Master thesis

Assessing circularity in the end of life phase of public assets and identifying essential requirements for performance measurement

Koen Verbruggen

18-09-2019

Assessing circularity in the end of life phase of public assets and identifying essential requirements for performance measurement

In partial fulfilment of the requirements of the degree of Master of Science in Construction, Management and Engineering at the Delft University of Technology

Author

Name	KJP (Koen) Verbruggen
Student number	4744780
E-mail	kjpverbruggen@gmail.com
Telephone number	0619485518

Graduation committee

Chairman	Prof. ir. P.G. (Peter) Luscuere *Faculty of Architecture and the Built Environment, Dept. of architectural engineering and technology*
First supervisor TU Delft	Dr. D.F.J. (Daan) Schraven *Faculty of Civil Engineering and Geosciences, Dept. of integral design and management*
Second supervisor	Dipl. Ing. A. (Alexander) Wandl MSc *Faculty of Architecture and the Built Environment, Dept. of environmental technology and design*
Company supervisor	H. (Henri) Veldhuis *Sweco Netherlands, transportation and mobility, GIS & ICT*

Preface

This master thesis is the result of eight months of research concluding my academic career. The decision to study civil engineering at the University of Twente has given me the opportunity to make an impact in people's lives by developing construction and infrastructure solutions. Moving to Delft for the master of Construction management and engineering at the TU Delft has given me insight into the broader implications of civil engineering works. At the TU Delft I had the opportunity to approach these projects not only from a technical but also a social, economic and ecologic perspective.

My interest in data management, technology and public space has brought me to this thesis subject at the public asset management department of the engineering bureau Sweco. I have demonstrated this interest before during my bachelor thesis in which I performed a GIS analysis of shared cycling in combination with public transport in Sao Paulo, Brazil. Throughout my thesis project at Sweco, I have been in touch with many different interesting people and departments whom all are developing expertise on the fairly new field of sustainability and circularity. Together they plan and design the communities and cities of the future.

Sweco has provided me with every opportunity to make the best of this thesis period by providing besides essential knowledge also: a great workplace, great colleagues, a laugh from time to time, the Sweco festivities and new friends.
Special thanks go out to my company supervisors Peter van Ossenbruggen and Henri Veldhuis who have made it possible to perform a case study at one of their large clients.

I also want to thank my TU Delft supervisors for their confidence in this project. For his ability to connect theory and practice and his inner motivation to change the industry I would like to thank Prof. ir. Peter Luscuere. For his tremendous experience in guiding thesis projects around the circular economy and for his motivational sessions, I would like to thank Dr. Daan Schraven. For his contribution from an academic and data analysis perspective, I would like to give special credits to Dipl. Ing. Alexander Wandl.

The municipality of Rotterdam has been very welcoming and open throughout the research. I would like to thank all of the asset managers and circularity advisors who contributed to this research. As one of the larger municipalities, Rotterdam takes a leading role in the developments towards circular asset management. Other municipalities can benefit from these efforts.

Lastly, I would like to thank those who have worked beside me in 'Het Hok' during this period as I do believe this has contributed to the quality of each of our reports. For their recommendations, after proofreading the thesis, I would like to thank Lars de Groot and Bart van den Akker.

Koen Verbruggen, September 2019

Executive summary

Introduction

It is stressed by both science and politics that there are not enough natural resources available to provide the needs of the growing middle class with the current linear consumption and construction patterns. The challenges of a circular economy run cross administrative boundaries, policy areas and scale levels.
On a local level, municipalities are responsible for municipal material flows and asset management. Several large municipalities, such as Amsterdam and Rotterdam, have been working on policy guidelines towards a circular economy and circular public space in recent years and see themselves as the leading group.

Policymakers and literature have expressed the need for a visual and tangible manner of mapping circular value, the progress towards a fully circular economy and the presence of materials (material passport) in public space. Several initiatives exist for the measurement of circular progress. However, none have explicitly aimed towards the urban public space yet. Also, the most promising frameworks have shown to run into technical and organisational issues that make them impracticable. This has resulted in the goal:

To develop actionable knowledge on performance measurement of the ecological and economic impact of the end of life phase in regional public asset management by developing a framework and identifying the technical and organisational barriers for implementation of these circularity parameters.

Methodology

Qualitative design-based research is conducted by means of the double diamond method consisting of a discover, define, develop and delivery phase. In these phases, the current goals and state of the circular economy in the end of life phase will be identified and assessed by stakeholders at both the municipality and the engineering firm. The first half of the research will result in criteria for performance measurement in the relevant domain and at this specific scale level, thereby creating a clear design brief. These criteria will be taken up in the next phase to develop a framework capable of supporting the implementation of performance measurement. The delivery phase will converge this framework by testing and evaluating the design in practice. After the second diamond, the result will be a validated and applicable framework incorporating the required aspects.

Results

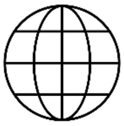
A framework for performance measurement has been set up consisting of category characteristics, economic- and ecological parameters. These indicators provide a holistic image of the current end of life asset management practice.
Data availability has been identified as a major issue in performance measurement frameworks that were discussed before. Therefore, the developed framework aims to assist in identifying these data gaps, their cause and proposal of a solution to aid the implementation of the end of life phase in local asset management.

Application to practice for asphalt roads, public lighting and greenspace has confirmed the usefulness of this framework in practice. Applying this analysis periodically could show potential growth in performance and data availability.
For academia the thesis has confirmed that rethinking the responsibility for materials at the end of their life cycle can stimulate circular behavior. This research has advanced the previous research that identified barriers for implementation of performance measurement in circular public asset management and takes this to practice.

Table of contents

1 Introduction: towards a circular economy on all levels

The amount of raw materials extracted from the earth has tripled in the last four decades due to a rapidly expanding middle class (UNEP IRP, 2016). It is stressed by both science and politics that there are not enough natural resources available to provide the needs of the growing middle class with the current linear consumption and construction patterns. The current model of ‘take, make and dispose that is prevalent in many sectors is based on easy access to these resources and therefore needs to change (The Ellen MacArthur Foundation, 2015c). The challenges of a circular economy run cross administrative boundaries, policy areas and scale levels:



On a global level, the sustainable development goals (Figure 1, next page) by the United Nations (UNEP IRP, 2016) have addressed the increase of natural resource consumption that is powered by economic growth and human development. The sustainable development goals now shape the global agenda to put an end to poverty, inequality and climate change.

Globally, a transition to a circular economy (CE) is seen as a part of the solution for the protection of biodiversity and ecosystems, ensuring sustainable production and consumption. “CE practices can be applied as a ‘toolbox’ and specific implementation approaches for achieving a sizeable number of the sustainable development goals (SDG targets)” (Schroeder, Anggraeni, & Weber, 2019, p. 77). It promises to reconcile the opposing objectives of continued economic development while preserving the resource base that is fuelling this economy (The Ellen MacArthur Foundation, 2015b).

On a national level, the SDG’s and definition of the circular economy by the Ellen MacArthur Foundation have been integrated into the Dutch government-wide program to reach a circular economy before 2050 (Rijksoverheid, 2017). This ambition was declared in a communal program published by the Ministry of infrastructure and environment, Ministry of economic affairs, Ministry of Interior and Kingdom Relations and the Ministry of Foreign Affairs. The Dutch cabinet sets the strategic goals to 1) reuse raw materials in existing chains while retaining value; 2) replace fossil- and critical materials with sustainably produced and commonly available resources and 3) develop new production methods and organise public space differently (Royal Haskoning, 2017).

On a local level, municipalities are responsible for municipal material flows and asset management. Also, they must set the example for their inhabitants. Within these processes, the municipality acts both as a client and as a contractor. Several large municipalities, such as Amsterdam and Rotterdam, have been working on policy guidelines towards a circular economy and circular public space in recent years and see themselves as the leading group (Gemeente Amsterdam, TNO, Circle Economy, & Fabric, 2015; Gemeente Rotterdam, 2017). Others, such as The Hague and most small municipalities, do not have a policy guideline towards circularity yet (Kok, 2018).

Large municipalities do admit the need for market parties to help them innovate towards a circular economy in public space (Kok, 2018; Vodovar, 2018). While material passports and measures for circularity in construction have been under development, literature and public parties stress the need for performance measurement of the circular economy in public space (Gemeente Rotterdam, 2017; Kok, 2018; Metabolic, 2019b; Potting et al., 2018;

Vodovar, 2018). After all, to make progress, it must be visible what the current state and progress are.
Material reduce, reuse and recycle activities are essential steps to move towards a healthier built environment that can regenerate itself time after time. Those activities can be managed and measured through the application of integral data-driven asset management methods during demolition and design life-cycle stages.

Figure 1 The sustainable development goals by the United Nations (UNEP IRP, 2016)

1.1 Practical relevance: an ambition without funding

The value of (technical) materials will soon be dependent on the scarcity of 'virgin' materials. The limits of the commercially viable extraction of raw materials will require organisations to work towards endless recyclability of materials (P. Luscuere, 2018b).
Municipalities must contribute to the national ambition to reach a circular economy by 2050. Currently, this is done by expressing their ambitions, setting up a policy guideline and supporting new initiatives that look at the material flows and integral asset management differently (Gemeente Amsterdam et al., 2015; Gemeente Rotterdam, 2017; Rijksoverheid, 2017).

Through interviews by urban planner Kok (2018) and the workshop 'Circular public space', policymakers have expressed the need for a visual and tangible manner of mapping circular value, the progress towards a fully circular economy and the presence of materials in public space (Elia, Gnoni, & Tornese, 2017; Bob Geldermans, Wandl, & Dobbelsteen, 2014; Leduc & Van Kann, 2013; Vodovar, 2018). Public organisations now are individually responsible for choosing key performance indicators internally and for communication to stakeholders such as contractors up- and downstream of the material chain and the general public (Pauliuk, 2018). The CBS, PBL and RIVM have together come up with an explorative study towards indicators which are, or should be, measured (Potting et al., 2018). This has not yet led to a national label for the progress of the transition to CE.

A fully circular economy is now an ambition without a budget, meaning it is challenging to motivate the investment for a circular alternative. A framework that makes, part of, the performance of the circular economy measurable will help in decision making, making available resources and emphasising the urgency of the matter. The focus of this research towards the end of life phase will help raise awareness regarding the value of assets after their practical life.

1.2 Academic relevance: no framework is available yet

Indicators are essential for circular economy assessment at all geographical scale levels (Saidani, Yannou, Leroy, & Cluzel, 2017). Scholars, however, refer to the lack of a comprehensible framework for policymakers to integrate CE in public space (Elia et al., 2017; Hoekstra, Delahaye, van den Tillaart, & Dingena, 2015; Pauliuk, 2018; PIANOo, 2018; The Ellen MacArthur Foundation, 2015a; van der Leer, van Timmeren, & Wandl, 2018; Verhagen, 2016). An increasing amount of research is performed in the direction of circular asset management and the circular economy as a whole. Material flow, material passports and other methods have been tested in the built environment but not to public space specifically. Previous studies have come up with substantiated frameworks for measuring circularity, but technical and organisational barriers prevent those from being executed (Metabolic, 2019b).
Evaluation of indicators specifically in the EOL phase and the technical and organisational barriers for implementing these in current practice is what this thesis will add to academia.

1.3 Problem statement: keeping track of progress

Several initiatives exist for the measurement of circular progress. However, none have explicitly aimed towards the urban public space yet. Also, the most promising frameworks have shown to run into technical and organisational issues that make them impracticable (Gemeente Rotterdam, 2017; Metabolic, 2019b, 2019a; Vodovar, 2018)
This research will add to the literature regarding the implementation of measuring circularity at the end of life phase of public asset management and help local governments to take the next step in keeping track of progress.

1.4 Research goal and objective

As municipalities do not have the knowledge or resources to come up with such a framework individually, they have requested market parties to explore the possibilities and limitations (Kok, 2018; Vodovar, 2018). The public parties (Table 1) as well as the market party Sweco, will be considered as stakeholders of the research product, the research will also contribute to current literature regarding the monitoring of progress towards CE in public asset management.

Table 1 interested parties that have signed to join in the development of this label

Organisation	Department
Municipality of Rotterdam	Data management public space Rotterdam Engineering bureau municipal works Rotterdam Program bureau sustainability
Municipality of Tilburg	Team beleid en beheer openbare ruimte
Municipality of Zwolle	Team beleid en beheer openbare ruimte
Province of South Holland	Team beleid en beheer openbare ruimte

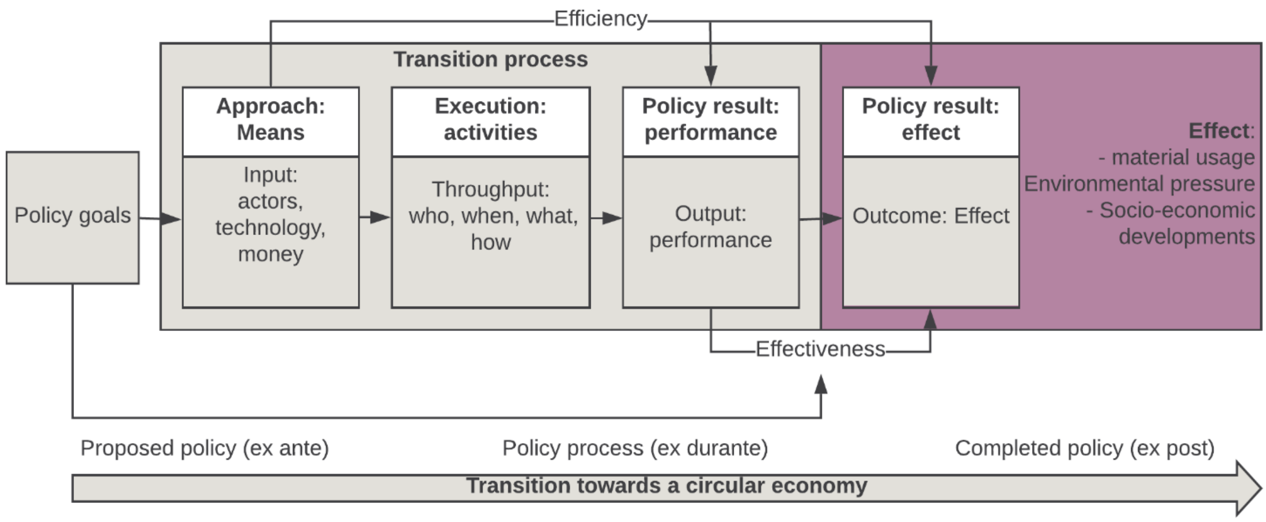


Figure 2 Circular economy: from policy to practice, and the focus of this thesis. Adjusted from Potting et al. (2018)

The focus is on the measurement of the effects of the transition process (Figure 2). The objective is therefore: **to develop actionable knowledge on performance measurement of the ecological and economic impact of the end of life phase in regional public asset management by developing a framework and identifying the technical and organisational barriers for implementation of these circularity parameters.**

Policymaking consists of agenda-setting, policy formulation, policy adoption, policy implementation and policy evaluation (Taelman, Tonini, Wandl, & Dewulf, 2018). This framework for showing the impact of the end of life asset will contribute to getting the circular economy on the agenda as well as to formulate and evaluate policy. The tool should allow public parties to monitor their progress towards their circular goals and visualise the effect of proposed measures by performing this assessment annually.

The framework will build upon the overview of assets (all public assets except for buildings) in public space that is currently present and extend this with insight into the quantity and quality of materials and environmental and economic consequences of applying specific reuse processes in public space.

The product of this research should be applicable by municipalities to assess their performance towards a circular economy. Meanwhile the framework shall be further refined by Sweco and scholars. The result must interconnect with national and international development in this knowledge field.

1.5 Research questions

The problem and research gap that have been introduced in the previous chapters have led to the main research question:

How can performance measurement of the economic and ecological impact of assets in public space in the end of life phase be performed in municipal practice?

1. Which parameters are available for monitoring progress towards CE in public end of life asset management?
2. How can the progress made in the performance of the circular economy in the end of life phase be assessed?
3. Which issues are encountered in the implementation of this performance measurement?
4. How can parameters be implemented in municipal practice for the evaluation of the current end of life scenario on circularity aspects?

1.6 Scope of research

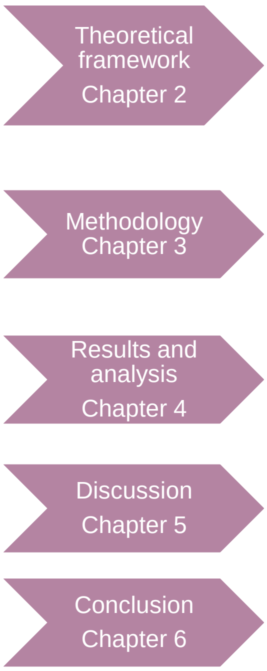
This thesis is conducted in cooperation with the engineering firm Sweco (Swedish Consultants). As consultants and engineers, they work on a daily basis to make the urban regions and societies of the future more sustainable, liveable and attractive. As the Dutch urban area and the needs of the users of the area changing; Sweco has started a knowledge program focused on knowledge development around European urban areas; Urban Insight. The aim is to contribute based on facts and data about European cities and develop knowledge about the cities of the future, from the perspective of a resident.
The knowledge is focussed around five core themes:

- Energy transition
- Smart and sustainable mobility
- Circular economy
- Climate adaptation
- Healthy and safe city

This thesis will contribute to the urban insight – circular economy by providing facts, data and insights regarding the end of life of urban assets. This specific focus has been chosen because there is 1) scarce literature focussing on the circularity of public assets at the end of life. 2) little knowledge regarding circularity in municipal practice. 3) no KPI's are currently available for assessing the circularity of processes in the end of life phase of assets.

1.7 Reading guide

This thesis is built up as follows to answer the research questions that were presented in this chapter (Figure 3).



A review of the current state of circularity in the Netherlands is required to gain insight into the goals and already applied state of performance measurement. Furthermore, asset management and performance measurement are explored. This will result in requirements for performance measurement in public asset management and answer research question one.

A research methodology is chosen to analyse the current state and develop a suitable performance measurement method. This will give an answer to the second research question.

This chapter will describe the result of the application of the methodology. Leading towards a performance measurement method applicable to public space end of life asset management hence answering question three and four.

The validity of results as well as the limitations of the research are addressed in chapter five.

Chapter 6, lastly, draws conclusions regarding the execution of performance measurement in public space end of life asset management. From these, limitations and recommendations follow.

Figure 3 Thesis outline

2 Theoretical framework

This chapter provides an answer to the first research sub-question: “Which parameters are available for monitoring progress towards CE in public end of life asset management?”. It will elaborate on what is known about the circular economy, circular goals within Dutch local governments and existing measurement frameworks for circular progress in public space.

2.1 Defining circular economy circular asset management

The intellectual roots of circular economy build upon several earlier principles, such as the 3R principle (reduce, reuse, recycle), regenerative design, performance economy, cradle-to-cradle, blue economy, green growth, natural capitalism, and biomimicry (Pauliuk, 2018). An often-cited and generally accepted definition of the circular economy (European Environment Agency, 2016) is by The Ellen MacArthur Foundation (2015d): “a circular economy is gradually decoupling economic activity from the consumption of finite resources, and designing waste out of the system. Underpinned by a transition to renewable energy sources, the circular model builds economic, natural, and social capital”. The circular economy stands in contrast to the linear economy that has a ‘take, make waste’ approach to materials.

The definition can be extended by stating that a circular economy “is restorative by design and aims to keep natural and technical resources (energy, water, air, materials and topsoil) at their highest utility and value, at all times” (P. Luscuere, 2018a).

Luscuere, Geldermans, Tenpierik, & Jansen (2016), use four principles to specify this definition. These are the principles that have also been used in this research to define a circular economy:

1. A building or group of buildings needs to generate more renewable energy than it uses, including the embodied energy.
2. Air, water and fertile soil must be cleaned (locally) in such a way that the emission and the final situation is cleaner than the intake and initial situation.
3. With biological materials, waste = resource applies.
4. Technical materials must be recyclable continuously

A net positive footprint is the ultimate goal, upcycling materials by adding green energy or (virgin) materials that can be recovered at the end of life phase are therefore allowed. New economic models that focus on the sale of the function rather than the product accelerate the transition towards products with a longer lifespan or products that are designed for reuse.

2.2 The state of circular policy in Dutch regional governments

The Dutch cabinet has set three strategic goals in their report ‘The Netherlands circular in 2050’ (Ministerie van Infrastructuur en Milieu, 2016):

1. Virgin materials in existing chains are used at their highest utility level
2. Where new materials are needed, fossil, critical and non-sustainably produced ones are replaced by sustainably produced, renewable and generally available raw materials
3. We develop new production methods, design new products and design areas differently. We also promote new ways of consumption.

To do so, the cabinet uses the following five instruments:

1. Stimulating legislation and regulations
2. Smart market incentives
3. Financing
4. Knowledge and innovation
5. International cooperation trough transition agendas

These instruments are applied to the areas food, construction, finance, education and the labour market, of which the construction sector in the Netherlands is responsible for approximately 50% of the total technical material consumption. Royal Haskoning (2017) mentions the lack of key performance indicators in the current vision documents of the cabinet and the province of South Holland.
Rotterdam, as one of the leading municipalities in circularity thinking, takes over the objectives of the cabinet and expands on them. Rotterdam states in goal 2: “circular municipal material chains” the objective to have 25% of their municipal material chains 100% circular by 2020 and 80% in 2030 (Figure 4). Rotterdam states that it will strive for a circular economy in 2050, where raw materials are used and reused efficiently, without harmful emissions to the environment (Gemeente Rotterdam, 2017).

Rotterdam strives to reach this objective by dismantling the released materials and efficiently reuse them with the help of a materials passport, building hubs (storage centres for used materials) and a digital materials marketplace. These tools are useful for the engineering of adequate maintenance and high-quality reuse. Market parties provide the data; the asset owner manages the data and delivers it to market parties for reuse in the next cycle.
Most municipalities already have an integrated software tool in use at their asset management department. However, asset inventory tools were designed with another purpose in mind: keeping track of inventory. The first versions of the software tools merely kept a list of all the assets present. The purpose is expanding towards integral data management, and more and more functionality is demanded of the software. This is one of the bottlenecks: requirements for the software as well as those using the software have changed. Obsurv facilitates in these demands and is used in 140+ municipalities. The software is further explained in paragraph 2.3, asset management.

As a public organisation, municipalities have a transparency obligation towards their citizens (Hermans, 2014). Performance measurement in asset management methods helps to create this transparency, learn and improve as well as to compare and identify opportunities for the city as a whole (Arthur, Hodkiewicz, Schoenmaker, & Muruvan, 2014). Related to this transparency obligation are the topics on the research agenda of Rotterdam to gain insight into indicators and measurability and map the circularity of material flows.

According to (Gemeente Rotterdam, 2017), several factors complicate the implementation of a circular economy currently:

1. Investment uncertainty for public and private parties because of a changing city council every four years and an unclear definition of circularity
2. The pace of legislation which cannot keep up with the innovation pace of private parties

Figure 4 Rotterdam circular ambition 2: municipal material chains (Gemeente Rotterdam, 2017)

3. The current pillarized structure of the government makes cooperation on integrated projects difficult. Climate is in a different jar than circularity or land allocation
4. The tendering method does not reward circular initiatives (sufficiently)
5. The definition of circularity is still unclear, because of which contractors have no certainty which direction is now required

Circular policy in public space appears to be an ambition for which no budget was made available as well as an ambiguous concept. Both should be addressed to pave the road towards a circular economy. Clear KPI's are identified as helpful for defending budgeting decisions.

2.3 Developments in data-driven asset management

Within the Province of South Holland, since 2005, management and maintenance of assets in the public space have been carried out according to an integral and process-based method. The integral approach has removed the barriers between different specialisations, such as green space and roads.
Since 2018, this is done according to the principles of asset management. This new management philosophy focuses on functionality and safeguarding the social importance of the infrastructure for a specified period (Provincie Zuid Holland, 2019). Goals of an asset management approach are: to reduce the capital costs of investing an operating while optimizing operating performance, the environmental impact, safety risks, and other risks associated with operating assets (Davis, 2013). The ISO 55000 standards support these goals and are designed as a guide for organizations involved in establishing, implementing, and maintaining asset management systems (Hastings, 2015).

Besides the transition towards integral and process-based methods, the process has also become data-driven. Clause 7.5 of the ISO standard 55001 speaks about the information requirement: "the organisation shall implement a process for managing information". Accurate, comprehensive parameters can be utilised throughout the life cycle of assets, whereas historical information aids in troubleshooting and identifying improvement opportunities by providing data for analysis and decision making (Hastings, 2015).

The asset management software tool Obsurv that is currently implemented in 140 public organisations in the Netherlands facilitates the work-processes within the asset management life cycle approach. Based on the desired quality standard of public space, a lifespan and maintenance regime are suggested (CROW, 2013). The municipalities apply visual quality standards, as shown in Appendix A.

Obsurv is used for the following processes which is shown in Figure 5 (Sweco, 2018):

- Integral management of public assets: planning and budgeting in one process
- Keep an inventory of assets and view them in maps and dashboards
- Schedule, execute and review inspections
- Record, approve, execute and handle citizen reports

The modules and functional characteristics of Obsurv are based on nationally established and widely used standards, norms and systems. Such as NEN 2767-4, CROW 146, CROW 288, NPR 3220, NPR 3398 and NEN 3399. The management, mutation and consultation of the administrative and graphical data of Obsurv is done in the spatial database of Oracle. The big advantage of this is that the data is stored according to open GIS standards and that it can be accessed directly by other applications. This allows Obsurv information to be used without conversion in CAD and GIS systems such as ArcGIS, AutoCAD and

MicroStation. Multiple users can also use the data at the same time, and management, authorization and availability are clearly arranged.
Data from Obsurv can be summarized visually in a so-called dashboard. The dashboard provides insight into the budget, stock, priority, trends and escalation of inspection- and citizen reports.

Figure 5 interface of the Obsurv software, showing the different disciplines (top) and an overview of the available tools for asset management of greenspace (Sweco, 2018)

An in-depth overview of exemplary asset passports is shown in Appendix B. These overviews show the current parameters used in asset management practice (specific for Rotterdam) as well as the lack of end of life parameters in the current overviews.

2.4 End of life decision making

The end of life (EOL) of an asset can occur because of two main reasons:

1. The technical lifespan has passed, making the material unfit for function
2. The practical lifespan has passed, the asset is replaced because of changes to the situation, because of new regulations or because it is being replaced with newer materials (Berg, 2019; CROW, 2013)

Given the complexity of the different end of life possibilities, the government of the Netherlands adopted an order of preferences of EOL solutions on which to base public policy. This is a shortlist of six EOL solutions (Figure 6), the so-called 'Ladder of Lansink' (Lansink, 2014). This order of preference was implemented in 1979 and is still the basis for decisions on regulations, legislation, taxation and subsidies at different levels of government.

Figure 6 Ladder of Lansink (Lansink, 2014)

Recycling is often seen as good environmental practice as it reduces the demand for new resources and reduces the cost and energy use incurred by landfilling. However, the major problem is that the recycled materials are often used in a lower grade application compared to the initial application and, consequently, that a significant proportion of the initially invested energy is lost (Berg, 2019)

Reuse can provide environmental benefits as the invested embodied energy is preserved (Iacovidou & Purnell, 2017; P. Luscuere, 2018b). Berg (2019) identifies the lack of recovery facilities, infrastructure, technology and markets; designs without provisions for future dismantling; tight scheduling and budgeting of projects; liability risks for using recovered items; building codes that fail to address reuse; and a lack of standards or guidelines as barriers for implementation of reuse processes.

Selecting the appropriate waste management alternative depends on the asset's condition and criteria set by the municipality. Multi-criteria decision-making analysis and life cycle analysis (LCA) can help decision-makers selecting the best waste management alternative compromise among alternatives (Berg, 2019; Gemeente Rotterdam, 2017). These tools as well as an appropriate performance measurement method can help overcome some of the barriers introduced by Berg (2019). The application of LCA will combine the following principles (European Commission, 2012)

- An undesired shifting of burdens between impact categories can be prevented by assessing a range of environmental problems in a framework
- Monitoring and comparison of different products are made possible scientifically and quantitatively by inventorying the impact on all streams (air, water, energy, material).
- LCA facilitates the comparison of the environmental performance of different systems on an equal basis and helps to identify areas for improvement.

Currently, the performance measurement indicators for end of life asset management are undefined (Berg, 2019; Metabolic, 2019a; Potting et al., 2018)

2.5 Performance measurement in asset management

Public organisations have a transparency obligation and therefore require clear KPI's to support and present their decision making (external) (Green, Masschelein, Hodkiewicz, Schoenmaker, & Muruvan, 2016; Hermans, 2014). Furthermore, performance measurement can be used for learning and improving (internal). More functions are shown in Figure 7. This figure also shows the increasing demand on the quality of indicators depending on the impact that one would like to make.

For the purpose of this research: to learn and improve (internal) and create transparency (external), the demand on the quality of indicators is limited. When the municipality has passed this station and aspires to compare, assess or even sanction the requirements become more strict. For learning, improving and creating transparency, an estimation or qualitative statement could suffice.

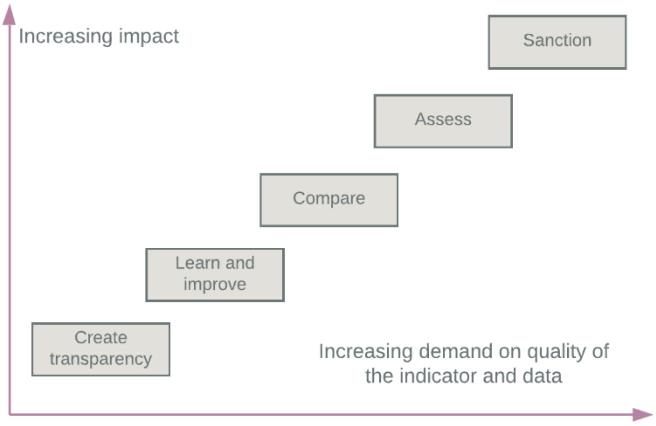


Figure 7 functions of performance measurement adjusted from Green et al., (2016)

Besides quality Green et al. (2016) describe three criteria for performance indicators which they have to comply to.

1. Validity and reliability: indicators need to be clarified in such a way that they measure what they intend to measure.
2. Functionality: The indicator needs to be relevant and contribute to the overarching objective. In this case, assessing the performance level of circular reuse of end of life assets.
3. Legitimacy: the indicator must be accepted and influenceable by the asset manager with available resources.

The absence of either of these criteria is an incentive for strategic behaviour, where the asset manager focuses on getting a good score instead of doing the right thing. Another risk of using parameters that do not comply to these criteria is a lack of ambition or the opposite: blocking innovation.

The measurement may be the process of quantification, but its affect is to stimulate action. It is only through consistency of action that strategies are realized (Neely, Gregory, & Platts, 2005). “Adequate and consistent resources must be allocated to creating and maintaining the data otherwise it will quickly become worthless” (Hastings, 2015, p. 229). One must be aware of the responsibility for data management and place this responsibility at the party that is best able to handle this. The municipality, as a ‘middle man’ between contractors in different phases of the lifecycle could act as a data manager, storing data and making it available to contractors in future life cycle phases. This does require that the municipality accepts the responsibility, internalizes it and makes available resources to do so.

2.6 Measuring circularity: the existing frameworks and parameters

Giving insight into the material stock and its reuse potential can fulfil a catalyst role to promote circular use of the material and create awareness (Verhagen, 2016). Furthermore, it will give insight into the transition process before effects are visible and provide the opportunity to steer based on data (Potting et al., 2018).
As said, the circular economy is a global challenge Figure 8 shows the appropriate models for measuring environmental effects on different scale levels according to (Peters, 2010)

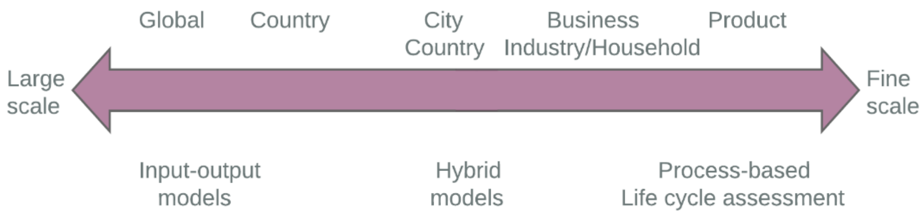


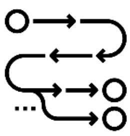
Figure 8 Appropriate models for assessing environmental effects at different scales (Peters, 2010)

It is interesting to have an understanding of what measurement methods are available already. Existing frameworks are described in this paragraph; their characteristics have been combined in Table 2 on page 15.

2.6.1 DuboCalc / Dutch environmental cost indicator

DuboCalc stands for Sustainable Building Calculator and was developed by Rijkswaterstaat to calculate and compare the sustainability and environmental costs of tenders. DuboCalc calculates all the effects of material and energy consumption. As a result, the effects are expressed in euros, the Environmental Cost Indicator (MKI). The method is based on the method of Life Cycle Analysis (LCA) according to the ISO14040 standard and on the Environmental Performance of Buildings and Structures Assessment Method (PIANOo, n.d.).
DuboCalc is based on a database of materials for which this information has been calculated and currently focuses on the infrastructure sector. Also, the impact of different end of life scenarios has not yet been incorporate

2.6.2 Material flow and Urban metabolism



Material Flow, Urban Metabolism and Flow analysis are different terms for “a systematic assessment of the flows and stocks of materials within a system defined in space and time” (Elia et al., 2017, p. 4). Where urban flow is based on the flow of physical materials, urban metabolism can also approach human systems where fluxes of energy flow based on the laws of thermodynamics (Bob Geldermans et al., 2014).

The limitation of the Material flow analysis concerning the circular economy, however, is that it only provides information about the quantity of materials used, not about their quality, nor their embodied energy (Elia et al., 2017; P. Luscuere, 2018b; Pauliuk, 2018). Furthermore, Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann (2015) and Luscuere (2018a) emphasize the natural flows which are underexposed in reviewed papers. These are air and water quality and quantity, mineral resource depletion and land use.

2.6.3 A material circularity indicator by The Ellen MacArthur Foundation MCI

Expanding on the concept of material flow, the Material Circularity Indicator (MCI) by The Ellen MacArthur Foundation poses an attempt to include the loss of materials and quality level utilizing a re-use potential indicator in the framework (Elia et al., 2017; The Ellen MacArthur Foundation, 2015a). The Ellen MacArthur Foundation has proposed a material circularity indicator for products based on the following inputs:

- Input in the production process [m^3 of virgin materials]
- Utility during the use phase [time and intensity of use compared to the industry standard]
- Destination after use [Re-use, repair, energy recovery]
- Efficiency for recycling

For the computation of the MCI, a detailed material passport for the product is required. However, as in the DuboCalc method proposed before, the use of a reference product approach in case less quantitative data is available is suggested.
The material circularity indicator provides a useful set of indicators but focusses on industry processes as these are generally better understood and have a high level of data availability. Also, the MCI lacks support for natural flows and biological materials.

2.6.4 Buildings as material banks, the material passport

The Reuse potential tool by BAMB (Durmisevic, 2019) addresses the technical reversibility of buildings and aims at informing designers but also manufactures and owners about the level of recovery of building materials and their reuse potential. Due to the number and complexity of data needed to assess Reuse Potential, the assessment process is time-consuming, and the tool can be best used by specialists (Durmisevic, 2019). BAMB proposes a next step where the method is integrated with data sources such as BIM or GIS (asset management) databases. Herewith BAMB is one of the promoters of a material passport to safeguard material value now and in the future (P. Luscuere et al., 2016a). Material passports are described as sets of data about materials characteristics (Berg, 2019), and may help to keep track of the material composition of building objects over different cycles of disassembly and reuse.

The integration of natural flows in the BAMB approach requires further research that incorporates the intrinsic and relational value potential of materials (B. Geldermans, Luscuere, Jansen, & Tenpierik, 2016)

2.6.5 Metabolic; a holistic approach

Commissioned by the province of South Holland and the Metropolitan region of Amsterdam. Metabolic has translated the principles of the circular economy into concrete goals and measurable critical performance indicators (Metabolic, 2019a, 2019b). This framework has been designed to give a holistic approach of progress towards a circular economy on a regional scale and covers materials, energy, natural capital, health & wellbeing and the economic effects of the transition.
Metabolic concludes that circular approaches are reasonably new on a regional scale, which causes issues when filling the framework with values due to the limited measurements being performed within the municipal practice.
Although the framework is not grafted on the end of life phase, it does pose an interesting method of presentation in which the main subject “circular economy” is divided into categories. Also admitting to the fact that there is little awareness at the public governments is a first step towards helping these public governments to first create awareness with a less sophisticated framework before requiring in depth knowledge.

2.6.6 Material passports

At the basis of each of the frameworks is an extensive material passport for assets. This is an interaction between the asset owner and market parties. Market parties provide this information; the asset owner manages the information and supplies it to other market parties for reuse in the next cycle. A material passport is not merely a ‘list of ingredients’ (L. M. Luscuere, 2017). Besides the type of material, also the location, their context regarding the complex systems that they are a part of and their value as an object instead of raw material.

Table 2 a comparison of CE measurement frameworks

Model	Application area	Potential	Parameters	Limitations
DuboCalc / MKI	EMAT	Considering environmental impact as an EMAT criterion	Environmental performance based on a material library	Re-use scenario is not included Lack of material passport data in many environments. The financial indicator gives limited insight.
Material flow / urban metabolism	Geographical areas or other delineated systems	Analysing material input and waste output to gain insight and come up with new ideas for connecting or reducing flows.	Input, output and flow of materials between sub-systems. Sometimes in terms of embodied energy	Does not consider the devaluation or quality loss of products and materials.
Material Circularity Indicator by The Ellen MacArthur Foundation	Products and technical materials	A complete indicator for technical materials that has the potential to be applied in public space.	Input, utility, destination after use, the efficiency of recycling	It lacks support for biological materials.
Buildings as material banks	Material reuse potential in buildings	Assessing the reuse potential of materials in buildings	Extensive material passports	BAMB focuses on buildings and does not consider the different natural flows.
Metabolic	local scale	A holistic view of the circular economy	materials, energy, natural capital, health & wellbeing and the economic	A comprehensive overview of what we would like to know. It is difficult to fill the framework due to several reasons and suggested to research these barriers

2.7 Conclusions from theory: guidelines for the framework

The Dutch ministry, as well as large municipalities, have set up guidelines towards the circular economy in recent years. However, these seem to lack a clear set of key performance indicators. The asset management approach has changed in recent years towards an integral data-driven process that could be improved by a clear set of indicators and an overview of the requirements for implementation or barriers that prevent implementation. Only the Lansink ladder is available as a basic tool that can rank different end of life scenarios in municipal practice currently.
Although several attempts to set up a framework for performance measurement in asset management have been taken; most of them focus on factory processes or buildings. Furthermore, the broad definition of the circular economy which is used in this thesis is not reflected in either of the assessed frameworks. This definition is based on the following four rules:

1. A building or group of buildings needs to generate more renewable energy than it uses, including the embodied energy.
2. Air, water and fertile soil must be cleaned (locally) in such a way that the emission and the final situation is cleaner than the intake and initial situation.
3. With biological materials, waste = resource applies.
4. Technical materials must be recyclable continuously

The current life cycle approach and integral asset management that is possible in tools such as Obsurv set the preconditions for including the end of life phase in public municipal asset management. To implement performance management in public practice, a framework of indicators needs to be set up and municipalities need support in identifying the barriers for implementation.
Literature regarding performance measurement identifies three basic requirements for frameworks which will be considered in this research which are: 1) the validity and reliability, 2) functionality and 3) legitimacy.

Lastly, it can be noted that little is known regarding performance measurement in the end of life phase of public assets. A short policy review of large municipalities indicates that performance indicators are vague or cannot be applied due to a lack of detailed data. These considerations should be taken into account in this research, the end goal should be to give insight into the current state with the current level of data availability and help public governments to improve on this in further iterations of the process.

3 Methodology: the double diamond

This chapter describes the research method used to develop a suitable framework for municipalities to assess their current performance. Paragraph 3.1 will introduce the design-based research methodology and its fit for this project. Then, paragraph 3.2 will describe the theory of the double diamond method. The next paragraph (3.3) explains the application of each of the steps for this project: discover, define, develop and deliver.

3.1 Design-based research

The objective of the study contains an intervention in the existing situation. It aims at solving the practical problem that local governments have with measuring progress and effect of measures towards a CE in urban public space. Verschuren & Doorewaard (2010) recommend applying a design-oriented approach in developing policy-induced solutions such as the development of assessment frameworks. In this type of research, the perspective can excite from a pilot or active cooperation between practice and academia. According to Wang & Hannafin, (2005, p. 2) design-based research is defined as follows: “design-based research is a research methodology aimed to improve educational practices through systematic, flexible and iterative review, analysis, design development and implementation, based upon collaboration among researchers and practitioners in real-world settings, and leading to design principles or theories”.

The objective is best met by creating an inventory of interpretations, experiences and opinions. Determining a research perspective, therefore, is not just part of the design of a research project, but also part of the research and result in itself (Verschuren & Doorewaard, 2010). Design-oriented research often results in prescriptive knowledge, which provides instructions on how to assess or change a situation. Lastly, design-based research is characterised by applying mixed methods to maximise the credibility and adaptability of the results in practice (Wang & Hannafin, 2005).

The research objective benefits from an outcome that is applicable in practice. Also, academia will benefit from the application of this design-based research method because it will explore the applicability of known performance measurement methods to the unexplored domain of municipal public asset management.

3.2 Double diamond

Design-based research is characterised by an iterative cycle of design, enactment, analysis and redesign (Verschuren & Doorewaard, 2010; Wang & Hannafin, 2005). The process is characterised by a phase of divergent, openminded, thinking before refining and narrowing down to the best idea (convergent thinking). This can be represented by a diamond shape (Figure 9) as described by the Design Council (2015).

The double diamond indicates that the diverging and converging phase happen twice; once to confirm the problem definition and once to create the solution. The diamond consists of a discover, define, develop and delivery phase. Diverging phases are approached with an open mind where insights are gathered from both academia and practice using mixed methods. The converging phases are characterised by sensemaking and analysis of what is feasible.

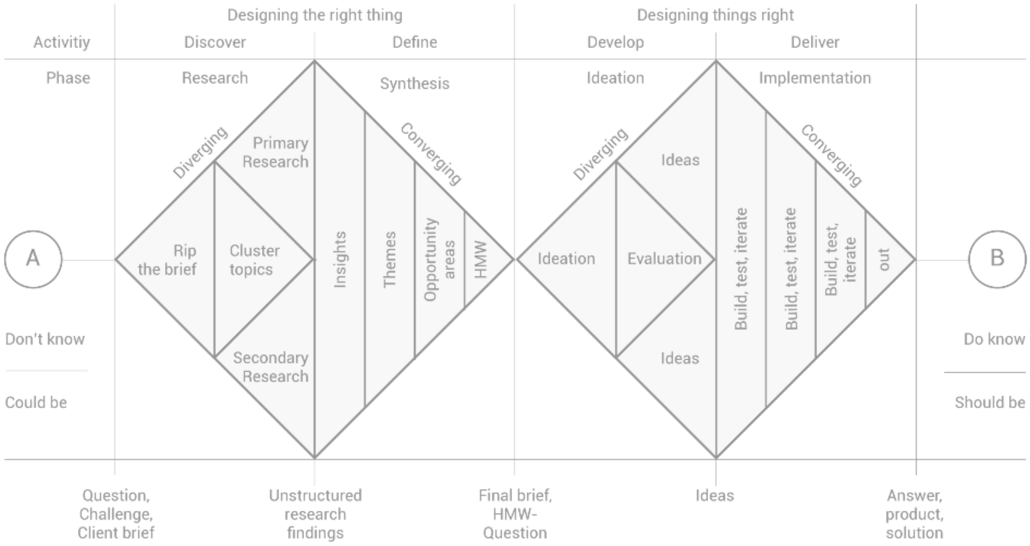


Figure 9 the double diamond (Design Council, 2015)

3.3 Application of the double diamond

Following the double diamond, this thesis research will start with problem analysis. the current state and goals of the circular economy in the end of life phase are identified by stakeholders at the municipality, as well as the engineering firm.
The first diamond will result in criteria for performance measurement in the relevant domain and at this specific scale level, thereby creating a clear design brief (Figure 10). These criteria will be taken up in the next diamond to design a framework capable of supporting the implementation of performance measurement. The delivery phase will converge this framework by testing and evaluating the design in practice. After the second diamond, the result will be a validated and applicable framework incorporating the required aspects.

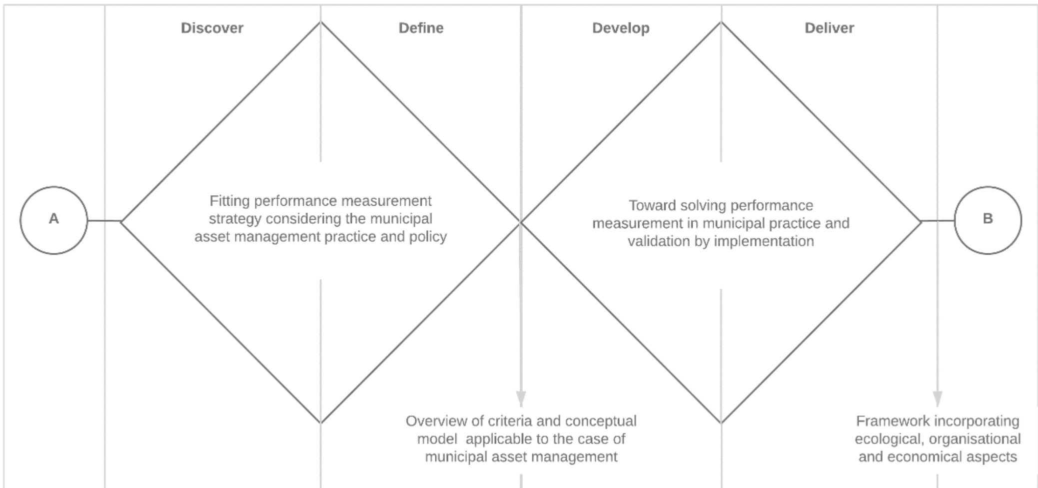


Figure 10 Application of the double diamond methodology in this research

3.3.1 Discover and define

The first phase is marked by an exploratory phase, where insights and inspiration are gathered. The literature framework has already shown the current state of performance measurement at different geographical levels as well as their limitations in this application. Knowledge of the background and goals of the circular economy within the municipal practice is necessary and will be acquired by a combination of academia and practice.

First, the circular economy goals and progress within local governments is examined by looking into policy guidelines and national guidelines. Also, reports by private parties who have analysed the circular economy at different scales levels are assessed.

Second, target sessions in the form of semi-structured interviews have been held at both the asset management departments of the case municipality and the engineering bureau. Key informants were identified during initial discussions with the host organisation; others were referred to during interviews. Due to this snowballing technique (Verschuren & Doorewaard, 2010; Yin, 2003), interviewees came from upstream and downstream the asset contractors' supply chains.

Study area

The municipality of Rotterdam sees itself as one of the precursors in the field of circular asset management and has therefore committed itself as a collaborator for this research study. Commitment by the department of asset management and grant of access to research-related data make this a productive cooperation. Within the asset management software Obsurv, Rotterdam is one of the largest clients when looking at the number of assets. The municipality has a large asset management department and because of its size employs individuals who specifically focus on the circular economy. Including also the perspective of the engineering firm Sweco, which supports the municipal asset management of 140 client municipalities, will strengthen the internal validity of this research.

Semi-structured, open-ended interviews were held with three overarching asset management experts at the municipality's asset management department as well as general circularity and asset management experts at the engineering firm (Table 3).

Table 3 overview of interviews in the discover and define stage

Client	Function
Sweco	Consultant sustainable and circular construction
	Consultant circular economy
	Consultant material passports and asset management
	Consultant sustainability in tender processes
	Consultant asset management roads
	Consultant asset management urban mobility
	Product owner Obsurv / data analytics
Rotterdam	Team manager city development and management
	Program manager digital asset management and BIM
	Circular economy advisor city development and management
	Advisor strategic market approach public asset management

These interviews were structured as follows:

Introduction
- Introduction of the thesis and previous attempts to measure circularity
- Introduction by the interviewee regarding responsibilities and tasks
- Defining circularity

Topics
- End of life processes within the organisation
- Economical: the value of material, business models
- Ecological: impact, data
- Organisational: issues, collaboration, data management
- Measurement: why? How? How?

Future perspective
- Which topics are missing in this discussion according to you?
- What is seen as the added value of performance measurement of the circular end of life scenarios in municipal asset management?

All interviewees were interviewed for around 60 minutes. These interviews were recorded, with the permission of the interviewee. The interview tapes will remain private. Although no full transcript has been made of the interviews and spontaneous conversations, the notes and recorded statements have been bundled per topic in a table to make qualitative analysis and drawing conclusions possible.

The next step is to compile requirements for the performance measurement framework by combining literature and research findings. Based on these requirements, the first conceptual version of the framework can be established.
Requirements are distinguished into four categories (Verschuren & Doorewaard, 2010): functional, contextual, user and structural. They describe the performance, fit in the (political) environment, wishes and form. The conceptual framework will clarify what exactly is measured and what application in practice will look like.

3.3.2 Problem solution: develop and deliver

Based on the conceptual model and responses to this mode; the framework is extended to fit the needs of large and small municipalities and guide asset managers in formulating an answer to each parameter. During the development and delivery stage, the framework is validated by the second round of semi-structured interviews. The interviewees now are asset managers in three selected asset categories: greenspace, asphalt roads and public lightning.

These three categories differ in their composition (natural, single material and hybrid) as well as how they are managed and processed (in house, partly in house and by external parties), the hypothesis is that this has implications on data availability and control over the process. These categories have been chosen to identify the organisational and technical issues that arise when applying a measurement framework to different categories in practice.
The sample of three asset categories has been chosen for its diversity (Table 4), which helps the generalisability of the result.

Table 4 Overview of responsibilities within the lifecycle of selected assets

Asset	Composition	Management and maintenance	End of life process
Natural capital	Biological	Internal	Internal
Roads	Single material (per type)	External	External
Public lighting	Multiple parts	Internal	External

Data gathering for this application is done through key informants that were identified during initial discussions with the host organisation; others were referred to during interviews (snowballing). Due to this snowballing technique, interviewees also came from downstream the asset contractors' supply chains, which supports the validity of results.
In these meetings, individuals were educated on the goals and workflow of the framework. The first step then was to fill parameters with (qualitative) data. When precise answers could not be given for a parameter, a discussion was induced regarding the data gap, barrier and possible solutions. Yin (2003) emphasizes the importance of a chain of evidence when snowballing in case research.
Table 5 therefore shows an overview of respondents.

As in the first round, the interviews have been recorded with the permission of the interviewees.

Table 5 overview of interviews in the develop and delivery phase

Client	Function
Sweco	Consultant asset management public lightning Consultant asset management natural capital Consultant asset management roads
Rotterdam	Asset manager roads Asset manager public lightning and innovation manager Asset manager green space
Dura Vermeer	Innovation and sustainability advisor in road and hydraulic engineering
Heijmans	Consultant road engineering and environmental impact

The experiences are translated to concrete actions that need to be taken in the organisational and technical field to make the circular economy at the end of life phase of public assets tangible. These recommendations will be addressed to local governments as well as others in the field of public asset management, such as contractors and data analysists.
Several iterations of the framework have been made throughout the research, each refining the parameters regarding ecological and financial consequences.

The aim is to confirm the completeness and practicality of the model in daily practice by taking it to up and downstream parties, therefore confirming the external validity of the framework.

4 Results and analysis of the study area

This chapter presents the results of the action research that was conducted. This chapter combines the result of the diagnosis phase, development of the performance measurement method as well as the study results from the municipality. This chapter follows the sructure of the double diamond. In 4.1, the major insights from the first rounds of interviews are sumarised. Paragraph 4.2 discusses the results of the develop and deliver phase. The parameters and scoring mechanism are explained in 4.3, followed by an analysis of the results from practice (4.4)

4.1 Major insights: discover and define

During the discover and define phase, interviews have been held with key players at the asset management department of both Sweco and the municipality of Rottterdam (Table 3). The major insights that are described here have been taken into account during the develop and deliver phase that follows.

A generally accepted method

It has been found through interviews and literature review that the short term implementation of a performance measurement system in municipal asset management is difficult due to the complexity of the subject and the unavailability of (centralised) data. The framework should contain the KPI’s necessary to evaluate end of life public asset management on at least ecologic and economic characteristics.

Implementation of end of life in current data- and asset- management

Meanwhile, the integration of the end of life process in the asset management approach of municipalities is relatively new. Traditional public asset management has evolved in the last decades from a practical hands-on profession to a data-driven, life cycle assessment approach. The end of life phase is in the process of being included in the decision-making process of municipalities. This is in line with literature insights.
Therefore, analysing the end of life process and identifying knowledge gaps is seen as a helpful method to create awareness within municipalities by interviewees from all three areas (engineering, municipal and downstream).
In practice it has been found in all three assessed asset categories that knowledge regarding the outflow streams is limited while this is a prerequisite for identifying opportunities in lost material and lost value.

The role of business models in reaching circular ambitions

Furthermore, the analysis of the current end of life processes will allow municipalities to rethink the division of responsibilities. The realisation that there is value in what was previously seen as waste can lead to new business models that can be stimulated by including the end of life process in EMAT criteria or rethinking the responsibility for the removal of material.

It became clear that up and downstream participants in the asset life cycle process are working on new business models and improvements to the end of life scenario of assets. However, they do not feel rewarded for this in tenders for new contracts. It is important to emphasize this in the perfromance measurement model.

Applying a developed framework in practice is expected to create awareness for the subject and the scope of the circular economy which is broader than materials alone.

4.2 Design steps: Develop and deliver

The following design steps have led to a framework for performance measurement in the end of life of municipal asset management. The framework is shown after the last step (Figure 11). After the visual, each parameter is further explained, as are the labels that belong to them.

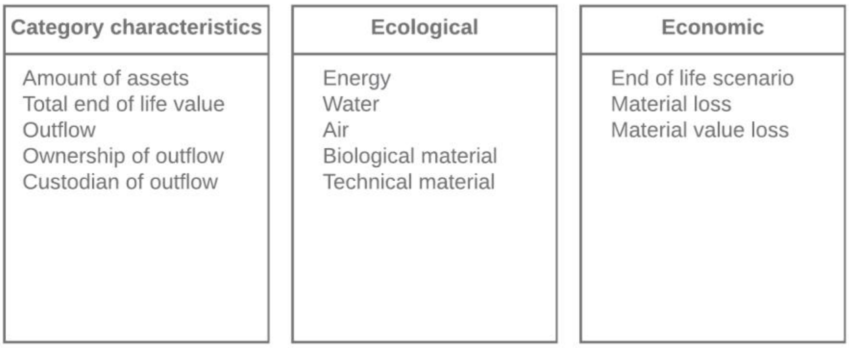
1. Following the literature research, the reason for applying performance measurement within an organisation is to create transparency (external) and meanwhile use the outcomes for learning and improving (internal). This is also what municipalities try to establish as was identified from interviews. The definition of circularity used in this research is broader than materials alone: it is about ensuring a positive footprint for energy, air and water, as well as the continuous reuse of technical material and seeing biological material as a resource. A net positive footprint is the ultimate goal; upcycling materials by adding green energy or (virgin) materials that can be recovered at the end of life phase are therefore allowed. Since the research goal is to develop actionable knowledge on performance measurement of the ecological and economic impact of the end of life phase in the regional public asset, these are the first two categories.

Ecological	Economic

2. New economic models that focus on selling the function rather than the product accelerate the transition towards products with a longer lifespan or products that are designed for reuse. Literature, existing frameworks and interviewees from all three divisions of practice confirm this. General characteristics of the asset category help gain insight into the possibility for these business models and the total impact that a category has.

Category characteristics	Ecological	Economic

3. None of the frameworks discussed in the literature review focus specifically on the end of life process of public assets. Analyses of the applied parameters show overlap between the frameworks as well as parameters that do not apply to end of life public asset management. The following indicators have been chosen for the framework based on the criteria:
    1. Giving a holistic understanding of the impact of the end of life phase
    2. Reliable determination and communication to a broad public is possible
    3. Applicable by policymakers to base decisions on
    4. Replicable for a broad range of assets and local governments

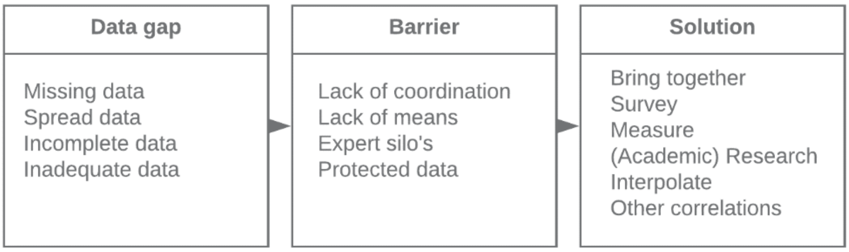


To help create awareness, incorporating (residual) values and ownership of materials in the asset management system can influence the way in which tenders are reviewed.

Step three has resulted in the conceptual model which is applicable to the case of municipal asset management for executing performance measurement.

4. In this study, bringing the conceptual model into practice and presenting it, it was noticed that the data availability is a major barrier for implementation of any performance measurement in municipal asset management. The acceptance of qualitative answers can help to give insight and create awareness regarding difficult topics when quantitative data is absent. For each parameter, general exemplary answers are given. These answers are given hierarchically in order of preference in the same manner as the Lansink Ladder.

5. To realise performance measurement in the near future and address the problem of data availability, an analysis section is added to the framework. When an answer to a parameter cannot be given, addressing the data gap and the technical or organisational barrier causing it will grant insight into the processes and the steps that need to be taken to operationalise performance measurement. The following gaps, barriers and solutions have been gathered through interviews with asset managers and data managers at Sweco as well as previous research by Metabolic (2019b).



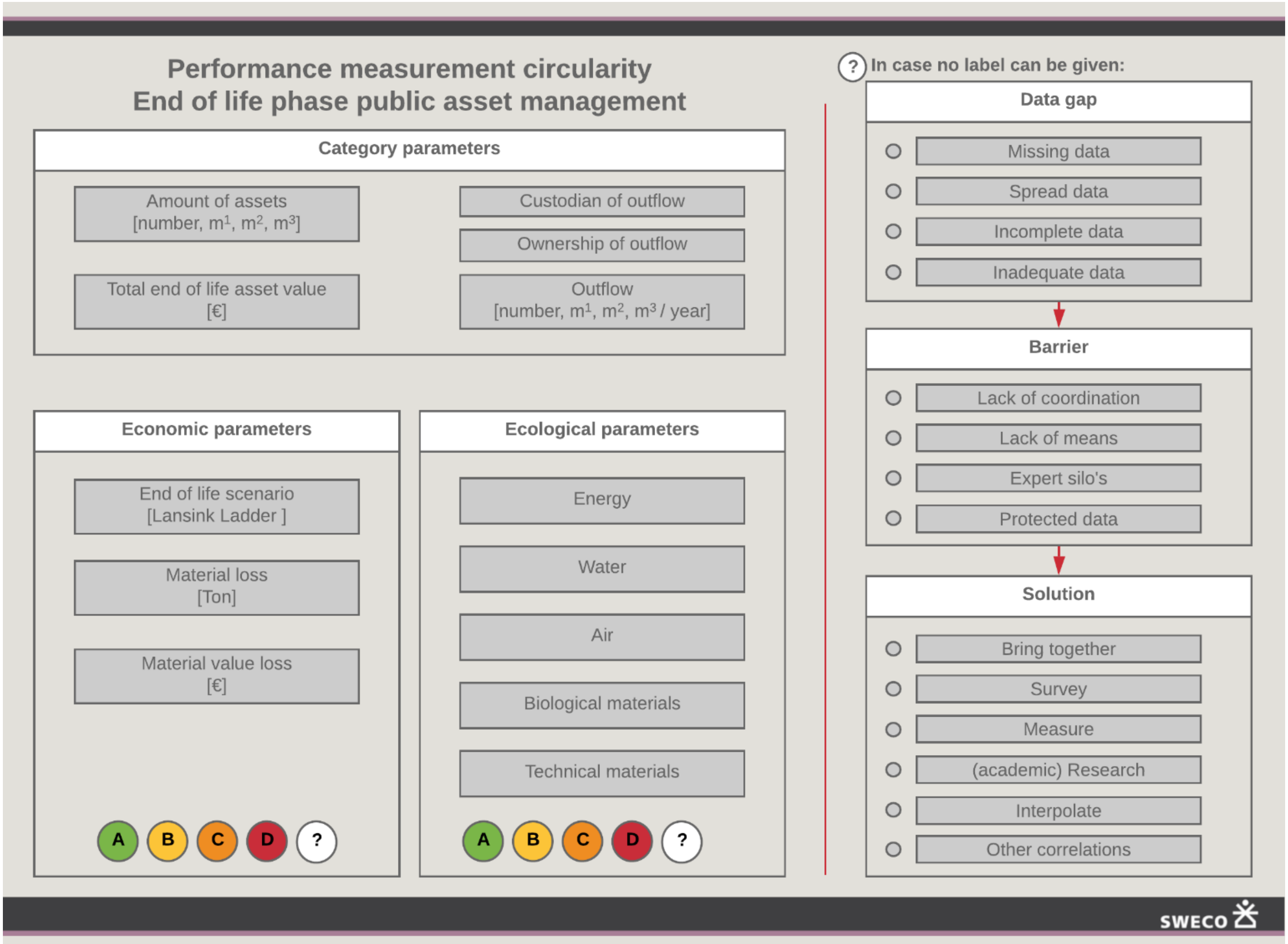


Figure 11 Performance measurement in end of life public asset management, the model

4.3 Quantifying impact with the available data

This paragraph will demonstrate the framework that has been set up and describes each aspect extensively. The results that have followed from a limited case application at the municipality of Rotterdam are presented as well. The sample of three asset categories; roads, public lightning and greenspace has been chosen for its diversity (indicated earlier in Table 4, page 21), which helps the generalisability of the result.

Furthermore, the gaps, barriers and solutions are elaborated on. To do so, the input of all three involved departments is used. The results that have come from the application of the framework to three categories in the study area do support the major insights presented in paragraph 4.1.

The following paraphs are built up such that the validity and functionality of the parameter are motivated. This is followed by the results from application at both the municipality and Sweco combined.

4.3.1 Category characteristics

Category characteristics define the size and flow of the asset category one is applying the framework to. This is important to identify large or valuable waste flows, but these characteristics do not receive a label. It consists of the following parameters:

Amount of assets

A stepping stone towards a material bank is an overview of assets. Keeping track of the size of the asset management task yearly will identify whether it is growing, shrinking or stable (Metabolic, 2019a). There is a large number of stocks such as capital goods (such as materials and objects) that will be released in the future, at the end of their useful life. These materials have the potential to be used as raw materials in the economy again (Potting et al., 2018).
With the growing strategic importance of scarce and critical materials, it is becoming increasingly crucial for the Netherlands and Europe to know what is stored in the urban mine (BAMB, 2017; Metabolic, 2019a).
Together with market parties and research institutes, public organisations work towards the accurate mapping of what is present in their urban mine. Depending on the type of asset considered and the available data accuracy, this can be either in m^1, m^2 (tiles, grass), m^3 (asphalt, concrete), or pieces (public lightning, trash cans).

In practice, due to the implementation of integral asset management software packages, municipalities have an up to date insight into the number of assets they are managing. Interviewees emphasise that, however this may sound obvious, the days of split departments with their own excel files and workflows have only just passed.

Total end of life Asset value

The monetary value is the value after the current recirculation process or for which the material is sold to a third party to process it. It is a prioritization parameter as high-value assets that are easy to separate are most attractive for a policymaker or manager. It must be noted that this value is negative in cases where the municipality pays for the removal of the material. Also, the value is dependent on the current state of technology. Future techniques for separating materials or increasing the percentage of reused material in new applications can increase the embodied value of assets.

Results show that the end of life of assets has only recently been embedded in the asset management practice. While some municipalities have set out consultancy assignments for revaluating their portfolio, this is not common practice yet. As mentioned, the value is also fluid and dependent on market developments.

Outflow
Besides the complete asset management task, the size of the recirculation task is essential. The outflow is the amount of stock that reaches end of its cycle per year and for which thus a future scenario needs to be selected (Metabolic, 2019b; Potting et al., 2018; The Ellen MacArthur Foundation, 2015a).
When numbers for the outflow of material are unavailable, an approximation can be made by dividing the number of assets present by the practical lifecycle.

For asphalt and public lighting, it is pointed out by practitioners that the asset volume generally does not increase. New material replaces end of life materials, and therefore, the correlation between orders and outflow might be used for getting to numbers.
For greenspace, a delivery note is created when the material is brought into the municipal depot. This data has not been made insightful for the asset management team up to now. Applying the framework with practitioners proves to open up discussions regarding data management and possible correlations.

Ownership and Custodian
The value hill assessment methodology developed in cooperation with the municipality of Rotterdam (Achterberg, Hinfelaar, & Bocken, 2016) emphasises the importance of the current business model. Positioning the current business model and evaluating who is the appropriate party to have ownership or custodian (where the second is the responsibility to process the material flow) can lead to new insights.

Previously, the materials or assets that flow out during the execution of projects automatically expires to the contractor (ownership). New business models, as identified through interviews, reconsider this and give the municipality more power over the process. For instance, both public lightning and greenspace make use of a municipal depot where the material is gathered, assessed on quality and repurposed. The 'Rotterdamse stijl', an alignment of the types of light posts, benches and other design elements enables the exchange of items between north, south, east and west.

The municipality is aware of the ownership and custodian and is actively reconsidering these as the deadline for new framework contracts is closing in.

4.3.2 Economical parameters

End of life scenario
"In the traditional linear economy, minerals are mined, processed to products and finally wasted in landfills or burnt in incinerators" (P. Luscuere, Geldermans, Tenpierik, & Jansen, 2016b, p. 5). More effective ways to recycle or even upcycle materials are mentioned in the Lansink ladder, as shown in the theoretical framework. The original ladder contains six stages, as shown in Figure 12 (Lansink, 2014):

- **Reduce**: reduce the amount of material applied, for instance by adjusting the design of an asset or by reducing the number of light poles applied (regulatory or technical)
- **Reuse**: Reuse materials in a new application, if necessary by upcycling them by adding renewable resources
- **Recycle**: The difference between reuse and recycling is that with recycling the materials are separated, collected and processed to manufacture new products

- **Energy**: High-quality energy recovery using incineration or composting. The downside is that materials are burned and lost forever
- **Incineration**: Without energy recovery.
- **Landfill**: The least favored and most polluting alternative is to dispose of material by burying it in the ground

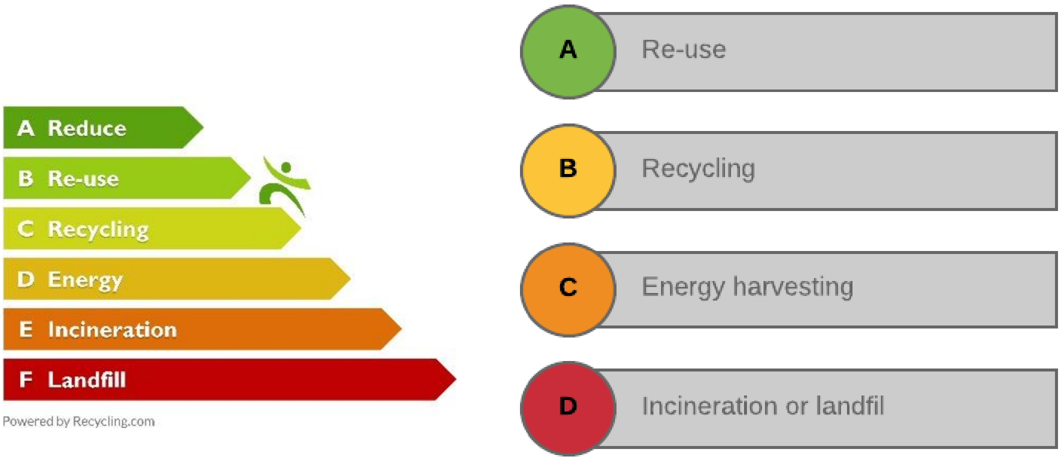


Figure 12 Lansink ladder with six steps (Left, Lansink (2014)) versus the implementation of these levels in the model (right)

Both in the case of incineration and landfill, 100% of the material is lost. In the framework, they are therefore combined. Also, a reduction of material applies to the design phase; it is not an option in the end of life phase anymore and therefore not considered.

Despite not being the owner of outflow materials, all asset managers involved in the project had a clear image of what is happening in the end of life. It is recognized that a reconsideration of ownership can give the municipality more power over this process to set demands or even set out a tender for processing material in the most circular manor. Because the end of life scenario is strongly correlated with the material (value) loss, it is

Material loss [%]
Material loss implies the percentage of material that is either burned, composted or dumped (Metabolic, 2019a; The Ellen MacArthur Foundation, 2015a). These are non-cyclic processes that originate from a linear waste management. The processes result in 100% material loss followed by replacement with virgin material. The material loss can be based on the expert knowledge of contractors or based on the EOL scenario. The framework labels contain large steps but are designed to give insight based on a very low level of available data which was encountered in the first diamond of the double diamond method. Again, the label is an opening to a deeper conversation about the topic, application to practice will deliver the combination of a label and a justification.

- **A** No material is lost, the assets are reused
- **B** < 50% of the material is lost
- **C** > 50% of the material is lost
- **D** Through waste to energy, incineration or landfill, all materials are lost

Material value loss [€]
Value loss is a comprehensible and relevant indicator for policymakers and managers as it identifies prioritisation areas

$\text{Value loss} = \text{Price}_{\text{virgin.material}} - \text{Price}_{\text{after.recirculation.process}}$

Value loss is dependent on the current end of life process. To determine the loss, the market prices for virgin and secondary material should be compared. Often the potential of secondary material is not fully appreciated yet; this analysis and other projects promoting the assignment of value to end of life assets can help raise awareness.

Based on the end of life process, an estimation of the value loss can be given with the following labels:

- **A** No value is lost, the assets are reused
- **B** < 50% of the value is lost. The main part of the asset can be reused or recycled
- **C** > 50% of the material is lost; by selling to a waste to energy process or landfil
- **D** Through waste to energy, incineration or landfil, all value is lost

Interviewees recognise the valuation of outflow materials as a useful strategy for prioritising the reuse of waste. However, the knowledge for doing so is on the contractor side and usually not communicated. In traditional project delivery methods “The value that can be extracted out of outflow material during a project will usually be included in the offer by the contractor” (Rotterdam, Asset manager roads). The municipality of Rotterdam does at this point not assign value to outflow materials.

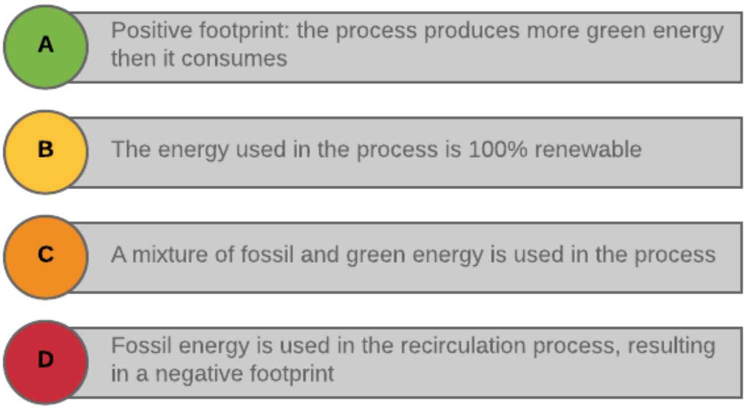
4.3.3 Environmental parameters

The use of materials does not only result in the depletion of these sources but also affects other resources during mining and recirculation. These are energy, water and air. Besides the continuous circularity of materials; natural resources should be renewable endlessly.

The energy, water, air and materials used in recirculation processes should be renewable or from renewable resources to reach a positive footprint (P. Luscuere et al., 2016b). The use, renewability and origin of these streams can be influenced by setting policy.

Energy
A neutral footprint in terms of energy implies that the only energy applied in the recirculation process originates from renewable resources. When more energy from renewable sources is generated than consumed, the footprint can become positive. The production and transport of material in the end of life should be included in this calculation.

The footprint can either be:



Application in practice brought up that for greenspace the energy footprint is positive; material that is not left in its original location is used as biomass to generate renewable energy within the municipality, keeping transport to a minimum. For asphalt this is entirely different, asphalt mixtures are heated in the process by natural gas, and therefore the process has a significant negative footprint.
The case municipality and contractors are aware of the positive or negative footprint of their processes and work towards improving these. Improved communication regarding the ecological impact from contractor to municipality can support the steering role the municipality sees for itself.

Water
Extraction of water [L] and eutrophication of water are a metric for determining the water footprint of a process (European Commission, 2012). Reduction of extraction, discharge measures and the improvement of water quality are principles that can be applied to improve the footprint (P. Luscuere et al., 2016a). For a positive footprint, contractors must ensure that the water that leaves their premises is cleaner than the water that went into their premises (P. Luscuere, 2018a) to get to a positive footprint.

The framework contains two questions regarding water.

- Is the freshwater quality affected by this process?

  - **A** Positive: the water used in the process is returned to the environment cleaner than it entered
  - **B** Neutral: the water quality is brought back to the entry level with renewable resources
  - **C** Negative: the water quality is polluted by the process
  - **D** Negative: the water quality is heavily polluted by the process and this has direct effect on the surroundings

- Is the freshwater quantity affected by this process?

  - **A** A positive contribution is made to the water ecosystem
  - **B** No water is extracted in the process
  - **C** Water is extracted from the ecosystem but this does not lead to damage
  - **D** Water is extracted from the ecosystem, leading to damage to the surroundings

Air quality

For air quality, the principle is the same as for water. The water that leaves the premises needs to be cleaner than the water that went into their premises to get to a positive footprint. The environmental protection agency in the USA has set an example for a scale on which to assess the air quality in cities (EPA US, 2014). An extensive calculation is available that combines the concentration of different pollutants (carbon monoxide, sulfur dioxide PM10, PM2.5, ozone and nitrogen dioxide) in the air; this can be applied if and when this data is available at contractors to come to an exact score in the justification of the label. Until this data is available, the qualitative description can be used to express a label as with the other parameters.

The framework contains two questions concerning air quality:

- Does the recirculation process affect air quality?

  - **A** Positive: the air used in the process is returned to the environment cleaner than it entered
  - **B** Neutral: the air quality is brought back to the entry level with renewable resources
  - **C** Negative: the air quality is polluted by the process
  - **D** Negative: the air quality is heavily polluted by the process and this has direct effect on the surroundings

- What is the impact on air (co2, for instance) because of logistics?

  - **A** Minimal: the material is processed within the municipality
  - **B** Neutral: the air quality is brought back to the entry level with renewable
  - **C** Negative: the material is processed within the country but requires logistic movements which are not compensated
  - **D** Negative: the material is transported over large distances with polluting road, rail, water or air traffic

Discussing the ecological footprint in practice has given the insight that this is an area of expertise in the early stages of development. Contractors and research institutions work together to set up a standard for measurement of the ecological footprint for materials. Until that time, using this framework as a discussion opener can help to give insight into the broad definition of circularity.

Biological material & Technical material
The studied existing frameworks all take into account the mass of virgin material used. The total consumption of technical and biological materials is considered by requesting the percentage of virgin biological and technical material that are added in the recirculation process (Metabolic, 2019b; Potting et al., 2018; The Ellen MacArthur Foundation, 2015a).

From practice, contractors that are in the asphalt innovation business can declare a bill of ingredients for their mixtures. However, they find that the client rarely requests this information. Asset managers and contractors indicate that the asphalt recycling business is running at the highest technically feasible recycling percentages. The municipality does not see a role for themselves to influence these developments.

4.3.4 Data gaps and barriers for implementation

Literature and practice have identified the lack of both clear KPI's and generally accepted KPI's and knowledge in the end of life process. The first part of the framework adresses the lack of knowledge which is present in local governments.

The goal of performance measurement in this case is as said before not necessarily to measure the current state but also to assist in the road towards concrete performance measurement.

When unable to fill a particular parameter with quantitative or even qualitative data; three phases of analysis are identified: the gap, barrier and solution are consecutively determined as proposed by Metabolic (2019b).
The first step is to assess the data gap before identifying organisational or technical barriers that complicate the process of data gathering. As the last step, solutions for managing this gap are identified. The framework is designed to be applied in evaluation sessions and start-up meetings for performance measurement in municipalities; the answer will therefore always consist of more than just ticking the box.

Gaps

- Missing data: no information is currently available regarding this topic
- Spread data: Knowledge exists on this topic, but it is spread over (many) different parties. This can either be within the municipal organisation or in several private parties such as contractors or material processors.
- Incomplete data: Data can be incomplete when it is known for some assets or materials but not for all of them
- Inadequate data: When the detail or quality of data is a problem the data might be inadequate to judge a specific parameter.

Barriers

- Lack of coordination: It might be unclear who is responsible for data management or collection of a particular parameter
- Lack of means: Data management has not always been a priority in certain parts of asset management. It might, therefore, be that resources are lacking while it is known what should be measured, by who and how.
- Expert silo's: Some specialist knowledge is accommodated in expert areas of an organisation.
- Protected data: Especially private parties do not always feel the urge to share data. This might be sensitive for their business case.

Solutions

- Bring together: One solution is to centralise data and connect systems between parties. This requires efforts from multiple parties in which the asset management software can play a central role.
- Survey: Processors and others involved in the asset management can be surveyed to combine knowledge. Surveying could result in asking for information during the process or including questions regarding the impact of an end of life process in EMVI criteria
- Measure: When it is know how to measure this method can be applied by the municipality. For internal processes it can sometimes be enough to start logging data in the asset management software which is otherwise lost.
- Scientific research: When it is unknown what to measure or how to measure this; scientific research into methods can help to identify key performance indicators and measurement protocols for certain parameters.

- Interpolate: When data isn’t readily available an estimation or qualitative judgement can fill this gap. For instance, if roads build in 1950 typically have a certain buildup, this might be extrapolated to roads of similar build year without data.
- Other correlations: Other data inputs such as the cadaster, national, global) might be used for the estimation of specific outcomes. Another example is to use the growth of an asset category and the input of assets to determine the outflow.

4.4 Analysis for selected asset categories

Three asset categories had been selected to apply the performance measurement model on: asphalt roads, public lightning and greenspace (Table 4). To do so, interviews have been held with one asset manager at the study area, Rotterdam, and one asset management consultant of the specific asset at Sweco. The aim was to fill the framework for Rotterdam and extend the knowledge with insights of Sweco consultants who work with many municipalities. The goal of this last part of the second diamond in the double diamond method is to confirm the completeness and practicality of the model in daily practice by taking it to up and downstream parties, therefore confirming the external validity of the framework.

Results of this application have briefly been included in the explanation of parameters above, those results have also been combined in a report per category. The goal of these summary reports is to give the asset management department a quick overview of the current state of circularity and data availability.

These reports are presented in this paragraph (Figure 13-Figure 15). Bellow the reports, an analysis of the identified gaps and labels is presented (Figure 16)

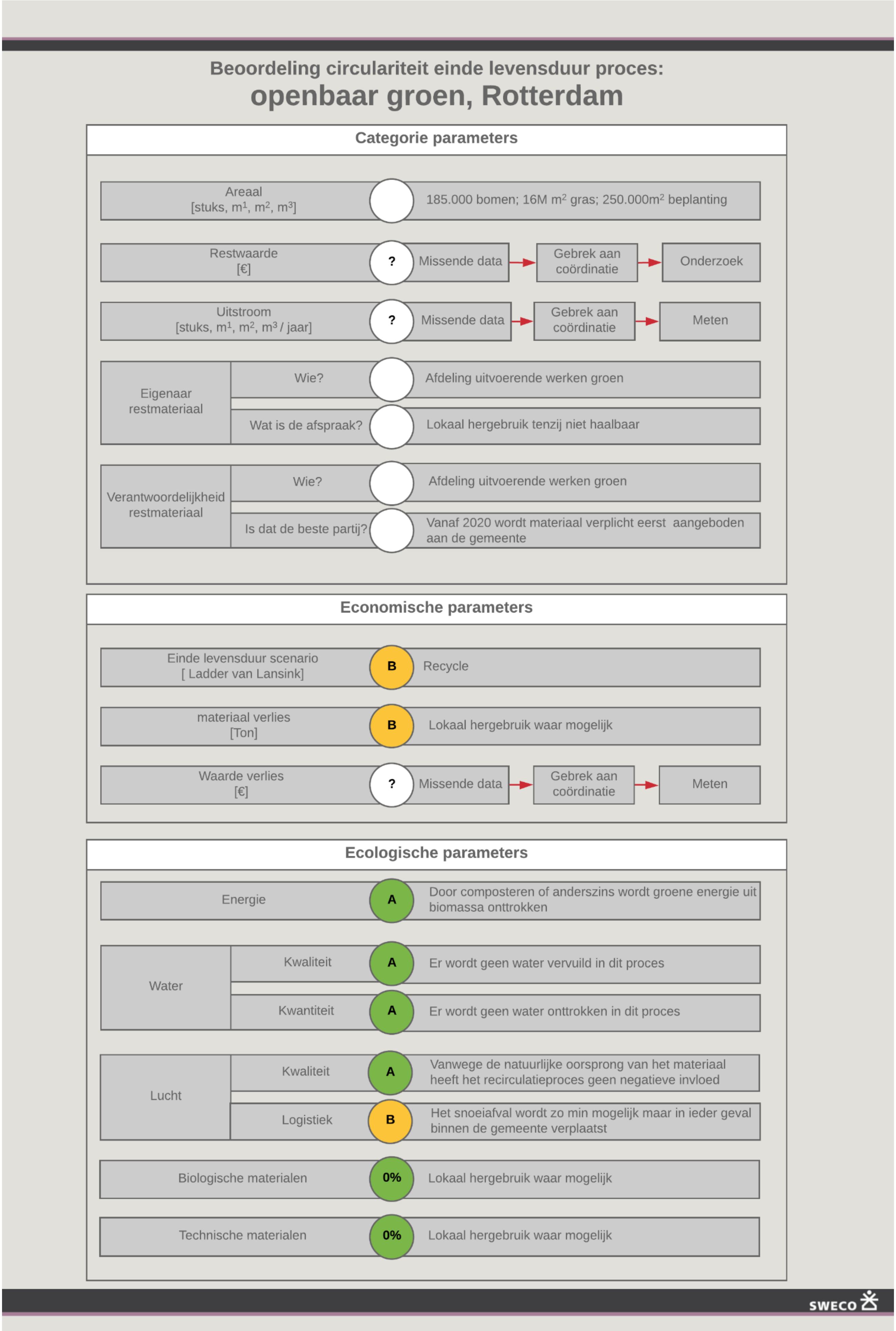


Figure 13 Summary report performance measurement greenspace, Rotterdam

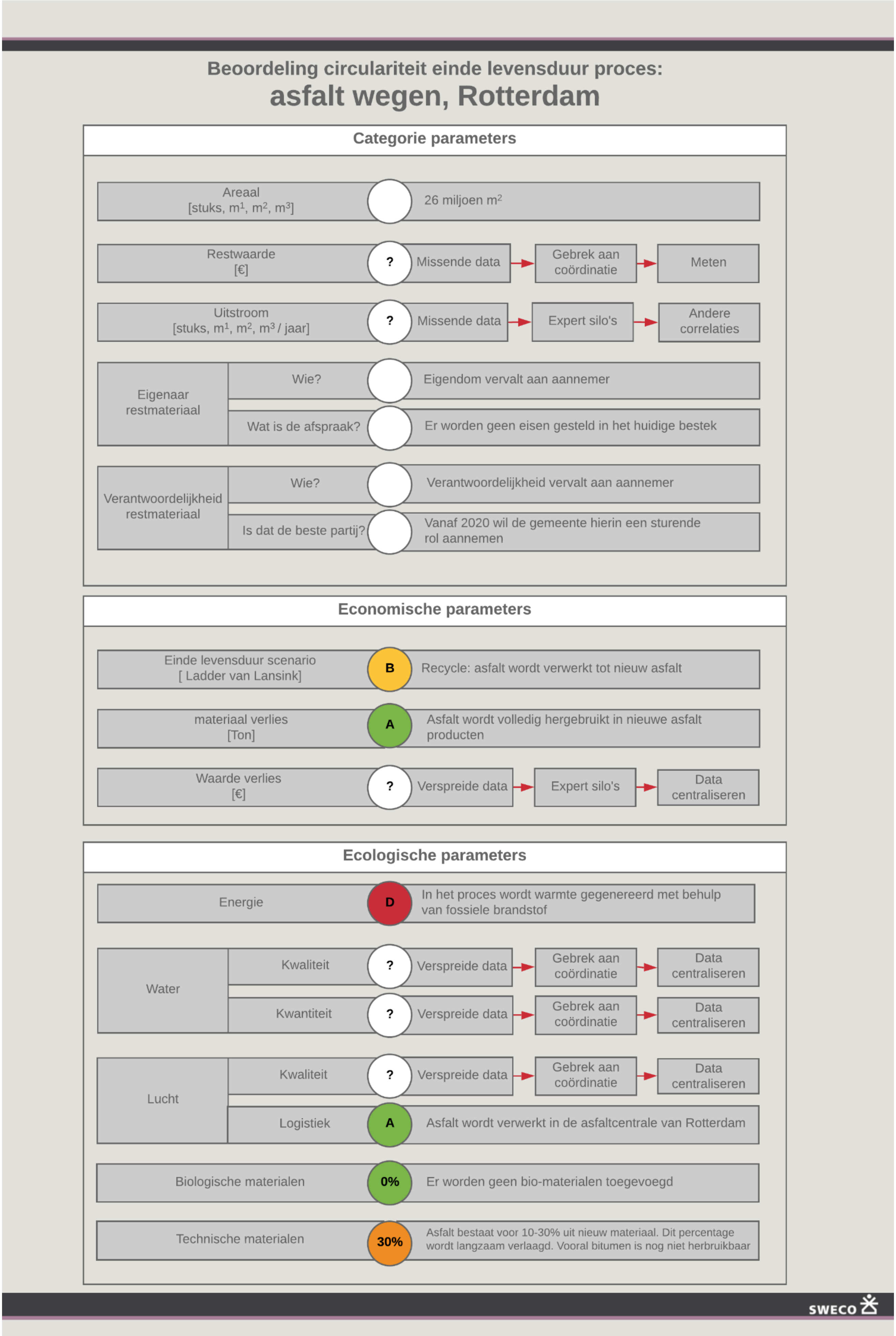


Figure 14 Summary report performance measurement asphalt roads, Rotterdam

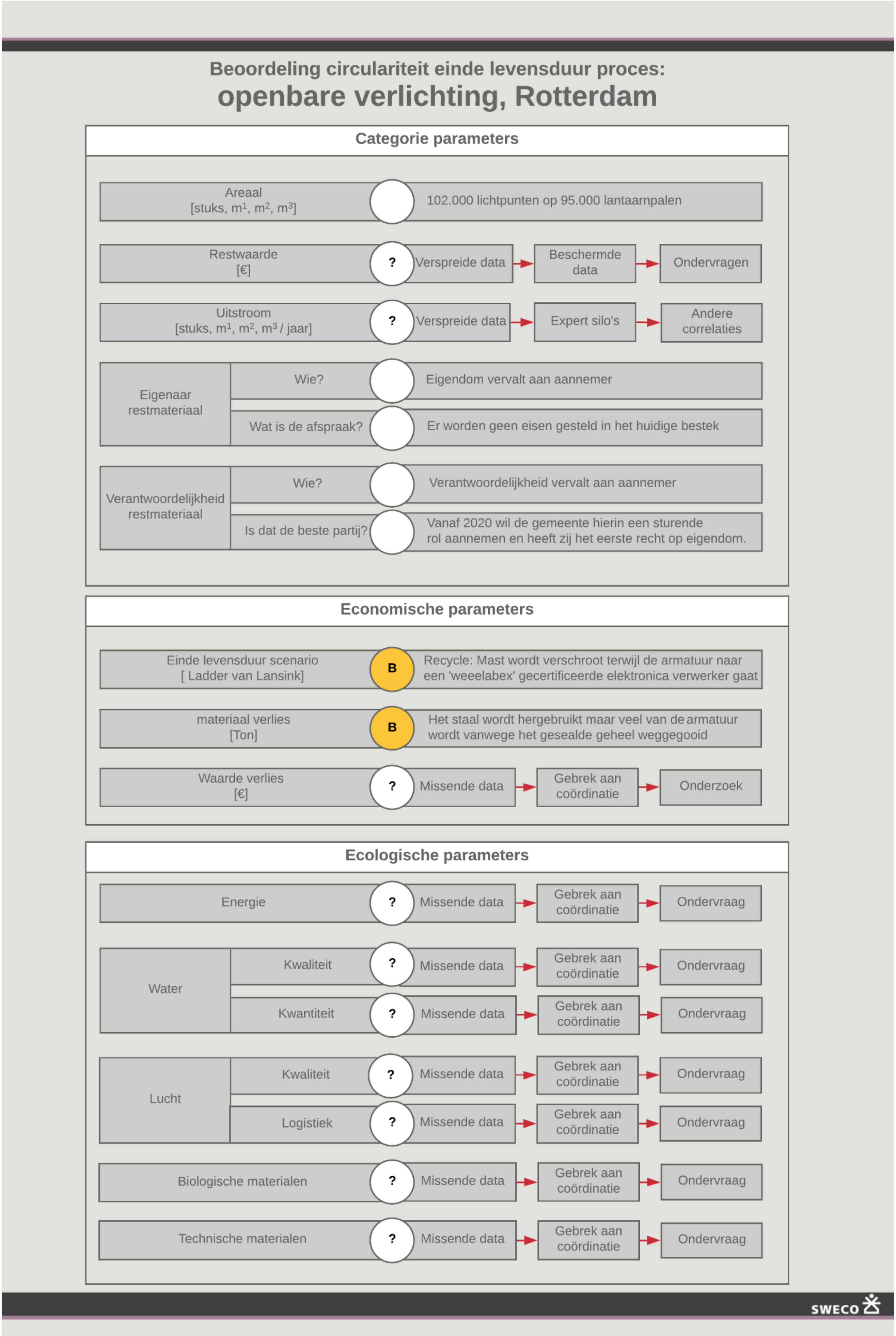


Figure 15 Summary report performance measurement public lightning, Rotterdam

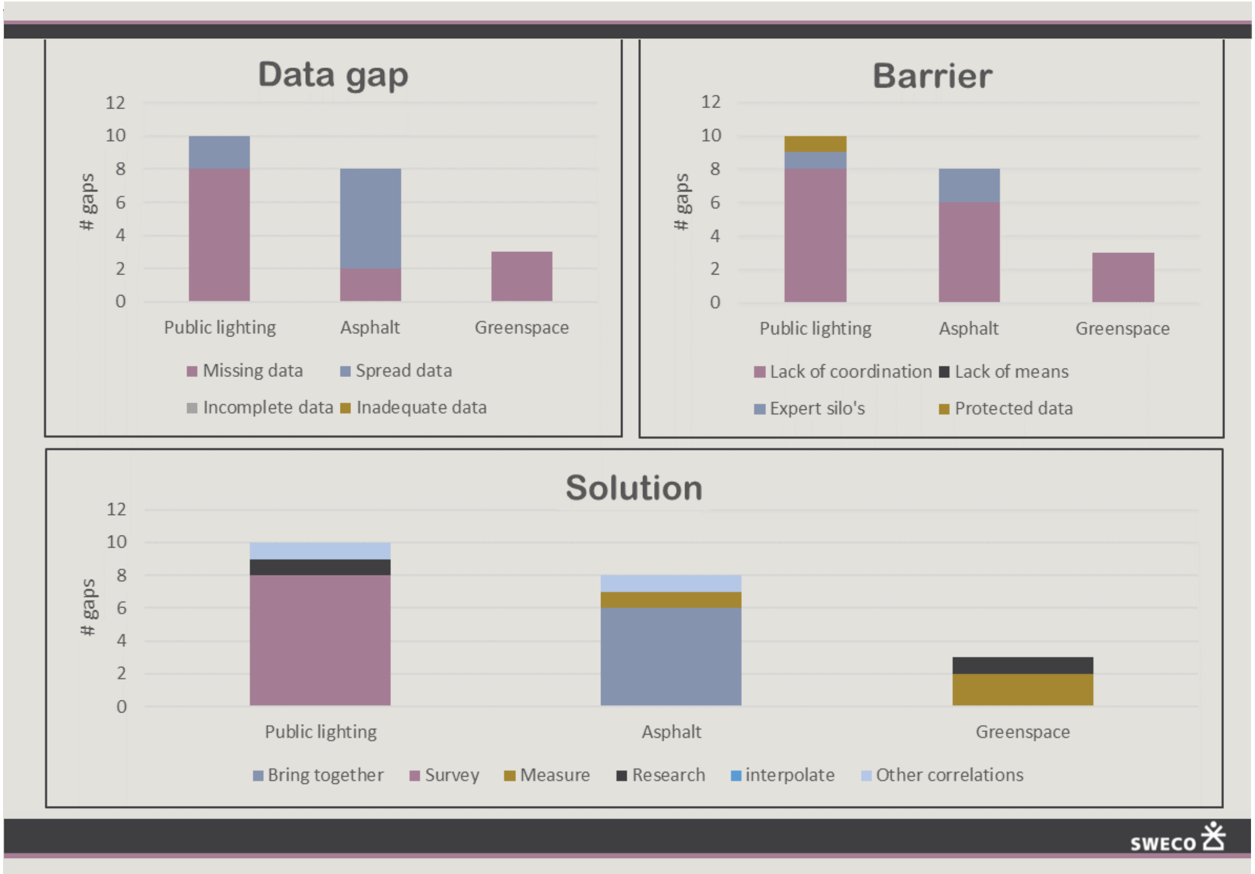


Figure 16 Results from application to the three asset categories in the study area with municipal and sweco experts. Within the three asset categories, a total of 21 gaps was identified.

From the interviews, in which the goal was to fill the framework for the asset category that the interviewee was an expert on, it appeared that missing data has the highest frequency (13/21 gaps) in cases where no answer was available.

The main cause for this is a lack of coordination which starts with the municipality. They now

Master thesis

Assessing circularity in the end of life phase of public assets and identifying essential requirements for performance measurement

Koen Verbruggen

18-09-2019

TUDelft SWECO

have a leading role on the field of data management where they are in the right position to gather data when assets are created to provide this data to maintenance and end of life contractors further on. It is mentioned by downstream parties and asset managers that 'you get what you ask for'. The solutions for missing data are therefore found in the surveying of data e.g. including the request for specific ecological and economic data in contracts and bringing together data from different parties by requesting and storing this data.

Outflow and value of assets
Practitioners of all three categories were unable to quantify the outflow of assets as well as the value of these streams. Identifying the size of flows is the basis for determining further monetary and material loss. The barrier for this appeared to be a lack of coordination. In case of internal flows (this goes for greenspace) the information is known at another internal department but is not documented. Expert silo's play a role for asphalt and public lighting, contractors are expected to have this data in house, however are not requested to share this. A solution would be to estimate the number with other correlations. Rotterdam asset managers mention that roughly 'input = output' in case of asphalt roads and light fixtures within the municipality. Requesting the information from contractors in the future would be a more resilient solution.
It is mentioned by asset managers as well that the current version of the asset management software is unable to keep a history of assets that are deleted or replaced. This research has brought up this issue which will be taken up with the software developers.

Gaps in the ecological parameters
Other gaps concentrated in the ecological section of the framework. Public lighting appears to have the lowest level of data availability of three assessed asset categories. Missing data (8/10) due to a lack of coordination (8/10) are the central identified gap and barrier. Practitioners explain this from the nature of the public lightning category; public lighting consists of different parts (pole, fixture, foundation) that each have a different supplier, different composition and different end of life scenario (in contrast to greenspace). Also, there is no national standard for handling these hybrids of materials (in contrast to asphalt). Municipalities could bring in more data by surveying the different stakeholders within the process.

Looking at the asphalt sector, great strides have been made towards higher horizontal reuse (up to 80 or even 90% now) and lower footprints. Contractors point towards the closed process with limited stakeholders involved which offers conditions where measurement of environmental impact is feasible. Part of the data gap here exists because data is not communicated back to the municipality. Practitioners explain the competing industry whose business models reside in the optimization of mixtures within the national standard and technical ability. Expert silos therefore explain part (2/8) of the gaps.
Bringing together data across organizations could solve the data gaps especially in the ecological section of the framework. The reports that can be made for each municipality with the proposed framework will help create awareness which is a first step towards correct and complete data management.

Lastly, asset management in greenspace is performed by the internal greenspace company. Therefore, awareness of the processes and their impact is highest in this category. However, the economic approach where the material has a monetary value has not been internalized in this department. To do so, documenting the value of dead material would fill the gap. To do so, (academic) research is necessary to determine the value of 'waste'.

5 Discussion

This study has offered actionable knowledge of performance measurement in the Dutch municipal end of life practice. This section will discuss the implications of the resulting insights to the body of empirical knowledge about end of life coordination and to the theoretical knowledge regarding performance measurement. Paragraph 5.1 first discusses the validity of the framework.

5.1 The validity and applicability of the developed framework

The framework was created to be applied specifically to the end of life phase of municipal public asset management with the objective to create actionable knowledge within the municipality. In the 'define and discover' and the 'develop and deliver' stages together, 19 interviews have been held. This includes the six interviews that focussed on the application of the framework to three different categories.

"The measurement may be the "process of quantification", but its affect is to stimulate action. It is only through consistency of action that strategies are realized"
(Neely et al., 2005, p. 1231).

Generally, interviewees were enthusiastic about the applicability of the framework for the goal of giving insight and affect the current process and gaps. The application of this framework will stimulate action. The tool is generally applicable for the purpose it was designed for, which is endorsed by the asset management department at Sweco which has 140+ municipalities as a customer to their asset management software and who will continue to develop and implement this approach.

The second part of the results are the specific conclusions that have been drawn up for the study area. These are based on two interviews per asset-category, therefore strictly limiting the results to the specific department, time and place. The conclusions from a single study may have limited generalizability. This analysis needs to be applied to either more categories within Rotterdam to generalise over categories or more municipalities to generalise over locations

The endorsement by Sweco and the municipality of Rotterdam are proof of the external validity of the research.

5.2 Implementation of performance measurement

The learning made from this research project can be categorized into a practical and scientific contribution:

For practice: a framework for performance measurement has been set up consisting of category characteristics, economic- and ecological parameters. These indicators provide a holistic image of the current end of life asset management practice based on the current level of knowledge.
Data availability has been identified as a major issue in performance measurement frameworks that were discussed before. Therefore, the developed framework aims to assist in identifying these data gaps, their cause and proposal of a solution.
It should be emphasized that the topic has been barely touched in literature up to now, therefore the relevance of this thesis and the framework that has followed has high value. Application of the framework in other municipalities will bring the broader definition of the circular economy as described by P. Luscuere (2018a) to the table and give input to performance measurement systems of the future.

Application to practice for asphalt roads, public lighting and greenspace has confirmed the usefulness of this framework in practice. Applying this analysis periodically could show potential growth in performance and data availability.

From the analysis, recommendations to practice can be given in three categories:
Material flow

1. Keeping track of materials throughout their use phases
2. Keeping track of the outflow of materials and their history instead of removing them from the database

Data management

3. Including the circular end of life indicators as obligatory fields in the asset management software, therefore setting the standard.
4. Performing this assessment with municipalities and contractors to see in which materials/assets hidden value resides
5. When data regarding a topic is not (yet) available, go for a qualitative approach and use the best possible data

Goals and circular economy policy

6. Include the end of life phase of assets in the project life cycle
7. Put the responsibility for the end of life phase at the right party
   Include clear KPI's in public policy such that different levels know what to expect

For research: A framework for the analysis of circularity in the end of life phase of public assets has been developed and confirmed that rethinking the responsibility for materials at the end of their life cycle can stimulate circular behavior. It furthermore complies to the broad definition of circularity that was used in this research and the basic requirements: 1) validity and reliability, 2) functionality and 3) legitimacy
This research has advanced the previous research that identified barriers for implementation of performance measurement in circular public asset management and takes this to practice.

The focus of this research was directed towards an unexposed area in literature. Namely the performance measurement of the circular economy by local governments and helping them define and understand the broader definition of the circular economy.

6 Conclusion and recommendations

In this research, the performance measurement of the circular end of life scenarios within municipal practice has been analyzed. The conclusions to the research questions lead to the conclusion to the main question and are presented in this chapter. Furthermore, several limitations need to be considered; these limitations have led to recommendations for practice and future research.

6.1 Conclusion

The objective of this research has been to develop actionable knowledge on performance measurement of the ecological and economic impact of the end of life phase in regional public asset management by developing a framework and identifying the technical and organizational barriers for implementation of these circularity parameters. An area in which little research has been performed as literature research shows. The timeliness and practical relevance of this topic have proven to be right and the report has resulted in a first step towards performance measurement in public end of life asset management by creating insight based on available data.

The research was based on a broad definition of circularity that does not include only the use of virgin material but also the other flows: air, water, biological- and technical materials associated with a recirculation process. The ultimate goal is a positive footprint for each flow.
To close the gap between theory (performance measurement in end of life public asset management) and practice (the data gaps and inclusion of the end of life phase) a framework was set up, based on a review of existing methods for performance measurement for entire economies, manufacturing processes and buildings. A list of eight important economic and ecological parameters and five category characteristics was defined that together form a holistic, applicable, replicable and influenceable view on the circularity of the current end of life phase.

The framework has been shaped in the form of a questionnaire designed to be applied to one asset category at a time. Considering the discovery of minimal data availability within the municipal practice, it is allowed to answer in qualitative terms when exact numbers are not available. The qualitative approach supports the goal of giving insight into the current practice based on the available information.

Another distinguishing feature of the developed framework is the second half of the framework in which the data gap and barriers for implementation are identified. The gap can either entail: missing data, incomplete data (quantity) or inadequate data (quality). Typical barriers that are the cause for this are a lack of coordination, lack of means, expert silos and protected data.
Interviewees at the municipality, contractor and engineering consultancy firm have identified these as valuable for creating actionable knowledge and improving performance measurement in the future at all municipalities.

The framework will be taken to practice to be applied in evaluation sessions and start-up meetings in municipal practice supervised by asset management consultants. The results of application will help to create awareness of the current behaviour and the current internal state of knowledge. Also, it will improve performance measurement and circular end of life scenarios in general.

From a limited application to practice it was found that the inclusion of the end of life phase in municipal practice is relatively new. Therefore, the data management process is lacking. Material passports which are currently being set up in public organisations should include also the impact of end of life processes on natural resources. Great differences have been found between categories but all three lack insight into the size and value of outflows.

6.2 Limitations of this research

The research has answered the questions posed in chapter 2, but the limitations should be considered. Based on the limitations, recommendations will be given for future application in practice as well as future research into this topic.

The developed framework has a clear focus on the end of life of assets, whereas research advises the use of a life cycle approach for assessing circularity levels. The framework does therefore not give a holistic overview of circularity within the municipality, it has however proven its effect for giving insight in a particular life cycle phase.

Furthermore, the tool considers economic- and ecological impact whereas a more holistic approach would also include social aspects to complete the people, planet, profit triangle. However, the social aspect is not embodied in the applied definition of a circular economy in this research. Further research could include this aspect.

Finally, the external validity of the framework has been addressed and endorsed by both Sweco and the municipality of Rotterdam. This framework is a useful tool to create awareness and gain insight into the current circularity of the end of life process as well as the state of data availability.
However, the internal validity is limited due to the small number of respondents in the Rotterdam asset management. For each of the three asset categories, only one respondent at Sweco and one respondent at the case municipality has been interviewed. To generalise over categories or even over municipalities, a more extensive case study is required.

6.3 Recommendations

Based on the conclusions and limitations of the study, recommendations for further research are presented here.

An in-depth analysis would greatly improve the internal validity of the study since only one, limited, case study has been performed. Incorporating market parties that are involved in all phases of the life cycle can bring more insight. Addressing multiple municipalities would provide the researcher with a generalizable overview of the state of circularity in end of life processes.

Literature and practice identified the use for applying value to end of life material. Further research could identify methods for doing so in public asset management, which can lead to the identification of quick wins or new business models. This thesis has brought the subject to the table and will bring value loss as a point of view to the table in future applications by Sweco.

“LCA is open to an extension to a full sustainability assessment that includes social LCA. Social LCA covers aspects such as job creation, equal pay and more” (European Commission, 2012, p. 20). Including social parameters in this framework would be a next step in creating insight into the circular end of life processes.

7 Literature list

Achterberg, E., Hinfelaar, J., & Bocken, N. M. P. (2016). Master Circular Business with the Value Hill. *Circle Economy*, 18.

Arthur, D., Hodkiewicz, M., Schoenmaker, R., & Muruvan, S. (2014). Asset Planning Performance Measurement Framework. *CEED Seminar Proceedings*, (SEPTEMBER), 73–78. https://doi.org/10.13140/2.1.3158.9128

Azhar, S. (2007). Improving collaboration between researchers and practitioners in construction research projects using action research technique. *Associated Schools of Construction, International …*, (August). Retrieved from http://ascpro0.ascweb.org/archives/2007/CERT81002007.pdf

BAMB. (2017). *Framework for material passports*. Retrieved from https://www.bamb2020.eu/wp-content/uploads/2018/01/Framework-for-Materials-Passports-for-the-webb.pdf

Berg, M. van den. (2019). *Managing Circular Building Projects* (University of Twente). https://doi.org/10.3990/1.9789036547703

CROW. (2013). *Kwaliteitscatalogus openbare ruimte 2013*. 188.

Davis, R. (2013). *An introduction to asset management*. Retrieved from www.eatechnology.com

Design Council. (2015). The Design Process: What is the Double Diamond? Retrieved February 26, 2019, from https://www.designcouncil.org.uk/news-opinion/design-process-what-double-diamond

Durmisevic, E. (2019). *D8 Reversible Building Design Reuse Potential Tool*.

Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, *142*, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196

EPA US. (2014). *Air Quality Index - A Guide to Air Quality and Your Health*. Retrieved from https://www3.epa.gov/airnow/aqi_brochure_02_14.pdf

European Commission. (2012). *The International Reference Life Cycle Data System (ILCD) Handbook: Towards More Sustainable Production and Consumption for a Resource-efficient Europe*. https://doi.org/10.2788/85727

European Environment Agency. (2016). *Circular Economy in Europe: Developing the Knowledge Base*. https://doi.org/10.2800/51444

Geldermans, B., Luscuere, P., Jansen, S., & Tenpierik, M. (2016). Beyond Cities: Materialen, producten & circulair bouwen. *TVVL Magazine, 45(1)*, 22–25. Retrieved from https://pure.tudelft.nl/portal/files/4872680/Geldermans_et_al_2016_Beyond_cities_materialen_producten_en_circulair_bouwen.pdf

Geldermans, Bob, Wandl, A., & Dobbelsteen, A. Van Den. (2014). Mapping and managing essential resource flows in airport regions – the case of Amsterdam Airport Schiphol. *AESOP 2014 Proceedings, 9-12 July 2014, Utrecht, Delft, The Netherlands*, 1–18.

Gemeente Amsterdam, TNO, Circle Economy, & Fabric. (2015). *Amsterdam circulair, een visie en routekaart voor de stad en regio*.

Gemeente Rotterdam. (2017). *Rotterdam gaat voor circulair*. Retrieved from www.rotterdamcirculair.nl

Green, D., Masschelein, S., Hodkiewicz, M., Schoenmaker, R., & Muruvan, S. (2016). Setting Targets In An Asset Management Performance Measurement Framework. *QR2MSE2016 & WCEMA2016*, (July), 1–7.

Hastings, N. A. J. (2015). *Physical Asset Management* (2nd ed.). https://doi.org/10.1007/978-3-319-14777-2

Hermans, M. (2014). *'Mag het iets meer zijn?'* (november).

Hoekstra, R., Delahaye, R., van den Tillaart, J., & Dingena, G. (2015). *Expanding the*

Material Flow Monitor. https://doi.org/10.1093/beheco/arv092
Iacovidou, E., & Purnell, P. (2017). Sustainability in the Built Environment: a Typology System for Supporting Construction Components Reuse. *5th International Conference on Sustainable Solid Waste Management*, (June), 1–3.
Kok, A. (2018). *Gemeente interviews uitgewerkt*.
Lansink, A. (2014). Ladder van Lansink. Retrieved February 21, 2019, from http://www.adlansink.nl/voorbeeld-pagina/
Leduc, W., & Van Kann, F. (2013). Spatial planning based on urban energy harvesting toward productive urban regions. *Journal of Cleaner Production*, *39*, 180–190. https://doi.org/10.1016/j.jclepro.2012.09.014
Lotteau, M., Loubet, P., Pousse, M., Dufrasnes, E., & Sonnemann, G. (2015). Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. *Building and Environment*, *93*(P2), 165–178. https://doi.org/10.1016/j.buildenv.2015.06.029
Luscuere, L. M. (2017). Materials Passports : Optimising value recovery from materials. *Waste and Resource Management*, *170*(WR1), 25–28. https://doi.org/http://dx.doi.org/10.1680/jwarm.16.00016 Paper
Luscuere, P. (2018a). *Circulariteit: Op weg naar 2050?* Retrieved from https://pure.tudelft.nl/portal/files/45763872/9789463660549_WEB.pdf
Luscuere, P. (2018b). Nederland circulair in 2050 - Wat betekent dat en kan het überhaupt? In *Circulariteit - Op weg naar 2050?* (pp. 15–27). Retrieved from https://pure.tudelft.nl/portal/files/45764429/Chapter_9789463660549_WEB.pdf
Luscuere, P., Geldermans, B., Tenpierik, M., & Jansen, S. (2016a). Beyond sustainability in the built environment. *RuMoer: Periodical for the Building Technologist*, (62). Retrieved from http://pure.tudelft.nl/ws/files/6323434/Luscuere_et_al_2016_Beyond_sustainability.pdf
Luscuere, P., Geldermans, R., Tenpierik, M., & Jansen, S. (2016b). *Beyond Sustainability v2*.
Metabolic. (2019a). *Circulaire indicatoren: een verkenning voor de provincie Zuid Holland*. Retrieved from https://www.metabolic.nl/publications/circulaire-indicatoren-een-verkenning-voor-de-provincie-zuid-holland/
Metabolic. (2019b). *Monitoring voor een circulaire metropoolregio*. Retrieved from https://www.metabolic.nl/publications/monitoring-voor-een-circulaire-metropoolregio/
Ministerie van Infrastructuur en Milieu. (2016). *Rijksbrede programma Circulaire Economie*. 1–14. https://doi.org/10.1007/s00244-010-9510-9.-
Neely, A., Gregory, M., & Platts, K. (2005). Performance measurement system design: A literature review and research agenda. *International Journal of Operations and Production Management*, Vol. 25, pp. 1228–1263. https://doi.org/10.1108/01443570510633639
Pauliuk, S. (2018). Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resources, Conservation and Recycling*, *129*, 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019
Peters, G. P. (2010). Carbon footprints and embodied carbon at multiple scales. *Current Opinion in Environmental Sustainability*, *2*(4), 245–250. https://doi.org/10.1016/j.cosust.2010.05.004
PIANOo. (n.d.). Handreiking Dubocalc. Retrieved February 22, 2019, from https://www.pianoo.nl/nl/handreiking-dubocalc
PIANOo. (2018). *Onderzoek over de transitie naar de circulaire Inhoudsopgave*. Retrieved from https://www.pianoo.nl/sites/default/files/media/documents/Onderzoek-over-de-transitie-naar-de circulaire utiliteits-grond-weg-en-waterbouw-mei2018.pdf
Potting, J., Hanemaaijer, A., Delahaye, R., Hoekstra, R., Ganzevles, J., & Lijzen, J. (2018).

Circulaire economie: Wat we willen weten en kunnen meten. Systeem en nulmeting voor monitoring van de voortgang van de circulaire economie in Nederland, Den Haag: PBL, CBS, RIVM. https://doi.org/10.1128/IAI.69.1.245-251.2001

Provincie Zuid Holland. (2019). *Def. Uitvraag Ingenieursdiensten Materialen Footprint Provinciale Infrastructuur*.

Rijksoverheid. (2017). *Nederland Circulair in 2050, Rijksbreed programma Circulaire Economie*. 1–72.

Royal Haskoning. (2017). *Verkenning Circulaire Economie Provincie Zuid-Holland*.

Schroeder, P., Anggraeni, K., & Weber, U. (2019). The Relevance of Circular Economy Practices to the Sustainable Development Goals. *Journal of Industrial Ecology*, *23*(1), 77–95. https://doi.org/10.1111/jiec.12732

Sweco. (2018). Product - Obsurv. Retrieved August 11, 2019, from https://obsurv.nl/product/

Taelman, S. E., Tonini, D., Wandl, A., & Dewulf, J. (2018). A Holistic sustainability framework for waste management in European Cities: Concept development. *Sustainability (Switzerland)*, *10*(7). https://doi.org/10.3390/su10072184

The Ellen MacArthur Foundation. (2015a). *Circularity indicators An Approach to Measuring Circularity*. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity-Indicators_Project-Overview_May2015.pdf

The Ellen MacArthur Foundation. (2015b). Delivering the circular economy; a toolkit for policymakers. *Delivering the Circular Economy: A Toolkit for Policymakers*.

The Ellen MacArthur Foundation. (2015c). *Towards a circular economy - economic and business rationale for an accelerated tranistion*. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

The Ellen MacArthur Foundation. (2015d). What is a Circular Economy? | Ellen MacArthur Foundation. Retrieved August 30, 2019, from https://www.ellenmacarthurfoundation.org/circular-economy/concept

UNEP IRP. (2016). *Global Material Flows and Resource Productivity: Executive Summary for Policy Makers Material Flow Accounts of Philippines View project Country-and global-scale drivers and forecasts of material stock & flow processes View project*. Retrieved from https://www.researchgate.net/publication/305597954

van der Leer, J., van Timmeren, A., & Wandl, A. (2018). Social-Ecological-Technical systems in urban planning for a circular economy: an opportunity for horizontal integration. *Architectural Science Review*, *61*(5), 298–304. https://doi.org/10.1080/00038628.2018.1505598

Verhagen, T. (2016). *Onderzoeksproject voor de grondstoffenmarktplaats*. Retrieved from https://www.cirkelstad.nl/wp2/wp-content/uploads/2018/01/onderzoek-hub-amsterdam.pdf

Verschuren, P., & Doorewaard, H. (2010). Designing a research project. In *Journal of Experimental Psychology: General*.

Vodovar, S. (2018). *Instrumentenanalyse voor circulair bouwen*. Amsterdam.

Wang, F., & Hannafin, M. J. (2005). Design-based research and technology-enhanced learning environments. *Educational Technology Research and Development*, *53*(4), 5–23. https://doi.org/10.1007/BF02504682

Yin, R. K. (2003). *Case study Research - Design and methods* (Vol. 5).

Appendix A Visual ambition level CROW

Figure 17 Visual ambition levels public lightning (CROW, 2013)

Ambitiethema open verharding

A⁺	A	B	C	D
Er is geen schade volgens CROW-systematiek voor wegbeheer.	Er is enige schade volgens CROW-systematiek voor wegbeheer.	De waarschuwingsgrens van CROW-systematiek voor wegbeheer is overschreden.	De richtlijn van CROW-systematiek voor wegbeheer is overschreden.	De richtlijn van CROW-systematiek voor wegbeheer is meer dan één klasse overschreden. Er is sprake van onderhoudsachterstand.
Er zijn geen zichtbare oneffenheden, dwarsonvlakheden (spoorvorming), openstaande voegen, hoogteverschillen of beschadigingen door wortelopdruk aanwezig.	Er zijn lichte oneffenheden, dwarsonvlakheden (spoorvorming), openstaande voegen, hoogteverschillen of beschadigingen door wortelopdruk aanwezig.	Er zijn enige oneffenheden, dwarsonvlakheden (spoorvorming), openstaande voegen, hoogteverschillen en beschadigingen door wortelopdruk aanwezig.	Er zijn aanzienlijke oneffenheden, dwarsonvlakheden (spoorvorming), openstaande voegen, hoogteverschillen en beschadigingen door wortelopdruk aanwezig.	Er zijn zware oneffenheden, dwarsonvlakheden (spoorvorming), openstaande voegen, hoogteverschillen en beschadigingen door wortelopdruk aanwezig.

Figure 18 Visual ambition levels open pavements *(CROW, 2013)*

Appendix B Inventory details for specific assets

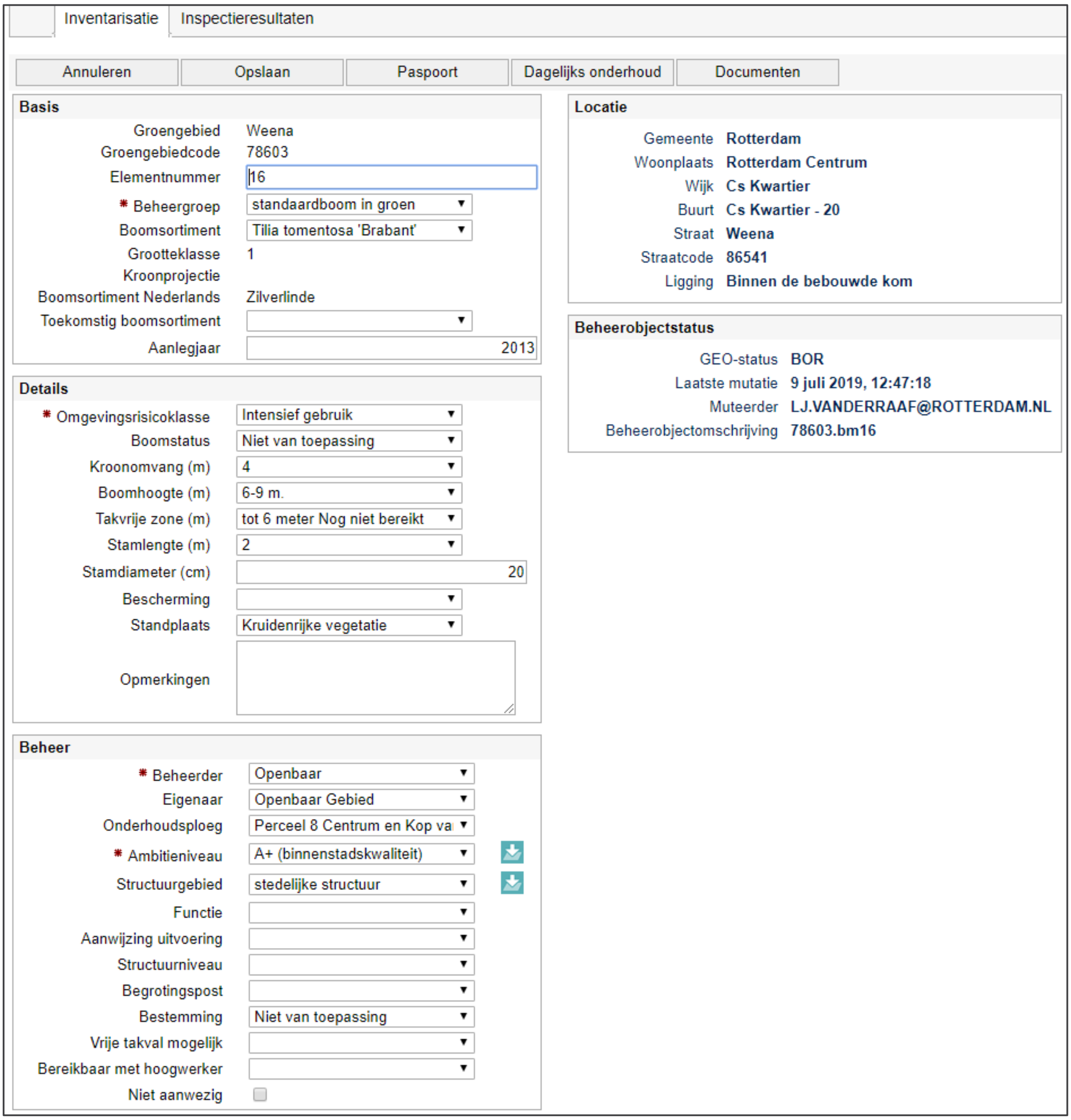


Figure 19 Inventory details for a typical tree

Lichtpuntonderdelen

- Lichtpunt 004 (Straatverlichting)
  - Mast (MAST 6M LPH 6M AL CON PT D76 FABR.NEDAL ART.K060PT | 01-01-2000)
    - Uithouder (REDUCEERSTUK D76/60MM INDAL ART.784890.000 | 01-01-2000)
      - Armatuur (270 FGS 104 HF 1X PLL 36W EVSA D60 | 01-01-2000)
        - Schakelsysteem (VSA 1W | 01-01-2000)
          - Lichtbron (PLL 36W KL.830 XTRA POLAR | 01-10-2013)

Lichtpunt

Algemeen

* Gemeente	Rotterdam
* Woonplaats	Delfshaven
Wijk	Nieuwe Westen
Buurt	Nieuwe Westen - 02
* Straat	Veelzigtstraat
Postcode	
* Lichtpuntnummer	004
* Lichtpunttype	Straatverlichting
Status	
Indicatie Schilderen	Ja / Nee
Geplande schilderdatum	01-01-2016
* X-coördinaat	90608,338
* Y-coördinaat	437337,295
* Ambitieniveau	B (basis)
Structuurgebied	woonomgeving
Betreft aansluiting netbeheerder	
Verlichtingsklasse	
Bereikbaarheid	
Remplacegebied	
Positie	
Geo-status	BGT
Tekeningnummer	
Opmerkingen	

Beheer

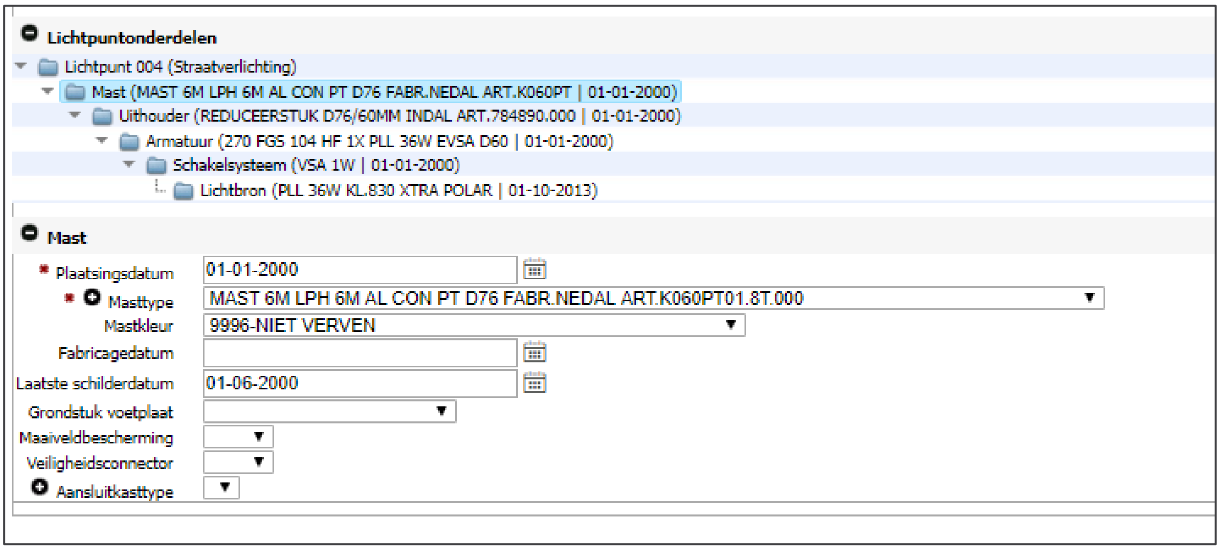
Beheerder	Openbaar
Eigenaar	Openbaar Gebied
Energieleverancier	
Netbeheerder	
Bestemming	Niet van toepassing

Extra informatie

Toebehoren	
Extra Label 2	
BSB ID	OVL-97855

Verdeelkast

Verdeelkast	
Groep	
Fase	



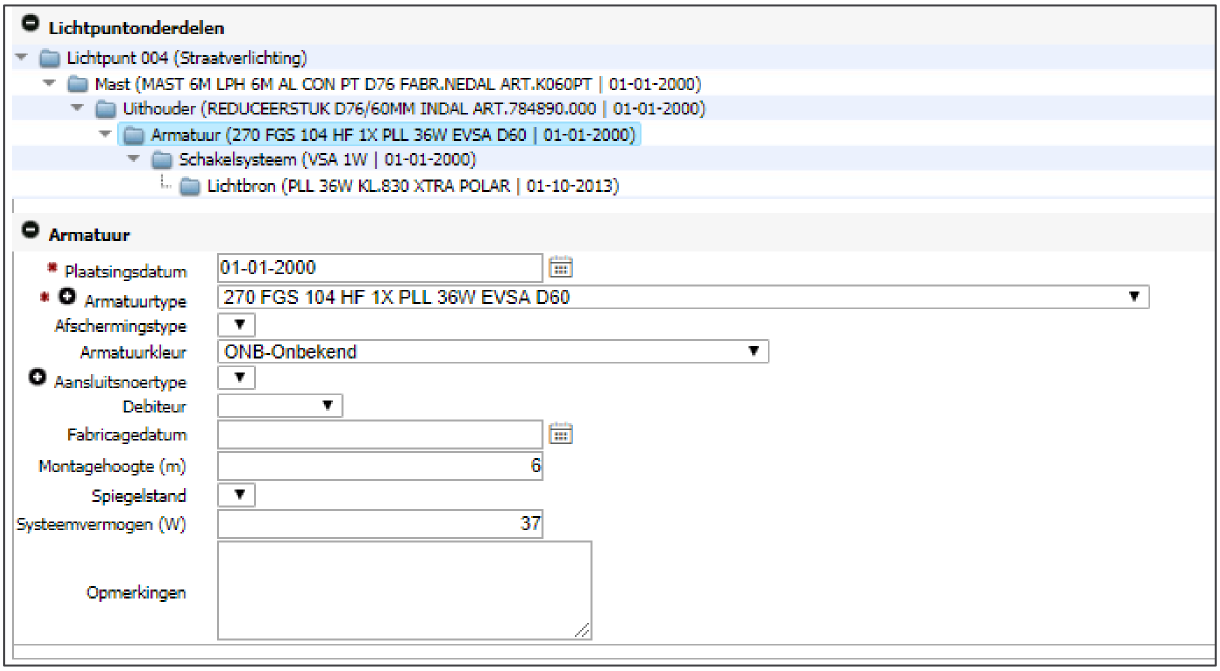


Figure 20 Inventory details for a typical light pole and its parts

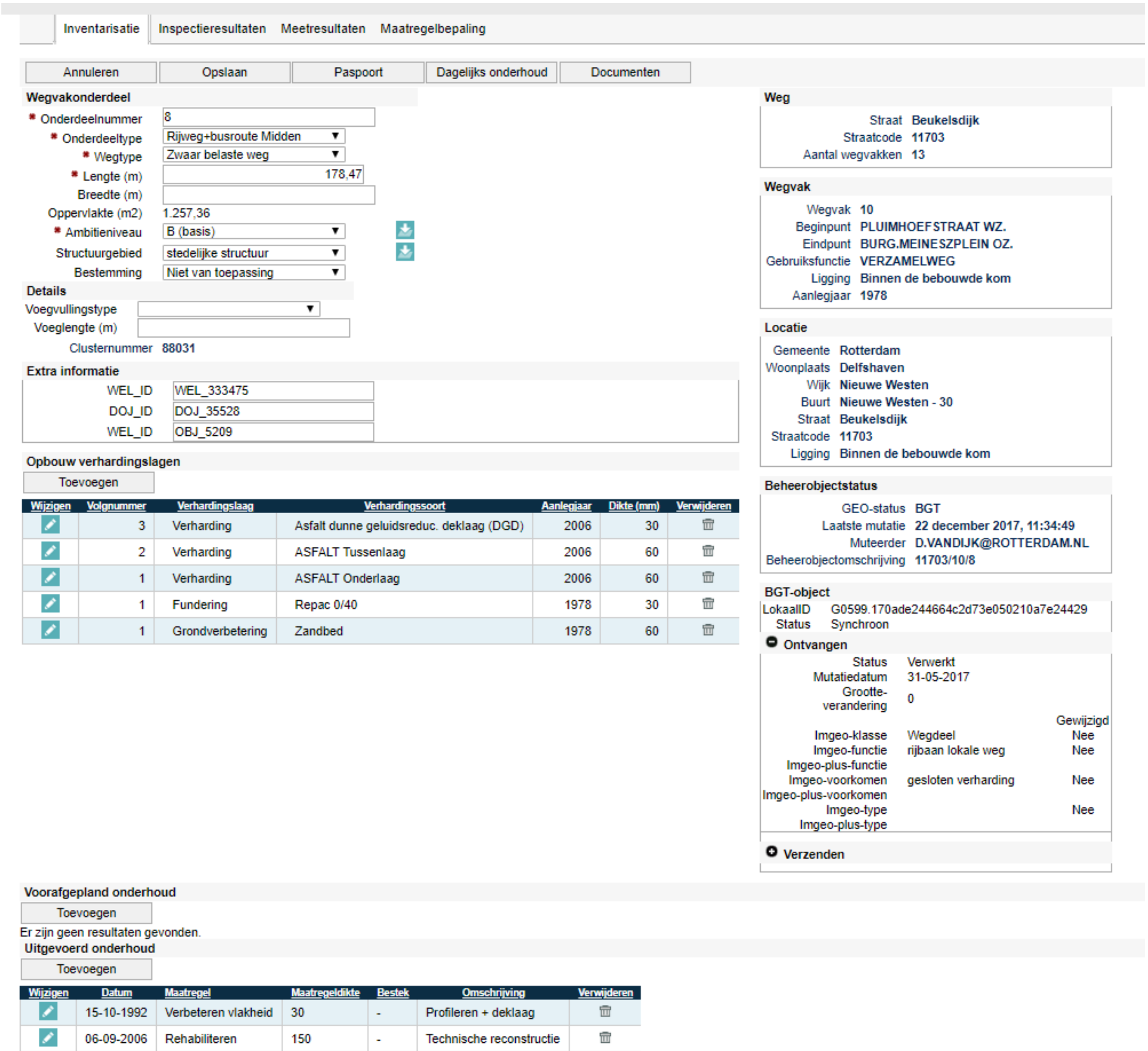
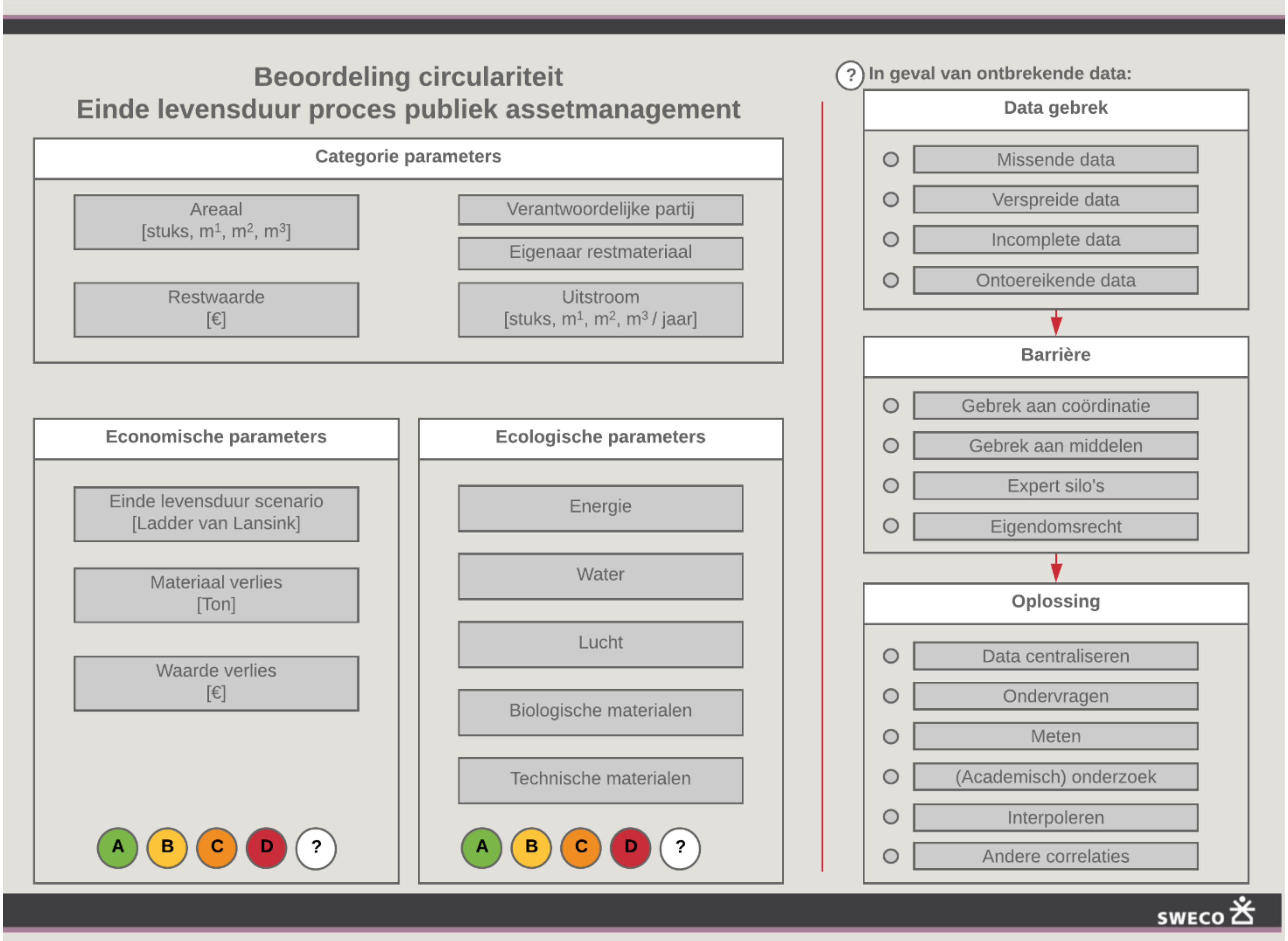


Figure 21 Inventory details for a typical asphalt road

Appendix C The proposed framework (Dutch)



TUDelft SWECO