In Pursuit of Sustainable Road Construction

Assessing the Environmental Impact of Circular and Bio-Based Asphalt Binders Compared to Conventional Bitumen Asphalt Binders

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Copernicus Institute of Sustainable Development
Faculty of Geosciences
Utrecht University

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Name:	Matthijs Crouwers
Student number:	6161383
Email:	m.r.b.crouwers@students.uu.nl
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Supervisor:	Prof. dr. Martin Junginger
Second assessor:	Dr. Blanca Corona Bellostas
Host organization:	Latexfalt BV
Host supervisor:	Dr. Hans Hendrikse

Abstract

The Dutch road construction sector is seeking environmental impact reduction for asphalt and in particularly asphalt binders. Within the CIRCUROAD project, three prototype circular and bio-based asphalt binders were developed. In addition to laboratory and real world testing, this study aimed to contribute by assessing the environmental impact of circular and bio-based asphalt binders compared to conventional bitumen-based asphalt binders. The employed research method was a Life Cycle Assessment, specifically an attributional one. The system boundaries are limited to the cradle-to-gate boundaries with a temporal scope of 2025 – 2030. The Functional Unit is defined as follows: the production of 1 kilogram of circular and bio-based asphalt binder for application in top layer asphalt for the Dutch road construction sector. For eight potential asphalt binder components, coming from for example pulp and paper industry, post-consumer waste plastic and fossil origin, Life Cycle Assessment inventory data was modelled using the Simapro software. Inventory data was sourced both directly from component suppliers and from scientific literature. The impact assessment was performed using impact categories aligned with standardized methods according to the Bepalingsmethode for the Dutch construction sector. Regarding biogenic carbon storage, the study acknowledges the lack of evidence for long-term carbon sequestration in circular and bio-based binders, thus presenting results both with and without consideration of biogenic carbon storage. Finally, the Environmental Cost Indicator (MKI) scores were also calculated based on the impact assessment results.

The findings reveal that the Global Warming Potential of circular and bio-based binder materials varies depending on their origin, with bio-based materials generally exhibiting lower greenhouse gas emissions compared to fossil-based counterparts. The Environmental Cost Indicator scores indicate that circular and bio-based binders generally have comparable or slightly higher environmental impacts compared to conventional bitumen binders. However, when considering biogenic carbon storage, the environmental impact of circular and bio-based binders can be reduced. An additional finding is the large contribution of fossil based compatibilizers to the environmental impact of circular and bio-based binders, identifying potential for further environmental impact reduction.

In conclusion, the study underscores the importance of considering environmental impacts in the selection of asphalt binder components, with circular and bio-based options showing promise for reducing environmental burdens, especially when accounting for biogenic carbon storage. These findings contribute valuable insights to the ongoing efforts towards sustainable road development in the construction sector.

Executive Summary

In this executive summary, the key findings of the research are outlined. In addition, supplementary findings for strategy opportunities and further sustainability improvements for Latexfalt are presented.

This research explored the environmental impact of three prototype circular and bio-based binders developed by Latexfalt. Using the environmental impact, the MKI scores were determined. The results show that the environmental impact and MKI score of the HK C95 binder are slightly lower in comparison with a conventional bitumen binder. The HK C60 and HK Bio binders employ higher environmental impacts and MKI score, compared to a conventional bitumen binder. Important to note is that a relatively small percentage (by weight) of fossil based components with high environmental impacts causes the higher overall impact of the circular and bio-based binders. The circular and bio-based components employed in the binders all have a lower environmental impact and MKI score compared to bitumen. This implies that further development of the circular and bio-based binders could result in even lower environmental impact when fossil based components are replaced by circular or bio-based components. These results were modelled using the Bepalingsmethode Milieuprestatie Bouwwerken, which as of now employs rather strict guidelines for biogenic carbon storage, which means that it is not included in aforementioned results. When permanent (more than 100 years) biogenic carbon storage is considered, the environmental impact of all binders is lower compared to bitumen. This also translates to lower MKI scores for all binders. Research verifying the permanent storage of biogenic carbon would therefore have a major impact on MKI score reduction and would be advised.

This research also shows the distribution of environmental impacts between life cycle phases A1-3. It shows the total A1-3 MKI score constitutes for around 95% of life cycle phase A1, raw material extraction. Life cycle phase A2, transport to Latexfalt, contributes for around 3.5% on average and the A3 phase, processes at Latexfalt, only contributes for 1.5% to the total MKI score. This research shows that the transport of materials to the Latexfalt facility and processes at the Latexfalt facility have a minimal impact on the cradle-to-gate MKI score. To acquire and maintain competitive advantage in the asphalt binder market, MKI scores could be a decisive factor. Therefore, Latexfalt can mainly differentiate from competitors by development of circular and bio-based binders using materials with lower environmental impact. A challenge is the selection of materials with lower environmental impacts and resulting MKI scores that enable the production of a quality asphalt binder. Exclusively seen from the viewpoint of MKI score reduction, the employment of bio-based materials over circular streams is advised especially when considering biogenic carbon storage. However, considering the concept of a circular economy, using waste or by-product streams is the preferred option.

Critical in the selection of materials, regardless of their environmental impact is the availability of LCA analyses from the manufacturer. In the past, LCA availability has been a dealbreaker for validating materials with a potentially a lower environmental impact. Preferably, the LCA results are presented using the industry standard method for the Dutch road construction sector: 'Bepalingsmethode Milieuprestatie Bouwwerken'.

Even though not being considered a major influence on the MKI scores, Latexfalt does produce significant amounts of direct (scope 1) and indirect (scope 2) CO_2 emissions, mainly through the usage of electricity and burning of natural gas. Eventually these CO_2 emissions also need to be abated. There is a weak correlation between production volume and energy consumption, which indicates large amounts of energy are consumed for storage of materials and end-products at high temperature. This implies that there is potential for further energy consumption reduction by optimizing planning and production processes, to minimize material or end-product storage at high temperatures. Part of Latexfalts' electricity supply is produced on-site by a renewable source, namely solar panels. This is a small fraction of the total consumption and there remains potential for at first, reducing energy consumption and secondly, decarbonising the energy supply. In theory, there is potential for increasing the on-site renewable electricity production through installing additional solar panels on available roof space. Although there is a weak correlation between production volume and energy consumption, advantageous about the production volume distribution throughout the year is the relatively high production volume in summer and low production volume in winter. This corresponds perfectly with the intermittency of solar power. Potentially, this poses opportunities for increasing renewable energy consumption both by increasing on site production and by importing renewable energy from elswhere.

In conclusion, there is potential for reducing environmental impact of asphalt binders through the development of circular and bio-based binders. Furthermore, this study highlights the minimal impact of transport and on-site processes. Moving forward, validating the permanent storage of biogenic carbon is recommended to accurately assess environmental impact reductions. Also, the availability of manufacturer-provided LCAs using industry-standard methodologies is crucial.

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Abbreviations

Asphalt Concrete	AC
Asphalt Recycling Train	ART
Attributional Life Cycle Assessment	aLCA
Biogenic Carbon Storage Indicator	BCS_{100}
Cashew Nut Shell Liquid	CNSL
Circular Economy	CE
Consequential Life Cycle Assessment	cLCA
Crude Tall Oil	CTO
Crumb Rubber	CR
End of Life	EoL
Environmental Cost Indicator	MKI
Function Unit	FU
Greenhouse gas	GHG
Highly Ecologic Recycling Asphalt	HERA
Kilogram	kg
Low Density Polyethylene	LDPE
Life Cycle Assessment	LCA
Life Cycle Impact Assessment	LCIA
Life Cycle Inventory	LCI
Milieu Kosten Indicator	MKI
Product Category Rules asphalt	PCR
Reclaimed Asphalt Pavement	RAP
Stone Mastic Asphalt	SMA
Tall Oil Pitch	TOP
Tonne	t

1 Introduction

1.1 Background

The Dutch Climate Agreement includes a comprehensive strategy to achieve substantial reductions in greenhouse gas (GHG) emissions by the year 2050. To realize this ambitious 95% reduction goal by 2050 the intermediate target for 2030 has recently been elevated to 55%, with further aspirations to reach 60% by 2030 (Dutch Government, 2019) (Dutch Government, 2023). This demonstrates the Netherlands' commitment to extend its efforts beyond mere compliance with international agreements.

Dutch infrastructure and in particular the road network, is vital for connectivity and economic development. However, road construction comes with significant environmental consequences, primarily resulting from the widespread use of asphalt (Sollazzo et al., 2020). Annually, the Netherlands produces 7.1 million tons of asphalt, contributing to 530 – 600 kilotons of CO_2 emissions, on average 43% originating from resource extraction and 42% associated with asphalt production (Topsector Energie, n.d.) (EIB, 2022). Asphalt, basically composed of bitumen and mineral aggregates, relies on bitumen as a binding agent to join its components. Because of the energy intensive processes involved in bitumen sourcing - bitumen is a by-product of crude oil refinery - bitumen constitutes the most environmentally impactful component (Bak et al., 2022). By recycling asphalt, resource extraction and primary processing steps are avoided, resulting in a reduction of environmental impact. Asphalt recycling does provide environmental benefits compared to using newly sourced asphalt. However, although the recycling rates increase, newly constructed asphalt surfaces continue to consist for less than half of recycled asphalt. In addition, there remains an ongoing debate on whether recycled bitumen can replicate the properties of virgin bitumen (Teugels, 2020). In most cases, even though recycled material is employed, a newly produced asphalt binder is needed to achieve desired asphalt properties. Asphalt properties and the resulting quality play a vital role in road construction given that road construction works can be incredibly complex from a logistics perspective and require a lot of financial resources. It is obvious that newly sourced asphalt binders are needed in the future. Substantial environmental impact reductions can be realized by replacing bitumen with circular and/or bio-based alternatives. Circular and/or bio-based sourced materials generally tend to have a lower environmental impact, therefore contributing to the reduction of GHG emissions.

Apart from GHG emissions, there are other reasons to explore alternative asphalt binders. Bitumen as a by-product of crude oil distillation for gasoline, diesel, and other fuels, is, from a commercial point of view, low graded in crude oil refineries (Teugels, 2020). As a result, refineries try to increase revenue by upgrading bitumen to products with higher economic value, such as synthetic crude oil (Oil Sands Magazine, 2022) (Canıaz et al., 2019). Consequently, bitumen-producing refineries have become scarcer making asphalt production dependent on a limited number of manufacturers (Teugels, 2020). Moreover, driven by the Paris Agreement, the eventual near phase-out of fossil-based fuels by 2050 is anticipated. Recent developments at COP28 emphasized the ambition of phasing out fossil fuels, which would eventually lead to very little crude oil refining and consequentially hardly any room for bitumen production (International Energy Agency, 2021).

1.2 Previous Research

As society is developing from its traditional linear economic models to more sustainable resource-efficient and environmentally responsible systems, the concept of Circular Economy (CE) has become more important in recent years (Reike et al., 2018). Central to the CE concept is the idea of reducing resource use and waste generation, a shift embodied by the R-strategies, which have become the cornerstone of this approach. The R-strategies are characterised by a set of principles to promote resource efficiency, waste reduction and the sustainable use of resources throughout the product lifecycle (Potting et al., 2017). As part of this global paradigm shift, the road construction industry is increasingly exploring alternatives to conventional bitumen-based asphalt binders seeking to reduce their environmental impact and contribute to CE. In this context, the environmental impact of asphalt binders emerges as a critical research area posing questions regarding both conventional and circular binder materials.

The environmental impact of conventional bitumen-based asphalt binders has been a subject of extensive research. These binders, derived from fossil fuel sources, have been essential in road construction for decades. Investigations into their environmental impact have led to a lot of data regarding greenhouse gas emissions, energy consumption and the depletion of non-renewable resources (Thives & Ghisi, 2017). By conducting Life Cycle Assessments (LCA), researchers have shed light on the contribution of bitumen to climate change and other environmental factors. For the 22 mostly used asphalt mixtures the environmental impact, and Environmental Cost Indicator (in Dutch; milieukostenindicator, MKI) scores were determined. These are shown in Figure 1 (Bak et al., 2022). All mixtures, except for mixture number 6, use bitumen as binding agent and have roughly the same MKI score. Mixture number 6 uses a colourless binding agent consisting of organic solvent and polyester Resin. As is illustrated in the figure by ‘A1’, the resource extraction phase is the main contributor to environmental impacts.

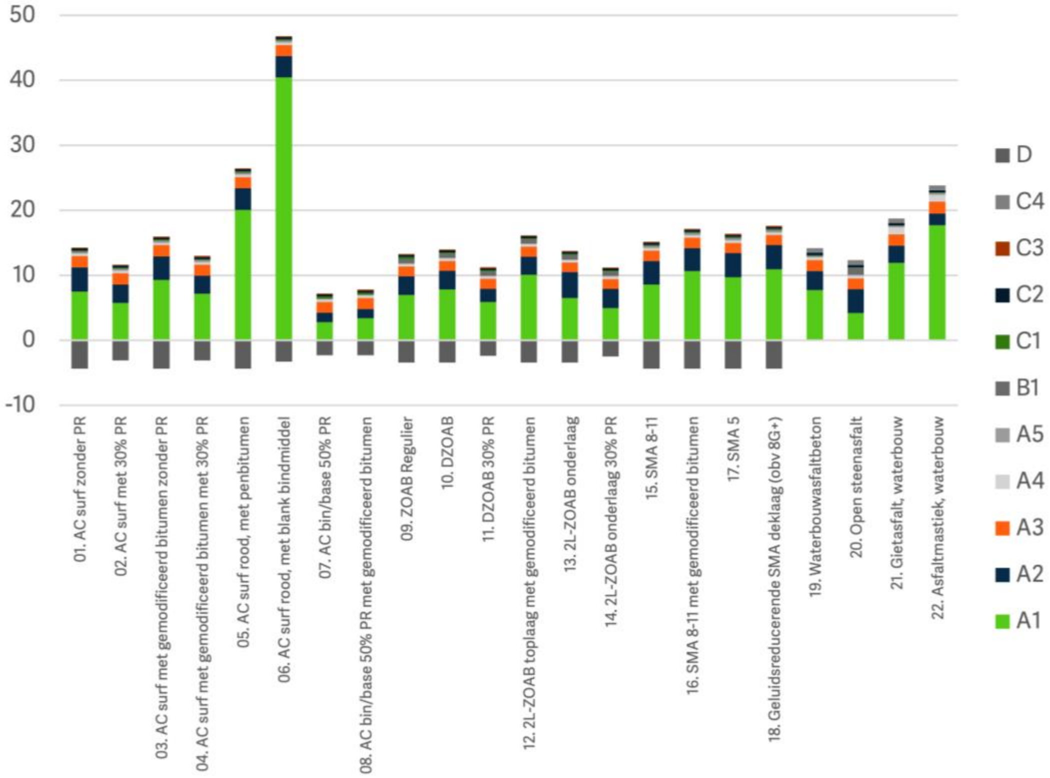

Figure 1 MKI scores in €/tonne for the 22 most used asphalt mixtures in the Netherlands for all life cycle phases in €/ton asphalt (Bak et al., 2022).

A key to the transition towards alternative asphalt binders is the identification of suitable materials to serve as alternatives to bitumen. Within the CIRCUROAD[1] project, the Dutch road construction sector has bonded with government and research institutions to accelerate the transition towards circular and bio-based asphalt binders, committing to the concept of CE (Circular biobased delta, n.d.). Important to note is the difference between circular and bio-based asphalt binders; the latter predominantly utilizes biomass feedstock, while the former incorporates not only biobased materials, but also non-biobased ones derived from waste streams. In the CIRCUROAD project it was found that one way to create a bio-based binder is by utilizing biomass-derived substances such as lignin, a by-product from pulp and paper industries or biorefineries (Moretti et al., 2021). While experiments with real world road sections of lignin asphalt are employed, the long term performance has not been established yet. The environmental impact of lignin asphalt has also been investigated. Recently, research by Moretti et al.

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[1] Previously called the CHAPLIN project.

(2022) showed that using a lignin-based binder, the climate change impact of asphalt can be reduced by 30-75% depending on the type of asphalt it is used in.

Many attempts have been made to incorporate waste plastic and rubber into road construction. Up until research from Hendrikse et al., (2023), a fundamental approach in these attempts has been lacking. In the research, various waste and bio-based streams were identified and their potential for integration into asphalt binders was discussed, using the concepts of CE and sustainable asphalt binder design. With this research as a starting point, Latexfalt in Koudekerk a/d Rijn, participating in the CIRCUROAD project, came up with three prototype asphalt binders incorporating various circular and bio-based streams. To evaluate their potential as sustainable alternatives to conventional asphalt binders, the life cycle impacts of identified potential binder materials and designed prototype binders need to be investigated.

There is a growing body of research on circular and bio-based asphalt binders and their potential environmental benefits. A comprehensive investigation that directly compares the environmental impact of circular and bio-based binders to conventional bitumen-based binders, however, remains scarce. Apart from environmental impacts, from the perspective of resource scarcity and availability, achieving a CE is also considered to be crucial. Currently, combining these those goals in environmental impact studies usually leads to misalignment of the two goals (Corona et al., 2022). Research that combines circularity and climate change aspects into a holistic assessment of circular and bio-based binders also represents an ongoing research gap.

1.3 Research Aim

Considering the pressing challenges posed by the Dutch Climate Agreement and the significant environmental consequences of asphalt production, this research is meant to contribute to understanding the potential for environmental impact reduction using circular and bio-based materials for road construction. By examining the environmental impact of circular asphalt binders in contrast to their conventional bitumen-based counterparts, this research seeks to provide valuable insights into the environmental impact of asphalt binders within the context of CE, including MKI scores, for the Dutch road construction sector for development of binders between 2025 and 2030. This timeframe is chosen as it may be expected that circular and bio-based binders can be implemented within the specified timeframe. This research is positioned as follow-up research of the CIRCUROAD project, and it will be hosted by CIRCUROAD partner organization, Latexfalt. Given the research is hosted by Latexfalt, it will focus on the three prototype binders designed by Latexfalt. This assessment will be carried out using the following research question:

What is the environmental impact of circular and bio-based asphalt binders compared to a conventional bitumen-based asphalt binder?

This question is divided in the following sub questions:

- *What is the environmental impact of a conventional bitumen-based asphalt binder?*
- *What are the environmental impacts of circular and bio-based binder materials?*
- *What is the environmental impact of the production of circular and bio-based binders?*
- *How do the environmental impacts of the production of bitumen and circular and bio-based binders compare?*
- *How do the environmental impacts of a bitumen and circular and bio-based binders translate to Environmental Cost Indicator scores?*

2 Theory & concepts

A Life Cycle Assessment (LCA) is a method for comprehensively evaluating the environmental impacts of products, processes, or systems throughout their entire life cycle, spanning from raw material extraction to disposal (ISO 14040, 2006). In this research, LCA plays a central role in assessing the environmental impact of circular and bio-based asphalt binders as compared to conventional bitumen. This chapter aims to provide an in-depth understanding of key LCA concepts and principles that are fundamental to this study, also in relation to potential biogenic carbon allocation and CE misalignment. In addition, this chapter provides concepts for Environmental Cost Indicator (MKI) scores of asphalt binder materials.

2.1 Concepts of Life Cycle Assessment

At the core of any LCA study are the four main phases: 1) determining goal and scope 2) inventory analyses, 3) impact assessment, and 4) interpretation, which are visualised in Figure 2. In the following paragraphs, the four phases will be discussed, including principles of allocation for multifunctional processes.

2.1.1 Goal and scope

A key part of determining goal and scope of an LCA is the Functional Unit (FU), a quantifiable measure of the performance or functionality of a product or system that is being evaluated (ISO 14044, 2006). In this research, the FU is a specific quantity or volume of asphalt binder. This chosen quantity will serve as the reference point for all subsequent environmental impact calculations. Obviously, it is essential to establish a well-defined FU to ensure meaningful and fair comparisons between different binder types.

Equally important in the goal and scope definition, is determining the system boundaries, specifying to what extend the impacts of different stages of the product will be considered (ISO 14044, 2006). This can include all stages from raw material extraction, production, transportation, and use phase to end-of-life scenarios. To these system boundaries is also often referred to as cradle-to-grave, which is the focus of the ISO 14044 standard. There is also the cradle-to-gate system boundary, assessing only the environmental impacts of the raw material extraction, transport to producer and production phase, neglecting transportation to consumer, use phase and end-of-life scenarios. For circular product design, usually the cradle-to-cradle approach is chosen, exchanging waste stages in the end-of-life scenarios for reuse/recycling steps. It will very much depend on the aim of the research and availability of data or possibility to gather data in experiments which stages will be subjected to study.

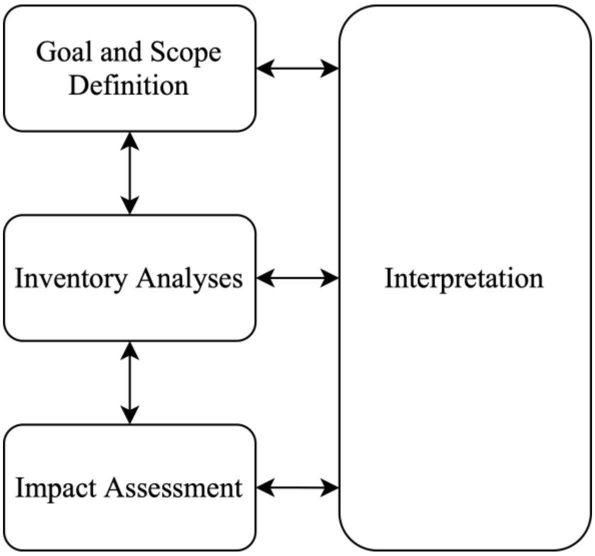

Figure 2 LCA framework (ISO 14044, 2006).

2.1.2 Inventory analysis

An integral part of LCA is data collection and inventory analysis, where data on the inputs and outputs of each life cycle stage are gathered (ISO 14044, 2006). A distinction can be made between primary and secondary data. Primary data are measured or collected directly from a manufacturer and are representative for a specific facility or manufacturer (Joint Research Centre, 2013). Mostly they are very specific and precise, in contrast to secondary data, which are sourced from a third-party life cycle inventory database, usually less accurate with a more general geographical and temporal scope. While gathering primary data is usually preferred for reasons of accuracy and completeness, it significantly increases time investments and makes the inventory phase of the research more complex. Secondary data are usually readily available in life cycle inventory databases, such as Ecoinvent (Miah et al., 2018) (Ecoinvent, n.d.). The accuracy and comprehensiveness of data collection are critical as they ensure reliability and validity of the LCA results. The inventory analyses usually also include a flowchart or table of all modelled flows and processes within the system boundaries.

2.1.2.1 Allocation procedures

Allocation methods are essential for distributing environmental burdens over co-products when multifunctional processes are involved. Multifunctional processes are defined as processes with multiple outputs that cannot be related to separate parts of the production process. For instance, the environmental impact of crude oil refinery should be allocated to both bitumen and other chemicals and fuels produced in the refinery process. This is exactly where allocation methods come into play. How are environmental burdens allocated to specific products or production processes and how do changes in conventional systems translate into the overall impacts of the system?

A distinction can be made between two types of LCAs: attributional (aLCA) and consequential (cLCA) (Ekvall, 2019). For attributional LCAs (aLCA), frequently used allocation methods are economic and physical allocation (Ardente & Cellura, 2012) (Williams & Eikenaar, 2022). Economic allocation is done based on the economic value a product represents in relation to co-products. Note that economic values of products may be susceptible to price fluctuations, impacting validity and credibility of LCA results. Physical allocation can be done based on physical properties, e.g. mass, volume or energy content.

While aLCA focusses on describing the environmental impacts and resource use associated with a product's life cycle, cLCA delves into the broader systemic consequences of changes in product demand, supply chains, and market dynamics (Ekvall, 2019). The assessment goes beyond the isolated product to consider the effects of its production or consumption on the entire system. This approach examines how changes in the demand for a product can influence various interconnected systems, potentially triggering effects throughout the economy and the environment. cLCA accounts for both direct and indirect consequences, providing a more comprehensive understanding of the environmental, economic, and social impacts associated with a specific product or process. Unlike aLCA, cLCA does not rely on fixed allocation methods but rather integrates dynamic modelling and scenario analysis to evaluate the real-world implications of decisions and policies. An often-used allocation method is allocation at point of substitute, which involves distributing the environmental burdens and benefits of a product's life cycle over different co-products or processes at the point where they can be substituted for one another (Brander & Wylie, 2011). The goal is to allocate environmental impacts based on the functional equivalency of co-products or processes, typically by comparing their performance or functionality. This means that if two or more co-products can serve as substitutes and perform the same function, the environmental impacts are allocated in a way that reflects this substitutability.

In addition to allocation for multifunctional processes, allocation for End of Life (EoL) scenario's is required to assess the environmental burdens at the end of a product's life cycle. One of the approaches is the 'cut-off' method, which operates on the principle of defining the system boundary at the point where a product reaches the end of its useful life or is disposed of (ISO 14044, 2006). At this juncture, all environmental burdens associated with the disposal or recycling of the product are allocated solely to the product itself, independent of its previous lifecycle stages. This method ensures that the environmental impacts incurred during the disposal phase are appropriately assigned to the product, rather than being distributed across other lifecycle stages (Stichting Nationale Milieudatabase, 2022).

2.1.3 Impact assessment

Impact assessment involves the quantification and evaluation of environmental impacts in various categories (ISO 14044, 2006). To quantify impacts, specific characterization factors and models tailored to each environmental category are used. These factors allow to convert raw data into standardized impact scores, enabling comparisons between different products. For LCAs to be comparable, some sectors, such as the road construction sector, have standardized methodological choices for the Life Cycle Impact Assessment (LCIA).

2.1.4 Interpretation

Following the impact assessment, the results are subject of interpretation, which is the last step in the LCA. In this part of the LCA one may perform a sensitivity analysis, depending on the accuracy and completeness of the data gathered. The interpretation phase also includes the identification of the materials or process steps that are the key contributors to the results, also called 'hotspot identification'.

2.2 Circular Economy and R-strategies

The Circular Economy (CE) framework represents a paradigm shift in economic thinking, offering an approach to sustainability by reimagining resource management and waste reduction (Stahel, 2016). At the heart of CE lie the 10 R-Strategies that provide a structured framework for achieving circularity in production and consumption processes (Morseletto, 2020). These strategies, categorized into short, medium and long loops, encompass a range of principles including refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover (Reike et al., 2022). Each strategy is designed to address specific stages of the products lifecycle, from conception to disposal, with the overarching goal of minimizing resource depletion and environmental degradation while maximizing economic value. Short loops strategies (refuse, rethink, reduce), positioned at the beginning of the value chain, emphasize waste elimination at the product design phase. By refusing to use environmentally harmful materials, rethinking waste as a resource, and reducing the amount of inputs required, environmental impact can be significantly reduced. Medium loops strategies (repair, refurbish, remanufacture, repurpose) focus on extending product lifespan through reuse and refurbishment, thereby keeping resources within the economic system for longer durations. By repairing, refurbishing, or remanufacturing products and components, the need for virgin materials and waste generation can be minimized. This approach not only conserves valuable resources but also creates economic opportunities through the development of new markets for refurbished goods. Long loops strategies (recycle, recover) center on material and energy recovery from waste streams, offering a way to extract value from discarded materials and by-products. While recycling and recovery are essential components of the circular economy, they are often considered less preferable than strategies that focus on waste prevention and reuse. However, when implemented effectively, recycling and recovery can play a crucial role in closing the loop and reducing the environmental impact of waste disposal.

In the context of road construction, short, medium, and long loop strategies may be employed: short loops by using waste materials as feedstock for road construction, medium loops by employing methods to extend lifespan of asphalt, and long loops in terms of recycling EoL asphalt pavement for new road construction.

2.3 Biogenic Carbon and Circular Economy

One of the difficulties encountered in LCA research concerns the allocation of biogenic carbon (Bishop et al., 2021). Circular binders may incorporate biomass-derived materials such as lignin, which sequester carbon during their growth phase. Carbon sequestration introduces complexities in LCA calculations especially when considering the concept of CE. There are different approaches in the LCA literature on how to account for biogenic carbon. In cases where biogenic carbon is not permanently stored (i.e. less than 100 years), some LCA studies consider biogenic carbon as carbon neutral, effectively assigning a characterization factor of zero to the carbon absorbed during biomass growth and emitted during end-of-life or throughout the life cycle (Bishop et al., 2021)(Corona et al., 2022). However, this simplification fails to capture the dynamic nature of the carbon cycle and may lead to misleading results as the additional CO_2 emissions in the atmosphere will continue to contribute to global warming until it is once more captured and stored in biomass. Others, in line with the European

Commission (2021), use an approach of separating inventory and characterization results for climate change in two categories: fossil and biogenic. At times when potential for permanent biogenic carbon storage (i.e., more than 100 years) is present, conflicts of interest arise with the concept of CE. For instance, from a circularity perspective, recycling or repurposing non-degradable materials containing biogenic carbon is favourable. However, from a climate change point of view, permanently storing non-degradable biogenic carbon leading to negative emissions, is preferable. Corona et al. (2022) found methods to combine an environmental assessment with material circularity metrics, especially focusing on biogenic carbon dynamics. By employing the 'Biogenic Carbon Storage' indicator (BCS_{100}), it enables the inclusion of negative carbon emissions in cases where biogenic carbon is not permanently stored in the initial product but instead becomes part of a recycling loop where the carbon is consistently re-stored. The amount of time the biogenic carbon is stored in the initial product as fraction of permanent storage (>100 years), results in the percentage of biogenic carbon sequestration. In this way the carbon storage component can be considered without giving an incentive for increasing bio-based resources extraction, opposing concepts of CE.

2.4 Environmental Cost Indicator

Most emissions of a product occur throughout multiple phases in its life cycle, making it difficult to measure environmental impact accurately. Especially since environmental data usually comes from various sources and are measured in different environmental impact categories, direct comparison is difficult. This is where the Environmental Cost Indicator, in Dutch 'MKI', comes in; it simplifies and translates diverse environmental impact results into a single monetary score allowing for easier comparison across products. These indicators can be calculated based on the environmental costs attributed to various impact categories from the LCIA results (Ecochain, 2023) (RIVM, 2016). Specific for the Dutch road construction sector, the MKI score enables comparisons between construction offers, since asphalt construction projects are allocated and assigned based on public tenders. Offers with lower MKI scores may be eligible for an imaginary discount on the total offered costs. This incorporation of environmental impacts in tenders creates an incentive for construction companies to reduce environmental impacts of road construction projects. Additionally, it potentially prevents projects with low costs and high environmental impact from being successful in public tenders.

3 Technological Background

It is important to understand the key components and processes involved in road construction, in particularly the use of asphalt binders. In this chapter, the principles of bitumen-based binders, circular and bio-based binders and the asphalt recycling process will be explored.

3.1 Principles of Asphalt

Understanding the composition of asphalt is crucial for optimizing its properties, its performance and, of course the environmental impact. The primary component of a conventional asphalt binder is bitumen, a viscoelastic, hydrocarbon-based material that plays a critical role in binding the aggregate particles together (Shell, 2015). Bitumen is a by-product of crude oil refinery for fuels and chemicals and is characterized by its high molecular weight and a complex mixture of hydrocarbons. Its properties, in particular its stiffness, viscosity and temperature susceptibility, significantly influence the performance of asphalt. The ‘penetration grade’ of bitumen is a measure of stiffness that historically has been the main performance indicator for quality road construction (Hendrikse et al., 2023). Bitumen has a rather wide molecular weight distribution, partially determined by the distillation end point during crude oil refinery (Figure 3). For bitumen with the same penetration grade, the molecular weight distribution may vary significantly, illustrated in Figure 3. Given the large variation and width of molecular weight distribution, there are opportunities for a variety of preferably circular and bio-based materials to be integrated in asphalt binders. This is because the individual components do not need to match the exact distribution of molecular weight of a conventional bitumen binder. It is the combination of different components that should result in a wide molecular weight distribution with a comparable molecular weight distribution of a conventional bitumen binder. To enhance asphalt's performance and tailor it for specific applications, various additives and modifiers may be included (Shell, 2015). These additives can include polymers, rejuvenators and anti-stripping agents, which can improve the mixture's resistance to cracking, aging and moisture damage (Yu et al., 2014).

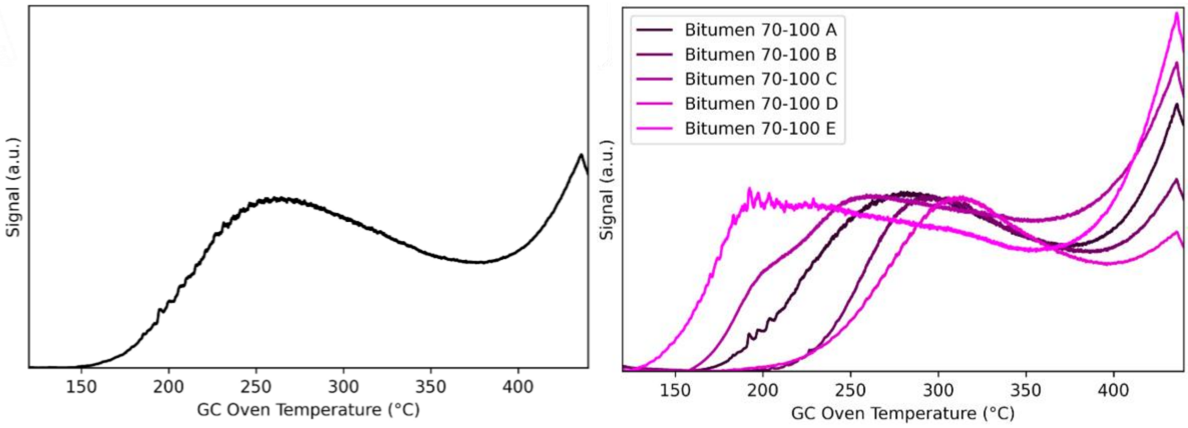

Figure 3 Left: typical gas chromatograph of a bitumen, showing its wide molecular distribution with various boiling points. Right: Bitumen of the same penetration grade, but from different supplier, can vary widely in molecular weight distribution although has comparable average molecular weight (Hendrikse et al., 2023).

In addition to bitumen, asphalt consists of aggregates: mineral particles that provide strength and durability to the mixture. These aggregates, such as crushed stone, sand and gravel, can vary in size and composition. The choice of aggregates influences the asphalt's mechanical properties such as its load-bearing capacity and resistance to wear and tear.

In road construction, asphalt is typically used in two main layers: the base layer and the top layer. These layers serve distinct purposes and exhibit some differences in their composition. The base layer is the lower layer of the asphalt pavement. It provides structural support and distributes the load from traffic to the underlying soil or subbase. Base layer asphalt is typically coarser in texture and contains larger aggregates compared to the top layer (Shell, 2015). This coarse composition enhances its load-bearing capacity and stability. The top layer is the upper layer of the pavement and is exposed to the traffic vehicles and environmental elements. It is designed to provide skid resistance, ride quality, and aesthetics. Top layer asphalt contains finer aggregates and is often designed for a smoother finish. It may also incorporate additives like polymer modifiers to improve resistance to wear and cracking (Shell, 2015). The required quality of an asphalt binder in the top layer is higher than in the base layer. When the quality of an asphalt binder is sufficient for top layer asphalt, it will most likely also be for usage in the base layer. Therefore, in asphalt binder development the focus is on application in top layer asphalt.

In the context of this study, top layer asphalts are limited to two specific types: Stone Mastic Asphalt (SMA) and Asphalt Concrete (AC). SMA is an asphalt mixture known for its exceptional durability and resistance to rutting (Brown & Mallick, 1994). It incorporates a high content of coarse aggregates and is characterized by a stone-on-stone structure. AC is a commonly used asphalt mixture that blends mineral aggregates, bitumen, and various additives to achieve desired performance characteristics (Liu et al., 2011).

3.2 Circular and Bio-based Binders

Circular and bio-based based binders are rather broad concepts. In theory, every ‘waste’ stream material without useful purpose could be incorporated in a circular asphalt binder, provided it gives the asphalt mixture the required properties. A waste stream with a relative low value application, such as energy recovery, may also be considered for a circular binder. This approach follows the principles of CE and the R-strategies, advocating a more circular use of materials instead of the linear approach. There is a clear distinction between circular and bio-based materials. While circular materials are characterised by being a by-product without useful purpose or waste stream, bio-based materials are identified by their origin of living organisms i.e. biomass (Pandit et al., 2018). Often, bio-based materials are virgin materials but they may at the same time also be classified as a by-product or as waste stream. This means that some bio-based materials are also classified as circular materials. Within the CIRCUROAD project the main goal is to design circular asphalt binders and a thoroughly researched potential asphalt binder material is lignin (Junginger et al., 2021). Lignin is a perfect example of a bio-based material that also qualifies as circular material given its low value application as energy recovery. Typical materials considered for circular and bio-based products come from pulp and paper industry, agricultural (by)products and plastic waste streams (Shogren et al., 2019). From a circularity perspective, one could argue that the reuse of plastic waste for packaging material is to be preferred over making it into asphalt binders, following the R-strategies from CE. Considering that only 30% of all plastic waste is recycled, and the remainder is used for energy recovery, i.e., is incinerated, or ends up in landfills, it would be advantageous for CE if these plastic waste streams were utilized for asphalt binders (PlasticsEurope, 2018). This approach of recycling and reusing waste plastic as feedstock in asphalt binders reduces the need for virgin resource extraction. Figure 4 displays a prototype circular and bio-based asphalt binder and a conventional bitumen. It is hard to see any difference between the binders.

In an alternative binder, the use of circular and bio-based materials may serve different purposes. The binders usually consist of one or two bulk materials making up most of the binders by weight. To achieve adequate quality and solubility of all components a compatibilizer may be needed. Compatibilizers of circular or bio-based origin with required properties may not be readily available (yet). Until circular or bio-based forms of these compatibilizers are available, alternative asphalt binders may not reach the full potential of circular and bio-based material content and fossil based components need to be employed.

Figure 4 Visual comparison of prototype circular and bio-based asphalt binder (left) and conventional bitumen (right) (Hendrikse et al., 2023).

3.3 Asphalt Recycling

The recycling of asphalt aligns with the principles of CE and the R-strategies. By doing so, it reintegrates waste materials into the production processes reducing the demand for virgin resources. In the road construction industry, recycled asphalt is referred to as Reclaimed Asphalt Pavement (RAP). RAP is widely adopted in the road construction sector, involving milling and removing the top layer of existing asphalt pavements, which is processed and reintroduced into new asphalt mixes. A limitation to increase the share of RAP in Dutch road construction, which is currently around 50%, is the limited availability of old asphalt (Teugels, 2020). Efforts to maximize value retention in asphalt recycling have led to innovations such as the Asphalt Recycling Train (ART) (Dura Vermeer, 2021). Using the ART, existing road pavement can be dismantled, recycled, and constructed, all incorporated in an onsite process. In this recycling process, top layer asphalt is not downgraded to a lower base layer quality, which usually occurs in asphalt recycling. Rather it is processed to be employed again in top layer asphalt. Another innovation is the Highly Ecologic Recycling Asphalt (HERA) system, developed by KWS, enabling up to 100% of asphalt recycling (Van den Brand, 2023). Unlike conventional systems, it uses indirect heating, preserving asphalt quality.

While RAP plays an important role in the road construction sector, more is needed to achieve sustainable road construction. Solely using RAP, creating the desired asphalt pavement properties is not guaranteed and the availability of RAP is limited. There remains a need for new asphalt (binders) to be mixed with RAP and that highlights the importance of compatibility of circular and bio-based binders with RAP.

4 Methods & Materials

This chapter deals with the methodological choices in Life Cycle Assessment (LCA), the allocation in multifunctional processes, biogenic carbon storage within the context of Circular Economy (CE) and explain the conversion of Life Cycle Impact Assessment (LCIA) results to Environmental Cost Indicator (MKI) scores.

4.1 Life Cycle Assessment

The goal of this research is to get a better understanding of the environmental impact of circular and bio-based asphalt binders as compared to conventional bitumen based asphalt binders. This will be done using an attributional Life Cycle Assessment (aLCA) approach. The use of an aLCA is chosen because it enables identifying the environmental impacts that are associated with the life cycle phases of a product and the opportunity for further environmental impact reduction through hotspot identification. This type of LCA is relevant for this study as there is not yet any establishment of circular or bio-based binder asphalt within the road construction sector. In addition, by means of this LCA a direct comparison between different asphalt binders can be made. In the Dutch construction sector it is common practice to use the assessment methods described in the Environmental Performance Assessment Method for Construction Works, which is based on the EN 15804(+A2) norm (Stichting Nationale Milieudatabase, 2022). This research will follow these LCA standards.

4.1.1 Goal and scope definition

The aLCA has two goals: 1) to assess the environmental impact of the production of the prototype circular and bio-based binders. 2) to assess the environmental impact of circular and bio-based binder asphalts as compared to conventional bitumen based binder asphalt. This breakdown in goals is chosen primarily because sufficient data about the production phase of prototype circular binders exists but for the other life cycle phases, i.e. use phase and end-of-life scenarios, very little data are available and making assumptions may be required. For instance, assumptions will be made about the lifespan of circular and bio-based asphalt as there are not enough data available. This aspect greatly affects the overall LCIA results for the use phase of the asphalt. Considering the two goals, the LCA will contain a cradle-to-gate and a cradle-to-grave analyses. This research aims to analyse cradle-to-gate environmental impacts and will make efforts to determine cradle-to-grave impacts, using the cradle-to-gate impact as input for the grade-to-grave analysis.

The system boundaries for both the cradle-to-gate and cradle-to-grave analyses are illustrated in Figure 5. The geographical scope is the Netherlands with a temporal scope of 2025 – 2030, when it is to be expected that circular based binder asphalts can be implemented. The FU is defined as follows: the production of 1 kilogram (kg) of circular and bio-based asphalt binder for application in top layer asphalt (SMA and AC) for the Dutch road construction sector. The Environmental Performance Assessment Method for Construction Works uses abbreviations to refer to certain life cycle phases, as illustrated in Figure 5. To the resource extraction phase is referred to as ‘A1’, to the transport phase referred to as ‘A2’ and to the production phase is referred to as ‘A3’. For environmental impacts and benefits outside the system boundaries, for example biogenic carbon storage, is referred to as ‘D’ (Stichting Nationale Milieudatabase, 2022).

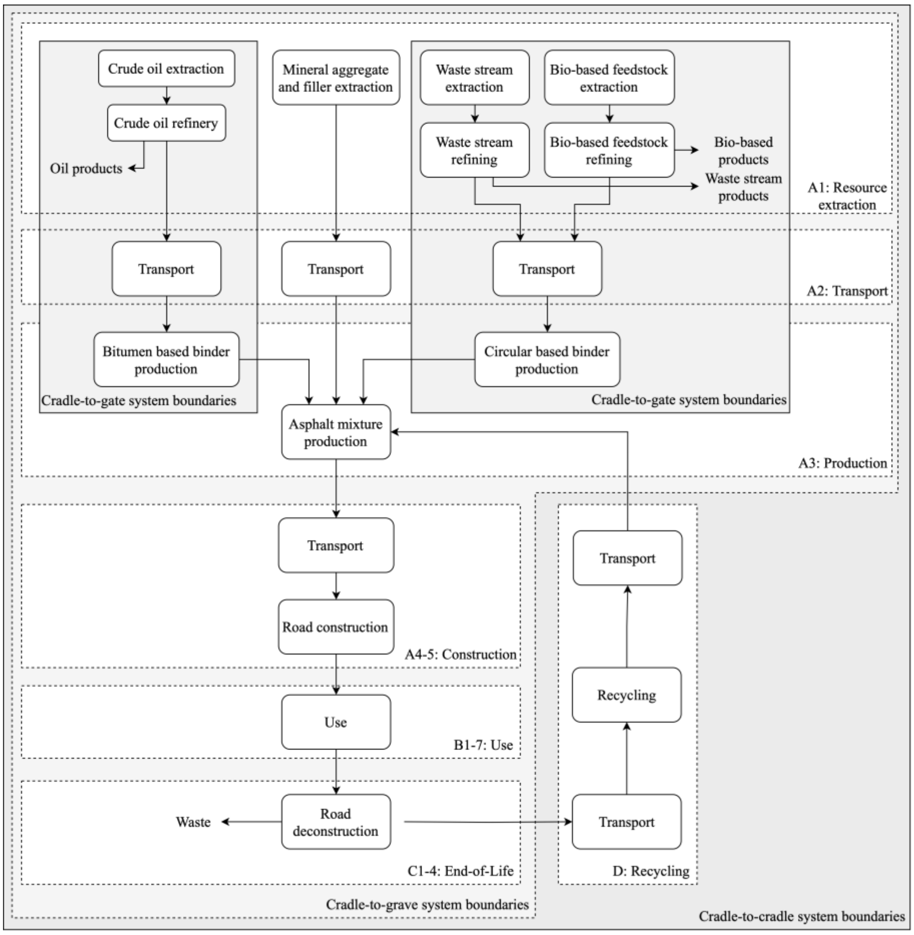

Figure 5 Product and process flow diagram for cradle-to-gate and cradle-to-grave LCA.

4.1.2 Life Cycle Inventory Analyses

Since 2015 the CIRCUROAD project is running experiments with real world test sections with lignin-based binder asphalt. As a follow-up on the lignin-based binder asphalt research, CIRCUROAD decided on proceeding research with three additional asphalt binder prototypes. Material inputs for the three prototype circular and bio-based binders consist of waste streams, bio-based materials and virgin non bio-based materials and can be found in Table 1. Note the difference in function for each of the components, being a base or compatibilizer. The production processes for the circular and bio-based components are briefly described below.

Cashew Nut Shell Liquid (CNSL) is an oil type liquid extracted from the shell of cashew kernels (Suwanmanee et al., 2020). CNSL has various applications for which the extraction process from the cashew shell may differ. While some applications require high or technical grade oil, for use in road construction, mechanical extraction using an oil expeller is considered state of the art. Crumb Rubber (CR) is a powder produced through for example cryogenic milling of rubber granules from EoL tyres. Low Density Polyethylene (LDPE) is sourced from waste plastic streams. Collected waste plastic goes through a process of washing, sorting, and milling to create LDPE granules. During the milling step, a waste stream of LDPE fines is created, which cannot be processed into LDPE granules. This waste stream from LDPE recycling is used for road construction. Tall Oil Pitch (TOP) is a by-product of the kraft pulping process in the pulp and paper industry. It is produced through the distillation of Crude Tall Oil (CTO) and an often used application is energy (heat) recovery to be utilised in industry processes. The Resin manufacturer produces both fossil and bio-based Resins. The manufacturer was not able to disclose inventory data for the production of the bio-based Resin. ISCC certificates for bio-based material input in the manufacturers facility are available, so it is treated as bio-based in the recipes of the circular and bio-based binders (Din Certco, 2024). However, as inventory data is not available yet, the Resin is treated as fossil based in this study

Table 1 Circular binder materials (Latexfalt, n.d.).

Components	**Function**	**Origin**	**Process**
Cashew Nut Shell Liquid	Base	Bio-based and circular	Cashew nut processing
Crumb Rubber	Base	Circular	End of life tire recycling
Extender Oil	Base/Compatibilizer	Fossil	Crude oil refining
Low Density Polyethylene	Base	Circular	Waste plastic recycling
Resin	Compatibilizer	Fossil/(bio-based)	(Bio-)Naphtha steam cracking
Polymer	Performace enhancement	Fossil	Naphtha steam cracking
Tall Oil Pitch	Base	Bio-based and circular	Pulp and paper processing
Wax	Compatibilizer	Fossil	Fischer-Tropsch process

Table 2 lists the prototypes in which the materials will be integrated. The prototype binders have been designed by Latexfalt and exact formulas and material suppliers are confidential and can be found in confidential Appendix.[2] For every binder prototype TOP and CNSL may substitute one another and the results for each prototype will be displayed for both the TOP and CNSL version. As described in section 3.2, some of the compatibilizers are not (yet) available in circular or bio-based from. Therefore, the amount of circular and bio-based material content does not yet live up to its full potential according to the prototype descriptions (Table 2). The amount of circular and bio-based components in the prototype binders can be seen in Table 2. For the environmental impact of the reference binder and asphalt, results coming from the Product Category Rules (PCR) asphalt methodology will be taken (Van der Kruk & Overmars, n.d.).

Table 2 Prototype asphalt binders (Latexfalt, n.d.).

Name	**Description**
HK C60	May contain up to 60% of circular/bio-based material
HK C95	May contain up to 95% of circular/bio-based material
HK Bio	May contain up to 100% of bio-based material

For the specific circular binder materials and accompanying processes, input and output data of each life cycle stage are collected. The goal is to collect as many primary data as possible and only if not available to consider secondary data collection. Primary data are gathered from the respective manufacturers of the circular, bio-based and non-bio-based binder materials as well as from the production facility from Latexfalt[3]. Secondary data will be sourced from publicly available scientific literature and LCI database Ecoinvent, which is the default database reference for the Dutch construction sector (Stichting Nationale Milieudatabase, 2022). Data from the LCI database such as geographical location of production or transport distances, may be adjusted to correct for the prototype binders from Latexfalt. In the Appendix the complete inventory data inputs and its sources, supplier information and assumptions can be found.

Especially important for the results of the LCIA is the lifespan of asphalt. For the conventional reference case, data are widely available, however for the circular binder based asphalt this is not the case. The assumption will be made that the lifespan of SMA and AC pavements with circular and bio-based binder is equal to the SMA and AC with conventional bitumen binders, relatively with a lifespan of 16 and 14 years, according to the PCR (Van der Kruk & Overmars, n.d.). For the environmental impact assessment, a reference lifespan of 16 years will be taken for all binders. In this assessment, the lifespan of asphalt is only relevant for module D.

4.1.2.1 Inventory circular & bio-based components

In this section an example of the inventory data for life cycle phase A1 for Crumb Rubber (CR) is shown in For the conventional bitumen binder, the environmental impact is determined using the industry standard methodology for bitumen, which is described by the PCR (Van der Kruk & Overmars, n.d.).

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[2] Available upon request.

[3] Some of these data need to be treated confidentially.

Table 3. In the Appendix, the detailed life cycle inventory (LCI) data for life cycle phase A1 and A2 for every component is given. For the conventional bitumen binder, the environmental impact is determined using the industry standard methodology for bitumen, which is described by the PCR (Van der Kruk & Overmars, n.d.).

Table 3 Life Cycle Inventory Data for the production of 1kg Crumb Rubber (Farina et al., 2017).

Process	Value	Unit	Allocation	Economic value
EoL tire mechanical recycling				
Material output				
Rubber granules	0.96	kg		$100
Steel scrap	0.22	kg		$310
Fibre fraction	0.20	kg		$50
Inert material	0.01	kg		$0
Material input				
EoL tires	1.40	kg	0.55 (economic)	
Steel knives	0.0008	kg	0.55 (economic)	
Rainwater	0.06	L	0.55 (economic)	
Energy input				
Electricity	0.49	kWh	0.55 (economic)	
Transport				
Road transport EoL tires	0.31	tkm	0.55 (economic)	
Crumb rubber production				
Material output				
Crumb rubber	1.00	kg		
Material input				
Rubber granules	0.96	kg		
Silica	0.004	kg		
Liquid nitrogen	1.21	kg		
Silane	0.04	kg		
Energy input				
Electricity	0.23	kWh		
Transport				
Road transport material inputs	0.0008	tkm		
Emissions				
Exhaust N2 emissions	1.21	kg		

4.1.2.2 Inventory Latexfalt production processes

At the Latexfalt facility the processes for the production of asphalt binders mainly consist of blending the different components. The main energy and resource inputs for the Latexfalt production facility consist of natural gas for heating, electricity for power equipment and tap water. In addition to energy inputs for blending of components, energy input is required for heating and storage of components and end products. The amount of time materials or end products are stored widely varies. Within the facility, a distinction between energy and resource inputs for different production processes and storage cannot be made. Therefore, dividing monthly consumption data metrics by the monthly production volume of the facility is not appropriate to gather accurate results. In Figure 6, the monthly consumption volumes of both natural gas and electricity compared to the monthly production volume is shown. It can be seen that there is little correlation between use of natural gas and electricity and the production volume. This implies that a rather large portion of energy usage can be considered as a baseload for component and end product storage. This would imply that the slope coefficient of the trendline formula from Figure 6, would give a good indication of the energy usage for only the production phase and short term storage of an asphalt binder. To validate these results, energy inputs for power equipment and heat losses during the production and short term storage of an asphalt binder were modelled (Latexfalt, n.d.). The energy input results from the modelling approach are roughly the same compared with the trendline approach. The energy requirements, from the modelling approach, and resource inputs for the production of 1kg of asphalt binder are shown in Table 4.

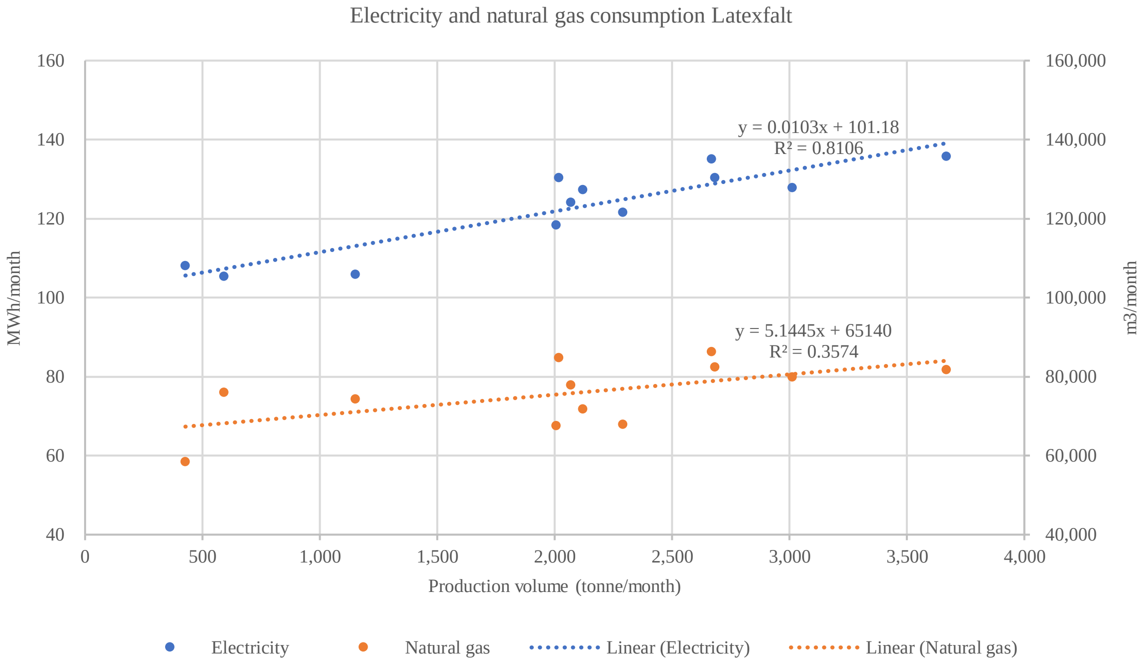

Figure 6 Electricity and natural gas consumption plotted with production volumes at Latexfalt facility (Latexfalt, n.d.).

Table 4 Energy and resource inputs for 1kg of asphalt binder production at Latexfalt facility (Latexfalt, n.d.).

Energy and resource inputs		**Unit**
Resource input		
Tap water	0.18	L
Energy input		
Natural gas	0.006	m3
Electricity	0.02	kWh

4.1.2.1 *Allocation*

Following the aLCA method and the EN15804(+A2) standard for the road construction sector, the preferred allocation method for multifunctional processes is physical allocation (ISO 14044, 2006). In case the difference in economic value between products or processes in multifunctional processes exceeds 25%, economic allocation is the preferred allocation method (Tim van der Kruk et al., n.d.).

4.1.3 *Impact Assessment*

The LCIA will be carried out using SimaPro, a widely recognized and standardized tool for LCA. The chosen impact categories will be based on the standardized methodological choices for LCAs in the Dutch construction sector, specifically referencing the Environmental Performance Assessment Method for Construction Works, which is aligned with the EN 15804(+A2) norm (Stichting Nationale Milieudatabase, 2022). The impact categories can be found in Table 5.

4.1.4 *Sensitivity analyses*

Inevitably, there will be a difference in accuracy between data of circular and bio-based binders and data of the reference conventional asphalt. It is expected that data accuracy and reliability for conventional asphalt will be higher. Therefore, sensitivity analyses will be performed on data from sources with lower accuracy, e.g. data that represents industry averages or has a wide geographical scope. In addition, multiple sources may be compared to validate results. Economic values of raw materials, intermediate- and end-products can vary significantly. When multifunctional processes are present and allocation is required, a sensitivity analysis will be conducted for the materials for which the allocation method likely has a major impact on the LCIA results.

Table 5 Impact categories according to EN15804(+A2) (Stichting Nationale Milieudatabase, 2022).

Environmental impact category	Indicator	Unit
Climate change – total	Global Warming Potential total (GWP total)	kg CO_2-eq.
Climate change – fossil	Global Warming Potential fossil fuels (GWP fossil)	kg CO_2-eq.
Climate change – biogenic	Global Warming Potential biogenic (GWP biogenic)	kg CO_2-eq.
Climate change – land use and land use change	Global Warming Potential land use and land use change (GWP luluc)	kg CO_2-eq.
Ozone Depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC11-eq.
Acidification	Acidification potential, Accumulated Exceedance (AP)	mol H+-eq
Eutrophication aquatic freshwater	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP freshwater)	kg P-eq
Eutrophication aquatic marine	Eutrophication potential, fraction of nutrients reaching marine end compartment (EP marine)	kg N-eq
Eutrophication terrestrial	Eutrophication potential, Accumulated Exceedance (EP terrestrial)	mol N-eq
Photochemical ozone formation	Formation potential of tropospheric ozone (POCP)	kg NMVOC-eq
Depletion of abiotic resources – minerals and metals	Abiotic depletion for non-fossil resources potential (ADP minerals & metals)	kg Sb-eq
Depletion of abiotic resources – fossil fuels	Abiotic depletion for fossil resources potential (ADP fossil)	MJ, net cal. Val.
Water use	Water (user) deprivation potential, deprivation-weighted water consumption (WDP)	m^3 world eq. deprived
Particulate Matter emissions	Potential incidence of disease due to PM emissions	health problems - incidence
Ionizing radiation, human health	Potential human exposure efficiency relative to U235 (IRP)	kBq U235-eq
Eco-toxicity (freshwater)	Potential Comparative Toxic Unit for ecosystems (ETP fw)	CTUe
Human toxicity, cancer effects	Potential Comparative Toxic Unit for humans (HTP-c)	CTUh
Human toxicity, non-cancer effects	Potential Comparative Toxic Unit for humans (HTP-nc)	CTUh
Land use-related impacts / Soil quality	Potential soil quality index (SQP)	Dimensionless

4.2 Biogenic Carbon

The LCIA results will be made using the proposed methodology according to the EN 15804(+A2) norm. This norm also considers biogenic carbon storage as discussed in section 2.3 and explicitly specifies that biogenic carbon shall not be allocated but must follow the physical flow (Durão et al., 2020). The components considered for potential biogenic carbon storage are CNSL and TOP, since only these components contain biogenic carbon. In order to account for biogenic carbon, according to the PCR methods, evidence must be presented that the carbon is actually stored for over 100 years. For the circular and bio-based binders this evidence is not there (yet), and therefore the results will be presented without biogenic carbon storage. However, the results will also be presented with the assumption that the carbon is sequestered over a period of at least 100 years. In addition, the results will also be presented using the BCS_{100} indicator as proposed by Corona et al. (2022).

4.3 Environmental Cost Indicator

Based on the results of the LCIA, the MKI scores will be calculated for the bitumen and the three prototype binders. The weighting factors used are displayed in Table 6. The scores will be calculated from the LCIA results carried out in SimaPro using the CLM-IA baseline method.

Table 6 Weighting factors for MKI calculation (Stichting Nationale Milieudatabase, 2022).

Impact categories MKI	Unit	Value
Abiotic depletion	kg Sb eq	0.16 €/kg
Abiotic depletion (fossil fuels)	MJ	7.7E–05 €/MJ
Global Warming (GWP100a)	kg CO_2 eq	0.05 €/kg
Ozone layer depletion (ODP)	kg CFC-11 eq	30.0 €/kg
Human toxicity	kg 1,4-DB eq	0.09 €/kg
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	0.03 €/kg
Marine aquatic ecotoxicity	kg 1,4-DB eq	0.0001 €/kg
Terrestrial ecotoxicity	kg 1,4-DB eq	0.06 €/kg
Photochemical oxidation	kg C_2H_4 eq	2.0 €/kg
Acidification	kg SO_2 eq	4.0 €/kg
Eutrophication	kg PO_2 eq	9.0 €/kg

5 Results

In this chapter, the results of the Life Cycle Impact Assessment (LCIA) and Environmental Cost Indicator (MKI) scores are shown. The results are presented excluding biogenic carbon storage and including biogenic carbon storage, employing two different methods for biogenic carbon storage. An overview of all data presented in figures and other detailed results is shown in the Appendix.

5.1 Components A1-2 excluding Biogenic Carbon Storage

In Figure 7, the LCIA results, excluding biogenic carbon storage, of the binder components for four of the impact categories are shown. As can be seen, life cycle phase A1: raw materials extraction, has a much higher contribution to the overall environmental impact compared to phase A2: transport to producer. Components originating from fossil sources, have a higher impact in the four categories; except for bitumen, which has lower Marine Aquatic Ecotoxicity impact than Crumb Rubber (CR) and Low Density Polyethylene (LDPE). In addition, all the circular and bio-based components have a significant lower Global Warming Potential impact as compared to bitumen.

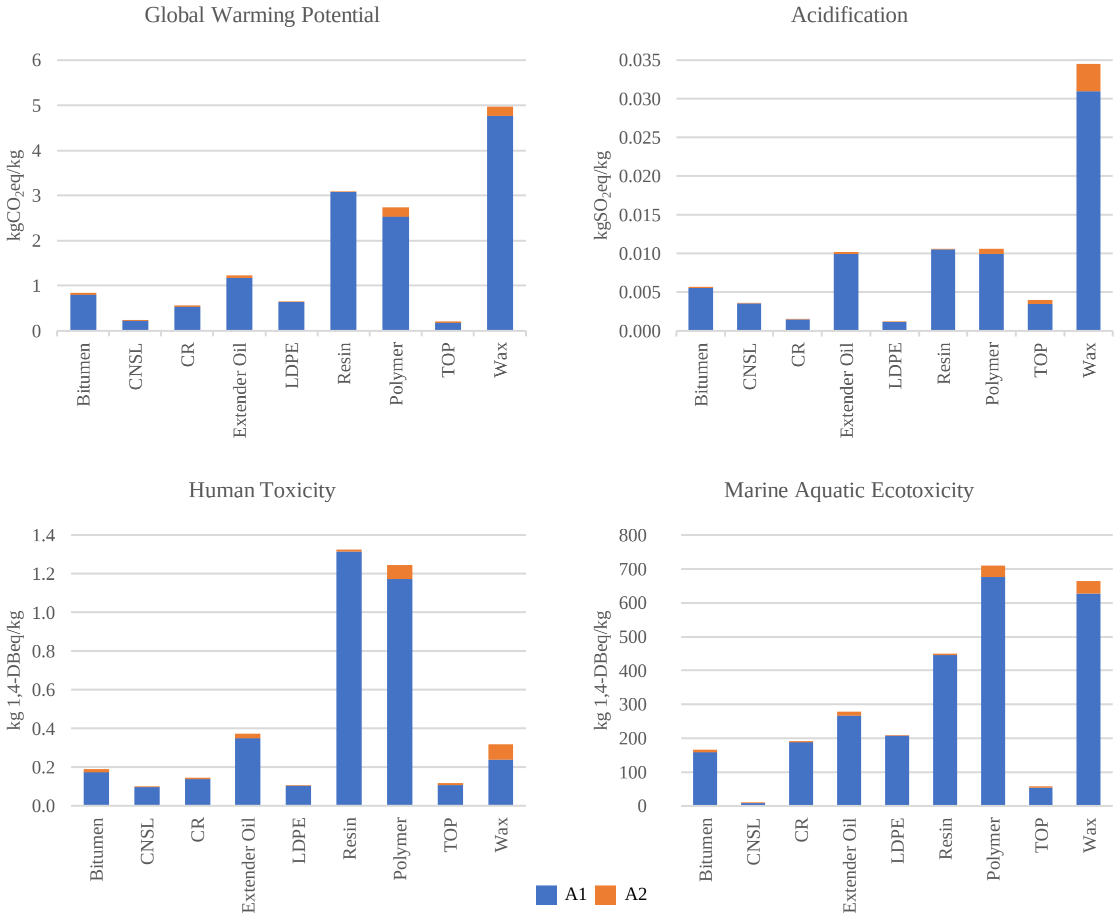

Figure 7 Global Warming Potential, Acidification, Human Toxicity and Marine Aquatic Ecotoxicity Environmental Impact Assessment Results for Life Cycle Phase A1 and A2.

Figure 8 illustrates the MKI score for all asphalt binder components. In addition, it shows the contribution of life cycle phases A1 and A2. As can be seen, life cycle phase A1, the extraction of raw materials, has by far the largest impact of all asphalt binder components. In addition, components originating from fossil sources, Bitumen, Extender oil, Resin, Polymer and Wax have the largest overall MKI score. Comparing the circular and bio-based components with bitumen, they all have significant lower MKI scores. Also, the relative contribution to the total MKI score for life cycle phase A1 and A2 of the eleven different impact categories is shown. For all components, except for CNSL, the Global Warming Potential impact category represents the largest contribution to the MKI score for all components, except for CNSL, where Acidification is the largest contributor to the MKI score. The major contributing impact categories to the overall MKI score are Global Warming Potential, Human Toxicity, Marine Aquatic Ecotoxicity, and Acidification. Noticeable is the relatively small contribution of Marine Aquatic Ecotoxicity and Human Toxicity of respectively CNSL and Wax, compared with other components. A distinction between the origin of component, circular/bio-based and fossil, and the relative contribution of the impact categories to the total MKI score cannot be identified from the results.

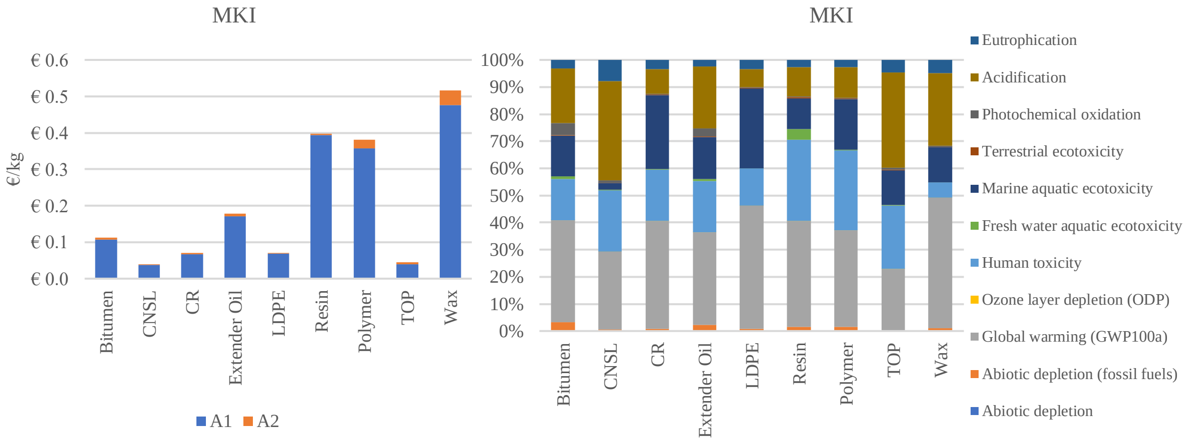

Figure 8 MKI scores per Life Cycle Phase (left), and the relative contribution of the different impact categories to the total MKI score (right).

5.2 Components A1-2 including Biogenic Carbon Storage

In Figure 9, the Global Warming Potential is displayed, using the both the EN15804(+A2) and BCS_{100} indicator approaches for biogenic carbon storage. It can be seen that biogenic carbon storage has a very large influence on the Global Warming Potential impacts, using the EN15804(+A2) approach. Using the BSC_{100} method, the influence is much smaller. However, the net Global Warming Potential impacts of the two components employing biogenic carbon storage, CNSL and TOP, are still negative.

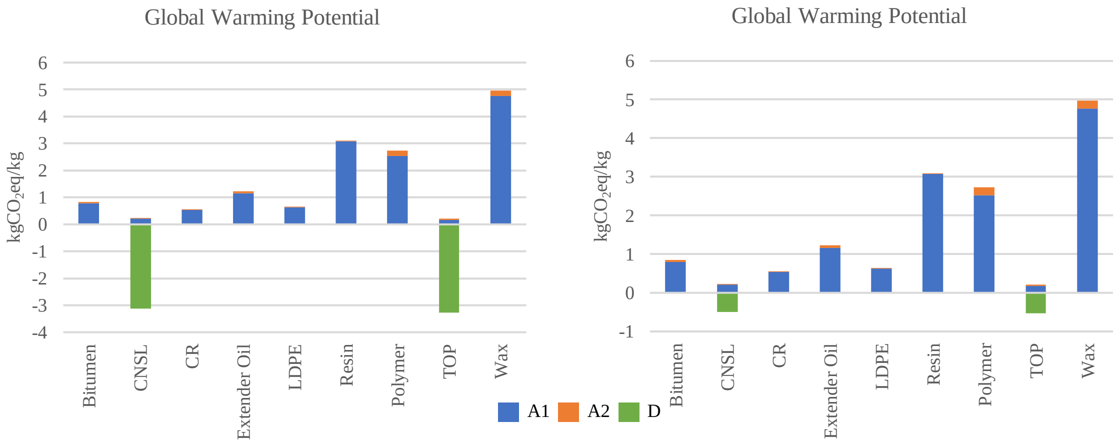

Figure 9 Global Warming Potential Environmental Impact Assessment Results including biogenic carbon storage using the EN15804(+A2) (left) and BCS_{100} (right) approach for Life Cycle Phase A1-2 & D.

Implementing the Global Warming Potential impacts including biogenic carbon storage into the MKI score, in Figure 10 it can be seen that the MKI for the EN15804(+A2) becomes negative. Using the BSC_{100} approach, the MKI does not become negative, however is just slightly above zero.

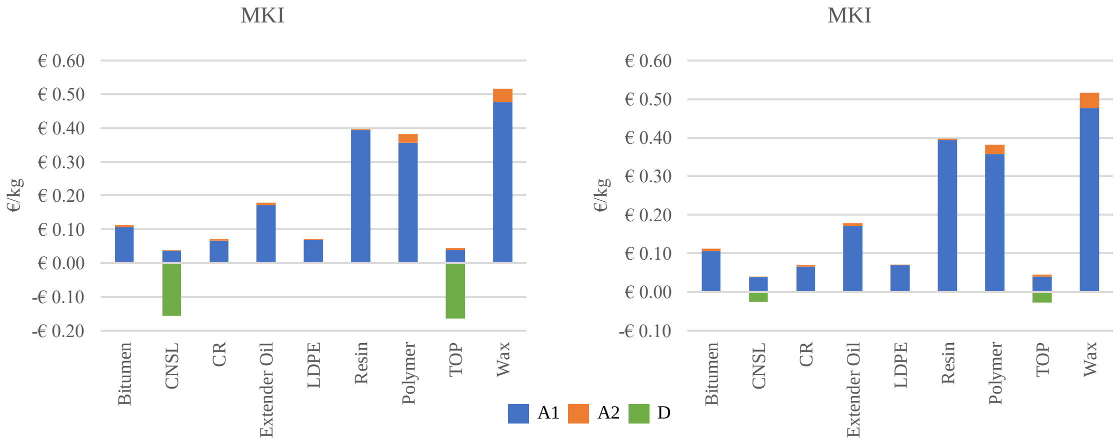

Figure 10 MKI scores including biogenic carbon storage using the EN15804(+A2) (left) and BCS_{100} (right) approach for Life Cycle Phase A1-2 & D.

5.3 Life Cycle Phase A3

Figure 11 shows the relative contribution of environmental impact to the MKI of the production processes at the Latexfalt facility. The impacts, coming from tap water, natural gas, and electricity use, vary significantly. Tap water has a very small contribution to the total environmental impacts of life cycle phase A3. For natural gas and electricity, the Global Warming Potential impacts are equal, whereas there is large different in relative contribution of the Human Toxicity, Marine Aquatic Ecotoxicity and Acidification impact categories.

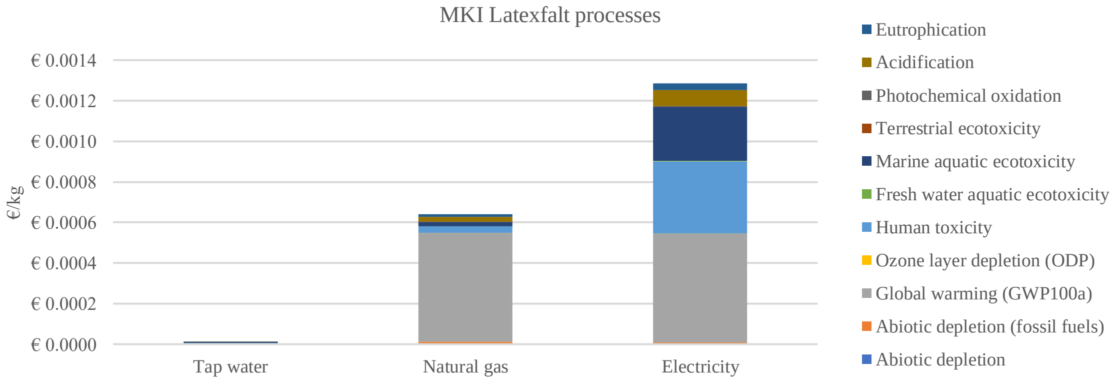

Figure 11 MKI scores for A3 processes at Latexfalt facility.

5.4 Binders A1-3 excluding Biogenic Carbon Storage

In
Figure 12, the LCIA results of the binder components for five of the impact categories are shown. The relative contribution of life cycle phase A2 and A3 is obviously very small for all asphalt binders. All the circular and bio-based asphalt binders have a lower Abiotic Depletion of fossil fuels, compared to the Bitumen binders. Both versions of the HK C95 binder have an Abiotic Depletion (fossil fuels) impact of around half the other two circular and bio-based binders. For Global Warming Potential, the HK C95 binders have a more or less equal score compared with bitumen. Noticeable is the Human Toxicity impact category, in which the bitumen binder has to lowest overall impact. Especially both the HK Bio binders have a high relative score on Human Toxicity.

The total MKI scores for the binders, also visible in Figure 12, illustrate that for all three circular and bio-based binders, there is only little difference between the CNSL and TOP version. This is a result of the small difference in impact between CNSL and TOP. In addition, it can be seen that the HK C95 binders and bitumen have an equal MKI score, with the other circular and bio-based binders having a MKI score that is roughly 35-50% higher. In the Appendix, the MKI score for the binders per component can be seen. For the HK C60, it is mainly a fossil material, Extender Oil, which has a large contribution to the overall MKI score. The Resin also contributes significantly, however note that the Resin considered is fossil based. For the HK C95, the CNSL/TOP, Resin and Wax have a roughly equal impact on the overall MKI score, next to other components with significantly smaller impacts. The Resin is the major contributor to the relatively high MKI score of the HK Bio binder.

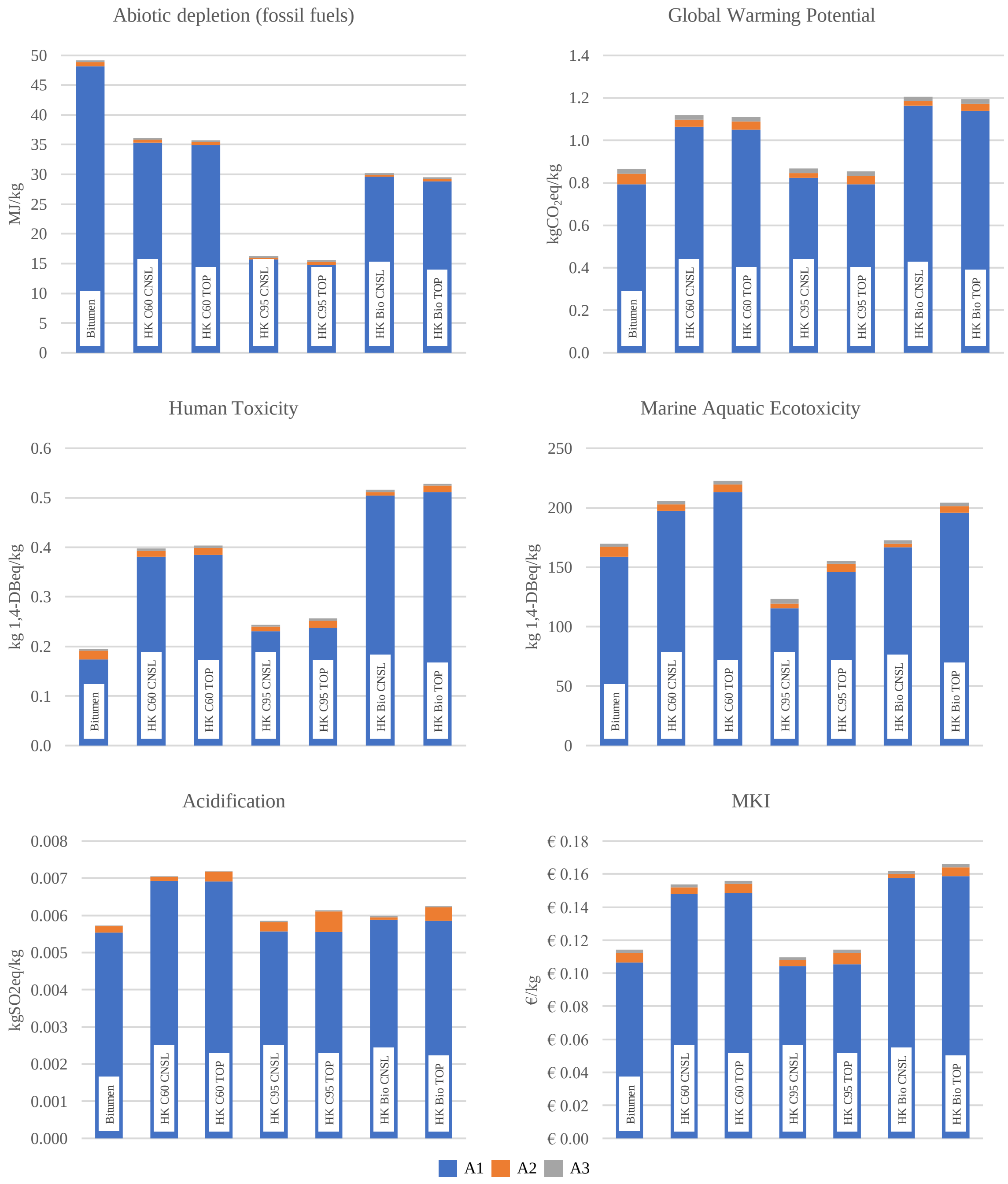

Figure 12 Abiotic Depletion (fossil fuels), Global Warming Potential, Human Toxicity, Marine Aquatic Ecotoxicity and Acidification Environmental Impact Assessment Results and MKI score for asphalt binders.

Comparing the relative contribution of all impact categories of all binders in Figure 13, it is shown that there is an equal distribution between impact categories. Figure 14 illustrates the difference in contribution between fossil and circular and bio-based components to both MKI and weight. It can be seen that for all circular and bio-based binders, the contribution of fossil components (in particular the non-circular and non-bio-based compatibilizers, as referred to in section 3.2 and 4.1.2) to the MKI score is much higher than the contribution by weight of fossil components to the total weight of the binder.

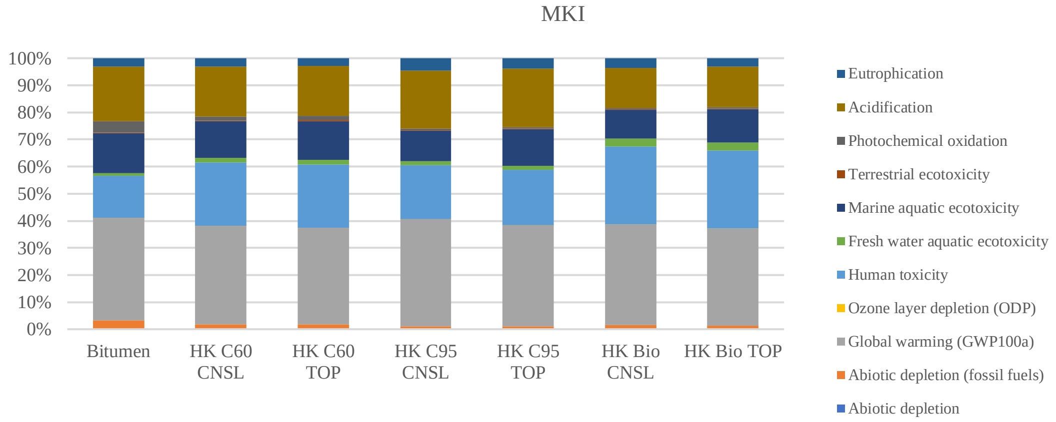

Figure 13 MKI scores per asphalt binder, including contribution per life cycle phase (left). Relative contribution per impact category to the total MKI score per asphalt binder (right).

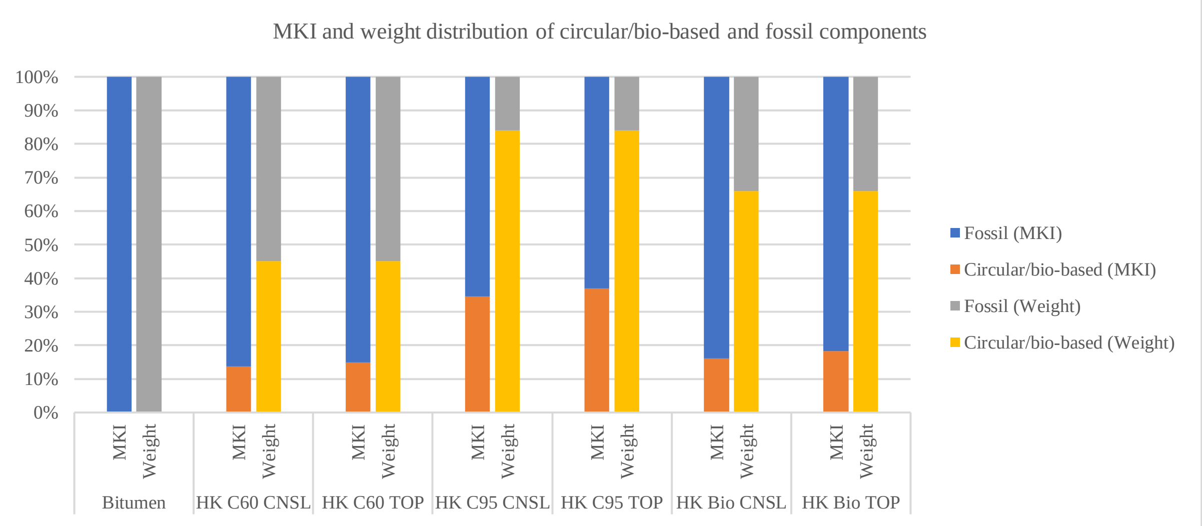

Figure 14 Contribution of fossil and circular and bio-based components to both the MKI score and weight of the binder for life cycle phases A1-3.

5.5 Binders A1-3 including Biogenic Carbon Storage

As can be seen in

Figure 15, including biogenic carbon storage has a significant impact on the Global Warming Potential impact results and de MKI scores. Using the EN15804(+A2) approach, the Global Warming Impacts become negative, thereby effectively sequestering instead of emitting carbon dioxide. The BSC_{100} approach results in roughly equal Global Warming Potential impacts for the Bitumen, HK C60 and HK Bio binders, with the HK C95 binder having the lowest impact. Given the HK C95 binder has the highest share of circular and bio-based material, this result is to be expected. The MKI scores show that all alternative binders have a lower score when using the EN15804(+A2) approach. Especially worth mentioning is that the MKI score of the HK C95 binder has a MKI score of nearly zero. Again, this is in line with the binder having the highest share of circular and bio-based content. Using the BSC_{100} approach, the HK C95 binder score is slightly lower than Bitumen while the HK C60 and HK Bio binders have a higher score than Bitumen. In Figure 16, the contribution of fossil and circular and bio-based components to both MKI and weight are shown, including life cycle phase D using the BSC_{100} indicator. It can be said that the relative contribution of circular and bio-based components to MKI score becomes even smaller compared to contribution of the binder weight.

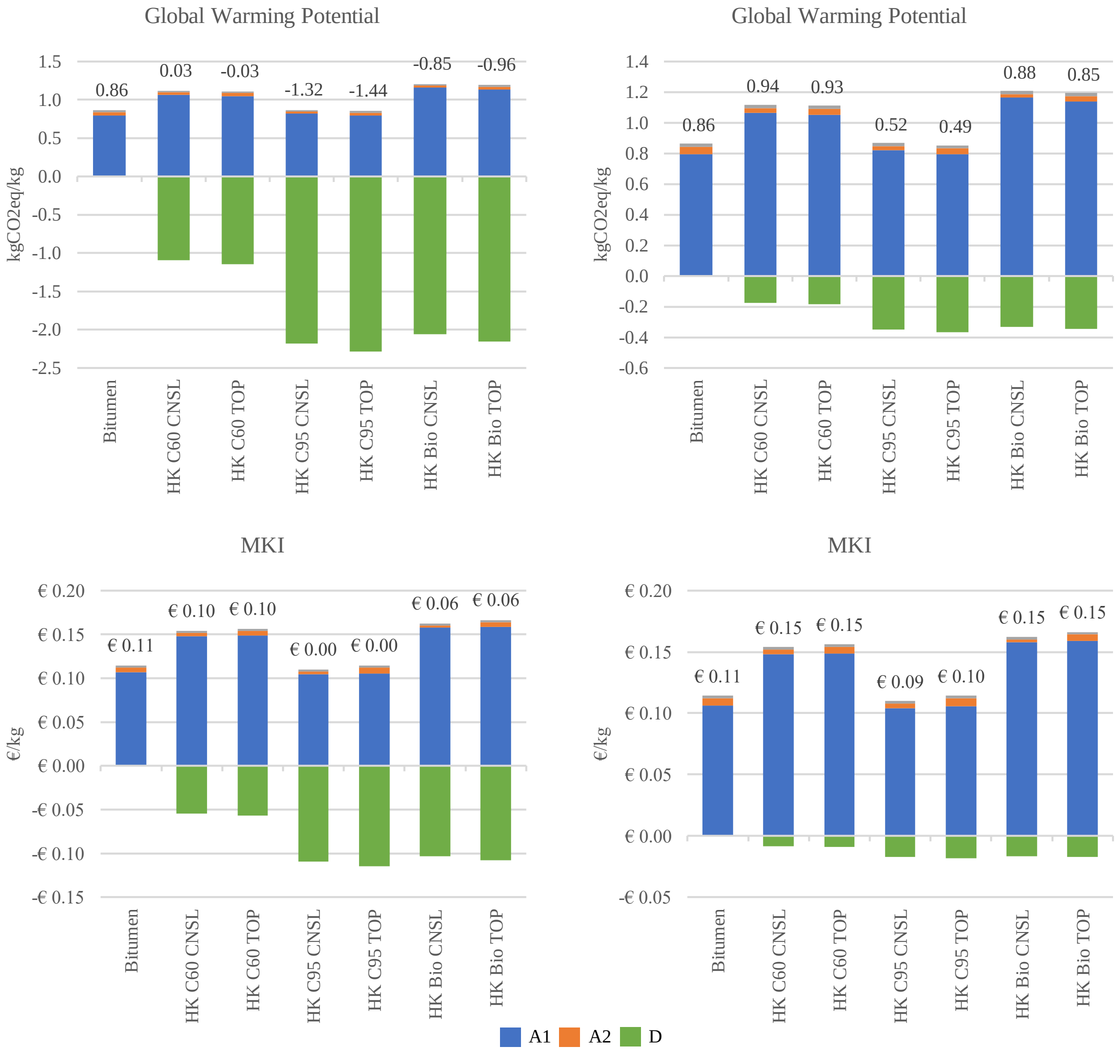

Figure 15 Global Warming Potential Environmental Impact Assessment Results and MKI scores including biogenic carbon storage using the EN15804(+A2) (left) and BSC_{100} (right) approach for Life Cycle Phase A1-3 & D.

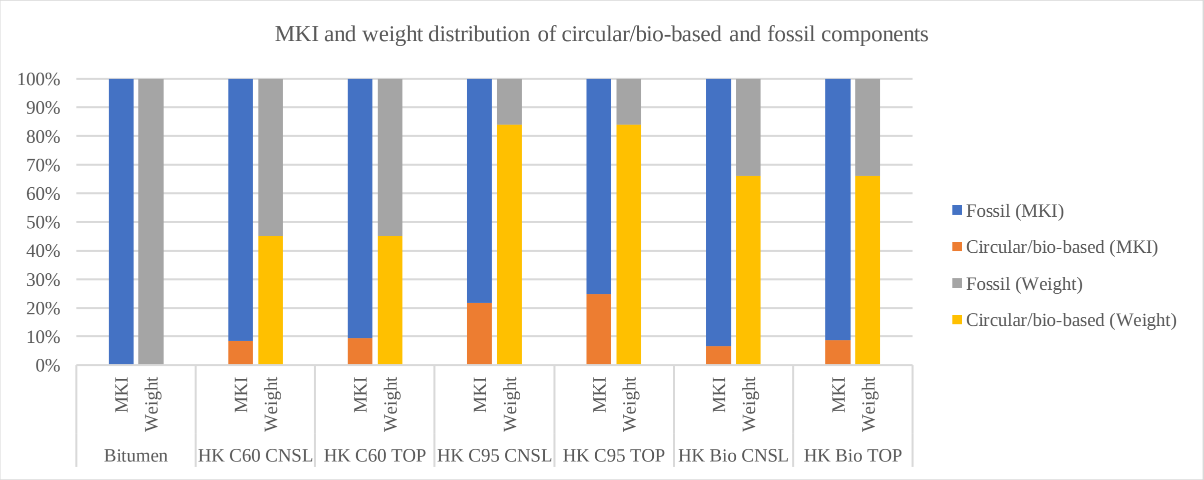

Figure 16 Contribution of fossil and circular and bio-based components to both the MKI score and weight of the binder, including biogenic carbon storage using the BSC_{100} approach for life cycle phases A1-3 & D.

6 Sensitivity Analyses

To improve the overall credibility of the results of environmental impact assessment, sensitivity analyses need to be employed. The choices for different allocation methods are not very robust due to older data on economic values, which makes it more difficult choosing the correct allocation method. Therefore, the alternative approach of physical allocation is employed. In this chapter, three sensitivity analyses are presented. In the Appendix, all inventory data and sensitivity variations are available. To the results presented in the chapter 5 is referred to as ‘reference’ results. A sensitivity analysis is made for CNSL and CR, comparing data supplied by the component manufacturer to the results from scientific sources. In addition, for CR, a sensitivity analysis is performed on the type of allocation method used. For TOP, the results for different sourcing locations and allocation methods are compared.

6.1 Cashew Nut Shell Liquid

The LCIA results for CNSL were supplied by the manufacturer of the CNSL. To check the validity of these results, the inventory data from Suwanmanee et al. (2020) were used to determine environmental impact of CNSL. Note that this paper describes the inventory data for the extraction of technical grade CNSL, which is a much higher quality than required for road construction. Therefore, the distillation and chemical extraction process in the inventory data was replaced by mechanical extraction. Comparison, expressed in MKI score, between the reference and the additional scientific source can be found in Figure 17. The resulting MKI score for the scientific source is higher when compared to the reference result. An explanation could be that the scientific source includes a rather long transport distance from cultivation area to processing facility (both in Thailand), which makes up half of the MKI score contribution. A big difference in contribution to life cycle phase A2 can be seen. The CNSL reference also finds its origin in Asia, however the transport impacts from Asia to Europe are incorporated within the A1 phase, while for the additional source this is included in the A2 phase.

6.2 Crumb Rubber

In Figure 17 the sensitivity results for CR are shown. In addition to the reference results (supplied by the manufacturer), the research data from Farina et al. (2017) were used to create a comparison between two different sources. In addition, to the two sources, both economic and physical allocation were applied, because the economic value of multifunctional process outputs is not very robust. As can be seen, the resulting MKI score for CR using the additional source is lower compared to the reference result. This is probably due to the simplified inventory data used in the scientific literature source where the process of cryogenic milling is not included. There is a slight difference between economic and physical allocation for both sources.

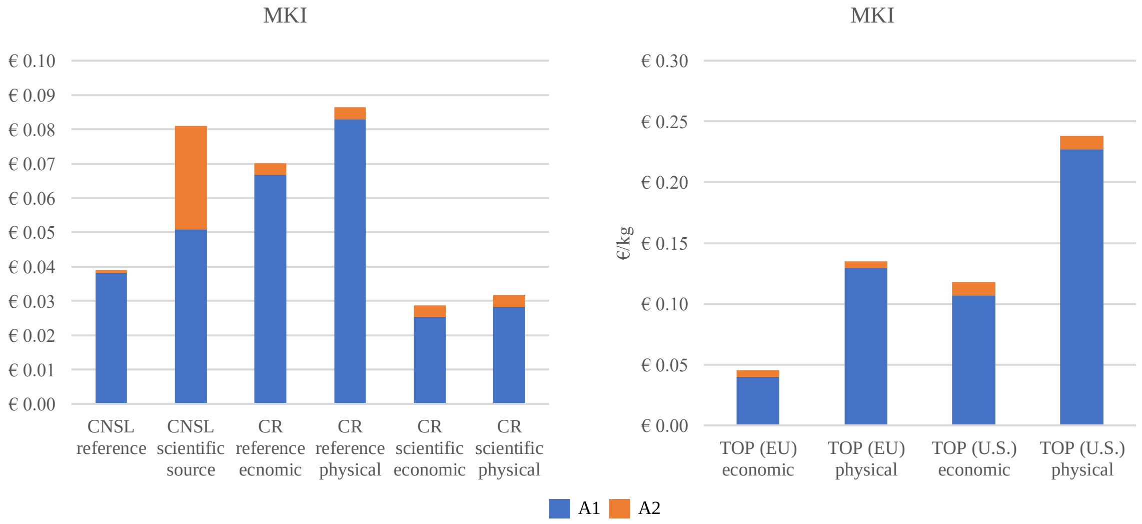

Figure 17 Sensitivity analyses results expressed in MKI score for CNSL and CR (left) and TOP (right).

6.3 Tall Oil Pitch

For the TOP component, a scientific source was used which supplied both inventory data for Europe and the U.S. For the sensitivity analysis of TOP the inventory data for both Europe and the U.S. were used. In addition, for both origins, economic and physical allocation was applied. In Figure 17, it can be seen that there is a major difference between the reference result (Europe, economic allocation) and the other results. The difference in MKI scores between Europe and U.S. mainly comes from the lower percentage of renewable energy in the energy mix of tall processing in the U.S. Because the difference in economic value between black liquor soap and pulp is smaller in Europe, the relative difference in MKI score between economic and physical allocation is larger for Europe.

7 Discussion

In this chapter, the impact is discussed of uncertainties in the inventory data, of methodological choices, of further binder development and of limitations of the research.

7.1 Uncertainty

7.1.1 Assumptions

Throughout the research process, various assumptions were made to fill data gaps and streamline analyses. These assumptions, particularly those regarding the lifespan of asphalt pavements and the availability of data for certain life cycle phases, introduced uncertainties of the results. For instance, assumptions regarding the lifespan of circular and bio-based asphalt binders were necessary due to limited data availability. These assumptions may have influenced the accuracy of the environmental impact assessments and should be acknowledged when interpreting the results. The assumption about lifespan in particular has an influence on the biogenic carbon storage results using the BCS_{100} indicator. In addition, the assumption of permanent biogenic carbon storage has a very large influence on the MKI scores of the circular and bio-based binders. Although it is an assumption that need be verified in future research, the storage of biogenic carbon is essential in order to achieve lower environmental impacts than conventional bitumen binders.

7.1.2 Data accuracy

Data accuracy is paramount in conducting robust LCAs. While efforts were made to gather primary data from manufacturers and secondary data from reliable sources, challenges were encountered, especially regarding the availability and reliability of data for circular and bio-based materials. Also, different sources presented data is differing detail, leading to different LCIA results for example for CR. A major impact on the results is the unavailability of inventory data of the bio-based Resin. Therefore, the fossil based version of the Resin was used in the LCA. The Resin has a large contribution to the overal environmental impact of all circular and bio-based binders. This means that the environmental impact potentially could be significantly reduced when the fossil based Resin is replaced by the bio-based version. Additionally, discrepancies were observed in data representations within the SimaPro software, particularly concerning the modelling of biogenic carbon storage. It was found that using inventory data from primary and secondary sources, sometimes would lead to odd biogenic carbon content results. Despite these challenges, steps were taken to mitigate inaccuracies, such as cross-referencing data with reputable sources like the Ecoinvent database.

7.2 Methodological choices

7.2.1 Biogenic carbon storage

In Figure 15 from chapter 5 it can be seen that including biogenic carbon storage has a major influence on the MKI score, especially when considering the EN15804+A2 approach. Given that permanent biogenic carbon storage for circular and bio-based binders can neither be proven or denied yet, in this research different methodology approaches for biogenic carbon storage were treated equally. Given the major impact on the MKI score, using the EN15804+A2 approach, it could be said that using this approach confirms the conflicts between biogenic carbon storage and concepts of CE in conducting LCAs. In this case, the BCS_{100} indicator seems to be a perfect alternative for the choice between not including biogenic carbon storage or using the EN15804+A2 approach.

7.2.2 Allocation and biogenic carbon storage

The allocation of environmental burdens in multifunctional processes raised important methodological questions. The choice between physical allocation and economic allocation has significant implications for the interpretation of results, particularly those regarding biogenic carbon storage. According to the EN15804+A2 norm, biogenic carbon shall not be allocated but must follow the physical flow (Durão et al., 2020). When multifunctional processes are present with outputs having a large difference in economic value and containing a lot of biogenic carbon, question can be raised. Taking CNSL as an example, due to the very small economic allocation to cashew shells, only very little of the processing burdens are account for to CNSL, however, in line with the norm of following physical flow, the CNSL output does benefit greatly from the high biogenic carbon content. This means that virgin materials with very low economic value and high biogenic carbon content are very attractive for permanent biogenic carbon storage, leading to conflicts with the concept of CE.

7.3 Future development circular and bio-based binders and research

Based on the results of this research, direction may be given to future research regarding circular and bio-based asphalt binders. One of the key results of this research is the contribution of different components to the overall MKI score, as illustrated in Figure 14 and Figure 16. The fossil (compatibilizer) components have a large relative contribution to the total MKI. This offers perspective for the potential development of circular and bio-based asphalt binder with significant lower environmental impact results compared to the conventional bitumen asphalt binder. When considering potential changes in the environmental impact assessment results for bitumen, which will likely increase due to the economic allocation method employed, circular and bio-based asphalt binders with a smaller environmental impact than bitumen will come sooner rather than later.

7.4 Limitations of research

While this study provides valuable insights into the environmental implications of circular and bio-based binders, certain limitations should be acknowledged. The focus on cradle-to-gate analyses neglects the influence of the use phase, which can significantly impact the overall environmental footprint of asphalt pavements. Furthermore, considerations regarding end-of-life recycling and the reusability of circular and bio-based binders were beyond the scope of this research and warrant further investigation to assess the full lifecycle sustainability of alternative binder compositions. Geographical sourcing locations of materials emerged as a significant factor influencing environmental impact assessments, as can be seen in Figure 17. Sensitivity analyses revealed that the environmental implications of material origin can vary significantly, underscoring the importance of considering regional factors in life cycle assessments. While the majority of inventory data used in this research was specific for the geographical scope of the supplier, this may be specified further. In addition, the economic allocation method is very susceptible to fluctuations in the economic value (by)products. Within the research, the accuracy of economic values remains an ongoing point of improvement, especially considering the large influence the allocation factor may has on the environmental impact results. Last but not least, in this research, multiple sources that are 5-10 years old were used, posing question marks about the representativity of the data used.

7.5 Future research

Future research should deal with questions about the global resource availability of circular and bio-based components in the quantities required for the Dutch road construction sector, given that the demand for circular and bio-based materials may increase for other applications. In addition, when considering a lower MKI score for circular and bio-based asphalt binders compared to bitumen, what would be the commercial advantage over the conventional situation. In that light, what additional cost associated with higher component prices are acceptable in order to maintain or increase profitability? Crucial for the road construction sector in the future and connecting to the R-strategies: how do circular and bio-based asphalt binders handle end of life recycling?

8 Conclusion

This research investigated the environmental impact of circular and bio-based asphalt binder components, conventional bitumen asphalt binders and the production of circular and bio-based asphalt binders. Furthermore, the MKI scores of circular and bio-based asphal binder components, circular and bio-based asphalt binders and conventional bitumen asphalt binders were determined. Using LCA as a tool to model the environmental impact results, it aimed to answer the following research question:

What is the environmental impact of circular and bio-based asphalt binders compared to a conventional bitumen-based asphalt binder?

This question is divided in the following sub questions:

- *What is the environmental impact of a conventional bitumen-based asphalt binder?*
- *What are the environmental impacts of circular and bio-based binder materials?*
- *What is the environmental impact of the production of circular and bio-based binders?*
- *How do the environmental impacts of the production of bitumen and circular and bio-based binders compare?*
- *How do the environmental impacts of a bitumen and circular and bio-based binders translate to Environmental Cost Indicator scores?*

The Global Warming Potential, an important environmental impact category, of circular and bio-based binder materials varies between 0.2 and 5.0 kgCO$_2$eq/kg, with the materials originating from fossil sources, being on the higher side of the spectrum and circular and bio-based materials being on the lower side of the spectrum. When biogenic carbon storage is considered, the Global Warming Potential of bio-based components can be reduced with up to 3 kgCO$_2$eq/kg. A conventional bitumen based asphalt binder has a Global Warming Potential of 0.8 kgCO$_2$eq/kg. The Global Warming Potential of circular and bio-based binders ranges from 0.9 to 1.2 kgCO$_2$eq/kg and when considering biogenic carbon storage, the Global Warming Potential of bio-based material containing binders can be reduced with up to 2.3 kgCO$_2$eq/kg. A conventional bitumen based asphalt binder has a Global Warming Potential of 0.9 kgCO$_2$eq/kg. Translating environmental impacts to MKI, the circular and bio-based binders score between €0.11 and €0.17 per kg and a conventional bitumen binder scores €0.11 per kg. These MKI scores could be lowered with up to €0.11 per kg when the binders are partly composed of bio-based materials. An additional finding is the large contribution of fossil compatibilizers to the environmental impact of circular and bio-based binders, identifying potential for further environmental impact reduction.

Concluding, the circular and bio-based asphalt binders have an equal or a slightly higher environmental impact compared with a conventional bitumen asphalt binder. When biogenic carbon storage is considered, the environmental impact of all three circular and bio-based asphalt binders can be lower than the conventional bitumen asphalt binder.

References

Ardente, F., & Cellura, M. (2012). Economic Allocation in Life Cycle Assessment. *Journal of Industrial Ecology*, *16*(3). https://onlinelibrary.wiley.com/doi/epdf/10.1111/j.1530-9290.2011.00434.x

Bak, I., Overmars, L., & Van der Kruk, T. (2022). *20220331_lca-achtergrondrapport-voor-nederlandse-branchereferentiemengsels_definitief*. https://www.bouwendnederland.nl/media/13788/20220331_lca-achtergrondrapport-voor-nederlandse-branchereferentiemengsels_definitief.pdf

Bishop, G., Styles, D., & Lens, P. N. L. (2021). Environmental performance comparison of bioplastics and petrochemical plastics: A review of life cycle assessment (LCA) methodological decisions. In *Resources, Conservation and Recycling* (Vol. 168). Elsevier B.V. https://doi.org/10.1016/j.resconrec.2021.105451

Brander, M., & Wylie, C. (2011). The use of substitution in attributional life cycle assessment. *Greenhouse Gas Measurement and Management*, *1*(3–4), 161–166. https://doi.org/10.1080/20430779.2011.637670

Brown, E. R., & Mallick, R. B. (1994). *STONE MATRIX ASPHALT-PROPERTIES RELATED TO MIXTURE DESIGN*. https://web-ha.eng.auburn.edu/research/centers/ncat/files/reports/1994/rep94-02.pdf

Canıaz, R. O., Arca, S., Yaşar, M., & Erkey, C. (2019). Refinery bitumen and domestic unconventional heavy oil upgrading in supercritical water. *Journal of Supercritical Fluids*, *152*. https://doi.org/10.1016/j.supflu.2019.104569

Circular biobased delta. (n.d.). *CHAPLIN– ketensamenwerking voor biobased, CO2-reducerend asfalt*. Retrieved February 20, 2024, from https://circularbiobaseddelta.nl/focus-themas/projecten/chaplin/

Corona, B., Hoefnagels, R., Vural Gürsel, I., Moretti, C., van Veen, M., & Junginger, M. (2022). Metrics for minimising environmental impacts while maximising circularity in biobased products: The case of lignin-based asphalt. *Journal of Cleaner Production*, *379*. https://doi.org/10.1016/j.jclepro.2022.134829

Din Certco. (2024). *ISCC PLUS Certificate*. https://www.synthomer.com/media/i43fvn23/iscc_plus_certificate_33300222_middelburg.pdf

Dura Vermeer. (2021). *START TESTFASE ASPHALT RECYCLING TRAIN*. https://www.duravermeer.nl/nieuws/start-testfase-asphalt-recycling-train/

Durão, V., Silvestre, J. D., Mateus, R., & de Brito, J. (2020). Assessment and communication of the environmental performance of construction products in Europe: Comparison between PEF and EN 15804 compliant EPD schemes. *Resources, Conservation and Recycling*, *156*. https://doi.org/10.1016/j.resconrec.2020.104703

Dutch Government. (2019). *Klimaatakkoord - 28 juni 2019*. https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/klimaatakkoord

Dutch Government. (2023, April 26). *Voorjaarsbesluitvorming Klimaat*. Https://Open.Overheid.Nl/Documenten/Ronl-77b639d132c52e5e1d75a36381fb6e60748ed8bb/Pdf.

Ecochain. (2023, August 10). *Environmental Cost Indicator (ECI) – Overview*. https://ecochain.com/blog/environmental-cost-indicator-eci/

Ecoinvent. (n.d.). *Ecoinvent Database*. Retrieved September 26, 2023, from https://ecoinvent.org/the-ecoinvent-database/

EIB. (2022). *De markt voor freesasfalt tot 2030*. https://www.eib.nl/pdf/EIB%20Eindrapport%20De%20markt%20voor%20freesasfalt%20tot%202030%20240522.pdf

Ekvall, T. (2019). Attributional and Consequential Life Cycle Assessment. In M. J. Bastante-Ceca, J. L. Fuentes-Bargues, L. Hufnagel, F.-C. Mihai, & C. Iatu (Eds.), *Sustainability Assessment at the 21st century*. IntechOpen. https://doi.org/10.5772/intechopen.89202

European Commission. (2021). *COMMISSION RECOMMENDATION of 16.12.2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental* *performance of products and organisations*. https://www.consilium.europa.eu/media/40928/st12791-en19.pdf

Farina, A., Zanetti, M. C., Santagata, E., & Blengini, G. A. (2017). Life cycle assessment applied to bituminous mixtures containing recycled materials: Crumb rubber and reclaimed asphalt pavement. *Resources, Conservation and Recycling*, *117*, 204–212. https://doi.org/10.1016/j.resconrec.2016.10.015

Hendrikse, H. C., El Khallabi, H., Hartog, T., Varveri, A., & Tolboom, A. (2023). Characterization and Design of Circular Binders. *Sustainability (Switzerland)*, *15*(17). https://doi.org/10.3390/su151712853

International Energy Agency. (2021). *Net Zero by 2050 - A Roadmap for the Global Energy Sector*. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

ISO 14040. (2006). *Environmental management — Life cycle assessment — Principles and framework*. https://www.iso.org/obp/ui/en/#iso:std:iso:14040:ed-2:v1:en

ISO 14044. (2006). *Environmental management — Life cycle assessment — Requirements and guidelines*. https://www.iso.org/obp/ui/en/#iso:std:iso:14044:ed-1:v1:en

Joint Research Centre, I. for E. and S. (2013). *Roadmap for the European platform on life cycle assessment : facilitating data collection and sustainability assessments for policy and business.* Publications Office. https://op.europa.eu/en/publication-detail/-/publication/a114280a-646c-4e50-8386-1de1246da043/language-en

Junginger, M., Jongerius en Ed de Jong, A., Iris Vural Gürsel, A., Haaksman, I., Slaghek, T., Gosselink, R., Martijn Verschuren, W., Albertus Steenbergen, A., Paul Landa, R., Post, H., Joop Groen, A., Ric Hoefnagels, C., Moretti, C., van Veen, M., & Corona, B. (2021). *Collaboration in aspHalt APplications with LIgnin in the Netherlands-eXtra Lignin (CHAPLIN XL) Openbaar eindrapport*.

Latexfalt. (n.d.). *Internal documentation*.

Liu, Y., You, Z., Dai, Q., & Mills-Beale, J. (2011). Review of advances in understanding impacts of mix composition characteristics on asphalt concrete (AC) mechanics. In *International Journal of Pavement Engineering* (Vol. 12, Issue 4, pp. 385–405). https://doi.org/10.1080/10298436.2011.575142

Miah, J. H., Griffiths, A., McNeill, R., Halvorson, S., Schenker, U., Espinoza-Orias, N., Morse, S., Yang, A., & Sadhukhan, J. (2018). A framework for increasing the availability of life cycle inventory data based on the role of multinational companies. *International Journal of Life Cycle Assessment*, *23*(9), 1744–1760. https://doi.org/10.1007/s11367-017-1391-y

Moretti, C., Corona, B., Hoefnagels, R., van Veen, M., Vural-Gürsel, I., Strating, T., Gosselink, R., & Junginger, M. (2022). Kraft lignin as a bio-based ingredient for Dutch asphalts: An attributional LCA. *Science of the Total Environment*, *806*. https://doi.org/10.1016/j.scitotenv.2021.150316

Moretti, C., Corona, B., Hoefnagels, R., Vural-Gürsel, I., Gosselink, R., & Junginger, M. (2021). Review of life cycle assessments of lignin and derived products: Lessons learned. In *Science of the Total Environment* (Vol. 770). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2020.144656

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, *153*. https://doi.org/10.1016/j.resconrec.2019.104553

Oil Sands Magazine. (2022, April 22). *UPGRADING 101: FROM HEAVY BITUMEN TO LIGHT SYNTHETIC CRUDE*. https://www.oilsandsmagazine.com/news/2022/4/21/upgrading-101-from-heavy-bitumen-to-light-synthetic-crude

Pandit, P., Nadathur, G. T., Maiti, S., & Regubalan, B. (2018). Functionality and Properties of Bio-based Materials. In S. Ahmed (Ed.), *Bio-based Materials for Food Packaging: Green and Sustainable Advanced Packaging Materials* (pp. 81–103). Springer Singapore. https://doi.org/10.1007/978-981-13-1909-9_4

PlasticsEurope. (2018). *Plastics-the Facts 2018 An analysis of European plastics production, demand and waste data*. https://plasticseurope.org/wp-content/uploads/2021/10/2018-Plastics-the-facts.pdf

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *CIRCULAR ECONOMY: MEASURING INNOVATION IN THE PRODUCT CHAIN Policy Report*.

https://dspace.library.uu.nl/bitstream/handle/1874/358310/Circular.pdf?sequence=3&isAllowed=y

Reike, D., Vermeulen, W. J. V, & Witjes, S. (2022). Conceptualization of Circular Economy 3.0: Synthesizing the 10R Hierarchy of Value Retention Options. In A. Alvarez-Risco, M. A. Rosen, & S. Del-Aguila-Arcentales (Eds.), *Towards a Circular Economy: Transdisciplinary Approach for Business* (pp. 47–69). Springer International Publishing. https://doi.org/10.1007/978-3-030-94293-9_3

Reike, D., Vermeulen, W. J. V., & Witjes, S. (2018). The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. *Resources, Conservation and Recycling*, *135*, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

RIVM. (2016). *Tools voor Maatschappelijk Verantwoord Inkopen*. https://rivm.openrepository.com/bitstream/handle/10029/620831/2016-0204.pdf?sequence=1&isAllowed=y

Shell. (2015). *The Shell Bitumen Handbook* (R. N. Hunter, A. Self, & J. Read, Eds.; 6th ed.).

Shogren, R., Wood, D., Orts, W., & Glenn, G. (2019). Plant-based materials and transitioning to a circular economy. In *Sustainable Production and Consumption* (Vol. 19, pp. 194–215). Elsevier B.V. https://doi.org/10.1016/j.spc.2019.04.007

Sollazzo, G., Longo, S., Cellura, M., & Celauro, C. (2020). Impact analysis using life cycle assessment of asphalt production from primary data. *Sustainability (Switzerland)*, *12*(24), 1–21. https://doi.org/10.3390/su122410171

Stahel, W. R. (2016). *Circular economy*. https://www.nature.com/articles/531435a

Stichting Nationale Milieudatabase. (2022). *Environmental Performance Assessment Method for Construction Works*. https://milieudatabase.nl/media/filer_public/89/42/8942d5dd-8d37-4867-859a-0bbd6d9fb574/bepalingsmethode_milieuprestatie_bouwwerken_maart_2022_engels.pdf

Suwanmanee, U., Bangjang, T., Kaewchada, A., & Jaree, A. (2020). Greenhouse gas emissions and energy assessment of modified diesohol using cashew nut shell liquid and biodiesel as additives. *Sustainable Production and Consumption*, *24*, 232–253. https://doi.org/10.1016/j.spc.2020.06.009

Teugels, W. (2020). *Asfalt Impuls*. https://www.crow.nl/getattachment/Asfalt-Impuls/Projecten/Grip-op-bitumen/Kennisdocument-Bitumen-september-2020.pdf.aspx?lang=nl-NL

Thives, L. P., & Ghisi, E. (2017). Asphalt mixtures emission and energy consumption: A review. In *Renewable and Sustainable Energy Reviews* (Vol. 72, pp. 473–484). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.01.087

Tim van der Kruk, Lisa Overmars, & Elisabeth Keijzer. (n.d.). *Product Category Rules voor bitumineuze materialen in verkeersdragers en waterwerken in Nederland (“PCR Asfalt”)*.

Topsector Energie. (n.d.). *Volledig elektrisch en C02 neutraal Laag Temperatuur asfalt productieproces*. Retrieved September 22, 2023, from https://projecten.topsectorenergie.nl/storage/app/exports/project-volledig-elektrisch-en-c02-neutraal-laag-temperatuur-asfalt-productieproces-34656.pdf

Van den Brand, P. (2023, May 8). *Op weg naar 100% circulair asfalt*. https://solidsprocessing.nl/artikel/op-weg-naar-100-circulair-asfalt/

Van der Kruk, T., & Overmars, L. (n.d.). *PCR Asfalt, versie 2.0*. Retrieved February 25, 2024, from https://www.bouwendnederland.nl/media/12923/pcr-asfalt-v20.pdf

Williams, E., & Eikenaar, S. (2022, July 14). *Finding your way in multifunctional processes and recycling*. https://pre-sustainability.com/articles/finding-your-way-in-allocation-methods-multifunctional-processes-recycling/

Yu, X., Zaumanis, M., Dos Santos, S., & Poulikakos, L. D. (2014). Rheological, microscopic, and chemical characterization of the rejuvenating effect on asphalt binders. *Fuel*, *135*, 162–171. https://doi.org/10.1016/j.fuel.2014.06.038

Appendix

For the public available version of this report, the appendix is not available. Please submit your request for acces to the confidential appendix to m.r.b.crouwers@students.uu.nl.