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Pavement LCM

PavementLCM Resources

Sustainability Data Analysis

Deliverable D3.1

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Life Cycle Management of Green Asphalt mixtures and Road Pavements

Deliverable D3.1 – Sustainability Data Analysis

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Author(s) of this deliverable:

Diana Godoi Bizarro, TNO, The Netherlands

Elisabeth Keijzer, TNO, The Netherlands

Ahmed Abed, University of Nottingham, UK

Tony Parry, University of Nottingham, UK

Luis Canhoto Neves, University of Nottingham, UK

CONTACTS

Keijzer, Elisabeth elisabeth.keijzer@tno.nl

Davide Lo Presti davide.lopresti@unipa.it – davide.lopresti@nottingham.ac.uk *(coordination)*

Executive summary

Background

National Road Authorities (NRAs) in Europe have an increasing interest in implementing sustainability assessment of roads and road infrastructure to tackle the following main goals:

1) Be able to manage their assets in a more efficient way, thus reducing costs;
2) To help their countries comply with carbon emission reduction goals;
3) Reduce environmental impacts of road construction and maintenance, meaning also a reduction in resource usage through the re-use and the recycle of waste materials;
4) Reduce the social impact of roads through noise reducing pavement and minimizing hindrance for road users (travel delays due to maintenance).

This deliverable from PavementLCM project WP3 contains sustainability assessment case studies that deliver a clear overview of costs, environmental and social impacts together covering the sustainability assessment of a road's wearing course considering only the most important indicators from the NRA's perspective.

Goal and Scope

The goals of this report are:

- To help the road authorities in their sustainability knowledge by giving an overview of the sustainability assessment methodology and how to apply the framework proposed in D2.1.
- To showcase how to perform a full sustainability assessment of case studies, covering costs, environmental and social impacts.
- To provide insight in the sustainability of several asphalt innovations.
- To provide insight in the long-term effects of different pavement activities over the life cycle of the pavement, by including maintenance schemes.
- To show the applicability of different Sustainability Assessment tools, how and why their results vary.
- To analyse the uncertainties involved in sustainability assessment in a simple way so that such an analysis can be reproduced by NRAs, to provide insight in the order of magnitude of uncertainties, and to give guidelines on how to take uncertainty into account for reaching robust results and conclusions.

Case Study Selection Process and Criteria

During the 1st CEDR PavementLCM workshop (May 2019) the relevant sustainability indicators, the six asphalt mixtures for the case studies and the three tools to be used were defined in discussion with the NRAs and other participating stakeholders.

The indicators which were prioritized by the NRAs, were:

1) Global Warming Potential,

2) energy consumption
3) recycled material content
4) costs
5) tyre-pavement noise
6) durability

As an optional indicator 7) “air quality” was selected.

During the workshop, Stone Mastic Asphalt (SMA) and Porous Asphalt (PA) were considered as the most representative mixtures to study wearing courses. Concerning innovations, the biggest interest laid on the use of Reclaimed Asphalt (RAP) and low temperature asphalt (LTA). The six asphalt mixtures selected for the case studies were:

1. SMA 16 (reference)
2. SMA 11 - 40% RAP + PMB + LTA
3. SMA 8 - 60% RAP + PMB
4. SMA 11 - Long service life
5. PA 8 - top layer 2L PA + PMB
6. PA 16 - long service life.

The three tools selected for comparison were Athena, SimaPro and Ecorce M. Athena is a north American LCA tool for roads, which contains its own database and American impact assessment method. SimaPro is a tool that allows all kinds of life cycle assessments and has many databases and impact assessment methods available; for this analysis, European methods and databases were used. Ecorce M is a French tool for infrastructure LCAs, which contains its own database and a European based impact assessment method.

Two analyses have been made, one focusing on a comparison of pavement materials/products and one focusing on pavement activities. The pavement materials/products analysis is a “cradle-to-gate” analysis which includes only the life cycle stages A1-A3 (materials). The pavement materials/products analysis included a comparison of the asphalt mixtures above, comparison of scores on several sustainability indicators, comparison of tools and an analysis of uncertainties.

The pavement activities analysis entailed multiple scenario analyses of a road composed of a wearing course and binder layer, being analysed over a period of 40 years, thereby including rehabilitations. The pavement activities analysis focused only on LCA, since all other questions were already investigated in the pavement materials/products analysis and repetition of these analyses would not lead to new insights on “how to use sustainability methods”.

The figure E1 below shows the system boundaries for both analyses.

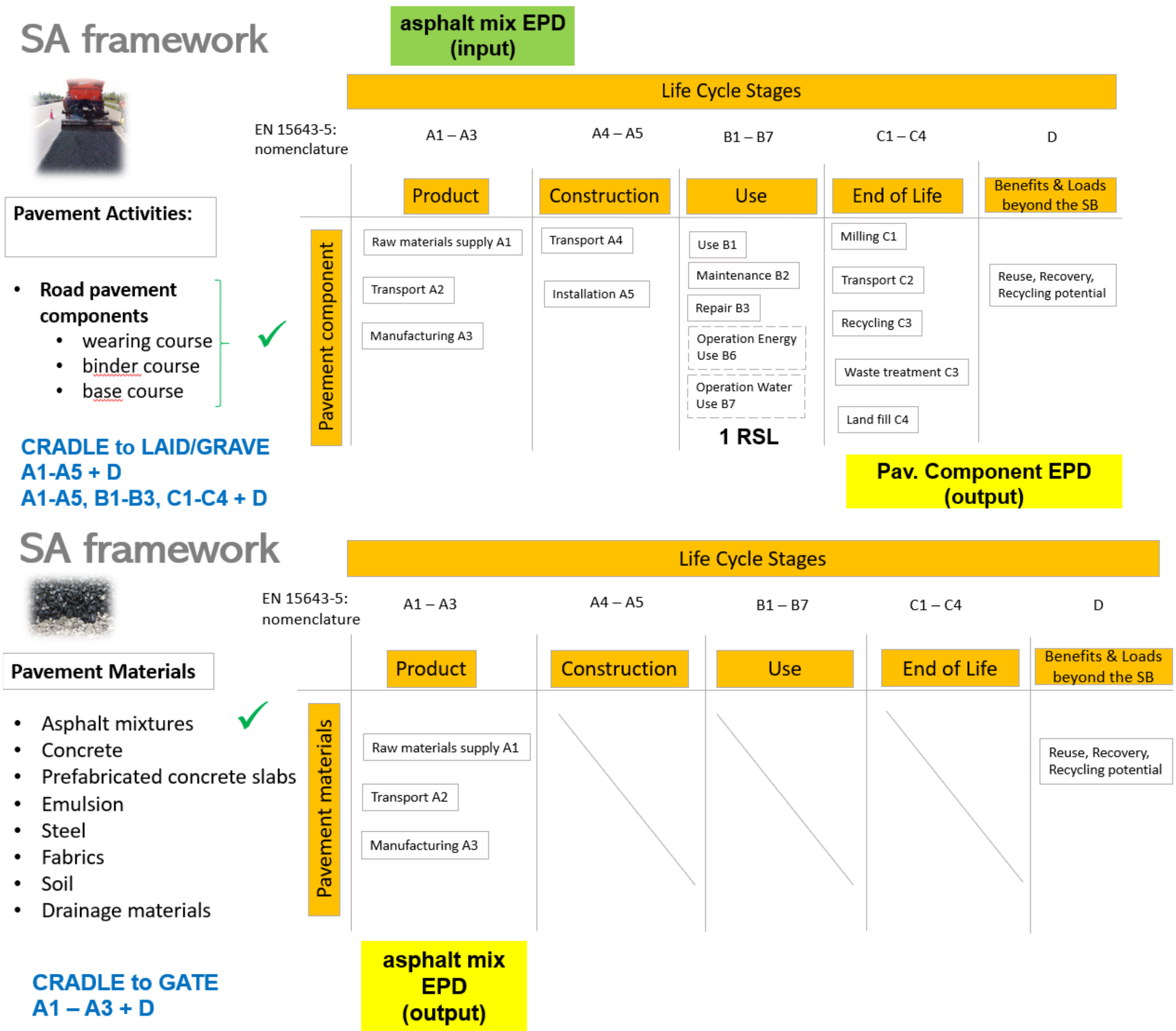

Figure E1: System boundaries and life cycle stages for pavement materials/products (cradle to gate) and pavement activities (cradle to grave). Source: PavementLCM D2.1 – Framework.

Results: LCA of Pavement materials/products

Figure E2 shows the results of the six case studies for the three environmental indicators, analysed with the generic tool SimaPro. Raw materials (A1) is the life cycle stage contributing the most to each of the three indicators, followed by transport (A2) and Production at asphalt plant (A3).

In terms of "which asphalt mixture is the greenest?", different indicators lead to different conclusions. The mixtures 1 and 6 show the best performance for Global Warming Potential and Eutrophication, while mixture 3 performs the best regarding Air Pollution. There is thus not a single conclusion about sustainability when these different indicators are involved.

For all indicators it can be concluded that the impacts that were avoided through the use of RAP, were offset by using additives (mixture 2 & 3). Secondly, the positive impact of reducing binder consumption was offset by the use of PMB instead of regular bitumen. Thirdly, as the production stage (A3) corresponds to only about 16% or less of the mixtures' footprints, lowering the temperature by 20°C had a negligible effect on the environmental impacts (mixture 2).

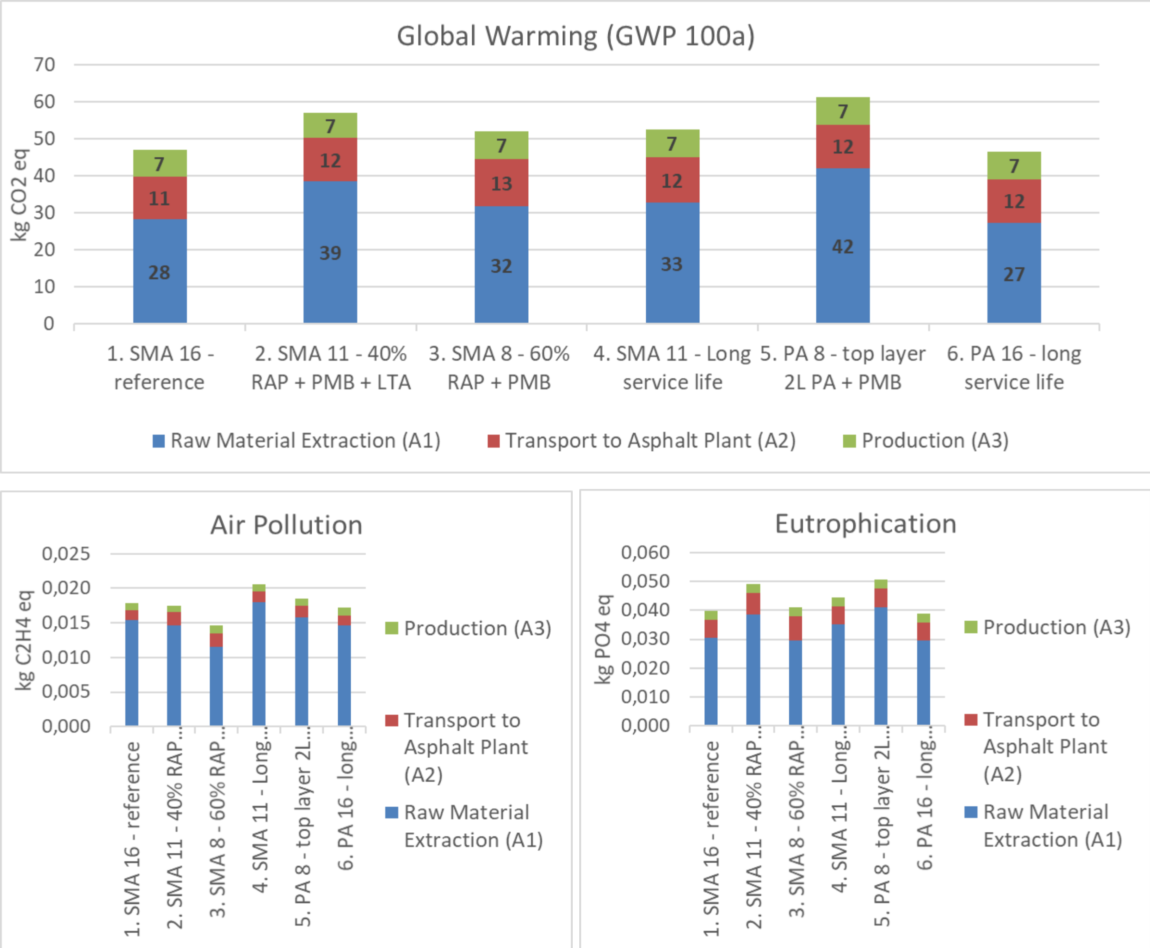

Figure E2: Environmental impact per tonne of asphalt. Top: results for Global Warming Potential; bottom left: results for Air Pollution due to photochemical oxidation; bottom right: results for Eutrophication.

Results: LCC of Pavement materials/products

Figure E3 shows the life cycle costs for the six mixtures. It can be concluded that mixture 4 is the one with the highest costs, while mixture 3 is the mixture with the lowest costs. Nevertheless, the relative difference between them is small, namely 17%.

The main contributors to the total cost of the asphalt mixture are raw materials, from which aggregates and the binder correspond to the biggest portion. The savings by using RAP are partially offset due to the higher prices of PMB instead of regular bitumen in RAP mixtures (#2 and #3).

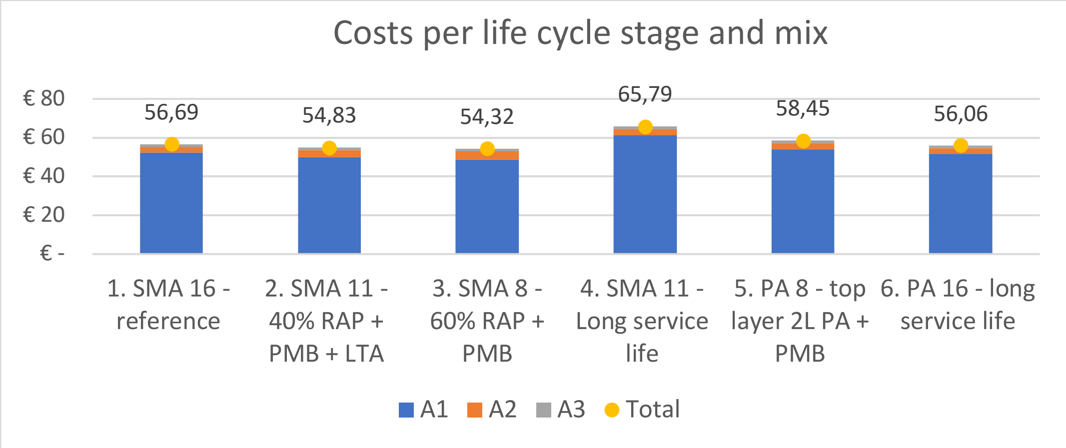

Figure E3: Total costs for producing the six asphalt mixtures per ton of asphalt, per life cycle stage.

Results: Integral sustainability assessment of Pavement materials/products

Table E1 displays the sustainability results for all pavement materials/products. For each indicator, it is indicated in green which pavement component has the lowest impact and which could thus be considered the "greenest". Determining which pavement component is the "greenest" is nevertheless not straightforward since there is no mixture scoring better than the others for all indicators. This could only be achieved if any kind of prioritization and/or weighing would be included.

When weighing is not be taken into account, and all indicators are thus valued "equally important", mixture 3 (SMA 8 - 60% RAP + PMB) would be the most sustainable asphalt mixture since it is the one having the largest amount of "best scores", outperforming other mixtures in 3 of the 7 indicators, while it has the second best carbon footprint and scores on the average for energy use. When, for example, carbon footprint would be considered more important than all others, the "greenest" mixture would be either mixture 1 (the reference SMA) or mixture 6 (PA with long service life). Other ways for decision making could be to include weighting factors, like in the Dutch green procurement system.

Table E1: Sustainability assessment results per ton of asphalt for the six asphalt mixtures assessed in the pavement materials/products case study. The mixtures with the lowest impact are highlighted in green, per indicator.

Sustainability pillar	Indicator	Unit	1. SMA 16 - reference	2. SMA 11 - 40% RAP + PMB + LTA	3. SMA 8 - 60% RAP + PMB	4. SMA 11 - Long service life	5. PA 8 - top layer 2L PA + PMB	6. PA 16 - long service life
Environment	Global Warming Potential	kg CO_2 eq.	47	57	52	53	61	47
	Air pollution (as Photochemical Oxidation)	kg C_2H_4 eq	0.018	0.018	0.015	0.021	0.019	0.018
	Energy use	MJ	75	68	75	75	75	75

Sustainability pillar	Indicator	Unit	1. SMA 16 - reference	2. SMA 11 - 40% RAP + PMB + LTA	3. SMA 8 - 60% RAP + PMB	4. SMA 11 - Long service life	5. PA 8 - top layer 2L PA + PMB	6. PA 16 - long service life
	Secondary materials consumption	kg	0	382	600	0	0	0
Economy	Cost	€	56.69	54.83	54.32	65.79	58.45	56.06
Society	Tyre-pavement noise reduction	dB[1]	0	0	-0.6 dB	0	-4.8 dB	-2 dB
Affects all pillars	Durability	years	16[2]	14-10[3]	14-10[12]	20[12]	10[11]	14[11]

Results: comparison of LCA tools for Pavement materials/products

In this section a comparison between the results for six asphalt mixtures in Ecorce M, Athena and SimaPro is made. The most important sources of divergences in the tools have been investigated and described. The tools are compared in pairs, because there was no indicator which could be calculated equally in all tools.

In the comparison of Ecorce and SimaPro, surprising differences were observed. In terms of ranking and conclusions, similar calculations with the tools often lead to different conclusions. When it comes to determining which mixture has the lowest impact, both tools show consistently that mixture 6 has the best performance for Global Warming Potential and Eutrophication. For Tropospheric Ozone Formation however, Ecorce and SimaPro draw different conclusions (respectively mixture 6 and mixture 3). Both tools also diverge concerning the worst performing mixture for two indicators (Eutrophication and Tropospheric Ozone Formation). For Global Warming Potential both tools show consistently mixture 5 as the worst performing mixture.

For Global Warming Potential, the conclusions about the ranking are thus rather solid. However, on an absolute level, the tools differ significantly in the calculated outputs. Divergences in Global Warming Potential results vary around 10% amongst Ecorce and SimaPro. For Eutrophication and Air pollution results may differ even more, up to 500%.

The reason for these differences amongst the tools, is that the underlying databases in both softwares differ from each other: while SimaPro uses datasets from EcoInvent, Ecorce M uses its own database, specifically developed for the software and not accessible otherwise. The differences in datasets, lead to major deviations in results even when the asphalt mixtures are modelled identically.

[1] Source: (EAPA, 2018)

[2] Source: Dutch Product Category Rules for Asphalt. (Keijzer, et al., 2020).

[3] The expected durability for an innovative SMA mixture ranges from 10 to 14 years considering a slightly worse performance than the reference mixture due to an early stage of development of the production technology. This is an expert guess based on the durability of the reference mixture and the uncertainty in amount of years that can be expected from an innovative mixtures.

Comparing the results amongst the three tools was impossible for most of the indicators, because Ecorce and Athena use different indicators, units and calculation methodologies. Even the results for Global Warming Potential, which is the most clearly described indicator in the world and for which the same methodology was used in all tools, showed largely deviating results because the underlying database is different in these tools.

Results: LCA of Pavement Activities

Comparing the performance of different asphalt mixtures offers a partial view of the total impacts asphalt has throughout its lifetime, because some mixtures might require more maintenance than others, or have longer lifetimes than others. To have a better overview it is necessary to analyse the full life cycle including the service life of the pavement materials/products and how they perform when a maintenance scheme is taken into account.

Asphalt wearing courses made of six different materials were analysed during a period of 40 years as specified in the framework of deliverable D2.1, thereby showing the effects of considering maintenance schemes and durability in sustainability assessment.

In the scenario analysis the best performing wearing course was the one consisting of mixture 4, because of longer service life. Observing that this conclusion differs from the pavement component analysis, clearly indicates the added value of considering the full context of the road and its rehabilitations.

In addition to the conclusions already drawn from the material analysis, several boundary conditions can be observed in the application of RAP. Use of RAP is beneficial only if it results in the reduction of the use of primary bitumen, if it does not result in a shortening of the service life of the pavement component and if it does not involve much more road transport than the primary materials substituted by RAP.

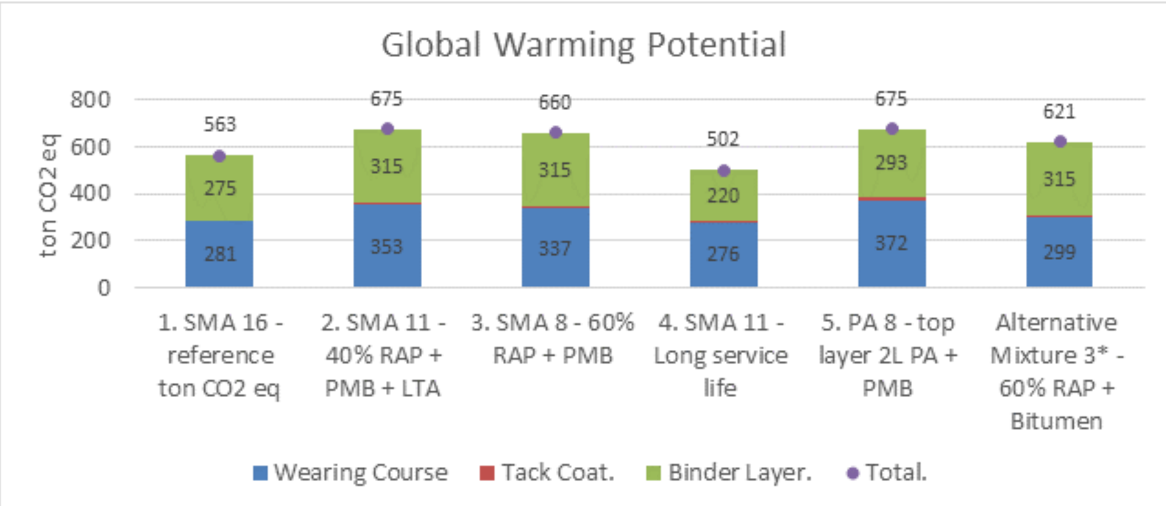

Figure E4: Results for Global Warming Potential per ton of asphalt for the six scenarios in this study.

Uncertainties in LCA

Uncertainty estimation of LCA data demonstrated that there are high levels of uncertainty in the processes that contribute to the environmental impacts, which could reach 122% in some of the analysed cases. This indicates that LCA studies should include the effect of LCA data uncertainty and its effects on the results in or order to draw true conclusions and make correct decisions.

Sensitivity analysis results can be used to identify the phases that contribute the most to the selected impacts, which can be used in turn to identify the most important processes that contribute to these phases. The results of this analysis can be utilised to concentrate the efforts and research on the phases and process that cause high impacts with large uncertainty in order to reduce the amount of the impacts and the uncertainty levels.

As a general rule of thumb, a process will have clear impact on the reliability of an LCA study results if it has a high impact and a large standard deviation. The high impact is to prove the process is an important one and can cause a large environmental impact whereas the high standard deviation is to prove that the impact is sensitive to uncertainty of this process.

The derived LCA uncertainty analysis can be run in two ways. The first one is to find the uncertainty of the LCA results per one unit of the analysed mix. The second one is to find the uncertainty of LCA results per certain analysis period by considering the durability and thus the maintenance scheme of the pavement component being analysed, which gives the probability distribution functions (PDFs) of the total impact over the design period.

The durability of pavement components is a critical factor that must be carefully considered in the LCA analysis. The material properties which contribute to the durability of pavement components is directly used to calculate the total quantity of asphalt required for a certain design period, which is directly related to the amount of the environmental impacts of asphalt. Accordingly, the uncertainty of component durability has a direct impact on the uncertainty of LCA results.

Conclusions and recommendations

This report illustrates the sensitivities in sustainability analysis, which reveal important messages for those who want to deploy activities to enhance sustainability.

The first lesson is that the most sustainable pavement component is not just the mixture with the lowest temperature or the highest amount of RAP. Innovations lead only to real improvements in sustainability when they are considered on a systemic level, comparing road systems over longer time periods than when only focusing on production. System analysis will reveal trade-offs, for example between using RAP and needing additives, as well as provide insight in the results of specific circumstances like traffic, climate, etcetera. Only with this approach, it is possible to have a holistic overview of the impacts and performance of an asphalt mixture.

> → *recommendation 1: always compare pavement solutions in a project context with a long term (at least 40 years) perspective, never on a mass-basis (1 ton of X vs 1 ton Y).*
>
> →*recommendation 2: be aware of potential trade-offs in sustainability, especially when additives or modifications are applied to ensure success.*

Since “sustainability” is an umbrella concept, it is hard to find a single solution which ticks all boxes and scores best on all indicators. For that reason, organizations who want to improve should define clearly what indicators they find most important and, in case they find many things important, how they will combine different indicators to a final decision. The Dutch system of shadow prices and MEAT procedures[4] is an example of the integration of different indicators into a decision-making process.

> → *recommendation 3: before you start to investigate sustainability and/or before you incorporate sustainability in a tender or a strategy document, define which indicators you find important.*
>
> → *recommendation 4: in case of multiple indicators, determine on beforehand how*

[4] MEAT stands for “Most Economically Advantageous Tender” and reflects a weighing system in which (environmental) impacts are taken into account in the decision-making process.

you will combine them. Options are: weighing (e.g. shadow prices) or equal weight (e.g. the solution with most "best scores" wins).

When implementing sustainability, users should be aware that sustainability calculations with different tools, databases and/or methodologies will definitely lead to different conclusions. There are dozens of tools available to perform Sustainability Assessments of roads. Each of them has its own specificities and is more appropriated to a certain region due to the impact assessment method employed in the calculations and the database in the background. Hence, the NRA should choose a tool that suits their needs in terms of indicators, impact assessment method and underlying database. The Sustainability Assessment Compass, delivered in WP5, will help NRAs to find the right tool for certain situations.

→recommendation 5: first decide what are your goals, then select the appropriate tool and only tolerate data or results which are generated by this tool.

→ recommendation 6: use the Sustainability Assessment Compass (WP5) to find the right tool for the right situation.

→recommendation 7: to make most efficient use of internationally available data, consider harmonisation of data on a European level; see "Roadmap to Harmonisation" (WP5).

However, there are more aspects than only tool selection when implementing sustainability; it is crucial to design a complete system with clear boundaries and conditions. In the case of the Netherlands, Rijkswaterstaat, the Dutch Road Authority, noticed that using the same tool and method was still not enough to ensure comparability of different products, therefore, together with market parties, they developed Product Category Rules. This document provides very specific guidelines on how to perform LCAs for asphalt in a uniform way, so that they can be used in tendering procedures.

→recommendation 8: set clear boundary conditions when starting a green procurement system.

→recommendation 9: consider the development of European guidelines on LCAs of asphalt, in line with the Dutch Product Category Rules.

This system relies also on the quality of the data available. Datasets driving the LCA results of the asphalt mixtures, namely binder, aggregates and transport datasets, should be carefully modelled with high quality primary data to ensure that results of the sustainability analysis are reliable. The comparison of tools showed clearly that it is undesirable to mix datasets from different tools, even though the methodologies may seem similar, because the background databases can have huge and unexpected influence on the final results.

→recommendation 10: never mix results generated with different tools or databases.

Uncertainty estimation of LCA data demonstrated that there are high levels of uncertainty in the processes that contribute to the environmental impacts. As a general rule of thumb, a process will have clear impact on the reliability of an LCA study results if it has a high impact and a large standard deviation. Sensitivity analyses can be used to identify the phases that contribute the most to the overall uncertainties. In the assessment of pavement activities, durability revealed to be a crucial factor. Uncertainties in durability have a direct effect on uncertainties of a whole project or study.

→recommendation 11: implement a basic form of uncertainty analysis in each project where sustainability is involved. The most basic form is to investigate the processes which are most impactful, and which have the largest standard

deviations.

→recommendation 12: be extremely careful with uncertainties in durability. When durability is involved (for example in scenario analysis of pavement activities), make sure that uncertainties are addressed, for example by using ranges and by quantifying the impact on the results. When anyone will receive benefits from a long durability, make sure that this decision is based on the worst-case scenario of durability.

Overall, this study highlighted the crucial role of critical judgement in sustainability assessment for NRAs. This does not mean that the NRAs have to become experts in sustainability or statistics, but it challenges them to think critically of what they really want to achieve and how they organize their systems. To achieve sustainability goals successfully, it is indispensable to take durability critically into account. The biggest challenge, for NRAs, innovating companies, sustainability researchers and statisticians altogether, is to reduce the uncertainties in durability predictions and thereby to support sustainability statements. Without reliable durability predictions, sustainability goals might easily be missed.

N.B. The PavementLCM framework has been updated in July2021, hence in this exercise some of the suggested elements of the SA exercise for pavement activities (i.e. refer to 1 reference service life, include Module D) might not be present since the content of this deliverable refers to a previous version of the framework

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Abbreviations

AB2P - AllBack2Pave

CEDR – Conference of European Directors of Roads

EoL – End-of-Life

GSA - Global Sensitivity Analysis

LCA – Life cycle Assessment

LCC – Life Cycle Costing

LCCA – Life Cycle Costing Assessment

LCM – Life Cycle Management

LSA - Local Sensitivity Analysis

LTA – Low Temperature Asphalt

NRAs – National Road Authorities

PA - Porous Asphalt

PDF - Probability Distribution Functions

PMB - Polymer Modified Bitumen

RAP – Reclaimed Asphalt Pavement

SA – Sustainability Assessment

SMA - Stone Mastic Asphalt

WC – Wearing Course

WP – Work Package

Table of content

1 Introduction

The CEDR Transnational Research Programme was launched by the Conference of European Directors of Roads (CEDR). CEDR is the Road Directors' platform for cooperation and promotion of improvements to the road system and its infrastructure, as an integral part of a sustainable transport system in Europe. Its members represent their respective National Road Authorities (NRA) or equivalents and provide support and advice on decisions concerning the road transport system that are taken at national or international level.

The participating NRAs in the **CEDR Call 2017: New Materials** are **Austria, Belgium-Flanders, Denmark, Germany, Netherlands, Norway, Slovenia, Sweden** and the **United Kingdom**. As in previous collaborative research programmes, the participating members have established a Programme Executive Board (PEB) made up of experts in the topics to be covered. The research budget is jointly provided by the NRAs as listed above.

National Road Authorities in Europe have an increasing interest in implementing sustainability assessment of roads and road infrastructure to tackle the following main goals:

- Be able to manage their assets in a more efficient way, thus reducing costs;
- To help their countries comply with carbon emission reduction goals;
- Reduce environmental impacts of road construction and maintenance, meaning also a reduction in resource usage through the re-use and the recycle of waste materials;
- Reduce the social impact of roads through noise reducing pavement and minimizing hindrance for road users (travel delays due to maintenance).

However, the interdisciplinary approach needed, vast number of tools, impact assessment methods, databases and environmental impact indicators can be overwhelming and make sustainability assessment seem to be more difficult than it needs to be.

This can hamper the effective implementation and systematic application of sustainability assessment methodology by NRAs.

Therefore, the PavementLCM project counts with the WP2 - LCM Knowledge transfer and WP3 - Sustainability data collection & analysis. The WP3 complements the WP2 which designs a framework for sustainability assessment implementation divided in 3 levels, from the most basic knowledge needed, provided in level 1, the first steps to be taken, provided in level 2, until the full implementation of sustainability assessment, described in level 3.

The WP3 provides a practical example of how to perform a sustainability assessment based on available data, tools and the experience gathered by NRAs that already have sustainability assessment incorporated in their routine work. The sustainability assessment presented in this deliverable was performed according to the European Norm EN 15804.

This deliverable from WP3 was written according to the guidelines provided in the chapter 5 of the D2.1 and it is part of the level 2 and 3 of the sustainability assessment framework developed in WP2.

2 Goal and Scope

Through interviews, questionnaires and a workshop with European national road authorities (NRAs) and market parties, a few opportunities[5] to help them implementing sustainability assessment were identified.

During the conversations with NRAs they often expressed the wish for guidelines and methods to support green procurement. They requested reading material that explains in a simple way all the principles and actions needed to get started in a pragmatic way and a roadmap with a clear path from square one to full implementation.

It was a consensus that case studies are very useful to understand how to perform a sustainability assessment themselves. This report contains sustainability assessment case studies that deliver a clear overview of costs, environmental and social impacts together covering the sustainability assessment of a road's wearing course considering only the most important indicators from the NRA's perspective.

The precise goal and scope of the following case studies are described in detail in the following sub-sections.

2.1 Goal

To provide the NRAs with the tools they need for successfully implement sustainability assessment in their work routine the goal of this report is rather broad.

The following list expresses the main three goals: showcasing sustainability practices, investigating sustainability and introducing uncertainties.

1. **Showcasing how to implement sustainability**
    - to help the road authorities in their sustainability knowledge by giving an overview of the sustainability assessment methodology and how to apply the framework proposed in D2.1.
    - To showcase how to perform a full sustainability assessment of six case studies, covering costs, environmental and social impacts.
2. **Investigating the factors influencing the Sustainability of asphalt**
    - To provide insight in the sustainability of several innovative technologies for asphalt mixtures.
    - To provide insight in the long-term effects of different pavement activities over the life cycle of the pavement, by including maintenance schemes.
    - To show the applicability of different Sustainability Assessment tools, how and why their results vary.
3. **Introducing uncertainties knowledge in Sustainability Assessments**
    - Analyse the uncertainties involved in sustainability assessment in a simple way so that such an analysis can be reproduced by NRAs.
    - Show of how big the uncertainties can be and give guidelines on how to take them into account for reaching robust results and conclusions.

[5] See the chapter 3 and 4 of the D2.1 for more detailed report of the interview & questionnaire results.

2.2 Intended audience

The target group for this study is primarily the National Road Authorities (represented in CEDR), who commissioned the PavementLCM project. The content of this report could also be of interest for road authorities and road administrators in other (non-European) countries who are seeking to assess and improve the sustainability of their roads. Thirdly, the asphalt and construction sector will have to take their role in this sustainability transition and this report is meant to inform them as well.

This report shows how to make the sustainability assessment of different types of asphalt layers, where environmental performance, costs and social aspects are taken into account also including technological innovations that aim for a better environmental performance while keeping costs and uncertainties into perspective.

2.3 Intended application

This study is intended to be used as an example of how to apply the guidelines provided in chapter 5 of Deliverable 2.1. It is also intended a reproducible example of how to perform an assessment that covers all the three pillars of sustainability and keeps the inherent uncertainties of such studies in perspective.

This report can also be used as a step-by-step guide of a practical sustainability assessment exercise according to the framework described in D2.1.

2.4 Scope

In this study six asphalt mixtures for wearing courses were evaluated in three different Sustainability Assessment tools considering economic, environmental and social indicators as well as uncertainties. Base and sub-base layers, underlying infrastructure such as signs, pavement markings, lighting etc. are out of the scope. In the scenario analysis, a binder layer and a tack coat are included.

A more precise description of the scope is given in details in terms of the elements listed in Table 1 below.

Table 1: Elements for scope definition and where to find them within this report.

Element of LCA study	Description in section
Asphalt mixtures and technologies included	2.4.1
Functional unit	2.4.2
System boundaries and life cycle stages	2.4.3
Analysis period	2.4.4
Indicators	2.4.5

2.4.1 Case study selection process and criteria

To select the case studies and tools to be analysed in this report the target audience was consulted through interviews and a workshop.

During the 1st CEDR PavementLCM workshop – Sustainability Assessment of Road Pavement at the University of Nottingham on 25th June 2019 four topics were discussed with the 20 participants from several National Road Authorities, industry and academia from which two are relevant.

1. Identification of innovative and greener asphalt mixtures for the case studies
2. The definition of the relevant sustainability indicators

The technologies identified as greener and therefore interesting to include in the case studies were:

- the use of recycled materials in asphalt production (RAP), because of the promising perspective of reducing costs during production;
- production at lower temperatures, which should allow to increase the content of recycled materials and reduce energy consumption during production, what ultimately also should lead to cost reduction;
- mixtures with extended service life, which reduce the need for maintenance and traffic disruption;
- Use of Polymer Modified Bitumen (PMB) as a way to reduce layer thickness and extend the service life of pavement components produced with recycled materials.

Apart from that it was decided to focus on wearing courses and two asphalt types, Stone Mastic Asphalt (SMA) and porous asphalt (PA) since they are the most widely used asphalts in highways throughout Europe and the United Kingdom.

The description of the asphalt technologies and the exact mixtures can be found in sections 2.4.1.3 till 2.4.1.8 and 2.4.3.1 respectively.

2.4.1.1 Tools

The selection of tools for the case studies has also been discussed and defined during the 1st CEDR PavementLCM workshop.

To choose from the tools described in the sustainability compass tool certain criteria needed to be met.

First of all the tools should provide environmental impact results in terms of the indicators described in section 2.4.5.

Second, the tool should provide datasets for different asphalt mixtures, asphalt components including RAP and low temperature asphalt or allow the inclusion of user defined mixtures to incorporate the mixtures described in section 2.4.3.1 in details.

The Table 2 below shows all the tools considered in the selection process and their characteristics considering the indicators of interest and modelling possibilities.

Table 2: Softwares included in the selection process of tools for the case study and the set of indicators and datasets available in them.

Tool	CO2	Air Quality	Costs	Components model-it-yourself (MIY) or predefined?	RAP	Low temp	Other green asphalt datasets
DuboCalc	Yes	NOx	No	Predefined	AC surf +	LEAB (base	No

Tool	CO2	Air Quality	Costs	Components model-it-yourself (MIY) or predefined?	RAP	Low temp	Other green asphalt datasets
					30% RAP	layer)	
					AC bin/base + 50% RAP	Greenway LA	No
EcoChain asphalt model	Yes	NOx	No	MIY	Can be modelled	Can be modelled	Additives based on ecoinvent
asPECT	Yes	No	No	MIY	Can be modelled	Probably - Can be modelled	Can be modelled
Athena	Yes	PM, O3	Yes	Predefined and MIY	Can be modelled	Can be modelled	No
Ecorce	Yes	O3 in kg ethylene eq.	No	MIY	Can be modelled	Can be modelled	No
SimaPro	Yes	NOx, PM, O3	Yes	Predefined and MIY	Can be modelled	Can be modelled	Can be modelled
GreenDOT	Yes	No	No	Predefined and MIY	Can be modelled	Can be modelled in terms of % of CO2 savings in relation to HMA	Crumbed rubber
PaLATE	Yes	NOx, PM	Yes	MIY	Can be modelled	No	Crumbed rubber
SMART SPP LCC	Yes	No	Yes	MIY	Can be modelled, but labour intensive	No	Can be modelled, but labour intensive
LCC AM-QM	No	No	Yes	No	No	No	No
LCCA express	No	No	Yes	No	No	No	No
RealCost LCCA - FHWA	No	No	Yes	No	No	No	No

Athena, Ecorce M and SimaPro were the tools selected for the tool analysis where the six mixtures were modelled, their environmental impacts were calculated, and the results obtained with the three tools were compared.

Each of these tools is different regarding their characteristics, resources, accessibility, user friendliness and how appropriated they are for performing Sustainability Assessment of roads.

A thorough analysis of all the tools considered can be found in the info sheets of the sustainability compass tool.

2.4.1.2 Asphalt mixtures and technologies

In conversation with NRAs and market parties five case studies and one reference mixture were chosen for this analysis. For the reference mixture SMA was chosen because of its widespread use in Europe. PA is included because of its noise reduction properties which contribute to less stress caused by noise thus being beneficial from the social point of view. For the greener asphalt, SMA mixtures produced using different innovative technologies were chosen. The innovative technologies included in this study are SMA produced at lower temperatures, high recycled content (in mass) using Reclaimed Asphalt Pavement (RAP) and one SMA and one PA with longer service life and Polymer Modified Bitumen (PMB).

All the mixtures are bituminous mixtures produced at a batch asphalt plant located in Ireland described in the D5.2 of Allback2Pave and D5 from EARN. The batch plant produces heat for warming up the asphalt using gasoil and does not have a parallel drum for heating up RAP separately when the asphalt mixtures incorporate it. This means that all of the aggregate is fed via the cold feed and then warmed up in the hot bins.

Table 3: Asphalt mixtures included in the study.

Asphalt type	Technology and mixture specification
SMA 16	SMA 16 – Reference
SMA 8	SMA 8 – 60% RAP content in mass with PMB
SMA 11	SMA 11 - 40% RAP content in mass with PMB + LTA (135°C)
SMA 11	SMA 11 - Long service life
PA 8	PA 8 – Top layer of a double layered porous asphalt with PMB
PA 16	PA 16 – Longer service life porous asphalt

2.4.1.3 SMA 16 – Reference (AB2P)

Stone matrix asphalt (SMA) is a hot mix asphalt mixture with about 4% air voids and high content of binder and fibres.

It is a gap-graded HMA (Figure 1) that is designed to maximize deformation (rutting) resistance and durability by using a structural basis of stone-on-stone contact (Figures 2-6). Because the aggregates are all in contact, rut resistance relies on aggregate properties rather than asphalt binder properties. Since aggregates do not deform as much as asphalt binder under load, this stone-on-stone contact greatly reduces rutting.

SMA is generally more expensive than a typical dense-graded HMA (about 20 – 25 percent) because it requires more durable aggregates, higher asphalt content and, typically, a modified asphalt binder and fibres.

In the right situations it should be cost-effective because of its increased rut resistance and improved durability. SMA, originally developed in Europe to resist rutting and studded tire wear. (Drüschner & Schäfer, 2000)

2.4.1.4 SMA 8 – 60% RAP content in mass with PMB (AB2P)

This mixture has the same profile as the SMA 16, but the size of the largest aggregate grade used is smaller which results in smaller voids between the large stones which is filled with the smaller grade aggregate.

The main difference in this case is the 60% RAP content in mass and the use of PMB instead of bitumen and the service life which is expected to be shorter than the primary SMA 16 since it is a technology under development.

2.4.1.5 SMA 11 - 40% RAP content in mass with PMB + LTA (135°C)

This mixture has the same profile as the SMA 16, but the size of the largest aggregate grade used is smaller which results in smaller voids between the large stones which is filled with the smaller grade aggregate.

The main difference in this case is the 40% RAP content in mass, the use of PMB instead of bitumen, the lower temperature during the mixing which is 135°C instead of 165°C and the service life which is expected to be shorter than the primary SMA 16 since it is a technology under development.

2.4.1.6 SMA 11 - Long service life SMA

This mixture has the same profile as the SMA 16, but the size of the largest aggregate grade used is smaller which results in smaller voids between the large stones which is filled with the smaller grade aggregate.

The main difference in this case is the higher bitumen content in mass, 6,6% instead of 5,5%, and the service life which is expected to be longer than the primary SMA 16 since it is a technology under development.

2.4.1.7 PA 16 – Longer service life porous asphalt (DZOAB)[6]

Porous asphalt is a mixture of bitumen, crushed rock, breaker sand, natural sand and filler (De Vos et al. 2018). It was developed in the Netherlands in the seventies, motivated by traffic-safety since the open structure of the material ensures that no water remains on the road surface.

As a result, the skid resistance and the view of the road remain good during rain (there is no aquaplaning and splashing and spraying water). Other advantages are the very good resistance to permanent deformation (track formation), noise reduction and the quality of run-off water. (reference)

The Porous asphalt 16 with a longer service life has a composition which is similar to the regular PA but with the addition of cellulose fibres and a higher amount of bitumen per

[6] DZOAB stands for Duurzaam Zeer Open Asfalt Beton, which means sustainable very porous asphalt. It has this name because it has a longer service life compared to the regular Porous Asphalt.

ton. This causes the service life of PA to be 4 years longer than the regular variant.

2.4.1.8 PA 8 – Top layer of a double layered porous asphalt with PMB

The most common construction of a double-layer porous asphalt (PA) consists of a bottom layer of PA 16 and a thin top layer of PA 8. The finer grading is used for the top layer because it provides better noise reduction and a lower rolling resistance. Especially at driving speeds lower than 70 km / hour, the noise reduction increases considerably when crushed stone 2/5 or 4/8 is used instead of the usual crushed stone 4/16. However, the finer the mixture, the greater the chance of contamination and clogging of the cover layer.

2.4.2 Declared unit

This report includes the analysis of the sustainability of asphalt mixtures at two different levels: pavement components and pavement activities.

The material assessment is done within the six case studies proposed and includes the sustainability assessment of the materials used to build a road i.e. asphalt mixtures.

Therefore, the declared unit in this case is "*The raw material extraction, transport and production of 1 ton of asphalt*".

The results of the sustainability assessment of the six case studies will be compared within the same tool they were calculated and between the different tools used.

Sustainability assessment of pavement activities is done within a scenario analysis where a road has been laid and goes through maintenance throughout a 40-year period.

For the scenario analysis the declared unit is "*The asphalt material, transport, laying, removal, end-of-service-life treatment and disposal necessary for a two-layer road composed of wearing course and binder layer for 40 years*".

SimaPro was the tool used to perform the sustainability analysis of the pavement activities due to its modelling flexibility. No comparison amongst tools was made for the pavement activities, because the material analysis will already have shown the differences between the tools.

2.4.3 System boundaries

To describe the inventory of the case studies the guidelines from the framework (D2.1 from PavementLCM) were followed. D2.1 follows the norm EN 15804 and define the life cycle stages that are applicable to civil engineering works.

2.4.3.1 System boundaries for pavement components

The system boundaries applied to the sustainability assessment of the case studies in this report are the ones established for pavement components in the deliverable D2.1 "*Pavement LCM SoA and SA framework*".

Thus, the systems for each case study include the impacts of extracting the raw materials, pre-processing them, transport to the asphalt plant and production at asphalt plant.

The system boundaries for pavement materials/products do not include layer thickness, traffic intensity, weather conditions and other aspects affecting the road life cycle which in turn make the datasets produced in the case studies flexible and adaptable to different road scenarios.

Below you can find the Figure 1 that graphically shows the system boundaries used for the six asphalt mixtures modelled.

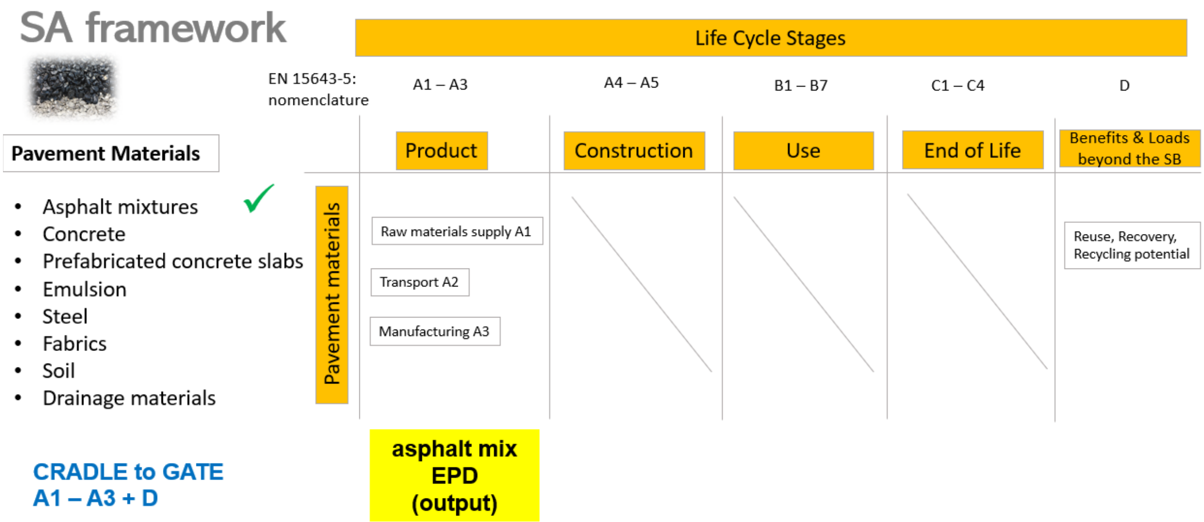


Figure 1: ***System boundaries and life cycle stages for pavement materials/products from D2.1***

2.4.3.2 System boundaries for pavement activities

The scenario analysis describes the whole life cycle of a road including the environmental impacts of a complete maintenance scheme from laying new asphalt up to removing and disposing it. Laying a new asphalt layer do include the impacts of asphalt production which was calculated for the case studies.

According to the framework in D2.1 the sustainability assessment of a road is called assessment of pavement activities because they include all the activities, machines, transport, etc. necessary to build a road.

The Figure 2 below shows graphically the system boundaries that were established for this scenario analysis.

Summarizing, the scenario analysis includes the following life cycle stages: asphalt production, laying the asphalt, leaching during use phase, asphalt removal at the end-of-service-life (EoL), processing of waste materials and secondary materials as well as all transport in between phases.

The life cycle stages are defined according to the EN 15804:2019 - Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products.

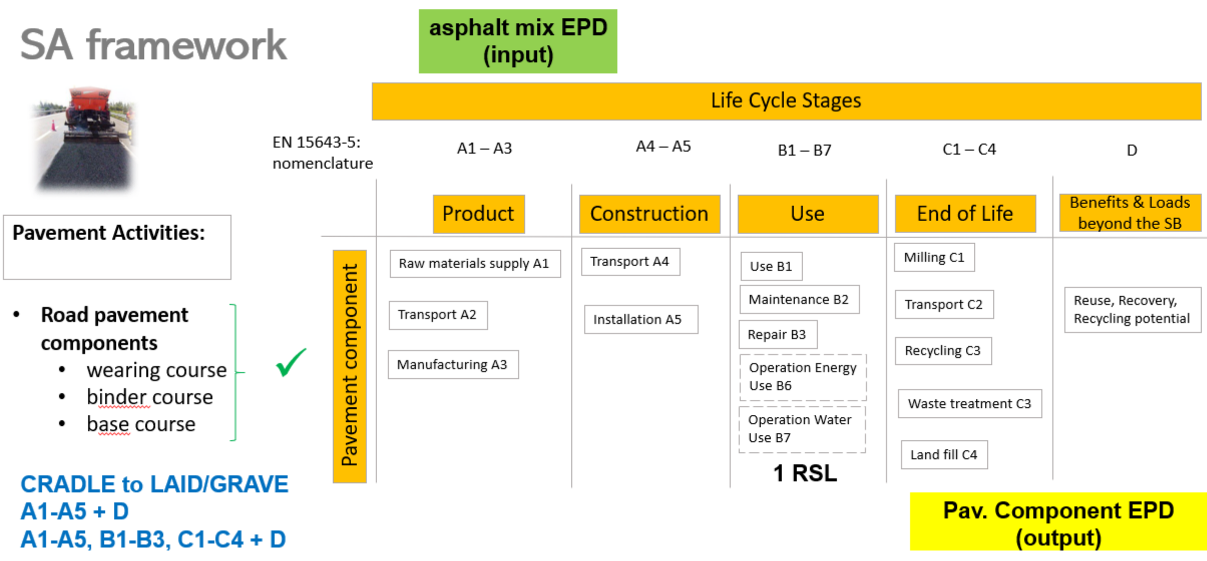


Figure 2: System boundaries and life cycle stages for pavement activities (road pavement component). Source: PavementLCM D2.1 – Framework

2.4.3.3 System boundaries for reuse, recycling and recovery

Currently many countries in Europe use asphalt mixtures that incorporate recycled materials. Therefore, some of the possible asphalt mixtures are included in the case studies as described in the section 2.4.1.2.

According to the documentation of the aSPECT tool:

"End of life is defined as the point where asphalt ceases to serve its original function in the road structure and is planed-off and moved to a stockpile or to a landfill site. This deposit is deemed to be the final point in the life cycle of asphalt. Taking planings from a stockpile in the future to serve another function constitutes the first step in another product life cycle." (Wayman, Schiavi-Mellor, & Cordell, 2020)

The following sections describe the system boundaries applied to the recycled materials used in asphalt mixtures which is applicable to the pavement materials/products analysis and the production of RAP at the end of the service life of a pavement component which Is applicable for the scenario analysis. The boundaries stablished are in agreement with the framework proposed in D2.1 and the main standards for sustainability assessment of roads such as the EN 15804.

2.4.3.3.1 Recycled content in the asphalt mixture

The recycled material most used in asphalt mixtures and asphalted pavement activities is Reclaimed Asphalt Pavement (RAP), which is the name of the secondary aggregate resulting from asphalt removal.

Asphalt mixtures with RAP in their composition only need to account for the transport from the construction materials recycling plant to the asphalt production plant because according to the EN 15804 secondary materials enter the following life cycle free of environmental burdens, which means they account for zero environmental impacts in their second life cycle.

2.4.3.3.2 Recycling of asphalt at the end of the service life

The recycling of asphalt is included in life cycle stage C2-C3, which are respectively the transport from where the asphalt has been removed to the recycling plant and the processing of the recyclable materials.

All the processes for preparing RAP to be incorporated in a new asphalt mixture, until the product reaches the "*end of waste*" status is included in life cycle stage C3 which accounts for the impacts of the fuel used by the breaking and screening machines that process the road debris and separate its different grades.

At the end of C3 the RAP is prepared to be used in the following life cycle.

2.4.4 Analysis period

For the sustainability assessment of the pavement materials/products, the case studies were modelled for a ton of asphalt independently from asphalt service life and road characteristics such as traffic intensity. However, to understand how to perform the sustainability assessment of a road it is necessary to analyse it as a whole for a period of time that covers small and major maintenance.

To provide NRAs with a valuable example and guidance on how to use sustainability assessment in an effective way we provide a scenario analysis for pavement activities, where the sustainability of a road is analysed through a period of 40 years. This allows to observe the effects of a road's characteristic on its sustainability, by including service life which depends on traffic intensity and road type and maintenance.

> N.B. An alternative approach, as suggested in the framework, would be to perform a project-level analysis and consider the period covering a major maintenance in each specific project. Normalisation can be used to compare results amongst alternatives

2.4.5 Indicators

The indicators used in this study have been previously defined during the 1st CEDR PavementLCM workshop – Sustainability Assessment of Road Pavement in a discussion with all the participants. The indicators selected reflect what NRAs consider to be the most important aspects of sustainability assessment of roads.

According to the feedback received from the NRAs, the usual list of more than 10 environmental indicators was overwhelming and unnecessary so 1) Global Warming Potential, 2) energy consumption, 3) recycled material content, 4) cost, 5) tyre-pavement noise and 6) durability are the indicators that represent NRA's priorities and are a reasonable number of indicators, meaning that results are easier to understand and to start implementing sustainability assessments in their work flow. 7) "air quality" was a seventh indicator which is optional.

The indicators listed in the Table 4 below have been selected amongst those detailed in D2.1.

> N.B. The table of indicators has been updated in July2021, hence in this exercise some indicators might not present since the exercise refers to a previous version of the framework

Table 4: Indicators selected for the sustainability assessment of an asphalt layer according to D2.1-Framework.

Indicator	Sustainability pillar/category	Methodology for calculation
Global Warming Potential	Environment	Life Cycle Assessment (LCA)
Energy use	Environment	Life Cycle Inventory (LCI)
Secondary materials consumption	Environment	Life Cycle Inventory (LCI)
Air pollution (optional)	Environment	Life Cycle Assessment (LCA)
Cost	Economy	Life Cycle Cost Analysis (LCCA)
Tyre-pavement noise	Technical and functional requirements / Social	Laboratory tests
Durability	Technical and functional requirements	To be defined in WP4 of PavementLCM

2.5 Assumptions and limitations of the study

No other layers are included in the study which is focused on top layers.

Regarding the life cycle of the six mixtures studied, they go through a similar production process varying only their compositions and energy consumption. The transport distances between the asphalt plant and the road construction site are presumed equal for all scenarios. Further, we consider that the differences in the impact of performing the activities of laying the asphalt, removing it and treating RAP are negligible and therefore were calculated as the same effort for all mixtures.

2.6 Data quality

Diverse data sources were used for modelling the asphalt mixtures in the case studies, the SMA 16 containing PMB and 60% RAP was taken from D5.2 and D5.3 from CEDR project AllBack2Pave, where LCA and LCC data is provided. For the reference SMA 16 and the SMA 11 containing polymer modified bitumen, 40% RAP and produced at low temperature (135°C) the data was taken from D5 from EARN CEDR project.

The LCA data for SMA 11 with extended service life, PA 8 and PA 16 mixtures was taken from de Vos et al. (2018) and the LCC data was provided by Rijkswaterstaat.

This means that all main processes were modelled with primary data provided by road authorities while the processes upstream in the supply chain were taken from EcoInvent v3.5.

The LCC data was taken from one single source for all asphalt types. It is described in the D5.2 from CEDR project AllBack2Pave and most of it has been provided by Matthew Wayman from Highways England for D5 from EARN CEDR project, therefore cost data is more representative of North and Central Europe. However, as prices fluctuate on a yearly basis, they should constantly be updated to allow a good quality cost assessment.

Table 5: Data quality aspects.

Data quality aspect	SMA 16 (reference)	SMA 11 (PMB, 40% RAP) produced at low temperature	SMA 16 (PMB, 60% RAP)	PA 8 and PA 16
Age of data and length of time covered	2014, one batch	2014, one batch	2015, one batch	2018, one year
Geographical coverage	Europe	Europe	Europe	Netherlands
Technology coverage	Hot mix asphalt, without recycled content.	Warm mix asphalt, with recycled content.	Hot mix asphalt, with recycled content.	Noise reduction, hot mix asphalt, without recycled content.
Completeness	100%	100%	100%	100%
Representativeness	These asphalt mixtures and technologies are representative of average mixtures used in Europe.			
Data sources	AB2P D5.2	EARN D5	AB2P D5.2	(Vos-Effting, et al., 2018)

3 Description of case studies, tools and scenarios

The coming subsections describe accurately the case study selection process inventory data used for the LCA and LCCA assessment of all six asphalt mixtures selected for the case studies and the scenario analysis.

3.1 System description and inventory of pavement materials/products case studies

Six case studies were designed to allow the sustainability assessment of one tonne of asphalt for different mixtures from Cradle to Gate and to compare their performance from environmental, economic and social points of view. These system boundaries are better described in section 2.4.3.1 System boundaries for pavement components.

The complete life cycle of a road is described and analysed in sections 3.2 and 4.2 respectively.

This will be demonstrated in the scenario analysis section where the impacts of a road as a whole are calculated, considering traffic intensity, service life, layer thickness, length and width of lanes, number of lanes and an analysis period covering maintenance works.

The six asphalt layers analysed have different characteristics and sustainability performances. Their environmental impacts and economic performance of mixtures containing high recycled content, low temperature mixtures or long service life mixtures will be compared with a reference asphalt mixture.

An analysis of the results of the case studies to determine which of the six options is the greener asphalt mixture was carried out in SimaPro 9 using EcoInvent 3.5 and to be consistent with the EN 15804 the impact assessment method *CML baseline V3.05* was chosen.

3.1.1 A1 - Raw material extraction and processing of secondary material input

From the six asphalt mixtures selected, SMA 16 is the reference mixture. All the other mixtures are SMAs with different compositions or Porous Asphalt mixtures with different durability.

Table 6 shows the composition of teach asphalt mixture used in the case study and Table 7 shows the costs per ton material and per amount used in each mix.

Table 6: Composition of the asphalt mixtures used in the case studies. The materials are given in percentage of the total mass.

Asphalt types	SMA 16	SMA 11	SMA 8	SMA 11	PA 8	PA 16
	(reference)	40% RAP+ PMB+LTA (135°C)	60% RAP + PMB	(long service life)	PMB	(long service life PA)
Material	Amount (% of mass)					
RAP[7]		38.20	60.00			
Bitumen	5.57			6.60		5.20
Polymer modified bitumen		4.71	3.48		5.20	
Weak filler	7.05	5.67		1.40		
Medium filler					5.00	5.10
Fibres			0.30	0.30		0.20
Crushed rock fines	22.31	16.99		24.10	6.80	4.30
Gravel	65.07	34.40	35.62	67.60	83.00	85.20
Additive		0.03 (cecabase[8])	0.60 (storbit)			
Data source	AB2P D5.2	EARN D5	AB2P D5.2	AB2P D5.2	(Vos-Effting, et al., 2018)	(Vos-Effting, et al., 2018)

[7] Because RAP is a secondary material, in line with the EN 15804, it has no environmental burden allocated to it. The norm determines that 100% of the burden of secondary materials gets allocated to the first life cycle.

[8] CECABASE™ RT945 is a surfactant belonging to the chemical family of "imidazolines". It can be further classified as an amphoteric surfactant because it has both acidic and basic properties.

Table 7: Material costs (A1) per asphalt mixture.

Asphalt types		SMA 16 (reference)	SMA 11 40% RAP+ PMB+LTA (135°C)	SMA 8 60% RAP + PMB	SMA 11 (long service life)	PA 8 PMB	PA 16 (long service life PA)
Material	Costs in € per ton material	Costs in € per ton asphalt mixture					
RAP	0.01	4.20	6.60	0.00	0.00	0.00	0.00
Bitumen	36.21	0.00	0.00	42.90	0.00	33.80	36.21
Polymer modified bitumen	0.00	34.42	25.43	0.00	38.01	0.00	0.00
Filler (lime)	1.41	1.13	0.00	0.28	0.00	0.00	1.41
Medium filler	0.00	0.00	0.00	0.00	1.00	1.02	0.00
Fibres	0.00	0.00	2.70	2.70	0.00	1.80	0.00
Crushed rock	3.74	2.85	0.00	4.04	1.14	0.72	3.74
Gravel	10.90	5.76	5.97	11.32	13.90	14.27	10.90
STORBIT	0.00	0.00	8.10	0.00	0.00	0.00	0.00
Cecabase	0.00	1.67	0.00	0.00	0.00	0.00	0.00

3.1.2 A2 – Transport of raw materials to asphalt production plant

The goods need to be transported from their production site to the asphalt production plant. This incurs environmental and economic costs which are listed in the Table 8 below.

Transport from production site to asphalt production plant for Central and Northern Europe extracted from the AllBack2Pave data.

Table 8: Transport distances and costs per km of transport. Source: Transport mode, distances and prices according to deliverable D5.2 from AllBack2Pave (2015).

Product	Transport mode	Transport distances one way (km)	Cost (€ per km)
RAP	Rigid>17t, 20t payload	70	
Bitumen		160	
Polymer modified bitumen		160	

Product	Transport mode	Transport distances one way (km)	Cost (€ per km)
Filler (lime)		0	1.03 €/km[9]
Crushed rock and sand		70	
Gravel		70	
Fibres		375	
STORBIT	Articulated >33 t, 24 t payload	1160	
Cecabase		1160	
Polymer modified bitumen	Product tanker	793	€0,14 per 24 t payload per km
STORBIT		107	€7,76 per 24 t payload per km
Cecabase		107	
STORBIT	Rail freight	51	€5,37 per 24 t payload per km
Cecabase		51	

3.1.3 A3 – Asphalt production (manufacture)

The reference SMA, the SMA 60% RAP + PMB, SMA 11, PA8 and PA 16 mixtures were produced at 150°C while the low temperature SMA was produced at 130°C.

Table 9: Energy needs for asphalt production at plant and their respective cost per ton asphalt produced.

Component	Electricity consumption	Diesel consumption
SMA ref.	4,8 kWh per ton asphalt €0.14/ton asphalt	1.60 l/t (€0.74 per litre oil)
SMA 60% RAP + PMB		1.60 l/t (€0.74 per litre oil)
SMA 40% RAP+LTA (130°C)		1.40 l/t (€0.74 per litre oil)
SMA 11		1.60 l/t (€0.74 per litre oil)
PA 8		1.60 l/t (€0.74 per litre oil)
PA 16		1.60 l/t (€0.74 per litre oil)

[9] To calculate the cost per ton asphalt the cost per km (1.03€) was divided by the truck payload, multiplied by the amount of material necessary to produce a ton asphalt, then multiplied by the transport distance in km and finally adjusted with a factor of 1.15 for the 15% average idle payload.

3.2 *Tool characteristics and use*

3.2.1 Athena

Athena is a Northern American tool, which contains its own database with pavement materials/products and machines. Each asphalt mixture was modelled as a "project", otherwise it would not be possible to model the six case studies. Six projects containing one "Roadway" with one "Lane" and "Lift" were defined.

For each "Roadway" the road dimensions and the "material" of the asphalt layer were defined so that the total mass of asphalt added up to one tonne. "Material" means the type of asphalt used to pave the road.

The asphalt mixtures of the case studies were not directly available in the software, therefore it was necessary to add them to the library, where the asphalt type "WMA" could be selected among hot mix asphalt and concrete types. Material contents in the asphalt mixtures were defined in terms of % mass.

Polymer modified bitumen and additives were not available in Athena's database, therefore it was necessary to model them with proxy datasets in order to consider their footprint in the calculations. While datasets for "RAP aggregate", fine and coarse aggregates, fillers and polymer modifiers are readily available to model roads.

After providing the road dimensions for one tonne of asphalt, the transport distances were set for each material. The energy usage in an asphalt plant is automatically calculated by the software when the "product type" is selected.

Regarding the life cycle stages of asphalt, Athena allows to include the transport to construction site (A4), laying (A5) and removing (C1) the asphalt, tyre-pavement interactions, emissions during the use phase of the road (B1), maintenance schemes and other functionalities. However, these life cycle phases are beyond the system boundaries of these case studies. These life cycle phases will be addressed in the sustainability analysis of pavement activities (section 4.2).

According to the documentation of Athena, the calculation of the environmental impact indicators is performed using TRACI impact assessment method (Bare, 2011).

3.2.2 Ecorce M

Ecorce contains its own database with pavement materials/products and machines. Each asphalt mixture was modelled in the tool in one "project" so that all the results could be extracted together. Six wearing courses with one "operation" were defined. For each layer within an operation it was possible to select the layer type, dimensions and the type of material (bituminous, tack coat, base etc).

The software only allows to calculate environmental impacts for a road or a layer of a road instead of a ton of material, therefore the dimensions for a fictive road were specified in the tool in order to result in 1 ton of material.

After providing the road dimensions, the composition of the wearing course was set as a content percentage of each material per asphalt layer, plus transport distances[10].

The energy usage in an asphalt plant is automatically calculated by the software when the "type of coating" is selected. Options for hot mix, warm mix, semi warm mix and cold mix

[10] Ecorce provides the possibility to model transport of raw materials for five different transport modes.

can be selected.

Polymer modified bitumen and several datasets for including reclaimed material in the asphalt mixtures were available in the dropdown menu to model the asphalt mixture, on the other hand, there is no dataset available for additives used to produce high recycled content or warm asphalt mixtures.

According to Ecorce M documentation the calculation of the environmental impact indicators are performed with a modified version of the CML 2001 impact assessment method (Guinée, et al., 2002).

Other functionalities from Ecorce M that were not used in the case studies include modelling the transport to construction site (A4), laying (A5) and removing (C1) the asphalt layer. However, the tool does not support the modelling of transport of waste materials (C3) and their treatment (C4).

3.2.3 SimaPro

SimaPro is a general LCA tool that allows to model any type of product or project, thus it does not offer a road-based framework to perform sustainability calculations for roads and road components.

Therefore, several aspects of each asphalt mixture have to be modelled up to the smallest details, such as the amount of diesel consumed to transport a determined material depending on the transport mode, type of vehicle, distance and mass transported as well as the number of trips and a loading factor. This means that a vast LCA knowledge is needed and that the workload is relatively big for each model. On the other hand, it makes possible to model accurately all the asphalt mixture characteristics and aspects of the life cycle described in the previous section 3.1.

From the databases available in SimaPro, EcoInvent 3.5 was used to model the six case studies. There are two reasons to use EcoInvent, first it is the most comprehensive database available and second it is widely used for life cycle assessment studies.

For stones and sand there are different datasets available, but the user must choose the most suitable as an asphalt component. Road grade bitumen, fillers and reclaimed materials are not directly available as datasets, therefore they have to be modelled using the datasets available to better represent the products used in asphalt production.

SimaPro also contains several environmental impact assessment methods, including TRACI, which is used by Athena, and CML 2001, the method that has an adapted version in Ecorce. For the sake of results comparability the impacts of the asphalt mixtures modelled in SimaPro were calculated using both methods so that the results could be compared with those of the other tools.

3.3 System description and inventory of pavement activities scenario analysis

3.3.1 Introduction to the scenarios

This section is dedicated to describe the setup of the scenarios regarding the scope, asphalt layers and other elements included and other details necessary to understand the results and analysis in section 4.2.

In this scenario analysis we will illustrate how several road pavement materials/products compare to each other when a road and its maintenance scheme are taken into account.

All scenarios include the life cycle of an existing road composed of a foundation layer, binder layer and wearing course analysed over a period of 40 years. Because foundation layers tend to last much longer than the proposed analysis period, they were not included in this analysis.

Impacts from removing old asphalt layers, producing the asphalt, all transport and effects of disposing and recycling asphalt materials were included, all other activities such as installing signs and painting markings are out of the scope.

Moreover, the road characteristics are the same for all scenarios considered, this means that traffic intensity, number of lanes, extension etc. are the same for all scenarios, thus the service life variation of wearing courses only depend on the type of asphalt being used.

3.3.2 Description of the products analysed in the scenario analysis

The asphalt mixtures 1, 2, 3 and 4 described in section 3.1 were used as wearing courses for the scenarios, besides that an extra mixture was added. This extra mixture is based on mixture 3, but using bitumen instead of PMB, in order to investigate the effects of high RAP mixtures without the high impact PMB.

The service life of each wearing course varies according to the type of asphalt used and the service life of the binder layer varies depending on the maintenance scheme adopted for the wearing course. The expected service life for each asphalt mixture and the respective sources of information can be found in Table 10.

Table 10: Service life for each wearing course as modelled in the scenario analysis considering a road with low traffic intensity, about 10000 AADT.

Mix	Average service life (years)	Layer thicknesses
SMA 16 - reference	16*	0.030 m
SMA 11 - 40% RAP + PMB + LTA	14**	0.030 m
SMA 8 - 60% RAP + PMB	14**	0.030 m
SMA 11 - Long service life	20**	0.035 m
PA 8 - top layer 2L PA + PMB	10*	0.025 m
SMA 8 - 60% RAP + regular bitumen	14**	0.030 m
Binder layer	28-45***	0.070 m

* Based on (Keijzer, et al., 2020).

** Expert guess based on the average service life of SMA 16

*** All back 2 pave D5.2 and (Keijzer, et al., 2020).

The binder layer and tack coat are included in all scenarios with similar characteristics and composition but as they are only part of the scenario analysis, they have not been described in previous sections yet. Table 11 shows the material, energy and transport needs for production (phase A1-A3) both the binder layer and tack coat.

Table 11: Composition of the binder layer and tack coat, energy needs for production and transport. Sources: transport distances and tack coat composition were taken from deliverable D5.2 from AB2P (2015), page 27, North Europe case; Binder layer composition was taken from (Keijzer, et al., 2020).

Layer	Material	Amount per ton	Unit	Transport distance (km)
AC Binder layer	RAP	501	kg	70
	Bitumen	20	kg	160
	Sand	192	kg	70
	Gravel	277	kg	70
	Filler	10	kg	0
	Heating (Fuel oil)	1,6	liter	-
	Electricity	4,8	kWh	-
	Transport to site	-	-	43
Tack coat	Bitumen	650	kg	160
	Water	350	kg	0
	Transport to site	-	-	160

The theoretical maintenance schemes take the service lives of wearing course and binder layer into account, one of the strategies adopted is to anticipate the substitution of the binder layer to match the foreseen maintenance year of the wearing course. For the binder layer a service life between 28 and 45 years was used.

For all scenarios except for the fourth the service life of the binding layer was shortened by a few years due to the end of the service life of the wearing course in which case both layers had to be renovated. The analysis period starts at year 0 with the substitution of a wearing course and a binder layer at an existing road.

The exact maintenance schemes used in the scenario analysis are given in Table 12. The number of life cycles are not round numbers because the asphalt layers are not necessarily at the end of their life cycle after 40 years, which is the analysis period. The asphalt layers with remaining service life time at the end of the analysis period, are thus only included proportionally.

Table 12: Maintenance schemes for the six scenarios with the maintenance years for each case and the amount of life cycles calculated for each layer in the scenario. WC = Wearing course, Binder = binder layer.

		Scenarios					
		1	2	3	4	5	6
		SMA 16 - reference	SMA 11 - 40% RAP + PMB + LTA	SMA 8 - 60% RAP + PMB	SMA 11 - Long service life	PA 8 - top layer 2L PA + PMB	Alternative Mixture 36 - 60% RAP + Bitumen
Maintenance year	0	WC + Binder	WC + Binder	WC + Binder	WC + Binder	WC + Binder	WC + Binder
	10					WC	
	14		WC	WC			WC
	16	WC					
	20				WC	WC	
	28		WC + Binder	WC + Binder			WC + Binder
	30					WC + Binder	
	32	WC + Binder					
	40				WC + Binder	WC	
Life cycles	Wearing Course	2.50	2.86	2.86	2.00	4.00	2.75
	Binder Layer	1.25	1.43	1.43	1.00	1.33	1.43

3.3.3 Description of the case study for the scenario analysis: road characteristics

The scenarios analysed include at least one event of major maintenance work, which is when the wearing course and binder layer have to be substituted at the same time.

The scenarios are modelled based on an average highway road in Northern Europe, composed of three layers, a wearing course, a binder layer and a foundation layer, though the foundation layer is out of the scope of this analysis. The road also has two lanes in each direction and two shoulders, as shown in Figure 3.

In all scenarios, maintenance occurs on the whole extension of the road.

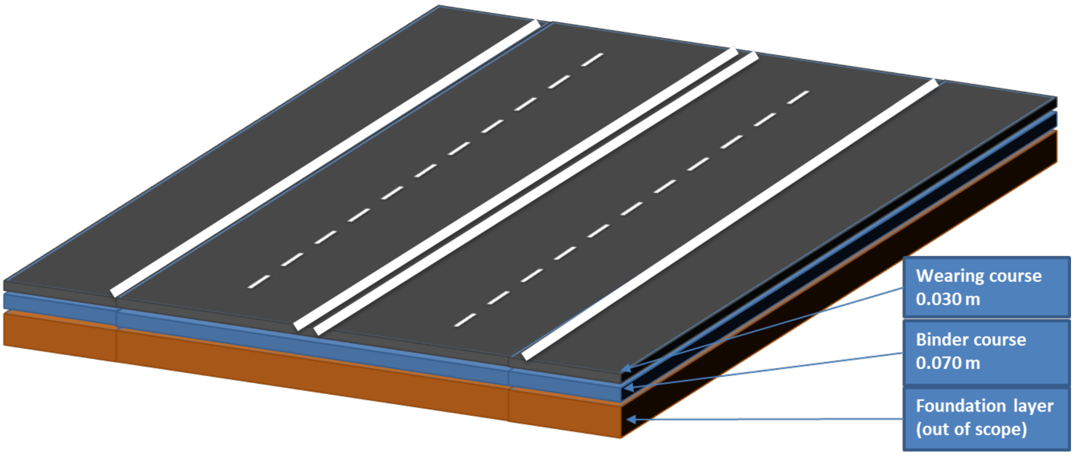


Figure 3: Graphic representation of the layers of a road as modelled in the scenario analysis. Layer thicknesses as shown in this figure are valid for scenarios 1 to 3 and 6.

This average road has low to moderate traffic and two lanes in each direction of 3.5 m width plus one shoulder of 1.25 m width on each side totalling 16.5 m width and 1km length. Since the road characteristics don't change, layer thicknesses and density varied according to the asphalt type being used, this information was taken from (Keijzer, et al., 2020).

Table 13: Description of the parameters used to model the road scenario using the data provided in the deliverable D5.2 from AllBack2Pave (2015).

Pavement course	North EU
Section Width	Four lanes (3.5 m), two for each direction plus two shoulders (1.25 m) Total width = 16.5 m
Section Length	1 km
Wearing course thickness	See Table 10
Binder thickness[11]	0.070 m
Traffic intensity	Low (10000 AADT vehicles/day)
Expected service life wearing course	See Table 10
Expected service life binder course	28 - 45 years

Tack coat bitumen emulsion was applied at a rate of 0,4 l/m^2 of laid asphalt[12]. The total site area is 16500 m^2, so 6600 l or 6600 kg of emulsion is needed in total, assuming a density of 1 kg/l.

The results of the scenario analysis can be found in section 4.2.

[11] Source: the Dutch Product Category Rules for Asphalt: Keijzer et al. (2020), Product Category Rules voor bitumineuze materialen in verkeersdragers en waterwerken in Nederland ("PCR Asfalt"), v1.0.
[12] AllBack2Pave (2015), deliverable 5.2.

3.3.4 A4 – Transport to construction site

The transport distance from asphalt plant to site is considered equal for all asphalt mixtures according to the deliverable D5.2 from AB2P the distance between the asphalt plant and the work site is 198 km and is done using a lorry EURO 4 with 20t payload.

3.3.5 A5 – Laying the asphalt

Installing the asphalt demands a series of equipment and machines. In this study only the most significant ones in terms of contributions to the environmental impact of 1 ton asphalt mixture were considered. De Vos et al (2018) identified that the largest part of the impacts is cause by the fuel consumption of the asphalt spreading machine and compaction rollers.

The diesel consumption and emissions of these machines can vary depending on diverse factors such as production volume per day, the tier/stage of a machine and their power. In this study a single machine set and production rate was modelled.

To determine the diesel consumption of the asphalt machines the following formula was used:

Diesel consumption (liter/ton asphalt) = machines power (kW) x conversion factor to hp (1.361) x nominal diesel consumption (liter/hp/hour) x production volume (ton/hour)

Where a nominal diesel consumption of 0.15 liter/hp/hour was used.

Table 14: Machines used for laying the asphalt and diesel consumption.[4]

Production volume	Asphalting set	Machine stages	Diesel consumption
75.5 t/h	Asphalt spreader 127 kW and rollers 55 kWp + 22 kW	75% stage IIIb 25% stage IV	0.57 l/ton

3.3.6 B - Use phase

The use phase accounts for the impacts that arise as a consequence of the use of the road such as pavement and vehicle interactions and the emissions of substances leached from the asphalt layer due to weathering.

Leaching does have some environmental impacts in the use phase of asphalt and might lead to significant increase of toxicity impacts for porous top layers (de Vos et al. 2018). However, since these impacts are highly uncertain, currently under revision and only contribute about 5% of the total environmental impact for porous top layers and less than 1% for dense top layers it is not included (de Vos et al. 2018). Also, since this CEDR study focuses primarily on CO_2 emissions, resources and air quality, toxicity does not influence in the impact assessment results and they can be omitted.

N.B. The PavementLCM framework has been updated in July2021, hence in this exercise some of the suggested elements of the SA exercise for pavement activities (i.e. refer to 1 reference service life, include Module D) might not be present since the content of this deliverable refers to a previous version of the framework.

3.3.7 C1 – Decommissioning of the asphalt layer

During milling, if it is ensured that only the surface course is removed. The properties of the high polished stone (PSV) aggregates can be preserved and reused into a new asphalt mixture, including wearing courses. In this case, the wearing course is considered to be milled separately from the other layers. After milling the asphalt, cleaning machines prepare the road for laying a new asphalt layer by removing all fine waste materials left behind.

The impacts of removing the asphalt were calculated in the same way as laying the asphalt, thus considering machine power and stages, production volume and nominal diesel consumption. The machine set for decommissioning the asphalt layer is composed of a milling machine, a sweeping truck and a road cleaner.

Table 15: Machines used for removing the asphalt and diesel consumption.[13]

Production per hour	Decommissioning set	Machine stages	Diesel consumption
150 t/h	Milling machine 403 kW Sweeping truck 300 kW Road cleaner 400 kW	75% stage IIIb 25% stage IV	1.012 l/ton

3.3.8 C2 – Transport to waste management plant

It is assumed that 50% of the RAP is forwarded to a landfill which is located 56 km away from the construction site and 50% is forwarded to a RAP treatment plant which is also at a distance of 56 km from the work site. For both the transport is done using a lorry EURO 4 with 20t payload which comes empty to the construction site and goes back completely full.

Table 16: Transport distances and destination of RAP. Source: AllBack2Pave (2015), deliverable 5.2.

Material	Destination	Transport distance	Massa
RAP	RAP treatment plant	56 km	0.5 ton
RAP	Landfill	56 km	0.5 ton

3.3.9 C3 – Waste processing for reuse, recovery and recycling (RAP)

At the end of the service life the asphalt layer is removed with the help of milling machines. The milling process decomposes the asphalt layer into particles varying composition and sizes, between 19 mm and 0.075 mm or smaller. At the end of the asphalt's service life the materials in the RAP partly lost their function due to aging processes and the fact that they cannot be completely separated from the asphalt planings.

[13] Source: the Dutch Product Category Rules for Asphalt: Keijzer et al. (2020), Product Category Rules voor bitumineuze materialen in verkeersdragers en waterwerken in Nederland ("PCR Asfalt"), v1.0.

However, RAP can still be used to make new asphalt layers which in turn spares primary materials.

In this study it is presumed that half of the RAP is forwarded to the asphalt plant to undergo screening using a Powerscreen™ Chieftain 1400 which will enable its recycling in a new life cycle and half of it is disposed at a landfill.

The machine can process 400 tons of RAP per hour and its stage 4 version has a peak power of 131 hp. Considering a nominal fuel consumption of 0.15 litres diesel per hp per hour the machine consumes 19.65 litres fuel per hour while processing 400 tons, thus the total fuel consumption to process 0.5 ton RAP amounts to 0.025 litres diesel.

Table 17: Powerscreen™ Chieftain 1400 profile according to machine producer specifications. Source: EARN deliverable D5.

Machine profile		Fuel consumption
Processing capacity	400 tons per hour	0.025 litres per 0.5 ton RAP
Tier/ stage	Tier 4f / Stage 4	
Power	131 hp	
Nominal fuel consumption	0.15 litres per hp per hour	

Following the EN 15804 the losses from the recycling process were set to 1% since there is no data available providing a better estimate. This means that the machine processes 0.5 ton RAP but delivers 0.495 ton RAP.

3.3.10 C4 – Waste disposal

As not all the RAP gets recycled in the case studies half of it is forwarded to a landfill in order to demonstrate the impacts of landfilling next to the recycling option.

N.B. The PavementLCM framework has been updated in July2021, hence in this exercise some of the suggested elements of the SA exercise for pavement activities (i.e. refer to 1 reference service life, include Module D) might not be present since the content of this deliverable refers to a previous version of the framework

4 Results and discussion

The first subsection of the results analysis presents a comparison of the results obtained when the case studies are modelled in three different tools, herewith we aim to answer two questions: what happens when you calculate the environmental impacts of an asphalt mixture in different tools and why results may look different?

Following, a subsection containing an analysis of the sustainability performance of the six asphalt mixtures compared to each other is presented. The main question to be answered here is: which asphalt is greener?

Lastly, a subsection containing the results of a scenario analysis are presented. An entire road was analysed over a period of 40 years, including all life cycle stages of asphalt, i.e. from raw materials extraction to removal and disposal. In this subsection we show how to use the sustainability data for a full road considering a maintenance scheme, how to compare the results for the different mixtures and which aspects influence the results the most.

The six case studies were numbered from 1. to 6. to allow an easier identification of the mixture in the multiple graphs and tables. The numbering has been used consistently throughout the report, so that 1. always refers to the SMA 16 reference. Below you can find the mixtures along with their numbers.

1. SMA 16 - reference
2. SMA 11 - 40% RAP + PMB + LTA
3. SMA 8 - 60% RAP + PMB
4. SMA 11 - Long service life
5. PA 8 - top layer 2L PA + PMB
6. PA 16 - long service life.

4.1 Sustainability Assessment of Pavement materials/products

4.1.1 Case study – comparing sustainability performance of several asphalt mixtures

Often a sustainability analysis is performed to help determining which product from a range of similar products is the more sustainable. To answer this question for this case study, the six mixtures were analysed taking the three sustainability pillars into account, environment, costs and social aspects.

In the next sections, first, the environmental impacts (calculated by LCA) are discussed, then the economic impacts (calculated by LCC) and finally the three sustainability pillars are compared altogether in the last section.

4.1.1.1 Environmental Impacts (LCA)

This section contains an analysis of the results of the case studies and investigates which of the six mixtures is the “greener asphalt” mix.

The results and conclusions were drawn based on the set of indicators proposed by the NRA’s in the workshop in Nottingham, described in D2.1 and section 2.4.5 of this report.

Besides the two environmental impact indicators chosen by the NRAs results for a third indicator was included in the analysis, namely Eutrophication which has been defined in section 4.1.3 already.

In Figure 4 the results for Global Warming Potential for the six mixtures are shown. Raw materials (A1) is the life cycle stage contributing the most to the mixtures’ carbon footprint followed by transport (A2) and Production at asphalt plant (A3). That is the case for the other two environmental indicators as well.

Concerning Global Warming Potential, Mixture 5 is the one with the highest footprint followed by mixture 2 while mixtures 6 and 1 are the ones with the lowest impacts respectively. The Eutrophication results shown in Figure 5 are similar to the ones for Global Warming Potential.

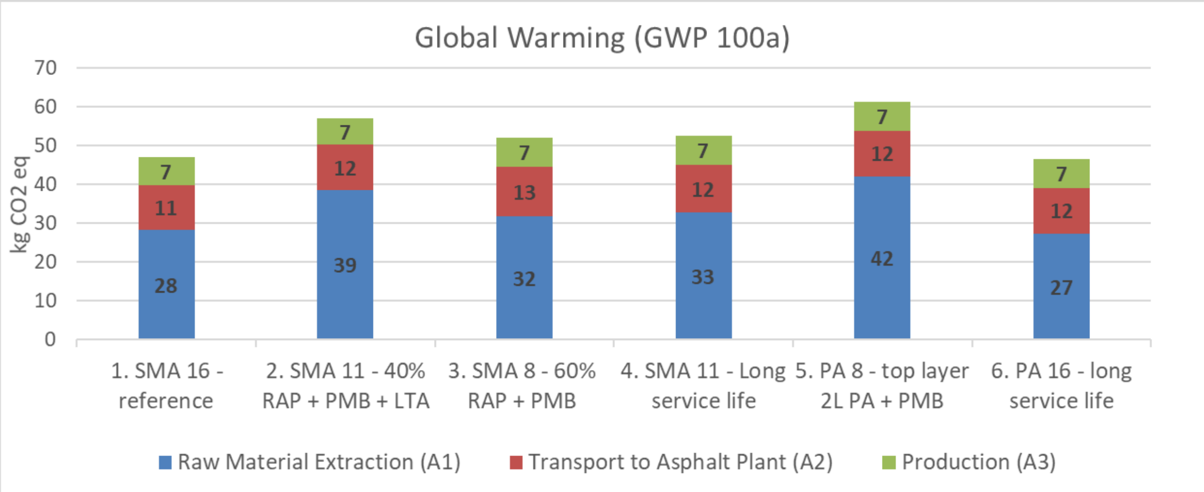
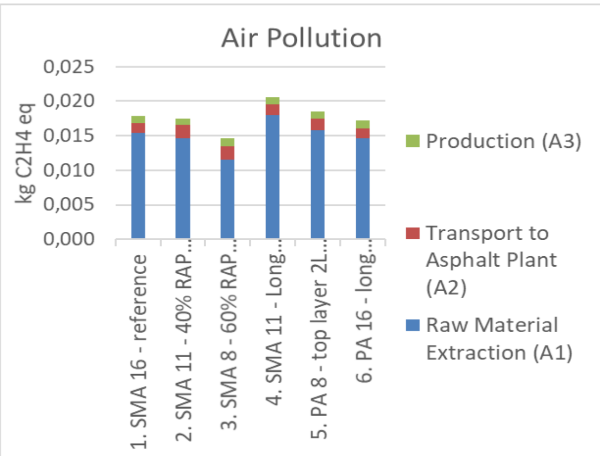


Figure 4: Results for Global Warming Potential per ton of asphalt.

For Air Pollution the mixture 3 is the one having the lowest impact, while mixture 4 has the highest.

To better understand these results it is necessary to analyse which components and processes of the asphalt mixtureture production are causing the biggest environmental impacts for each indicator.



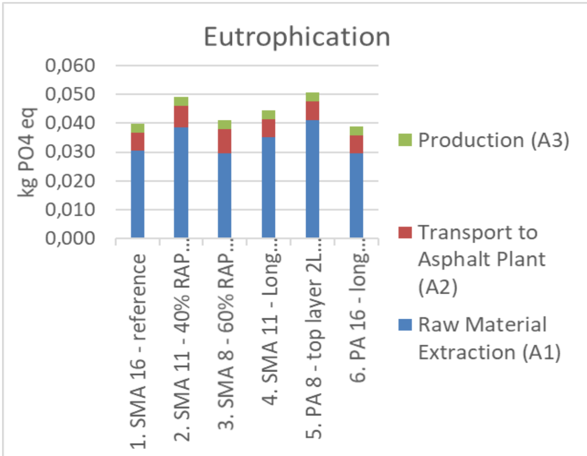


Figure 5: Results for the six case studies calculated in SimaPro, per tonne asphalt. Left: results

for Air Pollution due to photochemical oxidation; right: results for Eutrophication.

To analyse the contribution of the individual raw materials to the total footprint of the asphalt mixture, the mixture 1 (reference SMA), was analysed together with mixtures 2, 3 and 6.

The Figure 6 shows the impacts per raw material for the three indicators previously shown for which 80% of the environmental impacts of the raw materials comes from the binder. Although mixture 2 uses almost 9kg less binder per ton than mixture 1 it has a bigger footprint, this can be explained with the fact that mixture 1 uses bitumen while the mixture 2 has PMB in its composition therefore, the environmental benefits of using less primary material are offset by the higher footprint of PMB which is about 42% higher in comparison to bitumen for Global Warming Potential and Eutrophication.

Air pollution indicator also has the binder as the biggest contributor (about 90%) with the difference that mixture 2 has a slightly lower impact than mixture 1.

Regarding the use of an additive to allow a higher RAP content, Figure 6 also shows that for all indicators the impacts that were avoided through the use of recycled aggregates were offset by using the additive and the positive impact of reducing binder consumption was offset by the use of PMB instead of regular bitumen. A further analysis on the influence of RAP, PMB and additives on the results of asphalt mixtures is provided in section 4.1.2 Sensitivity analysis.

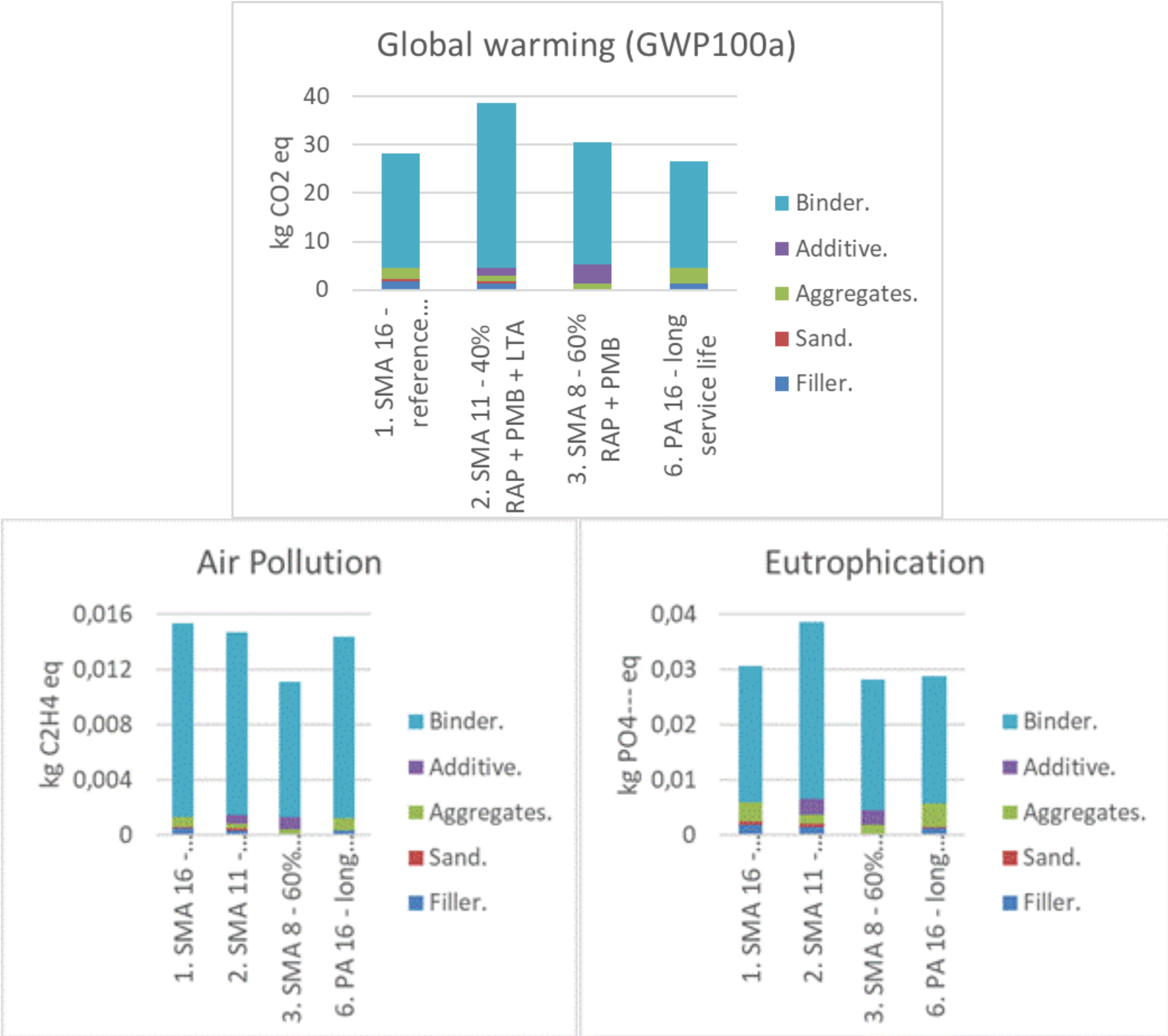


Figure 6: Results for phase A1 (per individual component), per ton asphalt. Top graph: results for Global Warming Potential; bottom left: results for Air Pollution due to photochemical oxidation; bottom right: results for Eutrophication.

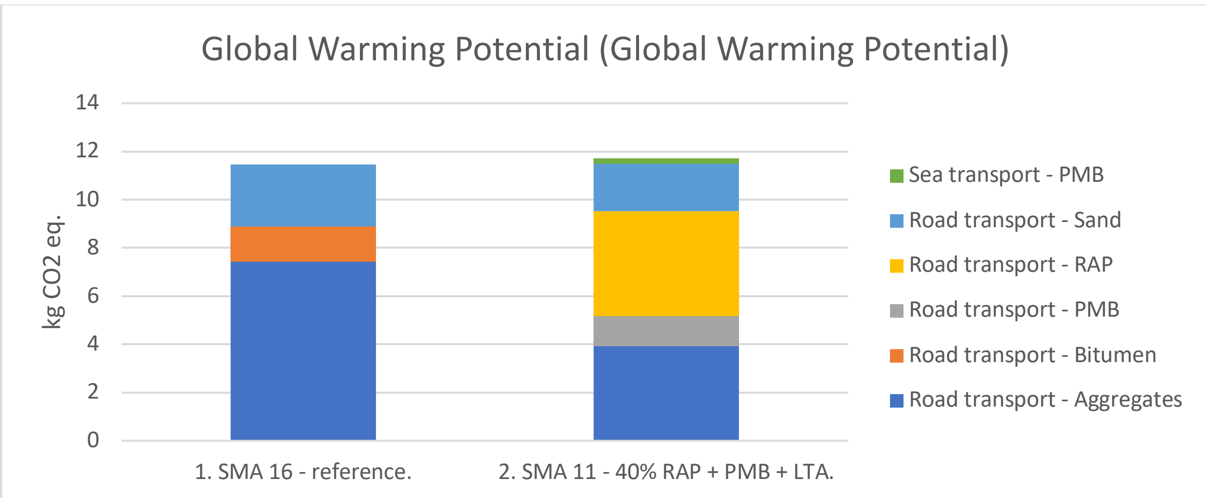


Figure 7: Global Warming Potential results for life cycle stage A2 – transport, for 1 tonne of mixtures 1 and 2, per material and transport mode.

Transporting materials to the asphalt plant is the second biggest contributor of the asphalt mixture’s footprint.

From all transport modes included in the analysis road transport has by far the largest impact. Since the distances between most of the raw materials and the asphalt plant are small this is the primary transport mode.

The transport of aggregates and sand represents the main contribution to this life cycle stage for mixture 1.

For mixture 2 the transport of RAP is the main contributor followed by transport of virgin aggregates and sand. PMB is transported by road and sea, so although it is used in smaller quantities than bitumen in mixture 2 its contribution to transport impacts for mixture 2 (12%) are similar than the contribution of bitumen to transport impacts from mixture 1.

Overall there is a very small relative difference (2%) between A2 results of both mixtures.

The results for Air Pollution and Eutrophication follow the same trend as Global Warming Potential.

The production stage (A3) corresponds to only about 16% or less of the mixtures footprints, for which burning gas oil to heat up the aggregates has the biggest impacts. Lowering the temperature by 20°C to produce mixture 2 at a lower temperature had a negligible effect on the environmental impacts of this life cycle stage for the three indicators studied.

However, because the results for A3 are based on data from a specific asphalt plant described in D5 from the EARN project this data may not be representative to other plants

A review study on Asphalt mixtures emission and energy consumption reported up to 18% footprint reduction at the production phase when the temperature is reduced by 20°C to 40°C. If the production phase corresponds to 10% of the footprint from A1 to A3, 18% footprint reduction for A3 translates into mere 1.8% reduction of the overall footprint of the asphalt mixture. (Thives & Ghisi, 2017)

Finally the results of this analysis show that mixture 6 “*PA 16 - long service life*” is the one with the lowest impacts for Eutrophication and Global Warming Potential but mixture 3. “*SMA 8 - 60% RAP + PMB*” is the one with the lowest Eutrophication impacts per ton of material.

Conclusions of the LCA analysis

The mixtures 1 and 6 show the best performance for Global Warming Potential and Eutrophication, while mixture 3 performs the best for Air Pollution and is the third best for Eutrophication. This shows that there is not a clear “winner” in terms of sustainability.

The binder contributes largely to the environmental impacts of an asphalt mixture. Because the PMB can have a much higher impact than bitumen, the use of PMB can offset the environmental benefits of using RAP and less binder.

Additives allow to increase the RAP content by maintaining the quality of the final asphalt mixture, comparable to the mixtures containing exclusively primary materials in the market. On the other hand, additives also lead to an increase in environmental impact.

Apart from that, the transport of raw materials to the asphalt plant can contribute significantly to the asphalt mixture footprint, and can offset the benefits of using recycled materials specially when the transport is executed by road covering relatively long distances.

It is important to highlight that the bitumen and PMB datasets used in this analysis did not use primary, high quality and representative data for a specific country situation.

This analysis’ results indicate that these datasets are of high importance and have to be modelled thoroughly with high quality and representative data before the results can be used for decision making and designing of policies.

4.1.1.2 Life Cycle Costing

This section contains an analysis of the costs involved in the production of the mixtures in this case study.

The results in Figure 8 are given in Euro per life cycle stage, per ton of asphalt mixture and show that mixture 4 is the one with the highest costs while mixture 3 is the mixture with the lowest costs, nevertheless the relative difference between them is small, namely 17%.

It is also possible to see that materials are the main contributors to the total cost of the asphalt.

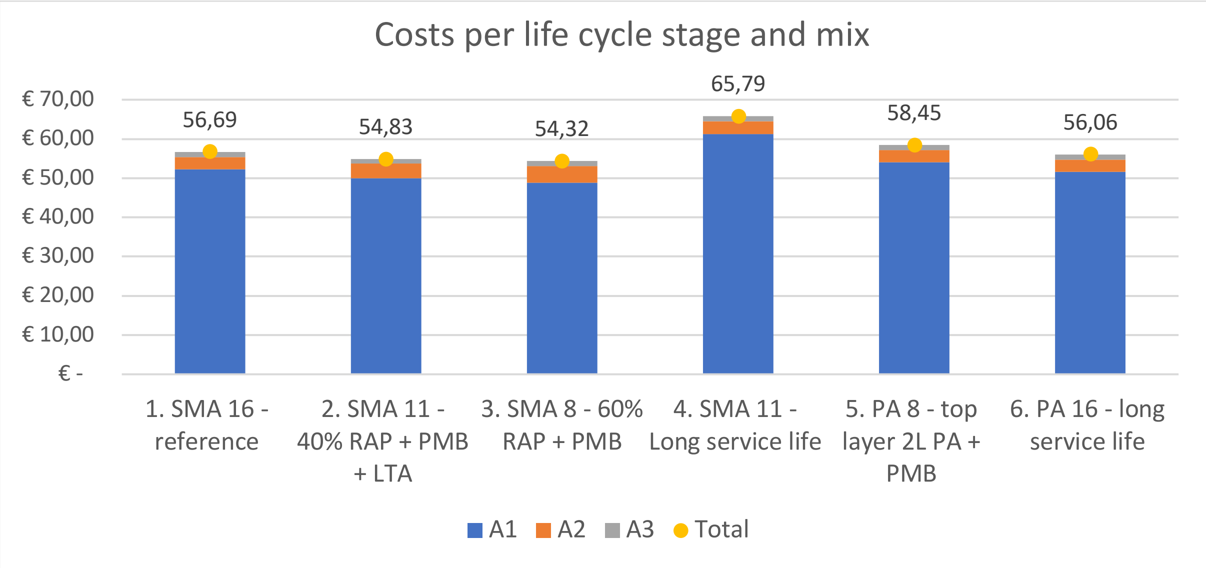


Figure 8: Total costs for producing the six asphalt mixtures, per ton of asphalt, per life cycle stage.

Aggregates and the binder are the main responsible for the costs of producing asphalt.

Figure 9 shows a cost breakdown per raw material used in the production of the asphalt mixture.

For mixtures that do not contain RAP the binder can be responsible for 65% of the production costs while in the case of mixture 3 which contains 60% RAP it is 47%.

In the case of aggregates, their contribution to the costs of production can be as high as 27% for mixtures that do not contain RAP, while for mixtures that have RAP in their composition the total cost of primary aggregates plus RAP correspond to 23% of the production costs.

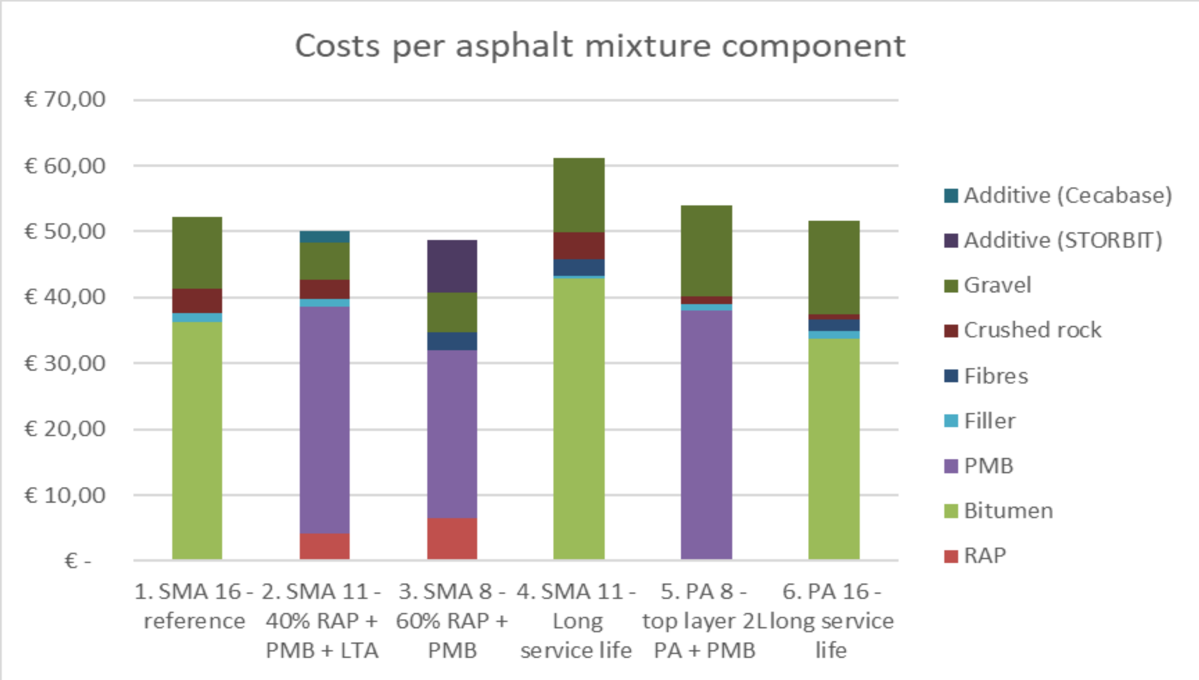


Figure 9: Costs of raw materials in life cycle stage A1, per ton of asphalt, per mix.

Because PMB is 11% more expensive than regular bitumen part of the savings made by using RAP and consequently less primary binder and aggregates is partially offset by the higher price of PMB.

For all mixtures aggregates and binder sum up to 90% of the production costs except for mixture 3 which uses Storbit as additive and contributes alone 15% of the production costs.

4.1.1.3 Results for the three sustainability pillars

The sustainability assessment of asphalt mixtures carried out in this study considers several indicators, including noise which is a social indicator and durability, an indicator that affects the three sustainability pillars.

Table 18 shows the results for the six asphalt mixtures included in the study in terms of the indicators selected for analysis.

Concerning the social indicator, noise, mixture 5 is the one with the best outcome since it can reduce up to 4.8 db noise in comparison to the reference. However it has the second highest cost and lowest durability.

Mixture 3 also offers 0.6 db noise reduction in comparison to the reference, it has the lowest costs, the highest amount of secondary material use and a relatively low Air Pollution and the third lowest Global Warming Potential but durability is uncertain since it is a new mixture it is expected to last from 2 to 6 years less than the reference mixture.

Table 18: Sustainability assessment results per ton of asphalt for the six asphalt mixtures assessed in the case study. The greenest results (i.e. the lowest impacts) are

highlighted in green.

Sustainability pillar	Indicator	1. SMA 16 - reference	2. SMA 11 - 40% RAP + PMB + LTA	3. SMA 8 - 60% RAP + PMB	4. SMA 11 - Long service life	5. PA 8 - top layer 2L PA + PMB	6. PA 16 - long service life
Environment	Global Warming Potential (kg CO_2 eq)	47	57	52	53	61	47
	Air pollution (Photochemical Oxidation in kg C_2H_4 eq)	0,018	0,018	0,015	0,021	0,019	0,018
	Energy use (MJ)	75	68	75	75	75	75
	Secondary materials consumption (kg)	0	382	600	0	0	0
Economy	Cost (€)	56,69	54,83	54,32	65,79	58,45	56,06
Society	Tyre-pavement noise reduction (dB)[14]	0	0	-0,6 dB	0	-4,8 dB	-2 dB
Affects all pillars	Durability (years)	16[15]	14-10[16]	14-10[12]	20[12]	10[11]	14[11]

Conclusions on the three sustainability pillars

Table 18 displays the sustainability results for all mixtures and which one score better at which indicator. Determining which mixture is the "greener" is not straight forward since there is no mixture scoring better than the others for the complete set of indicators.

For a certain project or NRA some indicators might be more important than others leading to a decision based on the scores for those indicators, this means that some results may have a bigger weight in the decision making.

Considering that all indicators have the same weight in the decision making process, mixture 3 (SMA 8 - 60% RAP + PMB) is the most sustainable asphalt mixture since it is the one having the best outcomes, outperforming other mixtures in 3 of the 7 indicators, (air pollution, secondary material consumption and cost) while it has the second best carbon footprint and scores on the average for energy use.

[14] Source: (EAPA, 2018)

[15] Source: Dutch Product Category Rules for Asphalt. (Keijzer, et al., 2020).

[16] The expected durability for an innovative SMA mixture ranges from 10 to 14 years considering a slightly worse performance than the reference mixture due to an early stage of development of the production technology. This is an expert guess based on the durability of the reference mixture and the uncertainty in amount of years that can be expected from an innovative mix.

4.1.2 Sensitivity analysis – alternatives for bitumen and transport

4.1.2.1 Introduction

In order to get a better overview of the environmental impacts of using bitumen or PMB, additives, RAP and effects of transport in an asphalt mixture a series of sensitivity analyses where these parameters vary have been performed.

In the case of transport, the distance was reduced by half, 35 km instead of 70 km, to help understanding the effects of this reduction on the results and how sensitive they are to variations of this variable.

For this analysis only the Global Warming Potential indicator was used since any increase or reduction for this indicator will be similar for the other two.

Mixtures 2 and 3 include PMB and RAP in their composition therefore they were used for the analyses in this section. In order to understand what the consequences are of varying those parameters mixture 1 and the unmodified version of mixture 2 were used to compare.

4.1.2.2 Results

Figure 10 below shows the results for two variations of mixtures 2 and 3, namely a mixture using bitumen instead of PMB and another one where the transport distance for RAP has been reduced to 50% of the original transport distance, the results are given per life cycle stage of each mix.

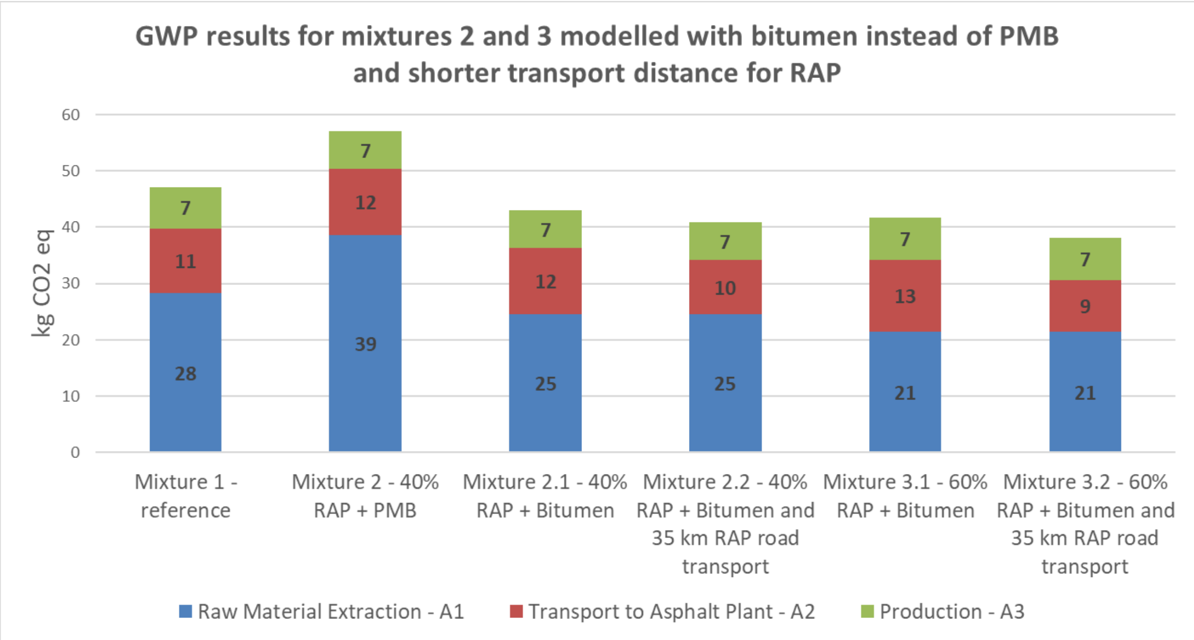


Figure 10: Global Warming Potential results per life cycle stage for mixtures 2 and 3 modelled with bitumen instead of PMB and shorter transport distance for RAP compared to the mixture 1 (reference) and compared to their original versions.

Substituting PMB by bitumen in mixtures 2.1 and 3.1 results in a 24% reduction of the Global Warming Potential in relation to their original results as in Figure 4 which correspond to a footprint of 43 and 42 kg CO2 eq. respectively. If compared to the six original mixtures these carbon footprints would be the lowest. This result stands for

Eutrophication and Air Pollution as well.

On the other hand, reducing transport for RAP by 50% can reduce the carbon footprint of mixtures 2.2 and 3.2 by 5%. An increase of RAP transport by 50% would result in a 5% increase of the footprint. Thus, if sourcing RAP results in bigger transport distances this has the potential to offset the environmental gains of using it.

Using the same binder as the reference mixture also shows more clearly the effects of using RAP when all the other parameters remain the same. Mixture 2.1 has 40% RAP in its composition, which means that for each ton of asphalt 40% of the mass is composed of secondary (recycled) materials, however the reduction of primary bitumen used is only 15%.

A mixture containing 40% RAP which has a 15% reduction in use of primary binder won't get its footprint reduced by 40% but by 16% instead. Figure 11 shows the carbon footprint of A1 per mixture broken down by asphalt component. It is clear that the carbon footprint reduction is intimately related to the reduction of binder usage.

Eutrophication and Air Pollution are also severely influenced by binder usage, therefore they follow the same trend of the Global Warming Potential.

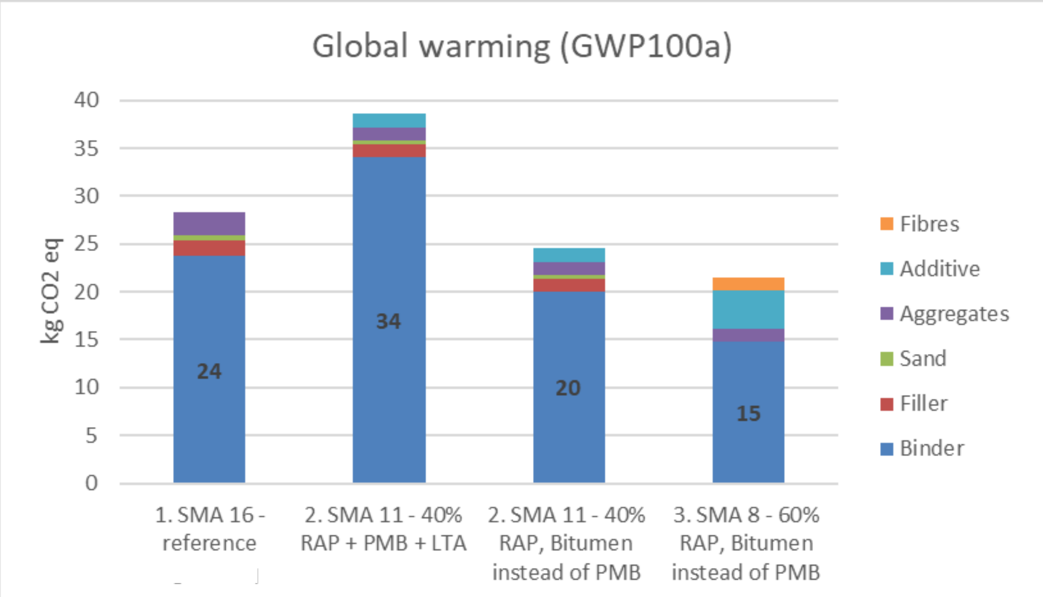


Figure 11: Global Warming Potential of life cycle stage (A1) for 1 tonne of mixtures 1, 2, 2.1 and 3.1, broken down per component.

4.1.2.3 Conclusions on the sensitivity analysis

The footprint results of the asphalt mixtures are very sensitive to the amount and type of binder used.

Substituting PMB by conventional bitumen has a positive effect on the environmental impact results of the mixtures analysed since PMB has more environmental impacts per kg of material. Of course, it is a sensitive discussion whether this would be technically achievable.

Reducing the footprint through the use of RAP is possible but the final footprint reduction depends mostly on the reduction of binder usage. RAP does reduce the amount of primary binder needed to make a new asphalt mixture, but because a big part of the binder in RAP has aged and therefore lost some of its characteristics, 40% RAP content does not translate linearly into 40% less primary binder.

Transport has a limited effect on the footprint, but it has the potential to offset the environmental gains of using RAP in case the total amount of transport needed to produce an asphalt mixture increases.

4.1.3 Case study – comparing results of three LCA tools

4.1.3.1 Introduction

Two of the tools used were developed specifically to calculate the environmental performance of roads. The third tool is SimaPro, a general LCA tool used by LCA practitioners to model the life cycle of all kinds of products or projects.

To explain the results obtained, the terminology of the tool being analysed was used, they appear in the text between “quotes”. Furthermore, the softwares provide results in terms of many indicators, however for the purpose of understanding how differences in calculations from different softwares arise it is better to concentrate in one or two indicators and investigate them in more details.

Therefore, initial results are provided for three indicators, however only one of them was chosen to be analysed in detail in this subsection, namely Climate Change which is used to determine the carbon footprint of a material or product.

The second indicator is related to air quality and the potential formation of smog, namely Tropospheric Ozone Formation (Ecorce) and Smog potential (Athena). Lastly we show the results for Eutrophication which is a consequence of human emissions of compounds that increase the amounts of nitrogen (N) and phosphorus (P) emitted to the atmosphere and subsequently deposited in surface soils and water affecting the health of freshwater and marine ecosystems and the economic and life support functions they provide (Morelli, et al., 2018).

4.1.3.2 Ecorce M x SimaPro

In this section a comparison between the results for six asphalt mixtures in Ecorce M and SimaPro is made where the most important aspects of the tools and the analysis are described.

The six asphalt mixtures were modelled using the same parameters on both softwares.

Ecorce and SimaPro provide results for nine different indicators from which only three are of interest to NRAs, namely Climate Change, Air pollution (tropospheric ozone formation) and Eutrophication (emissions of nitrogen-based substances). Below, on Figure 12 graphs containing results for both tools in terms of these three indicators can be found.

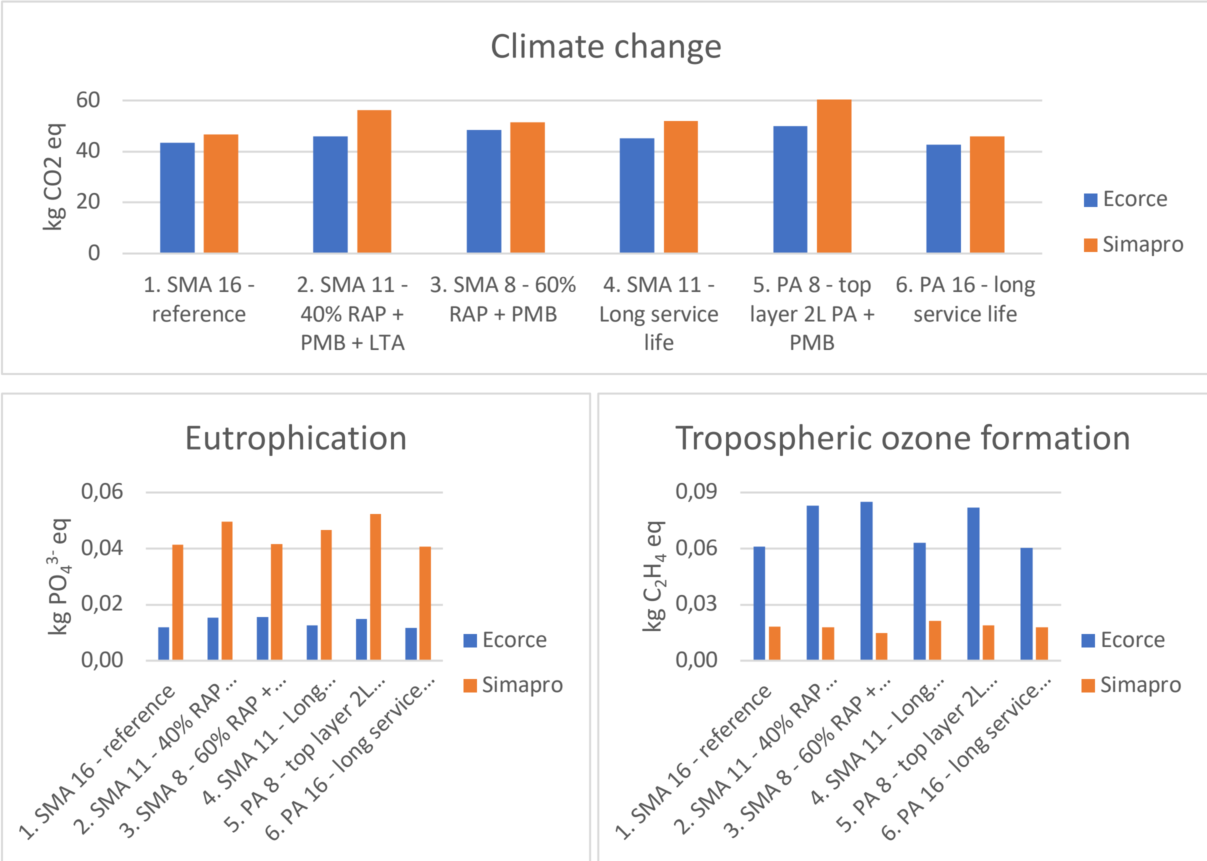


Figure 12: Results for the six case studies calculated in SimaPro and Ecorce M. Top: results for Climate Change; bottom left: results for Eutrophication; bottom right: results for Tropospheric Ozone Formation.

The figure shows different results for SimaPro and Ecorce, though for some mixtures this difference is bigger than for others. For the Climate Change indicator, the results in SimaPro and Ecorce differ by 7% for mixtures 1, 3 and 6 while for mixtures 2 and 5 this difference gets to 17%. This means that the CO2 eq. emissions can vary from 7% to 17% depending on the software chosen for the calculation.

When it comes to determining which mixture has the lowest footprint, both tools show that mixture 6 has the best performance for Climate Change and Eutrophication. For tropospheric ozone formation Ecorce still indicates mixture 6 as the best, while SimaPro shows that actually it is mixture 3 that has the best performance.

Both tools diverge concerning the worst performing pavement component for two indicators. According to SimaPro mixture 5 is the one showing the worst results of the six mixtures for Eutrophication, while mixture 4 has the worst result for tropospheric ozone formation. On the other hand, Ecorce points mixture 3 as having the worst results for both indicators. For Climate Change both tools show mixture 5 as the worst performing mix.

Divergence in the results indicate that there are differences in how the tools calculate the impacts for each asphalt mixture although they have been modelled similarly on both.

To understand the differences in the results it is necessary to investigate the possible differences in the Sustainability Assessment tools by taking a closer look on which aspects of the asphalt system influence the results the most. It can differ per tool because of their underlying database and calculation method implemented.

Pre-existent datasets in the underlying database of the tool used for modelling asphalt should be analysed in detail to help pointing out the sources of the differences.

In order to do that a contribution analysis per mix, life cycle stage and materials was performed for both tools.

Figure 13 contains a graph automatically generated by Ecorce which shows the major contributors to the Climate Change results per mixture and component, including transport and the energy used at the asphalt plant. The biggest contributor to the carbon footprint of the case studies is the energy necessary to warm up the asphalt mixture, followed by modified bitumen, bitumen and road transport. Together they sum up more than 85% of the mixtures' footprint.

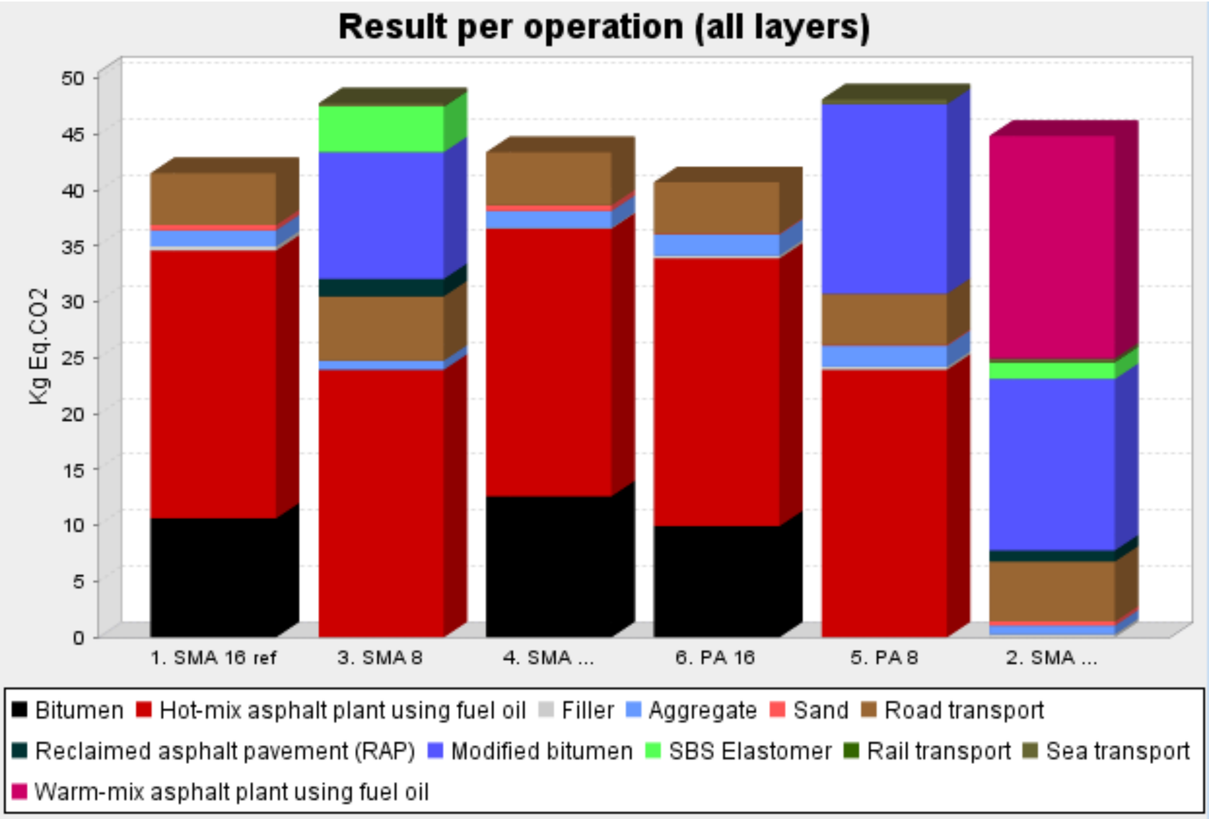


Figure 13: Contribution analysis of Climate Change results per material and process step[17] and per mix, extracted from Ecorce M..

Analysing the mixture 2, which is the one presenting the biggest differences in carbon footprint between the tools, helps understanding where these come from. The Figure 14 below, displays a flowchart automatically generated by SimaPro which shows the carbon footprint results for mixture 2 and the contributions of some processes necessary to produce one ton of asphalt.

"Bitumen seal production" is the EcoInvent 3.5 dataset used to model PMB and the biggest contributor (59%) to the asphalt mixture's carbon footprint. The second biggest contributor (21%) is road transport of aggregates and RAP by lorry. The third biggest contributor (8%) is heat production using light fuel oil. These three datasets correspond to more than 88% of the whole carbon footprint and therefore provide a good overview of which datasets are the most relevant for the investigation of sources of differences between tools.

There is a clear difference in the contributions of these three main datasets for the two

[17] "Results per Operation" is how Ecorce calls the results for each "road" modelled.

tools.

While for Ecorce M "*Warm-mix asphalt plant using fuel oil"* is the biggest carbon footprint contributor, for SimaPro it is the use of PMB that results in the biggest contribution. Moreover, the overall amount of CO2 eq. emitted per ton asphalt in SimaPro is 18% higher.

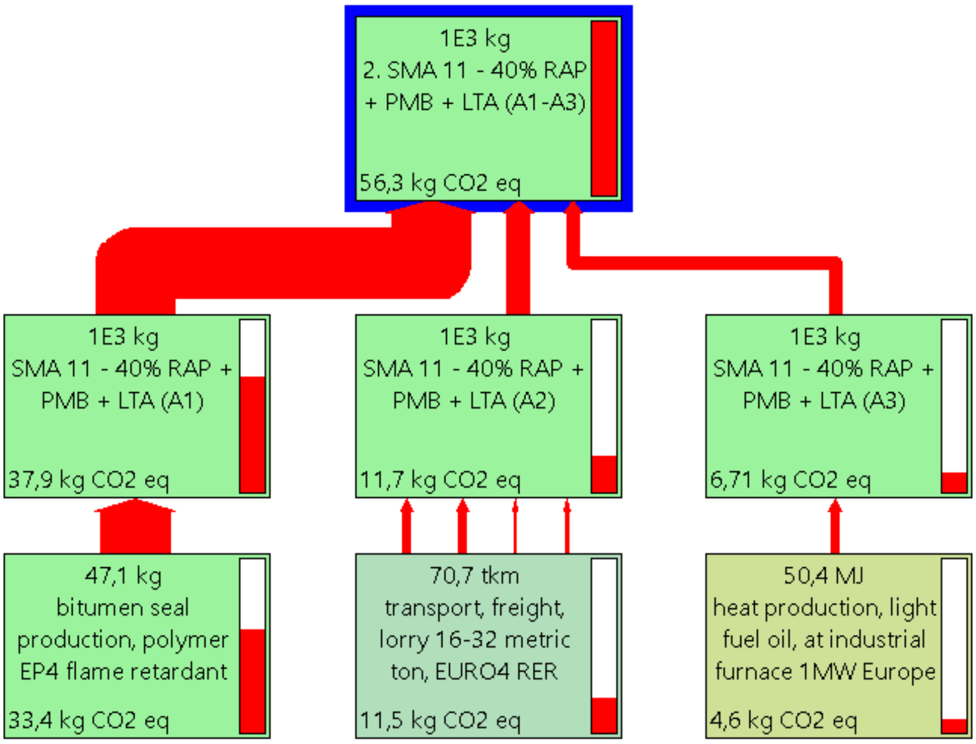


Figure 14: Graph extracted from SimaPro 9 showing the CO2 eq. contributions for mixture 2 which had the biggest deviation (36%) in results between Ecorce and SimaPro.

Since both tools use the same impact assessment method for calculating the indicators these results show that the modelling of the heat generation at asphalt plant, PMB and transport of materials is different in the databases of both tools.

The next step is to analyse the three datasets identified as the biggest contributors in both tools to see whether the differences in the results can be explained. On Table 19, the CO_2 emissions of PMB, Heat and transport for both tools are displayed. It can be concluded that most of the differences in the results can be explained in terms of these three factors.

Table 19: Carbon footprint results for one ton of asphalt mixture 2 in kg CO_2 eq. for each of the biggest footprint contributors.

	SimaPro (kg CO_2 eq.)	Ecorce M (kg CO_2 eq.)	Difference (kg CO_2 eq.)
PMB	33.4	15.4	18.0
Heat	4.6	20.0	-15.4
Transport	41.1	5.38	35.7

The last question to be answered is, why the results differ so much if the same parameters were used to model the asphalt mixtures in both tools? To answer that, it is necessary to pay a closer look to each process/dataset used to model a same element of the asphalt mixture.

Some tools do not allow to access the details of the datasets in their databases, this is the case of Ecorce that only provides the impact assessment results of its underlying datasets.

Knowing the impact assessment results on both tools allows to determine by how much the results for a product containing that dataset deviate and whether that explains most of the differences in the results for the asphalt mixtures on both tools.

In the case of Ecorce and SimaPro, the results for all indicators are provided for each dataset present in the database per ton of material.

Taking the binders available in the database of both tools as an example, namely Bitumen and PMB, one ton of Bitumen in SimaPro emits 417 kg CO2 eq. which is 2.2 times the emissions for this same material in Ecorce M. The same happens for PMB.

Figure 15 shows the carbon footprint results for both materials in both tools.

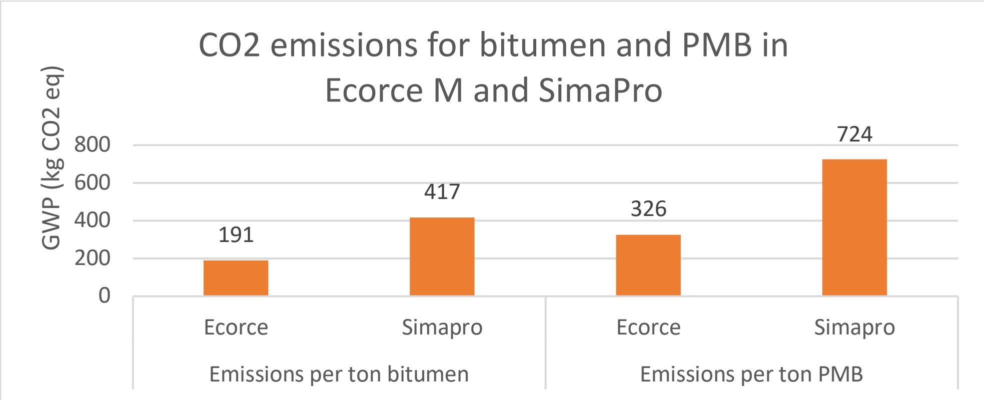


Figure 15: Carbon footprint results for PMB and Bitumen in SimaPro and Ecorce M given in kg CO_2 eq. per tonne of material.

Ecorce shows lower impacts for both binders what explains most of the 18% difference in emissions of kg CO_2 eq. for the asphalt mixtures indicating that the Bitumen and PMB datasets provided in the tools take different things into account and may not include the same processes upstream the supply chain. The same may happen for all other components of the asphalt mixture.

Conclusions of the comparison between Ecorce M and SimaPro

In the comparison, major differences between the results generated by both tools were observed. The reason for this, is that the underlying databases in both softwares differ from each other: while SimaPro uses datasets from EcoInvent, Ecorce M uses its own database, specifically developed for the software and not accessible otherwise. The differences in datasets, lead to major deviations in results even when the asphalt mixtures are modelled identically.

Furthermore, to be able to determine what are the exact differences and where they come from, a three-step analysis has been performed. First step was the determination of the major contributors to the results in both tools. In this case study, it was bitumen that contributed the most to all indicators.

The second step was to analyse the differences in the results of individual datasets which contribute the most to the environmental impacts of a product. In the case of bitumen and PMB, there was more than a factor 2 difference.

The third and final step was to check the information available for the underlying datasets used in the calculations. If the tool allows it, this will help showing why differences exist and where they are. Observed deviations for other indicators should also be analysed using the same methodology.

Ecorce does not allow the user to access the details of each dataset, therefore it is possible to determine that there are deviations and their consequences for the results but not their cause.

All in all, even if the asphalt mixtures are modelled similarly in both tools and the same impact assessment method is used, the results of these two different tools are not comparable.

4.1.3.3 Athena x SimaPro x Ecorce M

In this section a comparison between the results for six asphalt mixtures in Athena and SimaPro is made where the most important aspects of the tools and the analysis are described.

The six asphalt mixtures were modelled as similar as possible in the three tools where the same parameters were used. Athena and SimaPro provide results for more than 10 different indicators from which Climate Change, Eutrophication and smog potential (air pollution) were selected for this analysis. The Figure 16 below shows the results of SimaPro and Athena.

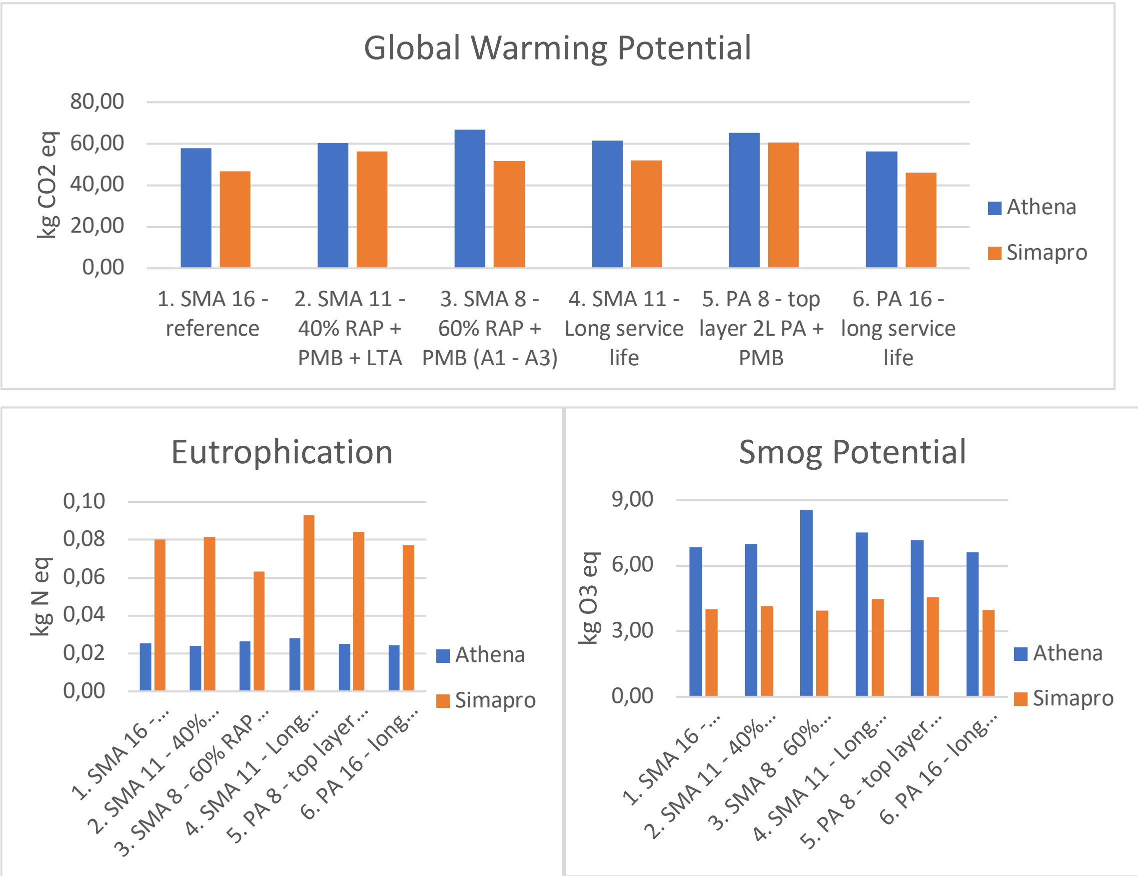


Figure 16: Results for the six case studies calculated in SimaPro and Athena. Top: results for Climate Change; bottom left: results for Eutrophication; bottom right : results for Photochemical Oxidation Potential (Smog Potential).

For Global Warming Potential the results in SimaPro and Athena differ by 23% for mixture 3 while for mixtures 1, 4 and 6 there are deviations of 19%, 15% and 18% respectively. The lowest deviation occurs for the mixtures 2 and 5 which differ by 7% for both tools.

Results in Athena show that mixture 6 has the best performance for all three indicators while SimaPro shows that the best results for Global Warming Potential are achieved by mixture 6 while for Smog Formation Potential and Eutrophication the best performing mixture is mixture 3.

Athena does not allow a detailed analysis of road components and activities since the environmental impacts per material or process needed to produce the asphalt mixture is not available, therefore a contribution analysis is not possible.

However, we know that the results calculated in both tools were generated by similar models using the same impact assessment method, namely TRACI 2.1, which is documented in the user guide of Athena and available in SimaPro.

Since the modelling is similar and the calculation method as well, it is possible to conclude that result deviations occur due to differences in the modelling of datasets provided in the underlying databases of the tools such as sand, aggregates, bitumen, asphalt plant energy and fuel consumption, transport emissions etc.

Pointing out exactly which differences are these is not possible though, since Athena does not allow users to explore modelling details of each material, product or activity individually.

Analysing datasets from different databases in SimaPro it is possible to see that modelling differences include, but are not limited to, emissions during production and transport, processes that are included or excluded in the upstream supply chain and consumption of resources during production.

A contribution analysis from the SimaPro results show that one of the elements contributing the most is bitumen, which is responsible for about 80% of the impacts of a ton of asphalt for several indicators.

Figure 17 shows the Eutrophication results in Athena and SimaPro for bitumen and PMB, these results confirm that there are modelling differences for these asphalt components in the databases of both softwares.

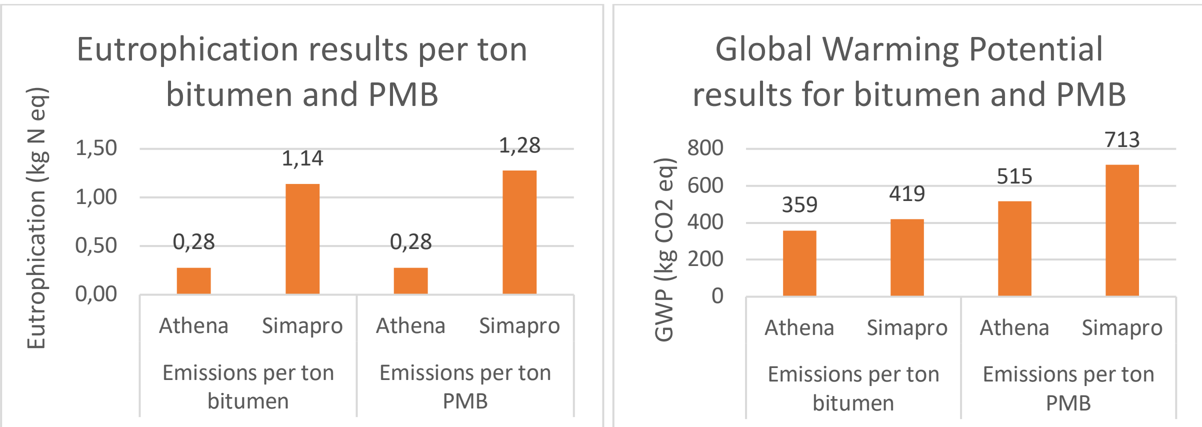


Figure 17: Global Warming Potential and Eutrophication results in Athena and SimaPro for bitumen and PMB.

It is worthwhile to notice that the dataset used in SimaPro has a much higher Eutrophication footprint, about 75% higher, than the one used in Athena. For Global Warming Potential this difference is smaller but the dataset in SimaPro still has a footprint 28% higher in the case of PMB and 15% higher in the case of bitumen. However, for smog formation Athena shows higher footprints than SimaPro, namely 45% higher for bitumen and 25% higher for PMB.

Herewith it is possible to see that the environmental impacts of the binder drive the results for these three indicators on both tools.

The last question to be answered in this section is, how do results in Ecorce M and Athena compare to each other?

The results for Climate Change in Figure 18 shows that the three tools deviate from each other but the numbers have the same order of magnitude. Athena show the highest carbon footprint results when compared to the other two tools, and Ecorce M has the lowest. Nevertheless, the biggest deviation between the tools is of 27% for mixture 3.

This can be explained by the fact that CML 2001 and TRACI 2.1 use the same protocol for calculating global warming effects which is based on IPCC reports about Climate Change, therefore from the environmental impact method point of view the results in the three tools are comparable, but because the asphalt component datasets are different in the databases of the three tools they lead to different footprints.

Regarding the six asphalt mixtures, the conclusion of each one has the smallest footprint may change depending on the software used in the analysis.

Athena and SimaPro provide different results, while SimaPro and Ecorce point the mixture 5 as having the biggest footprint, Athena shows mixtures 3 and 5 as having the biggest footprints.

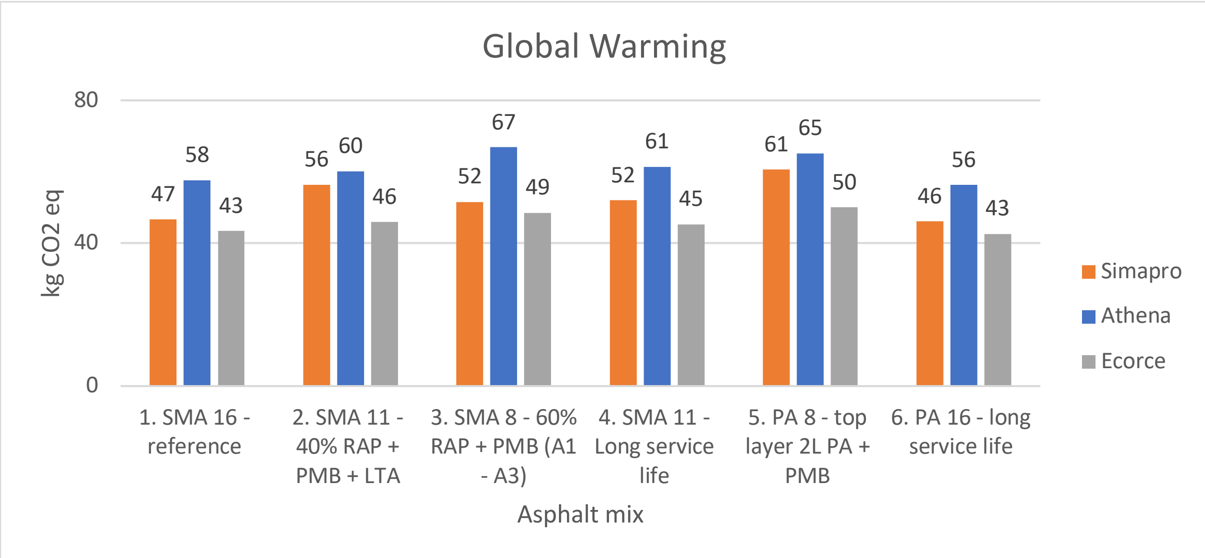


Figure 18: Results for Climate Change/global warming in kg CO2 eq. for the six case studies in the three tools.

In the case of the mixture with the lowest footprint the three tools indicate mixture 6 as the one having the best performance.

Doing the same analysis as in section 4.1.3.2, using bitumen and PMB as a reference and the Global Warming Potential as the indicator it is possible to understand most of the differences in results for all tools.

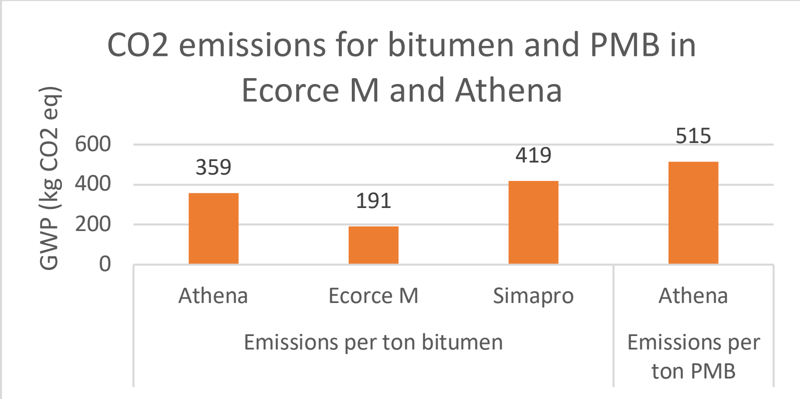


Figure 19: Carbon footprint results for PMB and Bitumen in Athena and Ecorce M given in kg CO2 eq. per tonne of material.

Figure 19 shows the carbon footprint results for one tonne of Bitumen in Athena (359 kg CO2 eq.) which is 1.9 times the emissions for this same material in Ecorce M. PMB has a footprint in Athena which is 1.6 times the one of Ecorce.

This shows that the Bitumen and PMB datasets provided in the tools do not include the same processes upstream the supply chain. The same may happen for all other components of the asphalt mixture.

However, bigger differences can be seen when it comes to Smog Formation Potential and Tropospheric Ozone Formation. Both indicators express the potential for smog formation due to the emission of Volatile Organic Compounds (VOCs) and other pollutants in the air, but in Ecorce the unit used to express this is kg Ethylene (C2H4) eq. while Athena expresses the results for this indicator in terms of kg Ozone eq.

This means that results for other indicators are not comparable since they are calculated in different ways for Athena and Ecorce M.

4.1.3.4 Conclusions of the comparison of Athena vs. SimaPro and Ecorce M

Athena is a USA/Canada tool, therefore it uses the TRACI impact assessment method which has been developed specifically for those countries taking their needs and preferences into account as well as the local conditions for the transport and deposition of pollutants.

Ecorce M, on the other hand, is a tool developed in France, which uses a modified version of the impact assessment method CML 2001 to calculate environmental impacts of the roads modelled. CML 2001 is a European impact assessment method developed to take into account the local needs and local conditions for the transport and deposition of pollutants as well.

Deviation in results due to dataset modelling can be big, in this case study it is more than a factor 2 difference between Ecorce and Athena for CO_2 eq. emissions.

The results of these two tools are not comparable at all because they are given in different units and substance equivalents in the impact assessment methods. The same happens for most of the other indicators of both tools.

Climate Change is a small exception because all the tools and impact assessment methods based their calculations on the Intergovernmental Panel on Climate Change

(IPCC) methodology[18] for calculating CO_2 equivalents, however these tools may contain adaptations or use different versions of the same calculation method, so slight differences might arise. Furthermore, as the databases used are different, results may diverge even more since the datasets are likely to be different.

4.2 Sustainability Assessment of Pavement Activities

4.2.1 Introduction

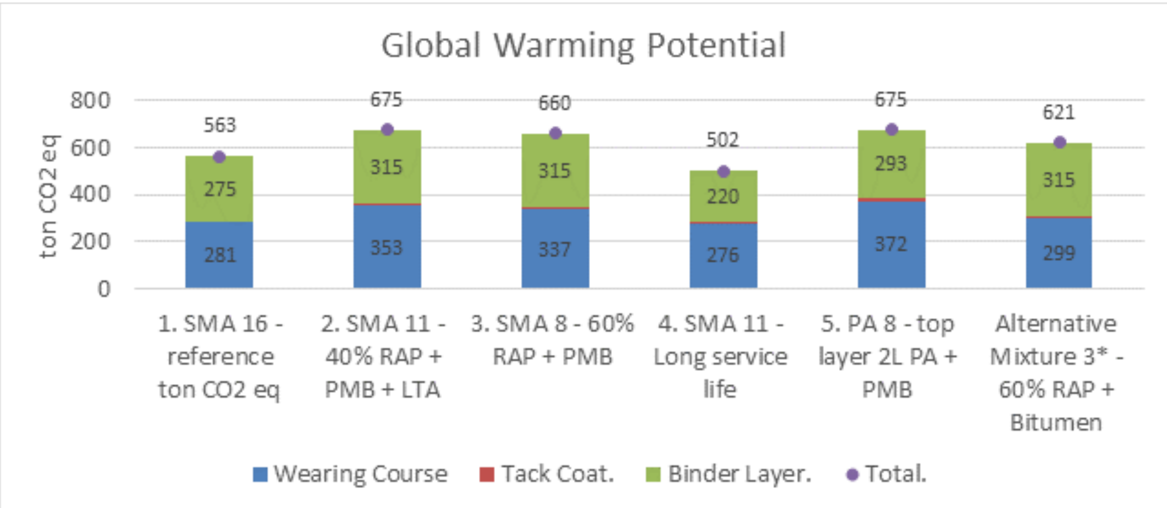
Comparing the performance of different asphalt mixtures offers a partial view of the total impacts asphalt has throughout its lifetime. To have a better overview it is necessary to analyse the full life cycle including the service life of the pavement materials/products and how they perform when a maintenance scheme is taken into account.

In this section the environmental performance of a road is evaluated over a period of 40 years where several maintenance rounds take place. For this analysis the results for the six asphalt mixtures from sections 4.1.1 and 4.1.2 are analysed considering their average service lives which combined allow to calculate the environmental impacts of a road using different wearing courses.

Using the environmental impact results for the wearing courses, together with datasets for the tack coat and a binder layer in a maintenance scheme allows to evaluate the environmental performance of roads that use different wearing courses and maintenance schemes.

4.2.2 Results

The Figure 20 below shows the results for three indicators in the six scenarios.



[18] Most impact assessment methods used in LCA calculate the impact of greenhouse gases relative to CO2 according to the Intergovernmental Panel on Climate Change 2001 report. Usually Global Warming Potentials at 100-year time horizons are considered, which is consistent with the guidance of the United Nations Framework Convention on Climate Change (UNFCCC).

Figure 20: Results for the six scenarios, per layer. Top: results for Global Warming Potential; bottom left: results for Eutrophication; bottom right: the results for Air Pollution.

Wearing course and binder layer contribute at the same proportion to the final results while the impacts of the tack coat is negligible. This means that the pavement activities increase significantly the environmental impacts of the road with each maintenance round. In which case elongating the service life of all layers from the road has the potential to reduce greatly the environmental impact of the road.

The life cycle stages A4-C4 (pavement activities) are common to all mixtures, varying only the amount of material that needed to be transported and installed at site and the amount of times they took place depending on the maintenance scheme. For mixtures with a shorter service life of the wearing course this impact is bigger.

The Figure 21 and Figure 22 show a breakdown of the scenario results per life cycle stage.

The transport of asphalt from the plant to construction site is by far the biggest contributor to the footprint of pavement activities followed by the transport of asphalt at the end-of-life to the recycling plant and to the landfill.

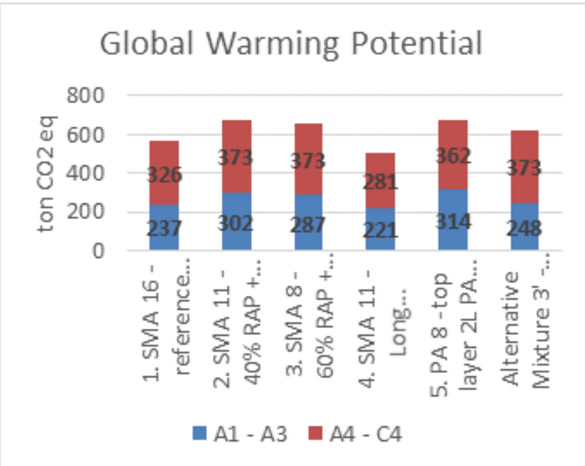


Figure 21: Scenario results for Global Warming Potential, for pavement materials/products (A1-A3) and pavement activities (A4-C4), per ton asphalt.

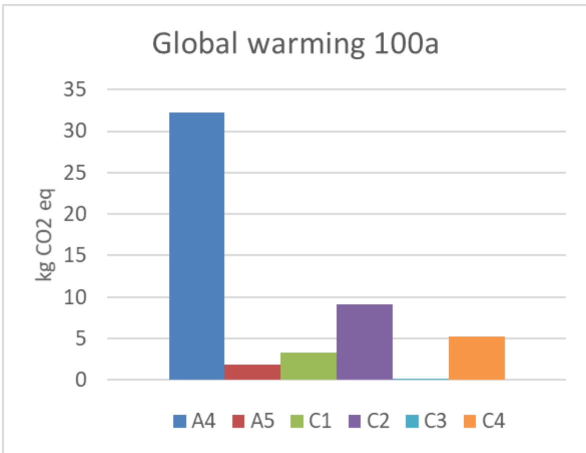


Figure 22: Global Warming Potential results of life cycle phases of pavement activities, per ton asphalt.

The results for the three indicators look similar in terms of the best and worst results for the six scenarios. Scenario 4 which was modelled with a long service life SMA (20 years) is the one with the lowest environmental impacts and scenarios 2 and 5 are the ones with the worst results.

Mixtures 2 and 5 have the same outcomes for Global Warming Potential although the components of the mixtures and their maintenance schemes are different. For mixture 5 the service life of the wearing course is shorter in comparison to mixture 2, therefore, the wearing course in scenario 5 needed to be substituted more often, considering that mixture 5 has a bigger environmental impact per ton than mixture 2 this leads a relatively high impact for the wearing course while the maintenance of the binder layer can be postponed by a few years to match the wearing course maintenance schedule, this partly compensates the higher impacts and shorter service life of the wearing course causing the results from scenario 5 to be similar to the results for scenario 2.

The scenarios 2, 3 and 3' have the same maintenance scheme, which means that wearing course and binder layer are substituted an equal amount of times in the three scenarios, this can be seen in Figure 21 where all three scenarios have the same impact for phases A4-C4, while the environmental impacts of each wearing course are different.

Scenario 3' uses a modified version of mixture 3 for the wearing course, this version uses bitumen instead of PMB as described in section 4.1.2, due to this modification the footprint for scenario 3' has decreased by 21% in relation to scenario 3.

Scenario 4 uses a long service life SMA as wearing course which is expected to last 20 years on average. The sustainability analysis in section 4.1.1 shows that mixture 4 has a similar environmental impact per ton asphalt as mixture 3 but because it has a longer service life that translates into less maintenance of wearing course and binder layer the environmental impacts along the analysis period are lower than for the other five scenarios.

4.2.3 Conclusions on the sustainability assessment of pavement activities

For a road, the aspects playing the most important role in the results are the expected service life of a pavement component, the impacts of using primary binder, the maintenance scheme and the amount of transport needed in phase A2, A4 and C2.

The use of RAP is beneficial mostly if it results in the reduction of the use of primary bitumen, if it does not result in a shortening of the service life of the pavement component and if it does not involve much more road transport than the primary materials substituted by RAP.

In the case of the Netherlands the use of RAP in binder layers and wearing courses is consistently increasing in order to reduce the environmental footprint of the asphalt. A condition for new mixtures including RAP is to maintain a similar technical performance to the primary asphalt mixtures currently being used. Thus, the service life of pavement materials/products with high content of RAP maintain a service life similar to the commonly used mixtures. The transport distances are shorter than for primary materials, especially for gravel and other aggregates which are usually imported.

The sustainability data of different types of asphalt should be used in the context of a full road and maintenance schemes. With this information, it is possible to know how many times the pavement activities need to take place and how much asphalt is necessary, allowing an upscaling of the environmental, economic and social aspects of the individual asphalt mixtures to a whole road. When determining the maintenance scheme, it is important to take into account specific traffic and climatic conditions. Only then it is possible to have a better overview of which option is more sustainable.

Establishing different weights (levels of importance) for each indicator and choosing indicators different than the ones present in this analysis is possible and can help the NRAs to perform sustainability analysis that are in line with their own goal.

For the decision making it is important to make sure that the same methodology is applied for all scenarios under analysis, that the same tool is used for all calculations, to evaluate asphalt mixtures in the context of a road with a maintenance scheme and define which indicators have priority. As in all (sustainability) studies, it is highly recommended to perform at least one sensitivity analysis on a crucial parameter or process. The role of uncertainties will be addressed in the next chapter.

5 Uncertainty in Sustainability Assessment

5.1 Introduction

LCA is defined as assembly of all inputs and outputs of a product system and assessment of all possible environmental burdens over the entire life cycle of the product (EN, 2013). With respect to asphalt mixtures and asphalt pavements, this involves inventory of environmental impacts starting from the stage of production and transportation the required raw materials, mixing and transportation of asphalt, construction activities, maintenance activities, and up to the end of life stage. This is a complex system includes a significant number of different physical, chemical, or mechanical processes. This raises several questions concerning the uncertainty of these processes such as:

- Are there any effects of process uncertainty on LCA analysis?
- How sensitive the results of LCA to the uncertainty associated with the different processes involved?
- How to include uncertainty of processes in the LCA modelling?
- How to interpret LCA results that involve uncertainty analysis?

Despite that researchers have realised the importance of integrating uncertainty of LCA data decades ago (Weidema & Wesnaes, 1996), unfortunately, only a handful of studies have included the effect of uncertainty on LCA results. This could be due to unavailability of data, due to the complexity of the modelling process, or unavailability of tools or direct methods to run that analysis. Accordingly, the aim of this section is to address these questions and propose a framework to include uncertainty in the LCA modelling based on Monte Carlo simulation method and assess the uncertainty associated with LCA results.

5.2 Uncertainty in Life Cycle Assessment

5.2.1 Background: overview of uncertainty estimation methodologies

Uncertainty of LCA outcomes has been identified as the one factor that affects the reliability of LCA studies and questions the decision making results (Chen, Griffin, & Matthews, 2018); (Romero-Gámez, Antón, Leyva, & Suárez-Rey, 2016). Incorporation of uncertainty of LCA data is therefore a necessity to enhance the reliability of LCA studies. In the literature of LCA topic, it seems that there is no generally accepted method to incorporate the uncertainty in the analysis. This can probably be explained by either the significant number of parameters involved in the analysis or the varying aims of LCA studies, which makes establishing a universal uncertainty analysis model for LCA analysis kind of pointless or inapplicable. However, some researchers have developed guidelines to incorporate data uncertainty and propagate its effects on the analysis outputs. Generally, Monte Carlo Simulation (MCS) is the most frequently applied method to investigate uncertainty of LCA. By this method, input parameters are defined by their probability distribution functions (PDF), then the model that links the inputs with the outputs is run for many times, every time a new set of inputs is randomly generated based on the input PDFs, and a new set of outputs is calculated and stored. Running this system for sufficient times, results in the PDF of the outputs rather than deterministic results. This system can be very efficient in incorporating data uncertainty in the analysis process, but it must be properly and accurately formulated. Also, the computation time of this system must be taken into consideration as some complex systems may take quite long time to complete. Furthermore, there is no rule of thumb to identify the required number of MCS iterations; but 1000 to 10000 simulations have been usually used in LCA studies (Igos, Benetto, Meyer, Baustert, & Othoniel, 2018).

In LCA literature, MCS approach has been implemented in different LCA studies. Cao et al. (Cao, Leng, Yu, & Hsu, 2019) used this method to quantify the energy consumption of warm mix asphalt mixtures with rubber over life. Their analysis scenario included simulating one km-lane of asphalt pavement over analysis period of 20 years. Five stages were considered in the analysis, these were: material extraction and production, transportation, construction, usage, and lastly the end-of-life stage. The study demonstrated that LCA result significance can be assessed by this method, it can also provide comprehensive supportive data for decision makers. AzariJafari et al. (AzariJafari, Yahia, & Amor, 2017) have also implemented MCS to assess the effects of uncertainty on a comparative LCA study between jointed plain concrete and asphalt pavements. The data uncertainty was estimated based on the ecoinvent method as explained in the next section. The study included four stages, material production, pavement construction, maintenance and repair, and end of life. It was concluded that it is feasible to incorporate the uncertainty in the analysis, and one way to reduce the uncertainty is to improve the quality of the inventory data. Furthermore, several other studies have also implemented MCS to incorporate uncertainty effects on LCA studies (Noshadravan, Wildnauer, Gregory, & Kirchain, 2013); (Yu, Liu, & Gu, 2016); (Ziyadi & Al-Qadi, 2018). These studies demonstrated that MCS is a valuable method to integrate uncertainty with LCA analysis and track its effects on the results. Accordingly, this method has been implemented in this project.

5.2.2 Uncertainty estimation by the ecoinvent method

Uncertainty is a general term used to describe the spread an observation and its distribution (Weidema & al., 2013). Data uncertainty can result from several causes such as accuracy of equipment used, deficiencies in production, factors related to data quality including completeness and reliability of the data, or even human error. It used to imply a fact that nearly any observed or measured data can never be replicated exactly again. But If sufficient data is collected, then the observed process can be described by the distribution of collected data which is usually reported as PDF; and data variation measures can be used to describe data variability, such as standard deviation or variance. However, LCA data are usually not sufficient or reported in way that makes it difficult to estimate the PDF of the data. Accordingly, researchers have developed descriptive methods to estimate and quantify the uncertainty of data when sufficient information are not available (Weidema & Wesnaes, 1996). This method has been adopted in the ecoinvent database to quantify the uncertainty of most of LCA processes (Muller, et al., 2014); (Weidema & al., 2013). Based on this method, uncertainty of LCA data is estimated based on two elements: basic uncertainty and data quality.

The basic uncertainty is used to describe uncertainty due to for example measurement inaccuracy; it highlights the fact that any observation can never be deterministic. In the ecoinvent method, a lognormal distribution is generally assumed to model this category of uncertainty. The variance of the underlaying normal distribution of the basic uncertainty can be calculated based on the type of exchange and process involved, as shown in Table 20. This table shows that the variance can be estimated based on the process type whether it is combustion “c”, process emissions “p”, or agricultural emissions “a”, and based on the exchange involved. The second type of uncertainty is called additional uncertainty and is related to the quality of the data used and data sources. Five quality indicators have been suggested in literature to describe the quality of the data and to estimate the associated uncertainty; these are reliability, completeness, temporal correlation, geographical correlation, and further technological correlation. These indicators have been grouped in one pedigree matrix as shown in Table 21. Every one of the indicators have a score from one to five, where one means the quality of the indicator is excellent, therefore, it has zero additional uncertainty; whereas a score of five means that there is a high level of additional certainty in the data. These descriptive indicators have been interpreted into quantified measures that express the uncertainty in terms of variance of the underlaying normal distribution of the data, as presented in Table 22. Therefore, to estimate the additional uncertainty of a dataset, five scores need to attributed to the five measures of data quality described in Table 21, then based on Table 22 the uncertainty can be estimated.

Accordingly, the total uncertainty can be estimated based on the normal distribution properties using the following equation:

$$\sigma^2 = {\sigma^2}_{bu} + \sum_{n=1}^{5} {\sigma^2}_n$$

Where:

- σ^2 is the total variance in the data,
- ${\sigma^2}_{bu}$ is the basic uncertainty variance, and
- ${\sigma^2}_{n=1:5}$ are the additional uncertainty variances from the pedigree matrix.

It can be seen that a lot of input data are required to estimate the additional uncertainty. In the ecoinvent library, these data have been very well documented and made available online[19]. For instance, the pedigree matrix to estimate the additional uncertainty of the process (transport, freight, lorry 16-32 metric ton, EURO4) with respect to Acetaldehyde which is an exchange to air is [2 2 2 4 1]. Different pedigree matrices are available for all types of related exchanges. However, this makes the estimation of uncertainty of LCA studies rather data extensive and tool dependent; and tracking the uncertainty propagation in this method is a quite complex process.

Table 20. Variance of the underlaying normal distribution of the basic uncertainty category.

Input/ output group	c	p	a
demand of: thermal energy, electricity, semi-finished products, working material, waste treatment services transport services (tkm) Infrastructure	0.0006 0.12 0.3	0.0006 0.12 0.3	0.0006 0.12 0.3
resources: Primary energy carriers, metals, salts	0.0006	0.0006	0.0006

[19] www.ecoinvent.org

Input/ output group	**c**	**p**	**a**
Land use, occupation Land use, transformation	0.04 0.12	0.04 0.12	0.002 0.008
pollutants emitted to water: BOD, COD, DOC, TOC, inorganic compounds (NH4, PO4, NO3, Cl, Na etc.) Individual hydrocarbons, PAH Heavy metals Pesticides NO3, PO4		0.04 0.3 0.65	0.09 0.04 0.04
pollutants emitted to soil: Oil, hydrocarbon total Heavy metals Pesticides		0.04 0.04	0.04 0.033
pollutants emitted to air: CO2 SO2 NMVOC total NOX, N2O CH4, NH3 Individual hydrocarbons PM>10 PM10 PM2.5 Polycyclic aromatic hydrocarbons (PAH) CO, heavy metals Inorganic emissions, others Radionuclides (e.g., Radon-222)	0.0006 0.0006 0.04 0.04 0.04 0.04 0.04 0.12 0.3 0.3 0.65	0.0006 0.12 0.04 0.12 0.3 0.4 0.3	0.3 0.008

Table 21. Pedigree matrix used to assess the quality of data sources.

Indicator\score	**1**	**2**	**3**	**4**	**5**
Reliability	Verified on measurements data based	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate	Representative data from all sites relevant for the market considered, over an adequate	Representative data from >50% of the sites relevant for the market considered, over	Representative data from only some sites (<<50%) relevant for the market considered or	Representative data from only one site relevant for the market considered or some sites but

Indicator\score	1	2	3	4	5
	period to even out normal fluctuations	period to even out normal fluctuations	an adequate period to even out normal fluctuations	>50% of sites but from shorter periods	from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

Table 22. Variance of the underlaying normal distribution used to convert quality indicators of the pedigree matrix into additional uncertainty.

Indicator\score	1	2	3	4	5
Reliability	0.000	0.0006	0.002	0.008	0.04
Completeness	0.000	0.0001	0.0006	0.002	0.008
Temporal correlation	0.000	0.0002	0.002	0.008	0.04
Geographical correlation	0.000	2.5×10^{-5}	0.0001	0.0006	0.002
Further technological correlation	0.000	0.0006	0.008	0.04	0.12

5.3 Uncertainty estimation in the PavementLCM project

5.3.1 Uncertainty in LCA data

In the previous section, the ecoinvent method to estimate data uncertainty was explained. However, this method, as stated earlier, require significant data about the pedigree matrix of all processes involved in the analysis, the nature of every process, and the type of exchange. Bear in mind that evaluating one single impact, such as global warming, may involve hundreds or even thousands of processes depending on the complexity of the analysis; and every single process have varying number of exchanges with environment that contribute to global warming. Also, since every process have different exchanges, then the same process contributes to different environmental impacts at the same time. It can be seen that it is impossible to provide all of these data; therefore, a simpler method is absolutely required.

Ecoinvent database have been adopted in different LCA software such as SimaPro which is the one implemented in this project. This software does run MCS, but it is limited to run a maximum of two scenarios at a time. Also, the type of the output does not provide certain information such as the sensitivity of the results to inputs or the important parameters in the analysis, which makes it difficult to draw practical recommendation to NRAs about the processes that contributes the most to the uncertainty or the important ones to track in order to reduce a specific impact. Accordingly, a different approach was followed in this project to extract the required data from SimaPro, as follows:

1- All case studies were analysed in SimaPro based on the prescribed conditions in section 2.4.

2- The process contribution to every impact were filtered in order to isolate the most important processes, which are defined as the ones contribute the most to the impacts. The filtering rule was to set cut-off value of 2%; this threshold means that every process contributes to less than 2% of the impact total will not be counted as important process but its value will be considered in the "remaining processes". An example of this step is shown in Table 23; this table shows that nine processes are identified as important ones whereas the other processes are summed in the category of the remaining processes. This threshold was decided in order to reduce the number of processes from approximately hundreds to the most important ~10-20 processes. On the one hand, this helps to isolate the processes that cause high uncertainty, it also helps to track the ones that worth tracking and investigating in order to reduce a certain impact. On the other hand, it is necessary to reduce the number of processes to a manageable number in order to perform the current analysis as will be explained in the following sections.

3- The previous steps give the mean impact value of the important processes. To estimate the uncertainty level in these data, MCS analysis was run to every one of the important processes identified in this project by utilising SimaPro. This step allows the estimation of the Coefficient of Variation (CoV) of every one of the important processes. Please, notice that the CoV is an independent measure of uncertainty of a process; the standard deviation can be calculated from this measure by simply multiplying it by the mean value. Since the chosen impacts in this are Eutrophication, Global warming, and Photochemical oxidation, then the CoVs of the important processes with respect to those impacts have been calculated as shown in Table 24.

This table shows that the CoVs vary between 0% which means the process does not contribute to that impact, up to 122% which quite high level of uncertainty. the results in this table demonstrate generally the high uncertainty in LCA data which shows the importance to include uncertainty in LCA analysis. This table represents the basis to estimate the uncertainty of all-important processes involved in the current project.

In conclusion, the uncertainty is estimated in two steps. Firstly, the mean value of the important processes with respect to every one of the case studies is calculated using SimaPro. Secondly, the standard deviation is calculated using CoV values reported in Table 24. Furthermore, it is assumed that all of the involved processes follow a lognormal distribution. This assumption is required to assure that none of the processes will have a value less than zero, which is particularly important since most of the processes show mean value very close to zero. Also, the type of distribution can have a marginal impact on overall uncertainty as reported in the ecoinvent library (Weidema & al., 2013).

Table 23. Processes contribute to global warming impact of the reference mixture filtered based on cut-off of 2%.

Process	A1	A2	A3	A4	A5	C1	C2	C3	C4	Total
Heat, district or industrial, other than natural gas {Europe without Switzerland}| refinery gas, burned in furnace | Cut-off, U	0.083	0.286	0.204	0.557	0.031	0.055	0.987	0.001	0.041	2.246
Waste natural gas, sweet {GLO}| treatment of, burned in production flare | Cut-off, U	1.643	0.076	0.049	0.147	0.016	0.029	0.261	0.001	0.045	2.267
Natural gas, vented {GLO}| natural gas venting from petroleum/natural gas production | Cut-off, U	1.691	0.078	0.049	0.152	0.017	0.030	0.269	0.001	0.047	2.334
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	2.622	0.015	0.002	0.030	0.005	0.008	0.053	0.000	0.005	2.742
Sweet gas, burned in gas turbine {RoW}| processing | Cut-off, U	2.248	0.103	0.067	0.201	0.022	0.039	0.356	0.001	0.062	3.099
Heat, district or industrial, other than natural gas {CH}| refinery gas, burned in furnace | Cut-off, U	3.554	0.006	0.000	0.011	0.000	0.000	0.020	0.000	0.001	3.593
Heat, district or industrial, other than natural gas {Europe without Switzerland}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U	0.000	0.000	4.498	0.000	0.000	0.000	0.000	0.000	0.000	4.498
Diesel, burned in building machine {GLO}| processing | Cut-off, U	1.267	0.184	0.011	0.359	1.518	2.696	0.636	0.067	1.091	7.829
Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U	0.034	6.208	0.002	12.103	0.000	0.001	21.436	0.000	0.000	39.785
Remaining processes	15.158	1.640	2.514	3.198	0.273	0.485	5.664	0.012	1.349	30.292
Total of all processes	28.302	8.597	7.397	16.759	1.882	3.342	29.683	0.083	2.641	98.686

Table 24. Uncertainty of the important processes estimated by the ecoinvent method using SimaPro software.

process \ impact	CoV%		
	Eutrophication	Global warming (GWP100a)	Photochemical oxidation
Diesel {Europe without Switzerland}| petroleum refinery operation | Cut-off, U	28.26	13.86	27.92
Diesel, burned in building machine {GLO}| processing | Cut-off, U	20.15	8.72	36.46
Diesel, burned in diesel-electric generating set, 10MW {GLO}| diesel, burned in diesel-electric generating set, 10MW | Cut-off, U	82.26	17.35	57.20
Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW | Cut-off, U	60.14	17.22	77.60
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	27.84	17.22	24.12
Heat, district or industrial, other than natural gas {CH}| refinery gas, burned in furnace | Cut-off, U	62.58	9.77	92.13
Heat, district or industrial, other than natural gas {Europe without Switzerland}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U	33.38	18.97	38.14
Heat, district or industrial, other than natural gas {Europe without Switzerland}| refinery gas, burned in furnace | Cut-off, U	54.97	9.92	122.12
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	36.61	17.57	6.65
Heavy fuel oil, burned in refinery furnace {Europe without Switzerland}| processing | Cut-off, U	17.85	4.07	32.23
Natural gas, vented {GLO}| natural gas venting from petroleum/natural gas production | Cut-off, U	0.00	22.73	22.75
Petroleum {RU}| production, onshore | Cut-off, U	43.30	26.80	4.39
Pitch {CH}| petroleum refinery operation | Cut-off, U	33.19	19.24	22.50
Sinter, iron {GLO}| production | Cut-off, U	36.95	14.93	76.95
Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Cut-off, U	60.88	44.47	9.68
Spoil from lignite mining {GLO}| treatment of, in surface landfill | Cut-off, U	59.16	22.34	20.42
Sulfidic tailing, off-site {GLO}| treatment of | Cut-off, U	71.20	8.88	21.27
Sweet gas, burned in gas turbine {RoW}| processing | Cut-off, U	19.75	20.69	112.92
Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U	16.19	6.05	19.22
Transport, freight, sea, transoceanic tanker {GLO}| processing | Cut-off, U	18.52	15.64	17.78
Waste natural gas, sour {GLO}| treatment of, burned in production flare | Cut-off, U	20.50	20.94	22.14
Waste natural gas, sweet {GLO}| treatment of, burned in production flare | Cut-off, U	19.24	20.01	90.24

5.3.2 Uncertainty of total asphalt quantity

The other source of uncertainty that is considered in this project is the total quantity of asphalt required per the analysis period. The durability results reported in Table 18 are used to calculate the expected total quantity of every mixture. This can be achieved by defining the PDF of the durability of pavement materials/products and using the following equation:

$$ATQ = \left(1 + analysis\ period\ ./PD_{durability}\right) .X\ (\ R_l\ X\ R_w\ X\ L_{th}\ X\ asphalt\ density\ )$$

Where:

- ATQ is the asphalt total quantity,
- R_l, R_w, R_{th} stands for road length width and thickness respectively,
- $PD_{durability}$ is a vector of pavement durability distribution in years.

The additional one cycle included in this equation is for the construction phase. This equation, however, requires the mean durability and standard deviation of the durability of every pavement component. Since these data are not fully available, some assumptions are made to complete the missing data for the analysis. With respect to SMA11-40%RAP and SMA8-60%RAP mixtures, the reported durability lifes in Table 18 are assumed to represent the 95% and 5% significance intervals, and the standard deviations of these are calculated accordingly. For other mixtures, due to the limited available data, the lifes in the table are assumed the mean values, and the 95%-5% are assumed to be the mean values plus/minus 3 years. For example, the 5% significance level of reference mixture will be 13 years, and the 95% will be 19 years; and the standard deviation can be calculated accordingly. Accordingly, the durability PDF of every mixture is calculated as presented in Figure 23 (the number of the mixtures follows the same order of the mixtures in Table 17). Obviously, mixture 4 shows the longest life whereas mixture 5 shows the smallest life. By using these distributions and the above equation, the PDF of the asphalt total quantity over the analysis period is calculated as presented in Figure 24. This figure demonstrates that the better the durability the lower the asphalt quantity that will be required over a certain design period. It can be seen that material properties which contribute to the durability of pavement components, are a very critical factor in controlling the required quantity of asphalt, therefore, limiting the environmental impacts of asphalt. However, other impacts must certainly be considered in the analysis to obtain a fuller understanding of the problem.

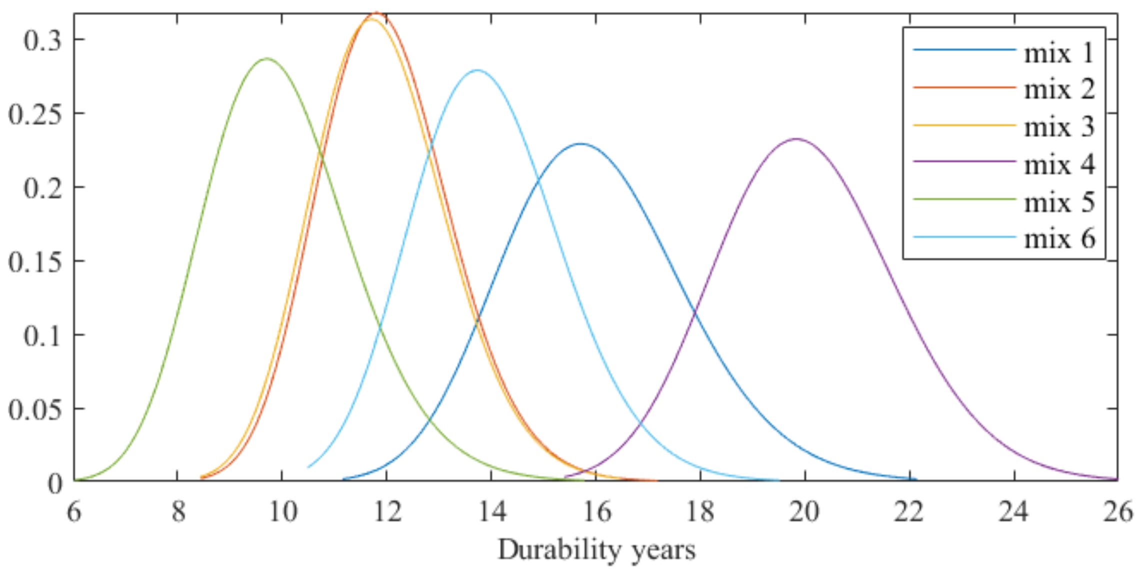


Figure 23. Durability PDFs of the investigated case studies

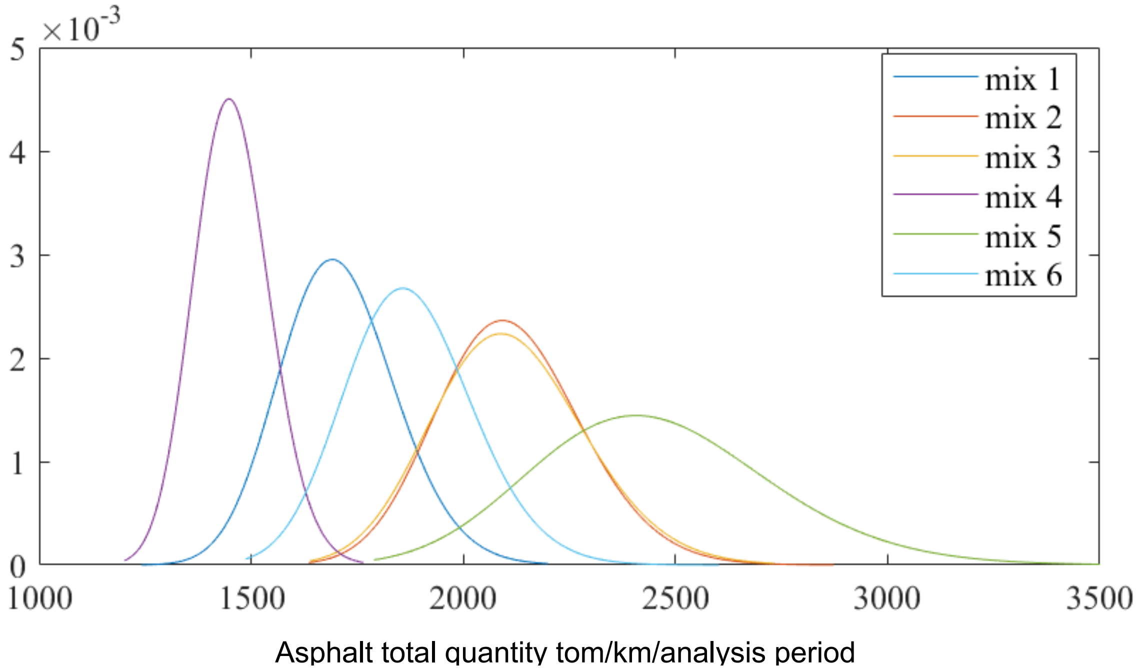


Figure 24. Distributions of asphalt total quantity per the analysis period

5.4 Uncertainty modelling in the PavementLCM project

5.4.1 Suggested model description

Based on the previous understanding of the problem, LCA uncertainty has been modelled as illustrated in Figure 25. The inputs of the model are pavement geometry which are used to calculate asphalt quantity for one cycle; mean and standard deviation of the component durability in years, mean values of all important processes which are precalculated using SimaPro; these value are reported in impact unit per ton of asphalt, and the remaining processes to account for the effect of the minor processes on the analysis. The proposed model has been programmed using Matlab language; it compromises the following steps:

1. The inputs are written in a text file in order to be imported and read by Matlab.
2. When model starts, it first generates the PDF of the total quantity of asphalt of the considered mixture using MCS method.
3. The model calculates the standard deviation of the important processes using the values reported in Table 24. This table has been coded in a function in Matlab and used as subroutine to estimate the standard deviation based on the process name and the type of impact involved.
4. Based on step three, the model generates PDFs of the important processes using MCS method.
5. The model then calculates the total of every impact at every phase and overall total of the impact (impact total of A1-C4 phases). In this step, the remaining processes are added as deterministic values as determined by SimaPro.
6. So far, impacts are calculated per one ton of asphalt. To calculate the absolute impact totals over the design period, impacts are multiplied by the expected total quantity of asphalt calculated in step two.

7. Run sensitivity analysis to analyse the effect of model input uncertainty on the output. This step is explained in section 5.4.2.
8. The last step involves plotting and interpreting the analysis.

By using the developed model, all case studies described in Section 3 were analysed. These mixtures were first modelled using SimaPro to calculate impact mean values of all phases and processes. The results were then fed into the current model to run the uncertainty analysis. It must be mentioned here that the effect of the binder course was included assuming that this layer has a deterministic influence on the results. This is because of two reasons; firstly, the focus of the project is to assess LCA of wearing courses. Secondly, one binder course has been assumed for all case studies. Thus, the effect of this layer will not have any effect on the uncertainty analysis. However, the effect of this layer has been included to have a better idea and a more accurate estimate of the impacts over the analysis period. Two deterministic cycles of this layer were included in the analysis; one at the beginning of the analysis period and the other one to be laid after approximately 28 years as shown in Table 12.

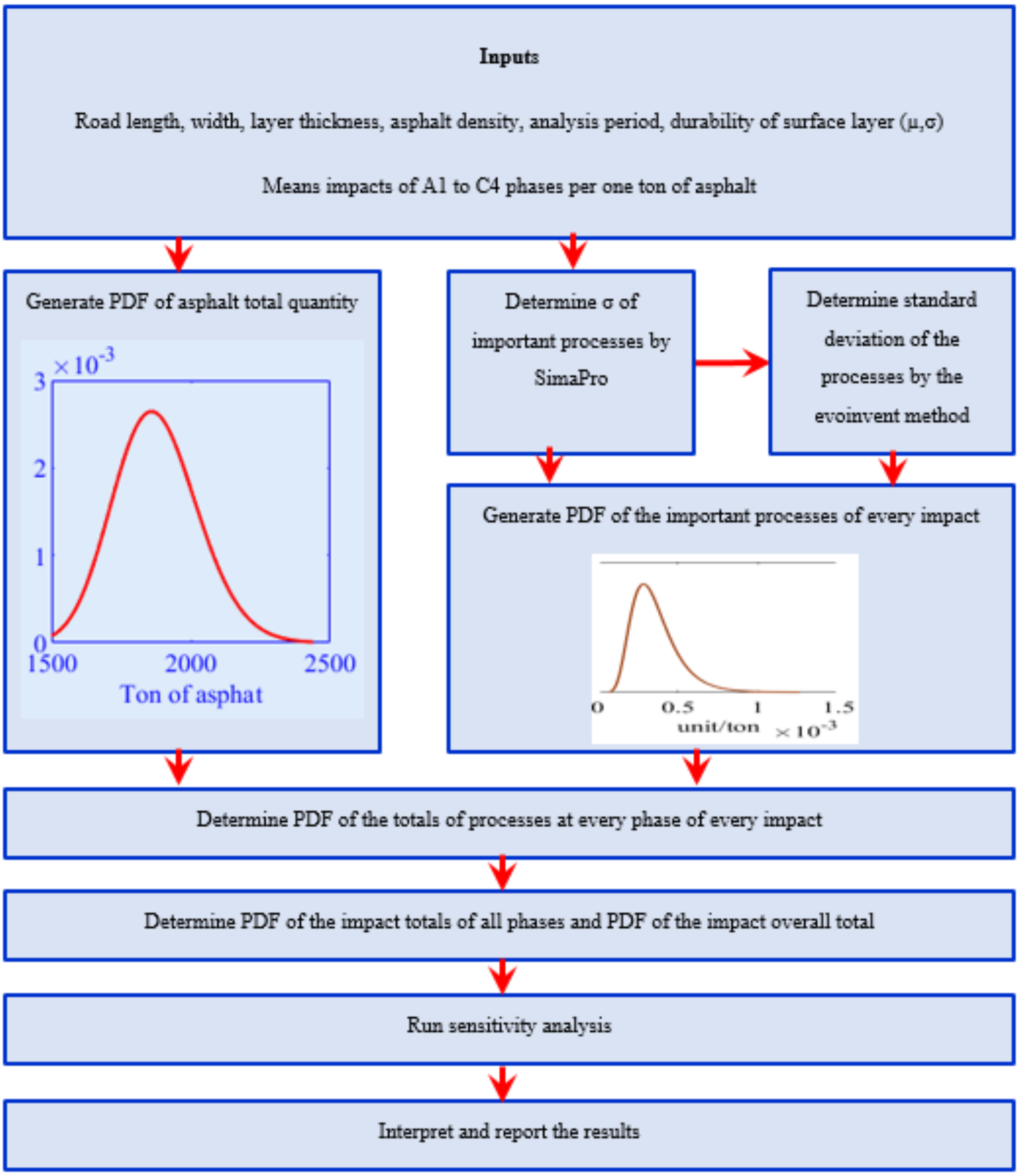


Figure 25. Uncertainty model flowchart

5.4.2 Sensitivity analysis method for uncertainties

In the previous section, the concept to quantify the uncertainty has been explained. The mean values of impacts are calculated using SimaPro. The variation of the processes contributing to the impacts is estimated by the ecoinvent method using also SimaPro. The variations of the outputs were then estimated using MCS method. The sensitivity of this system to the input variation, however, must be analysed to understand the effect of the input uncertainty on the output. Two sensitivity analysis methods are available in literature, Global Sensitivity Analysis (GSA) and Local Sensitivity Analysis (LSA) (Saltelli, Chan, & Scoot, 2000). In the former method, all inputs are allowed to vary at the same time, then the sensitivity of output to the variation of the input is estimated by different methods such as coefficient of regression (R^2), or by fitting a weighing model to link the output with the inputs and using the input parameter weights to express or quantify the sensitivity of the system to the inputs. In this case the parameter with the largest R^2 or weight can eb consider as the most important one. In the latter method, the sensitivity of the model to one of the inputs is estimated by varying this parameter only and keeping all other inputs at their expected values. The effect that the considered input causes when varied from a low estimate to a high estimate on the output is used to quantify the sensitivity of the model to that parameter. Thus, the LSA involves assessing the sensitivity of the inputs one by one or what is called in literature one at a time sensitivity analysis.

In this study, the LSA method has been implemented since it allows for the assessment of model sensitivity to the input parameters separately, which isolates the effects of the other inputs from the one being assessed. Also, since the total of any impact can be calculated by a simple summation equation such as:

$$Total\ Impact = \sum_{i=1}^{m}\sum_{j=1}^{n} impact\ value$$

Where:

- *m* is the number of phases, and
- *n* is the number of processes.

Then it can be assumed that the relation between the inputs and the outputs is linear which makes this method suitable for the current analysis. Another point to consider is that in the LSA method, the inputs should not be correlated with each other. This point was investigated in this study and most of the processes involved were not correlated; the coefficient of correlation was less than 0.2 in most of the cases. This proves the validity of the LSA method to assess the sensitivity of the data of this study. In this method, the low and high estimates of inputs are calculated at 10% and 90% confidence intervals from the input PDFs. The sensitivity of the model to the considered parameter is quantified using the following equation:

$$S_{p,i} = (PV_{90\%} - PV_{10\%}) \Big/ \sum_{p=1}^{np} S_{p,i} \times 100\%$$

Where:

- $S_{p,i}$ is the model sensitivity of impact *i* with respect to parameter *p* in %,
- the nominator represents the net effect that varying a process between 90% and 10% can make,
- the denominator represents the total effect that a group of processes can make when individually varied from 90% to 10%.

The larger the results of this equation, the bigger the impact of the considered parameters. Accordingly, the process that makes the largest change in an impact is considered as the one causing the largest uncertainty. So, sorting $S_{p,i}$ results in a descending order and plotting the results in a Tornado chart will present the sensitivity analysis results in user friendly and clear environment as shown in the following section.

5.5 *Results and discussion of the uncertainty analysis*

5.5.1 Uncertainty and LSA results of individual mixtures

In this section, the uncertainty results of every type of asphalt are presented and discussed. For every mix, there are two types of results, the first one shows the PDF of the considered impacts, Eutrophication, Global Warming, and Photochemical Oxidation at every phase and the total of all phases as well. Example of these results is presented in Figure 26 and Figure 27. These results show the PDFs of Eutrophication and Global warming impacts. It can be seen that these outputs show the large variation associated with the impacts; which raises the question “what is the reliability of LCA studies without considering uncertainty of LCA inputs?”. This question will be addressed in the comparative analysis of the case studies in the next section.

The second type of outputs is LSA results, as shown in Figures 22-30. These results are Tornado charts show the order of phases and processes with respect to their effect on the impacts. For instance, Figure 28 indicates that A1 and A4 phases contributing the most to Eutrophication; the other phases have less importance. Figure 31 show that the global warming is mostly affected by phase A4, followed by A1 and A2 phases, whereas C2 and A3 phases have approximately the same importance. Similarly, Figure 35 demonstrates that Photochemical oxidation is largely affected by phase A1, whereas other phases have less influence. Furthermore, LSA results also include the sensitivity of every phase to the involved processes. For example, Figure 29 shows the importance order of processes involved in A1; it can be seen that Petroleum production process has the largest effect followed by Spoil from lignite mining and Spoil from hard coal mining processes; whereas other processes have less importance. Figure 30 on the other hand indicates that phase A4 is mostly affected by fright transport process. With respect to phase A4 effect on Global warming which is presented in Figure 32, it can be seen that fright transport process have the most effect. Whilst, phase A1 is mostly affected by four processes involve head production from gas and diesel as shown in Figure 33. Whereas Figure 28 indicates that phase A2 is largely sensitive to fright transportation process. Lastly, Figure 36 indicates that the petroleum refinery operation process has the greatest influence on A1 phase which the most important one with respect Photochemical oxidation impact. The important phases of all case studies are presented in Table 25; this table shows that A1, A4, and A3 are the most important phases with respect to all impacts. Accordingly, these phases should be investigated in order to identify the processes contribute the most every impact and the uncertainty associated with these processes.

Moreover, the above results are for the reference mixture only. It can be seen that this analysis can offer a lot of critical data that can be utilised to understand the effect of uncertainty in LCA. The enormity of the data, however, must be considered. Every mixture may produce around sixty charts to show the entire results. Obviously, a method is required here to analyse the data and look for the important results. One way that is suggested in this study is that the analyst should only look for the critical phases that cause the largest impacts, then look for the important processes that contribute the most to the critical phases. This is like a tree analysis; for example, Figure 35 shows that phase A1 is the critical one with respect to Photochemical oxidation. The LSA sensitivity results of that phase which presented in Figure 36 show that the petroleum refinery operation and waste natural gas processes are the most important ones. Accordingly, to reduce the Photochemical oxidation and the uncertainty associated with that impact, the analyst should chase and investigate these processes rather than looking at other processes which will have rather less impact. The rest of the results of this section are presented in Appendix III.

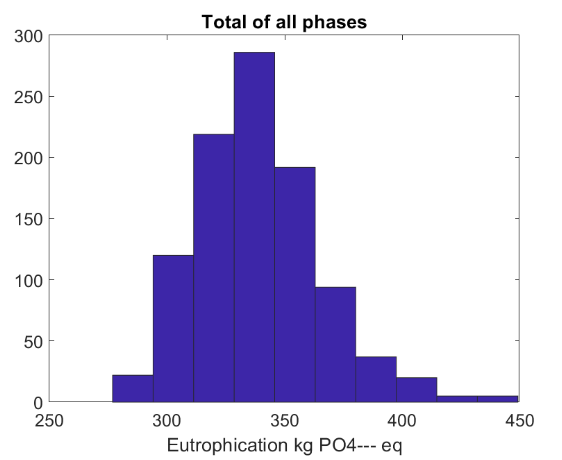


Figure 26. Eutrophication PDF of mixture 1

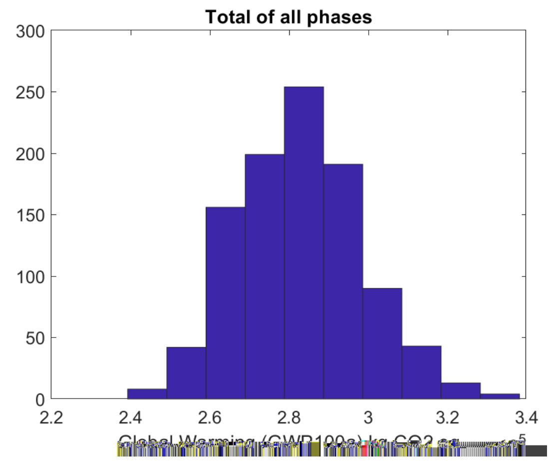


Figure 27. Global warming PDF of mixture 1

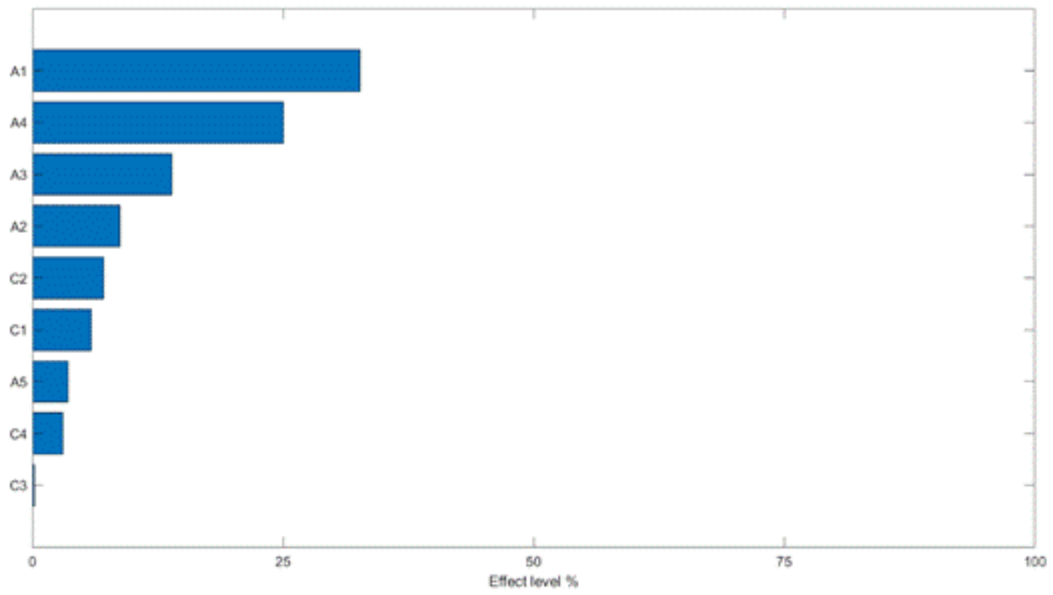


Figure 28. LSA results of Eutrophication to LCA phases

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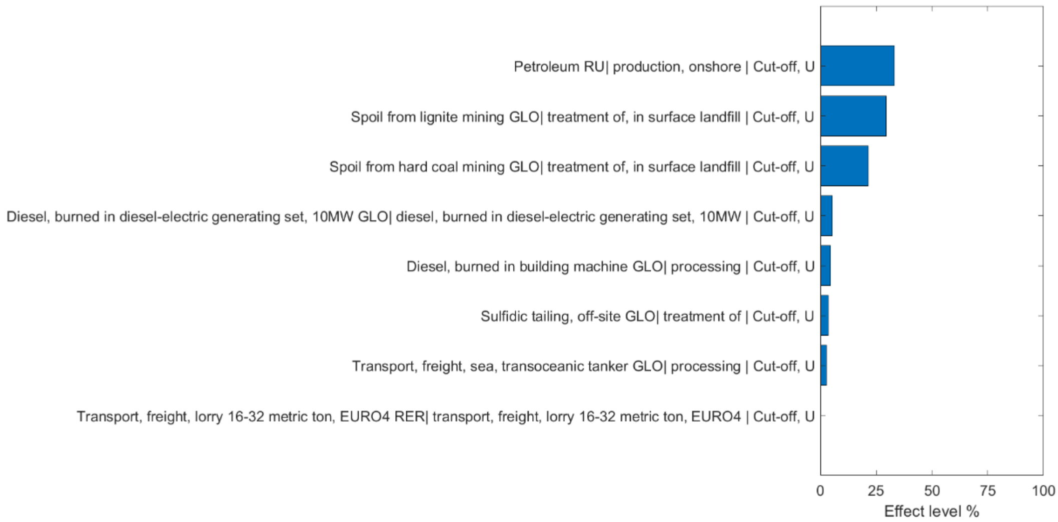

Figure 29. LSA results of Eutrophication to LCA A1 phase

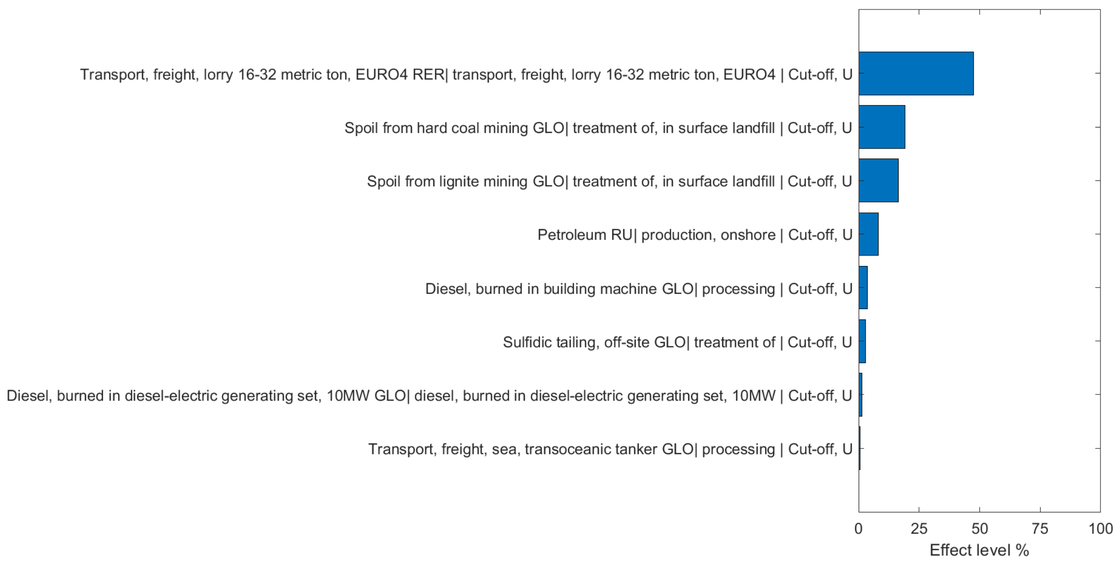

Figure 30. LSA results of Eutrophication to LCA A4 phase

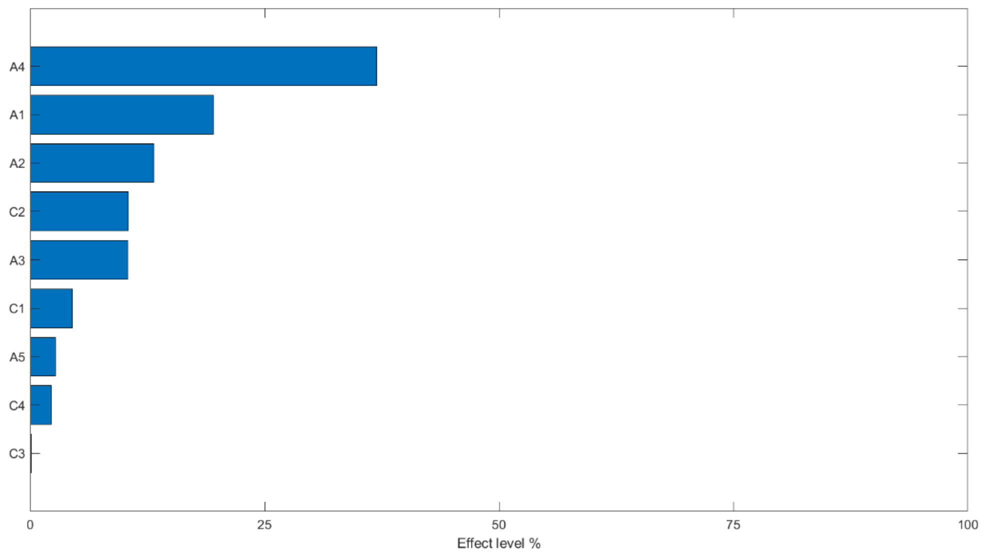

Figure 31. LSA results of Global warming to LCA phases

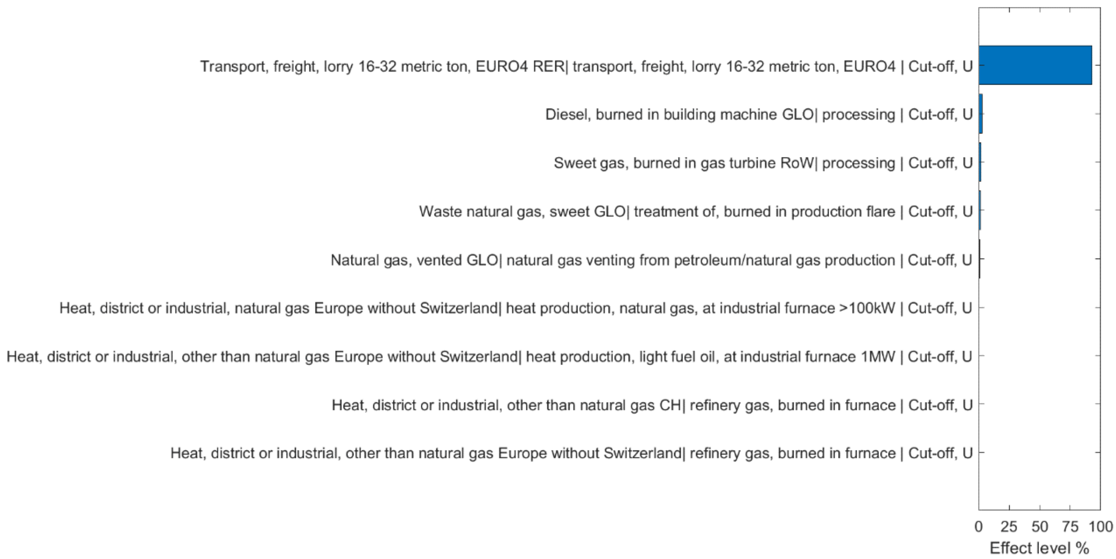

Figure 32. LSA results of Global warming to LCA A4 phase

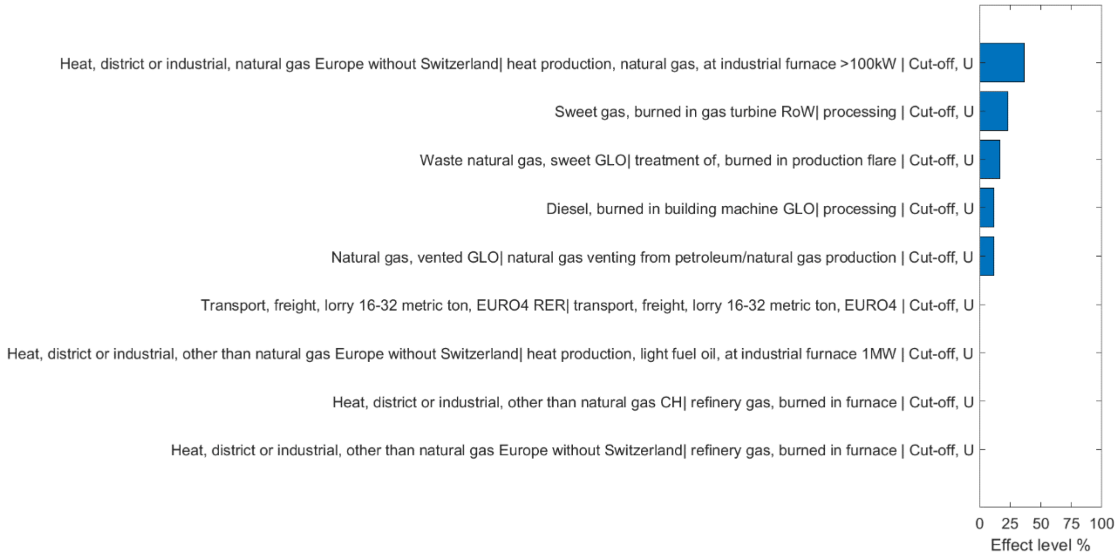

Figure 33. LSA results of Global warming to LCA A1 phase

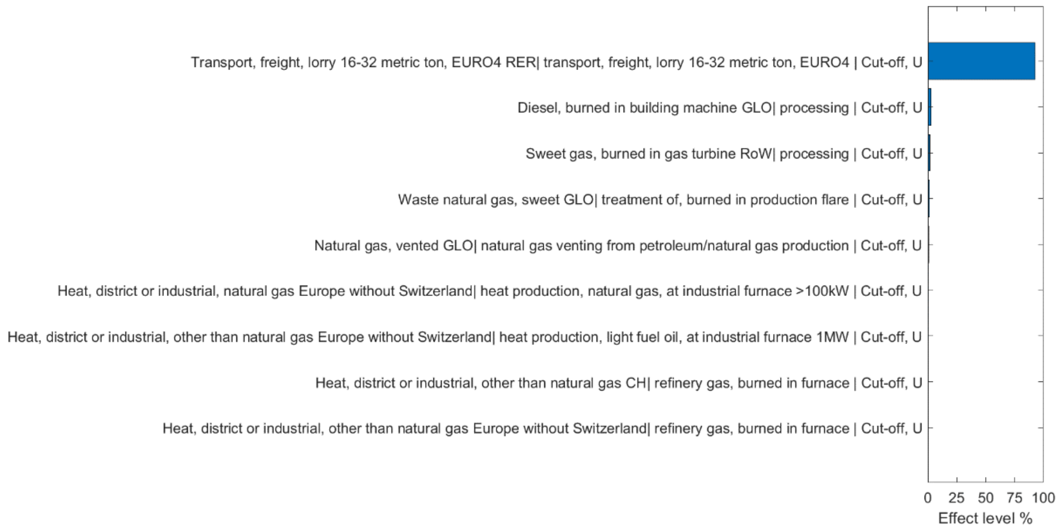

Figure 34. LSA results of Global warming to LCA A2 phase

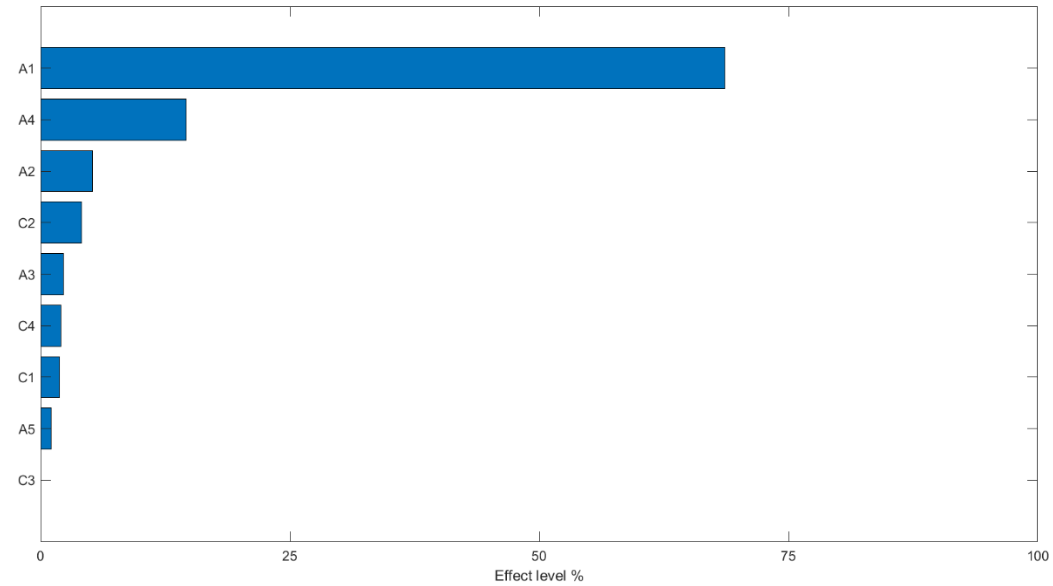

Figure 35. LSA results of Photochemical oxidation to LCA phases

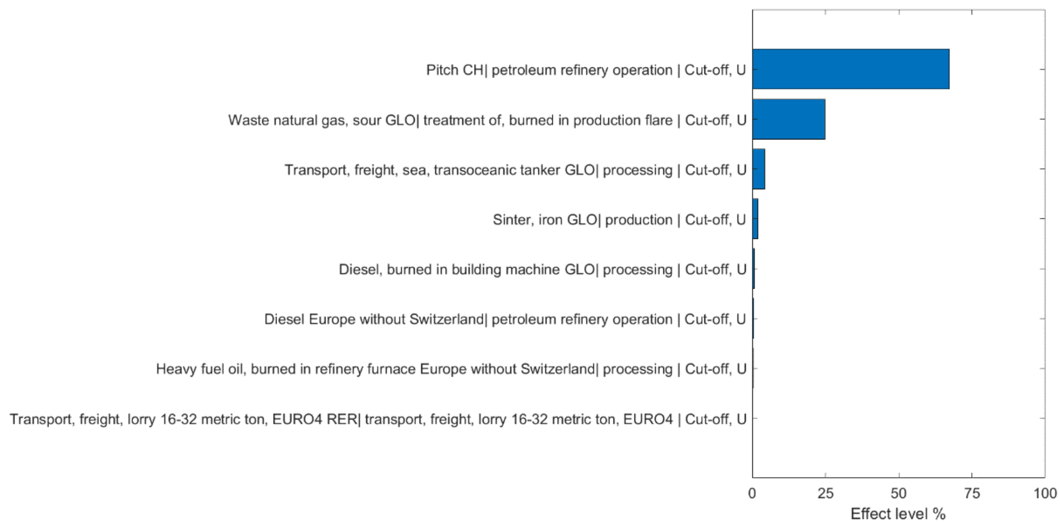

Figure 36. LSA results of Photochemical oxidation to LCA A1 phase

Table 25. Phase Importance order with respect to every impact of all case studies.

Mixture	Eutrophication								
Mixture 1	A1	A4	A3	A2	C2	C1	A5	C4	C3
Mixture 2	A1	A4	A3	A2	C2	C1	A5	C4	C3
Mixture 3	A1	A4	A3	A2	C2	C1	A5	C4	C3
Mixture 4	A1	A4	A3	A2	C2	C1	A5	C4	C3
Mixture 5	A1	A4	A3	A2	C2	C1	A5	C4	C3
Mixture 6	A1	A4	A3	A2	C2	C1	A5	C4	C3

Mixture	Global warming							
Mixture 1	A4	A1	A2	C2	A3	C1	A5	C4	C3
Mixture 2	A4	A1	A2	C2	A3	C1	A5	C4	C3
Mixture 3	A4	A1	A2	A3	C2	C1	A5	C4	C3
Mixture 4	A4	A1	A2	A3	C2	C1	A5	C4	C3
Mixture 5	A4	A1	A2	C2	A3	C1	A5	C4	C3
Mixture 6	A4	A1	A2	C2	A3	C1	A5	C4	C3
Mixture	**Photochemical oxidation**								
Mixture 1	A1	A4	A2	C2	A3	C4	C1	A5	C3
Mixture 2	A1	A4	A2	C2	A3	C4	C1	A5	C3
Mixture 3	A1	A4	A2	C2	A3	C4	C1	A5	C3
Mixture 4	A1	A4	A2	C2	A3	C1	C4	A5	C3
Mixture 5	A1	A4	A2	C2	A3	C4	C1	A5	C3
Mixture 6	A1	A4	A2	C2	A3	C4	C1	A5	C3

5.5.2 Comparative analysis of uncertainty results

In this section, the uncertainty results of all case studies are comparatively analysed. The PDFs of all impacts at every LCA phase in addition to the impact totals, are compared against each of the mixtures. Two different analysis scenarios are considered here. The first, is to analyse the data without considering the durability in the analysis. Thus, the impacts are calculated and compared with respect to one ton of asphalt of each mix. The second, is to consider the durability of the pavement components in the analysis; thus, the results show the expected total environmental impact per the analysis period of every mix. Both approaches give different conclusions; the first one shows the analysis results relatively to one unit of asphalt, whereas the second one shows the absolute value of every impact relatively to the considered analysis period.

Figure 37,Figure 38, and Figure 39 present PDFs of Eutrophication, Global warming, and Photochemical oxidation impacts respectively without considering the durability in the analysis. the first Figure shows that mixtures 1, 4, and 6 has similar Eutrophication impact; whereas mixtures 2 and 5 obvious higher impact. Mixture 3 showed a result that is close to the average of all mixtures. With respect to the global warming shown in the second Figure; fairly similar results of all mixtures can be seen. Mixture 5 has the highest global warming impact whereas mixtures 1 and 6 have the lowest. On the other hand, Figure 33 shows different trends; mixture 3 has the lowest Photochemical oxidation impact, whereas mixture 4 have the largest impact. Furthermore, the variations of these results are mixture type and impact type dependent. For instance, mixture 4 has low to medium impact with respect to Eutrophication and Global warming but it has higher Photochemical oxidation than other mixtures; also, the latter impact has a larger variation than the Eutrophication and Global warming results. Similar trends can be discovered for other mixtures. This observation can be explained by different factors such as the level of the uncertainty of the important processes with respect to each impact and mix, the inputs, and assumptions of the individual mixtures when LCA was modelled.

On the other hand. The comparison results of the case studies when the durability of each pavement component is included are presented in Figure 40,Figure 41, and Figure 42. These Figures show that the conclusions about uncertainty analysis can be dramatically changed when the durability of the pavement components is considered. First of all, the figures show that the pavement components with highest durability (long service life) have generally less environmental impacts. For example, mixture 4, which has an expected durability of 20 years, showed the lowest impacts amongst other mixtures, whereas it did not show that trend in Figures 31-33. This conclusion can be explained by the fact that the longer the durability the smaller quantity of asphalt will be needed over a design period. This observation coincides with the total quantities of asphalt per designed period of every mixture which are presented in Figure 43. Furthermore, these Figures also show that the variation level in the impact results decreases with the reduction in the asphalt quantity. This is related to the level of uncertainty per one ton of asphalt and its quantity per the design period. In other words, if two mixtures have the same level of uncertainty per one ton of asphalt but one of them is twice durable than the other, then the uncertainty level of the durable asphalt will be half of the uncertainty level of the less durable asphalt. Accordingly, consuming less asphalt leads not only reducing the environmental impacts, but also the level of uncertainty in the result. Thus, component durability is one of the most important factors to consider in LCA studies to reduce the environmental impacts of asphalt and the variation of LCA studies. However, other parameters must be considered in the analysis such as asphalt cost, noise, or skid resistance in the analysis to develop a full understanding of the problem and make the right decisions.

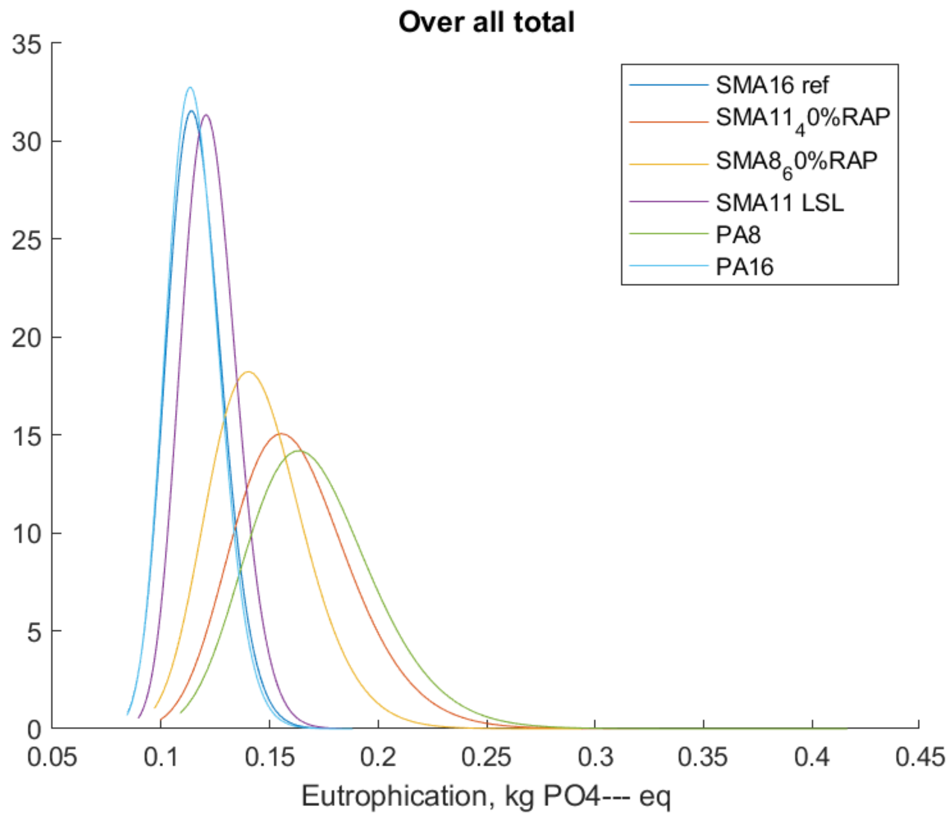

Figure 37. Eutrophication PDFs without considering durability

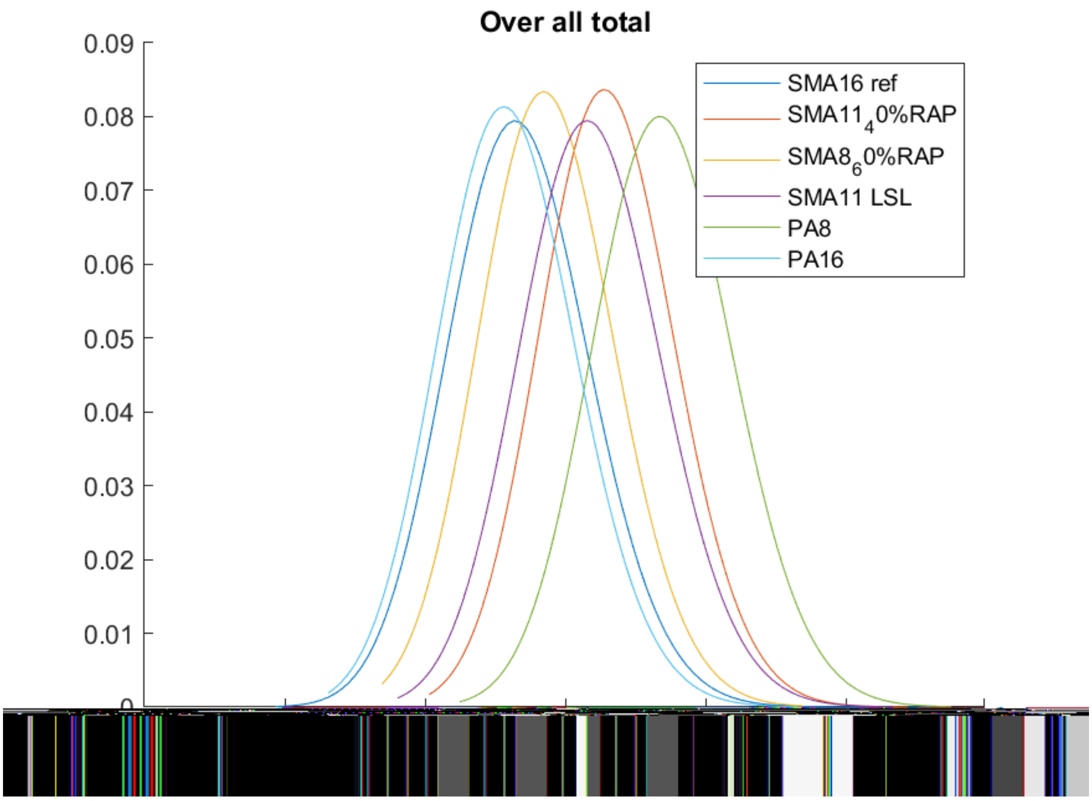

Figure 38. Global warming PDFs without considering durability

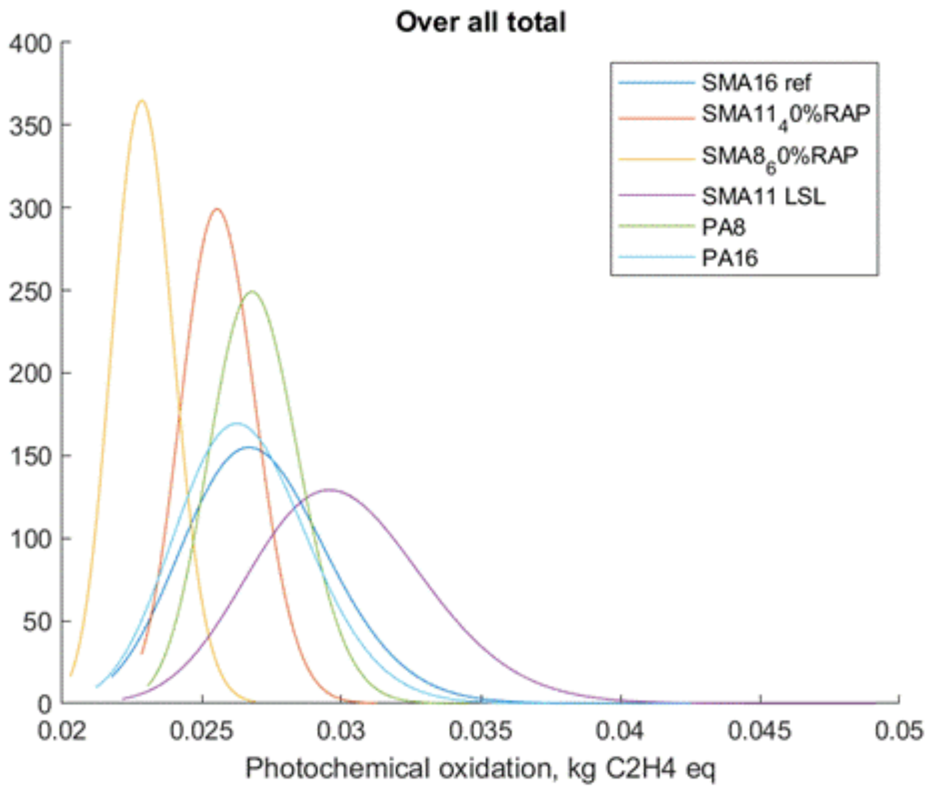

Figure 39. Photochemical oxidation PDFs without considering durability

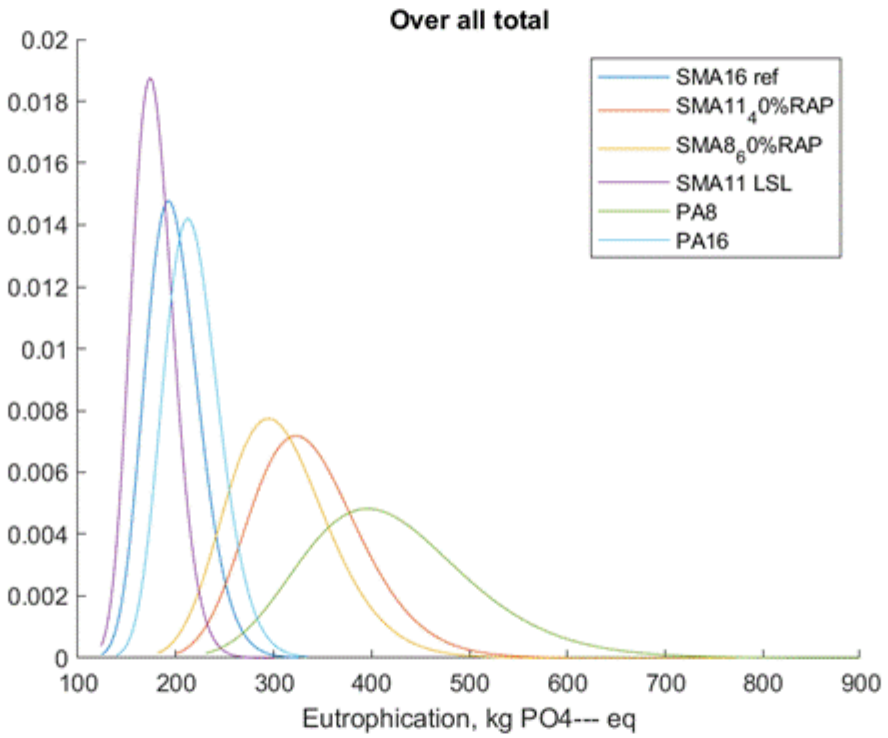

Figure 40. Eutrophication PDFs considering durability

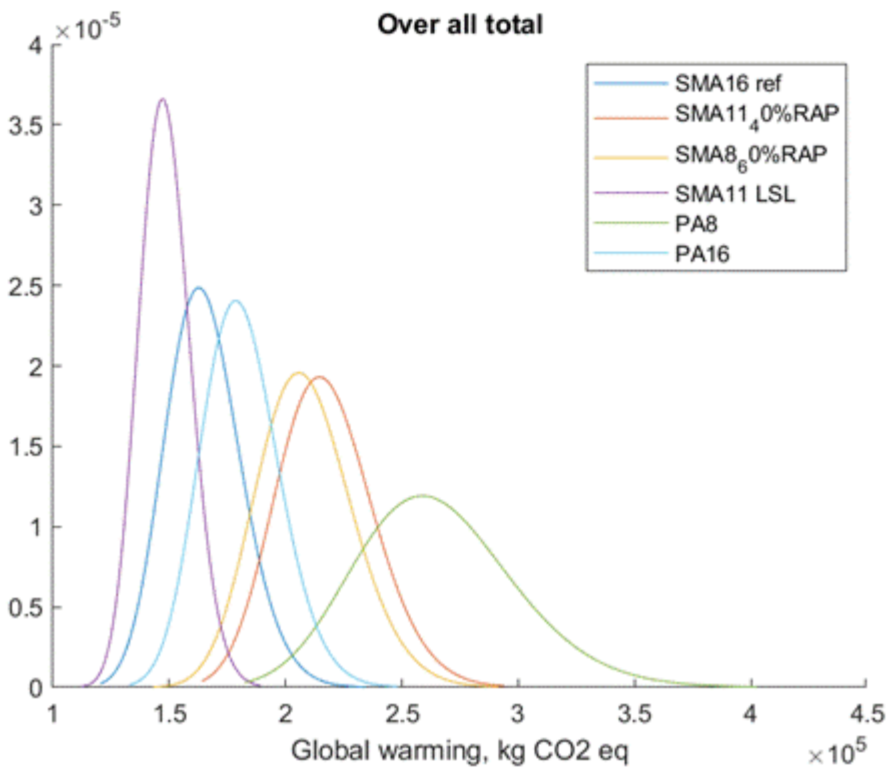

Figure 41. Global warming PDFs considering durability

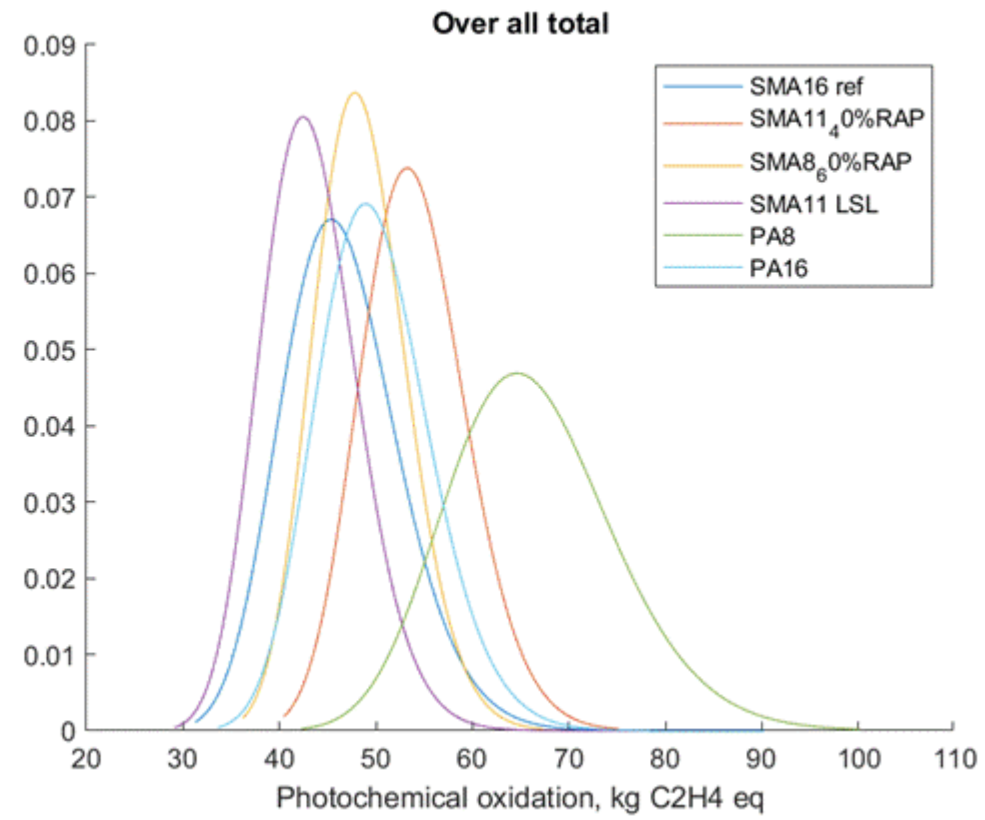

Figure 42. Photochemical oxidation PDFs considering durability

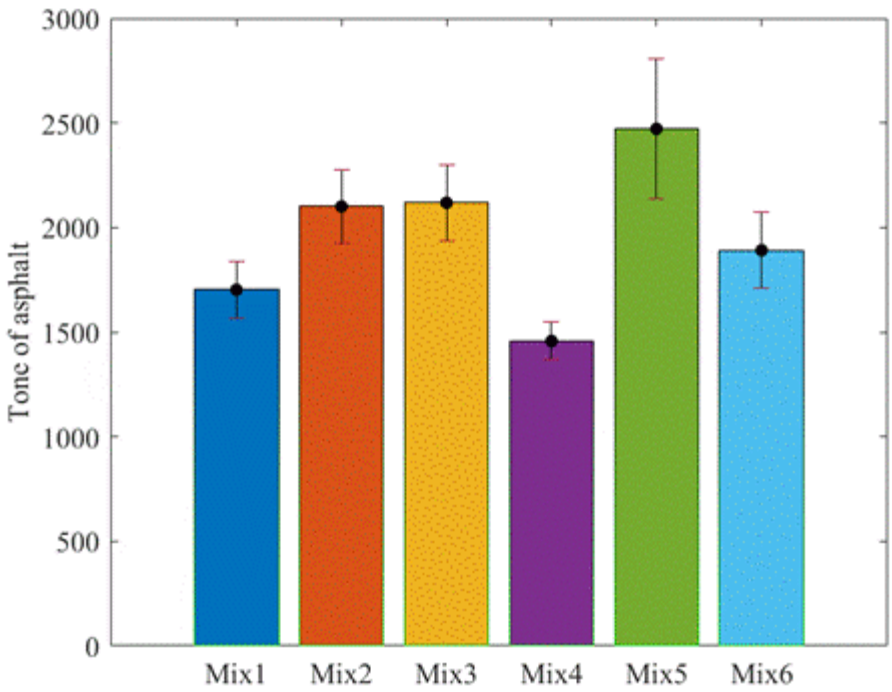

Figure 43. Expected asphalt quantity per the designed period for 1 km of road

5.5.3 Probabilistic analysis of uncertainty results

5.5.3.1 ANOVA test

Since the PDF of the impacts are available from the uncertainty model; then the significance of the results can be tested by running an ANOVA test. This test can be used to check the hypothesis that a mean impact value of a mixture is significantly different from the means of other mixtures. The null hypothesis is that the means from different groups are equal. If the P value is more than 0.05 then the null hypothesis is accepted; otherwise the null hypothesis is rejected. This test was run to test the significance of the impact results of all case studies with and without the inclusion of the durability. The test results of the case without the durability impact are presented in Table 26, whereas the results of the other case are shown in Table 27.

These tables show that most of the results of Eutrophication and Global warming impacts are significantly different from each other; except some cases such as the Eutrophication or Global warming tests between mixtures 1 and 6 which are insignificantly different from each other as shown in Table 24. After considering the durability effects in the analysis, however, all test results became significantly different; as shown in Table 25. This conclusion can be explained by the significant impact that the component's durability has on the results which increases the difference amongst the results. Furthermore, these results strongly suggest that the LCA results should definitely be considered by decision makers and in multi criteria sustainability assessment and decision-making processes to draw comprehensive conclusions and make the right decisions.

5.5.3.2 Kolmogorov-Smirnov test

The ANOVA test results proved that the means of the distributions are significantly different from each other. To test if the calculated impact results are from different distributions, however, a Kolmogorov-Smirnov test is required. This test is a non-parametric test that can be used to test if two samples are from two different distributions or not. The null hypothesis of the test is that the two tested samples are from the same distribution; the alternative hypothesis is the two samples are from two different distributions. In this study this test was applied to test the impact distributions of all case studies in comparison with the reference mixture; Table 28 Shows the results of the test. These results indicate that the tested samples are from different distributions except two cases between mixtures 1 and 6 when the durability was not included in the analysis. However, all the tested samples became from different distributions when the durability included in the analysis. This means that the impact results of mixture 1 to 5 are different distributions when compared to mixture 1 results.

Table 26. ANOVA test results without considering the durability.

Eutrophication			Global warming			Photochemical oxidation		
Mixtures		P value	Mixtures		P value	Mixtures		P value
1	2	<0.0001	1	2	<0.0001	1	2	<0.0001
1	3	<0.0001	1	3	<0.0001	1	3	<0.0001
1	4	<0.0001	1	4	<0.0001	1	4	<0.0001
1	5	<0.0001	1	5	<0.0001	1	5	0.7965
1	6	0.9758	1	6	0.0035	1	6	<0.0001
2	3	<0.0001	2	3	<0.0001	2	3	<0.0001

Eutrophication			Global warming			Photochemical oxidation		
Mixtures		P value	Mixtures		P value	Mixtures		P value
2	4	<0.0001	2	4	<0.0001	2	4	<0.0001
2	5	<0.0001	2	5	<0.0001	2	5	<0.0001
2	6	<0.0001	2	6	<0.0001	2	6	<0.0001
3	4	<0.0001	3	4	<0.0001	3	4	<0.0001
3	5	<0.0001	3	5	<0.0001	3	5	<0.0001
3	6	<0.0001	3	6	<0.0001	3	6	<0.0001
4	5	<0.0001	4	5	<0.0001	4	5	<0.0001
4	6	<0.0001	4	6	<0.0001	4	6	<0.0001
5	6	<0.0001	5	6	<0.0001	5	6	0.0038

Table 27. ANOVA test results considering mixture durability effects.

Eutrophication			Global warming			Photochemical oxidation		
Mixtures		P value	Mixtures		P value	Mixtures		P value
1	2	<0.0001	1	2	<0.0001	1	2	<0.0001
1	3	<0.0001	1	3	<0.0001	1	3	<0.0001
1	4	<0.0001	1	4	<0.0001	1	4	<0.0001
1	5	<0.0001	1	5	<0.0001	1	5	<0.0001
1	6	<0.0001	1	6	<0.0001	1	6	<0.0001
2	3	<0.0001	2	3	<0.0001	2	3	<0.0001
2	4	<0.0001	2	4	<0.0001	2	4	<0.0001
2	5	<0.0001	2	5	<0.0001	2	5	<0.0001
2	6	<0.0001	2	6	<0.0001	2	6	<0.0001
3	4	<0.0001	3	4	<0.0001	3	4	<0.0001
3	5	<0.0001	3	5	<0.0001	3	5	<0.0001
3	6	<0.0001	3	6	<0.0001	3	6	<0.0001
4	5	<0.0001	4	5	<0.0001	4	5	<0.0001
4	6	<0.0001	4	6	<0.0001	4	6	<0.0001
5	6	<0.0001	5	6	<0.0001	5	6	<0.0001

Table 28. Kolmogorov-Smirnov test results.

Excluding durability					
Impact \ tested mixtures	1-2	1-3	1-4	1-5	1-6
Eutrophication	TRUE	TRUE	TRUE	TRUE	FALSE
Global Warming	TRUE	TRUE	TRUE	TRUE	FALSE
Photochemical Oxidation	TRUE	TRUE	TRUE	TRUE	TRUE
Including durability					
Impact \ tested mixtures	1-2	1-3	1-4	1-5	1-6
Eutrophication	TRUE	TRUE	TRUE	TRUE	TRUE
Global Warming	TRUE	TRUE	TRUE	TRUE	TRUE
Photochemical Oxidation	TRUE	TRUE	TRUE	TRUE	TRUE

5.6 Summary, conclusions and recommendations from the

Uncertainty Analysis

5.6.1 Summary and conclusions about LCA Uncertainty in this Project

This section investigated the uncertainty of LCA data and its effects on the outcome of sustainability studies. A new methodology to estimate the uncertainty in LCA data based on the ecoinvent method has been developed; and an innovative model to incorporate the uncertainty in LCA inputs and tackle its effects on the outputs has been built.

The model assumes that all LCA inputs are lognormally distributed with mean μ and standard deviation σ, where the mean values are calculated by SimaPro and the standard deviations are precalculated based on ecoinvent database using the pedigree matrix method. The outputs of the model are the probability distribution functions of the considered environmental impacts. Furthermore, the effect of component durability and its uncertainty have also been included in the developed model. The durability is defined as the number of years a component can serve before the first major maintenance cycle. The durability PDF has been used to calculate the PDF of the total asphalt quantity required over a certain analysis period, which is used in the model to calculate the PDF of the total of the considered environmental impacts. Moreover, the model also runs a sensitivity analysis to identify the important phases and processes that contribute the most to the environmental impacts.

In the light of the results of this study, the following conclusions can be drawn:

1. Uncertainty estimation of LCA data demonstrated that there are high levels of uncertainty in the processes that contribute to the environmental impacts, as presented in Table 24 which shows that average the COVs of the selected impacts is 32% but it can reach 122% in some cases. This indicates that the LCA studies must include the effect of LCA data uncertainty and its effects on the results in or order to draw true conclusions and make correct decisions.
2. Sensitivity analysis results can be used to identify the important phases that contribute the most to the selected impacts which can be used in turn to identify the most important processes that contribute to the important phases. The results of this analysis can be utilised to concentrate the efforts and research on the phases and process that cause high impacts with large uncertainty in order to reduce the amount of the impacts and the uncertainty levels.
3. As a general rule of thumb, a process will have clear impact on the reliability of an LCA study results if it has a high impact and a large standard deviation. The high impact is to prove the process is an important one and can cause a large environmental impact whereas the high standard deviation is to prove that the impact is sensitive to uncertainty of this process.
4. The derived LCA uncertainty analysis can be run in two ways. The first one is to find the variability of the LCA results per one unit of the analysed mix. The second one is to find the variability of LCA results per certain analysis period by considering the durability and thus the maintenance scheme of the pavement component being analysed, which gives the PDFs of the total impact over the design period.
5. The durability of pavement components is a critical factor that must be carefully considered in the LCA analysis. The material properties which contribute to the durability of pavement components durability, are directly used to calculate the total quantity of asphalt required for a certain design period, which is directly related to the amount of the environmental impacts of asphalt. Accordingly, the uncertainty of component's durability has a direct impact on the uncertainty of LCA results.

5.6.2 Recommendations for Implementation of LCA Uncertainty Analysis for NRAs

The developed uncertainty analysis is used to incorporate the uncertainty of LCA inputs in the analysis and predict the variability of the outputs. The results of that analysis are the PDFs of the considered environmental impacts and the identification of the important phases and processes that contribute the most to the impacts. This kind of analysis enables the NRAs to examine the PDFs of LCA outputs and make reliable decisions regarding the usefulness and effectiveness on the considered green mixtures or new technologies. The implementation of this analysis, however, requires some quality data and some knowledge about Matlab and SimaPro or any programmes with comparable capabilities and applications. And in order for NRAs to implement the developed model, the following is recommended:

1. The first and the most critical point is to collect sufficient quality data regarding the durability of the considered new components. This is because the durability and its uncertainty have direct impacts on the environmental impacts and their variabilities.
2. Every available data about any new asphalt technology that is considered to be used should be documented. Such as the sources and types of raw materials used, mixture design data, type and quantity of used additives if any, production temperatures of the new asphalt, type of amount energy used in the production process, transport data such as transportation distances and trucks used. On top of these data is the durability of the new components. Since these data play important role in determining the environmental impacts of the new technology which therefore enhances the reliability of the LCA study.
3. To analyse the PDFs of the results probabilistically, a certain reliability level must be selected. Although a reliability level of 90% is recommended in this study and it is used to assess the environmental impacts of the case studies, the NRAs can select any other reliability level that suits their applications.
4. With respect to the methods that can be followed to reduce LCA uncertainty, two ways are recommended. Firstly, by improving component durability, this way can be used to reduce the required quantity of asphalt and therefore reducing the uncertainty of the total environmental impacts over the design period. Secondly, by analysing the sensitivity analysis results. This method can be used to identify the important phases and underlaying processes that contribute the most to the environmental impacts. The identification of the important processes should be followed by further research on the possibility of reducing the impacts they are causing and their uncertainties.

6 Conclusions and recommendations

This report illustrates the sensitivities in sustainability analysis, which reveal important messages for those who want to deploy activities to enhance sustainability. It also helps understanding how to apply the framework proposed in the D2.1 of the PavementLCM project by presenting case studies designed and described according to the framework.

It has been investigated what the sustainability was of several asphalt mixtures, covering how they are associated with expected service life, what happens when asphalt is produced at a lower temperature and when RAP is introduced. The asphalt mixtures were both investigated on a material level as well as on a systemic level, covering pavement activities over a time period of 40 years. The analysis was performed on multiple sustainability indicators and by means of several tools, thereby illustrating the benefits and limitations of the various ways in which sustainability can be implemented.

In addition, special attention was paid to the uncertainties, to provide insight in the order of magnitude of uncertainties, and to give guidelines on how to take uncertainty into account for reaching robust results and conclusions.

The case studies of this study serve as an example for other sustainability activities, to learn from. The first lesson is that most sustainable pavement component is not just the mixture with the lowest temperature or the highest amount of RAP. Innovations lead only to real improvements in sustainability when they are considered on a systemic level, comparing road systems over longer time periods than when only focusing on production. System analysis will reveal trade-offs, for example between using RAP and needing additives, as well as provide insight in the results of specific circumstances like traffic, climate, etcetera. Only with this approach, it is possible to have a holistic overview of the impacts and performance of an asphalt mixture.

> *→ recommendation 1: always compare pavement solutions in a project context with a long term (at least 40 years) perspective, never on a mass-basis (1 ton of X vs 1 ton Y).*
>
> *→recommendation 2: be aware of potential trade-offs in sustainability, especially when additives or modifications are applied to ensure success.*

Since “sustainability” is an umbrella concept, it is hard to find a single solution which ticks all boxes and scores best on all indicators. For that reason, organizations who want to improve should define clearly what indicators they find most important and, in case they find many things important, how they will combine different indicators to a final decision. The Dutch system of shadow prices and MEAT procedures[20] is an example of the integration of different indicators into a decision-making process.

> *→ recommendation 3: before you start to investigate sustainability and/or before you incorporate sustainability in a tender or a strategy document, define which indicators you find important.*
>
> *→ recommendation 4: in case of multiple indicators, determine on beforehand how you will combine them. Options are: weighing (e.g. shadow prices) or equal weight (e.g. the solution with most “best scores” wins).*

When implementing sustainability, users should be aware that sustainability calculations with different tools, databases and/or methodologies will definitely lead to different conclusions. There are dozens of tools available to perform Sustainability Assessments of roads. Each of them has its own specificities and is more appropriated to a certain

[20] MEAT stands for “Most Economically Advantageous Tender” and reflects a weighing system in which (environmental) impacts are taken into account in the decision-making process.

region due to the impact assessment method employed in the calculations and the database in the background. Hence, the NRA should choose a tool that suits their needs in terms of indicators, impact assessment method and underlying database. The Sustainability Assessment Compass, delivered in WP5, will help NRAs to find the right tool for certain situations.

> *→recommendation 5: first decide what are your goals, then select the appropriate tool and only tolerate data or results which are generated by this tool.*

> *→ recommendation 6: use the Sustainability Assessment Compass (WP5) to find the right tool for the right situation.*

> *→recommendation 7: to make most efficient use of internationally available data, consider harmonisation of data on a European level; see "Roadmap to Harmonisation" (WP5).*

However, there are more aspects then only tool selection when implementing sustainability; it is crucial to design a complete system with clear boundaries and conditions. In the case of the Netherlands, Rijkswaterstaat, the Dutch Road Authority, noticed that using the same tool and method was still not enough to ensure comparability of different products, therefore, together with market parties, they developed Product Category Rules. This document provides very specific guidelines on how to perform LCAs for asphalt in a uniform way, so that they can be used in tendering procedures.

> *→recommendation 8: set clear boundary conditions when starting a green procurement system.*

> *→recommendation 9: consider the development of European guidelines on LCAs of asphalt, in line with the Dutch Product Category Rules.*

This system relies also on the quality of the data available. Datasets driving the LCA results of the asphalt mixtures, namely binder, aggregates and transport datasets, should be carefully modelled with high quality primary data to ensure that results of the sustainability analysis are reliable. The comparison of tools showed clearly that it is undesirable to mix datasets from different tools, even though the methodologies may seem similar, because the background databases can have huge and unexpected influence on the final results.

> *→recommendation 10: never mix results generated with different tools or databases.*

Uncertainty estimation of LCA data demonstrated that there are high levels of uncertainty in the processes that contribute to the environmental impacts. As a general rule of thumb, a process will have clear impact on the reliability of an LCA study results if it has a high impact and a large standard deviation. Sensitivity analyses can be used to identify the phases that contribute the most to the overall uncertainties. In the assessment of pavement activities, durability revealed to be a crucial factor. Uncertainties in durability have a direct effect on uncertainties of a whole project or study.

> *→recommendation 11: implement a basic form of uncertainty analysis in each project where sustainability is involved. The most basic form is to investigate the processes which are most impactful, and which have the largest standard deviations.*

> *→recommendation 12: be extremely careful with uncertainties in durability. When durability is involved (for example in scenario analysis of pavement activities), make sure that uncertainties are addressed, for example by using ranges and by quantifying the impact on the results. When anyone will receive benefits from a long durability, make sure that this decision is based on even the worst-case*

scenario of durability.

Overall, this study highlighted the crucial role of critical judgement in sustainability assessment for NRAs. This does not mean that the NRAs have to become experts in sustainability or statistics, but it challenges them to think critically of what they really want to achieve and how they organize their systems. To achieve sustainability goals successfully, it is indispensable to take durability critically into account. The biggest challenge, for NRAs, innovating companies, sustainability researchers and statisticians altogether, is to reduce the uncertainties in durability predictions and thereby to support sustainability statements. Without reliable durability predictions, sustainability goals might easily be mistaken.

N.B. The PavementLCM framework has been updated in July2021, hence in this exercise some of the suggested elements of the SA exercise for pavement activities (i.e. refer to 1 reference service life, include Module D) might not be present since the content of this deliverable refers to a previous version of the framework

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Annex I – Results of the LCA

The tables below show the results for the six asphalt mixtures from the production phases (life cycle phase A1 to A3), for three environmental impact categories (Global Warming, Eutrophication and Air Pollution).

Table 29: Global warming results in kg CO_2 eq. for 1 ton of asphalt mixture, per life cycle stage.

Global warming (GWP100a)	1. SMA 16 - reference	2. SMA 11 - 40% RAP + PMB + LTA	3. SMA 8 - 60% RAP + PMB	4. SMA 11 - Long service life	5. PA 8 - top layer 2L PA + PMB	6. PA 16 - long service life
Raw Material Extraction	28.3	38.6	31.8	32.7	42.0	27.4
Transport to Asphalt Plant	11.4	11.7	12.8	12.4	11.9	11.7
Production	7.4	6.7	7.4	7.4	7.4	7.4

Table 30: Eutrophication results in kg PO_4^{3-} eq. for 1 ton of asphalt mixture, per life cycle stage.

Eutrophication	1. SMA 16 - reference	2. SMA 11 - 40% RAP + PMB + LTA	3. SMA 8 - 60% RAP + PMB	4. SMA 11 - Long service life	5. PA 8 - top layer 2L PA + PMB	6. PA 16 - long service life
Raw Material Extraction	0.0306	0.0385	0.0296	0.0352	0.0411	0.0297
Transport to Asphalt Plant	0.0081	0.0086	0.0093	0.0087	0.0087	0.0082
Production	0.0031	0.0030	0.0031	0.0031	0.0031	0.0031

Table 31: Air pollution results in kg C_2H_4 eq. for 1 ton of asphalt mixture, per life cycle stage.

Air Pollution	1. SMA 16 - reference	2. SMA 11 - 40% RAP + PMB + LTA	3. SMA 8 - 60% RAP + PMB	4. SMA 11 - Long service life	5. PA 8 - top layer 2L PA + PMB	6. PA 16 - long service life
Raw Material Extraction	0.0154	0.0147	0.0115	0.0180	0.0158	0.0147
Transport to Asphalt Plant	0.0019	0.0021	0.0022	0.0020	0.0021	0.0019
Production	0.0011	0.0010	0.0011	0.0011	0.0011	0.0011

The tables below show the results used for the other life cycle phases (from gate to grave: A4-C4), which were used scenario analyses.

Table 32: Results of life cycle stages A4 to C4 for 1 kg of all mixtures.

	All mixtures (A4)	All mixtures (A5)	All mixtures (C1)	All mixtures (C2)	All mixtures (C3)	All mixtures (C4)
Global warming 100a (kg CO_2 eq)	0.0323	0.0019	0.0034	0.0091	0.0002	0.0053
Eutrophication (kg PO_4^{3-} eq)	2.3E-05	3.1E-06	5.5E-06	6.4E-06	2.7E-07	6.8E-06
Air Pollution (kg C_2H_4 eq)	5.3E-06	3.8E-07	6.7E-07	1.5E-06	3.3E-08	2.0E-06

Table 33: Results for three LCA indicators, for 1 kg of two asphalt mixtures used in the scenario analysis and for 1 kg of the tack coat.

	AC bin/base 50% RAP	Tack coat	Alternative to scenario 3 60% RAP + Bitumen
Global warming 100a (kg CO_2 eq)	0.029	0.347	0.0397
Eutrophication (kg PO_4^{3-} eq)	2.2E-05	3.4E-04	3.2E-05
Air Pollution (kg C_2H_4 eq)	8.5E-06	1.8E-04	1.4E-05

Annex II – Results of the LCC

Table 34: Material costs in euros for 1 ton of asphalt mixture per material used in life cycle phase A1 (winning of materials).

Product	1. SMA 16 - reference	2. SMA 11 - 40% RAP + PMB + LTA	3. SMA 8 - 60% RAP + PMB	4. SMA 11 - Long service life	5. PA 8 - top layer 2L PA + PMB	6. PA 16 - long service life
	Costs (€ per tonne asphalt mixture)					
RAP	€ -	€ 4.20	€ 6.60	€ -	€ -	€ -
Bitumen	€ 36.21	€ -	€ -	€ 42.90	€ -	€ 33.80
PMB	€ -	€ 34.42	€ 25.43	€ -	€ 38.01	€ -
Filler	€ 1.41	€ 1.13	€ -	€ 0.28	€ 1.00	€ 1.02
Fibres	€ -	€ -	€ 2.70	€ 2.70	€ -	€ 1.80
Crushed rock	€ 3.74	€ 2.85	€ -	€ 4.04	€ 1.14	€ 0.72
Gravel	€ 10.90	€ 5.76	€ 5.97	€ 11.32	€ 13.90	€ 14.27
Additive (STORBIT)	€ -	€ -	€ 8.10	€ -	€ -	€ -
Additive (Cecabase)	€ -	€ 1.67	€ -	€ -	€ -	€ -

Table 35: Transport costs in euros for 1 ton of asphalt mixture, per material.

Product	1. SMA 16 - reference	2. SMA 11 - 40% RAP + PMB + LTA	3. SMA 8 - 60% RAP + PMB	4. SMA 11 - Long service life	5. PA 8 - top layer 2L PA + PMB	6. PA 16 - long service life
	Costs (€ per tonne asphalt mixture)					
RAP	€ -	€ 1.58	€ 2.49	€ -	€ -	€ -
Bitumen	€ 0.53	€ -	€ -	€ 0.63	€ -	€ 0.49
PMB	€ -	€ 0.45	€ 0.33	€ -	€ 0.49	€ -
Filler	€ -	€ -	€ -	€ -	€ -	€ -
Fibres	€ -	€ -	€ -	€ -	€ -	€ -
Crushed rock	€ -	€ -	€ 0.07	€ 0.07	€ -	€ 0.04
Gravel	€ 0.92	€ 0.70	€ -	€ 1.00	€ 0.28	€ 0.18
Additive (STORBIT)	€ 2.70	€ 1.43	€ 1.48	€ 2.80	€ 3.44	€ 3.53
Additive (Cecabase)	€ -	€ -	€ 0.34	€ -	€ -	€ -

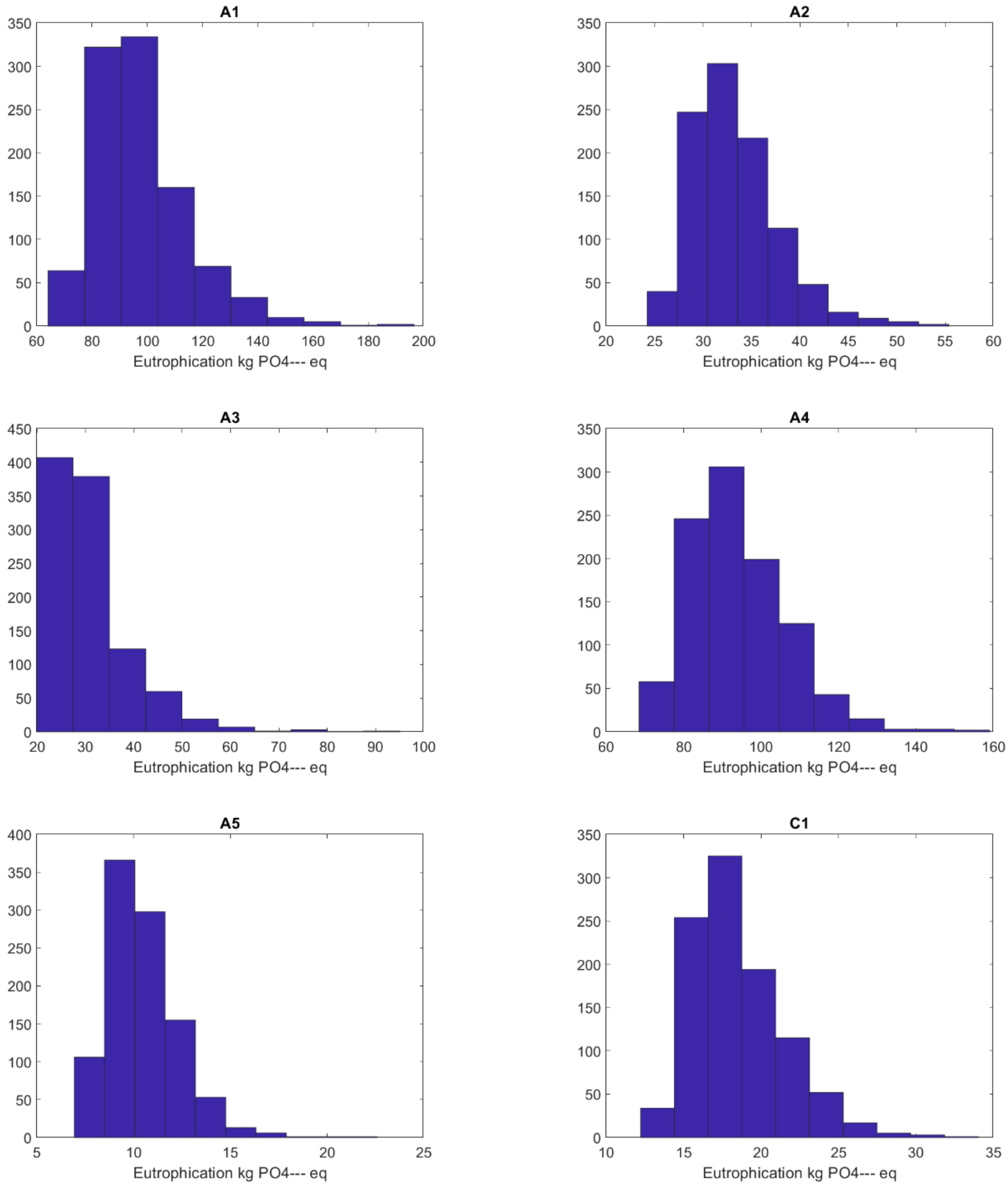
Table 36: Production costs in euros for 1 ton of asphalt mixture, per energy source.

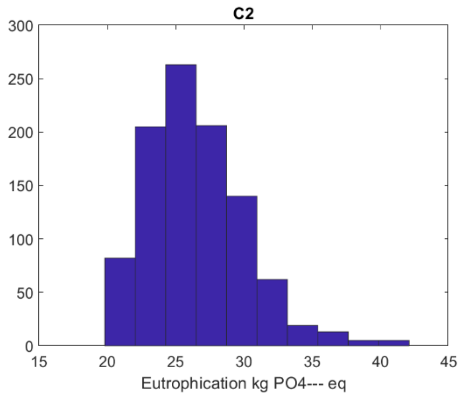
Product	1. SMA 16 - reference	2. SMA 11 - 40% RAP + PMB + LTA	3. SMA 8 - 60% RAP + PMB	4. SMA 11 - Long service life	5. PA 8 - top layer 2L PA + PMB	6. PA 16 - long service life
	Costs (€ per tonne asphalt mixture)					
Electricity	€0.14	€0.14	€0.14	€0.14	€0.14	€0.14
Diesel	€1.18	€1.18	€1.04	€1.18	€1.18	€1.18

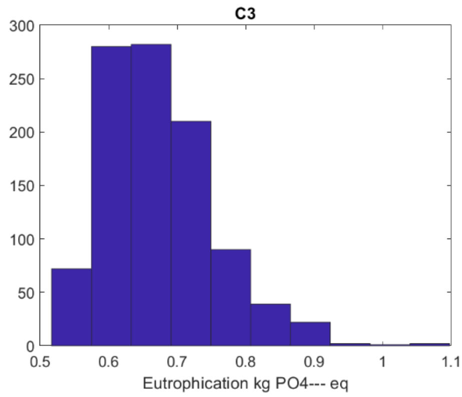
Annex III – Uncertainty Analysis Results

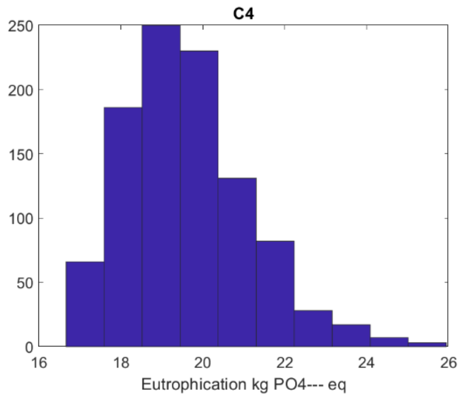
Mixture 1: SMA 16 (reference)

Mixture 1: Eutrophication

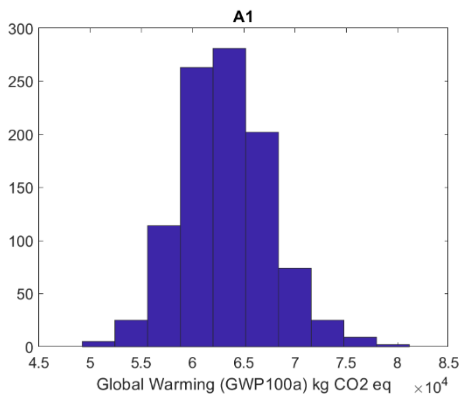


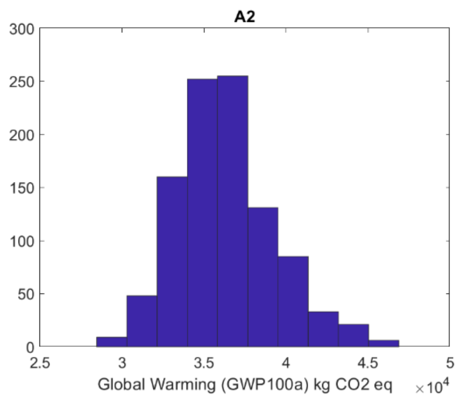


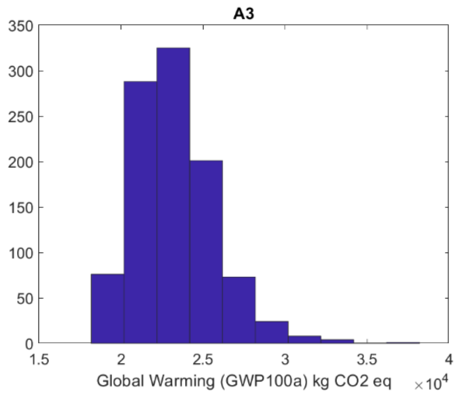


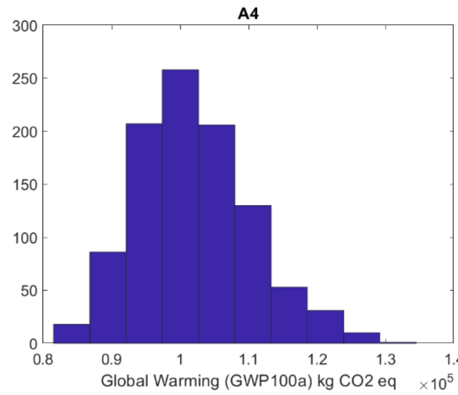


Mixture 1: Global Warming






A3
Global Warming (GWP100a) kg CO2 eq
×10^4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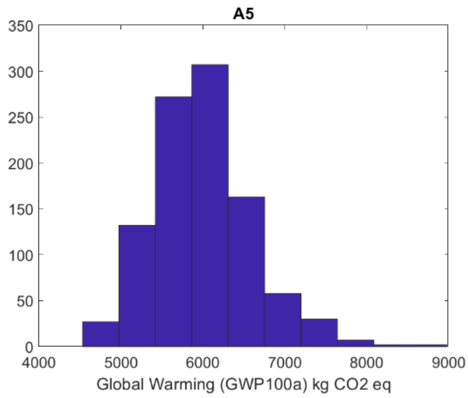
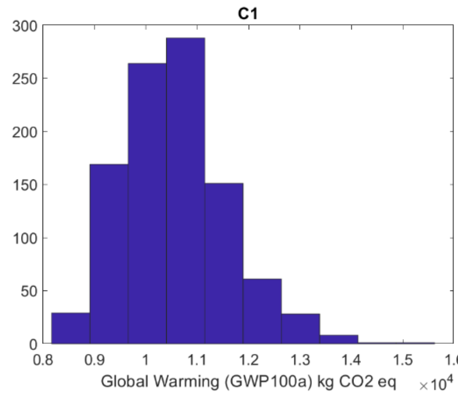
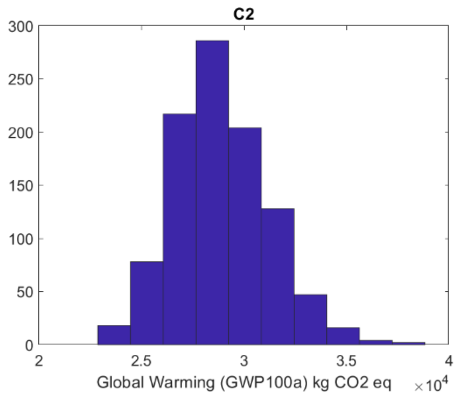
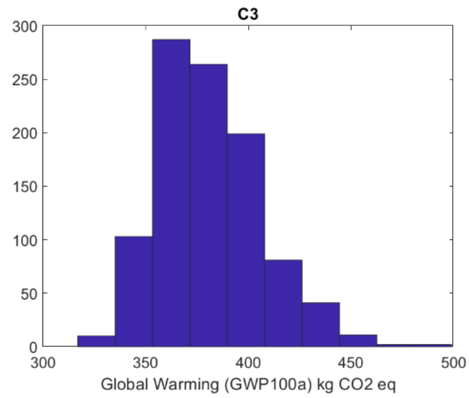
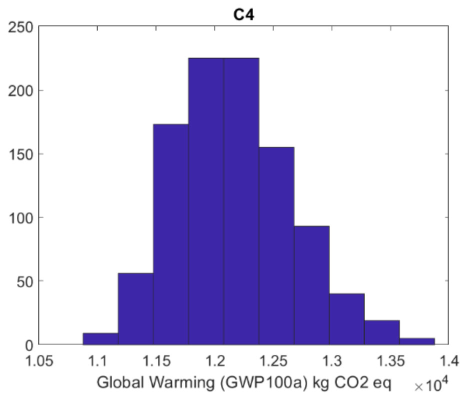
Global Warming (GWP100a) kg CO2 eq
×10^5


A5
Global Warming (GWP100a) kg CO2 eq

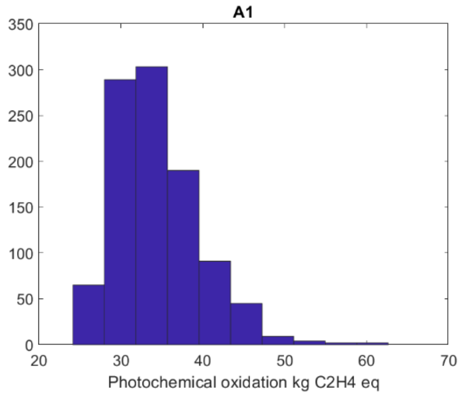

C1
Global Warming (GWP100a) kg CO2 eq
×10^4

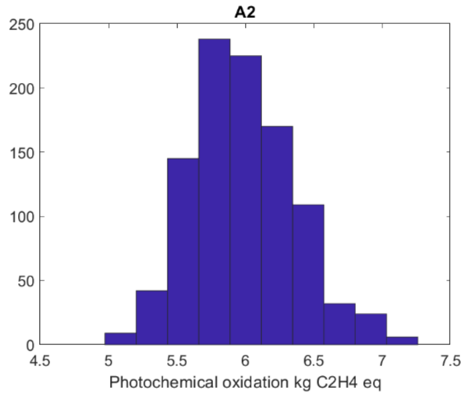

C2
Global Warming (GWP100a) kg CO2 eq
×10^4

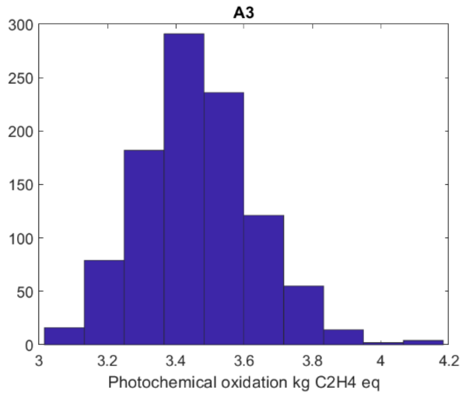

C3
Global Warming (GWP100a) kg CO2 eq

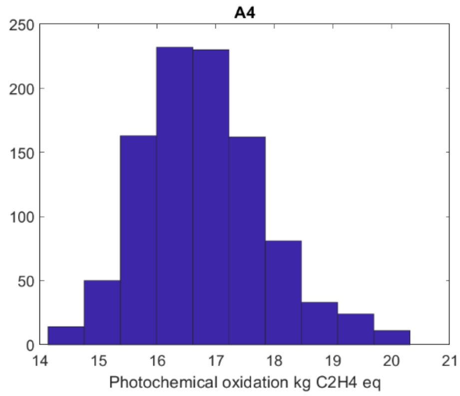

C4
Global Warming (GWP100a) kg CO2 eq
×10^4

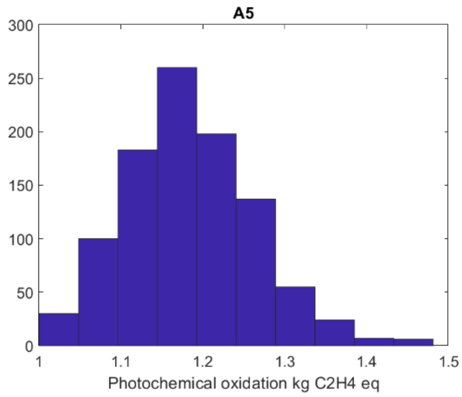
Mixture 1: Photochemical Oxidation

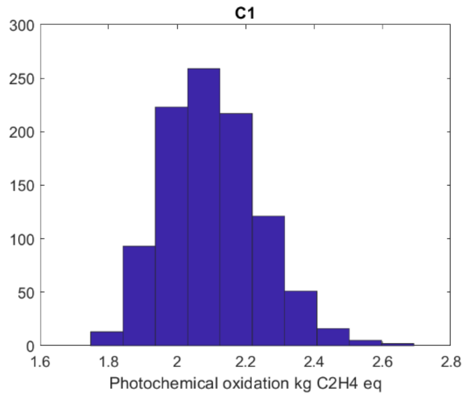


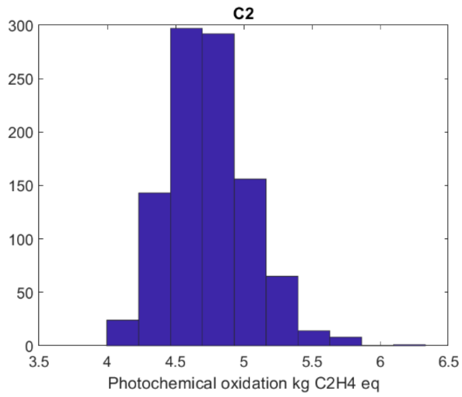


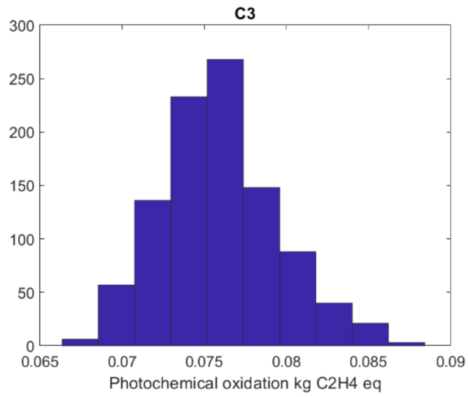


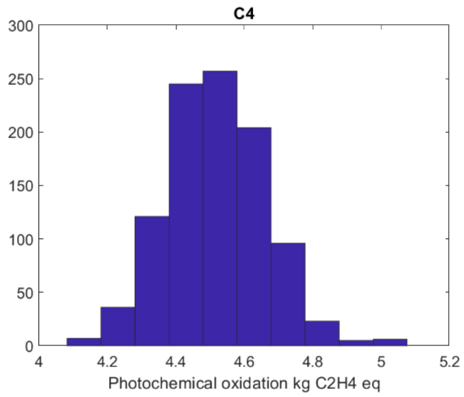






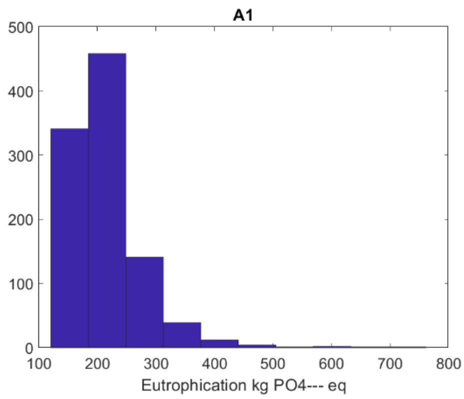


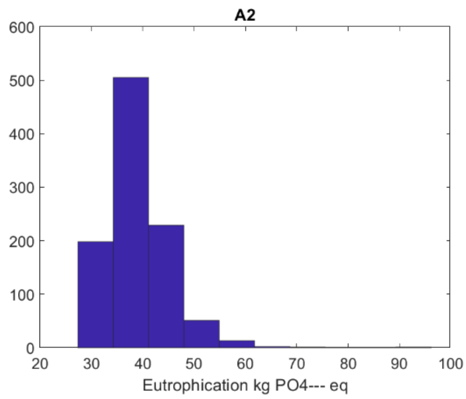


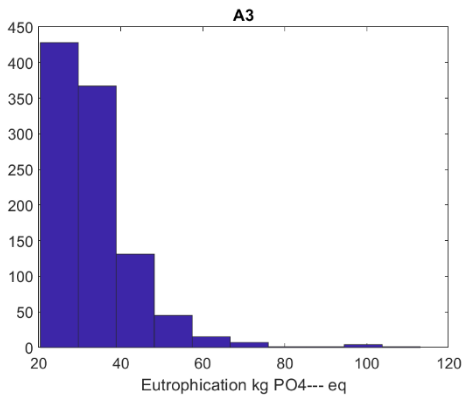


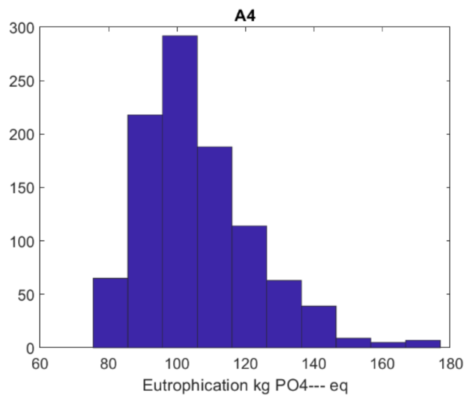
Mixture 2: SMA 11 (40% RAP+ PMB+LTA)

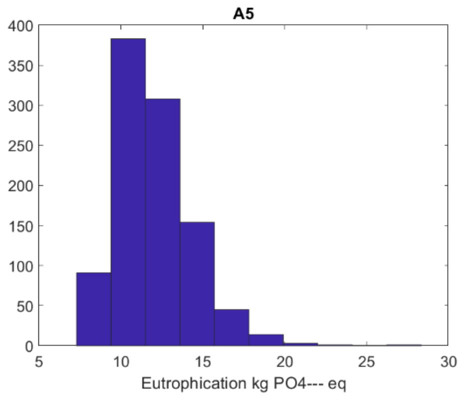
Mixture 2: Eutrophication

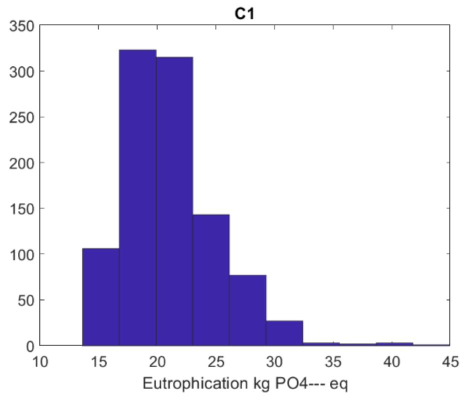


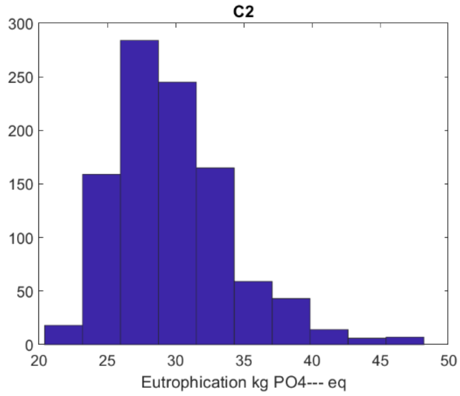


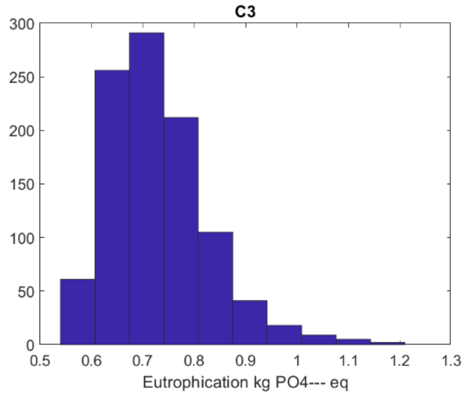


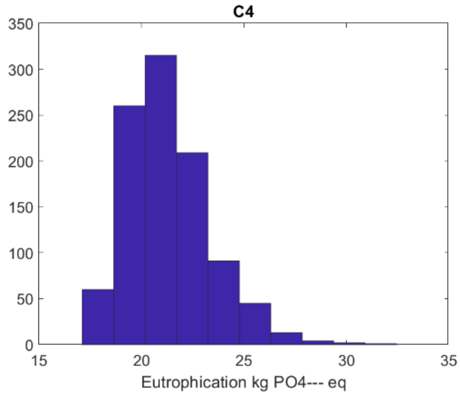



A5
Eutrophication kg PO4--- eq

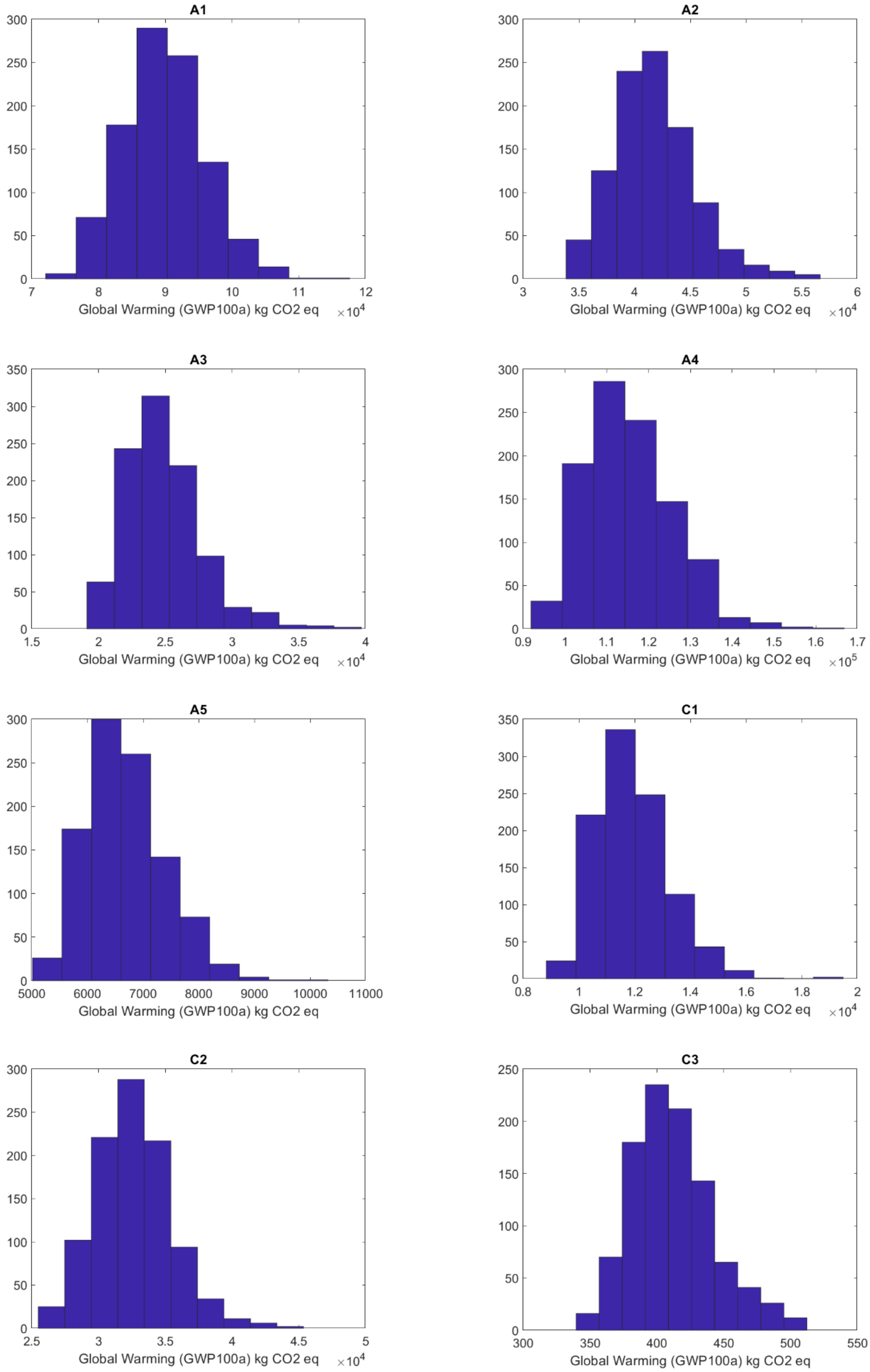

C1
Eutrophication kg PO4--- eq

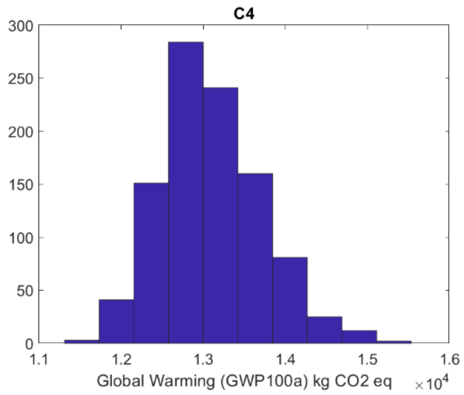

C2
Eutrophication kg PO4--- eq


C3
Eutrophication kg PO4--- eq

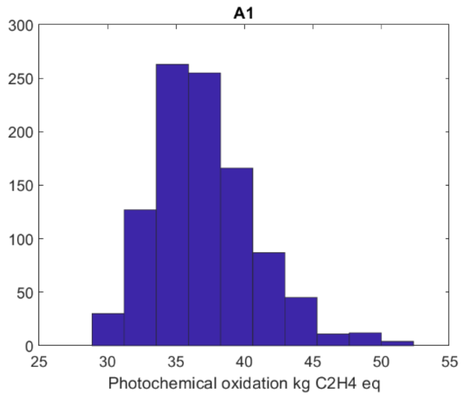

C4
Eutrophication kg PO4--- eq

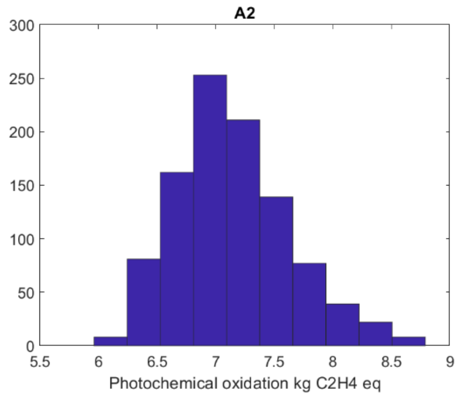
Mixture 2: Global Warming

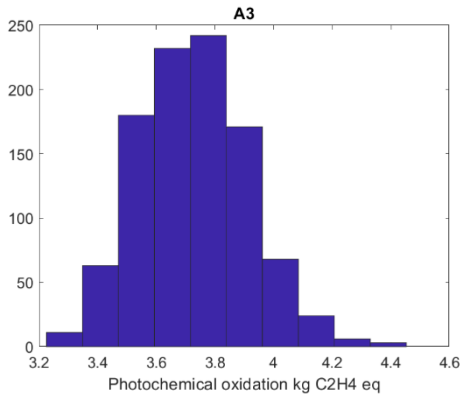


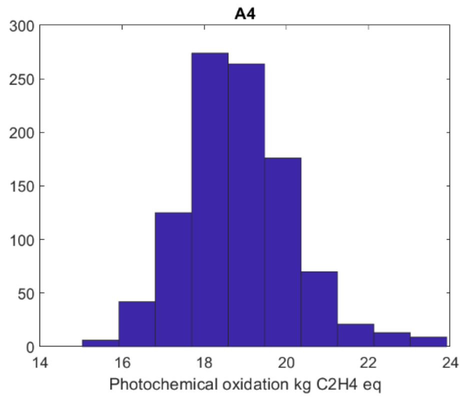


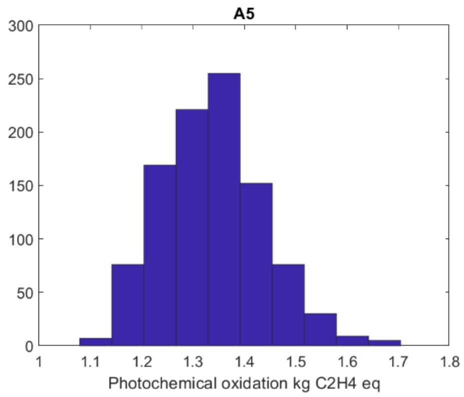
Mixture 2: Photochemical Oxidation

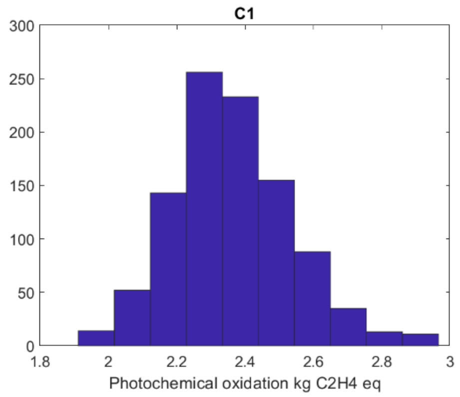


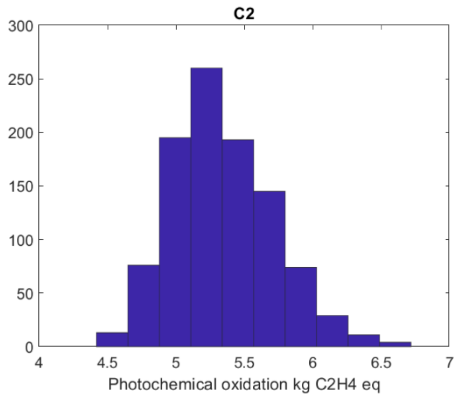


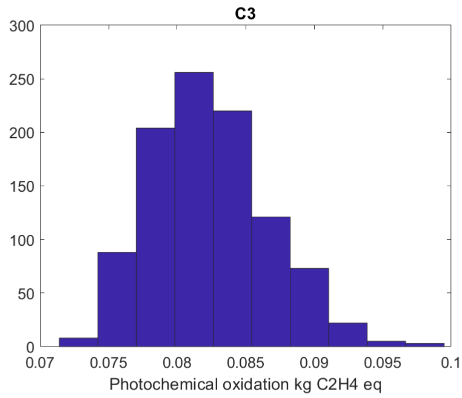


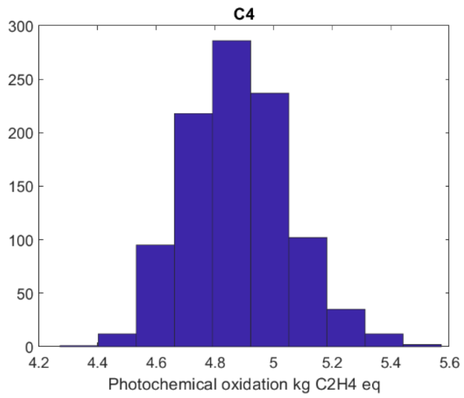



A5
Photochemical oxidation kg C2H4 eq


C1
Photochemical oxidation kg C2H4 eq

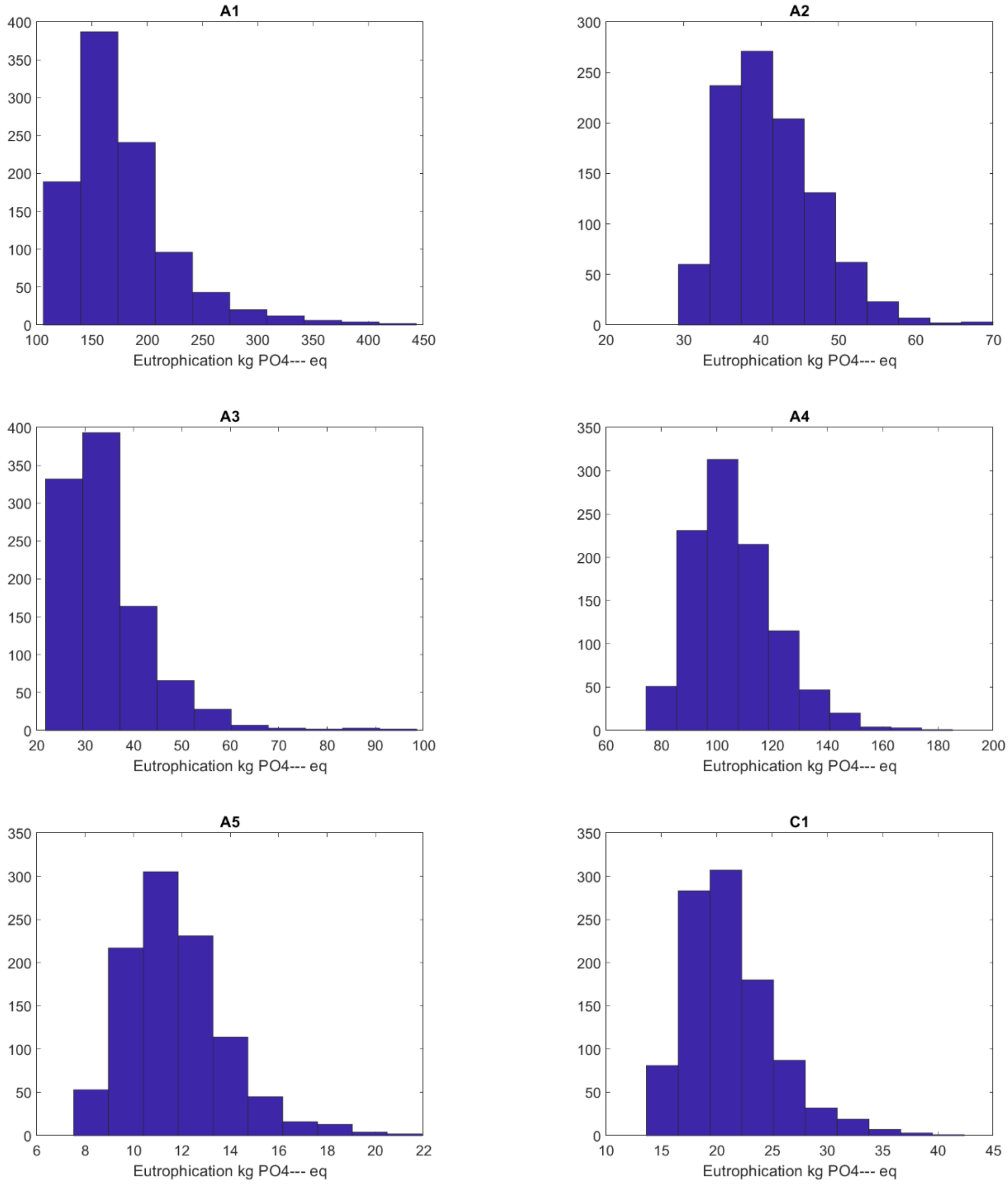

C2
Photochemical oxidation kg C2H4 eq


C3
Photochemical oxidation kg C2H4 eq

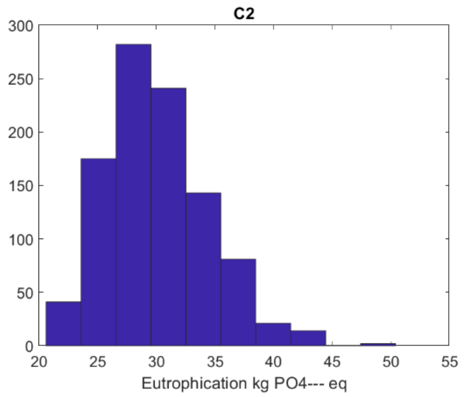

C4
Photochemical oxidation kg C2H4 eq

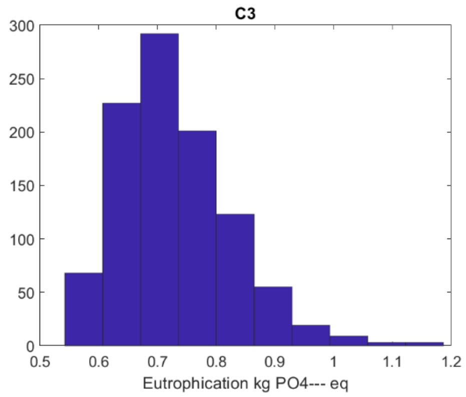
Mixture 3: SMA 8 (60% RAP + PMB)

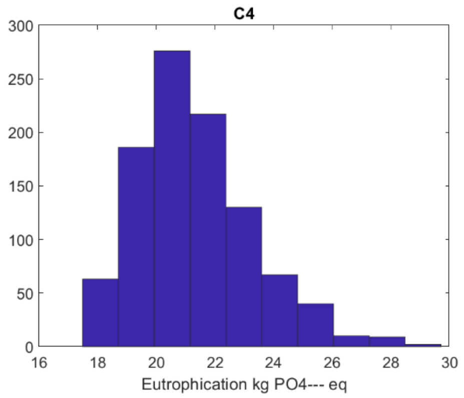
Mixture 3: Eutrophication



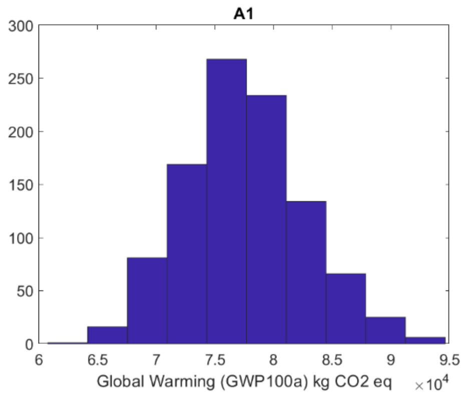
Conférence Européenne des Directeurs des Routes
Conference of European Directors of Roads

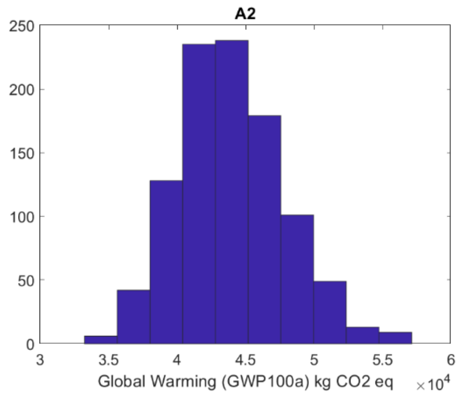


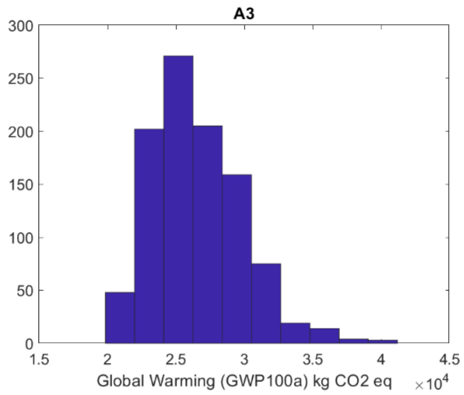


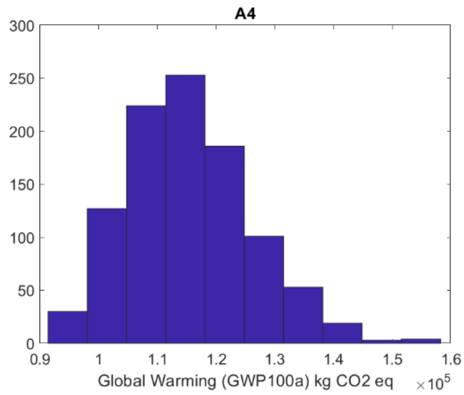


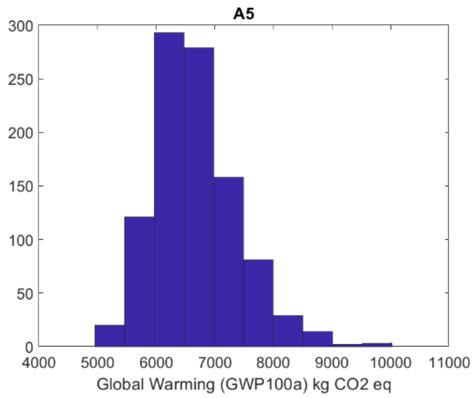
Mixture 3: Global Warming

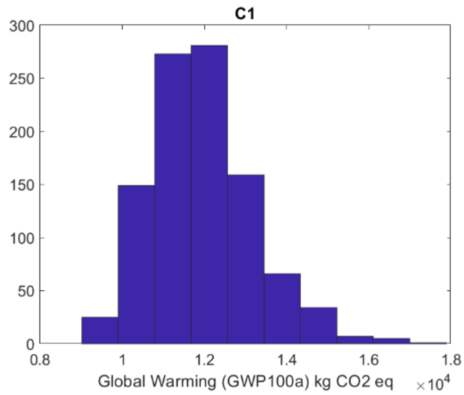


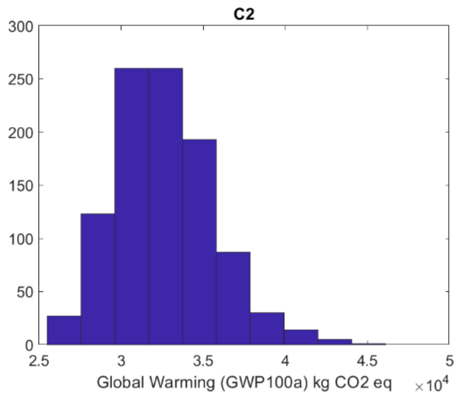


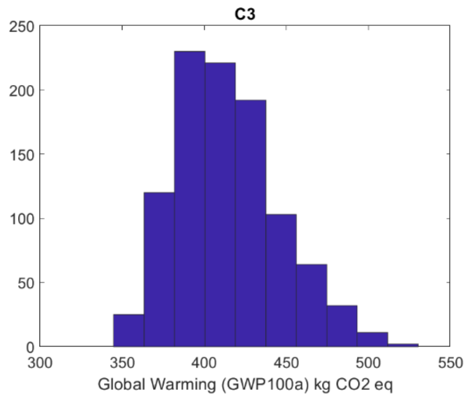

A3
Global Warming (GWP100a) kg CO2 eq
×10^4

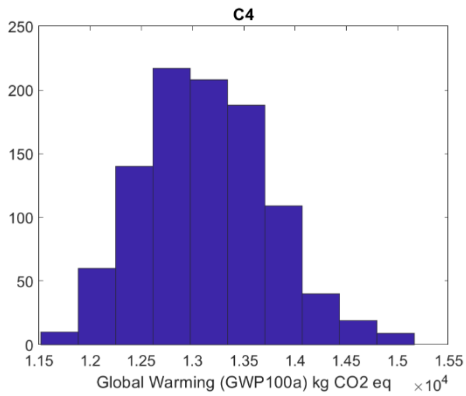

A4
Global Warming (GWP100a) kg CO2 eq
×10^5


A5
Global Warming (GWP100a) kg CO2 eq

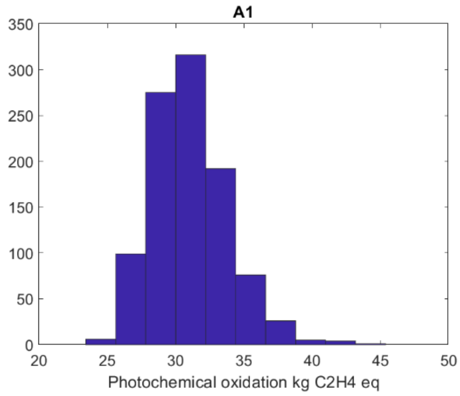

C1
Global Warming (GWP100a) kg CO2 eq
×10^4

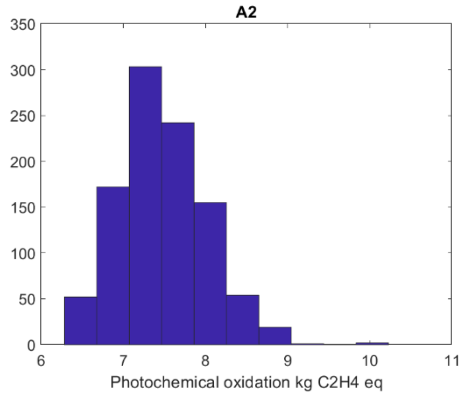

C2
Global Warming (GWP100a) kg CO2 eq
×10^4

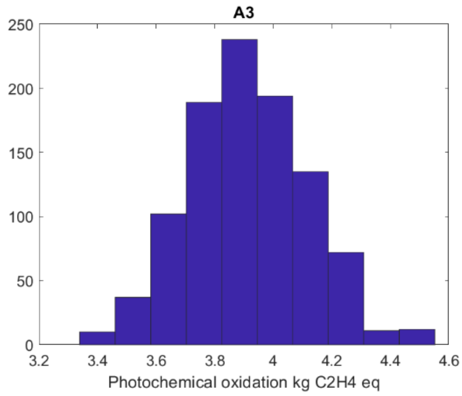

C3
Global Warming (GWP100a) kg CO2 eq

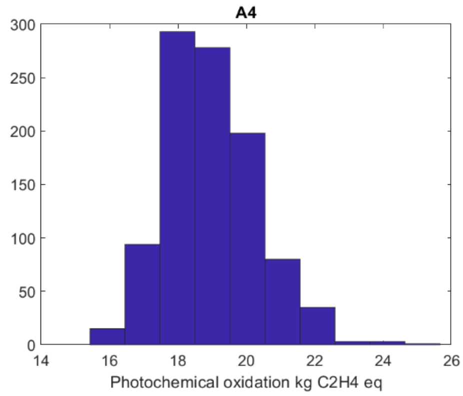

C4
Global Warming (GWP100a) kg CO2 eq
×10^4

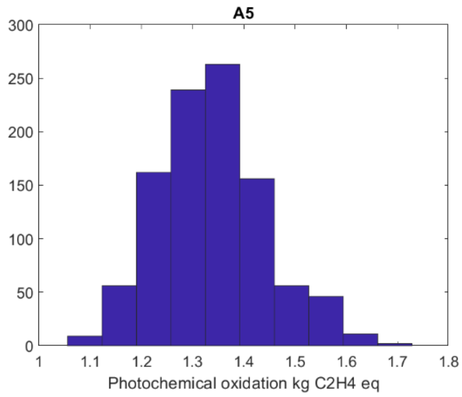
Mixture 3: Photochemical Oxidation

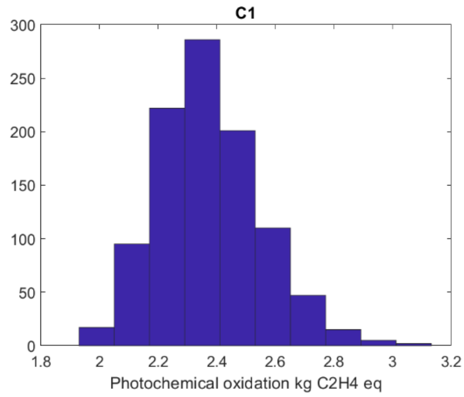


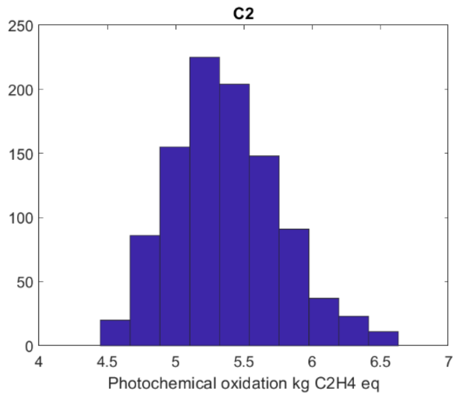


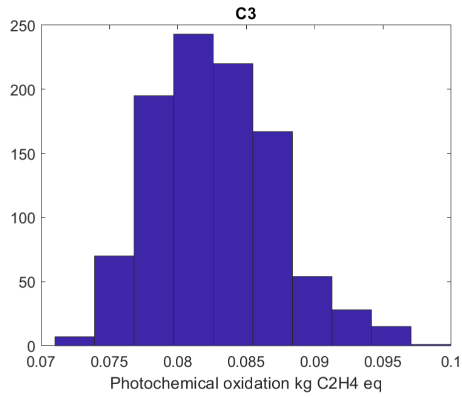


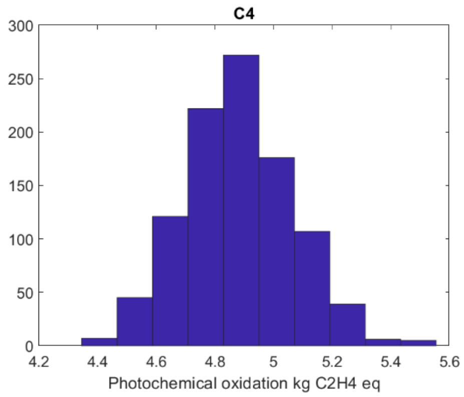






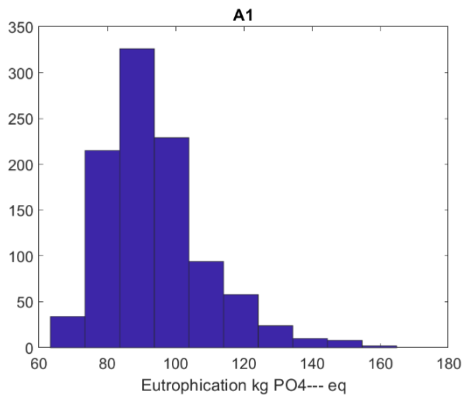


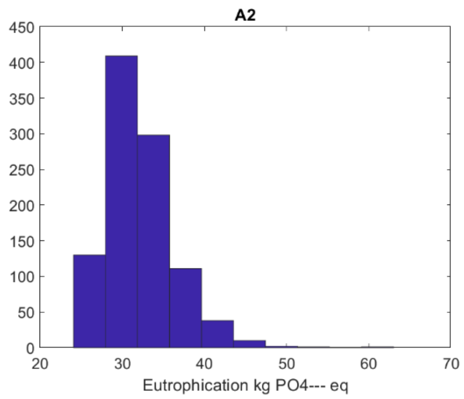


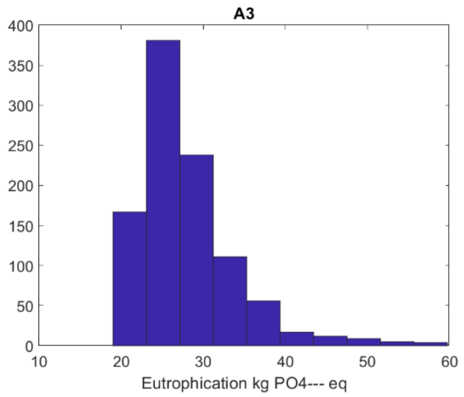


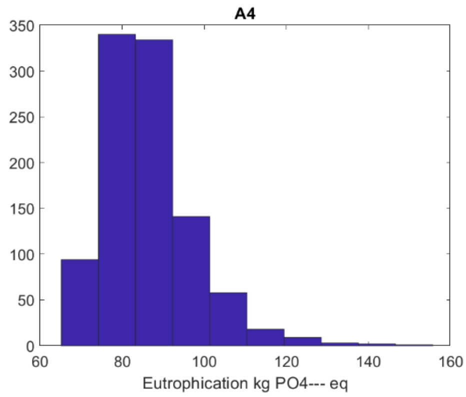
Mixture 4: SMA 11 (long service life)

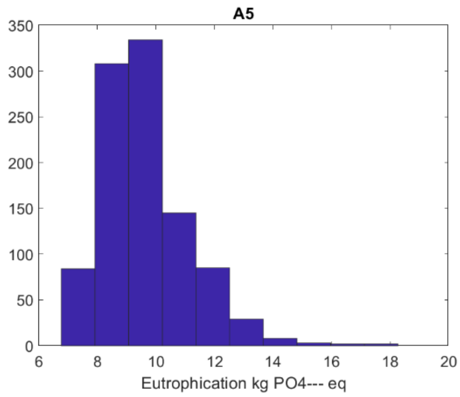
Mixture 4: Eutrophication

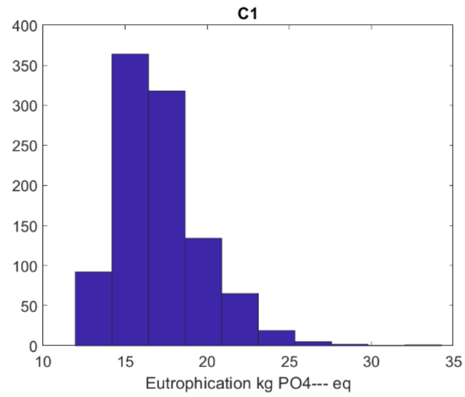


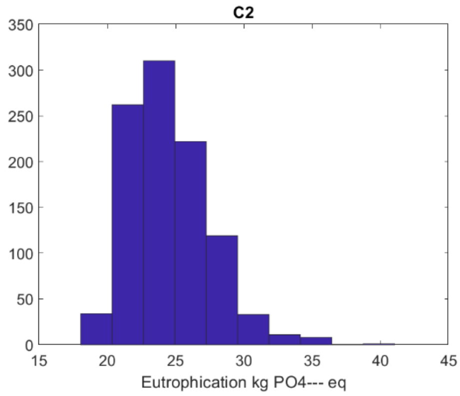


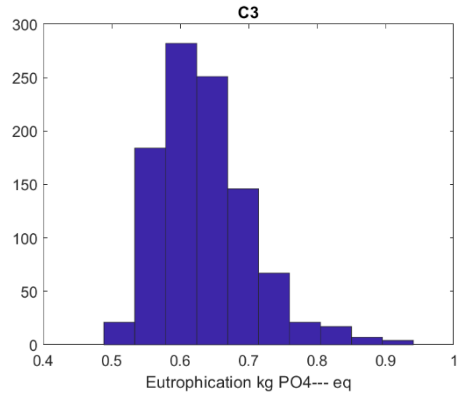


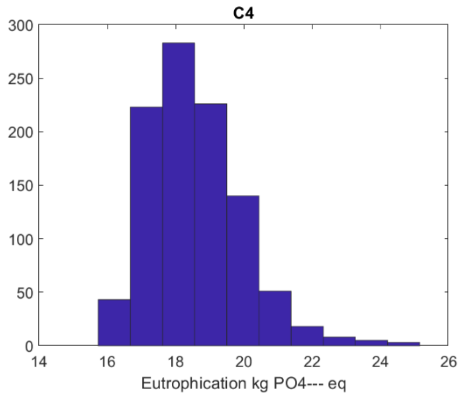



A5
350
300
250
200
150
100
50
0
6 8 10 12 14 16 18 20
Eutrophication kg PO4--- eq

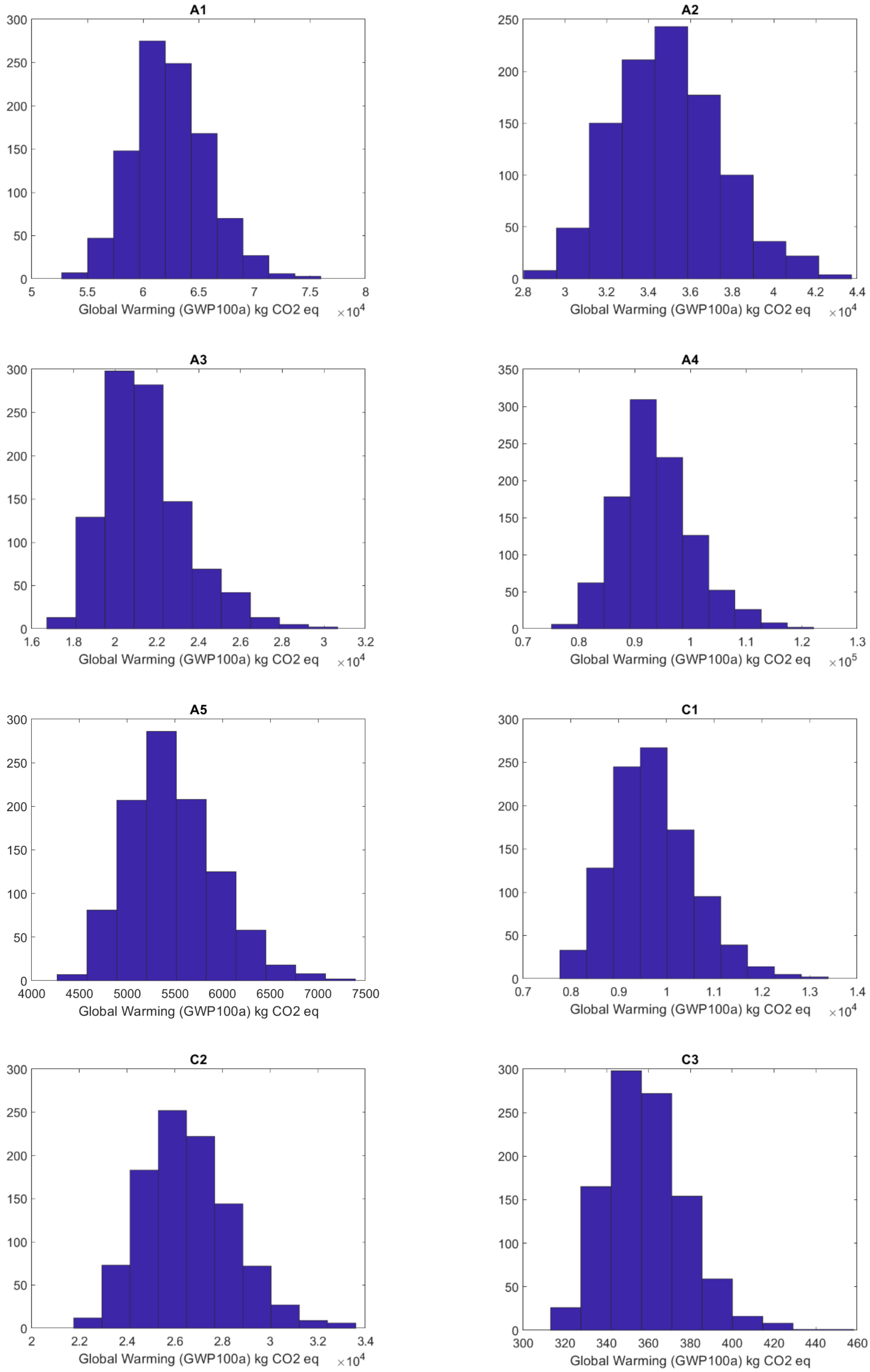

C1
400
350
300
250
200
150
100
50
0
10 15 20 25 30 35
Eutrophication kg PO4--- eq

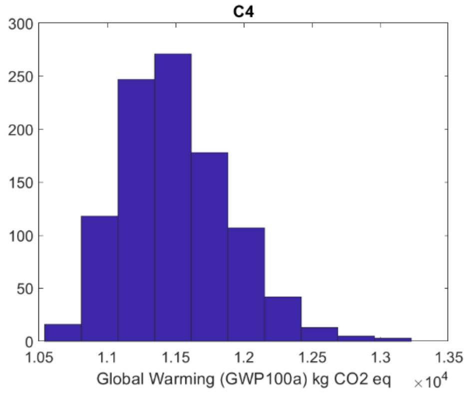

C2
350
300
250
200
150
100
50
0
15 20 25 30 35 40 45
Eutrophication kg PO4--- eq


C3
300
250
200
150
100
50
0
0.4 0.5 0.6 0.7 0.8 0.9 1
Eutrophication kg PO4--- eq

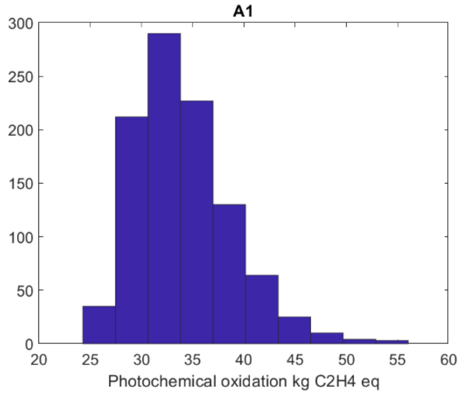

C4
300
250
200
150
100
50
0
14 16 18 20 22 24 26
Eutrophication kg PO4--- eq

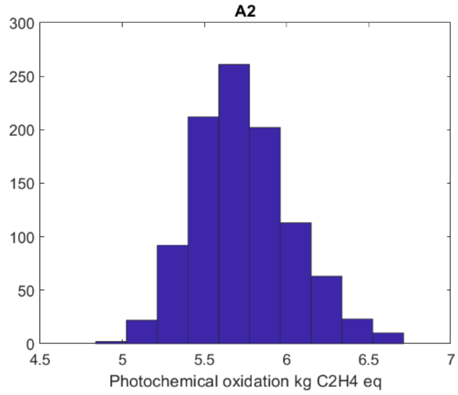
Mixture 4: Global Warming

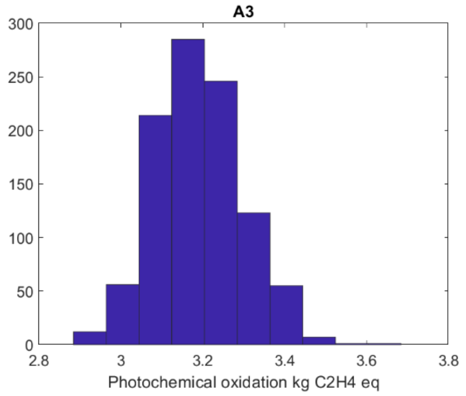


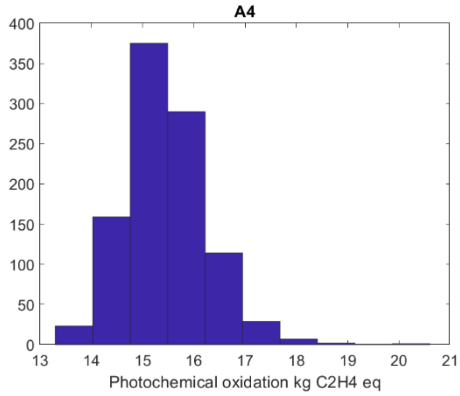


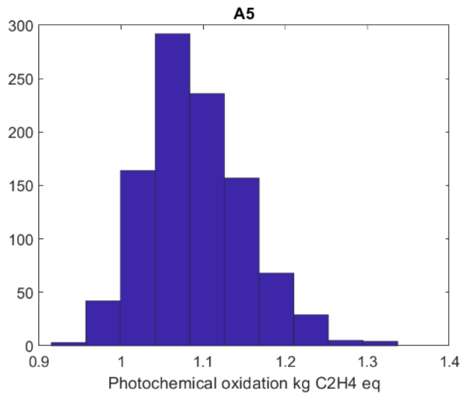
Mixture 4: Photochemical Oxidation

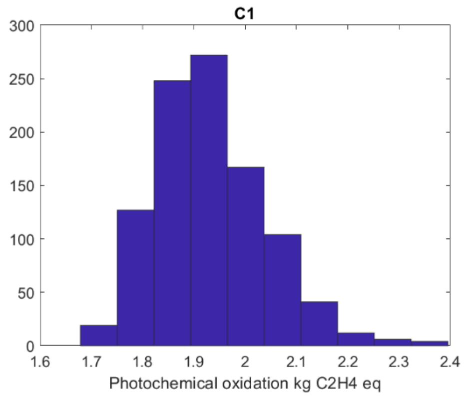


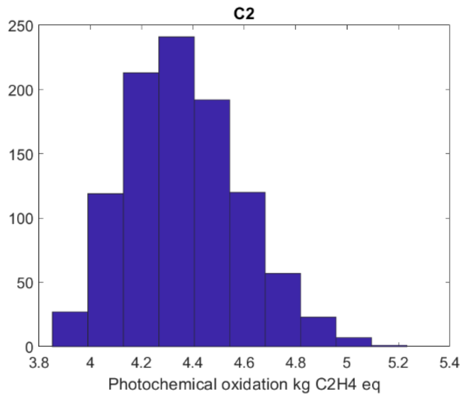


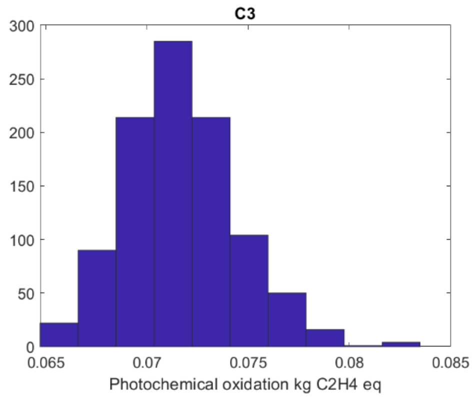


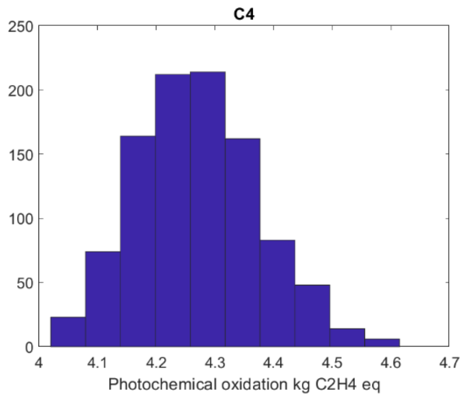



A5
300
250
200
150
100
50
0
0.9
1
1.1
1.2
1.3
1.4
Photochemical oxidation kg C2H4 eq


C1
300
250
200
150
100
50
0
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
Photochemical oxidation kg C2H4 eq

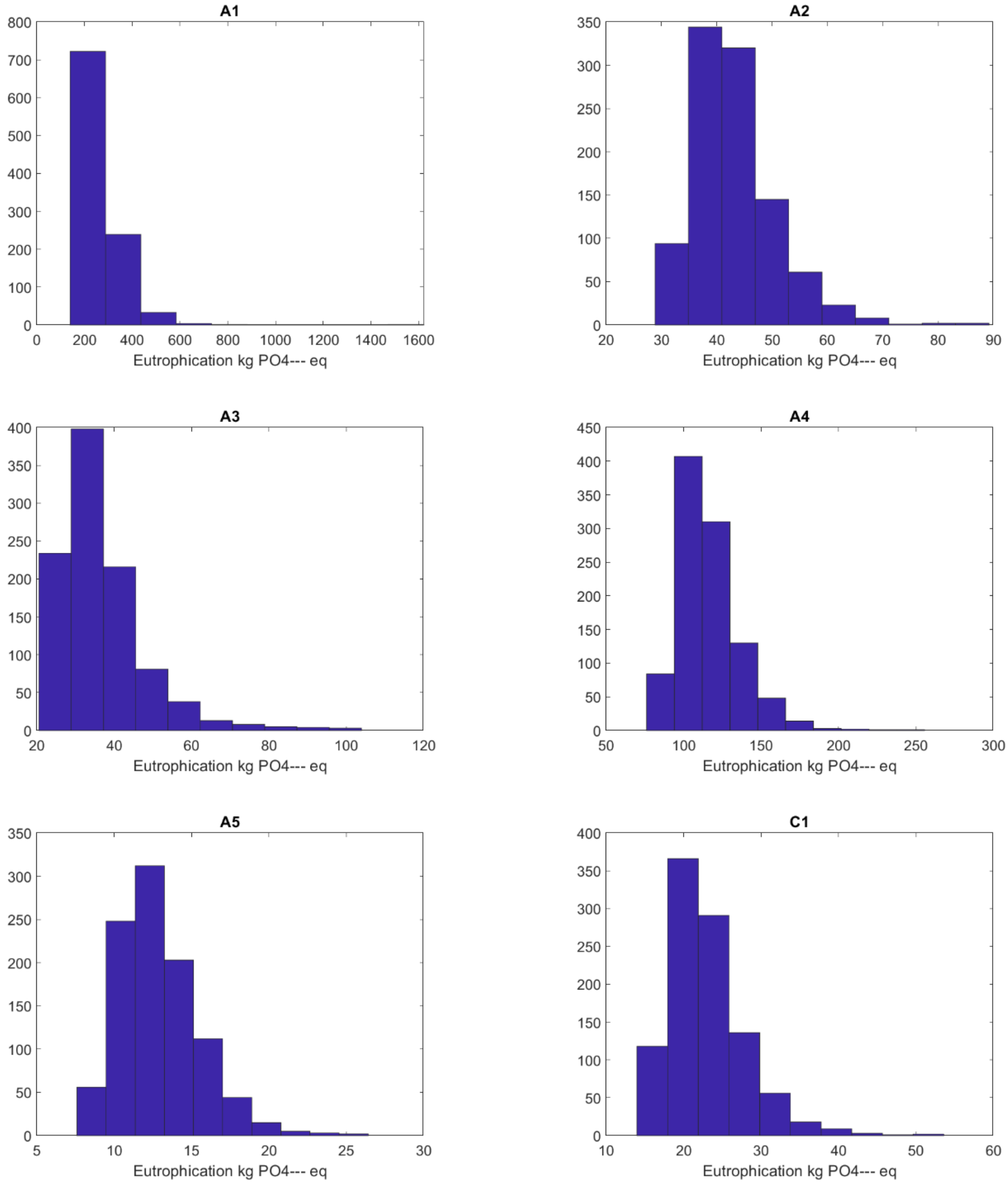

C2
250
200
150
100
50
0
3.8
4
4.2
4.4
4.6
4.8
5
5.2
5.4
Photochemical oxidation kg C2H4 eq

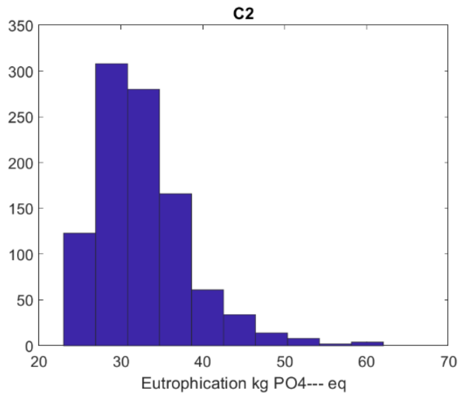

C3
300
250
200
150
100
50
0
0.065
0.07
0.075
0.08
0.085
Photochemical oxidation kg C2H4 eq

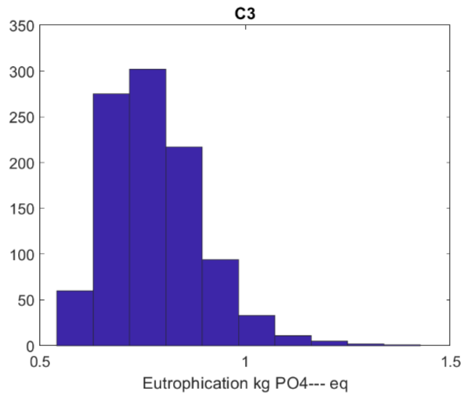

C4
250
200
150
100
50
0
4
4.1
4.2
4.3
4.4
4.5
4.6
4.7
Photochemical oxidation kg C2H4 eq

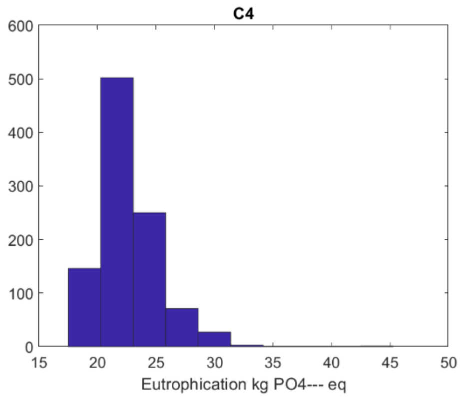
Mixture 5: PA 8 (PMB)

Mixture 5: Eutrophication

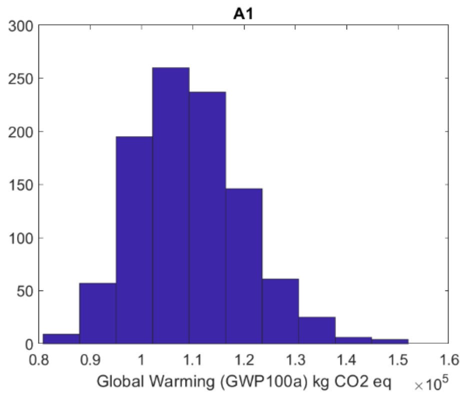


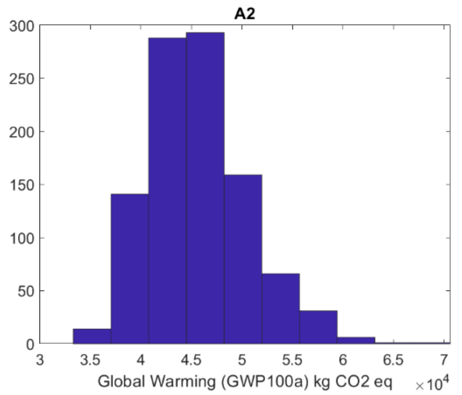


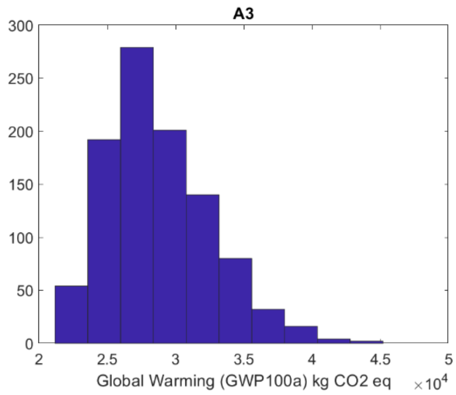


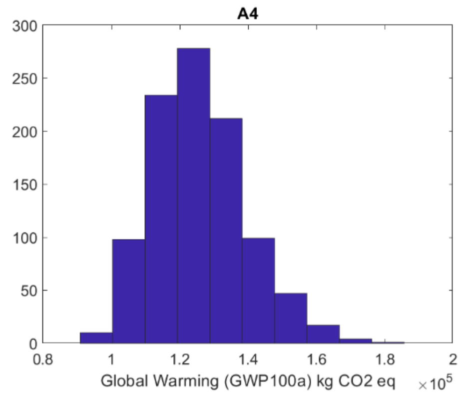


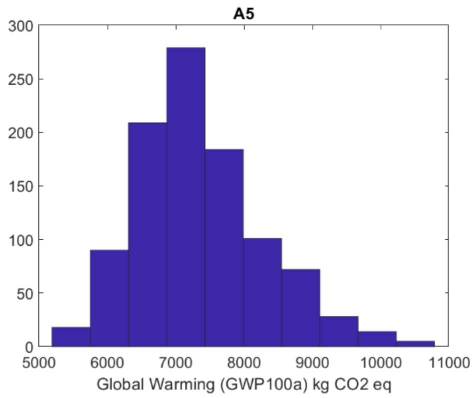
Mixture 5: Global Warming

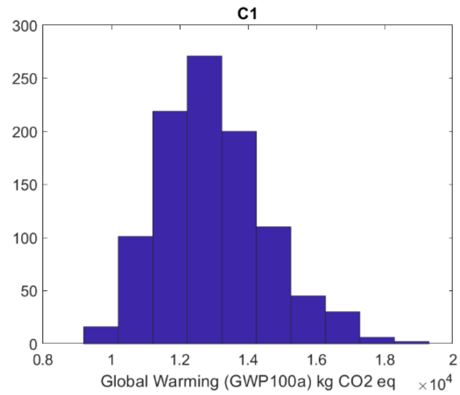


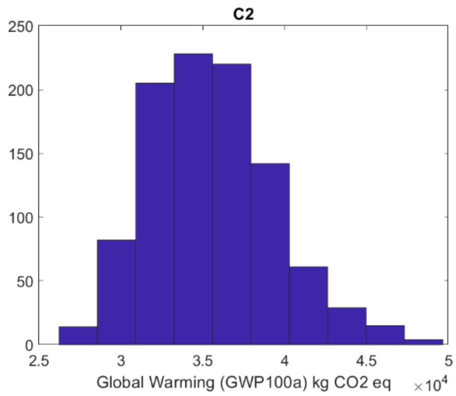


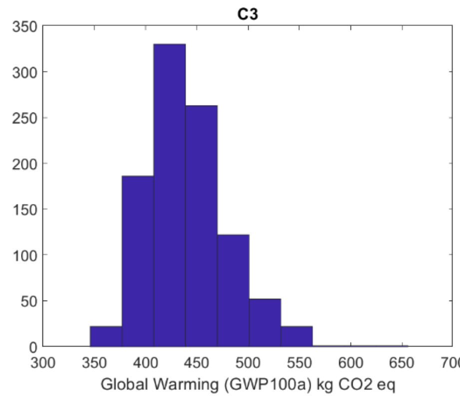

A3
300
250
200
150
100
50
0
2
2.5
3
3.5
4
4.5
5
Global Warming (GWP100a) kg CO2 eq
×10^4

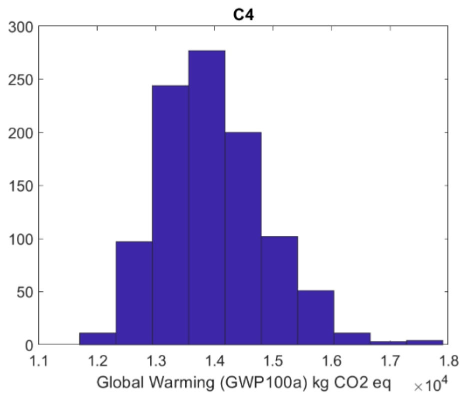

A4
300
250
200
150
100
50
0
0.8
1
1.2
1.4
1.6
1.8
2
Global Warming (GWP100a) kg CO2 eq
×10^5


A5
300
250
200
150
100
50
0
5000
6000
7000
8000
9000
10000
11000
Global Warming (GWP100a) kg CO2 eq

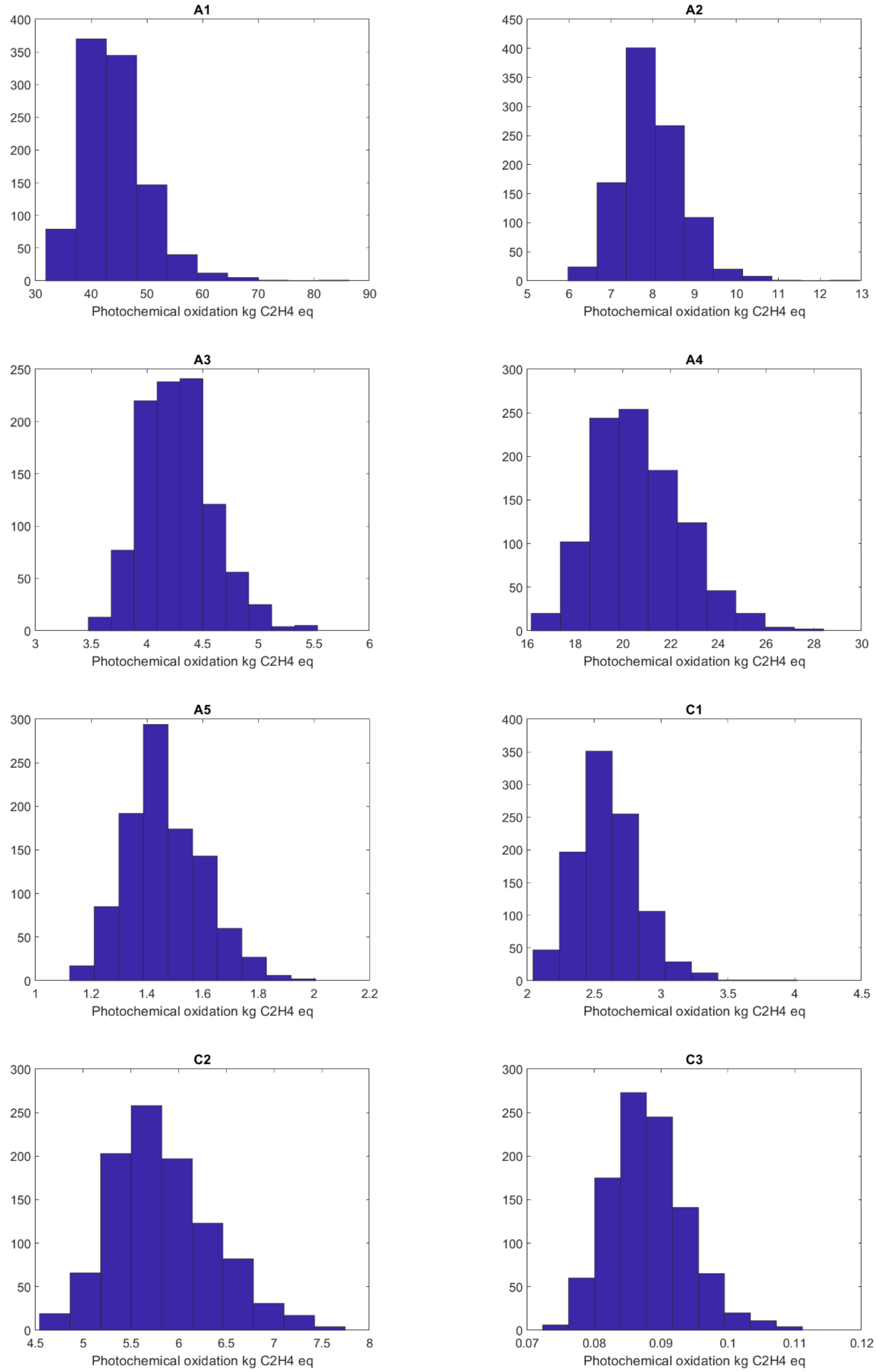

C1
300
250
200
150
100
50
0
0.8
1
1.2
1.4
1.6
1.8
2
Global Warming (GWP100a) kg CO2 eq
×10^4

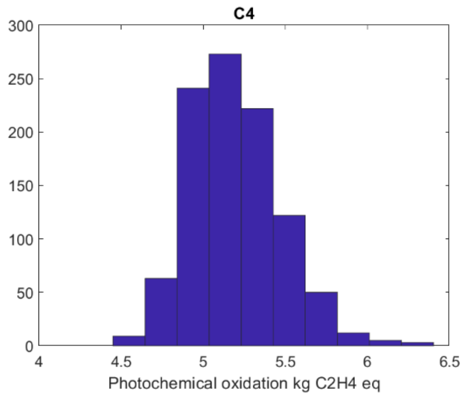

C2
250
200
150
100
50
0
2.5
3
3.5
4
4.5
5
Global Warming (GWP100a) kg CO2 eq
×10^4


C3
350
300
250
200
150
100
50
0
300
350
400
450
500
550
600
650
700
Global Warming (GWP100a) kg CO2 eq


C4
300
250
200
150
100
50
0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Global Warming (GWP100a) kg CO2 eq
×10^4

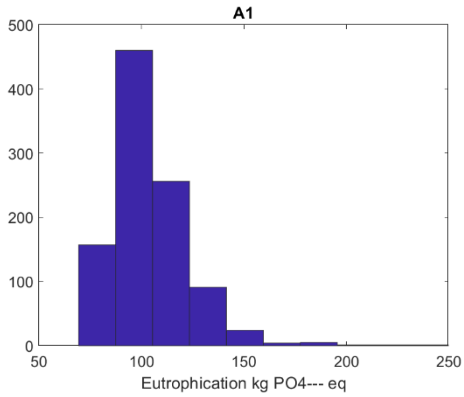
Mixture 5: Photochemical Oxidation

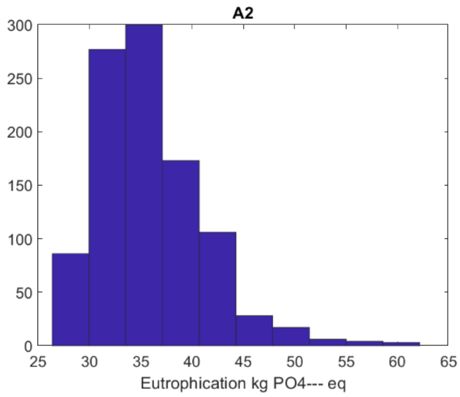


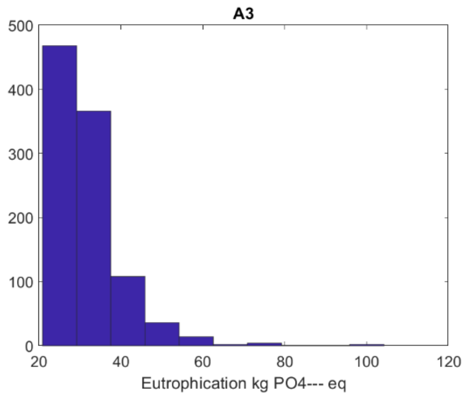


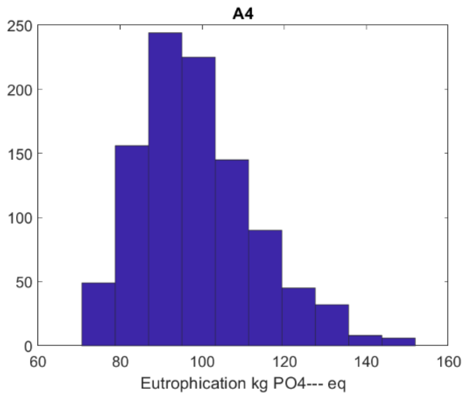
Mixture 6: PA 16 (long service life)

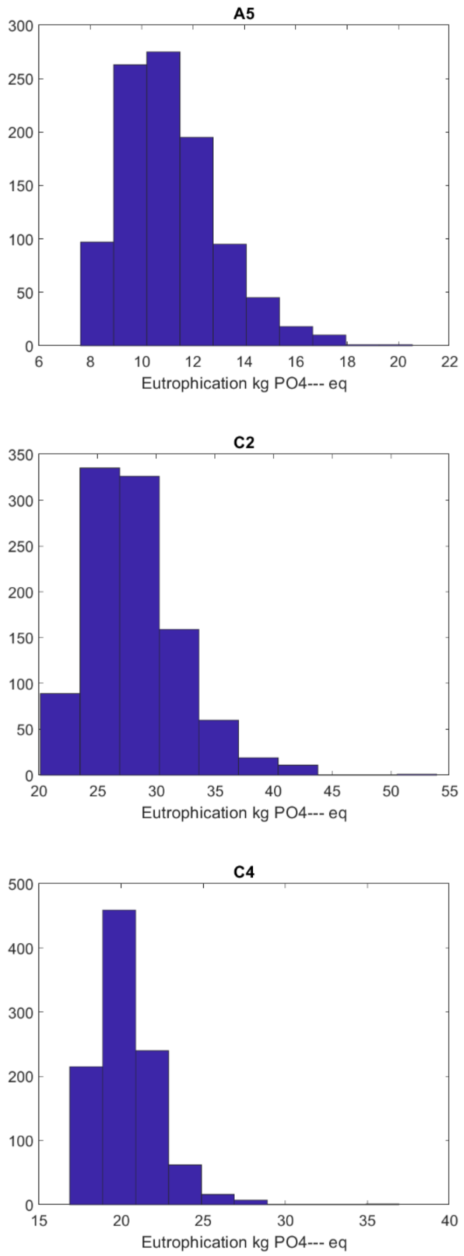
Mixture 6: Eutrophication



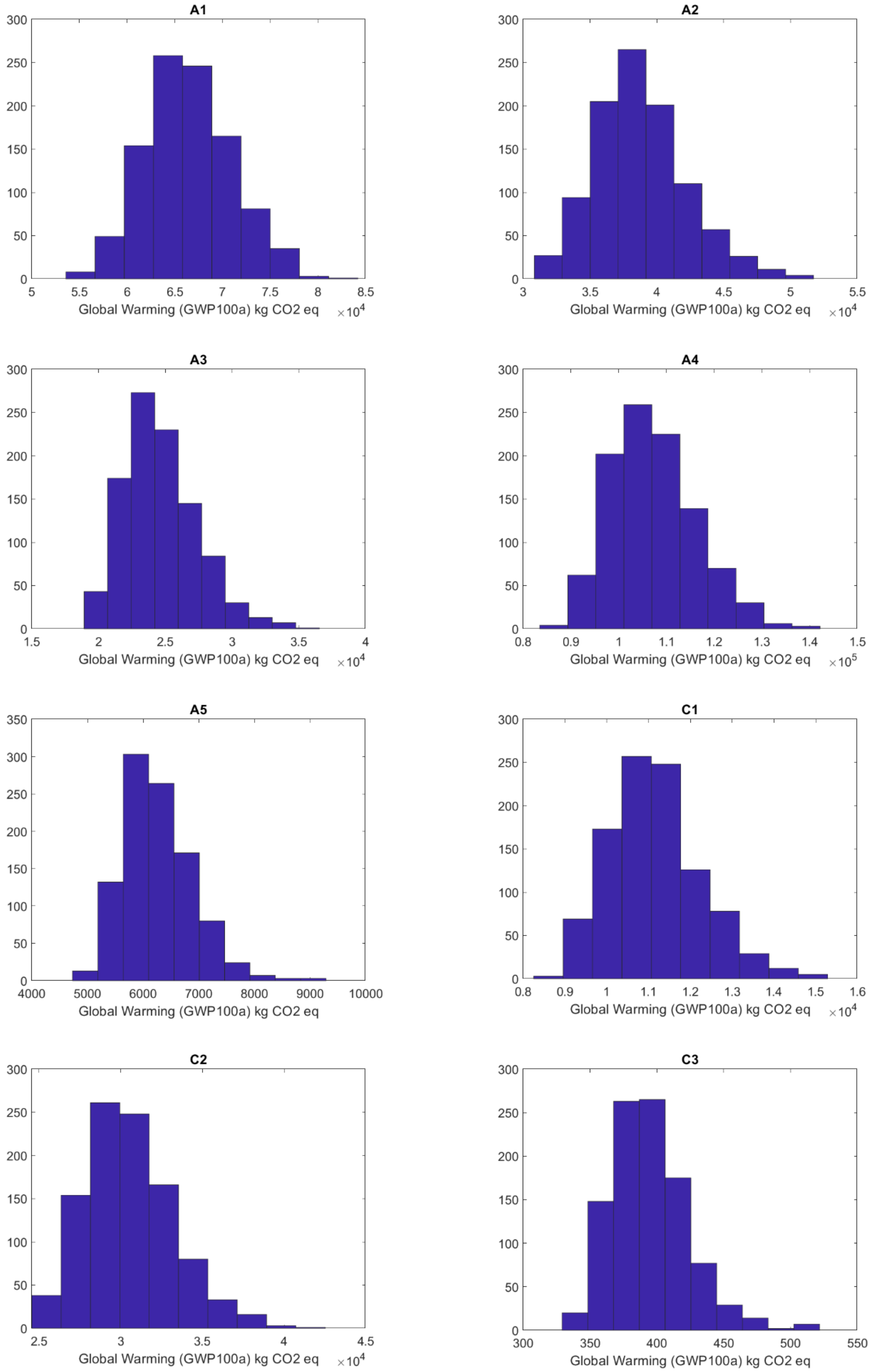


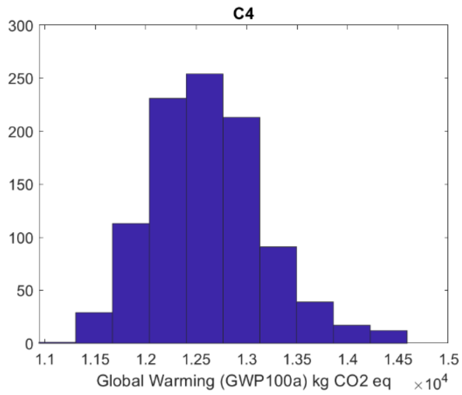




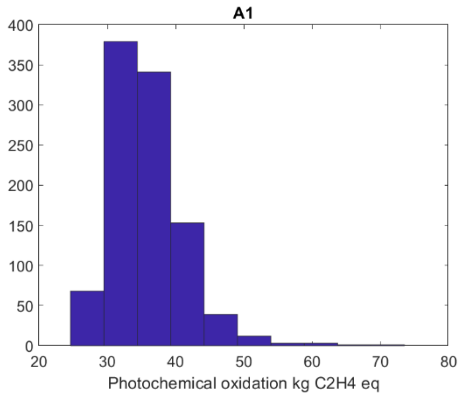

A5
C1
C2
C3
C4
Eutrophication kg PO4--- eq

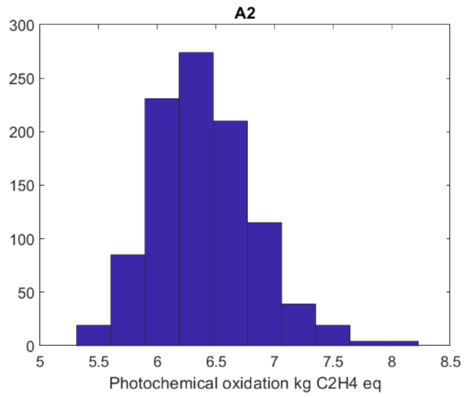
Mixture 6: Global Warming

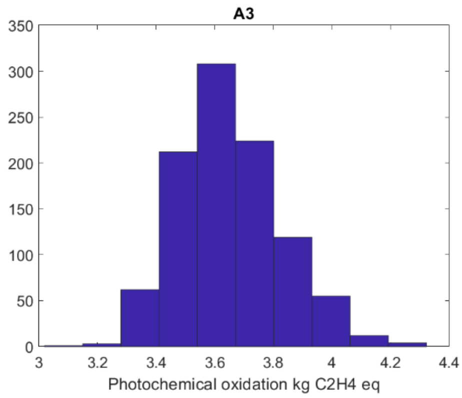


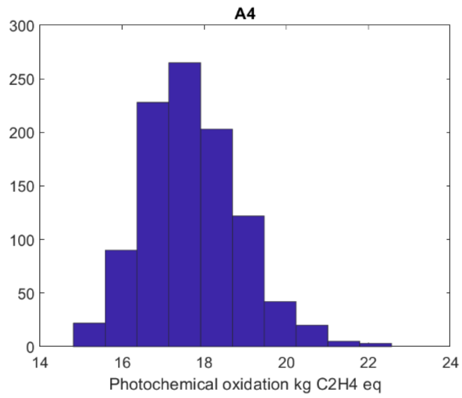


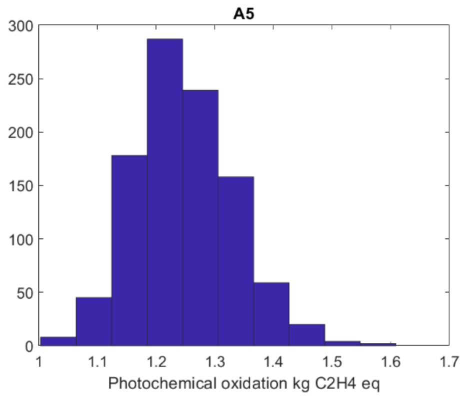
Mixture 6: Photochemical Oxidation

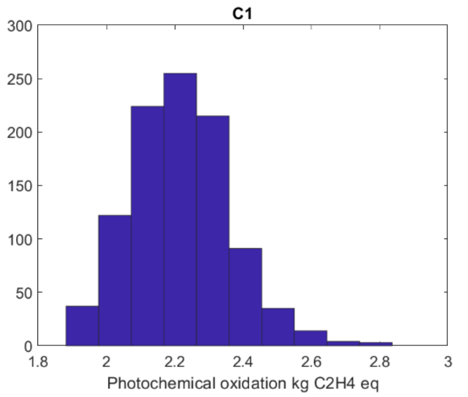


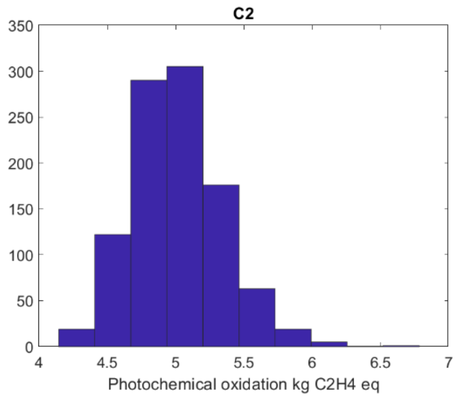


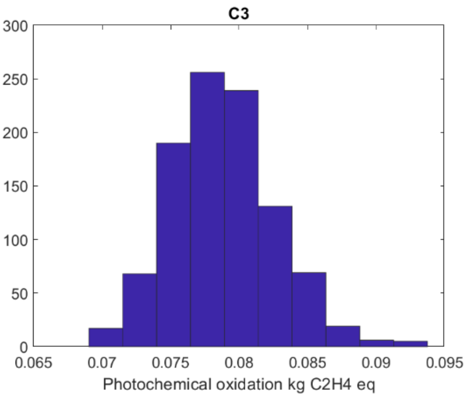


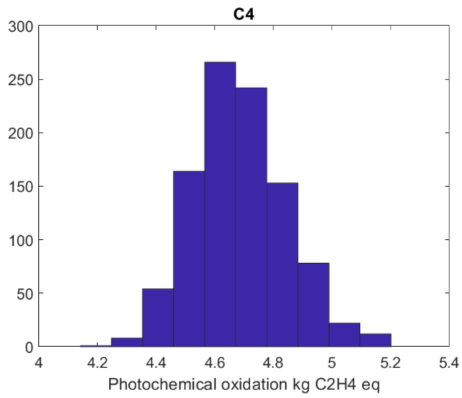



A5
Photochemical oxidation kg C2H4 eq


C1
Photochemical oxidation kg C2H4 eq


C2
Photochemical oxidation kg C2H4 eq


C3
Photochemical oxidation kg C2H4 eq


C4
Photochemical oxidation kg C2H4 eq