LIFE-CYCLE ASSESSMENT OF LIFE-EXTENDING PAVEMENT MAINTENANCE MEASURES

Bachelor thesis report Civil Engineering

AMANTAI JUMALIEV – S2425564

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Bachelor’s Thesis report

Author: Amantai Jumaliev
Student number: s2425564
Department: Construction management & Engineering
Date: 10.11.2023
Version: Final Version

Student information:
University of Twente
a.jumaliev@student.utwente.nl
+34627840950

Internal supervisors:
University of Twente
Joao Oliveira dos Santos
j.m.oliveiradossantos@utwente.nl
+31534898286

University of Twente
Andrea Vargas Farias
+31534899586
a.vargasfarias@utwente.nl

PREFACE

I'm pleased to share this bachelor's thesis paper with you, marking the culmination of a journey marked by challenges, growth, and perseverance. Along the way, there were hurdles to overcome and lessons to learn, but here we are, ready to present the results of our efforts.

I want to express my sincere gratitude to my supervisors, Joao Oliveira dos Santos and Andrea Vargas Farias, whose guidance and support have been invaluable. Every meeting and feedback contributed enormously to my final results. Their patience and encouragement have been crucial in navigating through obstacles and reaching this point.

I'm also thankful to my family and friends for their unwavering support and encouragement. Their support and believe in me had always supported me throughout my journey.

As I share this research, my hope is that it contributes to meaningful discussions and inspires further exploration in Pavement Management sector. Thank you to everyone who has supported me along the way; your contributions have been invaluable.

ABSTRACT

The mission of environmental sustainability has emerged as an essential priority in the construction and infrastructure sector. Pavement maintenance and rehabilitation, essential components of infrastructure management, have been under scrutiny due to their significant cumulative environmental footprint. In response, the pavement sector is looking at eco-friendly management strategies. However, well-informed decision-making processes within engineering firms and pavement management systems are hindered by an overall absence of thorough awareness about the environmental effects of various pavement maintenance systems.

The main goal of this study is to present the environmental impacts of specific maintenance treatments within the context of pavement management in the Netherlands. Moreover, this research aims to provide valuable insights to enhance the decision-making process concerning the selection of optimal treatments, tailored to specific environmental contexts and other pavement characteristics.

Four maintenance treatments are considered in this study, namely the *Emulsieasfaltbeton* (EAB), *Zeer Open Emulsieasfaltbeton* (ZOEAB), Single surface treatment and Crack filling. Following the LCA stages, the considered phases are the raw material extraction, transportation to construction site and the construction and application. This study focuses solely on maintenance treatments as one of the objectives of the study is to show the potential environmental impacts of maintenance treatments before rehabilitation takes place. Three FUs are defined to enable a fair comparison. The environmental impacts are calculated according to the CML method. The “openLCA” software and “ecoinvent 3.3” databases are the main tools to estimate the environmental impacts. In the final stage of discussion of results the sensitivity analysis is done to show the sensitivity of environmental impacts to certain materials.

The results of the study show that the EAB maintenance treatment has the highest environmental impact on all 11 impact categories of CML in comparison to the other 3 maintenance techniques. In turn, the crack filling has the lowest contribution to the environmental impacts out of 4 techniques. The most contributing stage to the total environmental impacts of ZOEAB, EAB and single surface treatment is found to be the raw materials extraction phase. For the crack filling, however, the most contributing phase is found to be the construction phase.

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LIST OF ABBREVIATIONS

BST	Bituminous surface treatment
CML	Centrum voor Milieukunde Leiden
EOL	End of Life
FU	Functional Unit
GHG	Green House Gas
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life-Cycle Impact Assessment
M&R	Maintenance and Rehabilitation
MKI	Environmental cost indicator
PAH	Polycyclic Aromatic Hydrocarbons
PM	Pavement Management
PCR	Product Category Rules
RAP	Reclaimed asphalt pavement
ZOEAB	Very Open Emulsion Asphalt Concrete (Zeer Open Emulsieasfaltbeton)
EAB	Emulsion asphalt concrete (Emulsieasfaltbeton)

1.Introduction

The core idea of sustainability is composed of three interrelated components: societal, environmental, and economic/financial considerations. Governmental organizations and private contractor organizations are realizing the need to implement sustainable practices, materials, and technology in all facets of construction and infrastructure, as the significance of environmental sustainability gains momentum. In terms of transport infrastructure/system, this involves taking sustainability into account while designing, building, running, and maintaining roads, airports, and railroads—including pavements. (Wang et al., 2014). A roadway section requires several forms of maintenance during its service life, and these procedures vary with time in accordance with technological advancements. Yet, it becomes more challenging to forecast road performance when a variety of maintenance options are used (Mandiartha et al., 2016).

Pavements can be rehabilitated by replacing their asphalt layers or treated with surface treatments to extend or retain their intended lifespan. In addition to helping pavements to last longer, proper maintenance practices, for instance, can also help road construction projects to save a significant amount of money. The degree to which a maintenance technique is environmentally friendly is among the most crucial aspects to take into account together with other pavement characteristics. Given the wide range of maintenance procedures available, it is necessary to examine, monitor, and take into account their impact on the environment to increase understanding and possibly improve the decision-making process underlying to their selection. The methods to prevent or counteract deterioration processes in pavements are maintenance and rehabilitation. By finding and fixing certain pavement defects that lead to general deterioration, maintenance procedures like crack sealing, and joint sealing, assist in reducing the pace of deterioration. Conversely, rehabilitation describes more intensive interventions meant to repair or strengthen the structure of the pavement; these typically take place only when the quality of the pavement has substantially decreased (Alimohammadi, 2020).

1.1. Problem description

Since road pavement maintenance and rehabilitation have a major collective environmental impact, the pavement industry is looking into more environmentally friendly PM strategies. Life cycle assessment is now a methodology widely used in PM to assess environmental performance and guide decision-making processes. It enables pavement managers to take several environmental factors into consideration when creating M&R initiatives and plans. These factors include the resources and power needed for materials manufacturing and construction, the emissions produced, and the results of using various materials and approaches.

The assessment of options for pavement restoration has historically prioritized technical and financial aspects above the environmental effects (Pellicer et al., 2016, Torres-Machi et al., 2014). This indicates that when choosing a certain method to maintain or repair pavements, the environment is hardly taken into account. Because the environmental effects of various maintenance treatments have not been well investigated, the environmental impact of pavement maintenance and repair methods is frequently disregarded (Torres-Machí et al., 2017). Thus, it can be said that abilities/opportunities of different maintenance treatments from an environmental perspective were not fully explored. In summary, due to the reasons described before, the environmental effects of maintenance actions are currently not completely understood, thereby hindering a sustainability-informed decision-making process.

1.2. Research Motivation

Concern over how people are influencing the environment has grown over the past several years. By 2050, the transport industry must have reduced its greenhouse gas emissions from 1990 levels by at least 60%. Local, national, and regional objectives and strategies are derived from these European objectives (Keijzer et al., 2015). Policymakers and road pavement constructors must take into account both the government's full sustainable procurement goals and the European emission reduction objectives. This is also the case of the Netherlands, where nearly all of the transportation network is under supervision and control by the government. (Keijzer et al., 2015). Therefore, it is important to study the environmental effects of different maintenance treatments to achieve the sustainable goal in the transportation sector, especially the pavement infrastructures. For instance, currently, there exist different maintenance measures such as sealing, bituminous surface treatments, surface roughening, crack filling, rejuvenating creams, and so on. Thus, it is essential to develop an LCA framework for specific maintenance measures in the Netherlands. The research will focus on various maintenance treatments and will not cover or study the rehabilitation techniques for pavements.

1.3. Research Scope

It is important to define the research scope as it clarifies the topics that will be studied and supports the researchers' concentration. An LCA study has four essential phases (ISO 14044, 2006; Harvey et al., 2016): (1) defining the purpose and scope; (2) analyzing the life- cycle inventory (LCI); (3) evaluating the life-cycle impact assessment (LCIA); and (4) providing an explanation/interpretation. Moreover, the pavement life cycle includes production, construction, usage, and end-of-life (EOL). To properly study the maintenance life-cycle phases, the information will be gathered on the production and construction of the various maintenance measures.

1.4. Research Questions

The following is the primary research question for this thesis assignment:

What are the environmental impacts generated from the maintenance of a pavement system?

Since the main target of this assignment is the maintenance treatments of various types, the assessment of environmental impacts will be one of the main stages of this evaluation. To properly answer the main question, it is important to answer the following questions and their sub-questions. The four stages of LCA —goal & scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation—are the basis for the questions and sub-questions. To assist in addressing the primary research question, the following supporting knowledge questions have been formulated.

1.What is the final goal & scope definition of this study?

2.What are the maintenance techniques considered in this study?

3.For every maintenance treatment, what are the inventory items (elements of system boundary) that should be considered?

4.What are the environmental effects of each maintenance treatment?

1.5. Research Methods

The research methods are directly linked to the questions and sub-questions that were previously described. In the section below the research method for each question and related sub-questions will be briefly described.

It is important to mention that the scope and goal definitions of this study can be influenced by the advice or decision of both the internal supervisors (UT) and external supervisors (company). For the first sub-question, close communication with them helps to properly set and establish the system boundaries, functions, etc. In order to formulate the goal & scope of this particular study the literature review is also done. The second sub-question is addressed in the early stages of the research. The list of predetermined maintenance techniques is presented and proposed to the supervisors for an expert opinion. After the consultation with supervisors and choosing final maintenance treatments, the chosen treatment techniques are studied and analyzed. To answer the third sub-question the main method used is the data collection. At this stage, the inventorying and cataloging of the maintenance treatments takes place. During the data collection stages, the experts (i.e., external supervisor) usually provide the information necessary for LCI and LCIA stages, also the data is collected from the available and relevant sources. The fourth sub-question will require mathematical calculations mainly for the FU conversions. Moreover, the "openLCA" software is used to calculate the environmental impact in terms of different emissions such as GHG, as well as other output variables, but in consultation with supervisors. The CML method is chosen to describe the impact categories. The reason for choosing the CML method is mainly because in the Netherlands MKI (environmental cost indicator) values are given to express the environmental impact of civil works, which are based on the CML methodology. Moreover, since only CML's MKI values are appropriate for environmental consequences, the impact method likewise places limitations on the MKI technique. Finally, for the last sub-question the sensitivity analysis for the output parameters is conducted. The outcome of the research as well as each phase and sub-question will be explained and interpreted.

2. Background

2.1. Life cycle assessment (LCA)

The process of evaluating the environmental impacts connected to a product's life cycle is called life cycle assessment (LCA). This approach starts from the beginning of a process or product and goes until its final stage. It covers and includes the extraction of raw materials, their production, processing, manufacture, distribution, transportation, upkeep, and recycling or disposal. The International Standards Organization (ISO) created the formal structure of Life Cycle Assessment. As seen in Figure 2, it consists of three fundamental stages: inventory analysis, impact assessment, and goal and scope determination.

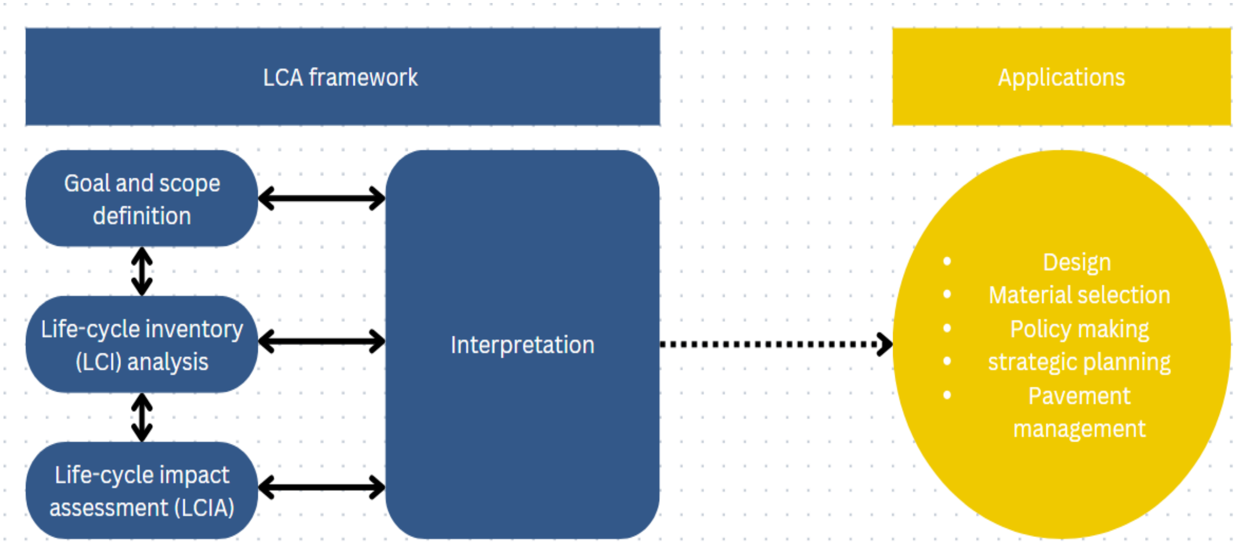


Figure 1. LCA framework as de ISO 14040:2006. (ISO, 2006)

Further, the stages of the LCA framework will be discussed.

2.1.1. Goal and scope

Determining the goal and scope of an LCA is a crucial step. A well-defined objective aid in defining the limitations of the system under research as well as the study's scope. Based on ISO 14040, the aim definition needs to encompass a description of the intended use, the reason behind the execution of the research, the target audience, and the decision about releasing the results publicly or not (ISO, 2006).Key components of LCA research are described during the aim and scope formulation. Here, the pavement system's functional unit (FU), system boundaries, and life-cycle stages are specified. It should be mentioned that establishing the FU is a crucial phase in determining the scope of the project.

2.1.2. Life cycle inventory (LCI)

Data collection and quantification of all important inputs and outputs related to the product or service systems that were outlined in the goal and scope phase are the main tasks of the LCI phase. Examples of inputs are energy, transportation, different kinds of materials, etc. Pollutants and emissions to the air, soil, and water, are only a few examples of system outputs. In order to do this, a process model built on the FU and boundaries of the system is created. The information needed to describe these processes is gathered from various sources, etc.

2.1.3. Life cycle impact assessment (LCIA)

The following step is the LCIA, which entails converting the various environmental effects into the environmental flows that are determined using the LCI data. These are usually stated in many impact categories related to the depletion of resources, as well as the effects on humans and nature (e.g., depletion of water resources, climate change potential, and population ecotoxicity). The purpose and scope of the research are taken into consideration while choosing from among the several sets of effect categories for life cycle assessments, or LCA studies, known as impact assessment techniques (e.g., CML, TRACI, PEF, ReCiPe, etc.).

2.1.4. Interpretation

Finally, the study's findings are shown and discussed during the interpretation phase. The findings are interpreted within the context of the FU and comprise an overview and explanation of the major environmental impacts linked to the pavement system. Based on the outcomes with respect to the objective and scope, conclusions and suggestions are made.

2.2. Pavement life cycle

Figure 1 presents the pavement life cycle. It consists of different phases, mainly: production, construction, use, end of life, and maintenance. Production includes the collection and/or extraction of secondary and raw materials, as well as the transportation and processing of those resources into asphalt. Construction takes into account all of the procedures involved in constructing pavement on-site, such as the usage of equipment/tools, traffic-diversion strategies, and the delivery of asphalt materials to the construction location. The use phase describes the activities that happen on pavements during their service life that affect the environment and are often associated with the pavements' properties.

Pavements require maintenance in order to be long-lasting, reliable, and useful. Maintaining the pavement properly may help keep small issues from growing into bigger ones, increasing its lifespan and lowering total ownership costs, which is an estimate of the costs involved in acquiring, implementing, using, and retiring a product. Pavements that have come to the end of their useful lives and require removal, disposal, and maybe replacement are referred to as being at the end-of-life phase.

In table 1 the definitions of key processes taking place in the production and construction phases displayed in Figure 1 are presented.

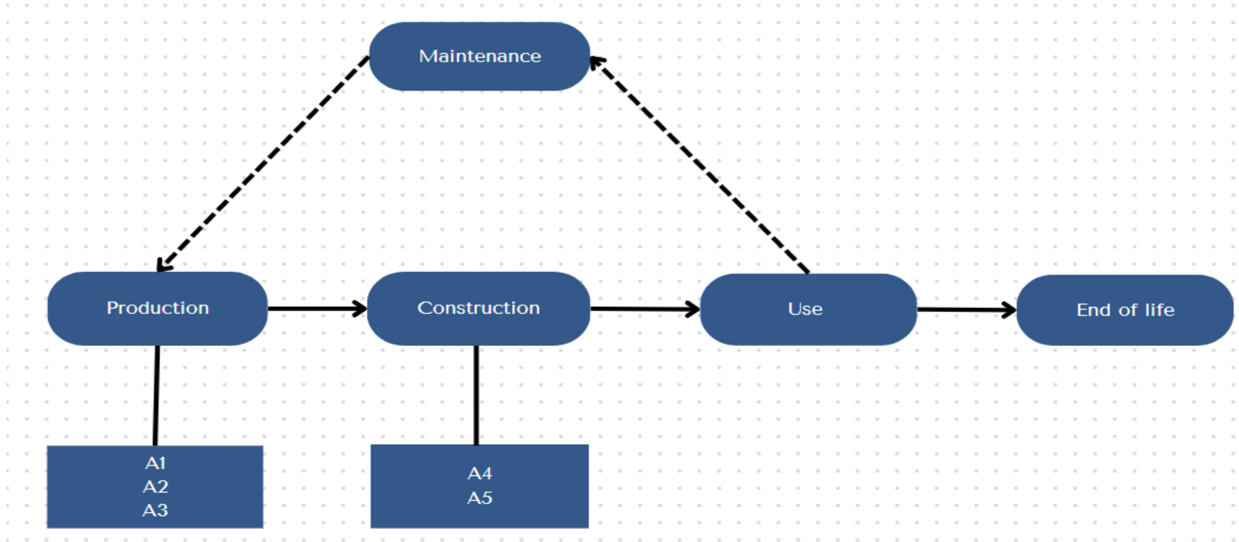


Figure 2. Pavements life cycle phases

A1	Acquisition of raw/secondary materials that compose asphalt mixtures and/or products: RAP(1), bitumen, aggregates, fabrics, fillers, etc.
A2	Transport of materials to the asphalt plant or production facility for production and processing into asphalt products.
A3	Processes applied to the materials to produce the asphalt mixtures, including heating, mixing, etc.
A4	Transport of asphalt materials from plant to construction site. For bituminous surface treatments cold-mixed on site, the transport of raw materials of raw/secondary materials to site is included here.
A5	Maintenance work processes, including, for instance, surface roughening measures, etc.

Table 1. Processes for production and construction

(1) - Asphalt and aggregate-containing pavement materials that have been removed and/or reprocessed are referred to as reclaimed asphalt pavement (RAP). These materials are produced during the reconstruction, resurfacing, or removal of asphalt pavements.

3. Methodology

3.1. Goal and scope definition

Determining the goal and scope of an LCA study in the pavement management is a crucial step. A well-defined objective aids in defining the limitations of the system under research as well as the study's scope. Key components of the LCA study are described during the aim and scope formulation. Here, the pavement system's functional unit (FU), system boundaries, and life-cycle stages are specified. It should also be mentioned that establishing the functional units is a crucial phase in determining the scope of the project.

3.1.1. Purpose and goal of the study

The primary objective of this research is to assess the environmental impact of various maintenance treatments within the context of pavement management in the Netherlands. This research aims to provide valuable insights to enhance the decision-making process concerning the selection of optimal treatments, tailored to specific environmental contexts. To accomplish this objective, a comprehensive comparative analysis of different maintenance techniques is employed to assess their respective environmental performance. Additionally, the usage of the “openLCA” software enables the identification of critical steps, procedures, and stages within each maintenance technique that contribute to environmental impacts.

3.2. Types of maintenance treatments

In this research four different maintenance treatments are analyzed for their environmental effects. Each of them is shortly described in this part of the report:

3.2.1. ZOEAB or ZOEAB+

ZOEAB (+) is a fraying correcting layer with a void of 25%, which is applied to frayed open covering layers. The “+” indicates that in one operation when applying ZOEAB, an additional modified adhesive emulsion with rejuvenating agent is first applied between the ZOAB to be treated and the ZOEAB to be applied. This type of maintenance technique is related to the Bituminous surface treatment and is used to eliminate frayed texture, restore skid resistance, and also restore some noise reduction of the road. ZOEAB is not used within built-up areas (50km/h), a ZOEAB (+) can be used as a temporary measure. On road sectors outside the built-up area (80 km/h) the lifespan of this treatment is approximately 5 years (Crow, 2016). It is applicable to asphalt (AC surf/SMA).

Figure 3. Applying ZOEAB (CROW, 2016).

3.2.2. Emulsion asphalt concrete (EAB)

EAB is a new thin asphalt covering layer that is applied to the existing pavement. EAB consists of a cold-prepared mixture of mineral aggregate (crushed stone, crusher sand and filler) and a bitumen emulsion. With the EAB+ variant, an adhesive layer with a rejuvenating agent is first applied to the existing pavement. This type of treatment is applicable to Asphalt (AC surf/SMA) in order to prevent fraying, slipperiness and eliminate driving marks and transverse unevenness in the covering layer. The application of this treatment extends the lifespan of asphalt pavement by 5-6 years on both types of roads in built up area (50km/h) and outside (80km/h) (Crow, 2016).

Figure 4. The application of EAB (Emulsie Asfaltbeton, n.d.)

3.2.3. Single surface treatment (chip seal)

Because of its easy construction method and inexpensive initial cost, chip seal is a highly preferred pavement maintenance technique (Sarkar et al., 2022). It is usually used on roads with little traffic to slow down the pace of pavement deterioration and postpone the need for expensive restoration projects (Mousa et al., 2020). A single surface treatment involves spraying once with a possibly polymer-modified bitumen emulsion or (polymer-modified) hot-sprayed bitumen. This is immediately covered with a layer of crushed stone. This type of treatment is mainly applicable to asphalt layers (AC surf/SMA). The lifespan of this type of treatment is 4 years in district access road within built-up areas (50km/h) and outside the built-up area (80 km/h) the lifespan is approximately 2 – 3 years (Crow, 2016). Since this report does not consider a specific case, the reference value of 3 (outside built-up area) years of lifespan for single surface treatment will be further used. This maintenance treatment restores the texture and/or roughness of the pavement. The required equipment for this technique is for instance the split spreader, roller, sweeper and spray cart. The further detailed characteristics, considered equipment, etc. will be implemented in the model and discussed.

Figure 5. Application of single surface treatment (Crow, 2016).

3.2.4. Filling cracks

Filling cracks involves repairing cracks in the covering layer with a filling compound. The filling cracks is mainly applicable to asphalt layers in order to prevent the water seepage/penetration of water into the structure (foundation). The lifespan varies for depending on the road dedication. For distributor roads within the built-up area (50km/h) the lifespan is approximately 3 years and outside the built-up area (80 km/h) the lifespan is around 1 year. Due to the lack of the example case, the lifespan is considered to be 1 year thus considering the outside of built-up area. Some of the materials used for this maintenance technique are the bituminous joint filling compound/mastic asphalt, crusher sand, crushed stone. This type of treatment is mainly applicable to asphalt layers (AC surf/SMA).

Figure 6. Crack filling (Crow, 2016).

3.3. System boundaries

In this section, the processes that are included in the system boundaries of the study are illustrated in Figure 7 and described below for each maintenance treatment.

The ZOEAB (+) maintenance treatment needs to follow the A1-A5 steps to be applied on the pavements sector, the short explanations of which can be found in Table 1. Only production and construction are used as models for maintenance procedures, and other modules mainly relate to the rehabilitation techniques same as in the NL-PCR (Van der Kruk et al., 2022). It is important to mention that the materials used for the four considered techniques are taken from the "Factsheets levensduurverlengende technieken voor asfaltverhardingen" (CROW, 2016).

ZOEAB (+)

Firstly, in the phase of A1 the necessary materials are extracted for ZOEAB, and these materials are crushed stone, bitumen which then is emulsified, cement and rejuvenator. Rejuvenator is not really extracted as aromatic oil, which includes carcinogenic pollutants and polycyclic aromatic hydrocarbons (PAH), is the primary ingredient in traditional asphalt rejuvenators. It is also challenging to strike a balance between cost and rejuvenating impact because the petroleum sector remains the upstream source of aromatic oil (Zhao et al., 2022). After the materials are extracted, they don't go to the production site due to the unique considerations of this treatment, because the bitumen surface treatment ZOEAB is mixed cold on site (CROW, 2016). Thus, phase A3 is excluded and consequently there is no phase A2. Instead of A2 we directly consider A4 as all materials are transported to the construction site. At the construction site the module A5 takes place and for this specific equipment is needed. The main considered equipment are mixing installation, road sweeper and mixing spreader. It is important to mention that the maintenance and rehabilitation of the equipment and vehicles such as trucks and commuting of personnel is not considered in this report due to the given time restrictions, although these mentioned units might have an additional environmental contribution.

EAB

The EAB follows a similar process as ZOEAB. Firstly, the raw materials are extracted and after they are transported to the construction site. Thus, the modules A2-A3 are neglected and only A4 and A5 are considered. The required materials are almost the same as for ZOEAB which are crushed stone, bitumen emulsified, cement but the rejuvenator is not used. After the required materials are transported to the construction site the EAB is then cold mixed (CROW, 2016). Then to apply this maintenance treatment the equipment used are the mixing installation and spreader. In contrast to this, for instance, for surface roughening treatments only module A5 is relevant, as the only activity involved in such processes is the use of specialized machines to roughen the surface layer.

Single surface treatment

The initial step in the single surface treatment's process is the raw material extraction. The materials to be extracted are the crushed stone, bitumen, emulsifier, and water. The materials such as bitumen, emulsifier and water are the components used to create the bitumen emulsion that is also used for ZOEAB (+) and EAB. The reason why the bitumen emulsion is used as a material to be extracted for ZOEAB (+) and EAB is because it is cold mixed on site and thus modules A2 – A3 are excluded from the system boundary. For a single surface treatment, the bitumen emulsion is hot mixed and thus it is prepared in special machine (GlobeCore, n.d.). I tis assumed that the modules A2-A3 are excluded from the study. Because the polymer modified bitumen is hot sprayed on site (CROW, 2016). After the necessary materials are manufactured the next process is transportation to construction site (A4) and then the last stage is the construction (A5). During the construction phase the required equipment are spreader, tire roller, road sweeper and spray cart.

Filling cracks

The filling cracks is a simpler maintenance technique compared to other 3 considered in this report. However, due to the wide range of environmental characteristics, severity of damage and material used, choosing the right materials for crack filling is essential. For example, using an ultrathin white topping overlay constructed of traditional cement concrete materials may cause the overlay and underlying concrete pavement to deform incompatible, resulting in cracks (Zhang et al., 2015). A wide variety of products, such as rubber modified asphalt, cementitious composites, and cement-emulsified asphalt mortar, are utilized in pavement repair to fill cracks. To maintain pavement quality and efficiency, these materials must be carefully chosen, and the best procedures should be followed while applying them to guarantee long-term efficacy. Following the recommendations of NL-PCR (Van der Kruk et al., 2022) and factsheets (CROW, 2016) the materials to be extracted are the crushed stone, crushed sand and bitumen. Crack-filling techniques might be cold-applied emulsion-based solutions or hot-applied rubber or polymer asphalts (State of California Department of Transportation, n.d.). The materials for this maintenance treatment are put into the stirring kettle and then after heating and mixing the substance is applied. The modules A2 and A3 are excluded for this maintenance technique based on the equipment and material choice. However, it is important to mention that composition of other A1 – A5 modules are possible.

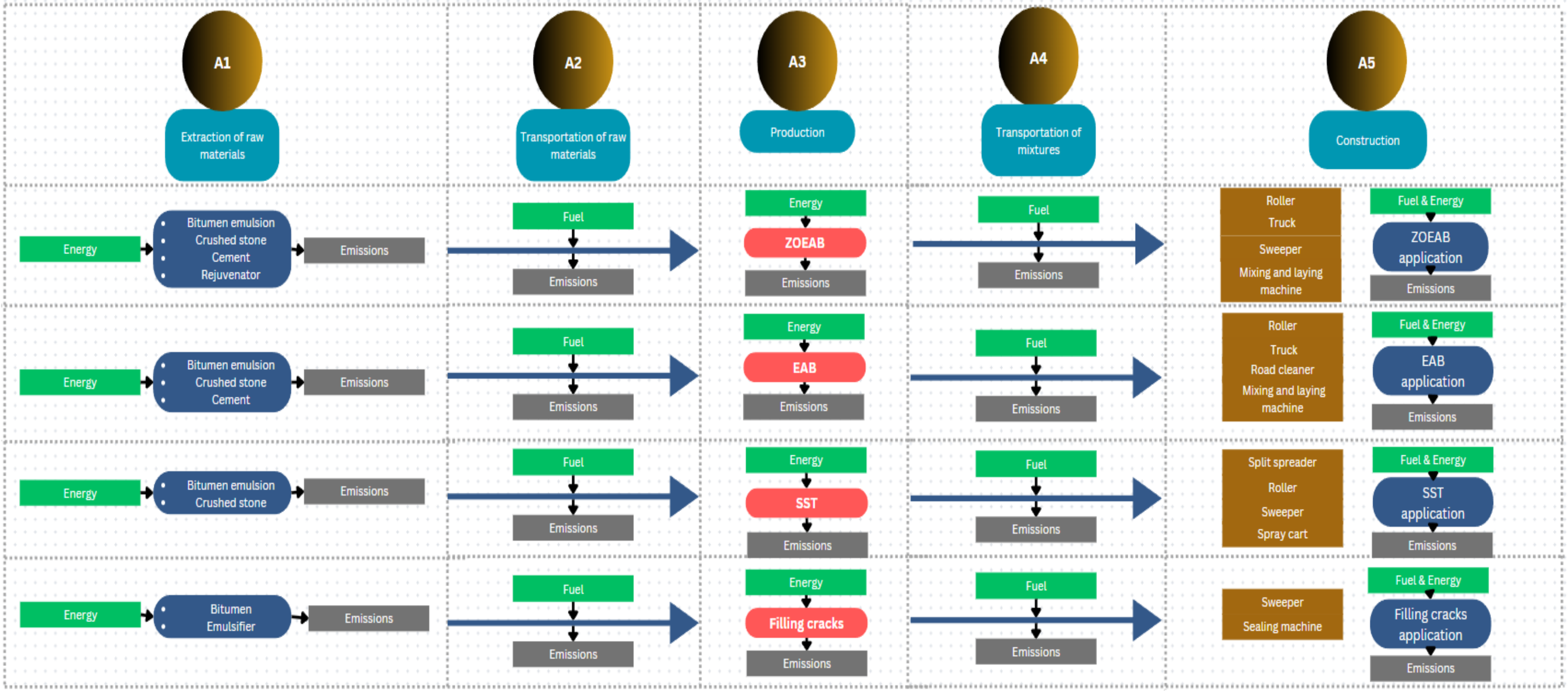


Figure 7. System boundary of this study

3.4. Functional unit

The FU outlines the methodology for quantifying the product's designated functions or performance attributes. According to ISO 14044, the main goal of the FU in LCA studies is to offer a standard by which material flows, LCA outcomes, and any other information are normalized to create data expressed consistently. This makes it possible to compare with other product systems that have been determined to satisfy the same functional need. A FU that enables the environmental performance of each maintenance treatment to be compared with one another must be chosen due to the comparative nature of this study.

The project's dimensions, including project length (kilometers or miles), lane length (lane miles or kilometers), capacity (material), etc., are taken into consideration by physical or geometrical FU. This is the FU that is utilized most frequently in the literature. Applying this FU can be appropriate depending on the study's objectives. Typical instances include the following: interpreting life-cycle stage contribution, reporting total GHG emissions or energy consumption given to a pavement system or network of pavements, etc. (Ziyadi et al., 2017).

There are three FUs defined for the LCA framework: default, alternative and comparative (Vargas Farias, 2023). With the help of these FUs it is possible to estimate the environmental effects more precisely as the masses of mixtures, travel distances and work done are normalized per 1 km which allows the fair comparison of environmental effects.

3.4.1. Classification of the FUs.

3.4.1.1. DEFAULT FU

According to Harvey et al. (2016), the default FU definition is in line with the traditional FU definition norms. This means that it is frequently described as a roadway portion with a given length (typically 1 km), a particular number of lanes with a provided dimension, specific functional performance characteristics, and over a predetermined analysis period (Bressi et al., 2022; Chong & Wang, 2017; Santos et al., 2022; Vega et al., 2020; Zheng et al., 2020). The definition of the FU for maintenance techniques differs from that for rehabilitation techniques. Depth is only taken into account in bituminous surface treatments measurements involving the employment of EAB, where X is the measured thickness of the bituminous layer used (Vargas Farias, 2023).

This study uses the following default FU: ***1km of a lane-/carriageway-wide, maintenance measure with a depth of X mm.***

3.4.1.2. ALTERNATIVE FU

For a new asphalt layer, the alternative FU is weight-based and satisfies the NL-PCR FU requirements (Van der Kruk et al., 2022). Determining a weight-based FU can make modeling jobs easier, as most LCI input quantities for asphalt are expressed in tons. It is important to mention that for instance the surface roughening treatments cannot be expressed in terms of alternative FU.

This framework uses the following alternative FU: ***1ton of lane-/carriageway-wide, maintenance measure with a depth of X mm.*** (Vargas Farias, 2023)

The conversion for the ZOEAB and EAB is applied in the following way:

Equation 2. main FU to alternative FU (ZOEAB+): **ZOEAB 1** $km\ of$ **maintenance** $measure$ **= (1000) ×** (Y) **×** $(ZOEAB$ **(+)** $quantity)$ $ton\ of$ **maintenance measure** (Vargas Farias, 2023)

Equation 3. From main FU to alternative FU (EAB): **1 $km\ of$ maintenance $measure$ = (1000) × (X) × (Y) × ($EAB\ Density$) $ton\ of$ maintenance measure** (Vargas Farias, 2023)

Bituminous surface treatment	Quantity or density
ZOEAB (+)	20 kg/m2
EAB	2500 kg/m3

Table 2. Quantities and densities for bst. (Vargas Farias, 2023)

3.4.1.3. Comparative FU

An area-based FU normalized according to the analysis period is the comparative FU. Comparing, for instance, lane-wide and carriageway-wide maintenance measures is made possible by evaluating the measures in square meters (Vargas Farias, 2023)

With regard to maintenance treatments, the standardized FU is: **1m2 of lane-wide, maintenance measure with a depth of X mm and an application width of Y m over a plain and straight carriageway segment with a road configuration Z of an asphalt pavement**.

The equation employed in this framework from default FU to comparative FU is the: 1 $km\ of$ maintenance measure = Y × 1000 $m^2\ of$ maintenance measure (Vargas Farias, 2023)

3.5. Life-cycle inventory (LCI) analysis

In this part of the report the life-cycle inventory analysis will be discussed. For each maintenance treatment the input values are discussed according to the appropriate module.

3.5.1. Asphalt mixtures

The ZOEAB (+), EAB, single surface treatment, crack filling are applicable to certain asphalt types. In this section the properties of these asphalt mixtures are presented and discussed. According to CROW (2016) the ZOEAB (+) is applicable to the open coatings (ZOAB, two-layer ZOAB, Thin Noise-Reducing Coatings (DGD)). The other treatments mainly EAB, single surface treatment and filling cracks are applicable to the Asphalt (AC surf/SMA). The properties of these types of asphalt mixtures can be found in the table below.

Material(kg)	AC Surf	AC Surf, 30% RAP	AC Surf, modified bitumen	AC Surf, modified bitumen, 30% RAP	ZOAB	SMA 8-11	SMA 8-11, modified bitumen	DGD
Drip-resistant material	-	-	-	-	-	3	3	2.4
Asphalt granulate(RAP)	-	294	-	294	-	-	-	-
Bitumen 40/60	58	46	-	-	-	-	-	-
Bitumen 70/100	-	-	-	-	45	68	-	-

Mod. bitumen 70/100	-	-	58	46	-	-	68	68
Crushed sand	279	258	279	258	43	75	75	53.9
Own material	16	9	16	9	-	91	91	10
Natural sand	92	-	92	-	-	73	73	45.5
Crushed stone 2	506	366	506	366	-	676	676	750
Crushed stone 3	-	-	-	-	860	-	-	-
Medium filler	-	-	-	-	52	-	-	-
Weak filler	49	27	49	27	-	14	14	70.7

Table 3. Contents of per kg for 1ton of asphalt mixed material (Van der Kruk et al., (2022).

River stones are excavated and broken to create crushed stone sort 2, whereas exploding materials are used at a quarry to produce crushed stone type 3.

3.5.2. ZOEAB (+) and EAB

The raw materials to be extracted for ZOEAB (+) and EAB maintenance treatments that are included in the system boundary are discussed in this module A1.

Material (kg)	ZOEAB	ZOEAB+	EAB
Crushed stone	880	880	880
Bitumen emulsion	100	100	100
Cement (Portland)	15	15	15
Rejuvenator, wax	-	Unknown	-
Rejuvenator, bio-based	-	Unknown	-
Rejuvenator, unspecified	-	Unknown	-

Table 4. Material composition for 1 ton of BST. (Van der Kruk et al., 2022).

The Table 4 provides the input values for further environmental calculations. These values are the reference values for a composition of one ton of ZOEAB (+) maintenance treatment. This thesis assignment focuses on the ZOEAB treatment. As far as the author is aware, little detail on the chemical structure of the "+ layer" in ZOEAB (+) is publicly available. It is believed to consist of a bitumen emulsion and a rejuvenator; however, the exact amounts are unclear. The rejuvenator may be omitted from the study if bitumen emulsion and rejuvenator ratios in ZOEAB (+) are unknown. If such data is accessible, the framework has to be modified to account for the real values. The NL-PCR does offer identical data for all other components, nevertheless, it is assumed that the integration of the adhesive layer doesn't appear in the system boundaries of the maintenance measure. The bitumen emulsion consists of 65% bitumen, 34% water and 1% of emulsifier that is cationic.

The module A4 stands for the transportation of asphalt mixtures from the production site to the construction site A5. Since the EAB and ZOEAB (+) are cold mixed on the construction site the previous 2 modules A2-A3 are excluded from the system boundary.

The NL-PCR suggests that each instance should have a separate model for the raw material transportation for ZOEA B (+) and EAB.

Table 5 lists the necessary reference transportation distances for ZOEAB (+). Conversely, for EAB, the project's scale determines the transportation needs.

Small projects (less than 1500 m2) should have transportation covered in Module A2 with an extra 100 km per axle in Module A4. Large projects (bigger than 1500 m2) require an extra 4 km of post-transport per axle to the usual distances from Table 5 when calculating transport in Module A4. An EAB project's classification as small or big is left to the executor's judgment because only limited data is available. It is assumed that this thesis assignment considers the value for the large projects (bigger than1500m2) and thus it follows that EAB excludes modules A2-A3. It is important to mention that because no specific example is considered the values are assumed, however many different variants are possible (i.e. small project, with specific provided data) (Vargas Farias, 2023).

Material	Truck (km)	Inland vessel(km)	Sea vessel (km)
Bitumen	89	-	-
Bitumen emulsion	200	-	-
Cement	100	-	-
Emulsifiers	100	-	-
Crushed stone3	-	53	933
Rejuvenator, wax	500	-	-
Rejuvenator, bio-based	150	-	-
Rejuvenator, unspecified	150	-	-

Table 5. Transportation distance(km) of raw materials for bituminous surface treatment (Van der Kruk et al., 2022).

The A5 module incorporates the fuel and energy consumption of the equipment needed for bituminous surface treatment. As opposed to the ICO's (Department of Conservation of Structure and Maintenance of the RWS, part of GPO) perspective of the building process, the definition of A5 in this system mostly conforms with the norms of the NL-PCR. The reason for this is that the assumptions made by ICO are mostly relevant for cost computations, rather than assessments of environmental effect. The reference data for this module were obtained from the NL-PCR (Van der Kruk et al., 2022). The considered equipment can be found in the system boundary or the Table 6.

Equipment	Diesel consumption (liter/m2)	Diesel consumption (liter/m2)
	ZOEAB (+)	**EAB**
Roller	0.010	0.010
Surface cleaner	0.018	0.018
Mixing and laying machine	0.020	0.020
Truck	0.01	0.01

Table 6. Energy use of equipment used in BST maintenance operations for construction and cold-mixing procedures (Van der Kruk et al., 2022).

3.5.3. Single surface treatment

The materials that are needed to be extracted for the single surface treatment are the bitumen emulsion and crushed stone. According to the Van der Kruk et al. (2022) the materials used for a bitumen emulsion are bitumen (65%), water (34%) and of emulsifier that is cationic (1%).

Nominal size of aggregate (mm)	Quantity of aggregate kg/m2	Quantity of emulsion l/m2
9.5 - 19	22–27	1.8–2.3
4.5 - 12.5	14–16	1.4–2.0
2.36 - 9.5	11–14	0.9–1.6
1.18 - 4.75	8–11	0.7–0.9

Table 7. Quantities of asphalt and aggregate for single chip seal application (FHWA, 1992).

From the Table 7 it can be assumed that for single surface treatment for nominal size of aggregate of 8.5 mm the quantity of aggregate will be 15kg/m2 and emulsion will be 1.7 l/m2. The density of bitumen emulsion is approximately 1.02 kg/m^2 and thus the amount of emulsion is 1.734 kg/m^2. The total application quantity of mixture is 16.734 kg/m^2. These amounts are assumed for a squared meter while for ZOEAB (+) and EAB considered unit is per ton. Due to the further comparison of maintenance treatments based on the FU the calculation of environmental impact will be done accordingly. The considered aggregate for this framework will be the crushed stone type 3.

The transportation distances used for further modelling can be found in the table below:

Material	Truck (km)	Inland vessel(km)
Bitumen emulsion	200	-
Crushed stone3	-	53

Table 8. Transport distance in km of raw materials (Van der Kruk et al., 2022).

The transport distances are considered for the crushed stone (type 3) and bitumen emulsion from the raw material extraction to the construction site directly. It is assumed that the mixture for a single surface treatment is cold applied based on the

The equipment involved in this process with their fuel and energy consumption values can be found in the table below:

Equipment	Diesel consumption (liter/m2)
Split spreader	0.060
Spray cart	0.001
Roller	0.010
Road cleaner	0.020

Table 9. Machinery and equipment for sst.

The values are obtained from the NL-PCR (Van der Kruk et al., 2022). In contrast to the ICO's interpretation of the building process, the concept of A5 in this framework mostly conforms with NL-PCR criteria. This is due to the fact that the assumptions made by ICO are mostly relevant to cost estimates rather than assessments of the environmental effect.

3.5.4. Crack filling

In module A1 the materials needed to be extracted for the crack filling maintenance treatment are discussed.

Due to the lack of the specific knowledge/data and large variability of materials and techniques employed in a "crack filling" maintenance technique it is decided to make assumptions according to the other LCA studies for "crack filling and sealing maintenance techniques". In the study conducted by Wang and Gangaram (2014) they considered the polymer modified bitumen emulsion as the main sealing material for this maintenance treatment. The other study conducted by Mazumder et al. (2018) also considers the polymer modified bitumen as a main component to fill the cracks. Now, in order to quantify the necessary amount of sealant per km or ton the following assumptions are made. According to the study by Mazumder et al. (2018) the sealing length per kilometer of road was calculated to be 450 meters (density = 0.45). A design profile of 3.2 mm (width) by 6.4 (depth) mm was found to be the average for filling cracks. This resulted in 11.635 kg/km of required material including the net application rate with the 15% waste of material.

In this part the necessary transportation distances are discussed. According to the table of Van der Kruk et al. (2022) with fixed single journey distances the emulsifier brought from abroad has a distance by truck of 1000 km. The polymer in this study is assumed to be taken from abroad. The polymer modified bitumen is a regular bitumen with an addition of polymer which provides increased cohesion, resistance to fatigue and higher strength (RAHA Bitumen Co., 2017). It is important to mention that polymer emulsifier can be found in the Netherlands and that the following considered values are assumptions in this study according to the reference values from appropriate documents for the Dutch context. Thus, the final transportation distances of raw materials to the construction site can be found in the Table 10. The different amounts of polymer present in polymer-modified bitumen emulsions greatly affect its characteristics. Depending on the type of polymer used and the desired properties of the finished product, the amount of polymer in polymer-modified bitumen can vary from 4% to 9%

by weight of bitumen (Mersha & Sendekie, 2022). In this study it is assumed that the content of polymer is 5% and thus this amount is transported.

Material	Truck (km)
Bitumen	89
Emulsifier	1000

Table 10. Transport distance in km of raw materials (Van der Kruk et al., 2022).

The equipment used for the crack filling are the vacuum sweeper and the sealing machine. Firstly, the pavement is needed to be prepared for further application of treatment. For this, the sweeping machine will be used to clean the cracks and the pavement. After the surface of pavement and the cracks are cleaned the filling component is applied to the damaged parts of the asphalt. The mixture is cold applied.

Equipment	Diesel consumption (liter/m²)	Power class
Sweeper vacuum	0.015	130-560 kW
Sealing machine	0.020	-

Table 11. Flat rate machines and energy consumption to treat 1 m² of asphalt surface (Van der Kruk et. al., 2022).

As it was mentioned earlier in this report the human labor is not considered in this study. During all 5 phases from A1 - A5 the human labor can also have environmental consequences, however it is excluded from this study. There might be other required equipment for all 4 maintenance treatments that this study considers. The equipment, for instance are mop, watering can, towing box, etc. but their implementation doesn't have any environmental consequences. Their production indeed has an environmental impact, but this study doesn't consider the life cycle of the equipment employed in the pavement management.

3.5.5. Physical boundaries and conversion

One of the main aspects to properly calculate the environmental impacts in pavement management is to consider the road profile. As it was previously mentioned, the FU requires the pavement characteristics.

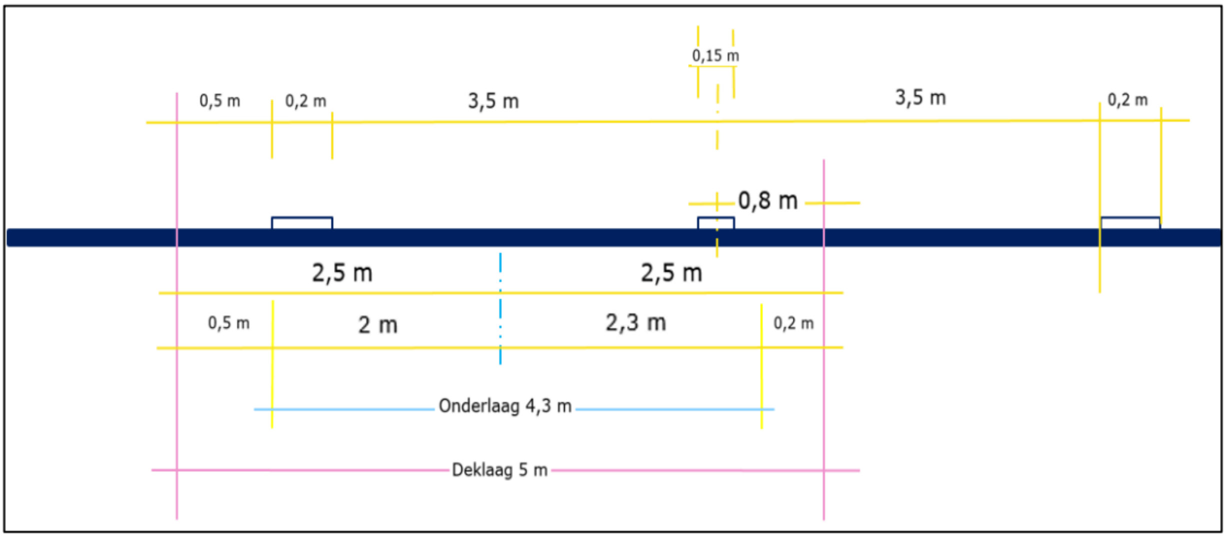


Figure 8. Lane application widths for road carriageways of two lanes + hard shoulder. GPO (2022).

This figure shows the road configuration with 2 lanes and shoulders. Application widths for maintenance treatments are just slightly smaller than the real lane width of 3.5 meters. Applications of BST ZOEAB treatments are made at 3.4 m breadth and since EAB is applied to longitudinal ruts, its application breadth is twice as wide as the wheel pathways (2 x 0.75 m).

Event	Type	Application	Pavement configuration	Application Width (m)	Depth (mm)
A	ZOEAB	Lane-wide	2 or more lanes + shoulder	3.4	-
B	EAB	Lane-wide	2 or more lanes + shoulder	2 x 0.75	20
C	Single surface treatment	Lane-wide	2 or more lanes + shoulder	3.4	-
D	Crack filling	Lane-wide	2 or more lanes + shoulder	3.4	-

Table 12. Road characteristics per treatment (Vargas, A. (2023)).

In the study of the Mazumder et al. (2018) the considered road width is 13 m where 2 traffic lanes of 3.75 m + inner shoulder of 1 m are used. Based on this information it is also decided to make an assumption for both single surface treatment and crack filling that the application width is 3.4 m. Since the application of crack filling is completely different from other 3 treatments the density of 450 meters per kilometer is considered as not the whole surface is covered by the sealant. In order to build the model in "openLCA" software it is necessary to make proper conversions. Thus, Table 13 provides the energy content (in MJ) of electricity, natural gas, and diesel.

Energy source	Energy content
Diesel	35.8 MJ/L
Electricity	3.6 MJ/kWh
Natural gas	31.65 MJ/Nm3

Table 13. Unit conversion rates. (Van der Kruk et al., 2022).

Module	Material	Process	Empirical quantity source	LCI database
A1	Crushed stone 3	Europe's quarry-produced crushed stone (excluding transport to Netherlands)	NL-PCR	Ecoinvent 3.3

	Bitumen emulsion	65% Bitumen adhesive compound, hot {GLO} | market for | Cut-off, U; 34% Tap water {RER}|| market for | Cut-off, U; 1% Emulsifier (see below)	NL-PCR	Ecoinvent 3.3
	Emulsifier	Esterquat {RER}|market for | Cut-off, U	NL-PCR	Ecoinvent 3.3
	Cement	Cement, Portland {Europe without Switzerland} | market for | Cut-off, U}	NL-PCR	Ecoinvent 3.3
A4				
	Truck	Transport, freight, lorry, unspecified {GLO} | market for | Cut-off, U	NL-PCR	Ecoinvent 3.3
	Transport 1, land	Transport, freight, lorry >32 metric ton, EURO 5 {RER}| Cut-off, U	NL-PCR	Ecoinvent 3.3
	Transport 2, land	Transport, freight, lorry >32 metric ton, EURO 6 {RER}| Cut-off, U	NL-PCR	Ecoinvent 3.3
	Inland vessel	Transport, freight, inland waterways, barge {GLO} | market for | Cut-off, U	NL-PCR	Ecoinvent 3.3
	sea vessel	Transport, freight, sea, transoceanic ship {GLO} | market for | Cut-off, U	NL-PCR	Ecoinvent 3.3
A5				
	Machinery: asphalt paving set	Diesel, burned in building machine {GLO} | Cut-off, U (with modified emissions); production of diesel based on Diesel, low sulfur {Europe without Switzerland} | Market for | Cut-off, U)	NL-PCR	Ecoinvent 3.3
	Machinery: BST	Diesel, burned in building machine {GLO} | Cut-off, U	NL-PCR	Ecoinvent 3.3
	Tack coat	Tack coat life cycle	NL-PCR	Ecoinvent 3.3
	Machinery: cleaning set	machine operation, diesel, < 18.64 kW, low load factor	NL-PCR	Ecoinvent 3.3

Table 14. Process map used in LCA framework.

3.5.6. Data sources and data quality goals

In order to maintain openness and reliability, the goal was to gather data as much as possible from authorized and licensed databases and reliable published sources and organizations. In case of this thesis assignment there was no possibility to collect site specific data due to the unavailability of the companies at the moment of the execution of assignment. However, the site-specific data might not be feasible under specific circumstances. It is crucial to mention that the documents used to collect data were taken appropriately for Dutch context and reference values are taken accordingly for Dutch pavement management. Given this, it was inevitable to employ secondary data. Furthermore, procedures deemed less significant/ crucial, or too difficult or time-consuming to fully analyze were assigned generic data. The data gathered and used in this assignment can be further found in detail in the section of LCI.

Also, the formulas from the NL-PCR (Van der Kruk et al., 2022) are used in the report. By creating particular calculation criteria and the general Determination Method calculation rules, the NL-PCR seeks to compare the environmental performance of asphalt mixes as employed in hydraulic and road building in the Netherlands. The NL-PCR adheres to the same structure as the Determination Method based on ISO 14040-14044 and EN15804+A2.

3.6. Impact categories

To estimate the possible environmental effects of industrial goods, LCA studies frequently employ the CML (Centrum voor Milieukunde Leiden) impact assessment approach (Amouri et al., 2023). It is a crucial step in the LCA study to choose the impact assessment method. To analyze environmental consequences in LCA studies, a variety of impact assessment techniques are provided and accessible. It is important to mention again that the study aims at the Dutch context. Thus, the impact evaluation strategies outlined in the Determination approach were aligned with the CML impact approach; however, starting in 2021, they are aligned with the PEF methodology. Table 15 presents the list of impact categories covered by the CML impact method “CML (baseline) [v4.4, January 2015]”. Here an indicator and unit are provided for each impact category.

Impact category	Indicator	Unit
Depletion of abiotic raw materials (excluding fossil energy carriers) (abiotic depletion)	ADP -elements	kg Sb-eq
Depletion of fossil energy carriers (abiotic depletion – fossil fuels)	ADP - fuel	kg Sb-eq.
Climate change (global warming)	GWP-100j	kg CO2-eq.
Ozone layer depletion	ODP	kg CFK-11-eq.
Photochemical oxidant formation	POCP	kg C2H4-eq.
Acidification	EP	mol SO2-eq.

Eutrophication	AP	kg PO4-eq.
Human toxicity	HTP	kg 1,4-DCB-eq
Ecotoxicological effects, aquatic (freshwater)	FAETP	kg 1,4-DCB-eq.
Ecotoxicological effects, aquatic (marine)	MAETP	kg 1,4-DCB-eq.
Ecotoxicological effects, terrestrial	TETP	kg 1,4-DCB-eq.

Table 15. Impact categories EN15804 + A1 according to the Determination Method (valid until 1 January 2021).

The “openLCA” software was used as the main calculation tool for the environmental impacts of the chosen maintenance treatments. The “ecoinvent 3.3” is used as the background database in the “openLCA” for this study.

4. Results and discussion

In this section the results of the LCA study for the maintenance treatments are discussed and compared.

4.1. Environmental impact assessment per maintenance treatment

ZOEAB

The Figure 9 provides the contribution ratios to the environmental impacts of the ZOEAB maintenance treatment. As it can be noticed the phase “A-1” has the highest scores on all 11 impact categories of almost 80% and above. This can be explained by the fact that considering the FU of 1 km the calculated amount of ZOEAB treatment for a road with a width of 3.4 m in this study is 68 tons. According to the content ratio described in the LCI stage the 60112 kg of crushed stone, 1020 kg of cement and 6868kg of bitumen emulsion are used. Based on this amount of material it is not surprising that the outcome for contribution of raw material extraction is as follows. It can be noticed in Figure 9 that the transportation has the minimal environmental impact. It should be mentioned that for the transportation distances the reference values were used as this study doesn’t consider any specific case. Moreover, in the “openLCA” model the transporting trucks were chosen from “EURO 5” and “EURO 6” categories that make them energy efficient and meet modern environmental requirements. Also, since in this study the module “A-2” is excluded, this has an influence on the final result of the environmental score of the overall transportation module. This all can explain why the result for the 11 impact categories of transportation is that low compared to other modules for this maintenance treatment. The last module is “A-5” and its environmental impacts according to CML categories are much higher than the module “A-4” however significantly less than the module “A-1”. The special equipment employed to apply the bituminous surface treatment have their own diesel consumption rate that differs from the transporting vehicles consumption rate. The assumed/estimated area (3400m^2) to be treated according to the FU and total diesel consumption rate of this special equipment shows that the result takes significant values for instance in “eutrophication” and “climate change” but not that significant for “freshwater aquatic ecotoxicity”, etc.

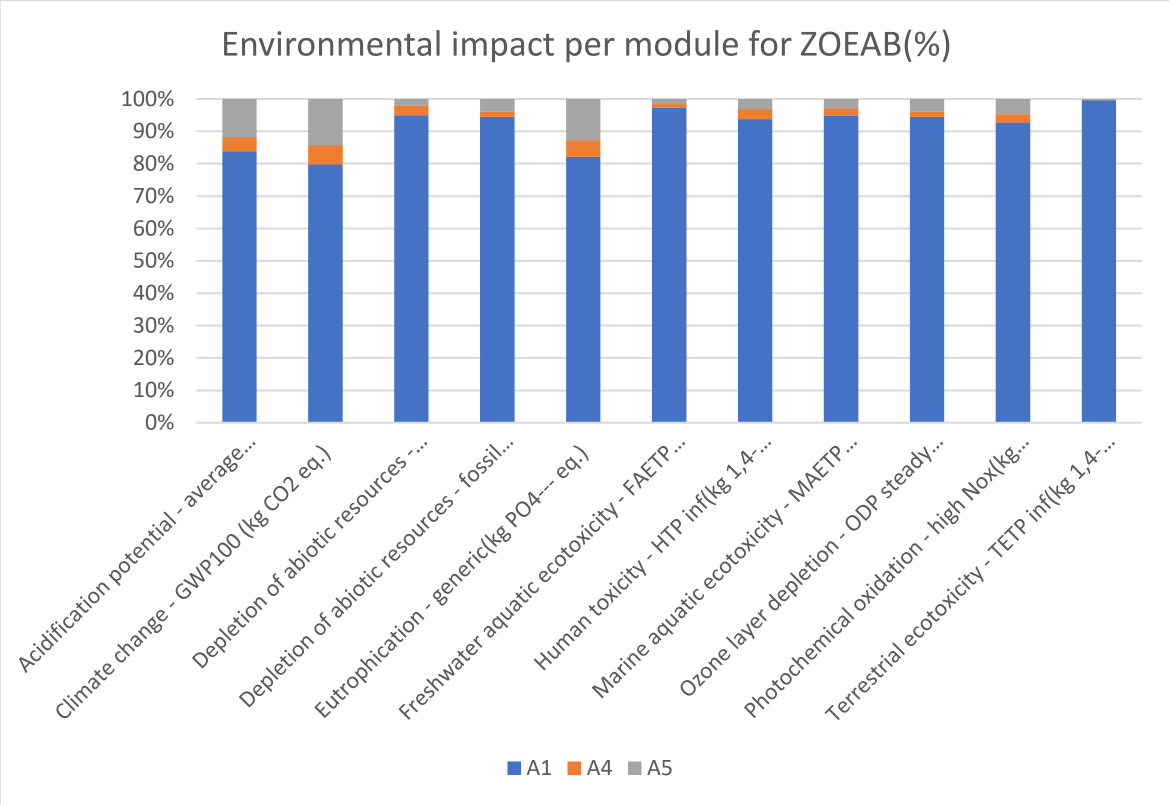


Figure 9. ZOEAB environmental impact ratios per phase

EAB

The result for environmental impact of "EAB" maintenance treatment can be found in Figure 10. It is important to mention that "ZOEAB" and "EAB" are almost similar to each other. However, the difference can be spotted instantly after comparing the outcomes of both techniques. Firstly, the raw material extraction shows interesting results as its impact is higher on almost all 11 categories compared to "ZOEAB". The total amount of required mixture is calculated to be 75 tons for 1 km of pavement with the application width of 1.5 m and 0.02 mm of depth. This is more than what is needed for "ZOEAB" even though their materials are the same in this study (rejuvenator ration is unknown). That is why the outcome for module "A-1" of "EAB" treatment is not surprising. The transportation distances and their assumptions remain the same, however since the number of materials to be transported is higher thus the environmental impact of transportation is higher respectively. The transportation of raw materials is assumed to the construction site directly once. During the application phase in module "A-5" it can be seen that the overall environmental impact ratio is less than what is in the "A-5" of "ZOEAB" compared to "A-1". The area of application for "EAB" is different which is 1500m^2 and thus the energy consumption of machinery is lower compared to the "ZOEAB". The calculated diesel consumption and conversion rates from diesel liters to joules can be found in the Appendix 3. It is assumed from the outcome that the process of raw material extraction is much more complicated and that it requires a lot more energy in contrast to other two modules.

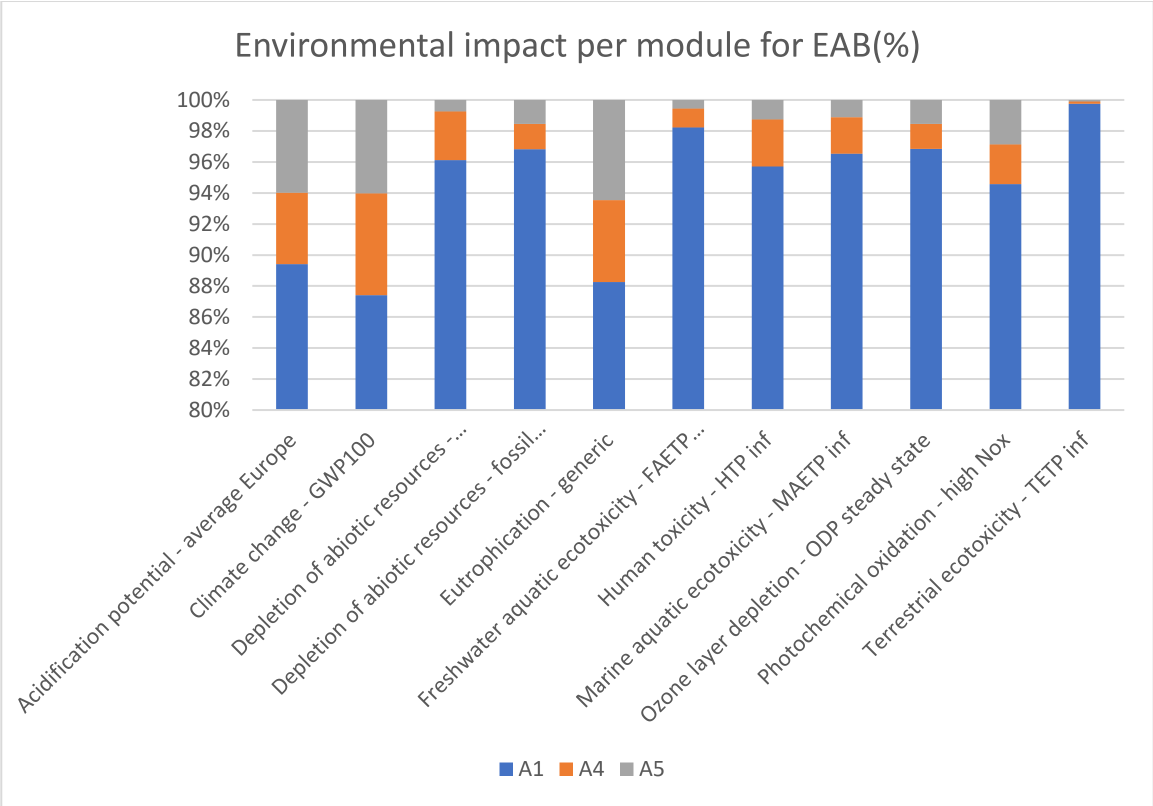


Figure 10. EAB environmental impact ratios per phase.

Single surface treatment

In Figure 11 the results for the ratio of environmental impacts can be found. The first thing that can be noticed when looking at the tables is that the highest percentage of environmental impacts belongs to the phase “A-1”. The total required amount for maintenance of 1 km of pavement is calculated to be 56.895 tons. This value is less than compared to the needed amounts for “ZOEAB” and “EAB”. And thus, the environmental contribution of “A-1” for “Single surface treatment” is slightly less than the contribution of “ZOEAB” and “EAB”, but still raw material extraction phase is having the highest influence on environmental impact among other modules. It seems like the transportation of raw materials to construction site (module “A-4”) has a little contribution but there is a reason for it. Since there are only 2 materials involved to create a mixture the transportation distance is considered for 2 materials respectively. Thus, the total transportation distance for single surface treatment and the required amount of mixture for 1 km is less than it is for “ZOEAB” and “EAB” and for this reason the environmental impact is lower. During the application phase “A-5” it was estimated that the total energy consumption of machinery is 11076.52 MJ. This value is significantly higher than energy consumption of machinery in “ZOEAB” and “EAB”. This is due to the variety of equipment employed to apply the single surface maintenance treatment. The outcome for environmental impact shows the expected ratios per module.

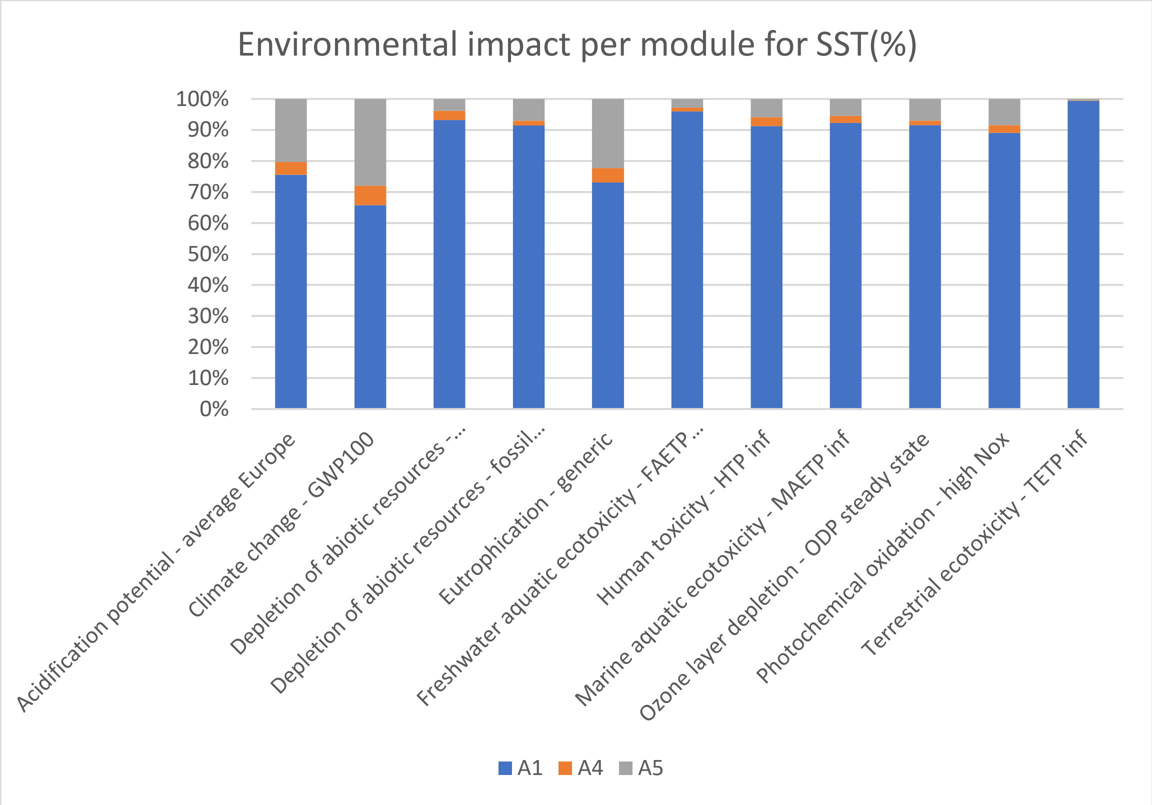


Figure 11. Single surface treatment environmental impact ratios per phase.

Crack filling

The crack filling maintenance treatment is different from the previous 3 treatments in all aspects starting with the material choice and ending with the application process. In Figure 13 there can be found the ratios for environmental impacts per module. Bitumen, a byproduct of the processing of petroleum, is included in asphalt pavement and maintenance treatments. Due to the energy and resource-intensive nature of its manufacture, there may be a substantial environmental cost (de Vos-Effting et al., 2018). Since there is only one material considered (bitumen) for this treatment the raw material extraction phase has minor contribution to the overall environmental impact compared to other LCA phases. The production of the polymer couldn't be estimated and thus in the model the polymer modified bitumen seal is chosen to be produced in module "A-1". However, for the transportation it was considered that both materials are transported separately, it is assumed that there is no difference between preparing the mixture on site or during the raw material extraction. The module "A-4" has no visible impact because for 1 km the required amount is 11.635 kg. This amount is too small compared to the amounts needed for other 3 maintenance treatments. The polymer is assumed to be taken from abroad which makes the reference travel distance by sea much longer than it would be taken inside the Netherlands, the results can be found in Appendix B. Almost in all impact categories for crack filling the major impact belongs to the construction phase "A-5". The construction phase of crack filling has the lowest energy consumption compared to other maintenance treatments in this study. The ratios between phases of crack filling make a logical difference. The real energy usage of construction equipment, however, may differ from the figures reported in this study. This is mostly because actual and site-specific data are not used for determining equipment running hours; instead, theoretical values are employed. Moreover, contractors could employ various tools for the job, work more efficiently or less efficiently, utilize different equipment than what was examined in this study, etc. (de Vos-Effting et al., 2018).

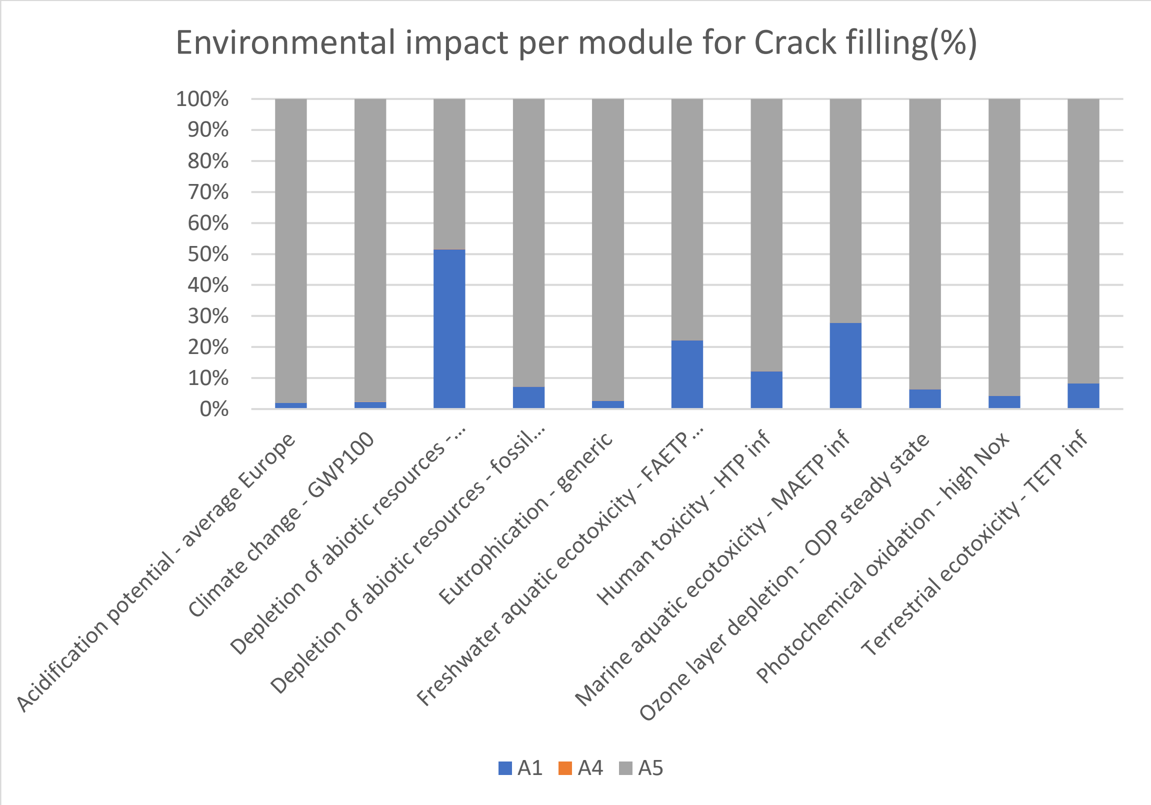


Figure 12. Crack filling environmental impact ratios per phase.

4.2. Comparison of environmental impacts

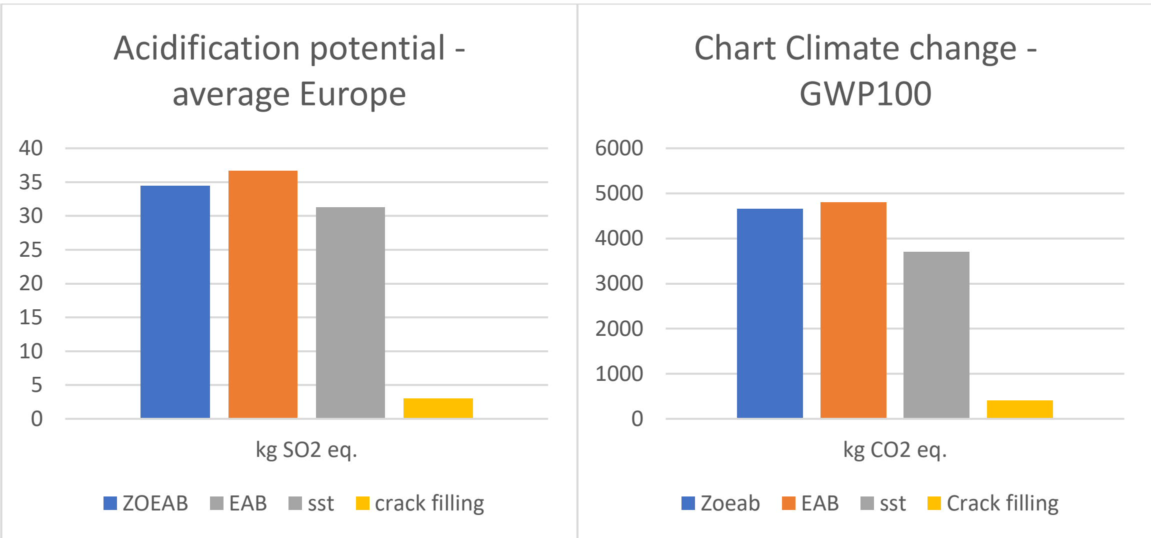
In this section the environmental impacts of the 4 maintenance techniques are compared to each other. By looking at Figure 13 the complete comparison of environmental scores for each maintenance treatment for each impact category can be seen. The “EAB” maintenance treatment has the highest score in all 11 impact categories of CML. This can be explained by the fact that the required material is 75 tons per 1 km, and this amount is largest among all 4 maintenance techniques. The most contributing module for “EAB” is the raw material extraction, as previously explained. The crack filling technique shows the lowest environmental impact. The scores for each impact category of crack filling are dramatically lower than the scores of other treatments. As it could be noticed from the results the highest contributing module among others is the raw material extraction. The amount of material to be applied for 1 km for crack filling is 11.635 kg, and this value is much lower than what other treatments employ. The single surface treatment has a lower environmental impact compared to the ZOEAB and EAB, however still has tremendously higher environmental effect compared to crack filling. In this study the considered cracks for crack filling maintenance technique were small and the application approach is different from other treatments. ZOEAB and single surface treatment cover the whole single lane surface with a width of 3.4 meters. EAB covers the wheel paths (each 0.75m) which are assumed and estimated and consequently result in 1.5 meters of single lane width to be considered. The crack filling considers 450 meters to be maintained for 1 km of pavement. The characteristics of each maintenance treatment such as material composition, material amount, machinery employed, assumed parameters have a huge influence on the output of the environmental impacts. All in all, the values for impact categories of each maintenance technique remain consistent and the EAB has the highest environmental influence. The second treatment with highest environmental impact after EAB is the ZOEAB. The single surface treatment scores lower than ZOEAB on all CML impact categories and finally the crack filling has the lowest influence on the environment. The values of each impact category for crack filling look insignificant compared to other treatments. The outcome values for each maintenance treatment calculate by the “openLCA” software can be found in the **Appendix 2.1 -2.4**. It is crucial to mention that each maintenance treatment serves a different purpose and has unique characteristics. The characteristics of deteriorated roads might require one maintenance treatment over another. Moreover, each maintenance treatment is applicable to a specific pavement type, so this factor plays a huge role too. Thus, despite the comparison of environmental impacts made in this section, the purpose and characteristics of each maintenance treatment remain unique.

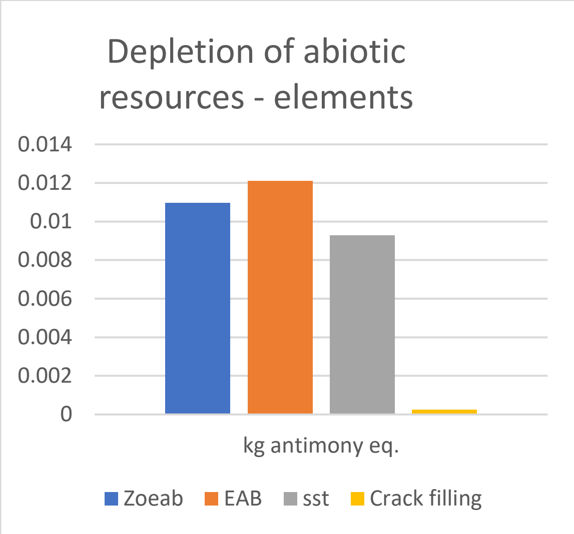
Impact category	**Reference unit**	**ZOEAB**	**EAB**	**Single surface treatment**	**Crack filling**
Acidification potential - average Europe	kg SO2 eq.	34.45001	36.68673	31.24048	3.022209
Climate change - GWP100	kg CO2 eq.	4661.26	4798.592	3706.49	399.8849
Depletion of abiotic resources - elements, ultimate reserves	kg antimony eq.	0.010973	0.012122	0.009282	0.000249
Depletion of abiotic resources - fossil fuels	MJ	243253.7	271537	215168.7	6106.266
Eutrophication - generic	kg PO4--- eq.	7.426723	7.814479	6.706031	0.700012
Freshwater aquatic ecotoxicity - FAETP inf	kg 1,4-dichlorobenzene eq.	2408.964	2714.909	2064.459	26.61011
Human toxicity - HTP inf	kg 1,4-dichlorobenzene eq.	3100.82	3460.248	2671.343	67.26582
Marine aquatic ecotoxicity - MAETP inf	kg 1,4-dichlorobenzene eq.	3766431	4151519	3158949	86545.72

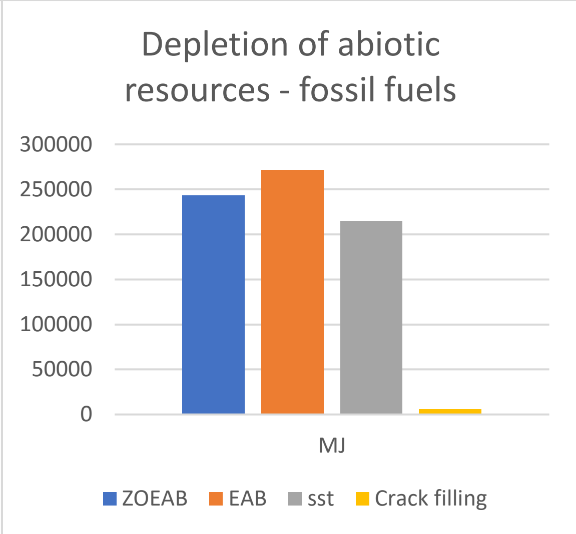
Ozone layer depletion - ODP steady state	kg CFC-11 eq.	0.003033	0.003386	0.002696	7.59E-05
Photochemical oxidation - high Nox	kg ethylene eq.	1.843043	2.061149	1.604301	0.083186
Terrestrial ecotoxicity - TETP inf	kg 1,4-dichlorobenzene eq.	659.5825	754.6326	573.3637	1.141319

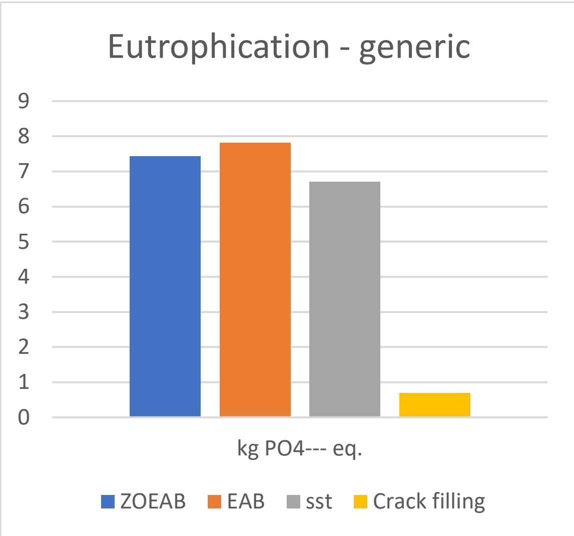
Table 16. Final results according to the CML impact assessment category.

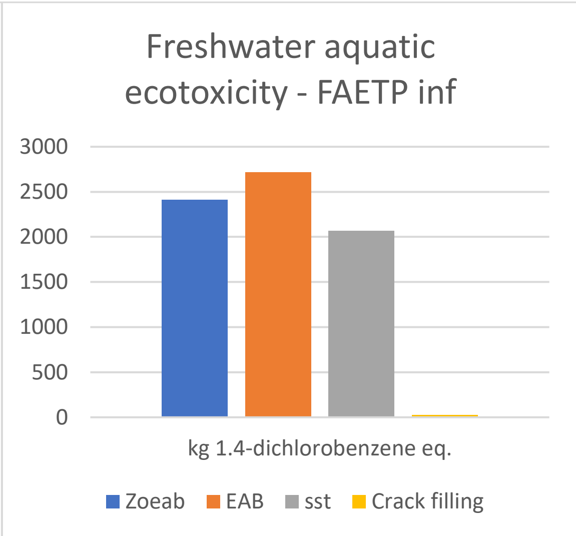
The Table 16 provides the final results for 11 impact categories calculated by the “openLCA” software. These values provide the data for environmental impacts for each maintenance treatment. Table 16 is classified and compared per impact category in Figure 13. Moreover, this table can be helpful, for instance, it can be used for further research for verification and validation techniques. Sargent (1998) recommends that the model findings of the concerned research be compared to the outcomes of another (valid) model as a validation strategy. In order to verify the environmental effects of the crack-filling maintenance approach during this period, the outcomes of this investigation were compared with those of previous studies.

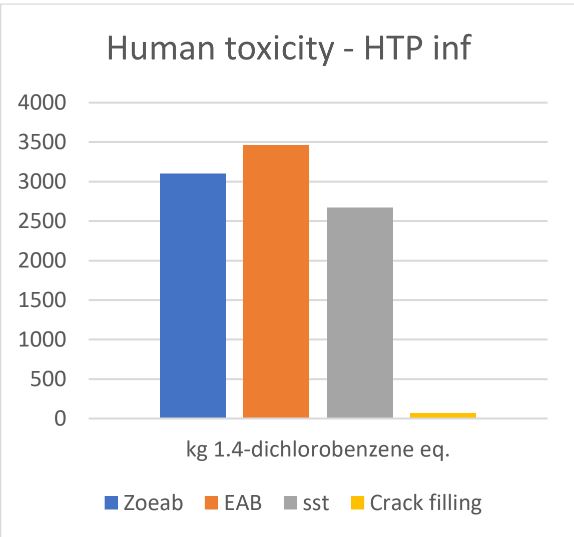


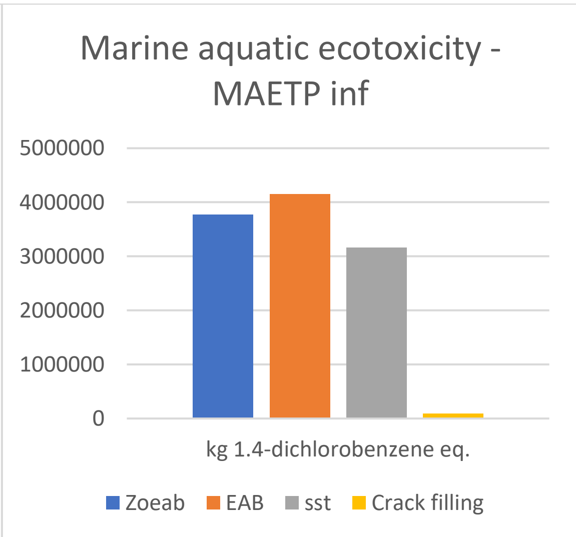

Depletion of abiotic resources - elements
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
kg antimony eq.
Zoeab
EAB
sst
Crack filling


Depletion of abiotic resources - fossil fuels
300000
250000
200000
150000
100000
50000
0
MJ
ZOEAB
EAB
sst
Crack filling


Eutrophication - generic
9
8
7
6
5
4
3
2
1
0
kg PO4--- eq.
ZOEAB
EAB
sst
Crack filling


Freshwater aquatic ecotoxicity - FAETP inf
3000
2500
2000
1500
1000
500
0
kg 1.4-dichlorobenzene eq.
Zoeab
EAB
sst
Crack filling


Human toxicity - HTP inf
4000
3500
3000
2500
2000
1500
1000
500
0
kg 1.4-dichlorobenzene eq.
Zoeab
EAB
sst
Crack filling


Marine aquatic ecotoxicity - MAETP inf
5000000
4000000
3000000
2000000
1000000
0
kg 1.4-dichlorobenzene eq.
Zoeab
EAB
sst
Crack filling

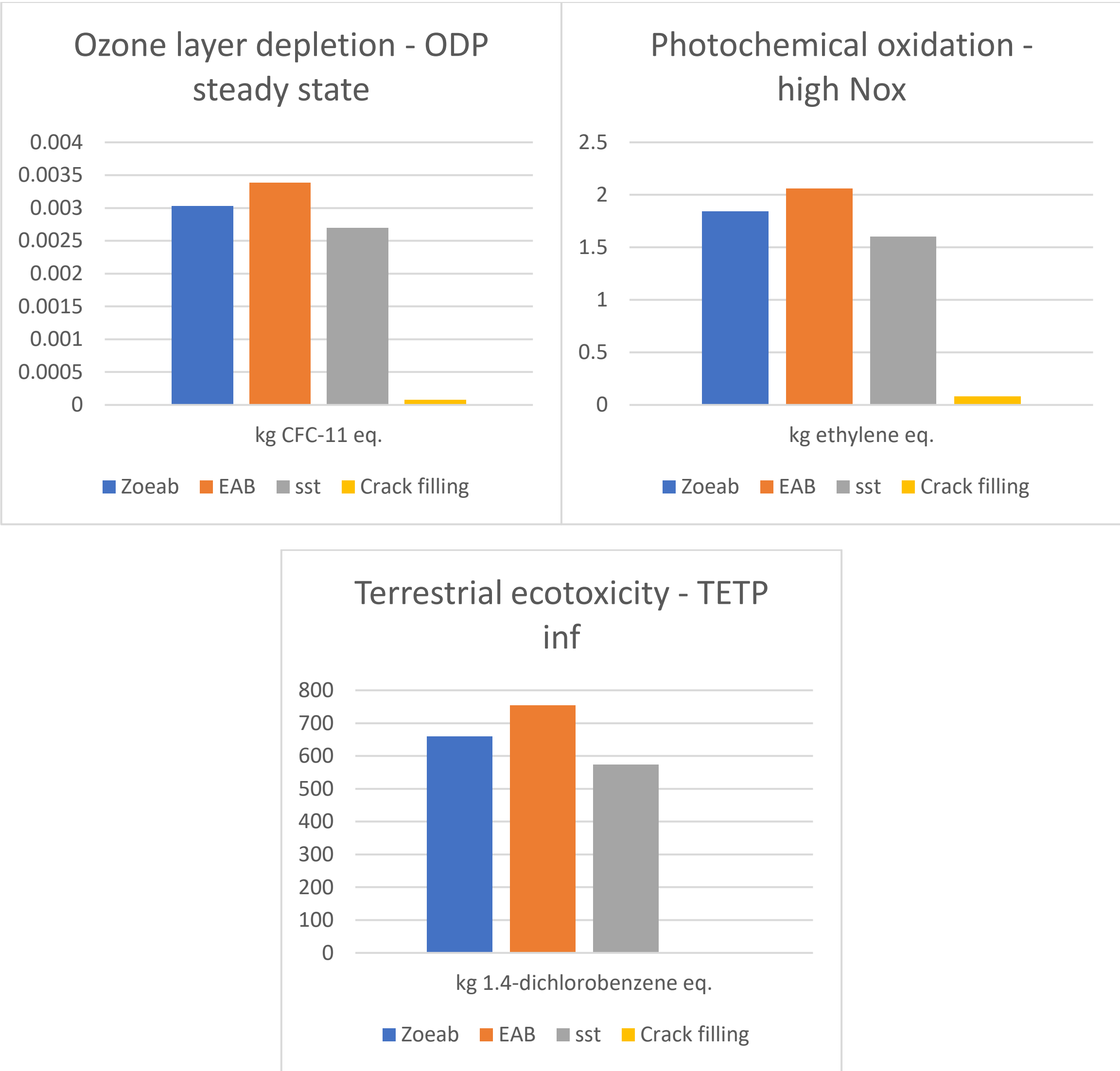


Figure 13. Comparison of environmental impacts between different maintenance treatments.

5. Summary and conclusions

The environmental sustainability is currently highly significant topic for both governmental and private companies and organizations. Therefore, there is an urgent need for the implementations of sustainable practices in all spheres of infrastructure and construction. The road pavement maintenance and rehabilitation have a significant negative cumulative environmental effect. Therefore, pavement industry is investigating more environmentally friendly pavement management solutions. The current lack of appropriate knowledge about the environmental implications connected with various pavement maintenance treatments prevents engineering companies from making well-informed judgments based on environmental considerations. Because of this, pavement management systems' decision-making procedures seldom ever take the environment into account.

This research provides a comprehensive exploration of the environmental impacts associated with pavement maintenance techniques in the Netherlands. Various maintenance treatments had been analyzed which resulted in valuable insights into the environmental consequences linked to different approaches in pavement management. There are many LCA research on rehabilitation treatments but not that many on maintenance techniques, thus this study contributes to the LCA of maintenance techniques in PM. The main goal of this thesis assignment was to find the environmental impacts associated with the life cycle of the maintenance treatments. The study was conducted according to the guidelines and requirements of ISO 14040 (2006). The ISO 14040 (2006) standard's methodology was implemented in the following key stages: 1) goal and scope definition, 2) life cycle inventory analysis, 3) life cycle impact assessment, 4) interpretation of results.

The primary finding of this study illustrates the diverse environmental impacts of maintenance treatments, with the "EAB" treatment standing out for its notably high environmental footprint, mainly driven by substantial material requirements during the raw material extraction phase. In contrast, the "crack filling" maintenance technique emerged as an environmentally friendly alternative, showcasing the significance of thorough selection in promoting sustainability within pavement management practices. However, in addition to the primary finding of this report it is important to mention that one maintenance treatment is not an alternative to another based on the unique nature of tackling different pavement damages of different pavement types. It was found that the raw material extraction phase plays a critical role for environmental impacts. As it is described in the LCIA part, when the amount of materials needed for treatment is high as it is for ZOEAB, EAB and single surface treatment, the environmental impact outcome turns out to be high respectively. When the amount of material is low, as it is for crack filling, then the environmental impact is also low. It is important to clearly state assumptions, and if possible, use the case specific data, as this will lead to more accurate results.

It is important to highlight that each phase plays a crucial role in the impact assessment method and contribute significantly to the result of environmental impact. The choice of machinery and equipment, transportation distances and means of transportation might result in different outcomes than those presented in this study. For instance, the environmental impact ratios can be different. Every maintenance treatment has its own lifespan for which it can increase the serviceability of the road. Considering all these factors described in this study it should contribute to the well-informed decision-making process in pavement management.

This research contributes to the academic literature by supplementing to the ongoing discussion regarding the sustainable practices in construction. The practical implications of this study extend to stakeholders in the pavement management sector, supporting the understanding of the environmental impacts of pavement maintenance treatments. This investigation examines such environmental impacts based on available data and assumptions made together with description of the characteristics of treatments and the presentation of the analysis.

6. Recommendations

6.1. Recommendations for improvements

A few recommendations can be made for further research and companies according to the results of this study. Based on the results and comparison of the outcomes it can be said that more sustainable means of transportation and machinery/equipment used for maintenance measures in the pavement management should be explored. Since the raw material extraction phase has the highest contribution to the environmental impacts of 4 considered measures, it can be advised that the targeted section of pavement is accurately studied, and all characteristics are taken into account. After analyzing the road characteristics to avoid major repair treatments, like rehabilitation of asphalt, it is necessary to set the maintenance work over a fixed period. This can help to avoid extra costs and additional environmental impacts.

6.2. Recommendations for further research

In this part of the report the recommendations for future research are discussed based on what has been done in this study. This study employs reference values mainly retrieved from Dutch and

American resources and studies. If there is a possibility to collect and observe the values of the specific case, then it is recommended to use this type of data, as it will result in a more realistic outcome. This study makes certain assumptions, and thus if the data is available, it is also recommended to employ it in the research. The modules “A-2” and “A-3” are excluded from this study for the 2 reasons: 1) evidence/recommendation provided by NL-PCR, 2) assumptions based on the on-site mixing. This situation can be unique for different countries and thus it should be checked with the context of the country and study. There are a lot more maintenance treatments used to extend the lifespan of the asphalt pavements, some of them might exclude certain modules from the LCA and at the same time other treatments can include all phases from A-1 to A-5. Only a limited number of maintenance treatments were studied for their environmental score in this study. Some of the other maintenance treatments worth mentioning for further studies are the slamming, double surface treatment, Micro-combi (surface treatment + EAB), overlays (Applying a new asphalt layer with a thickness of 25 up to 45mm), sealing (binder supplement and/or rejuvenator), etc. If possible, accurate energy consumptions of the machinery and equipment involved in the LCA should be used, as it can increase the accuracy of the overall outcome.

This study doesn’t consider the rehabilitation techniques. The rehabilitation techniques are also important in the pavement management. It is important to mention that they encompass more modules than A1-A5. If possible, the rehabilitation treatments to the asphalt pavements should be also studied as there are a lot more processes involved and thus it is more likely to result in higher environmental impacts. Labor force and production/maintenance of machinery and equipment employed in the pavement management is not covered by this study. In more extensive and detailed research with different time limits the maintenance of machinery and human activities can be also included. It is believed that addition of these units/variables can have an important contribution to the environmental impacts. The cost analysis might also be included in the study, even though it falls outside of the scope of a LCA study. However, they give a good picture on which maintenance or rehabilitation treatment can be the most appropriate and efficient from an economic perspective. It might be interesting to mention and study what exactly and how exactly the construction companies and contractors actually do, use and consider during the pavement life extending works.

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Appendix:

Appendix A:

A-1:

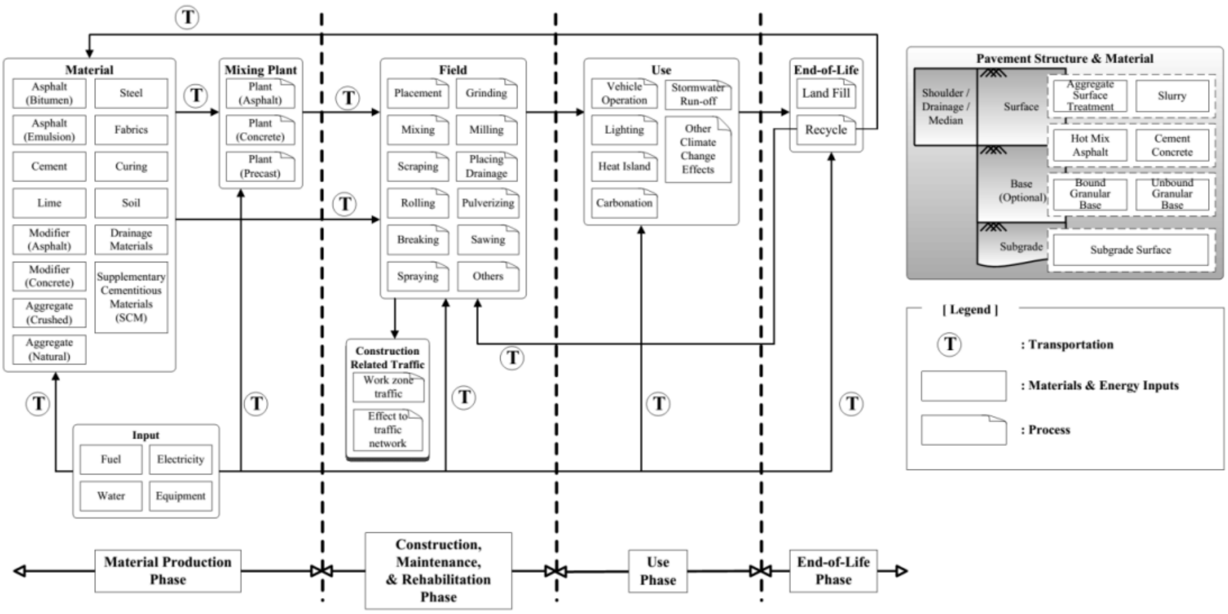

Figure 14. LCA framework showing major life-cycle stages. (Harvey et.al., 2011)

A-2:

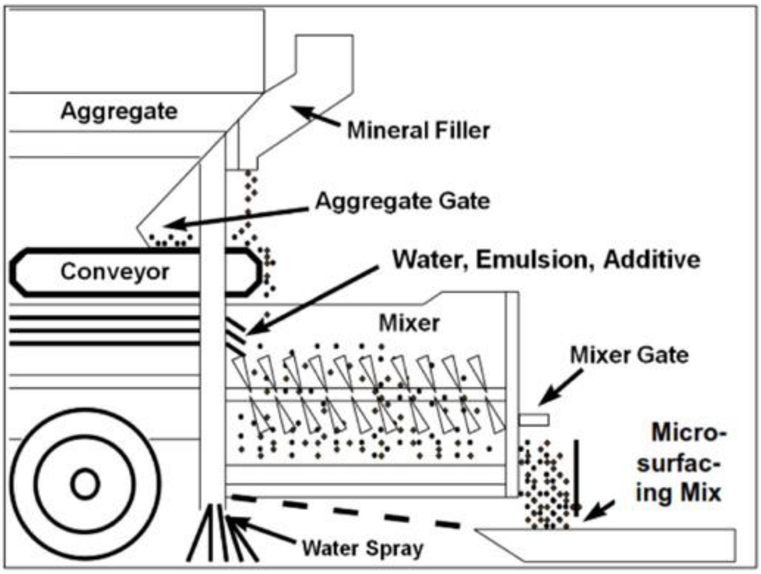

Figure 15. Example of machinery employed for BST.

A-3:

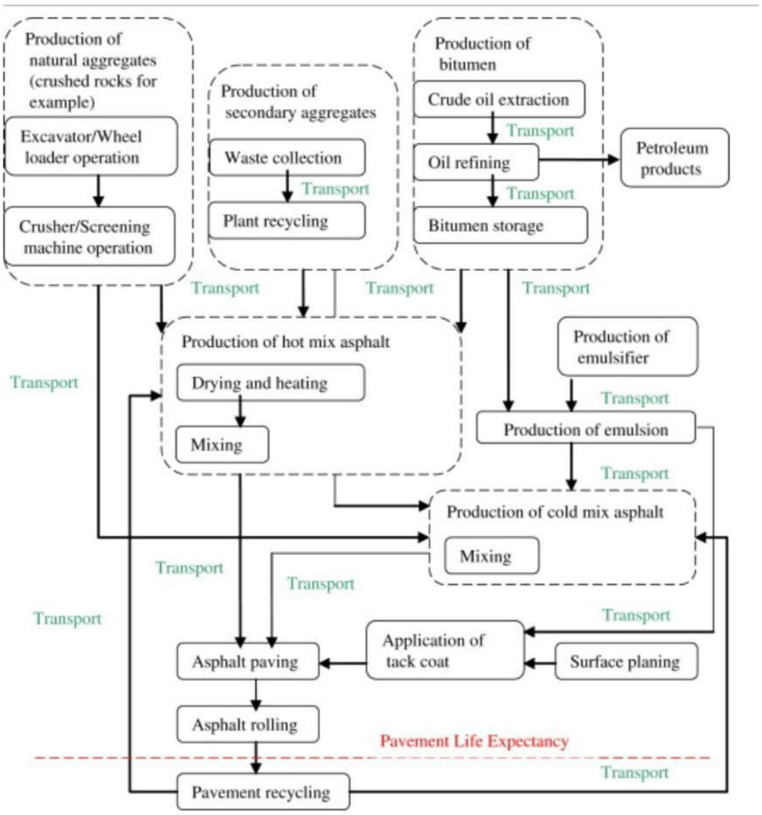

Figure 16. Unit processes in asphalt pavement construction.

Appendix B

ZOEAB

A-1

Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			28.88315 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			3718.55033 kg CO2 eq.
Depletion of abiotic resources - elements, ultimat	CML (baseline) [v4.4, January 2015]			0.01041 kg antimony eq.
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			2.29708E5 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			6.10113 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			2342.62309 kg 1,4-dichloro...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			2907.97770 kg 1,4-dichloro...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			3.56860E6 kg 1,4-dichlorob...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			0.00286 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			1.70928 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			656.75962 kg 1,4-dichlorob...

A-4

Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			1.52425 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			281.34292 kg CO2 eq.
Depletion of abiotic resources - elements, ultimate reserves	CML (baseline) [v4.4, January 2015]			0.00034 kg antimony eq.
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			3974.11903 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			0.37292 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			29.62500 kg 1,4-dichlorobenzen...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			93.15051 kg 1,4-dichlorobenzen...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			8.78477E4 kg 1,4-dichlorobenze...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			4.83629E-5 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			0.04715 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			1.02268 kg 1,4-dichlorobenzene...

A-5

Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			4.04261 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			661.36691 kg CO2 eq.
Depletion of abiotic resources - elements, ultimat	CML (baseline) [v4.4, January 2015]			0.00023 kg antimony eq.
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			9571.83074 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			0.95268 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			36.71566 kg 1,4-dichloro...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			99.69189 kg 1,4-dichloro...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			1.09987E5 kg 1,4-dichlor...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			0.00012 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			0.08661 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			1.80019 kg 1,4-dichlorob...

EAB

A-1

Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			32.79994 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			4194.59603 kg CO2 eq.
Depletion of abiotic resources - elements, ultimat	CML (baseline) [v4.4, January 2015]			0.01165 kg antimony eq.
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			2.62886E5 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			6.89645 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			2666.49155 kg 1,4-dichlo...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			3311.68610 kg 1,4-dichlo...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			4.00721E6 kg 1,4-dichlor...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			0.00328 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			1.94945 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			752.71542 kg 1,4-dichlor...

A-4

Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			1.69253 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			314.75341 kg CO2 eq.
Depletion of abiotic resources - elements, ultimate reserves	CML (baseline) [v4.4, January 2015]			0.00038 kg antimony eq.
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			4455.64188 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			0.41354 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			33.08678 kg 1,4-dichlorobenzen...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			104.83532 kg 1,4-dichlorobenze...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			9.80367E4 kg 1,4-dichlorobenze...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			5.42642E-5 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			0.05273 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			1.14198 kg 1,4-dichlorobenzene...

A-5

Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			2.19427 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			289.24210 kg CO2 eq.
Depletion of abiotic resources - elements, ultima	CML (baseline) [v4.4, January 2015]			8.91226E-5 kg antimony ...
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			4195.11591 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			0.50448 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			15.33034 kg 1,4-dichloro...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			43.72618 kg 1,4-dichloro...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			4.62713E4 kg 1,4-dichlor...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			5.26032E-5 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			0.05897 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			0.77520 kg 1,4-dichlorob...

SST

A-1

Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			23.61672 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			2435.05195 kg CO2 eq.
Depletion of abiotic resources - elements, ultima	CML (baseline) [v4.4, January 2015]			0.00865 kg antimony eq.
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			1.96861E5 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			4.89734 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			1982.22084 kg 1,4-dichlo...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			2438.11759 kg 1,4-dichlo...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			2.91328E6 kg 1,4-dichlor...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			0.00247 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			1.42917 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			569.68883 kg 1,4-dichlor...

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Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			1.28156 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			233.86039 kg CO2 eq.
Depletion of abiotic resources - elements, ultimate reserves	CML (baseline) [v4.4, January 2015]			0.00028 kg antimony eq.
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			3290.83648 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			0.31410 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			24.63709 kg 1,4-dichlorobenzen...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			76.82483 kg 1,4-dichlorobenzen...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			7.31184E4 kg 1,4-dichlorobenze...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			4.00137E-5 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			0.03925 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			0.85067 kg 1,4-dichlorobenzene...

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Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			6.34220 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			1037.57788 kg CO2 eq.
Depletion of abiotic resources - elements, ultimat	CML (baseline) [v4.4, January 2015]			0.00036 kg antimony eq.
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			1.50167E4 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			1.49459 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			57.60093 kg 1,4-dichloro...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			156.40048 kg 1,4-dichlor...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			1.72552E5 kg 1,4-dichlor...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			0.00019 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			0.13588 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			2.82421 kg 1,4-dichlorob...

Crack filling

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Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			0.05888 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			9.18598 kg CO2 eq.
Depletion of abiotic resources - elements, ultimat	CML (baseline) [v4.4, January 2015]			0.00013 kg antimony eq.
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			439.43561 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			0.01872 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			5.89646 kg 1,4-dichlorob...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			8.16272 kg 1,4-dichlorob...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			2.40285E4 kg 1,4-dichlor...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			4.85842E-6 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			0.00354 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			0.09412 kg 1,4-dichlorob...

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Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			0.00040 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			0.13385 kg CO2 eq.
Depletion of abiotic resources - elements, ultimate reserves	CML (baseline) [v4.4, January 2015]			2.64543E-7 kg antimony eq.
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			2.14460 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			8.49177E-5 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			0.01301 kg 1,4-dichlorobenzene...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			0.05941 kg 1,4-dichlorobenzene...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			36.82055 kg 1,4-dichlorobenzen...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			2.70624E-8 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			2.16671E-5 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			0.00044 kg 1,4-dichlorobenzene...

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Name	Category	Inventory result	Characterization factor	Impact assessment result
Acidification potential - average Europe	CML (baseline) [v4.4, January 2015]			2.96293 kg SO2 eq.
Climate change - GWP100	CML (baseline) [v4.4, January 2015]			390.56505 kg CO2 eq.
Depletion of abiotic resources - elements, ultimat	CML (baseline) [v4.4, January 2015]			0.00012 kg antimony eq.
Depletion of abiotic resources - fossil fuels	CML (baseline) [v4.4, January 2015]			5664.68588 MJ
Eutrophication - generic	CML (baseline) [v4.4, January 2015]			0.68120 kg PO4--- eq.
Freshwater aquatic ecotoxicity - FAETP inf	CML (baseline) [v4.4, January 2015]			20.70064 kg 1,4-dichloro...
Human toxicity - HTP inf	CML (baseline) [v4.4, January 2015]			59.04368 kg 1,4-dichloro...
Marine aquatic ecotoxicity - MAETP inf	CML (baseline) [v4.4, January 2015]			6.24804E4 kg 1,4-dichlor...
Ozone layer depletion - ODP steady state	CML (baseline) [v4.4, January 2015]			7.10304E-5 kg CFC-11 eq.
Photochemical oxidation - high Nox	CML (baseline) [v4.4, January 2015]			0.07962 kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	CML (baseline) [v4.4, January 2015]			1.04676 kg 1,4-dichlorob...

Appendix C: Conversion calculations (functional unit)

ZOEAB

1)1km = 1000 m * 3.4 m * 20 kg/m^2 =6800 kg - needed material for 1 km

2) Diesel consumption (1km) = 3400 m^2(area) * 0.058 l/m^2 (total machinery consumption) = 197.2liters

3) Conversion of diesel consumption to joules = 197.2 liters * 35.8 MJ/liters = 7059.76 MJ

EAB

1) 1km = 1000 m * 2500 kg/m^3 * 0.02 mm * 1.5 m = 75000 kg - needed material for 1 km

2) Diesel consumption (1km) = 1.5 m * 1000 m * 0.058 l/m^2 = 87 liters

3) Conversion of diesel consumption to joules = 87 liters * 35.8 MJ/liters = 3114.6MJ

Single surface treatment

1)Needed sst for 1km = 16.734 kg/m^2 * 3400 m^2 = 56895.6 kg

2) Diesel consumption per 1 km = 0.091 l/m^2 * 3.4 m * 1000 m = 309.4 liters of diesel.

3) Conversion of diesel consumption to joules = 309.4 liters of diesel * 35.8 MJ/l = 11076.52 MJ

4) For A1 in "openLCA" = > 89.5% - aggregates and 10.5% - emulsion => 50921.92kg of aggregates and 5974.08 kg of emulsion per 1km

Crack filling

1) **Diesel consumption per 1 km = 0.035 l/m^2 * 3.4 m * 1000 m = 119 liters**
2) **Conversion of diesel consumption to joules = 119 liters * 35.8 MJ/l = 4206.2 MJ**

Appendix D: Validation

The results from the study conducted by M. Mazumder, et. al. (2018) for the crack filling maintenance treatment can be found in the figure below. The study doesn't mention the tool or software employed in the research, but to measure and assess the environmental implications of items or processes, Life Cycle Assessment (LCA) studies like this one frequently employ specialist LCA software like SimaPro, GaBi, OpenLCA, or other tools. The study provides the data for different impact categories that align together with the CML.

Impact category	Impact category area	Unit of characterization factor	Crack filling (per km)
Depletion of minerals	Polymer modified bitumen	Kg minerals	–
Depletion of fossil fuels		GJ	0.0311
Global warming		Kg CO_2-eq. (100 years)	2.249
Acidification		Kg SO_2-eq.	0.016
Photo-oxidant formation		Kg C_2H_4-eq.	6.83E-04
Human toxicity	Emission to air	Kg 1,4-dichlorobenzene-eq.	826.986
	Emission to fresh water	Kg 1,4-dichlorobenzene-eq.	406.224
Eco toxicity	Emission to air	Kg 1,4-dichlorobenzene-eq.	2.147
	Emission to fresh water	Kg 1,4-dichlorobenzene-eq.	15.959
Eutrophication		Kg PO_4-eq.	2.63E-03

Figure 17. Construction phase of crack filling

Impact category	Impact category area	Unit of characterization factor	Crack filling (per km)
Depletion of minerals	Polymer modified bitumen	Kg minerals	11.635
Depletion of fossil fuels		GJ	0.133
Global warming		Kg CO_2-eq. (100 years)	6.889
Acidification		Kg SO_2-eq.	0.050
Photo-oxidant formation		Kg C_2H_4-eq.	0.011
Human toxicity	Emission to air	Kg 1,4-dichlorobenzene-eq.	1241.064
	Emission to fresh water	Kg 1,4-dichlorobenzene-eq.	814.45
Eco toxicity	Emission to air	Kg 1,4-dichlorobenzene-eq.	3.597
	Emission to fresh water	Kg 1,4-dichlorobenzene-eq.	32.002
Eutrophication		Kg PO_4-eq.	6.29E-03

Figure 18. Material phase.

The results of the study for crack filling conducted in this research are significantly different from the outcomes of study conducted by M. Mazumder, et. al. (2018). The study by M. Mazumder, et. al. (2018) contains 8 impact categories, and after comparing them with the similar impact categories out of 11 which are used in this report it can be noticed that the results are moderately less. The reason for this can be that the transportation distances and type of transportation are neglected. Moreover, the assumptions are made in the study of M. Mazumder, et. al. (2018) for machinery used in the application phase, the specific models of machinery are used. This can lead to the difference in the results as this study employs the diesel burned machine for module “A-5” with the total diesel consumption per m^2. Also, instead of the software the calculation in the study by M. Mazumder, et. al. (2018) is performed using the environmental impact factor and further manual calculations. Despite these factors being different for 2 studies the results are not tremendously different nor slightly different considering that they play an important role in environmental impacts. So, it is assumed and thought that the results of this thesis assignment are valid and appropriate.

For other 3 treatments the data was not available on the open-source platforms. The ZOEAB and EAB are the maintenance treatments mainly employed in the Netherlands and other countries in Europe. If the assignment was executed together with a company, more likely there would have been specific information to conduct an extensive validation and verification of the model and outputs. Moreover, the results or models using the “openLCA” for pavement management conducting LCA of maintenance treatments could not be found publicly available. However, based on the validation of crack filling maintenance technique, literature review, reference values employed for Dutch context it is believed that the results are accurate according to the assumptions and calculations made.