant procurement stage, the market price values of new objects and their carbon footprint are adjusted by plus and minus ten percent. The result of this adjustment is displayed in Figure 26. The error bars represent the values found based on the plus 10% and minus 10% adjustment. The significant impact emphasizes that the tool is not able to analyse a process' footprint in detail when the quality of input data is not assured.

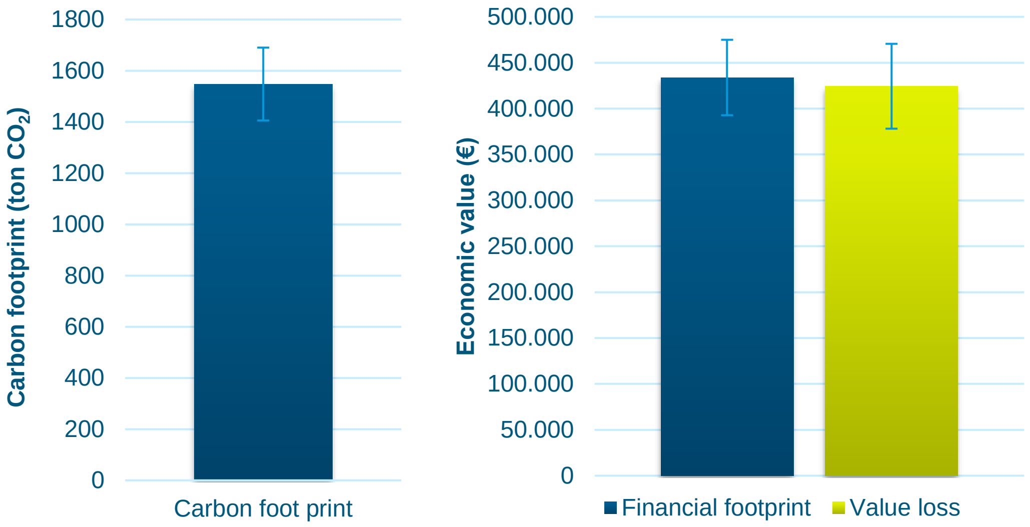


Figure 26. The error in value loss, carbon and financial footprint, due to a possible error in the data of the dominant procurement stage.

4.6 Applicability in decision-making

The conventional decision-making scheme is reconstructed, based on interviews with experts at Almere municipality (Figure 27). Based on inspections, malfunctions of assets in the municipality are reported. When large maintenance of the asset is necessary a project form is filed. Based on the project forms and the available budget, a selection is made of the assets going into maintenance. These assets are combined in 'Meerjaren Plan Beheer Almere' MPBA. For each project a proposal is written, after which a tender document is compiled. In the tender document, guidelines are given for the maintenance of the project. Hereafter, different contractors can apply for the tender. The most suitable project proposal is chosen for the maintenance of the project. The suitability of a proposal is evaluated based on conditions set by the municipality, which often results in the selection of the most cost-efficient proposal.

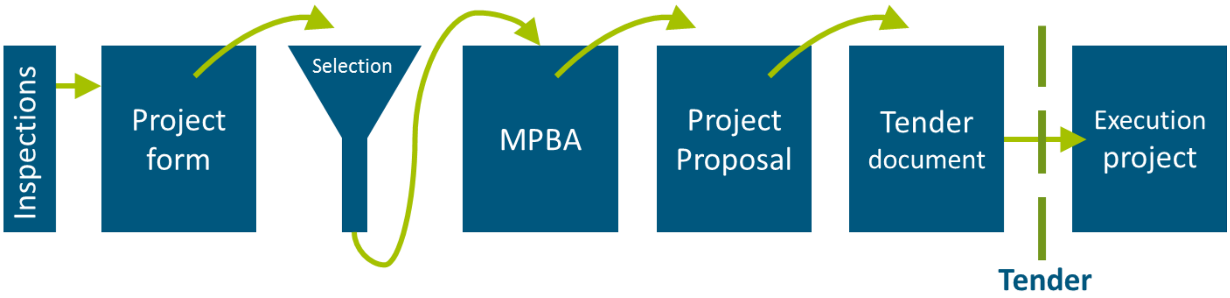


Figure 27. Conventional decision-making scheme for the selection of maintenance projects.

The PAVE tool is best implemented in the decision-making scheme during the stages project proposal and tender document. If circularity is proposed for the project, a stock inventory of the project system should be conducted. The selection criteria for a project are stated in the tender document. The municipality should state in the tender document whether they want to include the tool. Optimally, the implementation of the tool is ensured by making the provided budget depend on implementation. There will be no approval of the tender document if the tool is not implemented.

4.6.1 Guidelines for selection of maintenance plan

The optimal plan should be selected based on different proposed plans of contractors. Selection guidelines are proposed to enable the selection of the plan with the best implementation of CE. The three largest financial banking companies in the Netherlands, ABN AMRO, ING, and Rabobank formulated guidelines to fund initiatives which enhance the implementation of CE [73]. These guidelines are investigated and used as an inspiration to come up with appropriate criteria to select the best-proposed plan.

The proposed plans of contractors should be evaluated on their circularity. To enable this evaluation, the finance guidelines are included which are applicable to select the appropriate maintenance plan in the public space and are not addressed by the tool. These guidelines are adjusted and expanded to formulate relevant guidelines for maintenance. Together with the tool, these guidelines are the selection criteria based on which a proposed maintenance plan should be evaluated. Additionally, exclusion, communicating and reporting guidelines are included. The different selection criteria should be prioritized to optimize the selection strategy. Prioritizing of the different selection criteria is not addressed in this research.

Selection criteria for maintenance plans in the public space:

1. PAVE: the plan includes the tool and transparently documents the input data and assumptions made.

2. Circular design: the plan designs for easy disassembly, repair and modularity to promote reuse, recycling, and prevention. Furthermore, the use of toxic materials is reduced.

3. Product-as-a-service: the contractor remains the owner of the asset.

4. Circular facilitators and enablers: enablers establish networks, which facilitate the transition towards CE. Moreover, collaboration with facilitators in the circular economy is encouraged.

5. Social sustainability: the plan includes social sustainability by quantifying for example the job footprint or the health footprint. [33] This measure could be addressed in a qualitative manner with surveys of inhabitants or other plans to include citizen participation.

Exclusion criteria for maintenance plans

Waste management plans that use landfill techniques, without going to the fullest effort to divert recyclable materials are excluded (i.e. all recycling that is both economically and technically feasible).

The municipality should clearly communicate to contractors:

1. The prioritizing of criteria, including the exclusion criteria or any other process applied to identify and manage risks.

2. The environmental and social sustainability objectives and economic performance of the project.

Reporting during and after the maintenance event:

Transparency is of value in communicating the expected impact of projects. Changes in the original maintenance plan should be communicated and changes in the input data of the tool should be documented. After the maintenance event, the difference in the calculated impact by using PAVE compared to the original plan should be communicated with the municipality.

4.6.2 Review of tool applicability

This project gives the municipality insight on all the necessary steps that will have to be realized before a circular public space is feasible. Especially the inventory of the current situation gives insight on problems that arise from the lack of information stored in the database of the municipality. The lack of data also complicates the application of the tool in a decision-making scheme. Nevertheless, Johan Luiks (Decision maker, Municipality of Almere) emphasizes that the municipality aims to use the tool during their tenders. However, the asset database requires an update before implementation of the tool is feasible. A strategy to update the current asset database in a short time period needs to be implemented fast. Until the database is up-to-date, Luiks proposed to use the tool together with the contractor to emphasize the implementation of circularity in the neighbourhood, which shows the municipality the possible gains. Bas Mentink (Circular Economy advisor, Royal HaskoningDHV) mentioned that the tool could also be used as a quick scan for municipalities to investigate objects and see where the most significant impact can be made. This possibility to use the tool for other applications is emphasized by Jan Bart Jutte (Circular Economy advisor, Royal HaskoningDHV).

Furthermore, Luiks explicated the necessities to use the tool at the municipality. Though the background data can be complicated, the consumer interface should be comprehensible. The municipality will select one product owner, who knows the ins and outs of the tool. This can also be a department or a team at the municipality of Almere. The product owner is responsible for updating the database and setting up the tool per project. This ensures the quality of the tool.

Detailed info quality of the tool
Frederik Oudman (LCA advisor, Royal HaskoningDHV) concluded that the model of PAVE is well designed and the functionality of the tool is convenient. However, the usability of the tool could be compromised due to its complex hard coding. Additional clarification of these formulas would benefit the use of the tool. This could be solved by appointing a single product owner (Luiks). Furthermore, the problem in the data quality was highlighted by Oudman. According to his analysis, the data used in PAVE has a high uncertainty. For example, the data of cement as well as the data of concrete mortar could be used for concrete. The calculated environmental factors depend highly on which of the two is used. Similarly, Bas Mentink mentioned that at the procurement stage different material choices will result a large difference in impact. This emphasizes that the found values should be checked by an external expert. In addition, this tool would benefit from a more in-depth research towards the quality level of the data.

Conclusion & recommendations

5 Conclusion & recommendations

5.1 Conclusion

In this research, the aim was to develop a new tool, PAVE, that supports decision makers of Dutch municipalities in their choice between different maintenance plans for urban areas, considering both the environmental and economic burden. The main problem was found in the data collection, which is necessary to make an informed decision. Before implementing PAVE, the asset database of the municipality needs an update. The database uses several labelling systems, yielding the output of the database to be dependent on the selected label. The municipality must restructure its database and expand the information in the database with the material composition and related volume of assets to enable the use of PAVE.

Based on this renewed database, an inventory of the assets in the selected urban area was conducted. In PAVE only the object types were included, which together contain 80% of the volume and value in the urban area. This resulted in PAVE being a comprehensible tool, while still including the main contributing objects to the impact of the maintenance plan.

The tool, PAVE, quantifies the impact of maintenance plans by four criteria: the carbon footprint, financial footprint, material and value loss. PAVE indicated that using the new project plan for the case area results in approximately 1455 ton less CO_2 emissions and is €434.000 cheaper compared to the traditional linear maintenance plan. Furthermore, PAVE demonstrated that the use of the new plan leads to 238 m^3 and €424.000 less material and monetary value loss, respectively. Based on the contribution analysis it was concluded that concrete bricks, tiles and stair elements were the largest contributors. However, when the found values were normalized by the object stream's volume, these objects had proven to be the smallest contributors. This difference results from the large volume available of these three object streams in the case area. Furthermore, implementing Reuse instead of Recycling results in the highest decrease in material and value loss. The question is if similar results are found if another maintenance plan or another urban area is under investigation, however this does not fall within the scope of this research.

However, based on the data quality check and sensitivity analysis, it was concluded that the found impact values for the case study must not be presented as true. Instead, these numbers should only be compared with the numbers found for other maintenance plans for the same urban area. This is due to the poor quality of the secondary data used to calculate the criteria. To improve this quality, one should conduct a detailed study towards the supply chain of each object. In literature, process LCAs are used to do so [62]. While this yields the found values for the four criteria to be a better representation of the environmental and economic impact of the maintenance, it will not necessarily improve PAVE as a support tool for decision makers in the choice for the appropriate maintenance plan. Instead, this research benefits more from the input of more maintenance plans in PAVE.

Also, the applicability of PAVE can only be investigated by practical use. Based on expert interviews, the project proposal phase was selected to conduct the stock inventory of the project. Furthermore, the tender document should state if using PAVE is obliged. However, by practical experience one can conclude whether these locations are optimal. Similarly, making the provided budget depend on the use of PAVE in the tender and the formulated guidelines to include different aspect of circularity, are not necessarily comprehensive. However, this thesis gives a clear explanation for the use of PAVE and the necessary changes the municipality must conduct. The use of PAVE by municipalities results a better understanding of their assets in the public space and includes both their environmental and economic considerations. The implementation of PAVE will send municipalities on a path towards a 100% circular public space.

5.1.1 Limitations

Although PAVE has proven to meet the objectives of this research, its limitations should not be overlooked. The tool is a simplification of reality, indicating that parts of the supply chain are excluded which may influence the environmental and economic impact of the maintenance plan. This simplification of the reality by the tool improved the comprehensibility of PAVE for decision makers of municipalities, however this also yields a misrepresentation the actual environmental and economic burdens. This last problem results in PAVE not being applicable to represent one maintenance plan on itself and it only to be useful in the case of comparison of maintenance plans. This problem also arises from difficulties to collect reliable data. A detailed investigation of all stages in the supply chain is required to improve the collection of data. Furthermore, transparency of data is also necessary to improve the tool further.

Also, in this research only static data is used instead of making the economic impact dependent on time. The economic footprint can be used instead of the financial footprint to include this time-dependence of money. As the total direct and indirect economic impact of the stages in the Life Cycle Inventory appear to be presented by the economic footprint [33] and the economic footprint could also be represented by the net present value [64]. PSILA also uses the net present value to represent the costs of the process. This indicates the feasibility of making the economic impact time dependent. However, in this research the parameters to calculate the dynamic economic impact were not obtained. This resulted the selection of the financial footprint. It would be interesting to research the use of the economic footprint in PAVE and compare this with the financial footprint. One can question which of the two footprints is the best to support the decision of decision makers within municipalities.

Finally, PAVE only calculates the economic and environmental impact. Ideally the social impact is also included during the selection of the most appropriate maintenance plan. This will complete the three pillars of sustainable development: people, profit and planet. Also, full implementation of the concept CE not only promotes an environmental-friendly use of resources according to a new business model, but also improves the well-being and health of the community [34]. The inclusion of social impact is addressed briefly in this research in the selection guidelines. However, PAVE does not calculate this social impact. Quantifying the social impact is possible by including the job footprint or measuring noise disturbance during the maintenance project. These parameters are not compatible with PAVE as they focus on stages which are excluded in the tool: the construction and demolition stage. Further research towards the effect of the social impact together with the use of PAVE needs to be conducted.

5.2 Recommendations

Based on the conclusion and limitations of this study, recommendations for further research are presented below.

Data quality research
As stated in the Results section, the quality of the secondary data which was put in the tool is not sufficient. A more-elaborated examination of this data illustrates the achievable quality of the data. Moreover, in-depth research towards the data quality could validate the use of the tool for other applications than solely as a comparison tool.

Improved logistics
Implementation of CE in the infrastructure sector results in more complex logistics compared to the linear economy. This arises from difficulties in linking demand and supply in CE, which emerge from the unsure release rates of assets. A quick literature review indicates that the logistics aspect of CE is still in the exploring phase [74][75] and more in-depth research is essential.

Time dependence of impacts
It was explained in the limitations section that economic impact is time dependent. In literature, this time dependence is calculated using life cycle costing (LCC). The influence of the use of LCC to calculate the economic impact of maintenance plans is an interesting topic for research. Furthermore, this could be extended by also looking at the time dependence of the environmental impact. How do both impacts evolve with time?

Including the social impact in decision-making
The tool focuses on quantifying the environmental and economic impacts of the maintenance plans. In the selection criteria stated in paragraph 4.6.1, the social impact of these maintenance plans is incorporated. Including the social impact in the model should be further studied to improve the selection criteria and set clearer guidelines.

Prioritizing of selection guidelines
Prioritization of the selection guidelines will ease the implementation of the guidelines in the conventional decision-making. However, before prioritization, one should conduct detailed research towards the stated guidelines and their applicability per case.

Outlook

6 Outlook

The tool is developed for practical implementation. Actions and limitations for practical use are discussed in this chapter. Also, further development steps are explicated.

Actions and limitations

The municipality of Almere is going to implement PAVE. This thesis gives guidance in how to implement the tool. A change in traditional culture is crucial to achieve optimal implementation. In particular the concept circular economy should be borne by every employee. Moreover, cooperation of and collaboration with other stakeholders in the supply chain is essential, as companies and people tend to stick to traditional habits. Without a change in mind set, implementation of PAVE and the concept of circular economy will not be achieved within the set timespan.

Furthermore, Royal HaskoningDHV could promote the tool nationally. This can result in achieving national implementation of the tool and boosting their CE proposition. It will help improve the knowledge of the situation nation-wide. More cases advance the knowledge of assets in the public space and result in expansion of the tool towards other assets. Again, collaboration is key, as collaboration and knowledge exchange between municipalities will lead to an acceleration in implementation of PAVE and elimination of teething problems. Furthermore, the object database will be updated and expanded during each case; this continuous progress should be recorded and merged into one database.

Further development steps

Optimally, PAVE becomes an online platform. This will enable the use of the tool nationwide and ensure automatic updates of the object database. Royal HaskoningDHV has the expertise to develop the online platform and become the product owner. To achieve this platform, collaboration between different divisions within the company is fundamental. Moreover, a drive to achieve digitalization of the tool is necessary. Without this drive, rapid development remains absent.

To achieve the ultimate information level of assets, eventually the municipalities' asset database should contain the volume, material composition, location, the management regime, CE business model; the environmental and economic impact for each asset. To accomplish this level of detail in the asset database, first the current database should be restructured. Consequently, a strategy should be developed which will explicate a procedure for improving the database. This procedure contains means which impose the necessary level of detail for each maintenance and procurement event. Moreover, a schedule to achieve the optimal level of detail should be established.

Achieving the online platform and complete database makes the closing of the material loop in the public space and full implementation of the concept 'circular economy' feasible. Royal HaskoningDHV and municipalities should strive to achieve this goal and guide stakeholders in the Netherlands to achieve the ambition of 100% circularity in 2050.

7 References

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Appendices

A1 Contacted municipalities

During this research project, I contacted several municipalities to understand the current situation at municipalities regarding the implementation of circular economy in the public space. Also, this gave me understanding of the used tools, if any, and where the opportunities are for the to-be developed tool. In Table 12, an overview is given per municipality of the contacted person and his job. Also, a short summary of the approximately 15 minutes' phone calls is added.

Table 12. Info about contacted municipalities and the conversations

Municipality	Contact person	Job description	Details conversation
Apeldoorn	Jacco Winkelman	Policy advisor – Living environment	The municipality of Apeldoorn aims to implement circularity during maintenance. However, they are missing the tools to do so.
Haarlem	Alex Jansen	Program manager – Haarlem circular 2030	The municipality of Haarlem is aiming to be circular in 2030. However, they did not find a solution for the public space yet.
Haarlemmermeer	Maurits Korse	Policy advisor - Sustainability	The municipality of Haarlemmermeer aims to enhance high-quality reuse in their tenders. There are still many challenges, as it is unknown which materials they have available in the public space and who is processing them after demolition.
Rheden	Rob van Eldik	Policy advisor – Environment and waste	The municipality of Rheden does not have a detailed policy regarding the implementation of circular economy. The goal is to set this up the coming year.
Utrecht	Marin Zegers	Project secretary	The municipality of Utrecht has no policy regarding the implementation of circular economy. There is a network of people, which is trying to enhance circularity. This implementation occurs on a pilot base.
Venlo	Roel Ramakers	Project coordinator – civil operations	The municipality of Venlo uses Gisnet to map the location of their assets. Reuse of materials is only occurring on a project base. However, their procurement process is sustainable.

A2 Technological innovation sheet

The technological innovation sheet has to be filled in by the contractor, when he includes an innovation in the tool PAVE. Filling in of this form will yield transparency in used data and sources.

Technologische innovatie formulier

Dit formulier moet ingevuld worden als er een technologisch innovatie wordt toegevoegd in PAVE. Zeven getallen moeten ingevuld worden in het tabblad ‘Technologische innovaties’ van PAVE. In onderstaande tabellen kan de achtergrondinformatie per gevonden waarde in worden gevuld. De bron mag ook een contactpersoon zijn. In dat geval moet een telefoonnummer of emailadres toegevoegd worden om de referentie te kunnen checken. Op achterkant van dit formulier, kunnen de waardes ingevuld worden. Deze waardes moeten overeenkomen met de waardes in het Excel tabblad.

CO_2 proces	**Info**	**Uitleg in te vullen gegevens**
Berekening/uitleg:		Als er een berekening of aanname is gebruikt, deze hier invullen.
Bron:		Ter referentie

Stortkosten (bij uitstroom)	**Info**	**Uitleg in te vullen gegevens**
Prijs om materiaal te storten (€)		Stortprijs van een afvalverwerker of de prijs die aannemer betaald krijgt voor afgifte materiaal. In geval van verkoop: de waarde hier negatief invullen.
Bron:		Ter referentie

Aanschafkosten (bij instroom)	**Info**	**Uitleg in te vullen gegevens**
Berekening/uitleg:		Kosten om object aan te schaffen volgens marktprijzen of een uitleg van de gevonden indicatie.
Bron:		Ter referentie

Materiaalverlies	**Info**	**Uitleg in te vullen gegevens**
Berekening:/uitleg:		In geval van berekening deze hier invullen. Anders de aanname onderbouwen.
Bron:		Ter referentie

Waardeverlies	**Info**	**Uitleg in te vullen gegevens**
Berekening:		In geval van berekening deze hier invullen. Anders de aanname onderbouwen.
Bron:		Ter referentie

Variabelen	Waarde	Details
Instroom of uitstroom:		Invullen of het om in- on uistroom innovatie gaat.
Jaar van invullen:		
Locatie van proces:		
Afstand (km) van proces:		Afstand tussen proces en plek van verwijdering van objecten.
CO_2 proces (kg CO_2/m^3):		De carbon footprint van het proces kan o.b.v. van bronnen worden bepaald of d.m.v. een berekening. Dit kan gespecifeerd worden op CO2 proces tabel op de vorige pagina.
Stortkosten (€/m^3) bij uitstroom:		Kosten om materiaal te storten. Als deze kosten er niet zijn 0 invullen.
Aanschafkosten (€/m^3) bij instroom:		Marktprijs voor de aanschaf van een object.
Materiaalverlies (v%) tijdens het proces:		Materiaalfractie dat verloren gaat in proces.
Waardeverliers (€/m^3) tijdens het proces:		Berekend door nieuw prijs waarde van het materiaal/object af te trekken van de prijs na het proces. Waardeverlies= Prijs na proces/m3 – nieuw prijs object/m3

A3 Stock inventory

Table 13. Information needed for optimal system and availability in different sources for object type street furniture.

Nodes	Optimal system	GBI	GBI + outline zoning plan	Information contractor
Street furniture	Info about amount of pieces per street furniture type, volume and materials	Amounts	Amounts	Amounts + sometimes material
Fences	Meters of fences, with related materials and volume	m	m	m
Mixed	Material composition and related volumes	n.a.	n.a.	n.a
Electricity cabinet	Pieces, material and volume	Piece	Piece	Piece
Plastics	Material and volume	n.a.	n.a.	n.a.
Retaining wall	Meters, material and volume	n.a.	n.a.	m, material
Concrete	Volume	n.a.	n.a.	n.a.
Fire plug	Pieces, material and volume	Piece	Piece	Piece
Mixed	Material composition and related volumes	n.a.	n.a.	n.a.
Light pole	pieces, with related materials and volume	n.a.	n.a.	amount
Mixed	Material composition and related volumes	n.a.	n.a.	n.a.
Garbage bin	Meters of fences, with related materials and volume	Piece	Piece	Piece
Stainless Steel	volume	n.a.	n.a.	n.a.
Playground equipment	pieces, with related materials and volume	Piece	Piece	Piece
Mixed	Material composition and related volumes	Materials	Materials	n.a.
Traffic signs	pieces, with related materials and volume	Piece	Piece	Piece
Plastic	volume	n.a.	n.a.	n.a.
Aluminium	Volume	n.a.	n.a.	n.a.
Street bollard	pieces, with related materials and volume	Piece	Piece	Piece
Concrete	Volume	n.a.	n.a.	n.a.
Plastic	Volume	n.a.	n.a.	n.a.
Steel	Volume	n.a.	n.a.	n.a.

Table 14. Information needed for optimal system and availability in different sources for object type vegetation.

Nodes	Optimal system	GBI	GBI + outline zoning plan	Information contractor
Vegetation	Info about amount and volume	Amount	Amount	Amount
Trees	Piece and volume per piece	Piece	Piece	piece
Wood	Volume per piece	n.a.	n.a.	n.a.
Vegetation waste	Volume per piece	n.a.	n.a.	n.a.
Shrubs	Area and volume per area	m^2	m^2	m^2
Grass	Area and volume per area	m^2	m^2	m^2
Vegetation waste	Volume per area	n.a.	n.a.	n.a.

Table 15. Information needed for optimal system and availability in different sources for object type sewage.

Nodes	Optimal system	GBI	GBI + outline zoning plan	Information contractor
Sewage	Info about amount of pieces per sewage type, volume and materials	n.a.	Volume	Pieces and material
Road gully	Piece, material and volume	n.a.	Volume	Pieces and material
Cast iron	m^3	n.a	n.a.	n.a.
Concrete	m^3	n.a	n.a	Material
PVC	m^3	n.a.	n.a	Material
Sewage well	Piece, material and volume	Piece	Piece and volume	Piece
Cast iron	Volume	n.a.	n.a	n.a
Concrete	Volume	n.a.	n.a	n.a
Drainage well	Piece, material and volume	Piece	Piece and volume	Piece
Cast iron	Volume	n.a.	n.a	n.a
Concrete	Volume	n.a.	n.a	n.a
Sewage pipes	m, material and volume	n.a.	n.a.	m and material
PVC	Volume	n.a.	n.a.	n.a.

A3.1 Almere city vs. case area: Regenboogbuurt phase 1

The collected information in GBI of the different assets in Almere and in the case area: Regenboogbuurt phase 1. To ease the comparison between both, the total area in square kilometres is included and scaled values. The scaled values indicate if assets are over- or underrepresented in the case area compared to Almere.

Table 16. Values found in GBI of different assets in Almere and the case area.

Asset	Unit	Almere	Regenboogbuurt phase 1	Scale (Almere/Phase 1)
Area	km^2	248,7	0,3	830
Trees	Piece	19032	1033	20
Boulevard plants	m^2	1.188.326,6	661,4	1800
Shrubs	m^2	392.154	1.062,82	370
Grass	m^2	65.493.332,8	10.1359,1	650
Fences	m	441.471,4	1.193,67	370
Cabinet	Piece	421	1	420
Road gully	Piece	89.912	399	230
Bridges	Piece	558	4	140
Mechanical pipes	m	853	0	-
Wet plants	m^2	5642	2873,49	2
Bank protection	m	17164	2424,31	7
Playground	Piece	1552	9	170
Playground equipment	Piece	4099	18	230
Street furniture	Piece	75705	290	260
Road signs	Piece	22638	80	280
Sewage pipes	Piece	62716	300	210
Road – concrete	m^2	476.206,01	4550,15	100
Road – concrete tiles	m^2	2.610.014,97	18824,44	140
Road – concrete elements	m^2	-	823,25	-
Road – ceramic-concrete	m^2	663.296,46	0	-
Road - Grass tiles	m^2	-	4794,24	-
Road – gravel tracks	m^2	948.741,65	1123,7	840
Road – concrete bricks	m^2	4.574.464,66	15665,08	290
Road – cobblestones	m^2	144.527,76	0	-
Road – asphalt	m^2	5.237.072,72	11231,17	470
Waterways	m	7.280.443,44	963,4	7560

A3.2 Volume and value estimations

Underneath table gives an estimation of the volume and material per asset. Estimated dimensions or calculations are included for transparency. In the last column, the source for the information is displayed.

Table 17. Estimations of volume and material composition per asset.

Asset	Material	Unit	Volume per unit (m^3/unit)	Dimensions	Reference
Vegetation					
Trees	Wood	Piece	4	Average height x crown width / 20	https://bomenwijzer.be/nederlandsenamen
Shrubs	Vegetation waste	m^2	0,125	Average height x effective volume = 0.5 x 0.25	https://bomenwijzer.be/nederlandsenamen
Grass	Vegetation waste	m^2	0,364	(total harvest yield)/total area x area x 0.5	http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=7140GRAS
Sewage					
Road gully	Cast iron	Piece	0,012	450 x 450 x 20 mm	http://www.struykverwoaqua.nl/Downloads/st_1290-90_gb1_struyk.pdf
	concrete	Piece	0,182	450 x 900 x 100 mm x 4 + 450 x 450 x 100 mm	http://www.struykverwoaqua.nl/Downloads/st_1290-90_gb1_struyk.pdf
Drainage well	Cast iron	Piece	0,0141	450 x 450 x 20 mm	http://www.struykverwoaqua.nl/Downloads/st_1290-90_gb1_struyk.pdf
	Concrete	Piece	0,182	450 x 900 x 100 mm x 4 + 450 x 450 x 100 mm	http://www.struykverwoaqua.nl/Downloads/st_1290-90_gb1_struyk.pdf
Sewage well	Cast iron	Piece	0,0141	450 x 450 x 20 mm	http://www.struykverwoaqua.nl/Downloads/st_1290-90_gb1_struyk.pdf
	Concrete	Piece	0,182	450 x 900 x 100 mm x 4 + 450 x 450 x 100 mm	http://www.struykverwoaqua.nl/Downloads/st_1290-90_gb1_struyk.pdf
Sewage pipes	PVC	m	0,007854	Ø 125 mm Thickness ≈ 20 mm	Plan Dusseldorp
Street furniture					
Fences	-	-	n.a.		
Electricity cabinet			0,0377	700 x 600 x 350 mm Thickness ≈ 20 mm	https://staka-schakelkasten.nl/configurator/2
Retaining wall	Concrete	m	0,02	1000 x 500 mm	https://www.dejonghandelsonderneming.nl/beton-l-element-100-cm-hoog-grijs.html
Fire plug		Piece	0,0176	Ø 80 mm Height 100 mm Thickness ≈ 20 mm	https://www.dyka.nl/avk35-57-brandkraan-dn80-8g-1000.html
Light pole		Piece	n.a.		

Garbage bin	Stainless steel	Piece	0,0309	370 x 700 x 480 mm Thickness ≈ 20 mm	http://www.bammens.com/shop/afvalbakken/capitole/capitole.html
Playground equipment	-	Piece	0,6		Rough estimation
Traffic sign	Plastic	Piece	0,00048	80 x 300 mm Thickness ≈ 20 mm	http://www.straatnaambord.nl/straatnaam/straatnaambord-vlak-1.htm
	Aluminium	Piece	0,0089	700 x 150 mm Thickness ≈ 20 mm	http://www.straatnaambord.nl/straatnaam/straatnaambord-vlak-1.htm
Street bollard	Concrete	Piece			
	Plastic	Piece	0,0315	150 x 150 x 1400 mm	https://www.manutan.nl/nl/mnl/diamantkoppaal-kunststof-a052327
	Steel	Piece	0,00424	Ø 90 mm height 750 mm Thickness ≈ 20 mm	https://www.manutan.nl/nl/mnl/verwijderbare-parkeerpaal
Roads					
Bricks	Concrete	m^2	0,08	Thickness = 80 mm	Outline zoning plans Almere municipality
Tiles	Concrete	m^2	0,06	Thickness = 60 mm	Outline zoning plans Almere municipality
Gravel tracks	Sand/shells	m^2	0,05	Thickness = 50 mm	Plan Dusseldorp
Asphalt	Asphalt	m^2	0,05	Thickness = 50 mm	Outline zoning plans Almere municipality
Foundation	Sand/mixed granulate	m^2	0,15	Depth = 150 mm	Plan Dusseldorp

Similarly, as the volume table, the value table contains information of the found value per asset and corresponding reference.

Table 18. Estimations of value per asset.

Asset	Material	Unit	Value per unit (€/unit)	Reference
Vegetation				
Trees	Wood	Piece	50	https://www.betuwebomen.nl/
Shrubs	Vegetation waste	Piece	5	https://www.betuwebomen.nl/
Grass	Vegetation waste	m^2	0,25	https://www.werkspot.nl/gras-leggen-zaaien/prijzen-kosten
Sewage				
Road gully	Cast iron/ concrete	Piece	120	https://aquafix.nl/nl/categorieen/kolken,_opb trottoirkolk
	Cast iron/ PVC	Piece	90	https://aquafix.nl/nl/categorieen/kolken
Drainage well	Cast iron	Piece	170	https://aquafix.nl/nl/categorieen/inspectieputten
Sewage well	Cast iron	Piece	170	https://aquafix.nl/nl/categorieen/inspectieputten
Sewage pipes	PVC	m	6,4	PVC voordeel
Street furniture				
Fences	-	-	n.a.	
Electricity cabinet			60	https://staka-schakelkasten.nl/configurator/2
Retaining wall	Concrete	m	94	https://www.dejonghandelsonderneming.nl/beton-l-element-100-cm-hoog-grijs.html
Fire plug		Piece	500	https://www.dyka.nl/avk35-57-brandkraan-dn80-8g-1000.html
Light pole		Piece	n.a.	
Garbage bin	Metal	Piece	300	http://www.bammens.com/shop/afvalbakken/capitole/capitole.html
Playground equipment	-	Piece	400	https://www.westfalia.eu/nl/shops/tuin-en-buitenleven/speelplaats/bouw-je-eigen-speeltuin/speelhuisjes-en-speeltorens/
Traffic sign	Plastic	Piece	36,50	http://www.straatnaambord.nl/straatnaam/straatnaambord-vlak-1.htm
Street bollard	Concrete	Piece		

	Plastic	Piece	60	https://www.manutan.nl/nl/mnl/diamantkoppaal-kunststof-a052327
	Steel	Piece	240	https://www.manutan.nl/nl/mnl/verwijderbare-parkeerpaal
Roads				
Bricks	Concrete	m^2	12	https://www.onlinebetonstenen.nl/betonklinkers
Tiles	Concrete	m^2	10	https://www.onlinebetonstenen.nl/betontegels
Gravel tracks	Sand/shells	m^2	5	https://www.123natuurproducten.nl/product/kleischelpen-bigbag-1-kuub1000-liter/
Asphalt	Asphalt	m^2	10	https://www.zwammerdamgroep.nl/prijs-asfalt-per-m2
Kerbs	Concrete	m	6	https://www.betondingen.nl/traptreden-15x30x100cm-grijs-oud-hollands.html?
Stair elements	Concrete	m^2	40	https://www.betondingen.nl/traptreden-15x30x100cm-grijs-oud-hollands.html
Driveway entrance elements	Concrete	m	40	https://bestrating-online.nl/webshop/opsluitbanden/inritblokken/inritband-beton-45x20x50-tussenstuk-grijs/
Foundation	Sand/mixed granulate	m^2	10	https://www.sierbestratingsmarkt.com/a-36416754/grind-split-keien-en-zand/kijlstra-ophoogzand-1000-kg/

A4 PAVE

A4.1 Excel calculation sheet of the subsystem concrete bricks

The Excel sheet for both the tradition and implemented plan for concrete bricks can be observed below. The different sheets are linked to each other and the object database. Inflow, outflow and transport distance are filled in by the contractor in the sheet of the implemented plan and the same values will be inserted in the sheet for the tradition system. Values for the carbon footprint, financial footprint, material and value loss are based on found values in the object database.

Furthermore, the sheets calculate automatically the necessary amount of trucks based on the volume per waste management alternative. When all values are filled in, the sheets automatically calculate the values for the four criteria. These criteria are automatically updated in the overview sheet, where the calculated values for each subsystem is displayed. Moreover, when a value is updated in the object database, this will result an automatic update in all relevant subsystems.

Traditional system

1. Betonstraatsteen

FE: m3 m2 wordt ingevuld door aannemer

Details: alle betonstraatsteen-stromen en grastegels. Betonstraatstenen zijn de grootste uitgaande objectstroom. Daarnaast kunnen de gevonden waardes voor het recyclingproces van beton makkelijk door vertaald worden naar andere betonelementen, zodat de uitbreiding van de tool makkelijk kan.

Deklaag: klinkers

Totaal			
CO2 voetafdruk	Kosten	Materiaal verlies	Waarde verlies materiaal
kgCO2	€	m3	€
986.097,06	256.574,74	176,84	239.795,04

Uitstroom	Conversie		Processen		Afstand gebied - proces	Aantal benodigde vrachtwagens	CO2 voetafdruk proces/m3	Kosten proces/m3	Materiaalverlies	Waardeverlies	Materiaal terug naar gebied
m2	m3/m2	v%		m3	km	-	kg CO2/m3	€/m3	v%	€	v%
22105	0,08	0	R1: hergebruik	0	1	0	0	0	0	0	0
		100	R2: recycling	1768,4	6	138	28,152	3,6	10	239795,04	0
		0	R3: verbranding	0	6	0	n/a	n/a	100	0	0
		0	R4: storten	0	6	0	n/a	n/a	100	0	0
Instroom	Conversie	Verderling processen	Processen		Afstand proces - gebied	Aantal benodigde vrachtwagens	CO2 voetafdruk proces/m3	Kosten proces/m3	Waardeverlies		
m2	m3/m2	v%		m3	km	-	kg CO2/m3	€/m3	€		
20009	0,08	0	Terugkomend van gebied	0	0	0	0	0	0		
		100	Nieuw materiaal	1600,72	100	125	563,04	150	0		
		0	R1,0: hergebruikt materiaal	0	6	0	0	62,5	0		
		0	R2,0: recycled materiaal	0	6	0					
		100									

Implemented system

1. Betonstraatsteen

FE: m3 m2 wordt ingevuld door aannemer

Details: betonstraatstenen zijn de grootste uitgaande objectstroom. Daarnaast kunnen de gevonden waardes voor het recyclingproces van beton makkelijk door vertaald worden naar andere betonelementen, zodat de uitbreiding van de tool makkelijk kan.

Totaal			
CO2 voetafdruk	Kosten	Materiaal verlies	Waarde verlies materiaal
kgCO2	€	m3	€
87.225,50	24.211,32	26,53	35.969,26

Deklaag: klinkers
landelijk

Uitstroom	Conversie	Verdeling processer	Processen		m3	Afstand gebied - proces	Aantal benodigde vrachtwagens	CO2 voetafdruk proces/m3	Kosten proces/m3	Materiaalverlies	Waardeverlies	Materiaal terug naar gebied
m2	m3/m2	v%		Nr	m3	km	-	kg CO2/m3	€/m3	v%	€	v%
22105	0,08	85	R1: hergebruik		1503,14	1	118	0	0	0	0	97,63162
		15	R2: recycling		265,26	6	21	28,152	3,6	10	35969,256	0
		0	R3: verbranding		0	6	0	n/a	n/a	100	0	0
		0	R4: storten		0	6	0	n/a	n/a	100	0	0
		0	Technologische innovatie		0		0	0	0	0	0	
		0	Technologische innovatie		0		0	0	0	0	0	

Instroom	Conversie	Verderling processe	Processen			Afstand proces - gebied	Aantal benodigde vrachtwagens	CO2 voetafdruk proces/m3	Kosten proces/m3	Waardeverlies		
m2	m3/m2	v%			m3	km	-	kg CO2/m3	€/m3			
20009	0,08	91,679994	Terugkomend van gebied		1467,54	1	115	0	0	0		
		8,320005997	Nieuw materiaal		133,18	100	11	563,04	150	0		
		0	R1,0: hergebruikt materiaal		0	6	0	0	62,5	0		
		0	R2,0: recycled materiaal		0	6	0					
		0	Technologische innovatie		0		0	0	0			
		0	Technologische innovatie		0		0	0	0			
		100										

A4.2 Output values of subsystems

Values found per subsystem are displayed below. Blue is representing the object type roads and orange the object type sewage.

Overzicht per object

Wegen

Betonstraatstenen

Situatie	CO_2 voetafdruk kg CO_2	Kosten €	Materiaal verlies m3	Waardeverlies materiaal €
Coventioneel	986.097,06	256.574,74	176,84	239.795,04
Project	87.225,50	24.211,32	26,53	35.969,26
Δ	898.871,56	232.363,43	150,31	203.825,78

Betontegels

Situatie	CO_2 voetafdruk kg CO_2	Kosten €	Materiaal verlies m3	Waardeverlies materiaal €
Coventioneel	224.038,93	78.062,89	51,42	78.295,52
Project	7.154,20	4.344,67	5,14	7.829,55
Δ	216.884,73	73.718,22	46,28	70.465,97

Trapelementen

Situatie	CO_2 voetafdruk kg CO_2	Kosten €	Materiaal verlies m3	Waardeverlies materiaal €
Coventioneel	83.467,91	22.656,88	13,60	66.041,60
Project	19.759,25	3.702,21	3,19	9.741,00
Δ	63.708,66	18.954,68	10,41	56.300,60

Betonbanden algemeen

Situatie	CO_2 voetafdruk kg CO_2	Kosten €	Materiaal verlies m3	Waardeverlies materiaal €
Coventioneel	65.138,66	66.193,72	7,64	21.819,84
Project	33.884,99	34.947,43	1,91	5.454,96
Δ	31.253,67	31.246,29	5,73	16.364,88

Betonbanden 100/200

Situatie	CO_2 voetafdruk kg CO_2	Kosten €	Materiaal verlies m3	Waardeverlies materiaal €
Coventioneel	94.231,59	93.359,44	20,42	58.319,52
Project	48.203,90	49.428,45	3,82	10.909,92
Δ	46.027,70	43.930,99	16,60	47.409,60

Inritblok

Situatie	CO_2 voetafdruk kg CO_2	Kosten €	Materiaal verlies m3	Waardeverlies materiaal €
Coventioneel	7.566,15	2.635,64	1,83	11.936,48
Project	110,90	23,62	0,32	4.154,04
Δ	7.455,25	2.612,02	1,51	7.782,44

Riolering

Straatkolken: Beton

Situatie	CO2 voetafdruk kgCO2	Kosten €	Materiaal verlies m3	Waardeverlies materiaal €
Coventioneel	38.196,88	14.201,95	3,30	18.906,58
Project	3.571,66	1.406,20	1,56	8.897,21
Δ	34.625,22	12.795,75	1,75	10.009,37

Rioolleidingen

Situatie	CO2 voetafdruk kgCO2	Kosten €	Materiaal verlies m3	Waardeverlies materiaal €
Coventioneel	208.705,56	24.442,47	7,72	16.254,00
Project	52.332,83	6.200,80	1,93	4.063,50
Δ	156.372,72	18.241,67	5,79	12.190,50

A4.3 Transport & storage calculation

The environemental burden of transport is expressed kilogram carbon emitted per kilometer. This number is calculated based on found values for asphalt transport of the company KWS infra [82] and the well-to-wheel carbon emission factor for diesel (NL) [83]. The number is calculated using the following equation:

$$\frac{CO_2}{Distance} = \frac{L\ Diesel}{Distance} \frac{CO_2}{L\ Diesel}$$

The inserted value for the liters of diesel per km is based on the average value found in the KWS report. The carbon emission per kilometer is calculated to 1,315 CO_2/km.

The costs of transport consist of capital and operational costs. The capital costs are determined based on the average value found in the article of the transporter Fehrenkötter [84]. Also, the article expressed the costs per liter. Combining the data found in the KWS report for the kilometer liter with the costs per liter, the operational costs are calculated. The capital and operational costs add up to a total cost of 0,76 euro per kilometer.

	Transport	Carbon footprint			WT: well to wheel	
Referentiejaar	Type vrachtwagen	Inzetpercentage	Gemiddelde belasting (kg)	Verbruik (km/L)	CO2 (kg CO2/L)	CO2 (kgCO2/km)
2009	GINAF 4243 TS	41,92	26623	2,3	3,23	1,404347826
	GINAF 4241 S	19,94	25707	2,58	3,23	1,251937984
	GINAF 4243 S	9,75	26540	3	3,23	1,076666667
	GINAF 3335 S	7,02	19406	2,2	3,23	1,468181818
	VOLVO FM 440	6,19	18615	2,5	3,23	1,292
	TERBERG FM 1850-T	5,02	25794	2,5	3,23	1,292
	DAF AD 85 XC	3,61	26366	2,6	3,23	1,242307692
	VOLVO FH 440 4X2T FAL9.0 RAI	3,43	33395	2,6	3,23	1,242307692
	VOLVO FH 12-62TP-71S	3,12	33315	2,8	3,23	1,153571429
	Gewogen gemiddelde		25820,105	2,476202	3,23	**1,314663497**

Bronnen:
Data inzetpercentage, gemiddelde belasting en verbruik: https://www.kws.nl/dynamics/modules/SFIL0200/view.php?fil_Id=6417
CO2 Well to wheel kental: https://www.co2emissiefactoren.nl/lijst-emissiefactoren/

Referentiejaar	Type vrachtw:	Vaste kosten/km	Kosten (€/L)	Kosten (€/km)
2010	Renault Premi	24,76	1,26	0,792826087
	Mercedes Act	24,5	1,26	0,733372093
	Iveco Stralis	22,94	1,26	0,665
	DAF XF	24,05	1,26	0,817727273
	VOLVO FH 40(	26,19	1,26	0,749
	MAN TGA	24,09	1,26	0,749
	Scania R420	25,62	1,26	0,729615385
			1,26	0,729615385
			1,26	0,695
		24,5	1,26	**0,757840869**

Bronnen
Gronding, november 2010: http://edepot.wur.nl/158975

The storage carbon footprint is estimated based on values retrieved from Dusseldorp and the calculated transport carbon footprint per kilometer. The transport distance of one container for storage is estimated to be 100 km. The carbon footprint of the transport times the transport distance results in the one-way carbon emission. This should be doubled to calculated carbon emission related to the transport of the container. It is assumed that transport is only source of emission for the storage in containers. The calculated carbon emission per cube is 26,3 CO_2/m^3.

Dusseldorp pays a monthly price of 50 euo per container. If objects need to be stored, it is assumed they can be used in the next phase, which starts six months later. These assumptions result in the storage costs per cube to be 30 €/m^3.

Storage

Carbon footprint	Waarde	Eenheid	Bron
Afstand transport	100	km	Schatting gemiddelde transportafstand NL o.b.v. CE Delft Milieuimpact van betongebruik in de NL bouw
CO2	1,314663497	kgCO2/km	Zie transportberekening
CO2/container	262,9326993	CO2	
Per kube	26,29326993	CO2/m3	O.b.v. 10m3 container

Kosten	Waarde	Eenheid	Bron
Container prijs	50	euro	Dusseldorp
Volume container	10	m3	https://www.containeronline.nl/containerafmetingen/
Maandelijkse depotkosten	5	euro/m3 per r	-
Total depotkosten per kube	30	euro	Uitgaande van gemiddeld half jaar opslag: faseplan dusseldorp

A4.4 Object database

In the object database, data of every object is compiled and references are added.

A. Materiaalstromen per object

Beschrijving:

Objecttype	Object	Materiaal	Eenheid	Dikte	Volume materiaal/eenheid	Bron schatting volume	Verdeling coventioneel over R-opties				Bron verdeling
							R1	R2	R3	R4	
Bestrating	dubbel b.s.s., halfsteenverband	Beton	m2	0,08	0,08	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	dubbel b.s.s., blokverband	Beton	m2	0,08	0,08	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	dubbel b.s.s, P-vak aanduiding	Beton	m2	0,08	0,08	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	b.s.s. keiformaat, keperverband	Beton	m2	0,08	0,08	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	b.s.s. keiformaat, keperverband	Beton	m2	0,08	0,08	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	b.s.s. keiformaat, halfsteenverband	Beton	m2	0,08	0,08	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	b.s.s. keiformaat, elleboogverband	Beton	m2	0,08	0,08	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	betontegels 150x300mm halfsteensverband	Beton	m2	0,06	0,06	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	betontegels 150x300mm halfsteensverband	Beton	m2	0,06	0,06	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	b.s.s. keiformaat, halfsteens-stroomverband (molgoc	Beton	m2	0,08	0,08	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	betontegels 500x500mm, hafsteensverband	Beton	m2	0,06	0,06	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	betontegels 300x300mm, halfsteensverband	Beton	m2	0,06	0,06	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	prefab betonnen drempelelement met taludmarkeri	Beton	m2	0,17	0,17	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	grastegels	Beton	m2	0,08	0,08	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	asfalt	Asfalt	m2	0,05	0,05	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	halfverharding		m2	0,1	0,1	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	Trapelementen 1m breed	Beton	stuk	0,25	0,125	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	geleideband 50/200	Beton	m	0,2	0,02	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	opsluitband 100x200	Beton	m	0,2	0,02	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	inritblok	Beton	m	0,16	0,0304	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	verlaagde band 200x200mm	Beton	m	0,2	0,02	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	trottoirband 180/200	Beton	m	0,2	0,02	Dusseldorp	0	0	100	0	BRBS recycling
Bestrating	Zand/menggranulaat laag	Menggranul	m2			Dusseldorp	0	0	100	0	BRBS recycling
Bestrating		Zand	m2	0,5	0,5	Dusseldorp	0	0	100	0	BRBS recycling

Groen	Bomen	Hout	stuk		2,5	Schatting obv	-				
Groen		Groen	stuk		1,5	Schatting obv	-				
Groen	Heesters	Groen	m2		0,125	Schatting van	-				
Groen	Gras	Groen	m2		0,363888889	Schatting geb	-				
Inrichting	Hekwerk, leuningwerk (tuinhekken)	Mix	m		n.a.		-				
Inrichting	Keerwand	Beton	m		0,02	https://www.dej	0	0	100	0	BRBS recycling
Inrichting	Betonpaal en diamantkoppalen van hout en kunststo	Mix	stuk		0,0315	https://www.ma	-				
Inrichting	Uitneembare paal van metaal	Staal	stuk		0,00106	https://www.ma	-				
Inrichting	Straatpot/brandkraan	Mix	stuk		0,716	https://www.dyk	-				
Inrichting	Lichtmast	Mix	stuk		n.a.		-				
Inrichting	Afvalbak	Mix	stuk		0,007726	http://www.ban	-				
Inrichting	Speelobject/toestel	Mix	stuk		0,6	Estimation	-				
Inrichting	Verkeersbord: bord	Plastic/staal	stuk		0,00021	http://www.stra	-				
Inrichting	Verkeersbord: paal	Staal	stuk		0,002231	http://www.stra	-				
Riolering	Straat- of trottoirkolk	Gietijzer	stuk		0,01215	Struyk verwo	5	95	0	0	BRBS recycling obv staal
Riolering		beton	stuk		0,18225	Struyk verwo	0	100	0	0	BRBS recycling
Riolering		PVC	stuk		0,073125	Struyk verwo	0	79	21	0	Suez (2016)
Riolering	Putkop riolering	Gietijzer	stuk		0,014137	Struyk verwo	5	95	0	0	BRBS recycling obv staal
Riolering		beton	stuk		0,18225	Struyk verwo	0	100	0	0	BRBS recycling
Riolering	Putkop drainage	Gietijzer	stuk		0,014137	Struyk verwo	5	95	0	0	BRBS recycling obv staal
Riolering		beton	stuk		0,18225	Struyk verwo	0	100	0	0	BRBS recycling
Riolering	Rioolleidingen (m)	PVC	stuk		0,007853982	Ø 125 mm, Thic	0	79	21	0	Suez (2016)

B. Materiaalverlies per proces

Beschrijving:

Materiaalgroep	Materiaal	Dichtheid	Proces			
		kg/m3	R1	R2	R3	R4
Asfalt	Asfalt	2200	0	10	100	100
Beton	Beton	2400	0	10	100	100
Beton	Menggranulaat	1800	0	10	100	100
Hout	A-hout	800	0	10	100	100
Hout	B-hout	800	0	10	100	100
Hout	C-hout	800	0	10	100	100
Groen	Groenafval		0	10	100	100
Kunstof	Mixed		0	10	100	100
Kunstof	PET	1270	0	10	100	100
Kunstof	PPE		0	10	100	100
Kunstof	PVC	1450	0	10	100	100
Metaal	Aluminium	2702	0	10	100	100
Metaal	Gietijzer	7860	0	10	100	100
Metaal	Koper	8900	0	10	100	100
Metaal	Staal	7900	0	10	100	100
Zand	Zand	1500	0	10	100	100

Opmerkingen

Dit is een grove aanname voor het materiaalverlies per R en moet verder worden verbeterd

C. Waarde per object

Objecttype	Object	Eenheid	Nieuw prijs €/eenheid	2e handsp €/eenheid	Bron
Bestrating	dubbel b.s.s., halfsteenverband	m2	12	5	https://www.onlinebetonstenen.nl/betonklinkers
Bestrating	dubbel b.s.s., blokverband	m2	12	5	https://www.onlinebetonstenen.nl/betonklinkers
Bestrating	dubbel b.s.s, P-vak aanduiding	m2	12	5	https://www.onlinebetonstenen.nl/betonklinkers
Bestrating	b.s.s. keiformaat, keperverband	m2	12	5	https://www.onlinebetonstenen.nl/betonklinkers
Bestrating	b.s.s. keiformaat, keperverband	m2	12	5	https://www.onlinebetonstenen.nl/betonklinkers
Bestrating	b.s.s. keiformaat, halfsteenverband	m2	12	5	https://www.onlinebetonstenen.nl/betonklinkers
Bestrating	b.s.s. keiformaat, elleboogverband	m2	12	5	https://www.onlinebetonstenen.nl/betonklinkers
Bestrating	betontegels 150x300mm halfsteensverband	m2	10	5	https://www.onlinebetonstenen.nl/betontegels
Bestrating	betontegels 150x300mm halfsteensverband	m2	10	5	https://www.onlinebetonstenen.nl/betontegels
Bestrating	b.s.s. keiformaat, halfsteens-stroomverband (molgoo	m2	12	5	https://www.onlinebetonstenen.nl/betonklinkers
Bestrating	betontegels 500x500mm, hafsteensverband	m2	10	5	https://www.onlinebetonstenen.nl/betontegels
Bestrating	betontegels 300x300mm, halfsteensverband	m2	10	5	https://www.onlinebetonstenen.nl/betontegels
Bestrating	prefab betonnen drempelelement met taludmarkeri	m2	300		Grove schatting
Bestrating	grastegels	m2	12		https://www.pol.nl/recycling-busdrempel-zwart-3000x1800-mm/nl/product/47301/
Bestrating	asfalt	m2	12		https://www.zwammerdamgroep.nl/prijs-asfalt-per-m2
Bestrating	halfverharding	m2	5		https://www.123natuurproducten.nl/product/kleischelpen-bigbag-1-kuub1000-liter/
Bestrating	Trapelementen 1m breed	m2	40		https://www.betondingen.nl/traptreden-15x30x100cm-grijs-oud-hollands.html?gclid=CjwKCAjwlejcBRAdEiwAAbj6Kf6dn4vMiseoA-cZQ8LMvzdhiW3y8g2hJ1uxMcPMtAFl96gjKdxjjxoCaesQAvD_BwE
Bestrating	geleideband 50/200	m	6		https://www.betondingen.nl/traptreden-15x30x100cm-grijs-oud-hollands.html?gclid=CjwKCAjwlejcBRAdEiwAAbj6Kf6dn4vMiseoA-cZQ8LMvzdhiW3y8g2hJ1uxMcPMtAFl96gjKdxjjxoCaesQAvD_BwE

Bestrating	opsluitband 100x200	m	6		https://www.betondingen.nl/traptreden-15x30x100cm-grijs-oud-hollands.html?gclid=CjwKCAjwlejcBRAdEiwAAbj6Kf6dn4vMiseoA-cZQ8LMvzdhiW3y8g2hJ1uxMcPMtAFl96gjKdxjjxoCaesQAvD_BwE		
Bestrating	inritblok	m	40		https://bestrating-online.nl/webshop/opsluitbanden/inritblokken/inritband-beton-45x20x50-tussenstuk-grijs/		
Bestrating	verlaagde band 200x200mm	m	6		https://www.betondingen.nl/traptreden-15x30x100cm-grijs-oud-hollands.html?gclid=CjwKCAjwlejcBRAdEiwAAbj6Kf6dn4vMiseoA-cZQ8LMvzdhiW3y8g2hJ1uxMcPMtAFl96gjKdxjjxoCaesQAvD_BwE		
Bestrating	trottoirband 180/200	m	6		https://www.betondingen.nl/traptreden-15x30x100cm-grijs-oud-hollands.html?gclid=CjwKCAjwlejcBRAdEiwAAbj6Kf6dn4vMiseoA-cZQ8LMvzdhiW3y8g2hJ1uxMcPMtAFl96gjKdxjjxoCaesQAvD_BwE		
Bestrating	Zand laag	m2	10		https://www.sierbestratingsmarkt.com/a-36416754/grind-split-keien-en-zand/kijlstra-ophoogzand-1000-kg/		
Groen	Bomen	stuk	50		https://www.betuwebomen.nl/		
Groen	Heesters	m2	5		https://www.betuwebomen.nl/		
Groen	Gras	m2	0,25		https://www.werkspot.nl/gras-leggen-zaaien/prijzen-kosten		

Inrichting	Hekwerk, leuningwerk (tuinhekken)	m	n.a.		
Inrichting	Keerwand	m	94		https://www.dejonghandelsonderneming.nl/beton-l-element-100-cm-hoog-grijs.html
Inrichting	Betonpaal en diamantkoppalen van hout en kunststo	stuk	60		https://www.manutan.nl/nl/mnl/diamantkoppaal-kunststof-a052327
Inrichting	Uitneembare paal van metaal	stuk	240		https://www.manutan.nl/nl/mnl/verwijderbare-parkeerpaal
Inrichting	Straatpot/brandkraan	stuk	500		https://www.dyka.nl/avk35-57-brandkraan-dn80-8g-1000.html
Inrichting	Lichtmast	stuk	n.a.		
Inrichting	Afvalbak	stuk	300		http://www.bammens.com/shop/afvalbakken/capitole/capitole.html
Inrichting	Speelobject/toestel	stuk	400		https://www.westfalia.eu/nl/shops/tuin-en-buitenleven/speelplaats/bouw-je-eigen-speeltuin/speelhuisjes-en-speeltorens/
Inrichting	Verkeersbord	stuk	36,5		http://www.straatnaambord.nl/straatnaam/straatnaambord-vlak-1.htm
Riolering	Straat- of trottoirkolk: beton	stuk	120	n/a	https://aquafix.nl/nl/categorieen/kolken, opb trottoirkolk
Riolering	Straat- of trottoirkolk: pvc	stuk	90		https://aquafix.nl/nl/categorieen/kolken
Riolering	Putkop riolering	stuk	170		https://aquafix.nl/nl/categorieen/inspectieputten
Riolering	Putkop drainage	stuk	170		https://aquafix.nl/nl/categorieen/inspectieputten
Riolering	Rioolleidingen (m)	m	6,4		pvc voordeel

D. Waarde per materiaal

Per materiaal is de stortprijs en nieuwprijs gegeven.

Materiaalgroep	Materiaal	Nieuw prijs	2e hands pr	Stortprijs
		€/m3		€/m3
Asfalt	Asfalt			
Beton	Beton	102,5		3,6
Beton	Menggranulaat	14,4	-	4,5
Hout	A-hout	1149,6		
Hout	B-hout			
Hout	C-hout			
Groen	Groenafval	-		
Kunstof	Mixed			
Kunstof	PET	1397		
Kunstof	PPE	1397		
Kunstof	PVC	1406,5	261	
Metaal	Aluminium			
Metaal	Gietijzer	8286,3264		
Metaal	Koper	51179,45		
Metaal	Staal	8328,496		
Zand	Zand	11,13		
Gemengd materia	Mixed			88,08

Opmerkingen:
De stortprijs is op basis van een stortprijs van 120 euro/ton voor gemengd afval. Als omrekenfactor van ton naar m3 is de gemiddelde dichtheid van materiaal in een kolk (734 kg/m3)
Deze dichtheid is gebaseerd op gegeven volumes in tabel en dichtheden in tabel B
Deze stortprijs is gebruikt voor het storten van kolken en zal voor andere berekeningen verbeterd moeten worden.

E. Milieu-impact per object

Beschrijving:

Objecttype	Object	Materiaal	CO2 foot print (kg CO2/m3)				
			R1	R2	R3	R4	Nieuw
Bestrating	Betonstraatstenen	Beton	0	28,152	n/a	n/a	563,04
Bestrating	Betontegels	Beton	0	28,152	n/a	n/a	563,04
Bestrating	prefab betonnen drempelelement met taludmarkering	Beton	0	28,152	n/a	n/a	563,04
Bestrating	asfalt	Asfalt					
Bestrating	halfverharding						
Bestrating	Trapelementen	Beton	0	28,152	n/a	n/a	563,04
Bestrating	Betonbanden	Beton	0	28,152	n/a	n/a	563,04
Bestrating	inritblok	Beton	0	28,152	n/a	n/a	563,04
Bestrating	Zand/menggranulaat laag	Zand/ Mengg	0	28,152	n/a	n/a	6,72
Groen	Bomen	Hout					
Groen		Groen					
Groen	Heesters	Groen					
Groen	Gras	Groen					
Inrichting	Hekwerk, leuningwerk (tuinhekken)	Mix					
Inrichting	Keerwand	Beton	0	28,152	n/a	n/a	563,04
Inrichting	Betonpaal en diamantkoppalen van hout en kunststof	Mix					
Inrichting	Uitneembare paal van metaal	Staal					
Inrichting	Straatpot/brandkraan	Mix					
Inrichting	Lichtmast	Mix					
Inrichting	Afvalbak	Mix					
Inrichting	Speelobject/toestel	Mix					
Inrichting	Verkeersbord: bord	Plastic/staal					
Inrichting	Verkeersbord: paal	Staal					
Riolering	Straat- of trottoirkolk	Gietijzer	0	3187,35	n/a	n/a	18888
Riolering		beton	0	28,152	n/a	n/a	563,04
Riolering		PVC	0	315	2543,7	n/a	7011,16
Riolering	Putkop riolering	Gietijzer	0	3187,35	n/a	n/a	18888
Riolering		beton	0	28,152	n/a	n/a	563,04
Riolering	Putkop drainage	Gietijzer	0	3187,35	n/a	n/a	18888
Riolering		beton	0	28,152	n/a	n/a	563,04
Riolering	Rioolleidingen (m)	PVC	0	315	2543,7	n/a	7011,16

Bronnen milieu impact

Materiaalgroep	Materiaal	R1	R2	R3	R4	Nieuw
Asfalt	Asfalt	-				
Beton	Beton	-	Ecoinvent: k	-		https://core.ac.uk/download/pdf/2809778.pdf
Hout	A-hout	-				
Hout	B-hout	-				
Hout	C-hout	-				
Groen	Groenafval	-				
Kunstof	Mixed	-				
Kunstof	PET	-				
Kunstof	PPE	-				
Kunstof	PVC	-	Suez (2016)	Suez (201	-	Suez (2016)
Metaal	Aluminium	-				
Metaal	Gietijzer	-	Ecoinvent: S	-		Econinvent: 1 kg Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Cut-off, U
Metaal	Koper	-				
Metaal	Staal	-				
Zand	Zand/mengranulaat	-	Ecoinvent: k	-	-	Ecoinvent: kg/m3 1 kg Gravel, round {RoW}| gravel and sand quarry operation | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit

Opmerkingen:

Voor alle Ecoinvent bronnen is EcoInvent database 3.4 gebruikt. Deze waardes zijn vergeleken met waardes de database SHARE_Metrics & Data Bronnen & Database opgesteld door metabolic & DR2 New Economy

Bron suez 2016	R2	https://www.suez.nl/media/CO2prestatieladder/Ketenanalyse_kunststof_2016.pdf
	R3	https://www.suez.nl/media/CO2prestatieladder/Ketenanaylyse_verbanden.pdf
	Nieuw	https://www.suez.nl/media/CO2prestatieladder/Ketenanalyse_kunststof_2016.pdf