Residual Value Determination in the Context of Product-Service Systems Applied to Infrastructure Projects

Master Thesis

by

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Executive summary

This past century the demand for raw materials has risen sharply. This demand is expected to rise even further, which is not sustainable. Changing the linear model of consumption to a circular model can help to decrease levels of raw material demand. The application of service-oriented business models, called Product-Service System (PSS) can contribute to this change. For this application to become a reality within the highway infrastructure sector an approach is needed to determine the residual value of the asset beforehand, as it is an important element of PSS. No such approach is currently available in practice or literature within the highway infrastructure sector. Therefore, this research has answered the following research question: **How can the residual value be determined in the context of product-service systems applied to highway infrastructure assets?** This question is answered in collaboration with program 'De Circulaire Weg' (DCW), a set of partners investigating the applicability of PSS to highway infrastructure. This research contributes to this practical research, as well as to the scarce literature regarding PSS applied to highway infrastructure.

The methodology is structured along the Double Diamond model, dividing the research into the problem definition phase and the problem solution phase. The problem is defined using a literature review and expert interviews. The solution is found using three methodologies. First, expert consultations to form the initial design of the residual value determination approach. Then, this design is verified by applying it to a case. Finally, the resulting approach design is validated using expert interviews.

As for the results, the problem definition phase resulted in a basic model that reveals all requirements and additional considerations for the residual value determination approach. The problem solution, the resulting approach design, constitutes of three components, of which the last is optional because of difficulty regarding its financeability. The components and their approach for determination, as determined using practical insights primarily, are as follows:

- *Physical value*$_{Used,t}$ = *Market value*$_{New,t}$ – *Reuse reduction*$_{Used,t}$
- *Functional value*$_{Used,t}$ = *Prevented construction costs*$_{New,t}$ – *Renovating costs*$_{Used,t}$
- *Environmental value*$_{Used}$ = *Environmental costs*$_{Reference}$ – *Environmental costs*$_{Used}$

The difference in prices over time is determined using the Geometric Brownian Motion (GBM) method. The three components are combined a valuation approach in two scenarios. In the first scenario the currently used asset is still deemed functional and thus its physical value is not available as that is still used in the asset. In the second the currently used asset is deemed obsolete and thus the functional value is not applicable anymore. However, its materials can be sold on secondary markets. The environmental value of the asset is applicable to both scenarios. As the combined approach includes the components related to the CE, opting for the highest value at any time is in accordance the CE incentives. For these two scenarios the combined value can be determined as follows:

- *Combined residual value*$_{Functional}$ = *Functional value* + *Environmental value*
- *Combined residual value*$_{Obsolete}$ = *Physical value* + *Environmental value*

Concluding, this research shows that residual value depends significantly on the context and can be higher than the disposal value alone. It has found that not all aspects of the CE are elligible for incentives within the residual value. In line with the former it is found that to contribute to a CE, the CE principles should be regarded as goals and should not be implemented directly. The combined residual value determination approach as shown above creates a significant incentive (>10% of the initial construction value) to adhere to the CE principles. Specifically for practice, the research shows that practical solutions for determining the residual value are available, thereby bringing PSS applied to infrastructure one step closer to reality. However, for application to become a reality it is recommended that the significant assumptions in the research are investigated further and recent academic insights are incorporated. Additional recommendations include application of the resulting approach to more cases, further investigating alternatives to the GBM method for price evolution estimation, investigating the effect of partial renovations, implementing the approach in the PSS financial model and exploring and accounting for the exact conditions for financeability of the approach.

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List of Abbreviations

CBA	Cost-Benefit Analysis
CE	Circular Economy
DCW	De Circulaire Weg
DB	Design & Build (integrated PDM and contract type)
DBB	Design, Bid, Build (traditional PDM)
DBFM	Design, Build, Finance, Maintain (integrated contract type)
DT	Design Thinking
GBM	Geometric Brownian Motion
IPS2	Industrial Product-Service System (equal to PSS)
LCC	Life Cycle Costing
MCA	Monte Carlo Analysis
MKI	Milieu Kosten Indicator
NWB	Nederlandse Waterschaps Bank
NPV	Net Present Value
PC	Personal Communication
PDM	Project Delivery Model
PPI	Producer Price Indices
PSS	Product-Service System (equal to IPS2)
SE	Standard Error
WDRC	Written Down Replacement Costs

1 Introduction

This chapter addresses the essential aspects of the way the research has been set up. This is done by first analysing the context and the problem itself in Section 1.1, followed by the problem statement in Section 1.2 and the research objective in Section 1.3. The research questions are addressed in Section 1.4, after which the scope is discussed in Section 1.5. Then, the expected results are discussed in Section 1.6, followed by the research's relevance in Section 1.7 and finally the research design and thesis outline in Section 1.8.

1.1. Context and problem analysis

The demand for raw materials has risen sharply in the past century. Expectations are that this demand will rise even further (Remmerswaal et al., 2017), which is not sustainable (Van Leeuwen et al., 2018). This growing demand is characterised by a linear socioeconomic system of material use, which discards products at the end of their product life (Adrodegari et al., 2016; Castelein, 2018; Davidson & Wit, 2003; Mentink, 2014; Michelini et al., 2017). Changing this linear model to a circular model, which "aims to keep products, components and materials at their highest utility and value" (Ellen MacArthur Foundation, 2006), can help to reach more sustainable levels of raw material demand.

The Dutch government has adopted this idea and sees the Circular Economy (CE) concept as an integral part of the answer to rising demand for raw materials (Remmerswaal et al., 2017). To this end, the government has created the statewide program 'Circular Economy', aiming to "use scarce resources more effectively, smarter and more profitable" and to have a fully CE in 2050. Since the construction sector is responsible for a significant portion of demand for raw materials in the Dutch economy, achieving this goal requires changes in and by the sector. To this end, the Dutch Ministry of Infrastructure and Water Management (Rijkswaterstaat) has set its own aim of working fully circular by 2030.

A trend that has shown to assist in the transition towards a CE is the application of service-oriented business models, called Product-Service System (PSS). The PSS is defined as "an innovation strategy, shifting the business focus from designing (and selling) physical products only, to designing (and selling) a system of products and services which are jointly capable of fulfilling specific client demands" (Manzini & Vezzoli, 2003, p. 851). Research into the concept has shown that the application of PSS can potentially help to reduce pollution and resource consumption (Pessôa & Becker, 2017) since it allows the provider to offer a result closer to the final client need, using more degrees of freedom to design a low impact system (Tukker, 2004). More recent research has shown that with several changes to industry standards the PSS concept and its beneficial effects are also applicable to the infrastructure construction sector (Huizing, 2019). Investigating PSS applicability in the construction sector in further detail reveals that a multitude of aspects are still to be considered and tackled to fully realise its potential. One of these aspects is the residual value that should be incorporated in the business model. The residual value should be interpreted as the value of the asset at the end of the period contractually agreed upon. Research has shown that the implementation of residual value is important for achieving the CE benefits of PSS implementation (Huizing, 2019; Pitt et al., 2009). This follows from the fact that the residual value incorporation into the PSS business model makes it in the interest of the contractor to make the product last as long as possible and to allow reuse of its parts rather than scrapping them. In a broader sense, it aligns interests of contractor and client by de-coupling the contractual and technical lifespan (Remmerswaal et al., 2017). This knowledge gap should be resolved as to free up investments (Ganzevles et al., 2016) and for PSS implementation in the construction sector to be possible whilst realising the intended benefits.

Current theoretical research into the application of the residual value in the context of PSS has not yet focused on the construction industry. This is also the case for research into the residual value application in the construction industry, outside of the PSS context. This is most probably the case since this value is currently not taken into account for most assets, since these are mostly depreciated to zero (Banister & Berechman, 2003). Research into the residual value outside of the construction industry has shown to be context-specific. Thus, research on the application of the residual value applied in a PSS in the construction sector is lacking and bundling existing research does not deliver adequate results. These findings are further substantiated in the literature study in Chapter 2.

As for current practical research into the application of the residual value in the context of PSS, this is done in the partner program De Circulaire Weg (DCW). This is a collaboration between several public (three municipalities and three provinces) and private partners (a contractor, an engineering firm and two banks) as well as the Delft University of Technology. These partners represent the three main stakeholders: governmental institutions, contractors and banks. The program aims to contribute to the CE by researching the practical applicability of highway infrastructure as a service, which is equivalent to PSS applied to (highway) infrastructure projects. During the research, the partners have encountered lack of research on the residual value in this context and has started investigating the subject. This has not yet led to satisfying answers.

1.2. Problem statement

Summarising the previous section, PSS business models can help to solve problems regarding the constantly increasing demand for raw material, as well as help to solve the environmental problems surrounding this demand. This process occurs by converting the traditional linear product models to more circular models, thereby contributing to a more circular economy. Applicability of the PSS business model in the construction sector is currently being researched in theory as well as in practice. An important element in the application of this PSS on infrastructure construction is the determination of the residual value in the context of these PSSs. Neither theoretical nor practical research on this subject does as of yet stipulate how this determination should be done in the context of PSSs applied to infrastructure projects. This knowledge gap is reflected in the following problem statement:

To be able to apply the product-service system business approach and thereby the circular economy principles to the highway infrastructure sector, a suitable approach for determining the residual value in this context has to be used. Information on which approach this is is currently not available.

In this problem statement and the subsequent sections, suitable is defined as being applicable and preferred by the users or for the use-case, based on conditions that are yet to be researched and defined. Additionally, the residual value determination approach needs to be applicable for both the determination of the value at a certain point in time during the lifespan of the asset, as well as for estimating the value beforehand.

1.3. Research objective

Using the problem statement the research objective can be derived. Since this research is both theory- and practice-oriented, a research objective fitting both orientations is to be found. Additionally, it should be useful, realistic, feasible within the time scheduled, clear and informative (Verschuren & Doorewaard, 2010). This results in the following research objective:

To contribute towards the development of a product-service system business approach applicable to highway infrastructure, by designing an approach for determining the residual value that is suitable for this context.

1.4. Research questions

Following the analysis leading up to the problem statement and the research objective, the research should have a developmental or design focus. This means it should focus on creating a fitting solution to the problem as described in the problem statement. Because of this focus the main research question should be a "how can" type of question (Binnekamp, 2020)). Taking this into account and focusing on the research gap and objective that are to be addressed, the following research question is drafted:

How can the residual value be determined such that it creates an incentive adhering to the CE principles in the context of product-service-systems applied to highway infrastructure assets?

To be able to answer this main research question, the following subquestions are asked. These questions correspond to the chronological steps that have to be taken to answer the main research question. Reasoning for how each of the questions came to be can be found below each question as well as the result expected when answering the question. All questions are devised in such a way that these adhere to the efficient and steering principles (Verschuren & Doorewaard, 2010). This means that they address the actual type of knowledge that is sought (efficient) and that they describe the source of the activities that should be sought for to answer the question (steering). No hypothesis is formed because of the design-oriented nature of the research (Binnekamp, 2020).

Q1: What are current theories and practices in designing an approach for determining the residual value in- and outside of the context of product-service systems applied to highway infrastructure assets?
The first step in answering the main research question should be to obtain an overview of potential requirements, components of value and valuation techniques using literature. This exploratory question aims to attend to this need by presenting in an overview of these requirements and potential components and valuation techniques. Additionally, it will present basic information regarding valuation in general and the PSS context.

Q2: What methodologies can be applied to understand, design and evaluate the potential residual value determination approaches in the context of product-service systems applied to highway infrastructure assets?
Having an overview of the requirements, components and valuation techniques, methodologies for reviewing these should be determined. Additionally methodologies for combining them into a suitable residual value determination approach design should be determined. This methodological question serves to consider the potential methodologies in more detail, taking the variables from Q1 into account. Answering it results in an overview of the methodologies used in this research for obtaining more data, reviewing this data and designing and validating the residual value determination approach.

Q3: How can the potential residual value components and valuation techniques be combined to design a residual value determination approach that suits the context of product-service systems applied to highway infrastructure assets?
Using the information gathered by answering question Q1 combined with the research methodologies elaborated upon in question Q2 this results-oriented question can be answered. Answering this question results in a verified and validated design of an approach that is or suited for determining the residual value in the context of product-service systems applied to infrastructure assets.

Q4: Given the results as found using Q3, what are implications of the results on the application of product-service systems in highway infrastructure assets?
Since this research is context-specific, so are the results of Q3. Therefore, this result should be discussed with respect to this context, as well as what its implications are for further research into the subject or associated subjects. This meaning-driven question aims to do just that. Aspects that are addressed are among others the meaning of the research, as well as its applicability, its shortcomings, its significance and its consequences.

1.5. Scope

The scope is defined as follows:

- Limited to the PSS business model: as mentioned, the research is conducted within the PSS applied to infrastructure sector. The scope of the research is also limited to this context.
- Limited to highway infrastructure sector: within the scope of the previous bullet a specific focus is applied. The research gap and the parties involved in filling this gap are based in the highway infrastructure construction sector. Therefore, the research is scoped around this specific sector.
- Focus on residual value determination as opposed to the entire financing model: since cashflows change when applying PSSs, as discussed in the previous point, the financing model and the residual value determination aspects are quite dependent on each other. This research focuses on the latter, while incorporating the influences of the former.
- Limited to Dutch sector: the research is conducted in collaboration with Dutch partner program De Circulaire Weg. This means that all involved parties, as well as potentially involved projects are Dutch or done in the Netherlands. Subsequently, it is decided to limit the scope of the research to a Dutch perspective or the Dutch sector specifically.

1.6. Expected result

Answering the four subquestion systematically results in an answer to the main question. In short, the expected result of the entire research is as follows: an overview of the requirements for a residual value determination approach in the context of PSS applied to highways infrastructure assets, as well as a verified and validated design in the form of equations fitting these requirements. Additionally, the implications of these results in the aforementioned context are clear. Also, this research undertakes one of the first steps in the application of PSS to this specific context. Therefore, specifically the design process is documented extensively which can be relevant for further studies.

1.7. Relevance

The relevance of this research is discussed according to three types of relevance; social relevance, scientific relevance and project relevance.

Social relevance As stated in Chapter 2, this is a period of severe natural resource depletion (Michelini et al., 2017), fueled by the current linear socio-economic system. Some institutions, such as the European Commission (European Commission, 2014), the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015) and the Netherlands Environmental Assessment Agency (PBL) (Remmerswaal et al., 2017), propose a shift towards a more circular economic model for society to be able to sustain its current consumption. This research aims to help make a step in this direction. It does this by solving one of the problems currently faced when implementing a more circular business model for infrastructure construction and use. Thus, the social relevance of the research lies in the fact that it enables to make a step towards the CE, which is required to maintain society's current consumption. This relevance is supported by the fact that construction currently accounts for half of all material usage in the Netherlands (Van Leeuwen et al., 2018).

Scientific relevance Research on PSSs and their implementation has seen a surge in recent years. As described in Chapter 2, however, this research has mostly focused on the application of PSSs on products with more traditional customer-vendor relations. Research has not yet focused on the application of PSSs on infrastructure. Next to filling this gap, this research also allows for research on extrapolating the results onto other sectors that have not yet been researched in the context of PSS application. Additionally, it allows for research on the applicability of the results onto other contract types within the infrastructure sector.

Project relevance The relevance of the research for DCW is that it helps to achieve the program's goal of gaining experience in the application of PSSs in the infrastructure sector. It does this by proposing an initial approach design for residual value determination, one of the as of yet unsolved problems of PSS application the project is currently experiencing. The findings of this study can lay the groundwork to help find an approach that can be implemented in PSS applied to infrastructure, thereby contributing to make its application a reality.

1.8. Research design and thesis outline

The research design applied to this research closely follows the structure as provided by the research questions. An overview of the research design and thesis outline can be found in Figure 1.1. As a first step in the research, an overview of the current research into the application of PSS and the residual value both in the construction sector and in other sectors are investigated. Following this, requirements for components and valuation techniques that can be applied in residual value determination are identified and potential candidates are established. Chapter 2 aims to provide these aspects based on a literature study by answering the first research question. The second research question is answered in Chapter 3, which aims to determine what methodologies are applied to design and evaluate potential residual value determination approach. Applying this methodology results in findings that are discussed in Chapter 4. These findings contain an overview of the applicable components and valuation techniques, their combination in the design of a residual value determination approach, an evaluation of both of these findings and validation of the results. The fourth research question is answered in Chapter 5. Here, the results and their implications are discussed within the broader context of PSS applied to infrastructure projects. Aspects that are addressed are the interpretation and value of the research, as well as its applicability, its limitations and its implications for the field. Finally, conclusions for each of the research questions are given in Chapter 6, along with the relevance of the research, its limitations and recommendations for further research.

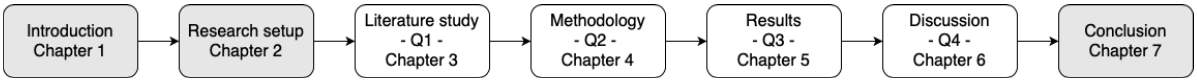

Figure 1.1: Overview thesis outline. The white blocks specifically denote the chapters that deliver answers to the research questions.

2

Literature study

Following the setup of the research, this chapter aims to provide an overview of the literature study with the purpose of answering the first research question. This is done by first addressing the concept of the CE in Section 2.1 to , followed by an elaboration on the implementation of services and specifically PSS in Section 2.2. Then, the literature on the residual value is discussed in Section 2.3, which is also the section that contains the knowledge gap that the problem statement is derived from. Finally, an overview of the literature on different techniques for valuation is shown in Section 2.4.

All sections generally adhere to the following structure: first the definition of the subject is discussed with findings regarding the subject in general. This is then followed by findings regarding the subject as researched in the context of the highway infrastructure sector.

2.1. The circular economy

First, this section elaborates on the concept of the CE, since this is the main concept driving the developments as detailed in Chapter 1. This is done by first diving into the definition of the concept in Section 2.1.1, followed by a reflection on the concept in light of the infrastructure sector in Section 2.1.2.

2.1.1. Definition of the circular economy

Several definitions of the CE exist (Ellen MacArthur Foundation, 2006; Kirchherr et al., 2017). The definition used for the purpose of this research is as follows: “a global economic model that decouples economic growth and development from the consumption of finite resources. It is restorative by design, and aims to keep products, components and materials at their highest utility and value, at all times” (Ellen MacArthur Foundation, 2006, p. 15). This definition is used since it is widely adopted and especially applied in previous research in this field (Huizing, 2019; Tukker, 2015). More elaboration on this definition is as follows: it is “an economic system that supplies a framework and possibilities for economic growth, whereby the focus is to downsize the impact on the environment. In addition, it aims to reduce the use of raw materials by focusing on quality, and preserve the value of the materials and product by extending their life cycle” (Huizing, 2019, p. 8). Following this definition, the CE concept rests on three principles, as described in the following list (Ellen MacArthur Foundation, 2015, p. 5-7):

- Principle 1: preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows;
- Principle 2: optimise resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles;
- Principle 3: foster system effectiveness by revealing and designing out negative externalities.

Sustainability versus the circular economy Before diving deeper into the CE concept, its relation with regards to sustainability is defined. Sustainability can be described as follows: sustainability comprises every activity or process that adheres to “the needs of the present without compromising the ability of future generations to meet their own needs” (Keeble, 1988, p. 16). It has the aim of being beneficial to the environment, the economy and society at large. Responsibility is not clearly defined, but everybody has a share in it. It can be regarded as one of the many concepts aiming to contribute to a more sustainable society. The CE concept is a human construct of intentional design with a specific focus on firms and governments. It exists within the umbrella of this definition of sustainability and thus is not the same as sustainability itself (Geissdoerfer et al., 2017).

Rise of the circular economy concept and its definition Research into CE related concepts started in the 1970's and gained traction in the 1990s. Current research is preceded, among others, by the following concepts: the functional service economy (Stahel, 2010), the cradle to cradle design concept (Braungart & McDonough, 2009), natural capitalism (Hawken et al., 2013) and the blue economy systems approach (Pauli, 2010).

Following this research and the more prominent place sustainability has received on (political) agendas, the CE concept became widely known and applied more broadly. In the Netherlands specifically, the government sees the circularity principles and with it the CE as the answer to rising demand for raw materials (Remmerswaal et al., 2017) and part of the answer to becoming a more sustainabile society. To this end the aforementioned goals of the government and Rijkswaterstaat to be fully circular by 2050 and 2030, respectively, have been set.

2.1.2. The circular economy in the infrastructure sector

The aforementioned goal as set out by Rijkswaterstaat is relevant for the national circularity goal as the construction sector is responsible for half of all Dutch material use (Van Leeuwen et al., 2018). Additionally, because of the regional characteristic of the construction sector, which means that it is regionally located and interdependent on a local level, applying circular concepts to an entire value chain is possible. Recent developments in the context of this goal are detailed in the following list (Rijkswaterstaat, 2019), after which the subsequent paragraph focuses on the last of these developments specifically because it is deemed significant.

- Projects as commissioned by Rijkswaterstaat are increasingly applying the circular design principles;
- Rijkswaterstaat is implementing environmental costs in award criteria more broadly in projects;
- Rijkswaterstaat and stakeholders have developed a shared view on the necessary innovations to be able to build viaducts and bridges fully circular from 2030 onwards. This is particularly relevant since Rijkswaterstaat has many of these assets that need renovation or replacement;
- Together with the partners in Platform CB23, a shared set of definitions and guidelines for measuring circularity has been established.

Developments by Platform CB23 Platform CB23 is an organisation comprising of many actors in the construction sector that aims to create a set of unambiguous agreements within the construction industry. These agreements aim to enable compliance with the Dutch Government's goal to have a fully circular Dutch economy in 2050 (Platform CB23, 2020b). The platform has been brought to life by Rijkswaterstaat, the Rijksvastgoedbedrijf, De Bouwcampus and NEN (Koninklijk Nederlands Normalisatie Instituut) and works closely with variety of different businesses and organisations active within the construction industry. The platform has been established as the involved parties agreed that more unambiguity is required, because of the following reasons:

- Suppliers and contractors currently need to invest more than required, as well as make more costs, because each order requires different data and results;
- Current claims on the extent of circularity are not unambiguous and verifiable;
- Because of the lack of agreements the ability to learn about circular applicability is limited.

Platform CB23 has established the following definition of circular construction: "developing, using and reusing buildings, environments and infrastructure, without exhausting natural resources, polluting the environment and affecting ecosystems. Building in a manner that is economically responsible and contributes to the wellbeing of human and animal. Here and there, now and later" (Platform CB23, 2020a, p. 7). This definition is adopted in this research as well. The platform investigates several aspects of the CE in the context of the highway infrastructure sector. Using stakeholder meetings, the following three main goals for achieving circular construction were found and agreed upon (Platform CB23, 2020a) for application of CE to the construction sector:

- Protection of material stock;
- Protection of the environment;
- Protection of existing value.

Following these three main goals, Platform CB23 has sought to find a measurement approach for measuring, not monetising, the circularity of assets. An extensive view of the different components of the measurement method for circularity can be found in Appendix A. When fully finished, the measurement approach is widely applicable (Platform CB23, 2020b): to both the building and utility sector as well as the infrastructure sector, to all scale levels of an asset (materials, products, etc) and to all phases of the building cycle. Therefore, its results are applicable to this research as well.

2.2. Transition to service-oriented business models and product-service systems

In order to adhere to the CE principles in the construction sector several innovations are needed. Especially innovations regarding the business model are essential (Adrodegari et al., 2016; Ellen MacArthur Foundation, 2015; ING, 2016; Potting et al., 2016). Business models should contribute to a more CE by “closing resource loops and by slowing and narrowing resource flows, thereby reducing the environmental footprint of economic production and consumption” (Re-circle & OECD, 2019). One of the changes in business models that has significant potential in contributing to CE is the move from product- or ownership-oriented models towards more function- or service-oriented models (Datta & Roy, 2009; Lenferink et al., 2013; Van Ostaeyen et al., 2013).

This section aims to provide insight in the transition to these service-oriented business models and specifically the literature on PSS. This is done by first diving into the definition of both aspects in Section 2.2.1, followed by the different types of PSS in Section 2.2.2. Then, these findings are reflected upon in the light of the infrastructure sector in Section 2.2.3.

2.2.1. Definition of servitisation and product-service systems

Servitisation is defined as the process of industries using their products to sell ’outcome as a service’ rather than a one-off sale. It has become a more popular strategy in the last decade (Visnjic Kastalli & Van Looy, 2013). The trend can be seen in nearly all industries (Vandermerwe & Rada, 2008). This change towards more service-oriented business models is driven by technology, skills, globalisation, a new and proactive role of state and societal and environmental challenges (Gallouj et al., 2015). Additionally, two factors are fueling the trend. First, the possibility for change of suppliers and customers towards a more sustainable behaviour by changing the way of consumption. Second, potential economic benefits contribute to this change (Tukker & Tischner, 2006). These economic benefits follow from the fact that servitisation allows firms to create new sources of added value and competitiveness, as servitisation (Baines et al., 2007):

- Allows for capturing new revenue streams;
- Creates stronger customer relationships;
- Enables a constant or recurring income stream;
- Changes service from a cost to a value creator;
- Often allows for scalability.

The potential environmental benefits combined with opportunities for economic benefits have created the incentive for research of the concept’s applicability to infrastructure construction in the Netherlands (Huizing, 2019). In this context, however, different terminology is used with regards to servitisation. In the construction sector the terms service-led, integrated and as a service are predominantly used. More broadly, but recently also specifically in this specific branch of research, the term PSS is used (Huizing, 2019). The only significant difference between servitization and PSS is that the PSS literature has a specific focus on environmental benefits, whereas servitization does not. As literature states that the application of PSS can help transitioning towards the CE (Adrodegari et al., 2016; Bastein et al., 2013; Tukker, 2015; Van Ostaeyen et al., 2013) and the fact that this research aims to follow up on existing studies in the field (Huizing, 2019) this terminology will be used.

PSS is defined as “an innovation strategy, shifting the business focus from designing (and selling) physical products only, to designing (and selling) a system of products and services which are jointly capable of fulfilling specific client demands” (Manzini & Vezzoli, 2003, p. 851). Furthermore, PSS are complex systems, in which the design process must take into account “products, services, support systems, business elements and the work flow and interactions amongst them” (Vasantha et al., 2012, p. 654). In business to business context, PSS is also referred to as Industrial Product-Service Systems (IPS2) (Meier, 2004; Michelini et al., 2017; Pessôa & Becker, 2017). In this analysis, both are referred to as PSS. PSS has been researched for some time now (Alderman & Ivory, 2010; Datta & Roy, 2009; Huizing, 2019; Mentink, 2014; Van Ostaeyen et al., 2013). This has resulted in the view that the application of PSS can potentially help to reduce pollution and resource consumption (Pessôa & Becker, 2017) in several sectors, among which is the construction sector. This follows from the findings that the PSS provider offers a result closer to the final client need and hence has more degrees of freedom to design a low impact system (Tukker, 2004). Additionally, the aforementioned potential environmental benefits still apply.

2.2.2. Types of product-service systems

Several types of PSS exist, that can be categorised in several ways. These categorisations are combined in Figure 2.1. Eight categories of PSS exist, which can be grouped according to three main categories: product-oriented, use-oriented and result-oriented (Tukker, 2004; Van Ostaeyen et al., 2013). These are represented along a scale of product- versus service-oriented. The former is more in line with the linear economy, whereas the latter is more in line with the CE concept. The characteristics and potential of the three main categories of PSS are specified in further detail in Table 2.1, as adopted from (Huizing, 2019).

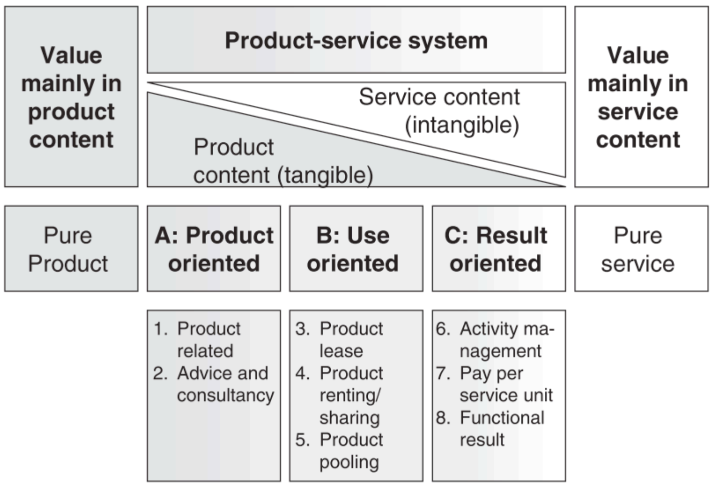

Figure 2.1: Categorization of the different types of PSS, in three main and eight subcategories. Depicted along a scale from more product-oriented (left) to more service-oriented (right) (Pessôa & Becker, 2017, p. 164).

Research has shown that the biggest opportunities for significant environmental improvement lie in decreased resource usage and innovations that make the delivery process more sustainable (Tukker, 2004). As Figure 2.1 (category C) and literature (Reim et al., 2015) shows, both opportunities are increasingly larger when the PSS is more result-oriented. This is specifically the case for type C8 as shown in Figure 2.1, the functional result. For this type the responsibility for process performance lies with the PSS provider. In more traditional models this responsibility lies with the customer. The customer only pays for the (faultless) results. This is accompanied by a performance-based revenue mechanism, which means that only functional performance of the product or service generates revenue (Pessôa & Becker, 2017).

2.2.3. Product-service systems in the infrastructure sector

This section aims to discuss PSS research in the infrastructure sector by first discussing the current use of servitisation and PSS in the sector in the following paragraph. This is followed by an assessment of theoretical research into the application of PSS in the infrastructure sector, followed by an assessment of practical research into the subject.

Table 2.1: The characteristics and potential for each of the three different main categories of PSS, as adopted from (Huizing, 2019, p. 11).

Category	Characteristics	Potential impact on the environment
Product-oriented	This business model is aimed to sell products, with some additional services being added. This category includes product-related services, advisory and consultancy. Examples are the application of take-back guarantees, maintenance contracts and financing contracts.	This system is comparable to the current integrated project delivery methods and therefore no major potentials are noticed. However, the application of the additional services can induce some environmental gains. Including a maintenance contract to the product can have an effect on the energy and resource use.
Use-oriented	In this business model the product is still important, however the focus of business is no longer on selling as much as possible. This category is characterised by the changing position of ownership, since ownership of the product remains with the provider. Hereby, the product is made available for use, e.g. shared by a number of users.	Research concluded that when ownership is no longer transferred to the customer it often leads to less careful behaviour by the user, meaning a shorter lifespan. In contrast, also positive outcomes are identified, since product sharing and product renting leads to a higher use of the capital goods.
Result-oriented	This business model is characterised by the agreement between the client and service provider on a result, while there is no predetermined product involved. Result- oriented is focused on performance in which value is mainly in the service content and no longer in the product content.	A result-oriented service has the largest effects on the environment, as there is no predetermined product involved. This creates freedom to come up with solutions that are different than the existing product concepts.

Current use of servitisation Currently several types of Project Delivery Model (PDM) are used in the infrastructure construction sector. The two main types are shown in Table 2.2, with the main contracts associated with the types grouped as well (Hoezen et al., 2010). Additionally, the table is adapted to include the PSS model characteristics in the right column. The table helps to identify the key differences when applying more product-oriented or more service-oriented approaches to construction projects. As can be seen in the table, the Design, Build, Finance & Maintain (DBFM) contract and thereby integrated PDM are the most significant service-oriented currently as currently used in the sector. However, the currently used integrated business models are largely economically driven, with a specific focus on minimising the total life cycle costs using the Life Cycle Costing (LCC) theory. The potential added value of the PSS business model is that minimising life cycle costs is not its main or only goal, allowing for considering the entire material flow. The former business models do not allow for this. Thereby, implementing PSS allows for helping in realising the transition to a CE.

As for the current use of PSS in the infrastructure sector: a comparison that is easily made is that of the application of PSS in infrastructure and toll system infrastructure assets as used in other countries and in rare cases in the Netherlands as well. Here, private parties construct the asset and will also take care of function and availability of the road. Furthermore, these private parties are also responsible for funding the asset themselves. This is then done by charging toll payments for use of the asset. This way, the users pay for the availability of the asset. This system is comparable to the activity management PSS type, category C6 as specified in Figure 2.1 (Huizing, 2019).

While literature on the application of these toll systems is not extensive, information is gathered. First, the role of contracts and the negotiation process is significant (Chung et al., 2010; Pagano, 2009; Rijkswaterstaat, 2020). Second, the risk allocation is an important aspect to consider in the context of these projects (Chung et al., 2010). Third, several studies have mentioned how the residual value of the contract at the end of the concession should be taken into account.

Table 2.2: Characteristics of the traditional and integrated PDM, subdivided according to contract types used for that specific PDM. Adopted from (Hoezen et al., 2010, p. 1178) and adapted to include the PSS model.

PDM	**Traditional (DBB)**	**Integrated (DB)**		
Contract	**Traditional**	**DB**	**DBFM**	**PSS**
Specifications	Input: design-led	Output: product-led	Outcome: service-led	Outcome: service- or result-led
Scope	Construct (design done separately beforehand)	Design and construct	Design, construct, finance and maintain	Design, construct, finance, maintain, disassemble/dispose
Selection criterion	Price	Design creativity, constructability and price	Overall quality and price	Overall quality, price and potentially CE or sustainability factors
Decision freedom for contractor	None: has to follow the specifications	Little: can have some influence on the design	Much: can make decisions as long as remaining within the scope	Most: can make decisions as long as remaining within enlarged scope (as opposed to DBFM)
Natural incentive	Low bid, with compensation through extra work	Low bid by design efficiencies	Low bidding and cost reduction by design and process efficiencies	Circular or sustainable thinking, low bidding and cost reduction by design and process efficiencies
Effect on the contractor's behaviour after contract closure	Opportunistic, mistake-hiding, quality-shirking, extra work claiming	Opportunistic, mistake-hiding, quality-shirking	Opportunistic, mistake-hiding	Not researched yet, expected comparable to DBFM with added effects due to CE and disposal incentives
Monitoring	Ongoing, by principal	Ongoing, by engineering firm	Ongoing, by contractor and by his financiers. Occasionally by the principal	Not researched yet, expected comparable to DBFM with added effects due to CE and disposal incentives

Significant differences between these projects and PSS include that toll asset projects are often funded using toll payments because of a lack of financing options as supplied by the government. However, this is not the case with the Dutch government (Huizing, 2019). Additionally, none of the literature on toll assets has mentioned the application of CE principles. Thus, these contracts were probably not set up with this idea in mind.

Theoretical research into product-service systems Following the potential of the application of PSS for the infrastructure sector, its more widespread application in recent years in other sectors and its larger significance because of political and societal environmental pressure, research into the application of PSS has started several years ago. The most recent findings of this result are presented here.

In order to apply PSS on infrastructure projects several aspects have to be realised within the sector: five so called states of affairs as well as seven changes are required to be made in the sector (Huizing, 2019). All these states of affairs are graphically represented in Figure 2.2.
This figure shows a model depicting the project life cycle together with the states of affairs and changes and their position within the project life cycle. "The most important change in relation to the existing

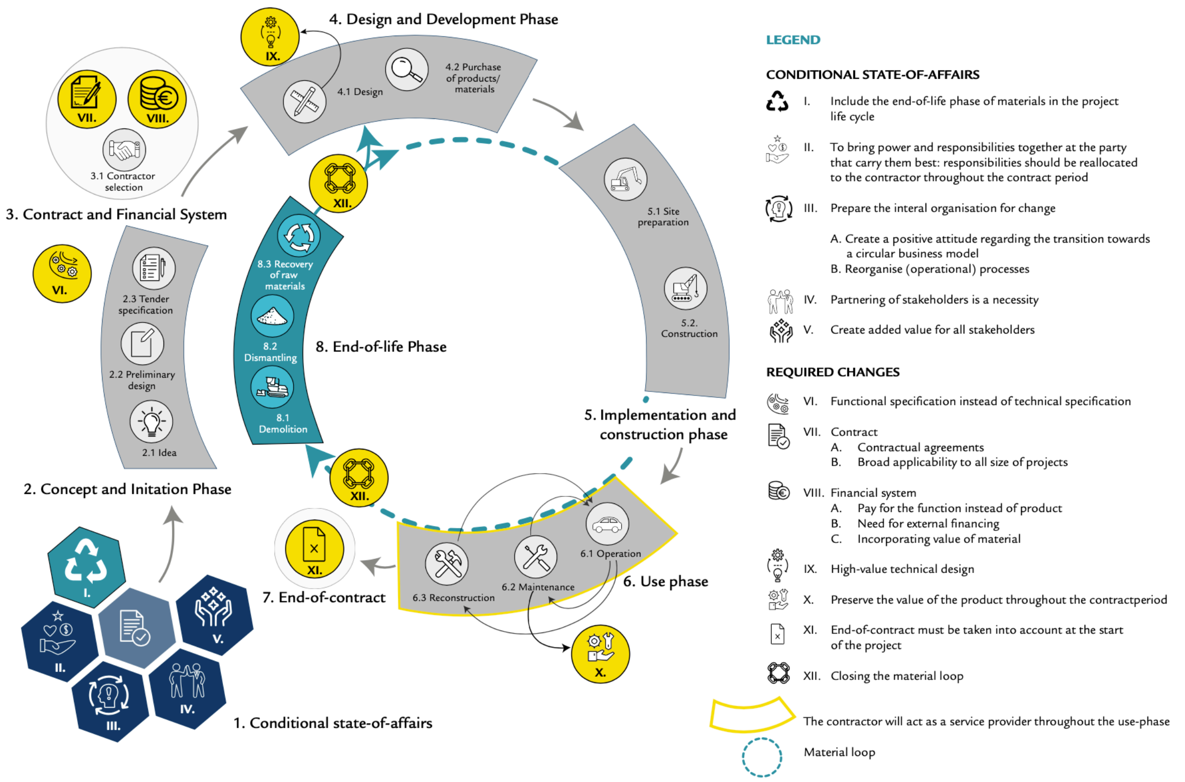

Figure 2.2: Model for incorporating PSS characteristics in infrastructure projects. It shows the adapted project life cycle on the left and reveals where the conditional states of affairs and required changes (stated on the right) should be addressed in yellow. Adopted from (Huizing, 2019).

project life cycle is the inclusion of the end-of life phase, which should be standard incorporated in project delivery of infrastructure projects to support the closing of the material cycle" (Huizing, 2019, p. VII).

Following the required states of affairs and changes, a more service-oriented contract introduces a different revenue model. This difference is shown in Figure 2.3. The figure shows the revenue stream of a traditional, buy-transaction business model on the left, which is associated with the product-oriented business model category. In this model, the construction costs are offset, in the same period, by the buy-transaction. This is because in this traditional model, the client gains ownership immediately after completion, for which the client has to pay (the buy-transaction). In the right of the figure the service-oriented PSS business model revenue stream is depicted, which shows that no buy-transaction occurs. Thus the developer does not receive a significant sum of funds with which to pay for the construction costs it has just made. However, the model does incorporate periodic service fees, as well as an end-of-contract fee, the residual value, which is generally paid during the transfer of ownership of the asset. This (not-to-scale) revenue stream shows that the end-of-contract fee for the residual value can potentially constitute a significant amount of the contractually agreed funds. This residual value is important as it creates an incentive for the contractor to preserve value of the product throughout the life cycle. This creates opportunities for closing the loop, which supports the application of PSS characteristics in relation to CE. It is explicitely mentioned in the research as a recommendation that a residual value determination approach is a required piece of the puzzle to be able to form a financial model so that the PSS contract can be applied in the infrastructure section (Huizing, 2019). Looking back at the model in Figure 2.2, the need for a residual value and its determination method is also shown by required changes VIII, X and XI.

In traditional lease contracts, the height of the periodic service fee and the residual value is varied to have the best market proposition. This will probably be done in the eventual PSS financial model as well. However, this research focuses solely on the most suitable determination of the residual value and thus leaves the relation with the periodic fee out of scope (see Section 1.5). After determination of the most suitable determination approach for the residual value, the value itself can be agreed to be different based on the needs of the financial model in a later stage.

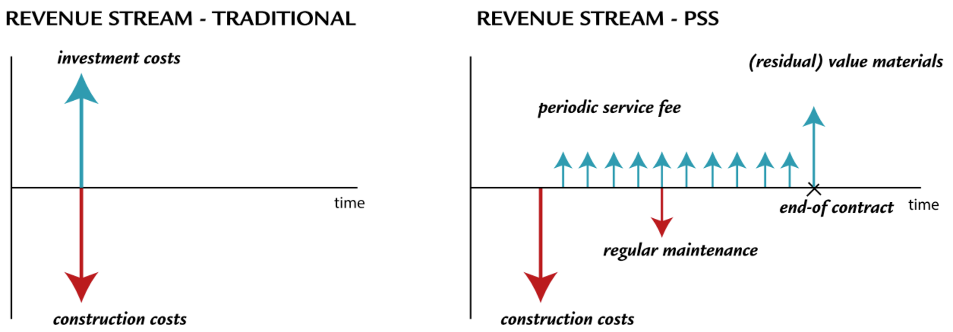

Figure 2.3: Revenue streams for infrastructure projects from a contractor's perspective. The left graph shows the traditional model revenue stream, whereas the right graph shows the revenue stream when a PSS model is applied. Adopted from (Huizing, 2019).

Practical research into product-service systems The application of PSS is currently being researched in a practical sense by the partner program DCW. The partners are provinces, municipalities, banks and contractors. Together, they aim to use infrastructure as a service to decouple the contractual and technical life cycles and thereby achieve true circularity. These are also the main stakeholders involved in PSS application, as shown in Figure 2.4. This figure, based on literature insights (Huizing, 2019), shows the governmental institution as the client and the contractor as being the service provider. The bank is involved as a financier, to enable the contractor to invest in the construction costs (see Figure 2.3) and earn revenue afterwards. All three have different desires and needs to make the application of PSS to highway infrastructure succeed for them.

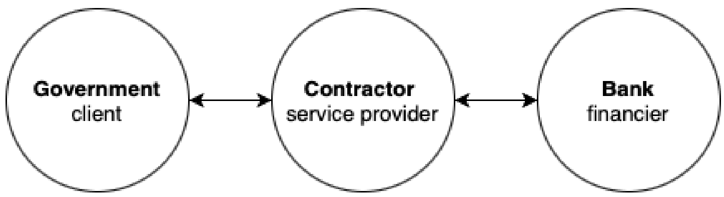

Figure 2.4: Overview of the main stakeholders involved in PSS application to highway infrastructure construction, as well as their relation to each other.

The current status of the program is that several pilots are running. The main conclusion from these pilots is that determining and agreeing on an approach for determining the residual value to be implemented in the contract appears to be difficult. Exactly what the difficulties are is not yet clear and only separate aspects of the residual value have been investigated; no combined approach is being researched or has been formed as of yet, something to which this research aims to contribute to a solution.

2.3. Residual value

This section aims to provide an overview of the literature on the subject of the residual value. This is done by first diving into its definition in Section 2.3.1, followed by an investigation into how literature states it can be determined in Section 2.3.1. Then, research in the context of the highway infrastructure sector is specifically highlighted in Section 2.3.2.

2.3.1. Definition of the residual value

As specified in the previous section, the residual value is an important aspect when aiming to achieve the CE benefits through the application of PSS. Several definitions of the residual value directly align with a specific direction as to how the residual value should be determined, namely disposal (Edgerton, 2009; European Commission, 2014). However, the definition in this research should not exclude specific directions beforehand. Thus, the following definition is used: the residual value of equipment can be the price achieved by disposing of a used asset in a fair transaction between an equally well informed buyer and seller in the overall market with a particular economic situation (Fan et al., 2008). Disposing in this definition does not mean the asset is regarded as scrap by either party. Additionally, since disposing does not mean the asset is regarded as scrap, what determines the value is not stated in the definition. This is on purpose, since it is as of yet undetermined and as previously mentioned does not become clear from literature. Therefore, the problem statement and objective as shown in Chapter 1 also do not exclude specific directions on how to determine determine the residual value.

In other words, incorporation of the residual value incentivises the shift from maximising production and sales to focus on quality and durability (Remmerswaal et al., 2017). This is confirmed in other research, that states that financial incentives can be a significant factor for promoting sustainability in construction (Pitt et al., 2009). Establishing an approach for determining the residual value is relevant now, because ambiguity about the residual value when the PSS is already implemented can block investments (Ganzevles et al., 2016). However, it should then also be noted that perfect agreement on residual value is viewed as nearly impossible, because “future changes cannot be accurately predicted and corresponding clauses are difficult to be designed” (J. Yuan et al., 2015, p. 3). Finally, it should be noted that literature does not mention how high the incentive provided by the application of the residual value can or should be to provide the circular benefits aimed for.

Residual value determination in general Overall it can be said that literature on the subject that is applicable to the context of this research is limited. There is sufficient information on (residual value) valuation in other contexts, but to what extent this information can be applied to this specific context is unknown. However, findings regarding three aspects are noteworthy; the components of the value and the valuation goal these follow from, as well as the valuation techniques. The first two are described in the following paragraph, whereas the third is described in the second paragraph.

Components and goal Literature deviates significantly on what components constitute the residual value of an asset. Several sources mention only the salvage value of the asset and its materials (Circle Economy, 2014), whereas others mention the value of all the physical assets present (Platform CB23, 2020b). Still others value the potential future financial benefits of the asset (X. Yuan & Li, 2018), the technical-functional value of the asset (Platform CB23, 2020b), or even the economical or environmental value that can be calculated using a Cost-Benefit Analysis (CBA) (Jones et al., 2014; Platform CB23, 2020b). Thus, no consensus can be found on the components that should constitute the residual value to be able to generate an incentive for circular use. An aspect several researchers do agree on is that the choice for an approach depends on the goal of the valuation as well as on the type of asset (Dewan & Smith, 2005; Gyamfi-Yeboah & Ayitey, 2009; Hoogmartens et al., 2014). Thus, this should be clear before progression can be made on the design of the residual value determination approach.

Valuation techniques Several techniques are mentioned in literature regarding the determination of value (Falls et al., 2004; Porras-Alvarado et al., 2015; J. Yuan et al., 2015). Literature on valuation techniques outside of the residual value context can be helpful too. Therefore, the choice is made to broaden the literature review outside of the residual value context. As such, the results of the complete literature review on valuation techniques can be found in Section 2.4.

2.3.2. Residual value in the infrastructure sector

In infrastructure, residual value is currently not applied broadly and literature on the subject is scarce. Literature does state that “unlike machinery equipment and other consumer products, infrastructure assets are usually less liquid and are often expected to continue the service beyond their design life through rehabilitation, reconstruction, or other life-extension technologies” (X. Yuan & Li, 2018, p. 3). This makes them eligible for the application of a residual value in the financial model. Further research into residual value application in the infrastructure section is discussed according to three perspectives. Namely, its application in traditional building contracts, in PPP toll asset contracts and in the perspective of DCW.

In the context of the application of the residual value in traditional contracts, several approaches follow from literature for determination of the residual value. This results in vastly different results (Annema et al., 2007; Jones et al., 2014). There is no consensus on which of these approaches suits best. However, in the Netherlands, residual values are mostly not taken into account (Banister & Berechman, 2003). Most financial models in the Netherlands use the historic cost technique, with a depreciation of the asset value towards zero at the end of the concession period. These models do not reflect actual residual value of an asset (J. Yuan et al., 2015). For example, the residual value of (toll) assets can be influenced by “the level and frequency of maintenance, the private sector’s capability of facility management and the the change in traffic flow”, among others. This is not reflected in the models using the historic cost technique. In some of these cases, some value is generated by selling the materials as scrap. This is called the net salvage value. However, this is only a small amount, approximately 2%-4% of the original construction costs (Rahman & Vanier, 2004).

In the perspective of application of the residual value on toll assets, literature is scarce. No consensus is reached on the different approaches to residual value determination, and that these depend heavily on the specific goals of the project and governmental influence.

Finally, in the context of the application of residual value in research already done by DCW, this research is as of yet in its infancy. The first pilot projects have encountered the problem of the residual value determination, and have established that it is an important factor to consider beforehand, some even considering it to be detrimental to the success of DCW. Additionally, several pilots are experimenting with ways to determine the residual value, however, these investigations have a rather practical approach, and miss an academic, holistic view on the problem. This is reflected in the fact that the different parties involved have different practical views on how to solve the problem of the residual value determination, and in some cases even wield different definitions regarding the subject. No universal terminology has been agreed upon regarding the subject, as is also the case in literature. This is also the case for the exact goal of the determination of the value. While this is broadly known, this has not been explicitly agreed upon. This research aims to make a start in addressing these issues.

Additionally, as mentioned before, it should be noted that neither literature nor current research at DCW mention how high the incentive provided by the application of the residual value to infrastructure assets can or should be to provide the circular benefits aimed for.

2.4. Valuation techniques applicable to the residual value

As specified in section 2.3, no consensus has been reached on the approach for determining the residual value of infrastructure assets. When the components that should be represented in the residual value are known, fitting techniques for the valuation of these components are to be found and implemented. This section aims to provide an overview of the candidate valuation techniques. These results are shown separately from Section 2.3, as these techniques are applicable outside the context of the residual value as well. First, the techniques themselves are discussed in Section 2.4.1, after which they are categorised in Section 2.4.2. Then these findings are discussed with respect to the infrastructure sector in Section 2.4.3.

2.4.1. Candidate valuation techniques

Using literature a list of potential candidate techniques for the residual value determination is determined. A broad range of valuation literature is researched, so as to gain a complete overview of the possibilities with regards to valuation. The list describes the names of the technique, as well as its applications and a short insight into its advantages and disadvantages. The list is as follows, with the bold text highlighting the names that are used henceforth:

- **Net Present Value (NPV)** of future benefits and costs in annuity / Annuity Technique / Going Concern Value / Income Technique / Productivity Realized Value / Income Capitalized Value - Represents the value of the asset in use (Amekudzi et al., 2002) by by calculating the NPV of the benefit and cost stream of its remaining service life (Kadlec & Mcneil, 1999; Lemer, 1999). It is mainly used for budgeting decisions (Lemer, 1999), for value-based asset management (Amekudzi et al., 2002) and as an approach for describing infrastructure’s relative importance (Dewan & Smith, 2005; Falls et al., 2004; Lemer, 1999). Upsides of this technique are that it has a proven track record, and is known well within many industries. Additionally, its future perspective fits well with infrastructure assets (X. Yuan & Li, 2018). Downsides are that it can require many assumptions, and that it has a relatively low accuracy level (Amekudzi et al., 2002; Dewan & Smith, 2005; Falls et al., 2004; Lemer, 1999).

- **Perpetuity Technique** / NPV of future benefits and costs in perpetuity - This technique is comparable to the previous technique other than that it assumes an infinite timeline (Verlaan & de Ridder, 2010). Therefore, the actual operating period of the asset is irrelevant (European Investment Bank & European Commission, 2005). The technique is used for projects that can be assumed to have an infinite lifetime (European Investment Bank & European Commission, 2005). The same up- and downsides as in the previous technique apply. Additionally, the technique does not have the ability to easily recognize future expenditures that can enhance the future economic benefits of the assets (South Australia Local Government, 2009).

- **PV of past costs** / Equivalent Present Worth in Place / Depreciated Historic Cost Technique - The technique uses the historical costs for construction of the asset, adjusted for inflation and wear through depreciation (Albitres, 1999; Amekudzi et al., 2002; Kadlec & Mcneil, 1999). The historical costs are found using historical records of procurement (Falls et al., 2004). It is one of the most used techniques for valuation and is used as an indicator of the health of the asset and financial accounting purposes (Falls et al., 2004; Porras-Alvarado et al., 2015). Positive aspects of the technique are that the required data is readily available and that the resulting calculations have a relatively high accuracy (Amekudzi et al., 2002; Dewan & Smith, 2005; Falls et al., 2004; Lemer, 1999). Several negative aspects of the technique are that it neglects the future perspective and thus that its use for investment decisions is debatable (Hedges et al., 2019), as well as that its results can be misleading for older assets such as bridges since the value is related significantly to the age of the asset.

- **Market Value** / Sales Comparison Technique - This technique is based on comparing an asset to similar asset sales in the subject's market area (Amekudzi et al., 2002; Herabat et al., 2002; Verlaan & de Ridder, 2010). The technique is widely applied (Falls et al., 2004; Porras-Alvarado et al., 2015). In the infrastructure sector its use is difficult at an asset level, since there is no secondary market to base the estimations on. It is mainly used for valuing non-cashflow producing assets, or for assets of which the cashflows are not representative of the market price (Damodaran, 2012). It is often applied in real estate, in which location is the most important factor the assets are compared on. Its applicability to these types of assets is also one of its main positive aspects (Damodaran, 2012). Potential negative aspects of the technique are its aforementioned limited applicability for infrastructure assets (Dewan & Smith, 2005; Falls et al., 2004; Lemer, 1999).

- **Written Down Replacement Costs (WDRC)** / Depreciated Replacement Costs - This technique uses current market prices to determine the cost to rebuild or replace the facility in its current condition (Amekudzi et al., 2002; Hastings, 2010; Hedges et al., 2019; Johnson, 2006). It does this by estimating the replacement cost and depreciating that to its current condition (Kadlec & Mcneil, 1999). The technique is often used when market evidence is non-existent (Gyamfi-Yeboah & Ayitey, 2009). Internationally, it is more common to value assets on the WDRC than on its historic costs (Hedges et al., 2019). Upsides of the technique include that it is a technique with a future perspective (X. Yuan & Li, 2018), that the technique reflects current prices and technology and that it provides for future budgeting (Falls et al., 2004). Downsides of the technique include that the technique requires accurate performance or condition modelling (Falls et al., 2004).

- **Net Salvage Value** / Net Liquidation Value - The net salvage value is the present worth of the amount obtainable from selling off the components of the asset over a reasonable period of time, including disposal costs (Edgerton, 2009; IASB, 2005; Park, 2004). It is one of the most used techniques for residual value determination because of its simple application in current business models (Falls et al., 2004; Porras-Alvarado et al., 2015) and is mostly used for assets at the end of their lifetime (Amekudzi et al., 2002). Advantages of the technique include that required data is generally available (Falls et al., 2004). Disadvantages of the technique include that it is mostly appropriate for abandoned assets (Amekudzi et al., 2002), that the technique neglects the value for reusing certain materials and the fact that the technique neglects value by the work (craftmanship) performed on the materials (Van Leeuwen et al., 2018).

- **Cost Benefit analysis (CBA)** - This technique is defined as “the process which identifies and evaluates net benefits associated with alternatives for achieving defined public goals” (Sassone & Schaffer, 1978, p. 2). It is mainly used to assess investments on their economic or social benefits and costs (US Department of Transportation, 2017). Advantages of the technique are that it allows for monetisation of a broad range of aspects (Hwang, 2016). Disadvantages of the technique are that its assumptions, conversions and results are debatable (Hwang, 2016). Finally, financing the resulting values as described by the CBA can turn out to be difficult, since this method relies on many assumptions and not all the components included are currently considered in financing.

2.4.2. Technique categorisation

The typologies used to characterise the different techniques are the time categories (Falls et al., 2004) and the categories that specify the typology of the technique (X. Yuan & Li, 2018). The choice for these two categorisations is made based on the fact that these are two of the most prominent differentiators for these valuation techniques. The combined grouping of the techniques according to these categories can be found in Table 2.3.

The time categorisation groups techniques based on whether the technique is past-, present- or future-oriented. The type categorisation groups techniques based on the input data that is used for the valuation. A note that should be made is that several techniques are elligible to be considered in multiple categories if altered somewhat. If that is the case, the basic technique as discussed in the previous section is categorised.

Table 2.3: The techniques as specified in section 2.4 specified according to the time categories (Falls et al., 2004) and type categories (X. Yuan & Li, 2018).

		Type categories			
		Income based (net income)	**Cost based (solely costs)**	**Market based**	**Other**
Time categories	**Past-oriented**	n.a.	PV of past costs	n.a.	n.a.
	Present-oriented	n.a.	Written Down Replacement Costs	Market value; Net Salvage Value	n.a.
	Future-oriented	NPV of future benefits and costs in annuity; Perpetuity technique	n.a.	n.a.	Cost-Benefit Analysis

2.4.3. Valuation techniques in the infrastructure sector

Currently, the bulk of the infrastructure valuations are done using cost-based methods (X. Yuan & Li, 2018). This is the case because “public infrastructure assets have as of yet not been constructed with the purpose of generating revenues, because of their contribution to the economy” (X. Yuan & Li, 2018, p. 2). This also means that “Market Value or revenue stream-based valuation techniques are not appropriate for highway assets with the current mindset” (X. Yuan & Li, 2018, p. 2). Additionally, it is generally agreed that future-oriented valuation techniques are “more useful for considering the condition-related value of assets decision making” (X. Yuan & Li, 2018, p. 2).

As this section shows, finding the optimal valuation technique to apply to infrastructure within the PSS context requires additional research. How this is done is described in Chapter 3.

3
Methodology

Following the literature study, this chapter considers the applied research methodology as well as the arguments for using it, with the goal of answering the second research question as described in Chapter 1. This is done by first discussing the applied model in Section 3.1, followed by its application in Section 3.2.

3.1. Double Diamond process model

For the purpose of this research, the Double Diamond process model is used, also called the 4D's model. The model, as graphically represented in fig. 3.1 has as main feature its focus on divergent and convergent thinking, where concepts are first generated, after being refined and narrowed down to the best fitting concept. The model does this twice, first to define the problem, secondly to find the solution to the problem. Applying this structure, the model consists of four phases (Hutchby & Moran-Ellis, 2005):

1. Discover phase (diverging): this phase helps people understand, rather than simply assume, what the problem is;
2. Define phase (converging): the insight gathered from the discovery phase can help you to define the challenge;
3. Develop phase (diverging): the second diamond encourages people to give different answers to the clearly defined problem, seeking inspiration from elsewhere and co-designing with a range of different people;
4. Deliver phase (converging): delivery involves testing out different solutions at small-scale, rejecting those that will not work and improving the ones that will.

The application of this model is chosen for several reasons. First, the first diamond's focus on defining the problem fits with the state of current research on the subject. The literature study has shown that knowledge on several subjects is lacking in the required context (see Chapter 2). Thus, next to the literature study some additional research is required to be able to fully comprehend the currently encountered problems and their context in theory and practice. Therefore, the diverging and converging phases of the first diamond are deemed fitting for the purpose of this research. The second reason for choosing the model is that the model fits the nature and research questions of the research. This is an inherently design-oriented study (Verschuren & Doorewaard, 2010). Thus, applying a methodology that operates within the Design Thinking (DT) umbrella, under which the Double Diamond model resides (Tschimmel, 2012), is beneficial to the research. The third reason has to do with the combined practical and theoretical orientation of the research. First, the research is meant to solve a problem encountered in the theory development in a particular scientific area (theory-oriented). Additionally the research aims to provide knowledge and information that can contribute to a successful intervention in order to change an existing situation (practice-oriented) (Verschuren & Doorewaard, 2010). The DT research umbrella is especially applicable to problems with both a theoretical and a practical orientation (Anderson & Shattuck, 2012; Collins et al., 2004; Delft University of Technology, 2021; Prediger et al., 2015). Fourth, the DT and Double Diamond's application of iterative steps in the final phase of the research (Amiel &

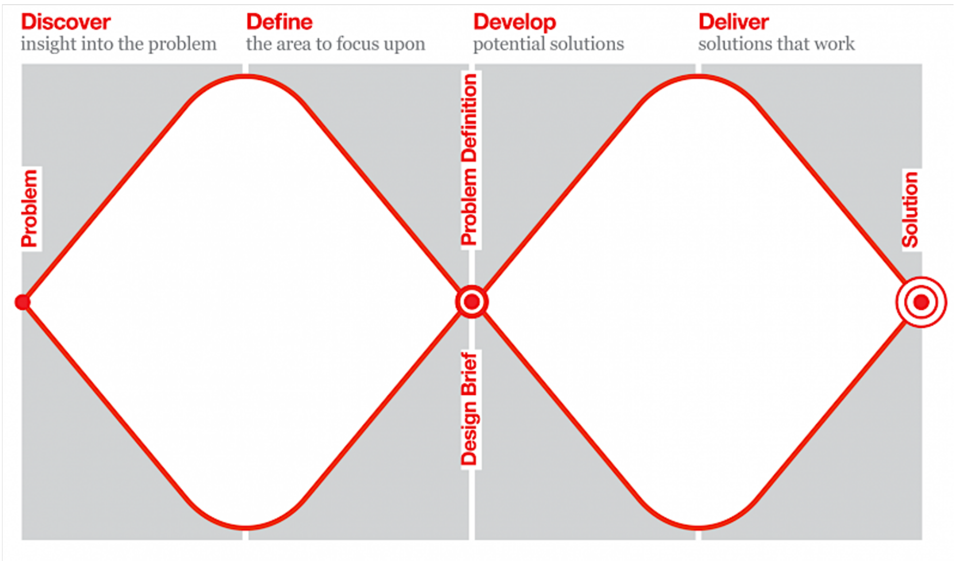

Figure 3.1: Graphical representation of the Double Diamond process model. Adopted from (Hutchby & Moran-Ellis, 2005).

Reeves, 2008) is beneficial for the for designing the approach. Fifth, with respect to other models the Double Diamond model is one of the more complete models applicable for many different researches and research types (Tschimmel, 2012). Fifth, as opposed to other design-oriented models the Double Diamond model is applicable to the research itself as opposed to specific aspects such as decision-making (Bos, 2020) and it allows for freedom as opposed to a structured approach (D'couthou, 2020).

Implementing the Double Diamond model means incorporating multiple design and research methodologies (Hannafin et al., 2005; Reigeluth & Frick, 2013). How this is done in light of the objectives of this research is detailed in the next section (see Section 3.2).

3.2. Application of the Double Diamond research methodology

The research will be split according to the two diamonds of the method, as represented in Figure 3.1. The first diamond can be regarded as the problem analysis diamond and will result in an extensive definition of the problem. This is a necessary aspect of the research since the problem statement as described in Section 1.2 still leaves aspects of the problem open to interpretation. The second diamond can be regarded as the problem solving diamond and will result in a solution that fits the problem definition as defined in the first diamond. The applied research methods within the respective diamonds are discussed in the following two sections (see Section 3.2.1 and Section 3.2.2, respectively). In these sections the specific goals for this research are also mentioned per diamond. For clarity Section 3.2.3 shows an overview of the used methodologies.

3.2.1. Diamond 1: problem analysis

As specified in the previous section, the first diamond can be regarded as the problem analysis diamond. To be able to define the problem more precisely, both theoretical and practical knowledge should be gained. This is done using the following methodologies:

- Literature study;
- Expert interviews.

These methodologies, reasoning for their use and their specifics are discussed in the following paragraphs. The results of these studies are presented in a combined manner in Section 4.1, leading up to a more extensive definition of the problem in the form of requirements the problem solution should adhere to as well as a structure these requirements fit into.

Literature study The literature study is a qualitative research methodology that comprises of going through many different literary sources to be able to gain insight on the theoretical circumstances regarding the relevant subjects. This methodology is chosen for the theoretical perspective since it is the only applicable method in this regard. The literature study is featured in Chapter 2.

To be able to obtain a broad perspective, this study has focused on four different subjects: the CE, service-oriented business models and PSS, the residual value and valuation techniques. The first three were determined before the start of the study to be relevant for the purpose of this research because of the context it exists within. The last is found to be a subject that is quite context specific and in which an overview for the context of this research is not available. The aim of this study is to gain a better understanding into the relevant concepts, as well as elaborate on findings regarding that can contribute to both the problem definition and its solution.

Expert interviews The interview is a qualitative research method that allows for obtaining a practical perspective on the problem that can provide essential information on the subject matter (Baarda, 2017). The methodology is chosen because of the practical perspective that it delivers on the subject, which fits well alongside the theoretical perspective of the literature study. Additionally, it is selected for the contextual awareness it can provide. The results of the interviews are featured in Chapter 4.

When aiming to conduct interviews, several choices should to be made. First, the choice is made to perform the interviews orally, instead of written interviews. Since this set of interviews exists within the exploratory phase of the research (first diamond) and oral interviews allow better for open questions and explanations of answers (Baarda, 2017), this type of interview is a fitting option. Following the same reasoning, it is determined that the interviews should be semi-structured (Baarda, 2017). This means that the interview will follow a checklist of subjects, which can be addressed in any order. This form of interview is ideal for asking open questions which are not predetermined, as opposed to the partially structured interview, which is characterized by a set of predetermined, often closed questions. As for the interviewees, in total nine people will be interviewed. For applicability and validity of the results, these are chosen according to the non-probability sampling method purposeful sampling. This means that the experts selected for the sample (the interviews) are chosen based on the judgment of the researcher being that the sample reflects the relevant expert knowledge in the population, saving both time and money (Coast et al., 2011). Specifically the criterion sampling methodology has been used, since this is one of the most widely applied purposeful sampling methodologies and it allows for choosing actors based on their respective roles, allowing for straightforward actor selection (Palinkas et al., 2015). The sample has been chosen such that all the relevant characteristics for assessing the applicability of PSS in infrastructure (financial, technical, legal and organisational) are incorporated (Huizing, 2019). This is the case when experts of the following types of organisations are included: contractors, several governmental institutions from different levels and banks, as shown in table 3.1.

Table 3.1: Perspectives of participants in the initial set of interviews, along with their associations and functions.

Perspective	Organisation	Function
Contractor	Dura Vermeer	Project Manager
	Independent	Manager Sustainability
Government	Rijkswaterstaat	Project Manager
	Provincie Overijssel	Project Manager
	Gemeente Amsterdam	Project Manager
	Copper8	Consultant
	Alba Concepts	Consultant
Bank	Nederlandse Waterschapsbank	Manager Project Finance
		Sustainability Officer
	ABN AMRO	Director Structured Finance

The organisational types as shown in Table 3.1 are also involved in DCW, in which no role is omitted (consultation meeting DCW, personal communication, February 8, 2021), further substantiating the choice for these organisation types. Experts within DCW have been approached according to these organisation types, satisfying the sample requirements as stipulated by the necessary characteristics. Additionally, independent advisors are involved in the set as well, since these have worked on associated problems extensively and can have an interesting perspective as well, as they are independent. These are grouped with the actor that they are associated with. For validity of the interview results the sample includes at least two experts per type of organisation are interviewed and the governmental organisations feature different levels of government. Further increasing the validity of the results is achieved by recording and transcribing all the interviews, which were relayed to the interviewees for approval. As for the structure, setup and conditions within which to conduct the interviews are established according to basic principles found in literature (Baarda, 2017; Fellows & Liu, 2008; Fowler, 1995).

The subject matter of the interviews is determined based on both missing insights as determined in the literature study, as well as discussing all the relevant concepts that are found in the literature study. The latter is also included because, as stated, the final results should comprise both the theoretical and practical perspective. Therefore, both methodologies should cover all relevant topics. This is reflected in the interview protocol (see Appendix B). The protocol shows an interview structured around two main subjects: the residual value and techniques for determining this residual value. The former dives into relevant aspects of the residual value such as the goal (questions 1-3), components that can constitute the value and conditions to be considered (questions 4 and 5). The latter considers specifics regarding current techniques for valuation of the components (questions 6 and 7), as well as discussing all techniques deemed relevant through the literature study (question 8). In the interview, questions 1-3, 6 and 7 are designed to generate practical information next to the theoretical information already found in the literature study, to be able to compare and challenge it and gain both theoretical and practical results on these subjects. Questions 4, 5 and 8 are designed to both compare and challenge, as well as to specifically introduce new knowledge on what components, techniques and conditions are potentially applicable. This is done by first allowing the interviewee to freely state his or her insights, then suggesting several options as found in PSS and valuation literature for the interviewee too reflect upon and finally allowing the interviewee to again freely state additional insights.

To the extent possible due to the semi-structured interview style, the results are gathered in database software such as Microsoft Excel. Using this overview the answers can be compared, to be able to provide conclusive results.

Formation of problem definition Combining the findings of the literature review and the expert interviews a structure for designing a residual value determination approach is found, together with a set of requirements regarding elements of this structure. These requirements can be presented along this structure. The combination of the structure and requirements is the conclusion of this first diamond, the problem definition. This can then be used to design a solution according to the methodology stated in Section 3.2.2.

3.2.2. Diamond 2: problem solution

Following the problem as defined using the methodology of Section 3.2.1, the solution to the problem is found according to the methodology as described in this section. More specifically for this research, the outcome of the second diamond is a fitting approach for determining the residual value for infrastructure assets in the context of PSS. This outcome is reached iteratively using the following methodologies, presented here preceded by their use and step in the process of the design of the solution:

- Step 1 - Formation of initial design: expert consultations;
- Step 2 - Verification of design: application to a case;
- Step 3 - Validation of design: expert interviews.

In short, to be able to understand the chronological order of the methodology: step 1 builds on the results of the first diamond and is used to form the initial design of the approach for the valuation. Step 2 allows for testing the designed approach and adapting and improving upon it. Step 3 aims to check the results against reality and applicability and perform final adaptations. As can be noted, this phase is of an iterative nature. This is done so that the design benefits from findings obtained throughout application of those methodologies.

These methodologies' specifics and reasoning behind their use are elaborated upon further in the following paragraphs. The results of these studies are presented in a combined manner in Section 4.2. This is done narratively since all the generated sub-results such as the results of the case analysis influence choices that are part of the final result: the residual value determination approach.

Step 1 - Formation: expert consultations The expert consultation is essentially a form of expert interview. However, unlike the previously used interviews, it is unstructured and the subject matter can differ significantly for each of the different sessions. It is used at the start of the iterative design phase, to be able to gain knowledge on a specific subject whilst not having to conduct an extensive round of interviews. This can only be done if the expert involved is trusted to be knowledgeable on the subject and if the subject's subjectivity is limited. Minding these conditions, the contacted experts were found with help of the experts involved in the first set of interviews as well as using the DCW partners. The subject matter for the sessions differed for each of them. However, in general, it can be stated that based on the results of the first diamond (problem definition) proposals were formed on a qualitative basis. These were then presented during these sessions, adapting them based on feedback and finally reviewing the adapted proposals if necessary. Multiple experts regarding different fields have been consulted. Relevant consultations are stated in the results in Section 4.2.2, where the expert and their field of expertise is also mentioned.

Step 2 - Verification: application to a case Following the expert consultations that have resulted in an initial approach design, this design is applied to a case. This process verifies that the value determination approach works correctly, as well as the fact that it is applicable and adheres to the requirements as set out in the problem definition (first diamond). The application of the case and the methodologies used for this should be viewed as a means to find the final result: the residual value determination approach.

The case the design is applied to is first described in the following paragraph. Then, the main approach used in applying the design to determine the residual value is elaborated upon: the Monte Carlo Analysis (MCA) method. Subsequently, methodologies for gathering the required input data used for the application of the case are discussed. The residual values calculated using the MCA are a multitude of probabilistic occurrences of the residual value at this point in time. However, the goal is to know the residual value at the end of the contract period as set out for the case by DCW: 15 years (consultation meeting Olga Teule, personal communication, March 31, 2021). This means that price evolution towards the future has to be accounted for as well, which is done according to the Geometric Brownian Motion (GBM) method, discussed next. Finally, to be able to assess these results as current values they are discounted as described in the final paragraph of this section.

Case description The case itself revolves around an infrastructure object: a segment of the N739 road, an expressway near the Dutch city Hengelo, as can be seen in Figure 3.2. The case and its data have been supplied by the Province of Overijssel and Dura Vermeer, partners in DCW and respectively owner of the segment and contractor. These parties have, together with several partners in the DCW program, already used this segment to conduct several other analyses in a pilot. Because of this, basic required data is available. The pilot aims to be the first to temporarily implement an as-a-service contract for infrastructure construction. Agreements between the province and contractor have been made regarding the goals of the pilot and currently the pilot is designing the first version of the as-a-service contract. This design is done collaboratively, minding the specifics of the case. Residual value determination appears to be a difficult aspect within the contract.

As for the case specifics: the specific segment that is researched is the N739b, as shown in Figure 3.3, comprising both directions of a segment of 3.247 meters in length. As shown in the figure, the segment includes several junctions that have more lanes, which need to be accounted for. To be able to align the results with the results of the other analyses done in DCW, the case is scoped to comprise only of the top two layers of asphalt. Other aspects, such as the lower layers of asphalt, the foundation, the rubble and signage are not taken into account. The condition of the road is given, whereas the planned maintenance and renovations are also provided. Further details on the basics of the material types included are also given.

Determining residual value using Monte Carlo Analysis The equations of the initial value determination approach design is applied using the MCA method. The reasons for using the MCA approach for this research are as follows:

- Allows for combining several inputs that are given as a (probabilistic) range, thereby incorporating probability through the use of random sampling (Meester, 2021);

Figure 3.2: National geographic representation of the expressway location, as shown by the red marker, just southwest of the city of Hengelo.

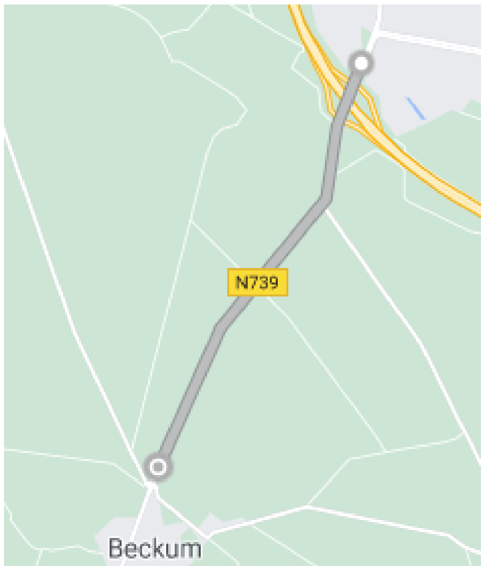

Figure 3.3: Local geographic representation of the expressway, in grey. The city at the top right is Hengelo, whereas the bottom left lies the town of Beckum

- Allows for interpreting the results as somewhat uncertain, which they are because of the uncertainty of the input data. Additionally, time factors heavily into the results' uncertainty and therefore these results should not be seen as a certainty.

Application of the MCA results in a set of residual values, each constructed using new random samples. These are presented in histogram form, showing the number of occurrences of a certain range of values. Additionally, the μ (average) and Standard Error (SE) are used as describe the results, since these provide the most accurate insights into the result and its accuracy (Meester, 2021). The μ is calculated according to Equation (3.1), in which the X denotes the result(s) and the N is the number of results. The σ is calculated as shown in Equation (3.2) using the same variables. The SE is determined using Equation (3.3), again using the same variables.

$$\mu = \overline{X} = \frac{1}{N}\Sigma_{i=1}^{N} X_i \qquad (3.1)$$

$$\sigma = \sqrt{\frac{\sum(X_i - \mu)^2}{N}} \qquad (3.2)$$

$$SE = \frac{\sigma}{\sqrt{N}} \qquad (3.3)$$

For the results of the MCA to be trusted, the number of runs (N), equal to the number of results, has to be high enough. Often, values of 1.000 or 10.000 are used (Heijungs, 2020). However, this is significantly dependent on the specifics of the case. To be able to assume the results are reasonable the deviation of the SE of the determined μ can be determined for several different number of runs. If the deviation of the SE of the μ is less than 1%, the values can be assumed to be reasonable (Meester, 2021). As can be seen in Section 3.2.2 and Figure 3.4, this is the case for 10.000 runs for all calculations done, which is also computationally viable. Therefore, this number of runs is used for the analyses.

Table 3.2: SE/μ of the results of the MCA for each of the three components as set out by the initial design in Section 4.2, showing the relative deviation is below 1% for all components for the number of runs of 10.000.

	10	**100**	**1.000**	**10.000**	**100.000**	**1.000.000**
SE/μ component 1 [%]	23,03	4,94	1,93	0,61	0,19	0,06
SE/μ component 2 [%]	12,54	7,22	2,31	0,73	0,23	0,07
SE/μ component 3 [%]	20,48	5,63	1,82	0,59	0,19	0,06

The application of this MCA is done using the Python programming language, mainly since Excel did not allow for adequate implementation of the MCA. The most relevant concepts and specifics of the

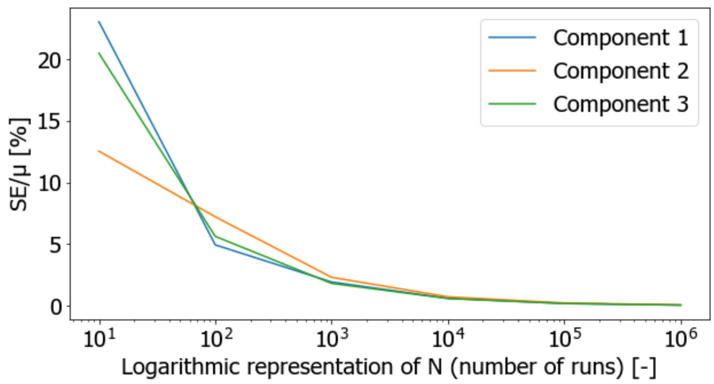

Figure 3.4: Graphical representation of the SE/μ of the results of the MCA for each of the three components as set out by the initial design Section 4.2, showing the relative deviation is below 1% for all components for the number of runs of 10.000.

code are discussed in this section. However, for replicability the code and specific choices associated with it are shown in Appendix C. The latter includes both detailed choices regarding the code, as well as detailed choices regarding how something could best be modelled.

Gathering input data using expert consultations and literature study For gathering the inputs to be used in the case application the literature study and expert consultation methodologies are used again. The application of these methodologies is the same as described previously in Section 3.2.1 and this section, respectively. These methodologies were used since both of them have already been applied earlier in the research and it was noted that the relevant information could be found using these. The list of eventual inputs and where they are derived from is shown in Appendix D. To verify the application of inputs, the manner in which they were used is verified by submitting them for review to the expert that provided them initially. It should be noted that all inputs are gathered or adjusted to eliminate inflation.

Several of the inputs are given as distributions, whereas others are given as a single value. Which of this is suitable for an input is mainly dependent on how they have been derived using the methodologies used. For example, a multitude of inputs as derived from the expert consultations is not able to be represented as a singular value, therefore it is represented as a distribution.

Estimating price evolution using Geometric Brownian Motion Estimation of price evolution is done since prices change and are subject to uncertainty (Ioannou et al., 2018), combined with the fact that the contract timespan is significant. Therefore, this influence is expected to be significant as well. Currently, this has largely not been accounted for in the academic world for asphalt valuation (Swei et al., 2015, 2017). To be able to estimate the evolution of prices several methods exist. Conventional approaches in the Netherlands include assessing the triangular distribution of the following values: timing of activities, volumes and costs. “Sampling from the distributions and discounting the life cycle costs of the various scenarios, result in a frequency distribution of their present values. Based on such graph a decision maker can conclude on the probabilities that life cycle costs will remain between certain confidence bounds” (Boomen et al., 2020, p. 13). The method’s strength lies in the fact that it is applicable with limited data. However, its weaknesses include subjectivity due to expert judgment being involved and the fact that time-variance remains neglected which therefore neglecting inflationary effects. The latter is often the case for such methods in infrastructure decision making and is important, “especially for public sector organisations which use low discount rates” (van den Boomen et al., 2020), as is the case here. These weaknesses of the triangular distribution method are solved by using the GBM. Thus, this method is chosen since it reduces subjectivity, includes inflationary effects, as well as that it accounts for uncertainty and is relatively simple in its application, especially when implementing it into an MCA (Boomen et al., 2020).

GBM describes the evolution of prices, by describing “a random walk around a time-variant expected value. Numerous random walks represent a cone of uncertainty which widens further in time around increasing or decreasing expected price values" (Boomen et al., 2020, p. 13). It does this using Producer Price Indices (PPIs), in this research adjusted for actual inflation, meaning inflation is taken out. The core of the method is shown in Equation (3.4). In this equation P_j denotes the natural logarithm of the price at time j, whereas P_{j-1} denotes the natural logarithm of th price at $j-1$. These price points are derived from aforementioned the PPIs. The μ is the drift obtained from the past prices, and the σ is the volatility obtained of these past prices. Finally, $\epsilon_j \sim$ N(0,1), a standard normal distribution, representing a shock to account for price uncertainty.

$$ln(P_j) - ln(P_{j-1}) = \mu + \sigma\epsilon_j \tag{3.4}$$

Equation (3.4) can be rearranged and used to determine price expectations for future timestamps. This is done to estimate prices at the end of the contract period. Determining the PPI regression period length is important. It should be such that it captures trends and seasonality or cyclic behaviour (Chatfield, 2003). This research uses two PPI data sets, of which one has a max regression period of 20 years. This is deemed enough to adhere to the aforementioned criteria. The other PPI can go further back, up to 1979, but to maintain similarity within the method and because it is deemed enough following the aforementioned criteria the same regression period of 20 years is used.

The price evolutions over the period of the contractual length as found using the GBM are multiplied with the MCA analyses, resulting in the residual value at the end of the contract period.

Discounting the residual value to the present The residual value as found after application of the GBM should be discounted to the current. This is done using Equation (3.5), in which the r_{real} represents the real interest rate, the interest rate without inflation. Additionally, the n represents the number of years the discounting should account for. The nominal interest rate is known (consultation meeting Remco van Duuren, personal communication, April 10, 2021) to be 5,95% and to remain comparable for the forseeable future. This should be converted to the real interest rate. This is done using Equation (3.6), in which r_{nom} expresses the nominal or inflated discount rate (including inflation, thus the 5,95%), r_{real} expresses the real discount rate and i_g represents the general inflation rate. The latter should be known to find the real interest rate. Since this concerns the future, this value can not be known. However, since the ECB targets the inflationary rate to be 2% (van Kuppeveld, 2021), this is assumed to be the value for i_g. This is in line with the past 20 years of inflation being 1,87% (CBS, 2021a). Calculating the r_{real} then results in a value of 3,87255%, which is used in the discounting calculations. Discounting the previously found residual values results in the residual values represented in current prices.

$$\textit{Present value} = \frac{\textit{Future value}}{(1+r_{real})^n} \tag{3.5}$$

$$r_{nom} = r_{real} + i_g + r_{real} * i_g \tag{3.6}$$

Sensitivity analysis The design and code as applied to the case are then further verified using a sensitivity analysis. This is done to verify if these products perform correctly and as intended. Additionally, it is used to investigate the sensitivity of the resulting design to specific variables, which is relevant for their application in the future. In essence, the sensitivity analysis is done using the following method: variables within the code are changed and the change in the results is inspected for anomalies. In this research, the sensitivity analysis is done per component of the value as set out in Section 4.2. The input variables for each of these components are changed incrementally from -50% to +50%. The change in the variable $t_{contractperiode}$, which is applied in the code for all three components, is restricted to integer values. Therefore, this is changed one year at a time ranging between 5 and 25 years. The outputs are again the μ and SE, and changes in their values from the starting input data are denoted relatively.

As to why this sensitivity analysis is done next to the already probabilistic MCA method: This research aims to find an approach for determining the residual value, as opposed to having the case application results be the final result of the study. Thus, for future application of the approach it is relevant to reveal sensitivity within this approach.

The most interesting findings of the sensitivity analysis are found in Section 4.2. All results can be found in Appendix E so that these sensitivities can be minded when applying the approach in the future.

Step 3 - Validation: expert interviews Validation is an essential aspect of the research. It is done to be able to state that the results are fulfill the need for a residual value determination approach. Several methodologies exist to validate the findings. This study adopts two of these (Creswell, 2013), next to the basic measures implemented for sound research such as asking for approval of transcribed interviews, gathering data from multiple sources two specific methodologies are used. The complete validation strategy is depicted in Figure 3.5 and the two specific methodologies are discussed in the following paragraphs.

As a first specific validation methodology, member checking is done by having the experts involved in the initial set of interviews reflect on the results as generated from the interviews. This allows for validation of the interpretation of the initial interviews (problem definition & step 1a in Figure 3.5). These experts also reflect on the final result of the research: the final residual value determination approach that is designed in the research (problem solution & step 2a). It should be noted that step 1a has validation aspects in it, as well as verification aspects. The former because it checks answers for their application in reality, the latter because it checks answers for correct interpretation. The second specific validation methodology questions a diverse set of independent experts that have not been involved in this research up until that point to reflect on both the initial interview results (step 1b) and the final residual value determination approach design (step 2b). Not being previously involved ensures their independence and adds an extra level of validation on both the results as generated from the interviews and the final design.

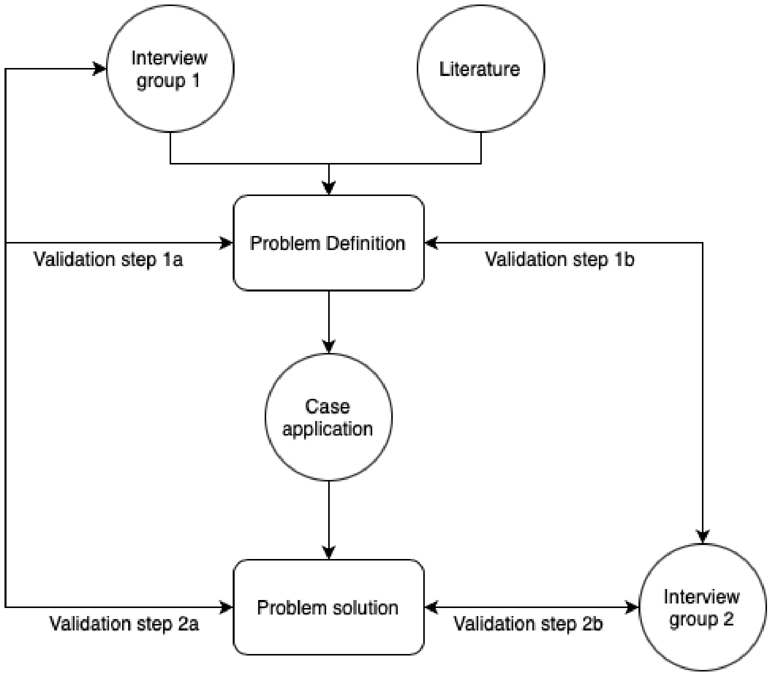

Figure 3.5: Overview of the validations done for each of the phases. The first phase (diamond 1), resulting in the problem definition is validated using the initial interview group (validation step 1a) as well as an additional independent group of experts (validation step 1b). The second phase (diamond 2), resulting in the problem solution, is validated using both this initial interview group (validation step 2a) as well as an additional independent group of experts (validation step 2b).

The two validation methodologies are done in focus groups. Focus groups constitute a research method that researchers apply for the purpose of collecting qualitative data, through interactive and directed discussions. The method is often used for validation practices (Jung & Ro, 2019). They rarely consist of more than 12 people (Wilkinson, 1998). The focus group is the method of choice since it allows to gather qualitative data from multiple participants at the same time. This is done since the participants can help each other in arriving at the right conclusions (Kitzinger, 1995). This interactivity was not desired in the initial set of interviews, since all independent viewpoints were sought for. However, for the validation this interactivity is desired since it allows for achieving consensus on what the superior approaches are for all actors on board. Two potential downsides of this approach can be that certain experts may guide the decision since they are more active in the discussion and the fact that the interviewees cannot independently state their views. The first is mitigated according to a strict agenda and actively leading the discussion. The second is mitigated using online collaboration tool Mural (Mural, 2021), elaborated upon further in this section.

As for the participants in both sessions, selection for interview group 1 (step 1a and 1b) was already done for the first round of interviews using the purposeful sampling method (see Section 3.2.1). Together with these interviewees a new session was planned, in which the participants and their associations are described in Table 3.3. Not all participants of the initial set of interviews were able to participate in this validation session. However, since all perspectives are involved in this session as well, the findings are deemed sufficient.

Table 3.3: Perspectives of participants in validation group 1, performing validation steps 1a and 1b of the interviews, along with their associations and functions.

Perspective	Organisation	Function
Contractor	Dura Vermeer	Project Manager
	Independent	Manager Sustainability
Government	Copper8	Consultant
Bank	Nederlandse Waterschapsbank	Manager Project Finance

The participants in the second validation session, with the independent, as of yet not involved experts, is again determined according to the purposeful sampling method (see Section 3.2.1), specifically the criterion sampling type. This sample should the same perspectives as that of the initial interviews, so that all perspectives influenced by the outcome are involved: the contractors, several governmental institutions from different levels and banks. Therefore, the interviewees are chosen to make sure all these organisational types are reflected in the sample. The result of this can be found in Table 3.4. For validity of the interview results the governmental organisations feature different levels of government.

Table 3.4: Perspectives of participants in validation group 2, performing validation steps 2a and 2b of the interviews, along with their associations and functions.

Perspective	Organisation	Function
Contractor	Dura Vermeer	Manager Asphalt Process
	DCW	Manager Business Development
Government	Municipality of Amersfoort	Senior Advisor Living Environment
	Rebel Group	Director/Consultant
Bank	Nederlandse Waterschapsbank	Manager Project Finance

The two focus groups have reviewed both the interpretation of the initial set of interviews as well as the final residual value determination approach. The approach and its application to the case is presented to the focus groups before the sessions, so that they can review the approach and its application. The experts received these items for review, including a guidance text, a week in advance of the session, so that they could prepare themselves. As for the structure, setup and conditions within which to conduct the interviews are established according to basic principles found in literature (Baarda, 2017; Fellows & Liu, 2008; Fowler, 1995). The sessions were guided strictly using the protocol as shown in Appendix F, which incorporates questions regarding both the interpretation of the initial set of interviews (subject 1 in the appendix) as the designed final approach (subject 2 in the appendix). This strict guidance is applied to allow all perspectives to be heard for the questions. The moderator did not argue on the results, only provided clarity or answers when desired. While the session protocols for the two groups were largely the same, the group of initial interviewees has more time on the first subject to allow extensive review of these interpretations. The interviews were performed digitally, because of the COVID-19 pandemic and associated rules as imposed upon society. The session used Mural (Mural, 2021), an online collaboration tool that functions as a whiteboard on which all participants can draw simultaneously. This allowed for easy individual answering followed by discussion to achieve consensus afterwards. For discussing each topic (see Appendix F) the following questions gave the discussion direction such that it served the purpose of the validation. It should be noted that the first question is only applicable to the group that had initially been interviewed already:

- Are the results of the interviews interpreted correctly?
- To what extent does this equal reality?
- How realistic and achievable is the application of the results for the desired goal of infrastructure residual value calculation in PSS context?

3.2.3. Overview applied methodologies

Figure 3.6 shows the Double Diamond model, together with the chosen methodologies for each of the phases. As shown, the literature study and expert reviews of the first diamond together lead to the problem definition. Then, the expert consultations lead to the first design, which is then applied to the case for verification purposes. Finally, using expert reviews the findings are validated. These three steps sequential steps are part of the second diamond that leads to the problem solution: the residual value determination approach. With respect to the second diamond the following is noted: this research undertakes one of the first steps in the application of the residual value to PSS in the infrastructure context. Therefore, specifically the design process of the second diamond is documented extensively, which can be relevant for further studies.

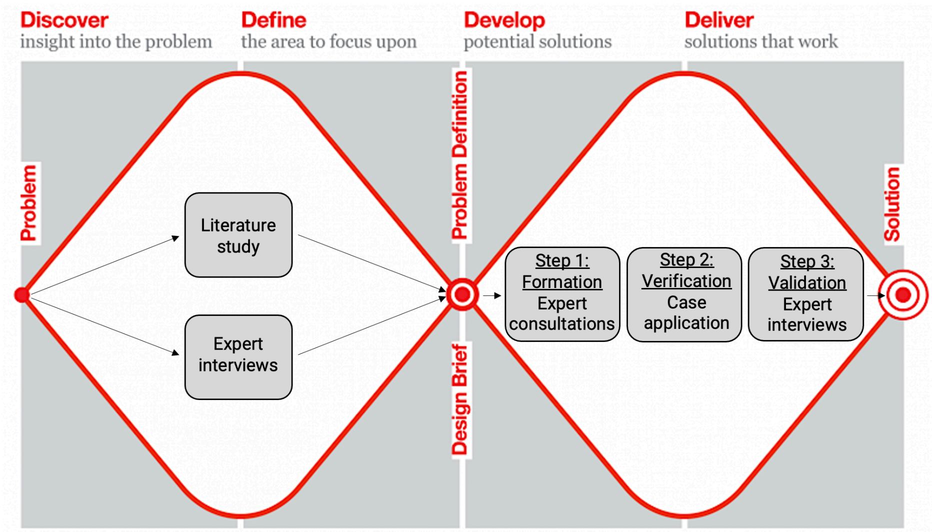

Figure 3.6: Graphical representation of the Double Diamond process model, together with the chosen methodologies for each phase represented in each of the diamonds.

4

Results

Applying the methodology as discussed in the previous chapter, this chapter contains its application and the results of this study. The aim is to answer the third research question. This is done by first presenting the resulting definition of the problem in Section 4.1, followed by a solution fitting with this problem definition in Section 4.2. A concise overview of the main findings and assumptions is given in Section 4.3.

4.1. Diamond 1: problem definition

As stipulated in Chapter 3, the first diamond results in a problem definition. The methodologies used for arriving at this defined problem are the literature study and the performed interviews. This section provides the combined results of these studies, to arrive at the integral problem definition. This is discussed according to a structure that has been identified using both the findings from the literature study and the interviews. This structure is described in the following list, and graphically represented in Figure 4.1.

- The goal of determining the residual value of the asset. Literature findings indicated this is an important first step to be able to find the relevant components to be incorporated in the valuation approach. Discussed in Section 4.1.1;
- Main components that should be featured within the residual value determination approach. Only following the establishment of the goal, the components that should constitute the value can be determined. Discussed in Section 4.1.2;
- Valuation techniques that can be used to determine the value of the aforementioned components. After determining which components should be featured within the value, fitting valuation techniques can be selected. Discussed in Section 4.1.3;
- The additional considerations that should be minded in the approach design. Several additional considerations, next to the more important requirements above, are relevant for the overall design of the approach. Discussed in Section 4.1.4.

These four topics have as of yet not been researched together and in this order within the infrastructure, residual value and PSS contexts. The results are combined to form a final problem definition, concluding the first phase (first diamond) of the research in Section 4.1.5.

4.1.1. Goal

According to the literature study the goal of determining the residual value should be known, as this enables a thoughtful consideration of which requirements, components, valuation techniques and additional considerations should be taken into account. This is also backed by the interview with a financial expert (interview, manager project finance NWB, personal communication (PC), 17-04-2021). The goal of determining the residual value is defined as follows:

To create a practically applicable financial incentive for the involved parties to adhere to the CE principles, within the context of PSS applied to infrastructure assets.

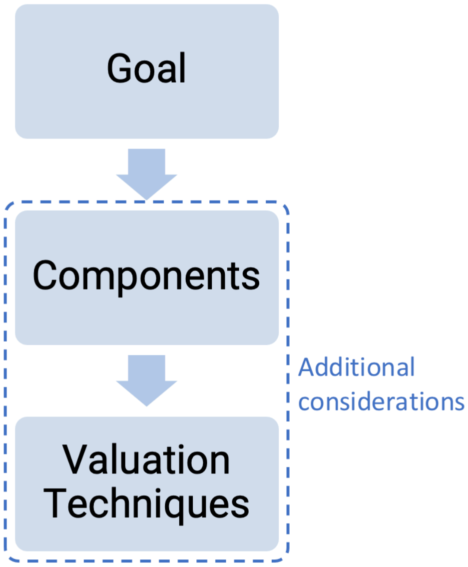

Figure 4.1: A visualisation of the structure that contains all the elements of the problem definition. As the visualisation reveals, recognising the goal allows for determination of suitable components, valuation techniques and additional considerations.

The four main aspects as mentioned in the goal were deemed important by the interviewees. These are discussed in the following paragraphs consecutively.

First, 'incentive to adhere to the CE principles'. For the interviewees, this is deemed one of the most important factors of investigating this subject. Nearly all interviewees mentioned circularity or a form of circular behaviour as the main driver for this endeavour. This is a logical find, since contributing to the CE principles is also one of the main goals of this research and DCW and the residual value should be a means to incentivise that project.

The second aspect is 'financial'. This is in line with the question as to why the financial residual value should be considered at all for creating an incentive, as opposed to other, non-financial alternative incentives. The following is found using the interviews: incentivising the contractors to behave in a circular manner can be done in several ways. One of these is using quality agreements at the end of the concession period, as is currently the case with integrated contracts. Another is using a financial stimulus in the form of a residual value. The interviews have revealed that the latter is the preferred option, since with the former option the contracts will optimise too much towards this quality, as opposed to maximising the lifespan by applying the financial incentive (interview, manager sustainability Dura Vermeer, PC, 19-02-2021 & interview, manager business development DCW, PC, 11-02-2021). This is because the business model for the contractors currently works as follows: the goal is to be able to operate at the lowest cost possible, which is done by narrowly satisfying the contractual agreements at the moment of delivery. Setting quality agreements for the contractor to meet still gives the contractor the ability to make the business model work in this fashion. By creating a financial incentive in the form of the residual value of the asset, the asset's technical lifespan is decoupled from its contractual lifespan. This creates a situation in which the perspective is aimed at the future, instead of at the moment of concession or delivery, thereby adhering to the first two principles of the CE as mentioned in Section 2.1.1. Additionally, financial stimulus allows for comparison of aspects of the business model, which helps to compare incentives (interview, sustainability officer NWB, PC, 25-02-2021). Finally, financial incentives allow for aiming beyond the initial goal as opposed to set agreements (interview, consultant Copper 8, PC, 01-03-2021). However, it is noted that agreements should be allowed to exist alongside financial stimulus as well (interview, consultant Alba Concepts, PC, 02-03-2021).

The third aspect is 'practically applicable'. As was found in the problem definition in Section 4.1, several requirements and considerations have to be met for the designed approach to work and potentially be implemented as intended. These include factors such as 'financeability', a factor that is significant for infrastructure construction (interview, manager project finance NWB, PC, 17-04-2021), 'acceptance of use', 'data available', 'comprehensible complexity', 'consistency', etc. These can all be grouped under 'practical applicability'. Several interviewees mentioned that it is an important factor to the extent that the final approach as designed in this research needs to be usable (interview, manager sustainability Dura Vermeer, PC, 19-02-2021), as long as this does not go at the cost of quality of the approach (interview, sustainability officer NWB, PC, 25-02-2021) or transparancy (interview, manager project finance NWB, PC, 17-04-2021 & interview, consultant Alba Concepts, PC, 02-03-2021).

The fourth, 'within the context of PSS applied to infrastructure assets' has not been mentioned with respect to the goal during the interviews. However, since that is the context within which this research operates and aims to find its result and since literature findings indicate strong influences of the context on the residual value, this is added so that this context is minded during the design phase.

Extent of the incentive Current residual value estimates, that are not applied in the Netherlands, are between 2%-5% of the original construction costs, using the Net Salvage Method. According to the interviewees, this is not enough to provide an incentive for circular behaviour. According to the interviewees, a residual value figure should be at least 10%-20% of the original construction costs to provide this incentive. It should be noted that several interviewees have mentioned that this is a rough estimate which is not based on existing data, but rather on experience. This is an interesting find, since information on this subject is currently lacking. While designing the approach for the residual value determination, achieving this percentage should not be a goal in itself, but it should be minded to check if the incentive is created.

4.1.2. Components

Following the establishing of the goal of determining the residual value, the components that should be represented therein can be considered. The interviewees mentioned two main requirements these components should meet:

1. **Serve the circular incentives:** since the main goal of implementing the residual value is to create an incentive to adhere to the CE principles, the components should also aim to achieve this goal. This aim was reflected in most interviews. The following finding from the interviews is relevant: when aiming for the goal as described in Section 4.1.1, the CE principles should not be incorporated in some direct form as components themselves. The components should be a means for achieving the goal of adhering to the CE principles. This is not done by incorporating the CE principles directly as goals.
2. **Be financeable:** for the residual value to be able to achieve its main goal the practical requirement of financeability should be maintained. As shown in the literature study external financing is an essential aspect of the application of PSS in the infrastructure sector. This was confirmed by the interviews in which the financial experts especially highlighted this aspect (interview, manager project finance NWB, PC, 17-04-2021 & interview, sustainability officer, PC, 25-02-2021). The requirement constitutes of two separate aspects:
    - Financeable by banks or investors: the components contained in the residual value should fit within the requirements as stated by these financiers. The interviews have revealed that investors will most probably not hesitate to finance a project, even though the cashflow resulting from the residual value is years out with all the associated financial risks, provided that the client, in this case the government, is willing to pay for the residual value. However, the residual values determined over the lifespan of an asset should be related continuously throughout time, for consistency purposes.
    - Financeable by government: first, this is important to be able to meet the first requirement. Second, without an agreement on the government's part on that all the components in the residual value determination approach will be paid for, the incentive can not be counted on and therefore will not work. Specifically mentioned during the interviews is that this is simpler to achieve when the determined value also represents aspects that are valued today, in the sense that other actors also apply comparable value to such aspects.

4.1.3. Valuation techniques

As mentioned in the literature study, several valuation techniques can be considered to determine the value of the different components discussed in Section 4.1.2. Following the literature study, the interviews have shed light on the applicability of the valuation techniques as well. First, findings regarding the requirements that the valuation techniques should fulfill are discussed. Then, all the discussed valuation techniques and the findings with respect to the requirements are discussed. Further on in the section the valuation techniques' fit with respect to the components (see Section 4.1.2) are discussed. The following list shows the requirements the valuation techniques should fulfill, according to the interviews:

- Be applicable: the techniques should be realistically applicable. What this means is shown using the following aspects:
  - Acceptance of use: as discussed in Section 4.1.2, financeability of the components is one of the two requirements. Turning towards the valuation techniques, this works through in the fact that organisations accept the use of this technique for valuating (aspects of) assets.
  - Comprehensible complexity: while complexity in itself is not regarded as a problem, choices for determination of the residual value in a certain manner should be able to be substantiated and should lead up to a an applied technique that is comprehensible for those involved. This should make the technique more practical in its use, which is important for conventional use (interview, consultant Copper8, PC, 01-03-2021). It should be noted that reducing complexity is inferior to transparency and quality of the approach (interview, consultant Alba Concepts, PC, 02-03-2021).
  - Data availability: for ease of use, the data required should be either readily available for a project, or easy to retrieve.
- Consider present or future perspective: following the components that provide a circular incentive, the valuation techniques implemented should adhere to this also. According to the interviews, this is achieved with the present- or future-oriented valuation techniques, as opposed to past oriented techniques (interview, director structured finance, PC, 31-03-2021).
- Consider condition: maintaining the condition of assets and materials is reflected in both the first and second principle of CE. Therefore, this should be reflected in the valuation techniques that are applied to the first two components. This is considered crucial by all interviewees.

4.1.4. Additional considerations for the approach

Now that the basic structure of the residual value determination approach has been established using the required components and the associated valuation techniques, several additional considerations, next to the requirements previously discussed, that have resulted from the literature study and interviews should be noted. The difference between the requirements and these considerations is that the requirements are of greater importance when choosing components and valuation techniques than the additional considerations. Additionally, the considerations apply to the designed approach in its entirety, encompassing the components and techniques, whereas the requirements are more specific to either the components or techniques. Because of this, some overlap exists between requirements specifically for the techniques and the considerations. The framework these additional considerations operate within is visualised in Figure 4.3. The considerations are shown in the following list, along with a brief reflection on their origin:

- Transparency: for the involved parties to be able to make sound decisions and therefore for the incentive of the residual value to work, the applied determination approach for the residual value should be used in a transparent fashion. All the considerations behind the approach, as well as the choices made for the estimation of the actual value, should be available to all those involved. This factor was noted to be important by all interviewees, especially for communicating the incentive (interview, manager business development DCW, PC, 11-02-2021) by the financial experts as it is required for financeability.
- Account for value fluctuations: fluctuations of the determined residual value during the contract period are not necessarily a bad thing, as long as strategies are implemented to know what to do in the instance of contract termination at another value than aimed for due to for example market conditions (interview, manager project finance, PC, 17-04-2021). Strategies can be implementing floor and ceiling prices, as well as including risk pricing. If these are then guaranteed by the client (governmental institution), fluctuating intermediate values will not pose a problem for either the financiers or the contractors (interview, consultant Alba Concepts, PC, 02-03-2021).
- Account for accuracy at concession: this consideration can be viewed in the same light as the previous bullet.

- Avoid complexity: the residual value determination approach's complexity should be avoided when possible, but as addressed in the first bullet, the approach and its choices should be handled with transparency first in mind, that is the more important factor (interview, manager project finance NWB, PC, 17-04-2021 & interview, consultant Alba Concepts, PC, 02-03-2021). Additionally, avoiding complexity should also not be at the cost of the flexibility as mentioned in the final bullet, since that allows for more circular innovation within the PSS context (see Section 2.2.2).
- Be in accordance with law: this is an important aspect, in which currently no problems are foreseen (interview, manager project finance NWB, PC, 17-04-2021 & interview, consultant Copper8, PC, 01-03-2021). It should be noted that specifically for the case of the municipalities, these are not allowed to account for inflation in their administrations, thus making the residual value incredibly low. This consideration does not mean that if this research results in findings that might need changing the law that these will not be discussed.
- Be consistent on approaches and agreements: not being consistent on these aspect results in inefficiencies and added risks, which will be priced accordingly (interview, manager project finance NWB, PC, 17-04-2021). Thus, to remain efficient and keep the price as low as possible, consistency on approaches and agreements should be ensured.
- Be flexible: as shown in the literature study (see Section 2.2.2), circular innovations in PSS business approaches are stimulated by giving away responsibility and freedom. Therefore, this is a significant additional consideration that should be minded in the design.

4.1.5. Resulting problem definition

The results as found in the previous sections can be grouped according to the structure as provided in Section 4.1, resulting in Figure 4.2. This combination of goal, requirements and considerations can be regarded as the extensive problem definition, thereby concluding the first diamond and partially answering the third research question. These results are used to find a suitable solution in Section 4.2.

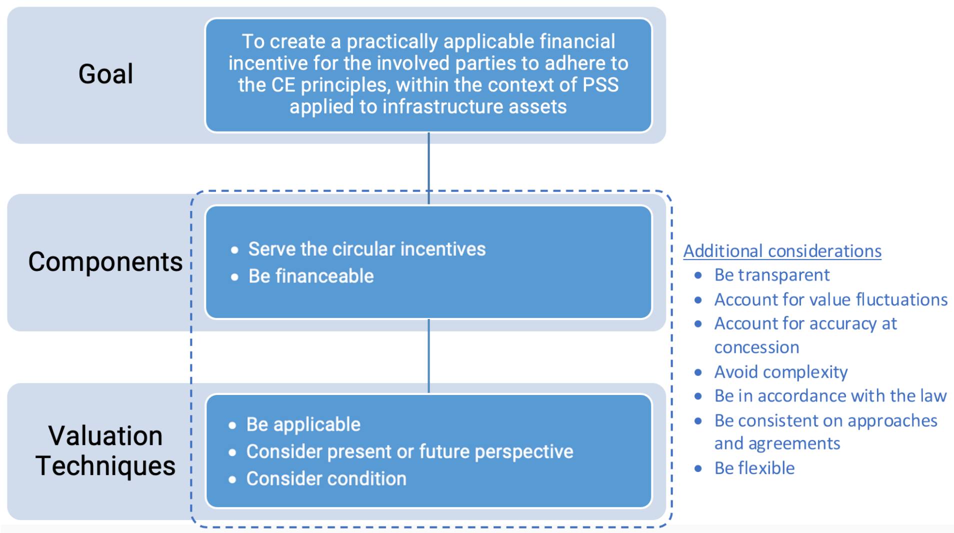

Figure 4.2: A visualisation of requirements as fitted within the structure provided in Section 4.1. As the visualisation reveals, recognising the goal reveals requirements for the components, followed by requirements for the valuation technique. Finally, several additional considerations are applicable to both the components and valuation techniques, in other words: applicable to the technique as a whole.

4.2. Diamond 2: problem solution

This section aims to elaborate on the results found in this research. This is done by first discussing the design of the basic model in Section 4.2.1, after which the separate component equations are detailed in Section 4.2.2. Finally, the combined design is shown in section 4.2.3.

4.2.1. Basic model design

Using the requirements found in Section 4.1, the structure as devised at the start of the aforementioned section (see Figure 4.1) and some additional research the basic model can be constructed. This is done in the same order as in Section 4.1, other than that the goal is already determined. This model serves as a basis for the following design steps in the subsequent sections.

Components Of the components found in literature and discussed in the interviews, two fully meet the requirements as stipulated in Section 4.1.2. Therefore, these should constitute the main components of the residual value determination approach. A third component is currently only partly in accordance with these requirements, but is expected to be more so in the future. Therefore, this component is mentioned as an optional third component.

1. Physical value: this value represents the value of the physical materials present in the asset. The first requirement, serve the circular incentives, is met since incorporating this value satisfies the first principle of the CE, as described in the literature study. The second requirement, be financeable, is met since the interviewees stated that the government already intends to take this component into account in future projects. Additionally, it is the expectation in literature as well as in practice is that in the near future, a market will exist for these materials, reducing the added cost of the government in this regard.
2. Functional value: this value represents the value the asset has for performing its function for the client, in this case a governmental institution. The first requirement is satisfied because the incorporation of this component meets the second principle of the CE, as described in the literature study. The second requirement is fulfilled since it is the core of this component that it represents the value the asset has for performing its function for the client. Therefore, the interviewees have expressed the expectation that this aspect will be financeable in some form.
3. Optional - Environmental value: this value represents the value of the prevention of environmental externalities of the life cycle of the asset. This value satisfies the first requirement, since it contributes to the third principle of the CE. The second requirement is currently not yet met. While the government contributes to measures preventing negative externalities and exact determination of the costs or benefits of these preventive measures is possible, the valuation techniques for this are not yet agreed upon. However, the expectation is that this will change in the future. To make the results of this study also applicable in the nearby future, the research will henceforth consider this component as an optional aspect of the residual value determination approach.

The extent to which the residual value consisting of these components achieves its goal of incentivising the contractors to behave in a circular fashion is difficult to ascertain at this point. However, incorporation of the first two and optionally the third component aligns the residual value determination approach with the first two and optionally the third principle of the CE. Therefore, it is for now assumed that this goal will be met, allowing the research to continue into the next phase, fitting the valuation techniques.

Valuation techniques How the requirements as described in Section 4.1.3 are reflected in the different techniques considered is shown in Table 4.1. The contents of this table are a combination of the outcomes of the literature study as well as the interviews. This table shows that there are four valuation techniques that should be considered. Both the NPV technique and the Market Value seem to be fitting options as they meet all the requirements. The WDRC can potentially meet all the requirements. Since it can be considered to be an elaborated version of the NPV technique, it will be considered in the continuation of this research as an option that exists under this umbrella. Finally, the CBA is an option that, however not meeting all the requirements, should be considered. First, it does not meet the acceptance of use criterion. Nonetheless, as described in the previous paragraph, this can be the case in the future for the environmental externalities. Secondly, the technique is not able to consider the condition of an asset. However, its potentially accepted applicability is limited to the third potential component as described in Table 4.1. This component is linked to the third principle of the CE, in which the condition does not play a role. Therefore, this technique is considered further as well.
Finally, the three components as described in the final list of Section 4.1.2 can be matched with the most fitting valuation techniques. This is done based on the results in this paragraph as obtained using the literature study and the interviews. The components and their respective techniques are stated in the following list:

Table 4.1: The suitability of the considered valuation techniques according to the requirements as set out using the interviews and literature study.

Valuation technique	**Acceptance of use**	**Comprehen-sible complexity**	**Data available**	**Present or future perspective**	**Able to consider condition**
NPV of future benefits and costs in annuity	Yes	Yes	Yes	Yes	Yes
Perpetuity technique	No	No	No	Yes	Yes
PV of past costs	Yes	Yes	Yes	No	Yes
Market Value	Yes	Yes	Yes	Yes	Yes
Written Down Replacement Costs	Potentially	Potentially	Yes	Yes	Yes
Net Salvage Value	Yes	Yes	Yes	Yes	Yes
Cost Benefit Analysis	No	Yes	Yes	Yes	No

- Physical value: the best suited technique for valuation of the physical value is the Market Value technique. The technique is chosen as opposed to the CBA and NPV techniques because of its high acceptance and easy application into existing markets. It should be noted the technique is specifically applied to the material or product level. Higher levels would introduce more significant incentives, as discussed in the literature study, however, are not applicable since market comparisons on this level will always remain difficult.
- Functional value: this can best be valuated using a type of NPV technique. The CBA technique is not used as it is not accepted and does not consider condition. The Market Value technique is difficult because market comparisons based on function are non-existent within the infrastructure sector. Several options exist within this typology, of which some are yet to be explored. From the interviews, two main techniques were concluded to be viable options. First, the WDRC technique and second a technique considering the future maintenance work that does not have to be performed due to the quality the road has at the end of the concession period. As can be seen, these options consider mainly the cost perspective, whereas the interviews have stated that finding what actually defines the functional value of an asset from a non-cost perspective. More research should be done in this regard, mainly into other valuation options as implemented in for example real estate, since this is a market where value does come from other perspectives than the cost perspective. To realise the highest value and thereby the biggest potential circular incentives, the valuation technique should be applied to the highest possible level. This is the most effective according to the interviewees.
- Optional - Environmental value: the only fitting technique in this case is that of the CBA, since NPV and Market Value do not allow for valueing benefits and costs that cannot directly be monetised. While its use is not yet accepted, it is the only practical option for considering the value of taking action to prevent negative externalities.

An aspect often linked to the CE concept that might seem to be missing is the split in primary and secondary materials, meaning materials that are used for the first time or materials that have been used before, respectively. This is not taken into account separately, for two reasons. First, from the interviews the expectation is derived that the growing market for materials accounts for this potentially conditional difference. Therefore, it is already reflected in the physical value of the materials. Second, if a client wishes to incorporate more primary or secondary materials in a project, this should be incentivised for each project specifically and this should in that case not be done using the residual value. Other mechanics, such as applying a bonus for using more secondary material at the inception of the project should be used for this purpose. This does not align with the goal and requirements of the residual value as set out in this research. Another aspect that might seem to be missing is that of an incentive for sustainable design choices. An example of this can be the addition of storage solution in the design for the storage of CO2 beneath the road. First, this is partly taken into account using the optional environmental. Second, as with the aforementioned aspect, such design choices are not directly aligned with the goal and requirements of the residual value as set out in this report and should therefore not be considered as a separate component. If a client has the wish to incorporate such constructions within the design, then this should be incentivised using another method. A third aspect that might not directly appear to be implemented in the components and their valuation techniques is that of the dismountability of the asset, which is one of the characteristics and prerequisites of the CE to work successfully. However, by applying the Market Value technique to the physical value, this is automatically incorporated in the residual value determination approach. This is because the value of the material or building product only exists once the buyer can use it again, which is the case if it is demountable. Therefore, this is accounted for in the residual value determination approach. Finally, an aspect that is not reflected is the land value or the value of rights such as the right of construction and exploitation for the region. These are not taken into account since these do not align with the goals and requirements of the residual value as set out in this research, since it does not contribute to the CE principles. These values might be represented in the complete financial model, of which this residual value is a factor, but investigating this lies outside of the scope of this research.

Resulting basic design Combining the results as described in the previous paragraphs with the structure as provided in Figure 4.1, reveals the results and their relations as graphically represented in Figure 4.3. This shows the main goal of the residual value determination approach, the components that follow from this goal, as well as the valuation techniques fitting for these components. The additional considerations are not specifically shown in the visualisation, but their area of effect is. This graphical representation can be viewed as the basic model for the approach this research set out to design. This model serves as a basis for the following design steps in the subsequent sections.

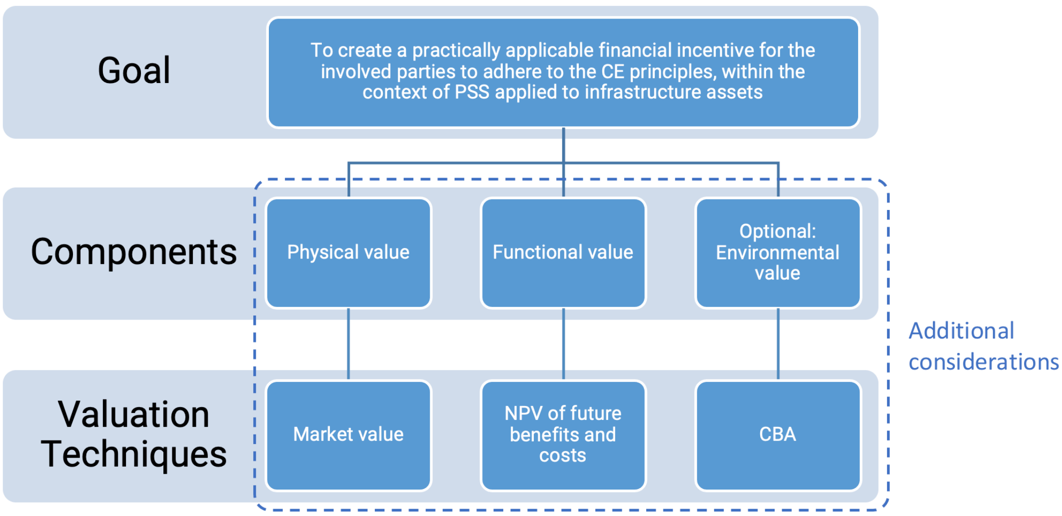

Figure 4.3: A visualisation of the results and their relations. As the visualisation reveals, recognising the goal allows for determination of suitable components: the physical value, functional value and optionally the value of externalities. Additionally fitting valuation techniques are matched and found. Finally, additional considerations have to be minded when designing the approach.

4.2.2. Equation design

Now that the basic design and its requirements are designed, the design of the residual value determination approach can be specified further. This section captures this process narratively, since all the generated sub-results such as the results of the case analysis influence choices that are part of the final result: the residual value determination approach. Additionally, it is done to reflect all steps and subsequent choices made during the process of this research, so that these can be reviewed if needed in further research. This narrative-style presentation is shown for the three basic components in the subsequent three sections. For readability purposes, all sections start with the final results, comprising of the basic idea behind the equation for that specific component, the devised equation and assumptions that the design of the equation resides upon. Then the iterative design process is described by reporting on the three subsequent steps in this process: formation of initial design by using expert consultations (step 1), verification of the design by applying it to a case (step 2) and validation of the design using expert interviews (step 3). Within all three steps, the formation, adaption, verification or validation of the aforementioned assumptions is discussed.

Regarding the reflection on the equation design and specifically the assumptions using the basic design and its requirements, it should be noted that for conciseness not all design criteria as reported in Section 4.1.5 are mentioned. The design criteria not represented can be expected to be met.

4.2.2.1. Physical component

The final result for the valuation of the physical component is described by first discussing the basic concept behind the resulting valuation approach. This is stated as follows:

The market value of an element present in the asset at a certain point in time.

This concept aims to value the physical aspect of (an element of) an asset, be that a low quality element such as its basic material or a more high quality element such as a product or even the entire asset. It does this in such a way that the decrease in market value as opposed to new(er) comparable products due to quality reductions or costs for making the asset available to the market such as disassembly, processing, transportation and storage are taken into account. Finally, it does this for a certain point in time in the future. Knowing the basic concept, the associated equation can be stated, which is shown in Equation (4.1).

$$\textit{Physical value}_{Used,t} = \textit{Market value}_{New,t} - \textit{Reuse reduction}_{Used,t} \tag{4.1}$$

In this equation variables denoted with *Used* describe the element that is currently present in the asset and has been used up until now. *New* describes equivalent elements as bought in the primary market, the market for virgin and unused elements. The *t* denotes the time at which the associated value is computed for the element. $\textit{Market value}_{New,t}$ represents the market value of an element if bought in the primary market at time t. The second variable is the $\textit{Reuse reduction}_{Used,t}$, which describes the reduction in price as compared to the $\textit{Market value}_{New,t}$ either as a percentage or absolute value for the $\textit{Physical value}_{Used,t}$ to be marketable. This means that the reuse reduction should be interpreted as broad as necessary for the contractor to arrive at a marketable physical value for the element. Generally this would include a quality reduction for currently using the element up until time t, as well as costs associated with disassembly, processing, transport and storage. Some costs might not be applicable or some might be added, dependent on the reuse type and how the element becomes marketable.

The equation and the variables are defined quite broadly. This is done on purpose to ensure applicability of the equation, as well as provide freedom and thus enable innovation to stimulate circularity goals, per the theory as set out in Section 2.2.2, while still maintaining proper boundaries to adhere to the definition of the value of the specific component.

As can be seen in the subsequent paragraphs, the main sources used for the expert consultations and expert interviews are actively involved in the infrastructure construction industry and the adjacent financial fields. Therefore, this result, as presented in the aforementioned equation should be viewed within this light as well: it is formed with mostly practical needs and generally accepted practices in mind.

The application of this equation rests on the following assumptions and conditions, that will be addressed in more detail in the following sections:

Assumption 1: A secondary market is available for all physical elements in the asset;
Assumption 2: The secondary market provides an incentive for delivering elements to this market allowing for the highest quality reuse reasonably possible;
Assumption 3: The secondary market provides an incentive for increased ability to disassemble assets or products;
Assumption 4: The equation does not differentiate between assets initially originating from the primary or secondary market;

Assumption 5: For this equation to perform correctly it does not matter whether regular maintenance is performed or not;

Assumption 6: The costs for bringing the elements to market are represented in the *Reuse reduction$_{Used,t}$*.

Step 1 - Formation of initial design: expert consultations As described in Section 4.2.1, the best fitting valuation technique for the physical value is the Market Value technique. Using this as a basis, the basic concept leading up to Equation (4.1) was formed by consulting experts on materials and their valuation (consultation material value experts, PC, 06-04-2021 & 22-04-2021). These expert consultations revolved around checking whether the Market Value technique seemed fitting to them, as well as how this could specifically be approached in the context of PSS and highway infrastructure assets. These expert consultations also led to two basic forms of the equation as presented in the previous section. The first is quite comparable to the final equation. The second is different in that it does not take costs such as disassembly, processing, transport or storage into account. This second form reasons from the idea that the value is based upon how the elements are represented in the asset, not how they are brought to market, whereas the first form reasons from the idea that an elements' value is represented in its value when it is brought to market. The concept behind this second form is that is is simpler and more free and therefore allows for higher applicability and innovation, leading to more circularity, as discussed in Section 2.2.2. These forms were then compared to the results of a parallel project (Alba Concepts, 2021). This raised questions regarding the equations, after which a consultation was held with an expert involved in the parallel project to review some of their choices (consultation expert parallel project, PC, 30-04-2021). Additionally an expert consultation was had with a real estate expert (consultation real estate expert, PC, 08-03-2021), to see to what extent valuation approaches in the real estate market could be applicable. This resulted in the view that most valuations are done using the Market Value technique, mainly based on the location of the asset. In case no market is available, a cost approach is used combined with a technical or economic depreciation. The former is applicable for this component, apart from the dependence on location. The second is not applicable since it it does not meet the requirements 'serve the circular incentives' and 'consider present or future perspective'. Using the information gained during this first step, the assumptions were formed as follows:

Assumption 1: Currently there is not a working secondary market for all significant elements in the construction sector. However, for the valuation to have any monetary value and thereby being financeable, this assumption has to be made.

Assumption 2: Literature has provided the insight that high quality reusability leads to higher value (Platform CB23, 2020b). In line with this finding, the assumption is made that higher quality elements provide enough extra value for an incentive to provide them to the secondary market at a quality as high as reasonably possible. This assumption is made to ensure applicability, flexibility and reduce complexity, thereby directly adhering to the PSS principle that states that more freedom leads to more potential for reaching circular goals.

Assumption 3: Generally, (more) simple disassembly allows for more circular use of assets, which is one of the main facilitators of the CE. The resulting equation's design does not provide a separate incentive for increasing the ability for disassembly. Therefore, it can be argued that the equation does not adhere to the first and second CE principles (see Section 2.1.1). However, the choice not to include this incentive follows from the assumption that the lower disassembly costs and higher prices following from high quality reusability (Platform CB23, 2020b) directly incentivises clean disassembly nearly as much as a specific stimulus. Clean disassembly is an important aspect of the first two CE princples. Not including this incentive ensures applicability, flexibility and reduces complexity, again leading to more potential for reaching circular goals.

Assumption 4: In literature, methods for measuring circularity do differentiate between the use of materials from primary or secondary markets (Platform CB23, 2020b). However, since this residual value determination approach aims to provide a real, financeable value, this distinction is not made or valued. This is not done since this can not be reflected in the pricing of the secondary market, as that only accounts for the quality of the product, not the amount of reuse it has experienced. The reason this is implemented in the Platform CB23 measurement method in literature is because their goal is to measure circularity in construction, which is significantly different from the goal of the approach designed here.

Assumption 5: The way the equation is set up only the quality at time t matters. Therefore, maintenance is indirectly included within the equation itself.

Assumption 6: The physical value should be determined as being the value at which the elements can be brought to market, in which the costs for bringing the element to the market should be represented. This is because this allows for much better representation of the value of the elements to all actors involved. Only if the aforementioned costs are significantly different for the different actors these should not be included. However, since that is not the case for the infrastructure sector, the costs should be included to give the best representation.

Step 2 - Verification of design: application to a case In the application of Equation (4.1) to this specific case it was easier to find material pricing in which the *Reuse reduction*$_{Used,t}$ is already taken into account. These prices are represented by variables 1-4 in Appendix D. The input variables are denoted by their number for conciseness and clarity of the report. In these variables a distinction is made between the asphalt material without bitumen and the bitumen itself. Combined with variables 6 and 7, the amount of tons material that can be retrieved by scraping the asphalt from the asset are determined. The expected future prices for the bitumen and other asphalt materials are determined using the GBM method, adopting variables 7-10 as the the drifts and volatilities, combined with the contract period, variable 12. Multiplying the expected prices with the amounts of material as retrieved from the asset results in the residual physical value. This is then discounted to the present using variables 11 and 12. All these calculations are done for multiple runs for the MCA. The calculations can be found in the code and its description in Appendix C.

The case analysis yielded the MCA results as depicted in Figure 4.4. The μ (average value) is 187.782,18 euros, with an SE of 1.147,79. Furthermore, 90% of the values ranges from 59.321,54 to 403.390,95. This 90% is chosen such that it cuts of the right tail of the results.

As for the significant spread of the results, this is shown to be mainly the case because of the high volatility as determined using the CROW input data for the evolution of the prices in the future using the GBM method (see Section 3.2.2, as decided based on consultation meetings. Using CBS data for this input as is done for the other GBM analyses yields significantly lower results, as is shown in Figure 4.5. Therefore, the assessment is made that this spread does not imply that the equation is not applicable, since a high spread using any input would not make the equation applicable for use in estimating a residual value, but that this is only dependent on the input chosen for this case analysis.

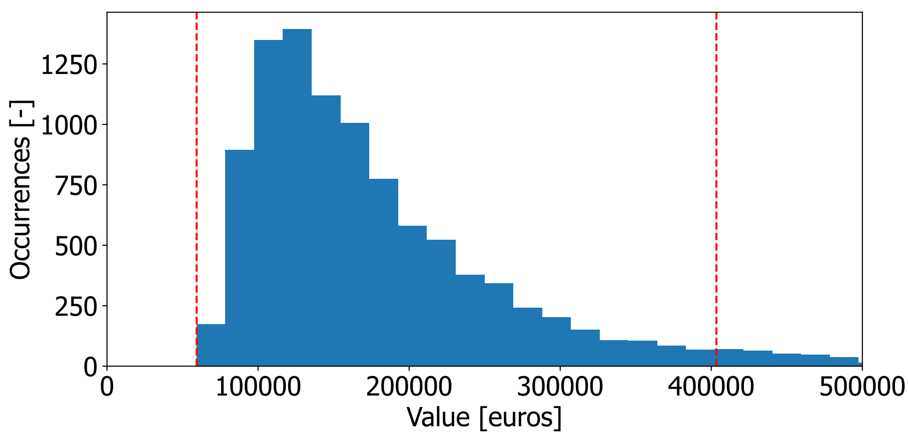

Figure 4.4: Results of a Monte Carlo analysis performed for the physical component of the residual value of the case. Represented discounted to 2020 euros.

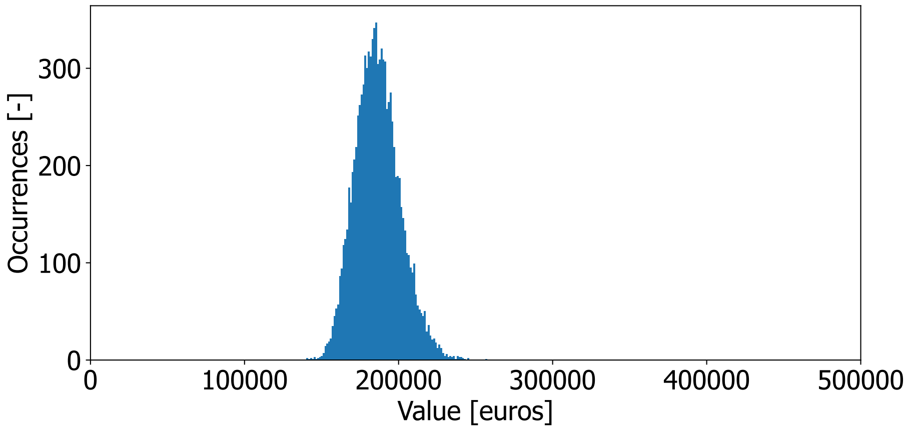

Figure 4.5: Results of a Monte Carlo analysis performed for the physical component of the residual value of the case using CBS data as used for the other components, resulting in a lower spread. Represented discounted to 2020 euros.

All results of this sensitivity analysis, for both the μ and SE were as expected with no standout values, thereby verifying that the equations performs its function as intended and that the application of the equation to the case has been done correctly. An overview of the results of the sensitivity analysis on the Monte Carlo analysis for the physical component can be found in Table E.1 in Appendix E.

Using the information gathered in applying the equation to a case the assumptions were adapted or verified as follows:

- Assumption 1: This assumption turned out to be existential. Without this assumption applying the equation would not result in a value that approaches reality. This does however, imply that it is important to validate this assumption, otherwise the equation will not be applicable in the future.
- Assumption 2: Applying the case has resulted in the view that this significantly increases applicability of the equation by reducing complexity and increasing flexibility of the application.
- Assumption 3: Through application of the case, it is found that this significantly reduces complexity and increases flexibility of the application, thereby increasing overall applicability.
- Assumption 4: Application of the case has revealed that this significantly increases applicability of the equation. This is done by reducing complexity and increasing flexibility of the application. Additionally, applying the case has also shown that this would be difficult to implement for the residual value, since this is assessed more easily at the start of the project.
- Assumption 5: This is confirmed during case application. While including maintenance has an effect on the value, this is compensated by the operational costs over the lifetime of the asset which lies out of the scope of this research.
- Assumption 6: While it is more resource intense to determine the associated costs than not having to do that, this can currently be done using many standards and does not take much resources in general.

Step 3 - Validation of design: expert interviews The validation, see Appendix G for the mural results, showed that the basic idea and the devised equation is an approach that gives a realistic estimation of the physical value and that it is an applicable approach as well. Regarding the assumptions, these are adapted or validated as follows:

- Assumption 1: During validation it was confirmed that this is a logical assumption since the expectation is that material demand will continue to rise and that a secondary market will therefore exist for most significant materials in construction in the near future. Specifically for asphalt materials this is expected to be the case.

Assumption 2: This was validated as being applicable and providing a result true to reality, since the underlying assumption is expected to be correct. The following note should be mentioned in this regard: this assumption can not be viewed as a certainty and it has a significant relation with the stimulation of use of reusable materials at the start of other projects.
Assumption 3: The validation has led to the conclusion that this incentive should indeed be the result of the higher value offered for clean disassembly in the secondary market.
Assumption 4: In the validation this was assessed to be valid, since this is in line with the perspectives on assumptions 1 and 2.
Assumption 5: In the validation this was assessed to be correct.
Assumption 6: This is the correct approach according to the validation.

Performing this validation is the final step in obtaining the results as described at the start of this section. The results are reflected upon contextually in Chapter 5.

4.2.2.2. Functional component

The final result for the valuation of the functional component is again described by first discussing the basic concept behind the resulting valuation approach. This is as follows:

The value the function of the asset has to the asset adopting actor, in the sense that this actor does not have to construct a new road.

This concept aims to value the functional value of an asset. The function referred to is the function of the asset to the actor adopting the asset, which is in most cases a governmental institution. The function itself is found to be the fact that the adopter does not have to invest in constructing a comparable asset that is able to perform the function, because the current asset is already in place performing that function. Knowing the basic concept, the associated equation is stated as in Equation (4.2).

$$\textit{Functional value}_{Used,t} = \textit{Prevented construction costs}_{New,t} - \textit{Renovating costs}_{Current,t} \tag{4.2}$$

In this equation variables denoted with *Used* describe values or costs associated with the current asset that is already present and is used. *New* describes values or costs associated with a potential new asset that can perform a similar function. Thus, both of these indicators have similarities with those used in the physical value, however, they are not exactly the same. The first variable, *Prevented construction costs*$_{New,t}$ describes the construction costs of a new, comparable asset able to perform the same function at time t, that are prevented by not having to construct it. Since having to construct a new comparable asset or not is dependent on the quality of the current asset in use, the costs for renovating the currently used asset to the state at which the potential new asset would be delivered are subtracted. This is done by subtracting *Renovating costs*$_{Used,t}$.

The equation and the variables are defined quite broadly. This is done on purpose, for the same reasons as stated in the previous component: ensure applicability and freedom to stimulate circularity goals whilst maintaining boundaries to adhere to the definition of the value of the component.

Again, as can be seen in the subsequent paragraphs, the main sources used for the expert consultations and expert interviews are actively involved in the infrastructure construction industry and the adjacent financial fields. Therefore, as with the previous component, this result, as presented in the aforementioned equation should be viewed within this light as well: it is formed with mostly practical needs and generally accepted practices in mind.

The application of this equation rests on the following assumptions and conditions, that will be addressed in more detail in the following sections:

Assumption 1: The function is assessed as being the fact that a new asset does not have to be constructed since the currently used asset performs the desired function;
Assumption 2: The representative ’new’ condition is chosen to be 20 years;
Assumption 3: The economic value is not seen as an element of the functional value;
Assumption 4: Prevented process costs, meaning costs saved for not having to finance for example tender processes are not taken into account;

Assumption 5: Analyses on the asset condition and associated renovating costs over time are known;

Assumption 6: *Prevented construction costs*$_{New,t}$ is chosen to be for an asset of the same design as the used asset currently in place.

Step 1 - Formation of initial design: expert consultations As described in Section 4.2.1, the best fitting valuation technique for the functional value is the NPV of future benefits and costs technique. Using this as a basis, the basic concept was formed by consulting experts on asset management, valuation and specifically asphalt (consultation asset management, asset valuation and asphalt experts, PC, 06-04-2021 & 14-04-2021). These expert consultations revolved around checking whether the NPV approach seemed fitting to them, as well as how this could specifically be approached in the context of PSS and highway infrastructure assets. Two main approaches were specifically suggested. One involves a focus on the value of not having to replace the asset, whereas the other focused on the value for reducing the amount of maintenance having to be performed in the future. Concepts such as the latter have been suggested already (Alba Concepts, 2021). The expert consultations led to the finding and confirmation that the combination of these two approaches would be best, since it combines both types of value in a form that is applicable due to the fact that this adheres to most standard practices in the industry. It is interesting to note that the initially suggested approaches use the NPV technique, whereas the combined approach does not strictly fit within this category. However, based on the expert consultations this seemed to be the best choice at this point in time. As mentioned in the previous section, an expert consultation was had with a real estate expert (consultation real estate expert, PC, 08-03-2021). The valuation techniques for real estate are not applicable here either, for the same reasons. Using the information gained during this first step, the assumptions were formed as follows:

Assumption 1: As specified in this section, this basic concept followed from the fact that that combines two types of values associated with the function, as well as the fact that this approach adheres to most standard practices in the industry. This is also reflected in the following element.

Assumption 2: This assumption was decided upon by the fact that current maintenance practices aim to provide a residual life of 20 years.

Assumption 3: Another concept (Platform CB23, 2020b) differs from the basic concept introduced here in the fact that it also takes the economic value into account under the umbrella of the functional value. This however, is not done in this equation for the following reasons: first, the economic value can be broadly interpreted, of which not all aspects are applicable or financeable. Second, other than socio-economic benefits, there are currently no direct financial benefits involved in infrastructure asset operation, therefore applicability of this aspect is difficult. These differences arise from the difference in the goal between the measurement method of Platform CB23 and the approach as designed in this study. The goal of the former is to measure circularity, which is not the same as the goal of the latter.

Assumption 4: During the consultation meetings process costs were deemed to be a small part of construction costs, as well as too variable and therefore complex to incorporate. This, however, does neglect value that exists in reality. With more research this can be incorporated in the future.

Assumption 5: This assumption was formed during the case application stage.

Assumption 6: This assumption was formed during the case application stage.

Step 2 - Verification of design: application to a case For the application of Equation (4.2) to the case *Prevented construction costs*$_{New,t}$ is represented by variable 13 in Appendix D. Calculation of the *Renovating costs*$_{Used,t}$ is done by first determining the lifespan of the asset using variables 17 and 18, after which variable 14 is used to assess the current condition of the asset and thereby its worth. The expected future prices for both construction and renovation are determined using the GBM method, adopting variables 15 and 16 as the drift and volatility, combined with the contract period of variable 20. These expected prices are then multiplied with the found values for *Prevented construction costs*$_{New,t}$ and *Renovating costs*$_{Used,t}$, which are then subtracted. Variables 19 and 20 are then used to discount the future values to the present. Multiple runs of these calculations are done for the MCA. Appendix C shows these calculations through the applied code and its description.

The case analysis yielded the MCA results as depicted in Figure 4.6. The μ is 163.672,50 euros, with an SE of 1.187,22. Furthermore, 90% of the values ranges from 0,00 to 361.737,23. This 90% is chosen such that it cuts of the right tail of the results.

The results show that the value 0,00 occurs approximately 1580 times out of 10.000, represented by the high bar in the left of the graph. These seemingly odd findings result from the fact that for this case specifically, in 15,8% of the runs the residual life of the asset reaches 0 years before the contract period ends. This is a specific use case, in which the asset currently in use requires full replacement and therefore $\textit{Renovating costs}_{Used,t}$ is equal to the $\textit{Prevented construction costs}_{New,t}$, resulting in a functional value of 0. Another choice can be to assume in these cases the road would be renovated, resulting in a high functional value for these 15,8% of the cases, since the condition of the road at the end of the contract. This would change the graph in Figure 4.6 to a graph with the 1580 occurrences of the value 0,00 removed, than the distribution as currently shown, followed by a significantly smaller distribution representing the 15,8% of values that previously had a value of 0 and now have a high value. This results is shown in Figure 4.7 on a significantly larger axis. Computing the results as such introduces renovating costs that, while having the aforementioned effect, are not reflected in the residual value. This would misrepresent the residual value, which would become too high in some cases. Thus the choice is made to represent the results as in the first option, in which the assets with lifespans shorter than the contract period are not directly renovated. This means that Figure 4.6 is representative of the used results. Having to make this choice is a direct result of the fact that this research does not focus on the entire financial model and all financial effects involved, in which the renovating costs would be featured, but that this research focuses on the residual value only. Finding this has several implications, which are discussed for the relevant assumptions in the following paragraphs.

As for the significant spread of the results, this is mainly a result of the assumption of a linear degradation and associated renovating costs of the asset over time. From a consultation meeting (consultation asphalt experts, PC, 14-04-2021) it is found to be most likely that degradation and renovation costs increase least at the beginning and end of life phases. Thus, these degradation and renovation costs are akin to an S-curve with the top, flat section of the curve close to the average lifespan. Because fitting input data on this S-curve proved difficult to retrieve, the assumption is made that this is linear. This results in a significantly higher spread as opposed to if an S-curve is implemented. Since the spread can be explained using the inputs and the expectation is that their uncertainty can be decreased using further research, the assessment is made that this spread does not imply that the equation is not correct or applicable.

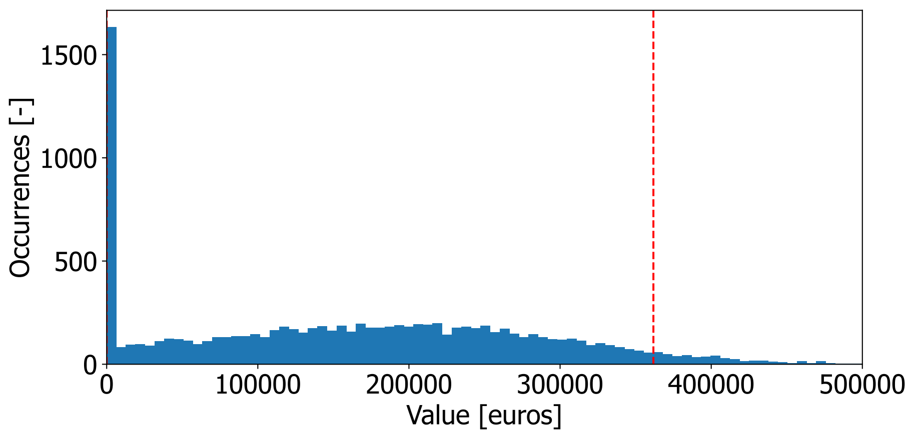

Figure 4.6: Results of a Monte Carlo analysis performed for the functional component of the residual value of the case if the choice is made not to renovate the roads that have a lifespan shorter than the contract period of 15 years. Represented discounted to 2020 euros.

All results of this sensitivity analysis, for both the μ and SE were as expected. Several of the changing

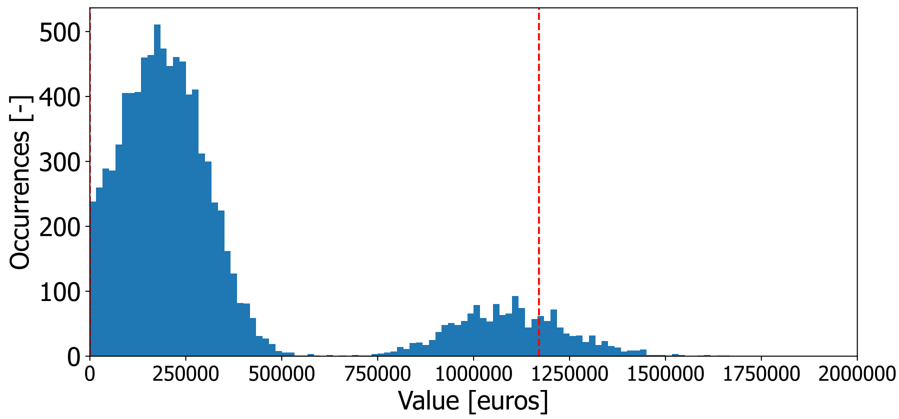

Figure 4.7: Results of a Monte Carlo analysis performed for the functional component of the residual value of the case if the choice is made to directly renovate the roads that have a lifespan shorter than the contract period of 15 years. Represented discounted to 2020 euros.

inputs have standout changes in outputs. For the input $\mu_{Restlevensduur}$, variable 17 in Appendix D, the significant changes were expected because of the close proximity of this value to $t_{Contractperiod}$, variable 20 in Appendix D, as discussed in the previous paragraph. The same occurs when changing the inputs of the latter, due to the same reason. For the SE output the same effects occur. These and all other non-standout results verify that the equation performs its function as intended and that the application of the equation to the case has been done correctly. An overview of the results of the sensitivity analysis on the Monte Carlo analysis for the physical component can be found in Table E.2 in Appendix E.

Using the information gathered in applying the equation to a case the assumptions were formed, adapted or verified as follows:

Assumption 1: Application of the equation to a case has led to the finding that this seems a function that is applicable to a case and the case data, minding that uncertainty in inputs should be decreased using better estimators. Furthermore, it was found that if the above requirement is met, this form seems applicable to the case.

Assumption 2: This allows for exact benchmarking of the costs relative to each other. Thus, this increases applicability of the approach.

Assumption 3: No specific findings by applying the equation to a case.

Assumption 4: Other than an increased applicability, no specific findings by applying the equation to a case.

Assumption 5: This assumption is made since the specific data required for application to this case was already hard to find, even though this is an extensively researched field. When the scope of a case is enlarged to include multiple aspects of an infrastructure asset this assumption should hold to be able to calculate the functional value without significant unknowns.

Assumption 6: If a design fulfilling a comparable function but for example with lower circularity requirements is chosen, this compares apples to oranges. This example specifically results in negative functional values in many cases. This is incorrect, since that does not allow for a fair comparison since that changes the definition of what the function of the asset should be.

Step 3 - Validation of design: expert interviews The validation, see Appendix G for the mural results, showed that the basic idea and the devised equation is an approach that gives a realistic estimation of the functional value and that it is an applicable approach as well. Regarding the assumptions, these were adapted or validated as follows:

Assumption 1: The validation showed that this form seems most applicable and realistic seeing current practices. It specifically revealed that this would separate the contract period from the technical lifespan, which is one of the goals of the applying PSS to infrastructure. However, it also revealed that while currently not applicable or financeable, measuring the function of the asset as its capacity would incentivise innovation on increasing circularity per desired amount of capacity even further.

Assumption 2: Validation has not led to any objections towards this assumption.

Assumption 3: Validation of this statement led to the conclusion that this is correct, since economic value is not specifically represented in the functional value, but in the entire business model, which is out of the scope of this research.

Assumption 4: Validation resulted in agreement on this choice, because it would decrease applicability significantly and varies too much for appropriate estimation.

Assumption 5: Discussing the applicability of the variables, this was not raised as becoming a problem.

Assumption 6: Validation has led to agreement on this subject, since the comparison would otherwise change be done on changing definitions, which would be incorrect.

Again, performing this validation is the final step in obtaining the results as described at the start of this section. The results are reflected upon contextually in Chapter 5.

4.2.2.3. Environmental component

The final result for the valuation of the environmental component is again described by first discussing the basic concept behind the resulting valuation approach. This is follows:

The value that arises because environmental costs are prevented by choosing an environmentally better design.

This concept aims to capture the environmental value of an asset. The costs referred to in the concept are the costs of having to compensate for the environmental damages over the entire lifetime of the asset. Knowing the basic concept, the associated equation can be stated as shown in Equation (4.3).

$$\begin{aligned} \textit{Environmental value}_{Used} &= \textit{Environmental costs}_{Reference} - \textit{Environmental costs}_{Used} \\ &= \textit{MKI}_{Reference} - \textit{MKI}_{Used} \end{aligned} \tag{4.3}$$

In this equation variables denoted with *Used* describe values or costs associated with the current asset design actually used. *Reference* describes the costs associated with a reference design. As described in the basic concept, $\textit{Environmental value}_{Used}$ describes the environmental value of the current asset design actually used, at any time t. As the first line of the equation depicts, it can be determined by first calculating $\textit{Environmental costs}_{Reference}$, the environmental costs of a reference design, after which the environmental costs associated with the currently used design, $\textit{Environmental costs}_{Used}$ should be subtracted. This delta represents the prevented environmental costs over the lifetime of the asset by opting for an environmentally better design, and in that sense the environmental value. The reference design that is used to calculate the referential environmental costs is agreed upon beforehand by the involved actors. In the Dutch infrastructure sector the Milieu Kosten Indicator (MKI) is a widespread approach for determining the environmental costs (consultation environmental costs experts, PC, 08-04-2021 & 28-04-2021). Therefore, the second line in the equation substitutes the original variables with the MKI variables. Finally, it should be mentioned that the *t* that was present in the previous two components' equations is not present here, since the environmental value does not differ for a different time since it is calculated for the entire lifetime of the asset.

The equation and the variables are defined quite broadly. This is done on purpose, for the same reasons as stated in the previous component: ensure applicability and freedom to stimulate circularity goals whilst maintaining boundaries to adhere to the definition of the value of the component.

The application of this equation rests on the following assumptions and conditions, that will be addressed in more detail in the following paragraphs:

Assumption 1: Environmental value is represented by the delta between the environmental costs for different designs;

Assumption 2: Environmental costs are determined using the MKI (Milieu Kosten Indicator) technique;

Assumption 3: The environmental costs are calculated over the entire life cycle, thereby making the analysis independent of variable *t*.

Step 1 - Formation of initial design: expert consultations As described in Section 4.2.1, the best fitting valuation technique for the environmental value is the CBA technique. Using this as a basis, the basic concept was formed by consulting experts on environmental valuation and costs (consultation environmental experts, PC 08-04-2021 & 28-04-2021). These expert consultations revolved around checking whether the CBA approach seemed fitting to them, as well as how this could specifically be approached in the context of PSS and highway infrastructure assets. In these meetings, several CBA techniques for estimating environmental costs were discussed (Platform CB23, 2020b; Van Alphen, 2018; Van Harmelen et al., 2004). The MKI technique is one of those, that is currently used in most tender processes in the infrastructure sector. This calculates the environmental costs for 11 categories of environmental damage, which is increased to cover 19 categories in the future (Platform CB23, 2020b). Its widespread use and acceptance made this the most fitting option for the purpose of this valuation. Adding to this, the consultation meetings showed that determining the variables $MKI_{Reference}$ and MKI_{Used} is already standard practice in many projects, further adding to its applicability. As mentioned in the previous sections, an expert consultation was had with a real estate expert (consultation real estate expert, PC, 08-03-2021). The valuation techniques for real estate are not applicable here either, since it does not allow for capturing benefits and costs that are not directly monetisable. Using the information gained during this first step, the assumptions were formed as follows:

Assumption 1: This seemed to be the most applicable approach following from the suggestions and discussions in the expert consultations. This is mainly because there is currently no real, accepted value in environmental value. Therefore a substitution such as this delta should be chosen.

Assumption 2: This seems to be the most applicable approach. Others are also available, but not used (as much) in the infrastructure construction sector.

Assumption 3: This is an (for applicability) positive side effect of the choice for the MKI technique.

Step 2 - Verification of design: application to a case Using the inputs as depicted in Appendix D and the code as shown in Appendix C, the following results were found: the case analysis yielded the results as depicted in Figure 4.8. The μ is 52.024,71 euros, with an SE of 307,41. Furthermore, 90% of the values ranges from 0,00 to 101.780,84. This 90% is chosen such that it cuts of the right tail of the results.

The significant spread shown in the results is a direct result of the fact that the variable MKI_{Used} is computed by multiplying $MKI_{Reference}$ with an expected reduction. This reduction is assumed to be uniformly distributed between 0% and 50% reduction. This input is chosen since the reduction for the design was at the time of performing the application to the case not yet known. When this is known, at which point the value should be calculated ideally, the equation results in a significantly lower spread. An example of this is found in Figure 4.9, that shows an MCA in case the expected reduction is to be 25%. Thus, since the spread can be explained and reduced, the assessment is made that this spread does not imply that the equation is not correct or not applicable.

All results of this sensitivity analysis, for both the μ and SE, were as expected, showing no standout values. This verifies that the equation performs its function as intended and that the application of the equation to the case has been done correctly. An overview of the results of the sensitivity analysis on the Monte Carlo analysis for the physical component can be found in Table E.3 in Appendix E.

Using the information gathered in applying the equation to a case the assumptions were adapted or verified as follows:

Assumption 1: This allows for simple application, since performing the final calculation is simple, as well as retrieving the inputs.

Assumption 2: Using the MKI ensures high applicability of the equation, since the inputs can be readily found or easily determined.

Assumption 3: Again, this makes the equation more applicable since it is simpler. Furthermore, this is fitting since all relevant inputs are already presented over the entire lifetime.

Step 3 - Validation of design: expert interviews The validation, see Appendix G for the mural results, showed that the basic idea and the devised equation is an approach that gives a realistic estimation of the functional value and that it is an applicable approach as well. Regarding the assumptions, these were adapted or validated as follows:

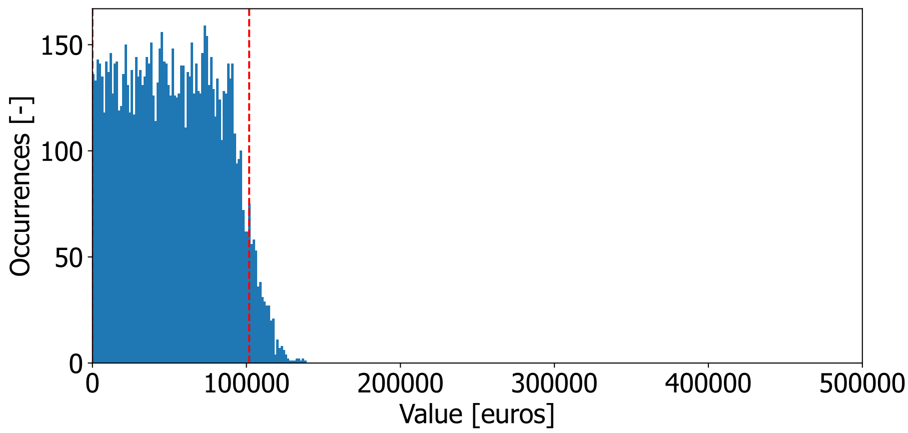

Figure 4.8: Results of a Monte Carlo analysis performed for the environmental component of the residual value of the case. Represented in 2020 euros.

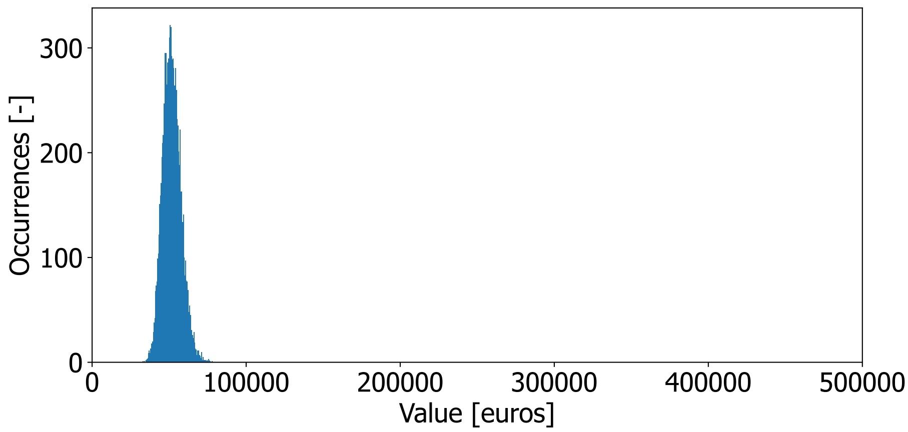

Figure 4.9: Results of a Monte Carlo analysis performed for the environmental component of the residual value of the case in case of an expected MKI reduction of 25%. Represented in 2020 euros.

Assumption 1: During validation it was found that this is the correct approach. Also, the fact that this value follows from a delta, whereas that is not the case for the other two components, is seen as logical.

Assumption 2: Using MKI is the correct approach, mainly since it ensures applicability. However, it should be noted that the $MKI_{Reference}$ has to be determined by an independent third party for the asset. According to the expert consultations and further questioning during the validation, that is feasible and necessary to create a level playing field.

Assumption 3: During validation the specific nature of the MKI calculation was understood and reflected upon to be a correct approach.

Again, performing this validation is the final step in obtaining the results as described at the start of this section. The results are reflected upon contextually in Chapter 5.

4.2.3. Combination of findings

This section first discusses how the different values relate to each other, followed by how the findings for each of the components can be combined to construct a single value. The latter is again done by first highlighting the initial concept, after which the adaptations through applying the findings to a case are discussed, followed by the final results.

Relation of findings to each other The findings from the case result in a μ that is highest for the physical value, almost directly followed by the functional value and trailed by the significantly smaller environmental value. For the case this is a logical result, based on the fact that the functional value is relatively low because the values for the contract period and lifespan estimations are in the same range (see Section 4.2.2.2). Additionally, the case only entails the top two layers of the pavement (see Section 4.2), whilst the bottom layers provide much of the functional value since they deteriorate slowly. Therefore, in most cases these results will be different than generated through application of this specific case and the following relation will be found, which is therefore generally applicable:

Functional value > Physical value >> Environmental value

This relation and the context of the findings of the case application have been validated with the validation interviews to be in line with reality.

Next to these comparisons the potential overlap of the different components was inspected. The following validated findings should be noted:

- The physical and functional component do not overlap. While the functional value does have an effect on the physical value, this is not overlap. This effect is the following: when a road is renovated or newly constructed, there are material costs associated, that are represented in the variables in the equation for the functional value. These material costs, however, are for new materials. Their eventual worth when they are present in the asset will be represented in the physical value after the renovation is complete. Their current costs, as represented in the functional value are not overlapping with the physical value as it currently stands, since that is the physical value of the asset currently in use.
- The environmental component has no overlap with either the physical or the functional component.

Construction combined value Following from Section 4.2.1 it is known which three components contribute to the residual value. Of these it is stated that the third (environmental value) is optional because its lack of financeability. For the combined value, it is assumed that this optional component is incorporated.

When aiming to determine the combined value summing the separate components is incorrect. This is because the value of the physical component is only realised when these materials can be sold freely, which is only the case when the road is disassembled. The reverse applies to the functional component. Here the functional value is only realised when the function of the asset is maintained, meaning that it can not be disassembled. Therefore, the combined residual value can be determined for two scenarios: the functional scenario (Equation (4.4)) and the obsolete scenario (Equation (4.5)). As can be seen in the equations, the environmental component is applicable to both scenarios. Now it is relevant which of these scenarios is leading in the combined residual value determination. As the combined approach includes the components related to the CE, opting for the highest value at any time is in accordance the CE incentives.

$$\text{Combined residual value}_{Functional} = \text{Functional value} + \text{Environmental value} \tag{4.4}$$

$$\text{Combined residual value}_{Obsolete} = \text{Physical value} + \text{Environmental value} \tag{4.5}$$

A good example of why this scenario split is required obtained through the case application is as follows: the functional component is, in the first few years after construction or renovation, equal or nearly equal to the costs of constructing the new road. This follows logically from the equation as stated in Section 4.2.2. Even though there is no direct overlap between the three components, simply adding the three components would result in an incorrect combined value for the first period. Incorrect because directly after construction, which has costs equal to *Prevented construction costs*$_{New,t}$, the combined residual value would be more than that. If this approach were to be applied, right after delivery of the asset the value of the asset would suddenly increase. This situation is accounted for using the scenario split of Equation (4.4) and Equation (4.5).

In the equations the following should be noted: in case of the functional scenario, when maintenance is conducted, materials or products might be freed. This would mean that the equation as just mentioned does not apply anymore. However, it is argued that this is not the case, since this physical value would constitute only a small portion of the entire maintenance costs and more importantly account for only a small portion of the physical value present in the asset at that point in time. Therefore, this does not negate the main concept between this division and the effects on the valuation should be neglected.
This design adheres to all the requirements and considerations as set out in Section 4.1 and thereby the goal of the residual value determination approach within the context of PSS applied to highway infrastructure. It can be considered to be the direct answer to the third research question.

4.3. Overview results

For clarity this section provides an overview of the results as found in Section 4.2, together with the assumptions the main assumptions these findings rest on. No new results are presented here.

Basic model design The basic design is shown in Figure 4.10.

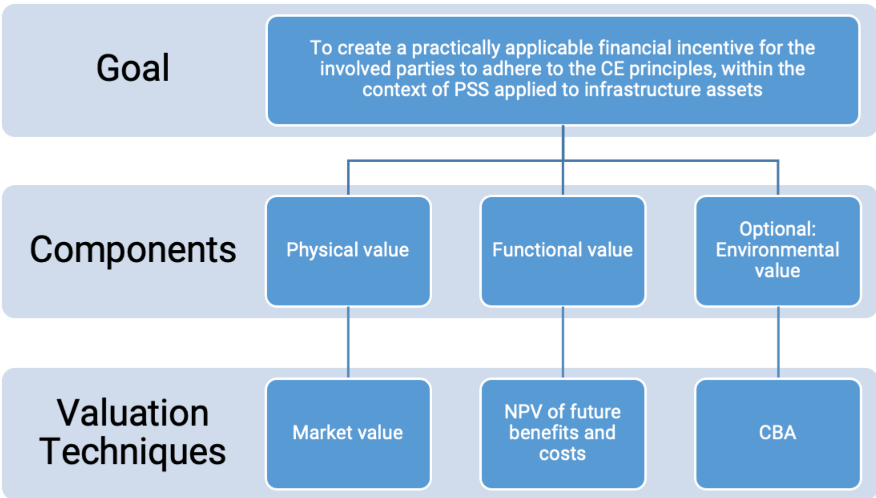

Figure 4.10: A visualisation of the results and their relations. As the visualisation reveals, recognising the goal allows for determination of suitable components: the physical value, functional value and optionally the value of externalities. Additionally fitting valuation techniques are matched and found.

Components design and assumptions Using the basic design, the specific components are determined as follows:

- $\textit{Physical value}_{Used,t} = \textit{Market value}_{New,t} - \textit{Reuse reduction}_{Used,t}$
- $\textit{Functional value}_{Used,t} = \textit{Prevented construction costs}_{New,t} - \textit{Renovating costs}_{Used,t}$
- $\textit{Environmental value}_{Used} = \textit{Environmental costs}_{Reference} - \textit{Environmental costs}_{Used}$

These components rest on the following assumptions and conditions, which are structured per component:

Physical component
- A secondary market is available for all physical elements in the asset;
- The secondary market provides an incentive for delivering elements to this market allowing for the highest quality reuse reasonably possible;
- The secondary market provides an incentive for increased ability to disassemble assets or products;

- The equation does not differentiate between assets initially originating from the primary or secondary market;
- For this equation to perform correctly it does not matter whether regular maintenance is performed or not;
- The costs for bringing the elements to market are represented in the *Reuse reduction*$_{Used,t}$.

Functional component

- The function is assessed as being the fact that a new asset does not have to be constructed since the currently used asset performs the desired function;
- The representative 'new' condition is chosen to be 20 years;
- The economic value is not seen as an element of the functional value;
- Prevented process costs, meaning costs saved for not having to finance for example tender processes are not taken into account;
- Analyses on the asset condition and associated renovating costs over time are known;
- *Prevented construction costs*$_{New,t}$ is chosen to be for an asset of the same design as the used asset currently in place.

Environmental component

- Environmental value is represented by the delta between the environmental costs for different designs;
- Environmental costs are determined using the MKI (Milieu Kosten Indicator) technique;
- The environmental costs are calculated over the entire life cycle, thereby making the analysis independent of variable *t*.

Designed residual value determination approach Finally, the components have been combined to form the final residual value determination approach. The residual value is equal to the highest of two scenarios, which can be calculated as shown below.

- *Combined residual value*$_{Functional}$ = *Functional value* + *Environmental value*
- *Combined residual value*$_{Obsolete}$ = *Physical value* + *Environmental value*

5 Discussion

In Chapter 4 the resulting residual value determination approach is presented. This chapter aims to discuss these findings in broader context and to answer the fourth research question. This is done using the following sections: first, the results are interpreted and valuated in Section 5.1, in which their applicability is also discussed. Second, the implications of the findings are discussed in Section 5.2. Finally, the limitations of the research and its findings are elaborated upon in Section 5.3.

5.1. Interpretation and value of the results

When viewing the resulting residual value determination approach, four general contextual remarks should be made, for correct interpretation and valuation of the results. These are discussed first in this section. Then, the valuation of the case results are specifically discussed, followed by the applicability of the results.

General interpretation and valuation of results The first contextual remark is that the results should be viewed within the context of the method chosen for establishing these results. There are several methods possible, as shown in the following list:

1. Establishing the goal of the residual value and fitting components and valuation techniques to it;
2. To determine the height of the results required to provide the desired incentives.

This first method results in an approach agreed upon by the actors, of which however, it is not known beforehand whether it delivers on creating the incentives to contribute to the CE. Using the second method a fitting approach can be found, resulting in an approach that will surely meet the goal of creating the desired incentives to contribute to the CE. This research has used the first method, since this allows for finding an approach based on principles and requirements that can be accepted among the involved actors. Additionally, this method reveals the current shortcomings in the approach, sector and market and these shortcomings can be corrected if desired. This is a more preferred method than the second method, since the approach needs to be accepted among all actors for it to be used, which is more difficult with the second method, even though that method can be better for achieving the aforementioned goals.

Because of the choice of the first method, it is necessary to investigate to what extent the results found using the designed approach meet the desired goal of contributing to the CE incentives. To this end the incentive is calculated for each of the component values by dividing them with the construction costs of a new highway, equal to the variable 13 in Appendix D. As mentioned in Section 4.1.1, the minimum height of the incentive is stated to be within a range of 10%-20%, with respect to the construction costs of a new highway. Keeping this in mind, the following incentives per component are computed and discussed:

- Incentive physical component: 9,47%. This results would indicate that the designed approach for determining the physical component of the residual value does not provide an incentive of the required height on its own. It should be acknowledged however, that this value is specific to the case, which focuses solely on the first two layers of asphalt which are highly reusable. While not researched, approaching reality by including more layers and foundations is expected to increase the physical value because reusability of these products is higher. Therefore, it is expected that this component does provide the incentive desired.

- Incentive functional component: 8,25%. Again, according to this result the component does not meet the required height for the incentive by itself. However, the same acknowledgment regarding the case inclusions is made here. Therefore, it is expected that this component provides the desired incentive.
- Incentive environmental component: 2,62%. This result does not provide the required incentive on its own. Currently however, the established inputs used to determine the value of the CBA for the MKI are currently being reassessed. During the validation session it was mentioned that this is expected to lead to higher input values and thus a higher environmental value and higher incentive. Although, the expectation is that this will not be high enough to provide the required incentive.

Thus, while the physical and functional component do not meet the required incentive height on their own when applied to this specific case, they are expected to do for more realistic cases.

While the components by themselves do not create the required height of the incentive, this is different for the combined residual value. Using the computed incentives per component with Equation (4.4) and Equation (4.5) the combined values for both the functional and obsolete scenarios are calculated. These are 10,87% and 12,09% and respectively. Both of these meet the minimum required height of the incentive, albeit in the lower end of the range. However, the acknowledgement as discussed for the physical and functional component also applies here. The expected increase for both of these components when applied to a realistic case also increases the combined residual value for both the functional and obsolete scenarios. Therefore, it can be said that the residual value determination approach creates the desired CE incentives.

A second contextual remark that ought to be made is that regarding the residual value as opposed to other methods for creating the desired incentives. As stated in Chapter 1, this research focuses specifically on the residual value, since that is an aspect that can help in achieving the CE within PSS contracts. Additionally, it is a subject on which little was known within this specific context as well as that a solution was needed to be able to create the PSS business model and contract in practice within this sector. There are aspects that do contribute to a CE, but do not fit within the specific requirements of a residual value. A good example of this is the incentive to use more materials or products that have already been used before, thus reusing materials in some form when using them in this project. Another good example is providing an incentive to allow for carbon storage within the design of the asset. While both can be incentivised in some form in the project since they incentivise contributions to the CE, they are not incentivised using the residual value (the latter only to some extent). This is because the residual value's required financeability, applicability and preferred direct link with the market for simplicity and applicability do not allow for this. Other incentives, such as bonuses for use of reused materials or bonuses for environmentally-improving asset designs should be created if these CE benefits are wished. For example, the circularity measurement method as created by Platform CB23 (Platform CB23, 2020b), which has another application than the residual value, does offer different incentives as well and accounts for the two examples stated here. Concluding this aspect, the residual value and its determination approach should be viewed in the context of its fitting abilities, it should not be viewed as being the sole contributor to CE incentives. Other incentives in the financial model can exist alongside it, and should exist alongside it if covering all aspects of the CE is demanded.

The third contextual remark that should be made is that the residual value and its determination approach are just one of the several aspects of the financial model of PSS applied to infrastructure. Others include the periodic fee and financial incentives provided at the start of the contract. The residual value determination approach as delivered in this research should also be considered within this light. This means that, while the approach as designed here is the ideal version, its application within the financial model might differ. As an example, in regular lease contracts the residual value and periodic fee are considered as communicating barrels. Their value is interchangeable and their height dependent on the customer. This view can not simply be copied to the PSS financial model as applied to infrastructure, since it aims to provide circular incentives, as opposed to regular lease contracts. However, this context is relevant for how to interpret, value and use the results of this study.

The fourth and final contextual remark is that this research does not offer a finalised answer as to how to determine the residual value within PSS applied to infrastructure assets that is readily applicable. The research should be viewed as a first step that aims to give direction on to how to deal with this aspect of the application of PSS to infrastructure. This is reflected in the fact that the application of the methodologies have a focus on insights gained from practice, whereas recent academic insights should also receive more attention and be included to arrive at a fitting residual value determination approach. Additionally, this is reflected in the fact that this research has chosen to provide several results narratively, as this allows to reflect all steps and subsequent choices made during the process of this research, so that these can be reviewed if needed in further research.

Interpretation and valuation of case results As a first, as can also be seen in the argumentation of the previous paragraph, a balance is struck between interpreting the results found using the application of the case directly and indirectly. This is done since the case that is applied in this research has several shortcomings that distance it from reality. Using qualitative reasoning the final results can be interpreted correctly, but this is an aspect that should be minded when reviewing these results, meaning there is some uncertainty as to how they exactly relate to reality.

Additionally, the inputs as used for the case have been acquired through expert judgment. Because of time constraints these have not been analysed more extensively. This does not imply that the results are incorrect and no expectations can be made regarding its effect, other than that this can introduce some uncertainty when putting the results to practice within or even more so outside of the actors involved in this research.

As for the computation of the evolving prices over time, two remarks should be made. First, because of time constraints only a limited analysis has been done on which method should be implemented to compute these evolving prices. A more extensive study might find different, better suited methods. Also, as described in Chapter 4, the spread of several of all three of the components is significant, however, retraceable for all three components as well. It is expected that the spread of the results will be lower if these are addressed.

Applicability of the results The application of the results and thereby its value is limited by the scope as defined in Chapter 1. However, by conducting the research insights have been gained so that the scope limitations as initially set in Chapter 1 can be challenged. This is done per item of the scope in the following list:

- Limited to PSS business model: as is touched upon during the research, the goal of the valuation is important to know to be able to find a fitting approach. The goal described within this research does mention the context 'PSS applied to infrastructure assets'. However, as can be seen in Section 4.1.5, most requirements or considerations, not all, are also applicable to many other valuation goals. In that sense, it can be said that the goal also applicable in a wider context. Thereby it can also be said that the residual value determination approach as designed in this research can be applicable within a wider context than solely PSS. Thus, this limitation is not as stringent as initially thought.
- Limited to highway infrastructure sector: One of the main requirements for the components, 'capable of being financed' relies heavily on the financial model and actors involved specific to this sector. Additionally, one of the requirements for the valuation techniques 'able to consider condition' is linked to the CE principles, but to the context of the infrastructure assets as well. Therefore, it is argued that this limitation holds even with the insights gained during the research. Finally, the case application significantly influences the resulting approach that is found for determining the residual value. Therefore, use of the approach is not advised outside of the highway infrastructure sector.
- Focus on residual value determination as opposed to entire financing model: this limitation is implied mostly to restrict the scale of the research. Accordingly, the results only focus on the residual value, the first piece of the financial model as applied to PSS in infrastructure puzzle. This defined scope holds.
- Limited to Dutch sector: The same reasoning as for the first two scope items is used here. Of the requirements, mainly the 'capable of being financed' requirement can be different for other

countries since these can have different organisational and financial models in place in the infrastructure sector. However, if this is comparable to the structure as applied in the Netherlands, the design as presented in this research can be applicable.

This shows that the application of the result is broader than initially thought to be based on the scope of the research.

5.2. Implications

The implications of the research are discussed in two steps. First, the implications with regards to literature are discussed in Section 5.2.1, in which this research's place within the literature is discussed. This is followed by the implications for practice in Section 5.2.2.

5.2.1. Implications for literature

Several interesting finds that are not in line with literature have been found. These are discussed in this section.

First, it is interesting to see that literature in the context of the residual value does not provide much insight into the required height of the value to provide certain (circular) incentives. This research has shown that experts also find it difficult to estimate this, but based on experience in the field this should be at least the aforementioned 10%-20%. While the research has not specifically focused on this topic and thus the result should not be viewed as final, it does provide insight in the direction and has also revealed that this is an area that lacks in literature available.

Second, as has already been touched upon in Section 5.1, the residual value is not a form in which all CE incentives can be created. This is opposed to expectations, since literature on the subject of CE incentives within the construction industry (Platform CB23, 2020b) does allow for many or most of the types of incentives possible. In hindsight, this is a logical find, since the mentioned piece of literature is aimed at measuring circularity in construction, which should encompass all its facets. This is different from the goal of the residual value as determined in this PSS context for infrastructure. However, it should be noted in future research that this research has found that not all forms allow for CE incentives equally well.

Third, several literary sources on circularity and the CE revealed the basic principles and aspects associated with the definitions (Ellen MacArthur Foundation, 2015; Kirchherr et al., 2017; Platform CB23, 2020b). Following this, the main practical aspects were found to be protection of the material stock, the environment and the existing value. These are shown in literature to exist on the same level or within the same scenario. However, as Section 4.2.3 shows, these aspects do not exist within the same scenario, meaning that physical value cannot be harvested while maintaining the functional value. In other words: the combined residual value is not simply a combination of the components, since their value only applies for a specific, partially exclusive scenario. In the approach designed in this research these scenarios are the functional and obsolete scenarios. This is an interesting find since literature did not reveal this. The implication with respect to literature is that literature should be mindful of this scenario dependency when considering valuations with regards to the circularity or the CE.

Fourth, significant portions of the literature on the residual value define the residual value as solely the scrap value (Edgerton, 2009; European Commission, 2014), as opposed to any value at the end of a certain period (J. Yuan et al., 2015). This difference has already been touched upon in Section 2.3. However, it is noted again here to emphasise that this definition should be comparable to the latter, since this research shows that different types of residual value exist. Research within this field should emphasize this difference as well.

5.2.2. Implications for practice

As discussed in Chapter 1 this research is linked to the DCW program, aimed at making infrastructure as a service a reality. The most noteworthy findings with respect to the research's practical use are as follows.

First, the research has found that determining the residual value in the context of PSS applied to highway infrastructure is possible, as well as that this value is expected to be large enough to incentivise contributing to the CE. When reviewing these findings it should be minded that these are based mainly on practical insights, whereas recent academic insights are also relevant to include in the design. Additionally, several significant assumptions are applied, which means other outcomes can not be ruled out. Thus, this research's results and its context implies that a residual value determination approach applicable to PSS in the infrastructure sector can be created and that the requirements and approach as presented in this research can be regarded as the first step for realising it, but that direct implementation is not advised.

Second, the detailed formation of the approach as shown in Chapter 4 allows for alteration, as well as reverse engineering towards the desired height of the incentives, so that the residual value determination approach fits well within the financial model of the PSS business model and contract.

Third, in line with the second implication, the findings' component structure and optionality of the environmental component create the possibility to tailor the approach so that it suits the goals of the project or program. With this, however, also comes the responsibility to choose on whether the environmental component, which is less easily financed, should be incorporated within the residual value or not.

Fourth, this research makes several significant though verified and validated assumptions to reach the end result. Several of these, such as the assumption that the market for secondary materials will arise, are quite existential to the use of the designed approach. To be able to use the findings of the research, the actors involved should investigate further whether these assumptions are realistic. Even more so, several of these assumptions, such as the example given here, are required aspects to be able to create a more circular CE according to several interviewees. Therefore, the actors involved should contribute to making these assumptions a reality.

Fifth, as stated in Section 4.2.3, the combined equations have not been checked for if weights of the different variables are necessary, for various reasons, including that Platform CB23 is expected to have interesting findings in this regard in the near future. Platform CB23 requires active collaboration between involved actors. Therefore, contributions to Platform CB23 are advised to make the CE in the infrastructure sector a reality. The same accounts for partner programs such as DCW.

Sixth, while applicability of the approach is one of the main requirements, not all aspects of the approach are tailored to the current way of working for the involved actors. For PSS applied to infrastructure to succeed, the actors involved need to continue to have an open mind. This is especially relevant to the contractors and governmental institutions,

Seventh and finally, as noted in Section 5.1, this research is the first step into designing a finalised residual value determination approach, in which the practical insights have received more attention than recent academic insights. To find a design that is both practical and aligned with recent academic insights the incorporation of the latter should be investigated further.

5.3. Limitations

As for the limitations of the research's findings and methods, several should be mentioned. For brevity, these are displayed in three tables for three categories: the research focus and methods in Table 5.1, the inputs in Table 5.2 and the results in Table 5.3. Some of these overlap with the previous text of this section, but that is done so that there is a singular overview of all the limitations. Limitations following from the set scope are not included in this overview.

Table 5.1: The limitations of the research focus and methods of the research, along with their expected effects.

Limitation	**Effect**
Method used does not guarantee desired incentives are created	As described in previous sections, this choice has the effect that the entire approach is in line with actors' wishes and its shortcomings are known, meaning they can be altered when necessary.
Limited analysis on price evolution determination methods	A potentially lower spread or more applicable range of price evolutions can be found, leading to better practical application of the approach and values.
Required incentive height not researched extensively	The findings regarding the required height of the residual value to provide the desired incentives can be questioned, which can lead to different conclusions regarding the results and their applicability

Applied case differs from reality.	The residual value and especially the functional component is expected to be higher in reality. The resulting approach and equations are not expected to change due to applying a more realistic case since the workings are not expected to differ.
The combined valuation scenarios' variables have not been weighted	The resulting approach for determining the combined value can result in higher incentives if specific weighting of the variables is found to achieve this.
Effects of premature discontinuation of contract have not been researched	Potential negative side-effects of contract cancellation. However, since the residual value over time does not make unexpected jumps this is not expected to be a problem from a financial perspective.
Governmental law has not been researched extensively	Interviews have resulted in the view that this is not expected to be a problem. However, influences of aspects such as that governments are not allowed to account for inflation and that firms are not allowed to simply note all future value on the balance sheet without consequences does give rise to potential limitations.
Options such as cap and floor prices and their need, required for ensuring financeability have not been investigated extensively	Interviews have resulted in the view financeability is extremely important, but that if the approach is agreed upon, solutions to this will arise. Therefore, this is not expected to become problematic for the approach application.
A significant portion of the input has been gathered from within DCW	Results can be biased, since the aim of DCW is the same as of this research. It is attempted to counter this by involving outside experts, but the following potential effect should be noted: potential constraints regarding CE incentives, applicability or financeability can be deemed trivial because the experts involved are motivated to overcome these.
The focus of the design process and eventual design has been insights gained in practice	Recent academic developments have not been incorporated in the design process and resulting designs. Therefore, results can lag behind the state of the art in research and potentially aspects recently found to be relevant to consider within the CE field might have been left out.

Table 5.2: The limitations of the research inputs, along with their expected effects.

Limitation	**Effect**
Expert judgment used for MCA input	The spread around the μ of the end result is uncertain. The absence of data can lead to the suggestion of a level of accuracy which does not exist (Boomen et al., 2020).
Limited analysis on PPI regression sets	As described in Section 3.2.2, the correct choice for the regression period is important. However, since all seasonality effects and trends are expected to be captured this is not expected to result in incorrect results of the case analysis.
Limited analysis on degradation of asphalt and associated renovating costs over time	High spread of the case findings and if not solved lessened fincanceability since high uncertainty and thus risks are involved.
High uncertainty GBM inputs	High spread of the case findings and if not solved lessened fincanceability since high uncertainty and thus risks are involved.

Significant assumptions	The results are dependent on several significant assumptions, that, while they are verified, validated and expected, if not true, result in findings that are incorrect. Because of the significance of the assumptions, the resulting approach can not be regarded as directly applicable. It should be regarded as a first step that contributes to the eventual forming of the approach, after assumptions have been investigated in more detail and recent academic insights have been incorporated in the approach.

Table 5.3: The limitations of the research results, along with their expected effects.

Limitation	**Effect**
Results do not create all desired CE incentives such as use of secondary materials	Not all incentives created. However, this is logical since the residual value is only part of the financial model. Other incentives can be created within other aspects of the financial model.
High spread of case findings	Less applicable results since their uncertainty is too high. This in effect requires more research.
The resulting valuation approach is only applicable to scale levels (raw) material, building product and element, and not to structure, complex and area.	This is as expected and this level of detail is desired by the parties involved.
In the functional scenario in reality some value also lies in the materials freed up during maintenance	This value is not represented in the functional scenario. Because of the expectation that this physical value from maintenance is small this can be assumed to be negligible, thus the approach can be considered to be correct
The approach does not stipulate how to handle in case of partial renovations	Partial renovations are not accounted for in the approach
Physical component 1. A distinction between different types of reuse is not made 2. A separate incentive for increasing the ability to disassemble the asset is not made 3. The equation does not differentiate between assets supplied by the primary or secondary market 4. This component might create the wrong incentive: that contractors mainly use primary materials, since that has little risks, less maintenance and therefore high value associated	Physical component 1. Higher quality is assumed and expected according to the validation to be incentivised by the market itself 2. Disassembly is assumed and expected according to the validation to be incentivised by the market itself 3. This incentive does not fit within the residual value form, it should therefore be incentivised elsewhere, for example through upfront bonuses 4. This is an unintentional, unavoidable side effect of the approach for this component. It can be solved in the long term by ensuring a change in expectations regarding products from the secondary market. In the short term it can be prevented by applying financial incentives to use secondary materials in construction

Functional component 1. Potential economic value that can arise in the future is not taken into account 2. Process costs have not been taken into account 3. This component might create the wrong incentive: that contractors mainly use primary materials, since that has little risks and therefore high value associated 4. Specific determination approaches for the *Reuse reduction*$_{Used,t}$ have not been provided	Functional component 1. If future economic value is expected from the PSS business model or elsewhere, which it currently is not, this is not included in the approach resulting in a lower functional value 2. A slightly lower functional value next to a more simple approach 3. This is an unintentional, unavoidable side effect of the approach for this component. It can be solved in the long term by ensuring a change in expectations regarding products from the secondary market. In the short term it can be prevented by applying financial incentives to use secondary materials in construction 4. As to how to determine *Reuse reduction*$_{Used,t}$ the aspects that make up the variable are provided. However, specific information on how to determine these different aspects that make up the variable is not provided
Environmental component 1. MKI inputs have not been updated recently, this is bound to happen, meaning the resulting value is currently relatively low	Environmental component 1. The desired incentives are not yet created. This leads to potential exclusion of the environmental component in practice, or inclusion while not creating desired incentive

6
Conclusion and recommendations

This research has the aim of contributing towards the development of a product-service system (PSS) business approach applicable to infrastructure. In other words, it aims to contribute to the development of infrastructure as a service. The goal of applying this new business approach to the infrastructure sector is to allow for significant increases in circular use, leading to a more circular economy (CE). This research aids this development by providing insight into what residual value determination approach is suitable for this context. Designing this approach is important for the development of the PSS business approach since the residual value, the value at the end of the contract, is an element of the financial model of PSS. This element specifically allows for creating significant incentives for contributing to construct, maintain and disassemble an asset with circularity and sustainability in mind.

This chapter provides the conclusions of this research. This is done by first answering the research questions in Section 6.1, followed by the research's relevance in Section 6.2. Then, limitations and recommendations are provided in Section 6.3 and Section 6.4, respectively.

6.1. Conclusions research questions

The research questions are answered in chronological order, leading up to the answer to the main research question.

Q1: What are current theories and practices in designing an approach for determining the residual value in- and outside of the context of product-service systems applied to highway infrastructure assets? It is found that significant literature on the subject exists, however, that the application of this literature is highly context specific. Additionally, it is found that literature within this specific context is scarce and that it mainly addresses the residual value in the context of the disposal value. Outside of the context, an overview of components that a residual value can constitute of is found, as well as a broad range of valuation techniques. These have been categorised according to literature. Finally, it is found that to be able to apply these components and techniques the specific goal and associated requirements of the valuation have to be determined first. This is the case since different components and techniques are applicable to different types of value.

Q2: What methodologies can be applied to understand, design and evaluate the potential residual value determination approaches in the context of product-service systems applied to highway infrastructure assets? This research has used the Double Diamond methodology to be able to include both theoretical and practical perspectives, as well as to allow for an extensive problem definition phase and an iterative problem solution phase. The first phase combines the two aforementioned perspectives using literature study and expert interviews. In the second phase an initial design is created using expert consultations. This design is then refined by applying the design to a case, after which the design is validated using expert interviews.

Q3: How can the potential residual value components and valuation techniques be combined to design a residual value determination approach that suits the context of product-service

systems applied to highway infrastructure assets? First, a model was created which formed the structure of the approach and from which the associated requirements flowed (see Figure 4.2). With this basic model, the resulting design is found to constitute of three components, of which the last is optional because of financeability. The components and their approach for determination, as determined using practical insights primarily, are as follows:

- *Physical value*$_{Used,t}$ = *Market value*$_{New,t}$ – *Reuse reduction*$_{Used,t}$
- *Functional value*$_{Used,t}$ = *Prevented construction costs*$_{New,t}$ – *Renovating costs*$_{Used,t}$
- *Environmental value*$_{Used}$ = *Environmental costs*$_{Reference}$ – *Environmental costs*$_{Used}$

The difference in prices over time is determined using the Geometric Brownian Motion (GBM) technique (Boomen et al., 2020).

These three components are combined in the following two scenarios. The first scenario is one in which the currently used asset is still deemed functional and thus its physical value is not available since that is still used in the asset. In the second the currently used asset is not deemed functional anymore, but deemed obsolete. Therefore, the function of the asset is not of value anymore, since the asset will be taken apart. However, its materials can be sold on secondary markets. The environmental value of the asset is applicable to both scenarios. For these two scenarios the combined value can be determined as follows:

- *Combined residual value*$_{Functional}$ = *Functional value* + *Environmental value*
- *Combined residual value*$_{Obsolete}$ = *Physical value* + *Environmental value*

Q4: Given the results as found using Q3, what are implications of the results on the application of product-service systems in highway infrastructure assets? As for literature, one of the main implications is that literature on CE incentives linked to value should be aware of the aforementioned scenarios, which is currently not the case. Additionally, to be able to assess whether these incentives are significant more literature on this ought to be available. Also, literature on the residual value specifically should be mindful of the difference between residual value in its broadest sense and residual value in the sense of disposal. These two are often described using similar terminology, even in CE literature, while the former leads to significantly more circular incentive. Finally, this research has shown many of the different requirements for determining the residual value for PSS application to infrastructure assets. PSS literature on residual value determination is scarce. This research can be a starting point for studies regarding residual value determination in other PSS contexts.

As for the practical implications, this research has shown that practical solutions for determining the residual value are available. Even more so, it has suggested one that all actors involved agree with. With regards to these results the research also mentions that they are based mainly on practical insights, whereas recent academic insights are also relevant to include in the design. Additionally, several significant assumptions are applied in the research, which means that other outcomes can not be ruled out, even though these assumptions have been verified and validated. Thus, this research's results and their context implies that a residual value determination approach applicable to PSS in the infrastructure sector can be created and that the requirements and approach as presented in this research can be regarded as the first step for realising it, but that direct implementation is not advised. Continuation of research into the field is possible because of the detailed narrative description of the results and design process, which also allow for the approach being tailored such that it fits the needs of a project or program specifically. Weighting of the variables in the combined result is not done yet, but interesting findings are expected from other research groups in the near future. These should be inspected and if need be the approach should be altered accordingly. Additionally, the spread of results of the case application is too high on several fronts, mainly due to uncertainty in inputs. This should and is expected to be able to be addressed in the future, to allow for practical application.

Main research question: How can the residual value be determined such that it creates an incentive adhering to the CE principles in the context of product-service-systems applied to highway infrastructure assets? To this end a basic model has been designed (see Figure 4.2), that reveals what goal and requirements the value's components and valuation techniques should adhere to in the context of PSS applied to highway infrastructure. This model was then used to determine which of these latter two should be incorporated. Using this basic model combined with experts consultations and application of a case the final approach was determined. This final approach is equal to the findings under Q3. These findings were validated according to experts that represent all actor types involved. The combined results contribute significantly to creating an incentive >10% for contributing to a more CE in the infrastructure sector, a requirement of the approach because of its PSS context. Only the optional environmental component currently does not create a significant incentive. Furthermore, the findings adhere to the other two main requirements of financeability and applicability. As for the former, it is found that if the approach is agreed upon and the associated risks are distributed, financeability should not be a problem even though uncertainty still resides within the determination of the residual value. With regard to these findings it should be mentioned that they have been made using significant assumptions and that recent academic insights have not been included. Therefore, this research should be regarded as the first step in designing the approach, that can be enhanced and applied using further research, before implementation is an option.

Another interesting find is that not all aspects of the CE, such as reuse of materials within the design, are elligible for incentives within the residual value in this context. Finally, in line with the former it is found that to contribute to a CE, the CE principles should be regarded as goals and should not be directly implemented, since that does not always lead to the desired results.

6.2. Research relevance

The research's literary relevance lies in the fact that PSS literature on the residual value is scarce, especially within the infrastructure context. This research partially fills that gap, by detailing what the residual value in the context of PSS can mean, what requirements for it can be and how it can be determined. Additionally, several interesting findings regarding the application of CE principles, creating CE incentives and that different components of value apply to different scenarios are found. Especially in the context of PSS these findings can significantly alter the direction of further research.

As for the research's practical relevance, this lies mainly in the fact that current development of PSS applied to infrastructure can use the findings of the research as a first step in designing the final approach. The results can be reviewed, assumptions can be investigated further and recent academic developments can be incorporated. Performing these and potentially additional steps can solve the in practice encountered problem of the residual value determination. This can then advance the development of these PSS business approaches.

6.3. Research limitations

The main research limitations can be concluded to be as follows, along with their effects.

- The approach used does not guarantee the desired CE incentives are created, as it is dependent on project specific characteristics. However, the chosen method has the effect that the entire approach is in line with actors' wishes and its shortcomings are known, meaning they can be altered if deemed necessary.
- Limited analysis is done on price evolution determination methods. This aspect of the approach has a significant effect on the value and its spread. Since this analysis is not researched as extensively as the valuation approach it is not known whether the applied method (Geometric Brownian Motion) is the best suitable method.
- The applied case has several shortcomings. First, it neglects significant segments of the assets (e.g. foundation). If this were to be taken into account both the combined residual value and especially the functional component is expected to rise. The second is that this case is only for one specific segment, meaning that different segments have not been investigated.
- Governance aspects such as potential premature discontinuation of contracts, the effects of law and risk mitigation efforts for enabling financeability have not been researched extensively.
- A significant portion of the input has been gathered from experts within De Circulaire Weg (DCW), a partner program developing the infrastructure as a service concept. While outside experts were involved, potential positive bias as to the CE incentives, applicability and financeability of the results can exist.
- The research's design process has focused predominantly on the insights gained from practice.

Recent academic developments have not been included. Therefore, results can lag behind the state of the art in research regarding residual value determination and potentially aspects recently found to be relevant within the CE field might have have been left out.

- The use of significant assumptions, while verified and validated, can not rule out other outcomes of the research. Therefore, the results are not directly applicable and these assumptions should be investigated in further detail.

6.4. Research recommendations

Following the conclusions and limitations, recommendations can be constructed. First, an overview of the scientific and practical recommendations is provided in two lists for the respective fields. This is followed by Figure 6.1, which graphically presents a general overview of the residual value determination approach design process. The figure highlights the most significant aspects to bear in mind when aiming to conduct further research into this specific research subject, for each step in the design process. Several aspects in the figure overlap with the discussion chapter (see Chapter 5), as well as with the limitations and recommendations as presented in this chapter, whereas others have not been mentioned before. First, the list of recommendations for scientific purposes:

- Application of the resulting approach to several cases that are more in line with reality. With the latter is meant that for highway infrastructure, no asphalt layers or foundations are neglected and potentially other aspects of a highway, such as guardrails and signage should be considered.
- Validate all results using experts outside of DCW, such that the potentially positive bias is negated. With all results the following results are meant: the basic model and its requirements as well as the found equations per component and the final combined scenario approach.
- Investigate how high incentives ought to be within and outside of the infrastructure and PSS context, for firms to deliver on (significant) positive contributions to the three CE principles.
- Investigate what regression period fits GBM application best in the context of the assets and contracts in the highway infrastructure sector applied to PSS. This recommendation applies to both theory and practice.
- Investigate which of the price evolution determination fits the context of PSS applied to infrastructure best, in the sense that it allows for low spread and thereby highest applicability. This should result in an assessment of the potential replacement of GBM, as well as on which inputs should be used.
- Perform this research in reverse, by starting from the required height of the residual value to create the required incentives for construction firms to invest in the CE. This can lead to other results that might deliver better on the goal as set out in this research.
- Investigate the following validated assumptions:
  - Higher prices leads to a significant incentive for involved parties to aim for high quality reuse of materials and products
  - Higher prices leads to a significant incentive for involved parties to aim for using materials and products that allow for relatively simple disassembly
- Investigate the potential of valueing the functional component according to highway capacity (cars/hour), as opposed to the construction and renovation costs as is now the case. That would create the ideal incentive when linked to the PSS (and DBFM) availability criteria for increasing capacity with as much circularity as possible. From validation, the current expectation is that this is not yet applicable, since that would rest on capacity using a CBA, which is deemed not fitting for this purpose.
- Further investigate the relation between the periodic fee and the residual value in the context of PSS applied to infrastructure, since literature on this topic within these contexts is scarce and is needed for further development of the PSS business model in infrastructure. Interviews has resulted in the view that these can be seen as communicating barrels, however, while this might be the case for regular lease constructions, this is not necessarily the case for PSS constructions in which incentivising CE contributions is desired.
- Partial renovations occur within infrastructure construction. Their occurrence is currently not accounted for within the approach. The expectation is that these situations can be accounted for within the current approach. However, to ensure this, this should be investigated both in theory and in practice further.

- To advance the field of residual value determination in the context of PSS as applied to infrastructure, research should be conducted to incorporate recent academic developments, since the design as described in this research has been formed based predominantly on insights gained from practice.

Second, the list of recommendations for practical purposes:

- Validate the final combined valuation scenarios approach in order to investigate if any unexpected complications have arisen by forming this design.
- Apply the coming results of the Platform CB23 study into measuring circularity to the results of this study by adjusting the weights of the variables in the equations if the outcomes of the former study are significantly different.
- Further investigate the potential effects of premature discontinuation of the contract for all three actors involved.
- Further investigate laws that lead to complications when implementing a residual value approach in the PSS financial model applied to infrastructure construction.
- Further investigate what exact conditions have to be met for financeability, such as at what height caps and floors have to be set.
- Investigate and review the significant assumptions made in this research. Additionally, review if all actors agree that all validated assumptions made in creating the approach (assumptions detailed in bold in Section 4.2.2) will become reality.
- Perform a more extensive analysis on the inputs used in the case application by, for example, letting experts from different associations come to combined values. This is the case for all inputs that are not a direct input from the case (see Appendix D).
- Review if the size of the process value is indeed not significant, and if it is deemed important enough to include, determine an approach for determining this value.
- Implement the updated MKI inputs when these are ready, as supplied by the Stichting Nationale Milieudatabase, so that the the environmental component is actualised.
- Contribute to creation of the secondary markets (in this case, asphalt) as required for the physical component's approach to be applicable.
- Validate the combined valuation scenarios approach using experts from the involved actors.
- Investigate the relations between residual lifespan over time of the assets to be included in the PSS model over time and whether all are available or able to be determined. This should occur for all materials or products that are to be incorporated in the PSS model, since the physical component's value rests on this relation. Potentially investigate doing this on an incremental basis when significant maintenance or renovation works are done, since that can be more in line with the workings of the PSS model that pays for availability, than the current continuous relations are.
- To enhance the design and thereby increase its chances for successful application, research should be conducted to incorporate recent academic developments, since the design as described in this research has been formed based predominantly on insights gained from practice.

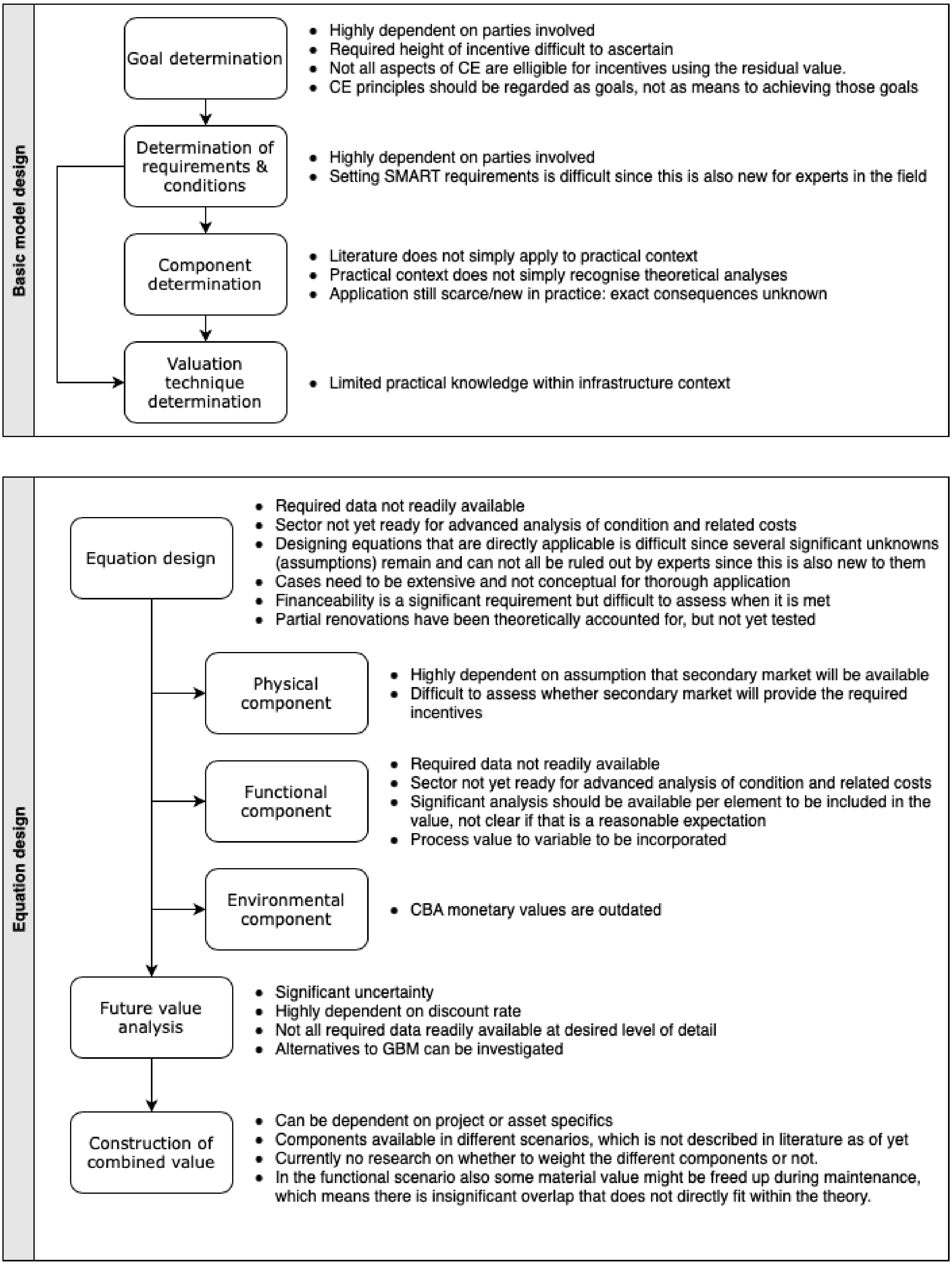

Figure 6.1: Graphical overview of the residual value determination approach design process. The first of the two large frames describes the steps undertaken for designing the basic model (see Figure 4.10). The separate steps within this frame are denoted with the subsequent blocks. The bullets to the right of each block represent the aspects to bear in mind when aiming to conduct further research into this specific research subject. The second frame does the same as the first, but for the equation design.

A

Measurement method Platform CB23

Section 2.1.2 elaborates on the developments within Platform CB23. This section aims to provide an extensive overview of one of the results that Platform CB23 has achieved: the determination of a measurement method for circular principles in the construction sector. The list below contains all elements incorporated in the measurement method. As can be seen, the measurement method has arrived at three main aspects with respect to circularity: protection of material stock; protection of the environment and protection of existing value. For nearly all of the subfactors grouped under these three aspects a method for its measurement has been established and (informally) agreed upon by a rather large group of parties involved in the construction sector (Platform CB23, 2020b). .

- Protection of material stock
  1. Quantity of materials used (input)
     - 1.1 The quantity of primary materials used
     - 1.2 The quantity of secondary materials used
       - 1.2a The quantity of secondary materials from reuse
       - 1.2b The quantity of secondary materials from recycling
     - 1.3 The quantity of materials used that are susceptible to becoming depleted
       - 1.3a The quantity of sustainably produced renewable materials used
       - 1.3b The quantity of non-renewable or unsustainably produced renewable materials used
       - 1.3c The quantity of scarce materials used
       - 1.3d The quantity of generally available materials used
  2. Quantity of materials available for the next cycle (output)
     - 2.1 The quantity of materials for reuse
     - 2.2 The quantity of materials for recycling
  3. Quantity of materials lost (output)
     - 3.1 The quantity of materials for energy generation
     - 3.2 The quantity of materials sent to landfill
- Protection of the environment
  4. Influence on the quality of the environment
     - 4.1 Climate change - total
     - 4.2 Climate change - fossil
     - 4.3 Climate change - biogenic
     - 4.4 CLimate change - land use and change in land use
     - 4.5 Ozone layer depletion
     - 4.6 Acidification
     - 4.7 Eutrophication freshwater
     - 4.8 Eutrophication seawater
     - 4.9 Eutrophication land
     - 4.10 Photochemical oxidation (smog)
     - 4.11 Depletion of abiotic raw materials - minerals and metals
     - 4.12 Depletion of abiotic raw materials - fossil energy carriers

    - 4.13 Water use
    - 4.14 Particulate matter emission
    - 4.15 Ionising radiation
    - 4.16 Ecotoxicological effects, aquatic (freshwater)
    - 4.17 Human-toxicological effects, carcinogenic
    - 4.18 Human-toxicological effects, non-carcinogenic
    - 4.19 Land-use-related impact / soil quality
- Protection of existing value
  5. Quantity of existing value used (input)
     - 5.1 Technical-functional value
     - 5.2 Economic value
  6. Quantity of value available for the next cycle (output)
     - 6.1 Technical-functional value
     - 6.2 Economic value
  7. Quantity of existing value lost (output)
     - 7.1 Technical-functional value
     - 7.2 Economic value

B

Interview protocol

- Interviewer: Sjef Hereijgers
- Contactgegevens interviewer: sjefhereijgers@gmail.com - 0620952106
- Geinterviewde:
- Contactgegevens geinterviewde:
- Organisatie geinterviewde:
- Datum:

Voorstellen

- Master Construction Management & Engineering aan de TU Delft;
- Momenteel bezig met thesis onderzoek onder Daan Schraven;
- Mijn onderzoek is aangesloten bij het programma DCW.

Mag ik het onderzoek opnemen om de validiteit te verzekeren?

Introductie

- Onderwerp: dit interview heeft betrekking op mijn thesisonderzoek, dat gaat over het implementeren van circulariteit in het bepalen van de restwaarde. Dit wordt onderzocht in de context van leasecontracten voor weg(-gerelateerde) infrastructuur assets. Het idee hierachter is dat allereerst circulair gedacht zal worden door circulariteit mee te nemen. Daarnaast is de verwachting dat dit resulteert in een hogere restwaarde, die dient als prikkel voor circulair handelen door de aannemer en andere betrokken partijen. De context zal zometeen nog wat verder toegelicht worden.
- Doel: de interviews zullen dienen als aanvulling op de literatuurstudie naar bovenstaand onderwerp, om in het verkennende gedeelte van de thesis ook de praktijk naar voren te laten komen.
- Vertrouwelijkheid: de resultaten van het interview zullen naar voren komen in de thesis, die online voor iedereen toegankelijk zal zijn. Hierin zal niet dit individuele interview naar voren komen. Wel zullen uw naam en functie hierin genoemd worden in verband met de resultaten van deze set interviews.
- Resultaten: de resultaten zullen een onderdeel vormen van het verkennende gedeelte van de thesis.
- Duur: het gesprek zal ongeveer een uur duren.
- Structuur interview: allereerst zal ik kort de theoretische context schetsen. Daarna gaan we allereerst in op het onderwerp restwaarde, het belang ervan, de technieken die op dit moment gebruikt worden voor het betalen daarvan en relevante factoren die meegenomen moeten worden in het bepalen ervan. Vervolgens gaan we in op de verschillende technieken die toegepast kunnen worden in het berekenen van de restwaarde. Het interview is van het type semi-structured, wat betekent dat ik een aantal vragen stel volgens een vast format, maar daar ook van af kan wijken.
- Overige vragen?

- Vragen naar persoonsgegevens:
  - Wat is uw naam?
  - Waar bent u werkzaam?
  - Wat is daar uw functie?

Theoretische context De huidige vraag naar materialen is hoog en groeit nog steeds. Dit maakt dat dit niet houdbaar is richting de toekomst. Een oplossing hiervoor is om ons huidige lineaire consumptiemodel om te zetten naar een meer circulair model. Dit kan onder andere gedaan worden door het meer inzetten van de product-service system business approach. In deze business approach vindt een verschuiving plaats van product-georienteerde verkopen naar het verkopen van services. Dit wordt meer en meer toegepast, maar helaas nog niet in de infrasector. De Circulaire Weg probeert uit te zoeken of het mogelijk is PSS in de infrasector, specifiek op weg(-gerelateerde) assets, toe te passen. Een van de aspecten waar in deze context nog onderzoek naar gedaan wordt is die van de restwaarde. Uit onderzoek is gebleken dat om de circulariteitsdoelen binnen PSS te halen het vooraf vaststellen van methode voor het bepalen van een restwaarde belangrijk is. Op dit moment is er nog onduidelijkheid over hoe circulariteit hier het beste in meegenomen kan worden, iets wat wel bij kan dragen aan het behalen van deze circulariteitsdoelen. Dit onderzoek dient dan ook om te bekijken hoe deze restwaarde bepaald kan worden op zo'n manier dat circulariteit daarin meegenomen wordt. Heeft u hier nog vragen over?

Overgangsvraag

- Kunt u wat vertellen over waar DCW nu staat?

Onderwerpen

- Restwaarde
  1. Wat is het belang van de restwaarde voor het bereiken van de circulaire doelen van PSS?
  2. Hoe hoog denkt u dat de restwaarde moet zijn, om te dienen als prikkel voor deze circulaire doelen, procentueel ten opzichte van de initiele constructiewaarde?
  3. Waarom proberen we de circulaire prikkel niet te dienen door afspraken te maken over de kwaliteit van de weg aan het einde van het contract, in plaats van het afspreken van een restwaarde?
  4. Welke bestanddelen moeten opgenomen worden in de restwaardeberekening?
     - Vereisten vanuit de geinterviewde
     - Vereisten voorgesteld vanuit de interviewer
       - Consistentie door door de tijd heen
       - Gemak van berekenen
       - Accuraatheid voorspelling
       - Financierbaarheid
       - Conditie meenemen
       - Voldoen aan wetgeving
       - Circulariteit: beschermen van materiaalvoorraden; beschermen van milieu; beschermen van bestaande waarde.
       - Herinvesteringen meenemen
     - Verdere aanvullingen vanuit de geinterviewde
  5. Niveau bepaling:
     - Op welk niveau (grondstof/material/product/element/bouwwerk) moet de restwaardeberekening worden toegepast?
- Technieken
  6. Wat is/zijn de huidige techniek(en) voor het bepalen van de restwaarde voor infrastructuurprojecten?
  7. Welke problemen is/zijn ziet u met de huidige techniek(en) voor restwaardebepaling?
  8. Welke technieken voor het bepalen van de restwaarde zijn er toepasbaar?
     - Technieken vanuit de geinterviewde
     - Technieken voorgesteld vanuit de interviewer

        - Net Present Value (NPV) of future benefits and costs in annuity / Annuity approach / Going Concern Value/ Income Approach / Productivity Realized Value / Income Capitalized Value
        - Perpetuity Approach / NPV of future benefits and costs in perpetuity
        - PV of past costs / Equivalent Present Worth in Place / Depreciated Historic Cost Approach
        - Market Value / Sales Comparison Approach
        - Written Down Replacement Costs / Depreciated Replacement Costs
        - Net Salvage Value / Net Liquidation Value
        - Cost Benefit analysis
    - Verdere aanvullingen vanuit de geinterviewde
- Overig:
  - Zijn er nog andere experts waarvan u denkt dat die van toevoeging kunnen zijn bij mijn onderzoek?

Afsluiting Ter goedkeuring zal ik een getranscribeerde versie van het interview uw kant opsturen. Mocht u verder nog vragen of toevoegingen hebben dan kunt u mij via mijn mail of telefoon bereiken.

C

Case application specifics

This section presents the python code used in the case application as described in Section 3.2.2 and Section 4.2.2. This is presented by first highlighting the code itself, in which basic information such as the unit of the variable, idea behind a line of code and the sources are stated. This is followed by additional information on choices and why the code is structured the way it is, to be able to replicate the findings. This can be found in the second section of the appendix. For this section, it should be noted that this does not provide an entire overview, but that it should be viewed as a section that provides better understanding of the code, so it can be replicated.

Python code

```
#!/usr/bin/env python3
# -*- coding: utf-8 -*-
”””
Created on Fri Apr 30 16:01:05 2021

@author: sjefhereijgers
”””

import os
import numpy as np
import scipy as sp
from scipy import stats
import matplotlib.pyplot as plt
from datetime import datetime
from scipy.stats import norm
from scipy.stats import skewnorm
from math import e

font = {’family’: ’Tahoma’,                  # Layout voor figuren
 ’weight’: ’light’,
 ’size’: 20}
plt.rc(’figure’, figsize=[10, 5])
plt.rc(’font’, **font)


# =======================================================================


# Basic inputs
f = 1                           #-, used to distinguish image names
```

```
np.random.seed(192326)           #-, seed for random sampling
M = 10**4                        #runs, amount of runs for MCA
t_contractperiode = 15           #years, contract period, source = DCW
DF = 0.0387255                   #%, discount factor without inflation, source = Remco van Duuren
A = 22729                        #m^2, total surface area of pavement in m^2, source = DCW


# ======================================================================


# Inputs Monte Carlo Analyses

# Inputs physical value (market value)
P_bitumenperton_current = 463          #euros, source = Roland Bouwman
P_zonderbitumenperton_current = 20.21  #euros, source = Roland Bouwman
M_bitumen = 316.302                    #tons, source = Roland Bouwman & Rob van den Burgh
M_zonderbitumen = 7214.70              #tons, source = Roland Bouwman & Rob van den Burgh
V_bitumenperton = M_bitumen / (M_bitumen + M_zonderbitumen)                                        #-, source = Roland Bouwman
M_loss_scrape = 0.024                      #ton/m^2, source = Roland Bouwman
Drift_mu_physical_zonderbitumen = 0.0050709 #-, source = CROW
Drift_mu_physical_bitumen = 0.007485067     #-, source = CROW
Volatility_sigma_physical_zonderbitumen = 0.020855975     #-, source = CROW
Volatility_sigma_physical_bitumen = 0.20659002            #-, source = CROW
dP_groei_materiaal_totaalcontractperiode_zonderbitumen = np.zeros(shape=(M,1))                                   #empty array for code
dP_groei_materiaal_totaalcontractperiode_bitumen = np.zeros(shape=(M,1))                                   #empty array for code


# Inputs functional value
P_nieuwbouw_newroadtype_current = 1982738       #euros, price construction new road, source = Emiel Wolbers
Mu_levensduur = 17.4                            #years, average lifespan asphalt, source = paper Rijkswaterstaat
Sigma_levensduur = 2.4                          #years, standard deviation lifespan asphalt, source = paper Rijkswaterstaat
Drift_mu_functional = 0.0035412                 #-, source = CBS
Volatility_sigma_functional = 0.0300509         #-, source = CBS
Macht_renovatielijn = 1                         #-, assumption relation degradation over time
dP_groei_functioneel_totaalcontractperiode = np.zeros(shape=(M,1))                            #empty array for code
P_functioneel_aftercontractperiod = np.zeros(shape=(M,1))                            #empty array for code


# inputs externalities (MKI)
```

```
MKI_referentie = 344561          #euros, MKI reference design, source = Rob van den Burgh
MKI_verdeling_lowerbound = 0     #euros, MKI reference design, source = Rob van den Burgh
MKI_verdeling_upperbound = 0.5  #euros, MKI reference design, source = Rob van den Burgh
Drift_mu_externalities = 0.0035412             #-, source = CBS
Volatility_sigma_externalities = 0.0300509     #-, source = CBS
dP_groei_externalities_totaalcontractperiode = np.zeros(shape=(M,1))                               #empty array for code
MKI_delta_aftercontractperiod = np.zeros(shape=(M,1))                               #empty array for code


# Monte Carlo Analyses
for i in range(M):      #M runs for MCA

    # Physical value
    Epsilon_physical_zonderbitumen = 0      #-, starting Epsilon required for GBM1
    Epsilon_physical_bitumen = 0            #-, starting Epsilon required for GBM2
    for j in range(t_contractperiode):      #-, calculation of Epsilons for GBMs
        Epsilon_physical_zonderbitumen = Epsilon_physical_zonderbitumen + np.random.normal(0,1)
        Epsilon_physical_bitumen = Epsilon_physical_zonderbitumen + np.random.normal(0,1)
    dP_groei_materiaal_totaalcontractperiode_zonderbitumen[i] = e**((t_contractperiode * Drift_mu_physical_zonderbitumen) + (Volatility_sigma_physical_zonderbitumen * Epsilon_physical_zonderbitumen))         #-, growth ratio following from GBM1
    dP_groei_materiaal_totaalcontractperiode_bitumen[i] = e**((t_contractperiode * Drift_mu_physical_bitumen) + (Volatility_sigma_physical_bitumen * Epsilon_physical_bitumen))                 #-, growth ratio following from GBM2

    # Functional value
    Epsilon_functional = 0                  #-, starting Epsilon required for GBM
    for k in range(t_contractperiode):      #-, calculation of Epsilon for GBM
        Epsilon_functional = Epsilon_functional + np.random.normal(0,1)
    dP_groei_functioneel_totaalcontractperiode[i] = e**((t_contractperiode * Drift_mu_functional) + (Volatility_sigma_functional * Epsilon_functional))     #-, growth ratio following from GBM
    restlevensduur_asfalt_voorreparatie_variabele = np.random.normal(Mu_levensduur,Sigma_levensduur)                  #years, choosing random lifespan with mu and sigma known
    if restlevensduur_asfalt_voorreparatie_variabele <= t_contractperiode:            #detection in case lifespan is shorter than contract period: in that case the functional value is equal to zero since the renovation price is equal to full construction price.
        P_renovatie = P_nieuwbouw_newroadtype_current
    else:
```

```python
        P_renovatie = ((t_contractperiode / restlevensduur_asfalt_voorreparatie_variabele)** Macht_renovatielijn) * P_nieuwbouw_newroadtype_current
    P_functioneel_aftercontractperiod[i] = (P_nieuwbouw_newroadtype_current - P_renovatie) * dP_groei_functioneel_totaalcontractperiode[i]      #application of designed equation using inputs from MCA, multiplied with price growth to obtain price at end of contract period

    # Externalities (MKI)
    MKI_nieuwdesign_reductie = np.random.uniform(MKI_verdeling_lowerbound, MKI_verdeling_upperbound)             #-, reduction in MKI for new design, randomly chosen from uniform distribution based on boundaries as provided (lowerbound and upperbound)
    MKI_nieuwdesign_variabele = (1-MKI_nieuwdesign_reductie) * MKI_referentie       #-, correction to correctly interpret the reduction in MKI
    MKI_delta_variabele = MKI_referentie - MKI_nieuwdesign_variabele        #euros, calculation of MKI delta using designed equation
    Epsilon_externalities = 0       #-, starting Epsilon required for GBM
    for l in range(t_contractperiode):      #-, calculation of Epsilon for GBM
        Epsilon_externalities = Epsilon_externalities + np.random.normal(0,1)
    dP_groei_externalities_totaalcontractperiode[i] = e**((t_contractperiode * Drift_mu_externalities) + (Volatility_sigma_externalities * Epsilon_externalities))     #-, growth ratio following from GBM
    MKI_delta_aftercontractperiod[i] = MKI_delta_variabele * dP_groei_externalities_totaalcontractperiode[i]     #euros, multiplication of MKI delta with price growth to obtain price at end of contract period




# Additional calculations

# Physical value --> multiplication with material prices and amounts and discounting to present
P_material_aftercontractperiod_zonderbitumen = dP_groei_materiaal_totaalcontractperiode_zonderbitumen * P_zonderbitumenperton_current * (M_zonderbitumen - 2 * M_loss_scrape * A * (1-V_bitumenperton))          #euros, multiplying the price of material with the price growth, the amount of material (without bitumen) minus twice the loss due to scraping of the material
P_material_aftercontractperiod_bitumen = dP_groei_materiaal_totaalcontractperiode_bitumen * P_bitumenperton_current * (M_bitumen - 2 * M_loss_scrape * A * V_bitumenperton)                                #euros, multiplying the price of material with the price growth, the amount of material (with bitumen) minus twice the loss due to scraping of the material
P_material_current = (P_material_aftercontractperiod_zonderbitumen + P_material_aftercontractperiod_bitumen) / ((1+DF)**t_contractperiode)          #euros, combination and discounting of both material
```

```
    ↪ values to the present

#Functional value --> verdiscontering naar heden
P_functioneel_current = P_functioneel_aftercontractperiod / ((1+DF)**
    ↪ t_contractperiode)         #euros, discounting the functional value
    ↪ to the present

#Environmental (MKI) --> verdiscontering naar heden
MKI_delta_current = MKI_delta_aftercontractperiod / ((1+DF)**
    ↪ t_contractperiode)     #euros, discounting the environmental value
    ↪ to the present


# ======================================================================



# Component final values and plots
# Physical value
Mu_P_physical = np.mean(P_material_current)
SD_P_physical = np.std(P_material_current)
SE_P_physical = SD_P_physical / M**0.5
Boundary_physical_low = float(min(P_material_current))
Boundary_physical_high = np.percentile(P_material_current,95)

print(’Fysieke waarde’)
print(’Mu_fysiek = ’,round(Mu_P_physical,2))
print(’SE_fysiek = ’,round(SE_P_physical,2))
print(’Boundary_physical_low = ’,round(Boundary_physical_low,2))
print(’Boundary_physical_high = ’,round(Boundary_physical_high,2))
print(’’)

plt.hist(P_material_current,100)
plt.axvline(x=Boundary_physical_low, color=’r’, linestyle=’--’)
plt.axvline(x=Boundary_physical_high, color=’r’, linestyle=’--’)
plt.xlabel(’Value [Euro]’)
plt.ylabel(’Occurrences [-]’)
plt.tight_layout()
plt.ticklabel_format(style=’sci’, axis=’x’, scilimits=(0,0))
plt.savefig(’Location/’ + datetime.today().strftime(’%m-%d_’) + str(f) + ’
    ↪ _Phys’  + ’_M=’ + str(M) + ’_Pbitumen=’ + str(
    ↪ P_bitumenperton_current) + ’_Pzonderbitu=’ + str(
    ↪ P_zonderbitumenperton_current) + ’_Mbitumen=’ + str(M_bitumen) + ’
    ↪ _Mzonderbitu=’ + str(M_zonderbitumen) + ’_A=’ + str(A) + ’
    ↪ _Mlossscrape=’ + str(M_loss_scrape) + ’_Driftzonderbitu=’ + str(
    ↪ Drift_mu_physical_zonderbitumen) + ’_Sigmazonderbitu=’ + str(
    ↪ Volatility_sigma_physical_zonderbitumen) + ’_Driftbitumen=’ + str(
    ↪ Drift_mu_physical_bitumen) + ’_Sigmabitumen=’ + str(
    ↪ Volatility_sigma_physical_bitumen) + ’_DF=’ + str(DF) +  ’_t=’ + str
    ↪ (t_contractperiode) + ’.pdf’)
plt.show()


#Functional value
Mu_P_functional = np.mean(P_functioneel_current)
SD_P_functional = np.std(P_functioneel_current)
```

```
SE_P_functional = SD_P_functional / M**0.5
Boundary_functional_low = float(min(P_functioneel_current))
Boundary_functional_high = np.percentile(P_functioneel_current,95)

print('Functionele waarde')
print('Mu_functioneel = ',round(Mu_P_functional,2))
print('SE_fysiek = ',round(SE_P_functional,2))
print('Boundary_functional_low = ',round(Boundary_functional_low,2))
print('Boundary_functional_high = ',round(Boundary_functional_high,2))
print('')

plt.hist(P_functioneel_current,100)
plt.axvline(x=Boundary_functional_low, color='r', linestyle='--')
plt.axvline(x=Boundary_functional_high, color='r', linestyle='--')
plt.xlabel('Value [Euro]')
plt.ylabel('Occurrences [-]')
plt.tight_layout()
plt.ticklabel_format(style='sci', axis='x', scilimits=(0,0))
plt.savefig('Location/' + datetime.today().strftime('%m-%d_') + str(f) + '_Funct' + '_M=' + str(M) + '_Pnieuwbouw=' + str(P_nieuwbouw_newroadtype_current) + '_Renolijn=' + str(Macht_renovatielijn) + '_Mulevens=' + str(Mu_levensduur) + '_Sigmalevens=' + str(Sigma_levensduur) + '_Driftfunc=' + str(Drift_mu_functional) + '_Sigmafunc=' + str(Volatility_sigma_functional) + '_DF=' + str(DF) + '_t=' + str(t_contractperiode) +  '.pdf')
plt.show()


# Externalities (MKI)
Mu_P_externalities = np.mean(MKI_delta_current)
SD_P_externalities = np.std(MKI_delta_current)
SE_P_externalities = SD_P_externalities / M**0.5
Boundary_externalities_low = float(min(MKI_delta_current))
Boundary_externalities_high = np.percentile(MKI_delta_current,95)

print('Milieu waarde')
print('Mu_milieu = ',round(Mu_P_externalities,2))
print('SE_milieu = ',round(SE_P_externalities,2))
print('Boundary_externalities_low = ',round(Boundary_externalities_low,2))
print('Boundary_externalities_high = ',round(Boundary_externalities_high,2))
print('')

plt.hist(MKI_delta_current,100)
plt.axvline(x=Boundary_externalities_low, color='r', linestyle='--')
plt.axvline(x=Boundary_externalities_high, color='r', linestyle='--')
plt.xlabel('Value [Euro]')
plt.ylabel('Occurrences [-]')
plt.tight_layout()
plt.ticklabel_format(style='sci', axis='x', scilimits=(0,0))
plt.savefig('Location/' + datetime.today().strftime('%m-%d_') + str(f) + '_Envir' + '_M=' + str(M) + '_MKIref=' + str(MKI_referentie) + '_MKIverlower=' + str(MKI_verdeling_lowerbound) + '_MKIverupper=' + str(MKI_verdeling_upperbound) + '_Driftphys=' + str(Drift_mu_externalities) + '_Sigmaphys=' + str(
```

```
    ↪ Volatility_sigma_externalities) + '_DF=' + str(DF) + '_t=' + str(
    ↪ t_contractperiode) + '.pdf')
207 plt.show()
```

Code elaboration

The code is discussed according to the lines shown to the left of the code.

- **Lines 1-26:** Basic file information, package imports as well as figure layout information
- **Lines 27-37:** Basic inputs, that are used in all component calculations
- **Lines 38-56:** Inputs for the MCA calculation of the physical value component
  - Line 48: determines the ratio of the mass of bitumen versus total asphalt mass
  - Line 54: empty array used later to input data, this makes code run more efficiently
  - Line 55: empty array used later to input data, this makes code run more efficiently
- **Lines 57-67:** Inputs for the MCA calculation of the functional value component
  - Line 64: variable used exponent (power), since adequate data on this relation was not available
  - Line 65: empty array used later to input data, this makes code run more efficiently
  - Line 66: empty array used later to input data, this makes code run more efficiently
- **Lines 68-78:** Inputs for the MCA calculation of the environmental value component
  - Line 71: Lower bound of the uniform distribution for the reduction of the MKI
  - Line 72: Upper bound of the uniform distribution for the reduction of the MKI
  - Line 75: empty array used later to input data, this makes code run more efficiently
  - Line 76: empty array used later to input data, this makes code run more efficiently
- **Lines 79-81:** for loop that enables the MCA to make its runs (10.000)
- **Lines 82-90:** MCA calculations of physical value required within loop
  - Line 83: calculation of epsilon for the first GBM needs a initial starting value (0)
  - Line 84: calculation of epsilon for the second GBM needs a initial starting value (0)
  - Line 85: for loop that allows for epsilon calculation cumulatively each year as long as the contract period is (15 years)
  - Line 86: cumulative epsilon calculation per year for the first GBM
  - Line 87: cumulative epsilon calculation per year for the second GBM
  - Line 88: calculation of price evolution over the timespan of the contract period (15 years) for the first GBM
  - Line 89: calculation of price evolution over the timespan of the contract period (15 years) for the second GBM
- **Lines 91-102:** MCA calculations of functional value required within loop
  - Line 92: calculation of epsilon for the GBM needs a initial starting value (0)
  - Line 93: for loop that allows for epsilon calculation cumulatively each year as long as the contract period is (15 years)
  - Line 94: cumulative epsilon calculation per year for the GBM
  - Line 95: calculation of price evolution over the timespan of the contract period (15 years) for the GBM
  - Line 96: determination of lifespan based on mu and sigma using random sample from said distribution
  - Line 97: if loop that detects if lifespan of as just determined (line 96) is shorter than contract period. This is relevant for this case specifically, as explained in Section 4.2.2.2
  - Line 98: if line 97 is true, the $P_{renovatie}$ is set equal to $P_{nieuwbouw-newroadtype-current}$
  - Line 99: if line 97 is not true, then line 100 happens
  - Line 100: this shows the regular calculation, which would also be present without the if loop of line 97. It calculates costs of renovation ($P_{renovatie}$) assuming a degradation line is equal to $Macht_{renovatielijn}$
  - Line 101: this line applies the designed equation and directly multiplies the value with the price evolution as found using the GBM
- **Lines 103-115:** MCA calculations of environmental value required within loop
  - Line 104: random sampling of the MKI reduction by using a new design

- Line 105: determining the MKI of the newdesign using the just sampled reduction (line 104)
- Line 106: calculates the MKI delta using the equation as designed
- Line 107: calculation of epsilon for the GBM needs a initial starting value (0)
- Line 108: for loop that allows for epsilon calculation cumulatively each year as long as the contract period is (15 years)
- Line 109: cumulative epsilon calculation per year for the GBM
- Line 110: calculation of price evolution over the timespan of the contract period (15 years) for the GBM
- Line 111: calculation of MKI multiplied with price evolution

• **Lines 116-122:** Additional calculations of physical value outside of MCA loop
  - Line 119: calculation of price of the non-bitumen asphalt material in the asset after contract period. This is done by multiplying the first GBM with the current price of non-bitumen asphalt material and multiplying that with a correction for the scraping of the material (two layers, therefore the 2)
  - Line 120: calculation of price of the bitumen material in the asset after contract period. This is done by multiplying the second GBM with the current price of bitumen asphalt material and multiplying that with a correction for the scraping of the material (two layers, therefore the 2)
  - Line 121: adding the results from lines 119 and 120 and discounting them to the present

• **Lines 123-125:** Additional calculations of functional value outside of MCA loop
  - Line 124: discounting the price after contract period to the present

• **Lines 126-129:** Additional calculations of environmental value outside of MCA loop
  - Line 127: discounting the price after contract period to the present

• **Lines 130-207:** Determination of Mu, SD and SE, as well as graphs representing these results

D

Case application inputs

This appendix presents the inputs for the code of the case application, per component in the following three tables.

Table D.1: An overview of the inputs used in the application of the case of the physical component with the terminology adopted, alongside a clarification of the input and the source. All inputs are reported without inflation. The table continues on the next page. The additional values for variable 1 and 2 denote other specific prices as used and explained in Chapter 5

#	Variable	Value	Unit	Clarification	Source
1	P_bitumenperton _current	463 (463/ 463)	euro/ton	Current price of bitumen per ton, corrected for processing	Roland Bouwman, expert on asphalt materials
2	P_zonderbitumen perton_current	20,21 (22,83/ 10,42)	euro/ton	Current price of asphalt material without bitumen per ton, corrected for processing	Roland Bouwman, expert on asphalt materials
3	M_bitumen	316,302	ton	Mass of bitumen present in the segment	Roland Bouwman, expert on asphalt materials & Rob van den Burgh, expert on environmental valuation and costs
4	M_zonderbitumen	7214,70	ton	Mass of asphalt material without bitumen per ton	Roland Bouwman, expert on asphalt materials & Rob van den Burgh, expert on environmental valuation and costs
5	A	22729	m^2	Total surface area of the asphalt segment	Olga Teule, expert on DCW & Roland Bouwman, expert on asphalt materials & Rob van den Burgh, expert on environmental valuation and costs & width validated using Google Maps
6	M_loss_scrape	0,024	ton/m^2	Loss of material because of disassembly (scraping)	Roland Bouwman, expert on asphalt materials

7	Drift_mu_physical _zonderbitumen	0,00507094	-	Drift associated with historic material prices of asphalt material without bitumen	Kennisplatform CROW, #22 (Kennisplatform CROW, 2021) & Rob Zantinge and Roland Bouwman, experts on asphalt materials. The choice is made specifically for CROW data, as opposed to CBS data for the other two components, as that is directly available and was the clear recommendation of aforementioned experts.
8	Volatility_sigma _physical _zonderbitumen	0,02085598	-	Volatility associated with historic material prices of asphalt material without bitumen	Kennisplatform CROW, #22 (Kennisplatform CROW, 2021) & Rob Zantinge and Roland Bouwman, experts on asphalt materials. The choice is made specifically for CROW data, as opposed to CBS data for the other two components, as that is directly available and was the clear recommendation of aforementioned experts.
9	Drift_mu_physical _bitumen	0,00748507	-	Drift associated with historic material prices of bitumen	Kennisplatform CROW, #20 (Kennisplatform CROW, 2021) & Rob Zantinge and Roland Bouwman, experts on asphalt materials. The choice is made specifically for CROW data, as opposed to CBS data for the other two components, as that is directly available and was the clear recommendation of aforementioned experts.
10	Volatility_sigma _physical _bitumen	0,20659002	-	Volatility associated with historic material prices of bitumen	Kennisplatform CROW, #20 (Kennisplatform CROW, 2021) & Rob Zantinge and Roland Bouwman, experts on asphalt materials. The choice is made specifically for CROW data, as opposed to CBS data for the other two components, as that is directly available and was the clear recommendation of aforementioned experts.
11	DF	0,0387255	-	Discount factor for infrastructure road projects	Remco van Duuren, financial expert
12	t_contractperiode	15	year	Contract period as set for the case	Olga Teule, expert on DCW

Table D.2: An overview of the inputs used in the application of the case of the functional component with the terminology adopted, alongside a clarification of the input and the source. All inputs are reported without inflation.

#	Variable	Value	Unit	Clarification	Source
13	P_nieuwbouw _newroadtype _current	1982738	euro	Current price for the construction of a new road, specifically for the case segment	Emiel Wolbers, expert on infrastructure construction pricing
14	Renovatielijn (y = x^?)	1	-	The power representing the relation of degradation over time. A value of 1 denotes a linear relation, whereas a value of 2 denotes an exponential relation	Assumption since information regarding this for the found mixture and lifespan findings was not available.
15	Drift_mu _functional	0,0035412	-	Drift associated with road construction prices	CBS, closed road total costs (4211b) (CBS, 2021b)
16	Volatility_sigma _functional	0,0300509	-	Volatility associated with road construction prices	CBS, closed road total costs (4211b) (CBS, 2021b)
17	Mu_restlevensduur	17,4	year	Average lifespan of ZOAB asphalt of an 'adjacent' strip of a highway, with no previous renovations done	Rijkswaterstaat, levensduur van ZOAB studie (Verra et al., 2003)
18	Sigma _restlevensduur	2,4	year	Standard deviation of ZOAB asphalt of an 'adjacent' strip of a highway, with no previous renovations done	Rijkswaterstaat, levensduur van ZOAB studie (Verra et al., 2003)
19	DF	0,0387255	-	Discount factor for infrastructure road projects	Remco van Duuren, financial expert
20	t_contractperiode	15	year	Contract period as set for the case	Olga Teule, expert on DCW

Table D.3: An overview of the inputs used in the application of the case of the environmental component with the terminology adopted, alongside a clarification of the input and the source. All inputs are reported without inflation.

#	Variable	Value	Unit	Clarification	Source
21	MKI_referentie	344561	euro	MKI of the reference design for the case segment	Emiel Wolbers, expert on infrastructure construction pricing
22	MKI_verdeling _average - lower bound	0	-	Lower bound of the expected relative MKI reduction of the new design	Rob van den Burgh, expert on environmental valuation and costs
23	MKI_verdeling _average - upper bound	0,5	-	Lower bound of the expected relative MKI reduction of the new design	Rob van den Burgh, expert on environmental valuation and costs
24	Drift_mu _externalities	0,0035412	-	Drift associated with road construction prices	CBS, closed road total costs (4211b) (CBS, 2021b)
25	Volatility_sigma _externalities	0,0300509	-	Standard deviation associated with road construction prices	CBS, closed road total costs (4211b) (CBS, 2021b)
26	DF	0,0387255	-	Discount factor for infrastructure projects	Remco van Duuren, financial expert
27	t_contractperiode	15	year	Contract period as set for the case	Olga Teule, expert on DCW

E

Sensitivity analysis

An overview of the results of the sensitivity analyses can be found in Table E.1, Table E.2 and Table E.3, for the physical, functional and environmental components respectively. Because of table fitting, the tables can be found on the following pages. The input variables within the tables are not presented with subscripts, since that would make the tables less clear. Subscripts are therefore denoted using a lower dash (_).

Table E.1: The sensitivity analysis for the physical value, giving the change in the two (first left column) for a change in the variable inputs (second left column). The relative difference as applied to the input variables is given in the top row. For the input variable t_contractperiode these inputs are not relative but changed in incremental steps of 1 year, since that is a coding constraint.

Output	**Input variable ↓, Input change (percentage / years for t_contractperiode) →**	-50% / -10	-10% / -6	-5% / -5	-1% / -1	+1% / +1	+5% / +5	+10% / +6	+50% / +10
Mu	P_bitumenperton_current	-30%	-6%	-3%	-1%	1%	3%	6%	30%
	P_zonderbitumenperton_current	-20%	-4%	-2%	0%	0%	2%	4%	20%
	M_bitumen	-30%	-6%	-3%	-1%	1%	3%	6%	30%
	M_zonderbitumen	-33%	-6%	-3%	-1%	1%	3%	6%	27%
	A	8%	2%	1%	0%	0%	-1%	52%	-8%
	M_loss_scrape	8%	2%	1%	0%	0%	-1%	-2%	-8%
	Drift_mu_physical_zonderbitumen	-2%	0%	0%	0%	0%	0%	0%	2%
	Drift_mu_physical_bitumen	-3%	0%	0%	0%	0%	0%	1%	3%
	Volatility_sigma_physical_zonderbitumen	0%	0%	0%	0%	0%	0%	0%	0%
	Volatility_sigma_physical_bitumen	-13%	-4%	-3%	0%	0%	2%	4%	32%
	DF	33%	6%	3%	1%	-1%	-3%	-5%	-24%
	t_contractperiode	16%	2%	1%	-1%	-2%	-10%	-11%	-18%
SE	P_bitumenperton_current	-48%	-10%	-5%	-1%	1%	5%	10%	48%
	P_zonderbitumenperton_current	-2%	0%	0%	0%	0%	0%	0%	2%
	M_bitumen	-48%	-10%	-5%	-1%	1%	5%	10%	48%
	M_zonderbitumen	-18%	-2%	-1%	0%	0%	1%	2%	8%
	A	8%	2%	1%	0%	0%	-1%	-2%	-8%
	M_loss_scrape	8%	2%	1%	0%	0%	-1%	-2%	-8%
	Drift_mu_physical_zonderbitumen	0%	0%	0%	0%	0%	0%	0%	0%
	Drift_mu_physical_bitumen	-5%	0%	-1%	0%	0%	1%	1%	6%
	Volatility_sigma_physical_zonderbitumen	-2%	0%	0%	0%	0%	0%	0%	2%
	Volatility_sigma_physical_bitumen	-62%	-17%	-9%	-2%	2%	10%	21%	174%
	DF	33%	6%	3%	1%	-1%	-3%	-5%	-24%
	t_contractperiode	-38%	-20%	-16%	-5%	1%	9%	13%	16%

Table E.2: The sensitivity analysis for the functional value, giving the change in the two (first left column) for a change in the variable inputs (second left column). The relative difference as applied to the input variables is given in the top row. For the input variable t_contractperiode these inputs are not relative but changed in incremental steps of 1 year, since that is a coding constraint.

Output	**Input variable ↓, Input change (percentage / years for t_contractperiode) →**	-50% / -10	-10% / -6	-5% / -5	-1% / -1	+1% / +1	+5% / +5	+10% / +6	+50% / +10
Mu	MKI_referentie	-50%	-10%	-5%	-1%	1%	5%	10%	50%
	MKI_verdeling_average_lowerbound	-49%	-10%	-5%	-1%	1%	5%	10%	49%
	MKI_verdeling_average_upperbound	-50%	-10%	-5%	-1%	1%	5%	10%	50%
	Drift_mu_externalities	-3%	-1%	0%	0%	0%	0%	1%	3%
	Volatility_sigma_externalities	0%	0%	0%	0%	0%	0%	0%	1%
	DF	33%	6%	3%	1%	-1%	-3%	-5%	-24%
	t_contractperiode	40%	21%	17%	3%	-4%	-16%	-19%	-30%
SE	MKI_referentie	-50%	-10%	-5%	-1%	1%	5%	10%	50%
	MKI_verdeling_average_lowerbound	48%	9%	5%	1%	-1%	-5%	-9%	-43%
	MKI_verdeling_average_upperbound	-50%	-10%	-5%	-1%	1%	5%	10%	50%
	Drift_mu_externalities	-3%	-1%	0%	0%	0%	0%	1%	3%
	Volatility_sigma_externalities	-2%	-1%	0%	0%	0%	0%	1%	4%
	DF	33%	6%	3%	1%	-1%	-3%	-5%	-24%
	t_contractperiode	37%	20%	18%	4%	-4%	-15%	-17%	-27%

Table E.3: The sensitivity analysis for the environmental value, giving the change in the two (first left column) for a change in the variable inputs (second left column). The relative difference as applied to the input variables is given in the top row. For the input variable t_contractperiode these inputs are not relative but changed in incremental steps of 1 year, since that is a coding constraint.

Output	Input variable ↓, Input change (percentage / years for t_contractperiode) →	-50% / -10	-10% / -6	-5% / -5	-1% / -1	+1% / +1	+5% / +5	+10% / +6	+50% / +10
Mu	P_nieuwbouw_newroadtype_current	-50%	-10%	-5%	-1%	1%	5%	10%	50%
	Renovatielijn (y=x^2)	-47%	-9%	-4%	-1%	1%	4%	9%	42%
	Drift_mu_functional	-3%	-1%	0%	0%	0%	0%	1%	3%
	Volatility_sigma_functional	-1%	0%	0%	0%	0%	0%	0%	1%
	Mu_restlevensduur	-100%	-46%	-24%	-5%	5%	26%	51%	206%
	Sigma_restlevensduur	-2%	-1%	0%	0%	0%	1%	1%	6%
	DF	33%	6%	3%	1%	-1%	-3%	-5%	-24%
	t_contractperiode	621%	321%	256%	40%	-35%	-95%	-98%	-100%
SE	P_bitumenperton_current	-48%	-10%	-5%	-1%	1%	5%	10%	48%
	P_zonderbitumenperton_current	-2%	0%	0%	0%	0%	0%	0%	2%
	M_bitumen	-48%	-10%	-5%	-1%	1%	5%	10%	48%
	M_zonderbitumen	-18%	-2%	-1%	0%	0%	1%	2%	8%
	A	8%	2%	1%	0%	0%	-1%	-2%	-8%
	M_loss_scrape	8%	2%	1%	0%	0%	-1%	-2%	-8%
	Drift_mu_physical_zonderbitumen	0%	0%	0%	0%	0%	0%	0%	0%
	Drift_mu_physical_bitumen	-5%	0%	-1%	0%	0%	1%	1%	6%
	Volatility_sigma_physical_zonderbitumen	-2%	0%	0%	0%	0%	0%	0%	2%
	Volatility_sigma_physical_bitumen	-62%	-17%	-9%	-2%	2%	10%	21%	174%
	DF	33%	6%	3%	1%	-1%	-3%	-5%	-24%
	t_contractperiode	-38%	-20%	-16%	-5%	1%	9%	13%	16%

F

Validation protocol

- Validatie sessie nummer:
- Datum:

Voorstellen

- Master Construction Management & Engineering aan de TU Delft;
- Momenteel bezig met thesis onderzoek onder Daan Schraven;
- Afrondende fase, nu valideren resultaten die ik jullie opgestuurd heb;
- Mijn onderzoek is aangesloten bij het programma DCW.

Mag ik het onderzoek opnemen om de validiteit te verzekeren?

Introductie

- Onderwerp: dit interview zal draaien om het valideren van bepaalde resultaten betreffende mijn onderzoek.
- Doel: het controleren van de resultaten op geldigheid (niet correctheid!). Deze sessie richt zich daarbij specifiek op de eerste deelresultaten: het basismodel en de bijbehorende gemaakte keuzes.
- Vertrouwelijkheid: de resultaten van deze sessie zullen naar voren komen in de thesis, die online voor iedereen toegankelijk zal zijn. Hierin zal geen deelresultaat gekoppeld worden aan een persoon. Wel zullen uw naam en functie hierin genoemd worden in verband met de resultaten van deze set interviews.
- Resultaten: de resultaten zullen een onderdeel vormen van het afrondende gedeelte van de thesis.
- Duur: de sessie zal ongeveer twee uur duren.
- Structuur sessie:
  - Presentatie onderzoeksresultaten (zoals reeds toegestuurd)
  - Onderwerp 1: basismodel
  - Onderwerp 2: formules & case uitwerking
  - Afsluiting
- Iedereen elkaar in 30 seconden voorstellen

Presentatie resultaten

- Idee restwaarde & PSS
- Resultaten basismodel
  - Doel
  - 3 componenten
  - 3 bijpassende rekenmethoden
  - Additionele condities

- Resultaten formules
  - Idee achter formules
  - Exacte formules
- Resultaten case
  - Resultaten
  - Verhouding resultaten tov elkaar
- Uitleg opzet sessie & Mural

Onderwerp 1: basismodel

- Reactie op doel
- Reactie op componenten en splitsing daartussen
- Reactie op rekenmethodes horend bij componenten
- Reactie op bijkomende condities model
- Overige reactie op algehele model
- Reactie op wijze afnemen interview
  - Interview prettig afgenomen?
  - Alles kunnen zeggen?
  - Geen onderwerpen vermeden?

Onderwerp 2: formules & case uitwerking

- Formule fysieke waarde
  - Idee achter formule
  - Uitwerking idee tot formule
  - Uitwerking case
  - Specifieke vragen indien nog niet beantwoord
    - Hoe wordt er tegenaan gekeken dat er uitgegaan wordt van een werkende tweedehands markt voor materialen (die er nu nog niet is op ieder vlak)?
    - Hoe wordt er tegenaan gekeken dat er geen onderscheid wordt gemaakt tussen verschillende vormen van hergebruik (hoogwaardig vs laagwaardig, recycle vs reuse, vs repurpose, etc)?
    - Hoe wordt er tegenaan gekeken dat er geen specifieke maatregel is om demontabelbaarheid te stimuleren?
- Pauze
- Formule functionele waarde
  - Idee achter formule
  - Uitwerking idee tot formule
  - Uitwerking case
  - Specifieke vragen indien nog niet beantwoord
    - Hoe wordt er tegenaan gekeken dat er bij het bouwen van een nieuwe weg uitgegaan wordt van een weg met hetzelfde niveau circulariteit? Dat kan namelijk ook goedkoper wat meer ruimte laat voor innovatie zoals het PSS idee werkt.
    - Vanuit Platform CB23 wordt ook de economische levensduur hieronder geschaard. Ik heb die niet verwerkt omdat ik niet vond dat dat vanuit circulair perspectief onder de restwaarde viel. Hoe kijken jullie daarnaar?
    - Process value (proceskosten) worden hier niet meegenomen vanwege de complexiteit en ambiguiteit van de berekening daarvan. Vinden we dat logisch?
- Formule milieu waarde
  - Idee achter formule
  - Uitwerking idee tot formule
  - Uitwerking case
  - Specifieke vragen indien nog niet beantwoord
    - Haalbaar om MKI met een referentiedesign te vergelijken en een referentiedesign vast te stellen?
- Overlap componenten
  - Eens dat er geen overlap zit tussen functional en material value?

– Hoe wordt er tegenaan gekeken dat de totale waarde van de weg boven de nieuwbouwprijs uit kan komen door de fysieke waarde en de functionele waarde bij elkaar op te tellen bij oplevering?

Afsluiting

- Interview prettig afgenomen?
- Alles kunnen zeggen?
- Geen onderwerpen vermeden?

G

Validation results

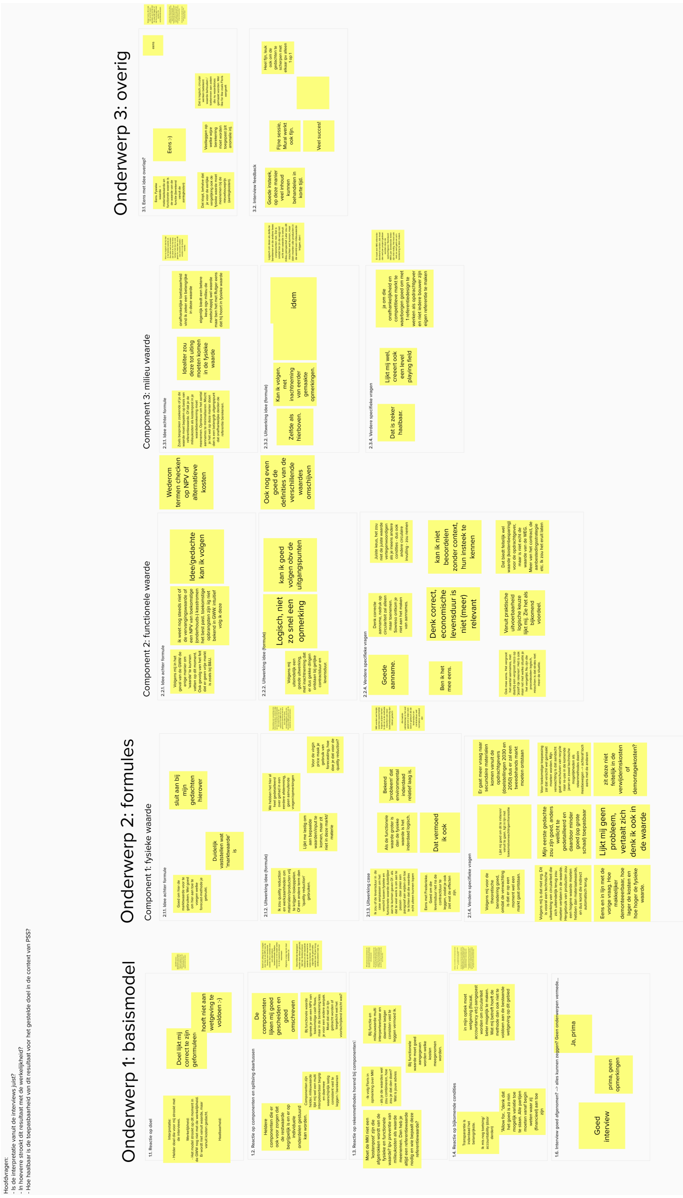

Figure G.1: Results of the use of Mural for the validation session 1.

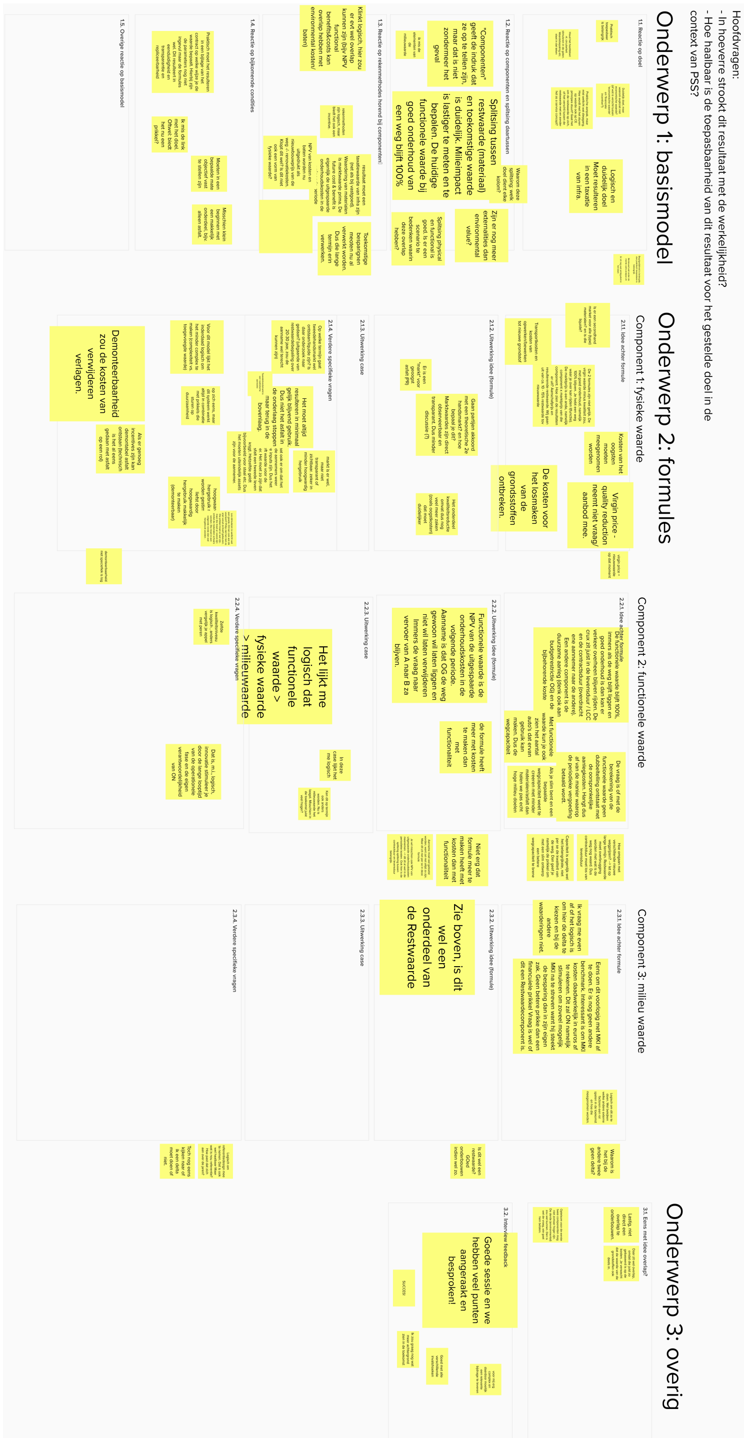

Figure G.2: Results of the use of Mural for the validation session 2.

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