Plastic Waste in Road Construction in Iceland: an Environmental Assessment

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A thesis presented for the degree of
M.Sc. in Environmental Engineering
Residual Resource Engineering study line

Department of Environmental Engineering
Technical University of Denmark
June 2018

Abstract

This study investigates the environmental consequences of utilizing residential source separated plastic waste for a wearing course of a road constructed in Iceland. The study is specifically adjusted to Icelandic conditions, both in the context of the road construction, maintenance, service and recycling and how the plastic waste management is currently executed. The most relevant application method of plastic to asphalt mixtures was found to be polymer-coated aggregate (PCA) method. The five most common types of waste polymers were investigated in the context of being used for road construction. The literature review was used for the evaluation of the road parameters; Abrasion, Wheel track formation, Fracturing, Lifespan and Recycling. As a result it was concluded that literature indicates that hot asphalt mix properties will be enhanced by using 3-15% waste plastic using a polymer-coated aggregate (PCA) method.
Data specific to Icelandic conditions were gathered and reported in order to perform a quantitative environmental assessment. The assessment was then made by modelling two scenarios using the software EASETECH. Scenario 1 consists of the processes included in a life cycle of a traditionally constructed wearing course in Iceland and the processes included in plastic waste management for residential source separated plastic waste from Iceland. Scenario 2 consists of the processes included in a life cycle of a plastic waste enriched wearing course constructed in Iceland, in which plastic waste requires cleaning and pelleting before use. A life cycle assessment (LCA) based on the ISO14040 standards (14040:2006 (2006) and 14044:2006 (2006)) was then performed accompanied by a sensitivity analysis and uncertainty propagation. According to the LCA performed Scenario 2, has statistically lower impact scores than Scenario 1 connected to every impact category investigated. Although there are uncertainties connected to the quality of data used, the most critical assumptions were tested for in perturbation analysis, scenario analysis and uncertainty propagation. The results of the study should not be used to evaluate the environmental consequences of using virgin plastic in road construction nor the application method of polymer modified bitumen (PMB).

Preface

The present study is a Master's thesis for the degree of environmental engineering with a focus on residual resource engineering written at the Technical University of Denmark (DTU). The study was made under the supervision of Senior researcher Anders Daamgard working within the department of environmental engineering at DTU. External supervisor of this study are, R&D manager, Jamie McQuilkin and, CEO and Head of Development, Nicolas Marion Proietti from the company ReSource International ehf based in Iceland. The thesis is written in the period of January 22nd to June 22nd 2018 and is credited with 30 ECTS points. Additionally, the study was funded by the research fund of the Road Administration of Iceland for the year 2018-2019.

My sincere thanks go to my supervisors; Senior researcher Anders Daamgard at DTU and Nicolas Marion Proietti and Jamie McQuilkin from ReSource International ehf. for their support, valuable inputs and guidance throughout the project. I would also like to thank all of the professionals that took the time to meet with me and explain various procedures. In this context I would like to mention;

- Birkir Hrafn Jóakimsson, Civil engineer at the Road Administration of Iceland (Vegagerðin)
- Bjarni Gnýr Hjarðar, Chief engineer at SORPA bs.
- Elín Ásgeirsdóttir, Quality and R&D manager at Malbikunarstöðin Höfði hf
- Gísli Eymarsson, Head of quality department at Malbikunarstöðin Hlaðbær Colas hf
- Skúli Thordarson, Dr.ing. Specialist, service department at the Road Administration of Iceland (Vegagerðin)
- Steingrímur Bragason, Production manager at Malbikunarstöðin Hlaðbær Colas hf

Disclaimer

The author of this study is responsible for its content. The results of the study should not be considered to be a declared policy of Vegagerðin nor does it represent the opinion of DTU, Vegagerðin, Malbikunarstöðin Hlaðbær Colas hf. or ReSource International ehf.

Contents

List of Abbreviations

AC Asphalt Concrete
AUTL Asphalt for Ultra-Thin Layer
EASETECH
Environmental Assessment System for Environmental TECHnologies
HFO Heavy Fuel Oil
HMA Hot Mix Asphalt
ILCD International Reference Life Cycle Data System
ISO International Organization of Standardization
LCA Life Cycle Assessment
LCI Life Cycle Inventory Analysis
LCIA Life Cycle Impact Assessment
MRF Material Recovery Facility
PCA Polymer-Coated Aggregate
PE Polyethylene
PET Polyethylene Terephthalate
PMA Polymer Modified Asphalt
PMB Polymer Modified Bitumen
PP Polypropylene
PROSUITE
PROspective SUstaInability assessment of TEchnologies
PS Polystyrene
PVC Polyvinyl Chloride
RAP Reclaimed Asphalt Pavement
RCA Recycled Concrete Aggregate
SBS Styrene-Butadiene-Styrene
SC Sensitivity Coefficient
SMA Stone Matrix Asphalt
SR Sensitivity Ratio
TT Type Testing
VMA Void of Mineral Aggregate

Glossary

Abrasion: The process of scraping of wearing of material.

Bleeding/creeping of asphalt: Bleeding is the term used when binder material fills aggregate voids during hot weather or compaction.

Dynamic viscosity: is a measure of a fluid's resistance to shear flow when an external force is applied

Fraas breaking point: the temperature at which the first crack appears in the coating while flexing a thin layer of bitumen at descending temperatures

Fracturing: are cracks or potholes which are formed in asphalt. Cracks can form due to the stiffness characteristics of the asphalt mixture. Potholes form due to weathering, defects in the pavement or other impact.

Grain distribution: is a test performed on an aggregate sample which indicates the amount of each size of gravel in the sample. Grain size of a sample is given as a distribution.

Kinematic viscosity: is a ratio of a particular fluid's dynamic viscosity to its density

Los Angeles abrasion (LA) test: The Los Angeles abrasion test is a test method applied to demonstrate the toughness of the aggregate and abrasion characteristics.

Marshall test: Marshall test includes a Marshall hammer to test void and compression characteristics of an asphalt sample.

Marshall stability: is the peak resistance to a load during a constant deformation loading.

Marshall flow: is a measure of deformation of an asphalt sample that has undergone the Marshall test.

Marshall Quotient: is an index of stiffness, Marshall stability divided by Marshall flow.

Moisture absorption: Moisture absorption is the characteristic of a material to absorb moisture from its environment.

Prall test: In a Prall test asphalt specimens are first submerged in water and then put into frames with 40 stainless steel ball bearings and pressed

Rutting resistance: The practice of minimizing rutting and/or improving the pavement performance against rutting.

Soundness test: The soundness test determines an aggregate's resistance to disintegration by weathering and, in particular, freeze-thaw cycles.

Strippind test: Stripping test is a test method to demonstrate the cohesion of binder and aggregate.

Surface resistance/Skid resistance: Skid resistance is the power generated between a tire and road surface when a vehicle brakes.

Viscoelasticity: is a physical property of a substance. A substance that is viscoelastic exhibits both elastic and viscous behaviour. Therefore the application of stress causes temporary deformation if the stress is quickly removed, but permanent deformation if it is maintained.

Wheel path rut: Rutting is a depression or a groove formation in a road or a path. Wheel path rut is the subsequent depression after wear by wheels and/or by deformation of the asphalt pavement or subbase material.

Chapter 1

Introduction

Road construction is heavily reliant on fossil fuels and virgin materials. Traditionally, roads are made of 95% aggregate and 5% bitumen (binder) by weight of the road. In 2011 there were 15 companies in the asphalt business in Iceland; one focused on production only, four producing and laying asphalt and ten focusing on laying only. That same year there were four stationary asphalt production sites and four mobile plants producing 0.2 million tonnes of hot and warm mix asphalt (Marchand (2015)). The total amount of material used for road construction in 2008 in Iceland was about 60% of the total aggregate used that year. Similar proportions are seen in the Nordic countries however the total amount of material used per inhabitant is much higher in Iceland compared to other European countries (Vegagerðin (2017)).
Icelandic asphalt has the reputation of having a short lifetime expectancy compared to other European countries. Specifically, Icelandic asphalt has had a problem regarding wheel-track formation (Jóakimsson et al. (2014)). Regardless, if it is due to the different type of aggregate used, constant frost-thaw fluctuations, high precipitation and/or because of the frequent use of spiked tires it has a need to be improved.

The waste reception and classification center of the capital region of Iceland (managed by SORPA bs.) received approximately 900 tons of sorted plastic in 2016 (Björnsdóttir (2016)). This amount of plastic waste received is expected to rise in the next few year after SORPA bs. has implemented and established a new air classifier system for plastic waste called Kári (SORPA (2018a)). Residential source separated plastic waste in Iceland is bailed and shipped to Sweden for recycling or incineration.

There is a consensus among researchers that polymer and latex asphalt modification can improve road properties. Quality differences can be seen in increased cohesion, increased elasticity, better temperature susceptibility in high and low temperatures which lowers the risk of bleeding/creeping of the asphalt and wheel-path ruts (Kalantar et al. (2012), Salomon (2006) and Giavarini (1994)). Additionally, the addition of plastic waste has been found to decrease the amount of bitumen and aggregate needed for a good asphalt mixture (Vasudevan et al. (2012)). The explanation is that the plastic waste occupies space in the mixture.

The aforementioned improvement possibilities due to polymers and waste polymers in road construction need to be investigated in the context of how they affect endurance (lifetime) of a road layer. Yet, there is reason to believe that there might be consequential environmental impact savings connected to utilizing plastic waste for road construction in Iceland in comparison to the current management.

1.1 Objective

This study aims to investigate the environmental consequences of utilizing plastic waste for road construction in Iceland.

The study is specifically aimed at:

- Residential source separated plastic waste
- Hot asphalt mixtures used for bound surface layers
- Plastic waste management used for Icelandic source separated plastic waste (in 2018)
- Road construction standards used in Iceland
- The capital region of Iceland
- Icelandic conditions, e.g. material extraction, pavement construction, wearing due to weather and spiked tires, recycling of reclaimed asphalt pavements and plastic waste
- Life cycle assessment based on the ISO14040 standards (14040:2006 (2006) and 14044:2006 (2006))

The study is specifically adjusted to Icelandic conditions, both in the context of the road construction, maintenance, service and recycling and how the plastic waste management is currently executed. The study starts with a theory chapter that aims to provide evidence that plastic waste additives improve road quality. Firstly, the methods of applying plastic to roads are considered. Second, the five most common types of plastic will be assessed in the context of polymer modified asphalt. Lastly, possibilities of improvements of roads will be assessed. It is important to keep in mind that the literature on plastic waste additives in road construction is more often than not based on results found in warmer climate than typically found in Iceland. Moreover, the theory chapter is made from an environmental perspective and is not exhaustive from a civil engineering point of view.
Next, an inventory describes the scenarios and situations specific to Iceland. In this chapter, data collection on material extraction for road construction and energy use in all stages of the scenarios is considered as well as the plastic waste management situation in Iceland.
Thereafter, a life cycle assessment is performed which is based on the ISO14040 standards. The life cycle assessment is performed on two scenarios which are defined in the

chapter. The study does not aim to be a hotspot analysis for road construction. Results, discussion, conclusion and recommendations are summarized for the ease of the reader.

Chapter 2

Theory

2.1 Roads

Roads are constructed of aggregate and bitumen in different layers which differ in number, thickness and materials depending on the type of road. A traditional structure of a road consists of a subgrade, sub-base, base course and wearing course (see figure 2.1).

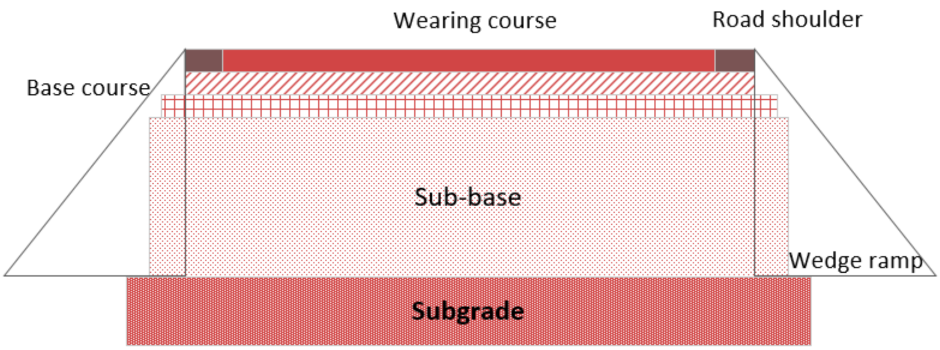

Figure 2.1 Road layers of a typical road in Iceland

Different amounts of road material is used in each layer. To give an example of the different magnitudes of aggregate used in each layer, in Iceland in 2008 the total amount of material used for road construction was 5 million cubic meters of which approximately 77% was used for the sub-base layer, 21% for the base course and 2% for the wearing course (Vegagerðin (2017)).
The subgrade is the underlying soil at each location. The sub-base is made of material found on location or other nearby sources, which is then pressed and has the purpose of evening out the surface of the subgrade. The sub-base should have a gradient and the adjacent base course should prevent water from flowing through to the sub-base and be able to carry the traffic load. The base course adjacent to the wearing course should prevent the deformation of the wearing course and it needs to be strong but partly permeable. The wearing course ensures a firm and even layer for vehicles and it offers resistance between the wheels and road that minimizes skidding and should (particularly in Iceland) withstand spiked tires. The wearing course can be bound or unbound where the binding element is either bituminous or concrete materials. The road shoulders have similarities

with the wearing course and more often than not they are identical to the wearing course (Vegagerðin (2017)).
The thickness of each layer is designed according to traffic patterns and the layer separation is mostly due to the different standards the layers need to fulfill. In general, the closer to the traffic the layer is the stricter are the standards. Similarly, the carrying capacity of the layers should gradually grow as the layers are closer to the traffic. The right road materials are essential in order to meet these standards (Vegagerðin (2017)). For more information on road materials and how they are chosen see appendix A .

2.1.1 Important Parameters

In order to enforce the quality standards of roads, series of tests are made according to the European technical guide EN13043. There are multiple variables that ensure road quality. A high quality road has good adhesion between aggregates and binding materials. The binder should have good cohesion, a low temperature susceptibility in extreme temperatures and low viscosity at normal temperatures. The susceptibility to loading time should be low along with a high permanent deformation resistance, high breaking strength and high fatigue characteristics. Moreover, there is need to consider the aging characteristics of the bitumen (McQuilkin (2017) and Vegagerðin (2017)).
These quality parameters inherently have an effect on abrasion, wheel track formation, fracturing, temperature susceptibility, volume and voids, surface- and skid resistance, safety, usability and lifespan of the road.
Apart from these variables the mixing and application characteristics of the asphalt should be such that the asphalt is applicable to machinery currently used. Therefore the stiffness, flow and viscoelasticity of the mixture should be such that paving efforts are unchanged or easier.

Asphalt types

European standards for asphalt mixing indicates 9 different types of asphalt (Vegagerðin (2017));

1. Asphalt Concrete (AC)
2. Very Thin Layer Asphalt Concrete
3. Soft Asphalt
4. Hot Rolled Asphalt (also known as hot mix asphalt (HMA))
5. Stone Mastic Asphalt (SMA)
6. Mastic Asphalt
7. Porous Asphalt
8. Reclaimed Asphalt

9. Asphalt for Ultra-Thin Layer (AUTL)

The type of road chosen depends on the location, estimated traffic and designer of road. Each of these types have different quality standards (ÍST EN 13108-1 to -9). In this study there will be a focus on warm and hot mix asphalts (asphalt types 3 to 5).

Definition of road quality

In order to ensure a quality road aggregate, bitumen and asphalt specimen need to be analyzed. There are several test included in each analysis made, some of which are specific for Icelandic conditions. These tests are described in "Efnisrannsóknir og efniskröfur" published by the Road administration of Iceland (Vegagerðin (2017)).
The aggregate analysis performed by evaluating the following tests; grain distribution, moisture, humus, compression strength and rock quality (strength and resistance to weathering) and sometimes Los Angeles (LA) test. The performance requirements of the aggregate are dependent on the assumed volume of traffic (for additional information see Vegagerðin (2017), chapter 64.5).
To perform an analysis on the quality of bitumen the following test are made; Needle test, softening temperature, ignition temperature, solubility, dynamic viscosity, kinematic viscosity and Fraas breaking point (Vegagerðin (2017)).
Each test performed for aggregate and bitumen analysis have specific performance requirements dependent on the which type of asphalt mixture it will be used for. Because there are nine different types of asphalt these performance requirements will not be listed. Therefore, for the purpose of this study, it will be assumed that aggregate and bitumen meet the requirements for the respective asphalt type.

Asphalt sample analysis Asphalt sample analysis is made by evaluating the following tests; (i) Before asphalt is paved; Marshall test, moisture absorption and fracturing test and (ii) after the asphalt has been paved; void, surface resistance and surface roughness. The Road administration of Iceland suggests performance values of the aforementioned tests based on which type of asphalt type is made (see table 2.1).

Table 2.1 Suggested performance values of asphalt samples in the design stage (before asphalt is paved). This table is a part of a table found in Vegagerðin (2017). SMA 8, 11 and 16 indicates that the aggregate is good for stone matrix asphalt, 8-11-16 mm diameter stones respectively. Similarly, AC 8, 11 and 16 indicates the aggregate is good for asphalt concrete.

Type of asphalt	**Marshall test**				**Moisture absorption, fracturing resistance [%]**
	Void [%]	**Stability [kN]**	**Flow [mm]**	**Stability/Flow [kN/mm]**	
AC 8	1,0-3,0	5,0	1,5-5,0	>1,0	>70
AC 11	1,0-3,0	5,0	1,5-5,0	>1,0	>70
AC 16	1,0-3,0	5,0	1,5-5,0	>1,0	>70
SMA 8	1,5-3,5	5,0	1,5-5,0	>1,0	>70
SMA 11	1,5-3,5	5,0	1,5-5,0	>1,0	>70
SMA 16	1,5-3,5	5,0	1,5-5,0	>1,0	>70

Moisture absorption and fracture resistance is here referring to the interplay between the two characteristics which determines the resilience of asphalt to frost-thaw fluctuations.
When the asphalt has been paved and compressed, AC pavements are allowed to have a void volume of 1.0-4.0% of the total volume and SMA pavements 1.5-4.5%. The surface resistance of the paved road is dependent on the allowed speed on the road. However, the surface resistance should not be below 0.4 in any case, no upper limit was found (Vegagerðin (2017)). The surface roughness is suggested to be 6 mm for roads with a traffic of >3000 ÁDU, (ÁDU is a unit that indicates the average daily traffic in a year on two lanes). No upper or lower limits were found for surface roughness.

According to Vegagerðin (2017) a road of high traffic (>8000 ÁDU) with road material SMA 11/SMA 16 with the hard bitumen (70/100) can contain polymers if tests are made that indicate that the asphalt withstands quality standards in wheel track formation and Prall testing. Asphalt needs to meet the requirements of type testing seen in table 2.2.

Table 2.2 Asphalt quality requirements of type testing for high traffic roads (>8000 ÁDU) according to Icelandic standards (Vegagerðin (2017))

Test	**≥ 8000 (ÁDU)**	**≥ 15000 (ÁDU)**	**≥ 30000 (ÁDU)**
Wheel track test, mm	6	5	4
Prall test, ml	24	24	20
Water sensitivity test, %	70	70	70

Because of high humidity, frequent frost-thaw fluctuation and abundant use of salt for ice-thawing in Iceland there is a need for good adhesion properties between bitumen and aggregate (Vegagerðin (2017)). The road administration of Iceland additionally has an intricate discussion on how asphalt should be paved which, for the sake of this study, is assumed to be followed.
If all of the aforementioned parameter suggestions and requirements are fulfilled a wearing course is considered of good quality.

2.2 Plastic Additives in Roads

Additives are primarily added in order to improve important parameters of roads, to make them cheaper or to utilize otherwise discarded resources. Additives either compensate for natural aggregates, bitumen or improve the cohesion between the two. Generally, bulky and low quality additives are added to the sub layers of the road and the finer and high quality additives are added to the wearing course.
There is a consensus among researchers that polymer and latex asphalt modification can improve road properties. Quality differences can be seen in increased cohesion, increased elasticity, better temperature susceptibility in high and low temperatures which lowers the risk of bleeding/creeping of the asphalt and wheel-path ruts (Kalantar et al. (2012), Salomon (2006) and Giavarini (1994)). Polymers typically increase the stiffness of bitumen which improves rutting resistance and allows the use of relatively softer bitumen and better low temperature performance (Awwad and Shbeeb (2007)). Latex is particularly suited to the modification of emulsions and the most commonly used in paving grade emulsions are SBS, polychloroprene and natural rubber (Salomon (2006)). The aforementioned additives have been used globally since the 1990s and since the 2000s low grade mixed waste polymers have been rapidly-developing and used notably in India, Iran and China (McQuilkin (2017)). Polymer additives have been used in Iceland for the purpose of reducing the risk of separation of bitumen and aggregate in the process of mixing and transporting of asphalt. However, polymer additives have only been used for SMA pavements (Vegagerðin (2017)).
The optimum modifier content has the maximum bulk density and Marshall stability with a minimum flow, air void content of 4% and maximum void of mineral aggregate (VMA) (Awwad and Shbeeb (2007)).

2.2.1 Application methods

Achievable improvements of the polymer modified asphalt (PMA) are heavily dependent on how the polymers are applied. There are predominantly three different methods of adding plastic in an asphalt emulsion; (i) Polymer modified bitumen (PMB), (ii) Plastic-coated aggregate (PCA) and (iii) Plastic and aggregate mixture.

(i) Polymer modified bitumen (PMB)

In this method the plastic is melted at approximately 160°C and mixed with the warm bitumen where it is stirred for about 30 min (Becker et al. (2001)). The plastic will replace 10% or less of the binder material.

Considerations. In some cases the PMB yields a poor asphalt compatibility, higher cost and higher viscosity during asphalt processing and application (Becker et al. (2001)). A myriad of polymers have been used as binder modifiers and in table 2.2 the characteristics of the PMB of the five most common polymers are listed reported by Becker et al. (2001).

Polymer	Advantages	Disadvantages	Uses
Polyethylene (PE)	High temperature resistance Aging resistance High modulus	Hard to disperse in the bitumen Instability problems High polymer contents are required to achieve better properties	Industrial uses Few road applications
	Low cost	No elastic recovery	
Polypropylene (PP)	No important viscosity increase even though high amounts of polymer are necessary (ease of handling and layout)	Separation problems	Isotactic PP is not commercially applied
	High RandB	No improvement in elasticity or mechanical properties	
	Low penetration	Low thermal fatigue cracking resistance	Atactic PP is used for roofing
	Widens the plasticity range and improves the binder's load resistance		
PVC	Lower cracking PVC disposal	Acts mostly as filler	Not commercially applied
Styrene–butadiene block copolymer (SBS)	Higher flexibility at low temperatures	High cost	Paving and roofing
	Better flow and deformation resistance at high temperatures	Reduced penetration resistance	
	Strength and very good elasticity Increase in rutting resistance	Higher viscosity at layout temperatures Resistance to heat and to oxidation is lower than that of polyolefins (due to the presence of double bonds in the main chain)	
Styrene–isoprene block copolymer (SIS)	Higher aging resistance	Asphalts suitable for SBS blends, need an asphalt with a high aromatic and a low asphaltene content	
	Better asphalt-aggregate adhesivity Good blend stability, when used in low proportion		

Figure 2.2 Characteristics of polymers used to modify bitumen (Kalantar et al. (2012) and Becker et al. (2001))

As described by Kalantar et al. (2012) polymer characteristics such as chemical composition, structure, crystallinity and molecular weight affect the PMB mixture. Giavarini (1994) reports that a number of researchers have studied the complex interrelationships between polymer and bitumen and in conclusion found three main factors influencing their compatibility. The factors are (1) amount and molecular weight of asphaltenes, (2) aromatic of the maltene phase, and (3) storage temperature.
Even though the polymer and bitumen are considered compatible there is need to consider the mixing conditions such as the mixing equipment and time-temperature profile (Kalantar et al. (2012)). This statement is backed up by Giavarini (1994) who refers to the different procedures of implementing thermoplastic- and thermosetting polymers among others.
Despite, the difficulties with PMBs there are a great number of them offered on the market. Many of these PMBs are produced by petroleum and petrochemical companies and are more often than not based on SBS plastic types (see more about SBS in appendix A). Bitumen manufacturers may also offer different types of PMBs based on specific climate conditions (Giavarini (1994)).

(ii) Polymer-coated aggregate (PCA)

This method includes heating the aggregate to approximately 160°C and adding plastic particles, stirred in a tumbler for about 30 sec. This way the plastic coats the aggregate. The plastic particles need to be the right size, clean and somewhat homogeneous mixture. Vasudevan et al. (2012) suggests that the use of plastic waste coated aggregate can reduce the quantity of bitumen needed for a good mix by 0.5% of the total weight of the road. Hence, a 10% reduction of bitumen used.

Considerations. The method implies that the influential polymer characteristics is melting temperature, thermoset/thermoplastic classification and the presence of toxic additives. This method has been found to increase the roughness of the road and more efficiently bind the bitumen to the aggregates (Awwad and Shbeeb (2007) and Ahmadinia et al. (2011)). The grain size of the plastic makes a difference in outcome as Awwad and Shbeeb (2007) reported. Pelleted plastic provides a better coating of the aggregate leading to a good cohesion between bitumen and aggregate but non-pelleted plastic was found to provide a rougher surface texture.

(iii) Plastic and aggregate mixture

This method uses plastic granules with aggregate which reduces the amount of aggregate used in the road construction. Using traditional asphalt production methods, plastic granules (usually large particles) are mixed with aggregate and bitumen at the same time. In this method the plastic is partly melted, coating aggregate and binding to bitumen, and on the other hand not melted which replaces aggregate. While the other two methods use about 0.5 to 1% plastic, this method gives about 12% total plastic content by the weight of the road (Zoorob and Suparma (2000)).

Considerations. This method technically describes the behavior of those types of plastic that have a melting point above 180°C (working temperature of HMA). This is supported by Ahmadinia et al. (2011) who concluded by investigating PET (melting point around 250°C) that it gave stiffer mixture and higher stability because of the glass transition temperature (70°C for PET) allowed the PET particles to become more or less crystalline. However, this method has not been researched to the same extent as the other two methods.

2.2.2 Plastic Waste Additives in Roads

Waste polymers may help to improve the performance of pavement and at the same time solve a waste disposal problem (Kalantar et al. (2012)). If waste polymers improve pavement performance their use would be beneficial from an economical and environmental point of view.
This study will focus on the PCA method since it has less uncertainties regarding application, it is applicable to machinery currently used in asphalt production in Iceland and a good reference base in literature. Additionally, the PMB method has proven to be energy intensive (due to mixing and storage methods) which is not typically positive for environmental impact assessment. However, it would be possible to investigate the PMB methods and Plastic-aggregate mixture method in the regards of an environmental assessment.
The type and amount of waste plastic used proportional to aggregate and bitumen is influential to the quality retained. However, the best outcomes usually fall between the range of 5-8% of waste plastic to the weight of bitumen (Kalantar et al. (2012)).
Since this study intends to simulate the quality effect of using a constantly variable heterogeneous mixture of waste plastic in road construction it is important to consider how the most common types of plastic affect road quality.
To begin with the PE, PP and PS polymers soften easily around 130-140°C without any evolution of gas (Vasudevan et al. (2012)). PVC however releases hydrogen chloride at around 250°C that forms hydrochloric acid upon contact with water vapour.

Polyethylene (PE)

In general, Attaelmanan et al. (2011) found PE to give high thermal expansion but low stiffness. Awwad and Shbeeb (2007) investigated different PE types on HMA using soft bitumen. Although the study did not investigate waste polymers it gives an excellent overview of high- and low density polyethylene (LDPE and HDPE) behavior in HMA and recommends using the PCA method at 180-190°C. The study found that in general, PE reduces pavement deformation, decreases fatigue flaws and provides better adhesion between bitumen and aggregate.

HDPE - Awwad and Shbeeb (2007) recommend HDPE for HMA and found increased stability, reduced density and increased air voids and voids of mineral aggregate by using 12% grinded HDPE by the weight of bitumen. Furthermore, HDPE is reported to have good impact resistance, light weight, low moisture absorption and high tensile strength (Awwad and Shbeeb (2007)). This is confirmed by Ahmadinia et al. (2011) who studied how 8% HDPE plastic bags to the weight of bitumen with recycled concrete aggregate (RCA) mixtures gave an 30-15% increase to Marshall stability and high tensile strength.

LDPE -Awwad and Shbeeb (2007) report that LDPE offers good resistance to abrasion and low moisture permeability but lacks in the fields of stiffness and structural strength. Another research by Al-Hadidy and Yi-qiu (2009) on using LDPE on stone matrix asphalt (SMA) achieved the results that the overall durability of the original asphalt was significantly improved. Moreover, Ahmadinia et al. (2011) found that the method could meet the various requirements of different climates such as; with extreme temperature fluctuations and excessive rain fall.

Polypropylene (PP)

PP has the reputation of providing good chemical and fatigue resistance. However, it has been found that the binder is susceptible to oxidative degradation and thermal expansion (Attaelmanan et al. (2011)). A study made by Vasudevan et al. (2012) investigated PP, PE and PS using the polymer coating (PCA) method and soft bitumen. The samples made were tested for moisture absorption, soundness, Los Angeles abrasion (LA), stripping of bitumen and Marshall stability. The amount of voids and moisture absorption declined as the plastic content was increased resulting in low disintegration. The LA test showed that the PCA had a better resistance to abrasion compared to a traditional road and stripping test found a stronger binding of the bitumen and aggregate. Moreover, a bitumen extraction test found that the higher the plastic content, the harder it was to remove bitumen using trichloroethylene. Finally, the results showed that as long as the percentage of plastics was below 15% to the weight of bitumen it showed an increase in Marshall stability value. PP was found to be a better additive than PE and PS.

Polyvinyl Chloride (PVC)

PVC is made flexible with the addition of plasticizers and it is not uncommon for PVC to contain other additives such as heat stabilizers (Kaley et al. (2006) and Wypych (2016)). PVC releases toxic gases such as hydrogen chlorides and dioxins when burnt or heated which can cause issues for the work force during production and therefore it is are not recommended as additives in wearing courses.

Polyethylene Terephthalate (PET)

Ahmadinia et al. (2011) researched waste PET bottles as additives for SMA and found significant increase in Marshall stability, increased air void and lower bulk specific gravity by using 6% PET by weight of bitumen.

Polystyrene (PS)

PS asphalt samples seem to give a lower bending strength, compression strength and binding property compared to PE and PP. Nonetheless, PS gives the same test results as were discussed in "Polypropylene" section above (Vasudevan et al. (2012)). There seems to be less literature on PS as road additives than other types of plastic. This could be due to the fact that the recycling of PS is problematic, therefore it is not common that it is source separated and collected, hence it is not easily accessible for research.

Styrene-Butadiene-Styrene (SBS)

SBS has been widely researched and used in the context of being used as a bitumen modifier. Attaelmanan et al. (2011) found SBS to have a good fatigue resistance, high creep rate but susceptible to oxidation. In general, SBS modified bitumen increases tensile strength, increases the elasticity of the asphalt, performs better at lower temperatures and can be recycled. SBS has been used in pavements in Iceland which showed a lowered wheel-track formation than a traditional road paved in the same area (Örn Haraldsson and Sigurðsson (2012)). However, as has been mentioned before some researchers have experienced a problem with the storing and aging effects of the PMB (Yildirim (2007)).

To summarize the characteristics of each plastic type using the PCA application method, tables 2.3 and 2.4 were made. SBS was not included in the table since the literature found used the PMB application method.

Table 2.3 Characteristics of waste polymers used for the polymer-coated aggregate (PCA) application method summarized. Listing softening temperature, advantages, disadvantages, uses and sources of Polyethylene (PE), high-density and low-density. The table is inspired by Becker et al. (2001)

Polymer	Softening temperature	Advantages	Disadvantages	Uses	Sources
Polyethylene (PE)	100-120°C	High thermal expansion Reduced pavement deformation Decreased fatigue characteristics Good adhesion	High thermal expansion Low stiffness	12% of weight of bitumen HMA at 180-190°C Less than 15% of weight of soft bitumen	Attaelmanan et al. (2011) Awwad and Shbeeb (2007) Vasudevan et al. (2012)
-HDPE	120°C	Increased air voids Good impact resistance Low moisture absorption High tensile strength Increased Marshall stability	Increased air voids	12% of weight of bitumen Grinded HDPE HMA at 180-190°C	Ahmadinia et al. (2011) Awwad and Shbeeb (2007)
-LDPE	not found	Abrasion resistance Low moisture permeability Overall increased durability	Decreased stiffness Decreased structural strength	12% of weight of bitumen Grinded LDPE HMA at 180-190°C and SMA	Al-Hadidy and Yi-Qiu (2009) Awwad and Shbeeb (2007)

Table 2.4 Characteristics of waste polymers used for the polymer-coated aggregate (PCA) application method summarized. Listing softening temperature, advantages, disatvantages, uses and sources of Polypropylene (PP), Polyvinyl Chloride (PVC), Polyethylene Terephthalate (PET) and Polystyrene (PS). The table is inspired by Becker et al. (2001)

Polymer	Softening temperature	Advantages	Disadvantages	Uses	Sources
Polypropylene (PP)	110-160°C	Good chemical and fatigue resistance Low moisture absorption Low disintegration Good adhesion Resistance to abrasion Increased Marshall stability	Oxidative degradation High thermal expansion	Less than 15% of weight of bitumen Soft bitumen PP foam and grinded	Attaelmanan et al. (2011) Vasudevan et al. (2012)
Polyvinyl Chloride (PVC)	apr. 95°C		Not suitable		Becker et al. (2001)
Polyethylene Terephthalate (PET)	apr. 140°C	Increased Marshall stability Increased air void	Needs more evidence	6% of weight of bitumen SMA	Ahmadinia et al. (2011)
Polystyrene (PS)	110-140°C	Good adhesion Increased Marshall stability Good chemical resistance Low moisture absorption Low disintegration	Low bending strength Low compression strength Needs more evidence	Less than 15% of weight of bitumen Soft bitumen	Vasudevan et al. (2012)

To summarize, polymers used as additives in road construction can be classified into three groups; Thermoplastic elastomers, plastomers and reactive polymers. Thermorplastic elastomers tend to increase the elastic properties of binders. Plastomers and reactive polymers on the other hand help enhance stiffness and strength of heavy loads (Ahmadinia et al. (2011), Al-Hadidy and Yi-qiu (2009) and Al-Hadidy and Yi-Qiu (2009)).

2.2.3 Effect on Road Performance

This sections aims to connect the results of the asphalt sample results found in literature to road parameter behavior. The variables chosen for evaluation are: Abrasion, Wheel track formation, Fracturing, Lifespan and Recycling. These parameters are holistic and not easily distinguished from one another, excluding recycling. The variables are chosen because of their relevance to the environmental outcome of the study. Abrasion will give an idea of the particulate matter formation; Wheel track formation relates to the maintenance required for the road due to bleeding/creeping of asphalt; Fracturing connects to the temperature susceptibility and tensile strength of the road. Eventually, all of these variables relate to the achievable lifespan of the road which eventually and hopefully is recycled.

Abrasion
A good adhesion between aggregate and bitumen reduces abrasion. When aggregate is damp with water the bitumen binds poorly with the aggregate since bitumen is essentially oil. Similarly to bitumen, PE, PP and PS waste polymers are long hydrocarbon chains. Therefore when aggregate is coated with polymers bitumen binds with more ease to aggregate, creating a good adhesion and lowering abrasion.
When abrasion is reduced there is less risk of particulate matter formation. Particulate matter are small particles which travel long distances via the atmosphere and can set on any type of surface, ocean or lungs.
When plastic is used as additives in roads there will be microplastic particles in the particulate matter (although, probably tightly bound with bitumen). Microplastics are a severe problem for aquatic ecosystems. However, it can be argued that because of the increased rutting resistance by the addition of plastic in roads there will be less bitumen in the environment and bitumen is a secondary product derived from crude oil just like plastic.
A high air void content combined with frequent frost and thaw periods leads to fracturing and abrasion. However, a low air void content leaves the wearing course impermeable and non-expandable which is important to prevent bleeding and flushing (Awwad and Shbeeb (2007)). Air void content can be altered in the construction stage of the road by pressing more to compensate for high air void content. If however the pavement has too low air void there might be need for repaving.

Wheel track formation
The softening point of the asphalt layer is determining for the bleeding of the asphalt that leads to wheel track formation. Although the temperature is not high in Iceland, 50°C has been measured at 20 mm depth on the roads and the softening temperature of hard bitumen is in fact around 43-51 °C (Vegagerðin (2017)). Several researchers have shown

that the softening temperature is increased with the addition of plastic. An example of that is that Costa et al. (2013) found increased softening point of asphalt to 71.1°C using 5% HDPE and 59.5°C using LDPE PMB.
Rut formation in Iceland is also due to the use of spiked tires. The spiked tires are used because of slippery and icy roads. Weather conditions in Iceland will not be changed so the use of spiked tires is inevitable. However, the strengthened bond between bitumen and PCA gives hope for there being less wheel track formation. As an example the lowest wheel track test results measured in Iceland was measured at 2.4 mm in a sample mixed with 6% SBS mixed PMB (Vegagerðin (2017)).

Fracturing

Fracturing includes cracking and pothole formation. The higher tensile strength, the higher cracking resistance and as has been mentioned before HDPE and LDPE were reported to give a high tensile strength. Pothole formation is interconnected to the air void and adhesion strength and PP, PE and PS have been found to improve adhesion strength. Lastly, a good temperature susceptibility lessens the frequency of fracturing and the softening point of asphalt has been found to increase.
In general, plastic waste additives have been found to improve Marshall stability. Marshall stability describes the maximum load required to produce shear failure of a substance using a Marshall test device an is dependent on internal friction and cohesion. Therefore, an increased Marshall stability could be described as an increased resilience of a sample. However, because the test is also dependent on cohesion it can determine the optimum binder needed for a specific asphalt mix.
According to literature Marshall flow seems to either increase or decrease with the addition of plastic waste. Marshall flow describes the deformation of a compact sample under a maximum load found by the Marshall stability. Marshall quotient (MQ) is an index of stiffness and is Marshall stability divided by Marshall flow. Plastic additives give improvements in MQ and as an example Al-Humeidawi (2017) found 35% improvement using 8% plastic bags. The MQ describes how slope of deformation under increasing pressure, therefore Al-Humeidawi (2017) found that there is less deformation per load of the sample before it breaks.

Lifespan

The parameters mentioned above have an effect on lifetime. It is uncertain to what extent the lifespan could be improved. On the other hand, Shukla et al. (2003) calculated that by using SBS PMB in India they would be able to decrease the surface layer and simultaneously almost double its lifespan.
The effects of mixing of the different plastics are unknown i.e. either an antagonistic or synergistic mix response dependent on the different types. This would effect the quality improvements that collectively have an impact on the lifespan of the road.
In spite of the uncertainties of lifetime expansion of the PMA the Inventory chapter will try to make a conservative estimation by assuming synergistic mix response. The sole purpose of the estimation is to be able to perform an environmental investigation.

Recycling

At the end of the lifespan the road will be recycled. The fairly recent application of the waste polymer mixed asphalt (10-15 years) results in the lack of data on its recycling possibilities. However, SBS has been used for PMB for more than two decades and Mohammad et al. (2003) recovered an eight year old polymer modified asphalt binder from a wearing course mixture located on route US61 in Livingston Parish, Louisiana. The binder was quite brittle at low temperature and extensive oxidative age hardening had occurred. In spite of this SBS PMB was found to be recyclable.

2.3 Introduction to Life Cycle Assessment

A life cycle assessment (LCA) is the quantification of all relevant environmental impacts of a life cycle of a product or a system. A life cycle includes every process of a product from cradle-to-grave or from the material extraction to the disposal. Essentially, a LCA aims to convert complex systems into communicable numbers which can aid decision making to achieve improvements in a system set up, choice of technology or operation. The environmental impacts that are covered in the assessment are dependent on how the LCA is performed. Therefore, the reporter has an influence on coverage of environmental impacts that can be from local to global and may span over decades or centuries. An LCA is typically comparative in which the alternatives must provide an equal service or function in quantitative and qualitative terms.
The LCA starts with a definition of the goal and scope. From there the life cycle inventory (LCI) is accounted, followed by a life cycle impact assessment (LCIA). Programs are commonly used to calculate results that are presented in an LCIA chapter via impact categories which support the comparison or further analysis. The working phases of LCA are further described in ISO14040 (14040:2006 (2006) and Hauschild et al. (2017)).

2.3.1 LCA of Roads

The life cycle stages of roads are; material stage, manufacturing stage, use stage and recycling stage. The material stage is composed of the processes of extracting bitumen and aggregate. The manufacturing stage combines the processes of production and construction of asphalt roads and the use stage is combined by fuel combustion and emission of the different machinery throughout the life cycle of a road. For information on the life cycle of roads see appendix A.
According to Birgisdóttir (2005) the processes that are the most influential to the environmental outcomes of the LCA of roads are related to the emissions of carbon dioxides and nitrogen oxides associated with the burning of fossil fuels. Material- and construction stages reportedly contribute to approximately 50% of these outcomes and the other half is influenced by the use stage of the road (assuming 100 years of operation).
However, it is unusual that a wearing course is continuously used for a 100 years and to emphasize the differences in LCA results in the field of LCA of roads a couple of examples are given. By focusing on the vehicle emissions of the use stage Araújo et al. (2014) found that by lowering the rolling resistance of the wearing course, it could lower the emissions from users and compensate for the emissions and fossil fuel burnt during construction of the road. However, these results are heavily dependent on the operation time of the wearing course.

Additionally in the use stage, the effects of salting could potentially pollute groundwater as has been the case in many countries (Blomqvist and Johansson (1999) and Kaushal et al. (2005)) and the clearing of snow can scrape and damage the wearing course. However, these services differ considerably dependent on weather and the location of the road.
It is expected that most water enters through unpaved shoulders. However there is a knowledge gap on how much water percolates dependent of the road structure, location and condition. The infiltration rate is estimated to be between 1-20% of the annual precipitation (Birgisdóttir (2005)). The melting of ice during freezing/thawing cycles are relevant in Icelandic climate and the cracks developed over time due to these cycles gives access to considerable amounts of water (Apul et al. (2002)). The amount of water penetrating the road is important for the fracturing of a wearing course and the potential leaching of the plastic utilized.
These affects on the use stage doubtlessly have an effect on an LCA of a road and the way in which these LCAs are conducted either embolden or diminish these effects.

There are several models available for making LCA of roads such as SimaPro, ROAD-RES, PaLATE, BE2ST and EASETECH. SimaPro is the most commonly used LCA program, ROAD-RES, PaLATE and BE2ST are specifically designed for LCA of roads but have not been updated recently (Birgisdóttir (2005)). Finally, EASETECH specializes in LCA of heterogeneous material streams and is most commonly used for waste management systems. Since this study aims to assess the use of plastic waste in road construction, EASETECH has been chosen to bridge the waste and road modelling.

Chapter 3

Inventory

As the scenarios are framed it is essential to keep them as simple as possible without compromising a sensible and practical idea of what can be achieved or expected.

3.1 Scenario description

Road construction in Iceland requires imported bitumen and excavation of aggregate. Aggregate extraction for this study is assumed to be local although it is in some cases imported. In order to assess a road that utilizes plastic waste that is comparable to the scenario of a traditional road there is need to consider the plastic waste management system. In table 3.1 the included processes of the two scenarios are shown. Scenario 1: A traditionally constructed road and plastic waste management in Iceland. Scenario 2: Plastic waste utilized in road construction, the plastic needs to be cleaned and pelleted before use. Scenario 2 will produce a road that has different road parameters and a longer lifetime.

Table 3.1 Processes included in each scenario

Processes	**Scenario 1**	**Scenario 2**
Road	Bitumen extraction	Bitumen extraction
	Aggregate extraction	Aggregate extraction
	Construction	Construction
	Use	Use
	Demolition	Demolition
Plastic waste	Bailing	Cleaning & Pelleting
	MRF	
	Recycling	
	Incineration	
Subsitution	Virgin plastic	
	Aggregate	
	Heat	
	Electricity	
Transportation	Transoceanic	Truck
	Truck	

The theory is that utilizing plastic waste for road construction will result in savings in environmental impact scores in comparison to the current management. However, there is need to consider the composition of the residential source separated plastic waste available in the capital region of Iceland and the avoided recycling of this plastic waste.

3.2 Inventory, Considerations and Limitations

Some of the information in the following chapters will be repeated in the sub chapter Life Cycle Inventory Analysis. This chapter should be considered as a more detailed description of the data used and its collection.

3.2.1 Road: Material, Manufacturing, Use, Disposal & Transport

The processes of a life cycle of a road is listed in appendix A.

Materials

The specific amount of material needed for the two alternative roads can be found in appendix B, table B.2 and table B.5 along with energy use, transportation distances and their sources. It is assumed that 8% of plastic waste to the weight of bitumen will be utilized in the asphalt mixture. For that amount of plastic, Vasudevan et al. (2012) found that a reduction of bitumen by 0.5% of the total weight is obtained for a good mix. The amount of bitumen needed in the plastic enriched road was found to be 89.5% of the weight needed for the traditional road and likewise the amount of aggregate was found to be 99.5% of the weight.
The extraction of the bitumen used in Iceland is assumed to take place in Venezuela and the process is assumed to be identical to that of the rest of the world with the addition of oceanic transport (assumed to be 11000 km). Additionally, the extraction of aggregate in Iceland is also assumed to be identical to the processes used in rest of Europe.

Manufacturing

The manufacturing includes asphalt production and paving. Average data for these processes were given by Hlaðbær Colas. The reason for using average data is that production and paving can consume different amount of energy according to weather conditions, design of production facility and distance of road from asphalt production facility etc. An average day in May an asphalt production facility consumes 90 kWh electricity per ton finished product and 87 kWh fuel per ton finished product (Bragason (2018)). Note, that this does not include the maintenance and does not assume drying of aggregate due to rain. There could be some added energy use in the asphalt production stage because of the implementation of plastic aggregate which is neglected.
Fuel consumption of asphalt paving was also estimated by Hlaðbær Colas which they calculated from an average paving job. It was assumed that the paving would take place 52 km away from asphalt production facility, five different types of machines would be used and it includes paving and the transportation of material, workers and machinery. The average fuel consumption was calculated as 4.1 L fuel for each ton of asphalt (Þras-

tardóttir (2018)).

Use

The use stage assumes maintenance and service of the roads throughout a whole year. Emissions of traffic on road is neglected but if it had been included there could be more or less emissions from traffic in proportion to surface resistance change due to plastic additives. Included services are road painting, pothole filling, salting, sweeping and snow removal and can be seen in table 3.2. Transportation of maintenance and service machinery to road location, upstream impacts and environmental impacts of the materials are not included. Maintenance due to traffic accidents were also neglected.
Data about use stage in table 3.2 has mostly been gathered by email and personal communication with professionals. The majority of the data is specific to Icelandic conditions and represents what can be expected in an average year.

Table 3.2 Maintenance and services included in the use stage. Frequency, speed and fuel consumption of road painting, pothole filling, salting, sweeping and snow removal.

Maintenance/Service	Amount	Unit	Source
Road paint			
Frequency	1	times/year	Jóakimsson (2018)
Speed	12	km/hour	KONTUR (2018)
Fuel consumption	3.8	l/h	KONTUR (2018)
Fuel type	Diesel		KONTUR (2018)
Pothole filling			
Amount	3	holes/km	Assumption
Fuel consumption	3.5	l/hole	Wilson and Romine (2001)
Fuel type	Diesel		Wilson and Romine (2001)
Salt			
Salt	60-240	kg/km	Þórðarson (2018)
Frequency	85-100	times/winter	Þórðarson (2018)
Fuel consumption	0.3	l/km	Þórðarson (2018)
Fuel type	Diesel		Þórðarson (2018)
Sweeping			
Frequency	2	times/year	Assumption
Fuel consumption	0.3	l/km	Þórðarson (2018)
Fuel type	Diesel		Þórðarson (2018)
Snow removal			
Frequency	85-100	times/winter	Þórðarson (2018)
Fuel consumption	0.4-1	l/km	Þórðarson (2018)
Fuel type	Diesel		Þórðarson (2018)

Disposal

The demolition of the road at end-of-life includes an asphalt miller, dumping truck and transportation to the storage site, seen table 3.3.

Table 3.3 Data on the demolition of an average road

Operation	Amount	Unit	Reference
Asphalt miller			
Speed	200	m^3/hour	Wirtgen (2008)
Speed	15	m/min	Wirtgen (2008)
Fuel consumption	0.9	l/m^3	Wirtgen (2008)
Fuel type	Diesel		Assumption
Dumping truck			
Speed	15	m/min	Wirtgen (2008)
Fuel consumption	0.3	l/km	Assumption
Fuel type	Diesel		Assumption
Transportation to storage	50	km	Assumption

The sources for table 3.3 are gathered from a job report published by Writgen GmbH in 2008 along with some assumptions. It is evident that this is not high quality data. However, the demolition of a road does not have an environmental effect to the same extent as other processes since it happens once and takes only a few hours.
When the wearing course has been removed it is transported to storage. Storage involves reclaimed asphalt pavement (RAP) that is kept in piles outside until it can be used in the sub-layers of other roads. According to Marchand (2015) the amount of available reclaimed asphalt in Iceland in 2011 was 15 thousand tonnes, 25% of which is used in unbound layers and 2.5% of the new hot and warm mix production contains reclaimed material. In comparison to the 15 thousand tonnes of reclaimed asphalt, the production of hot and warm mix asphalt that same year was reported to be 0.2 million tonnes (Marchand (2015)). Because of this small amount of reclaimed asphalt used, the RAP for this study was assumed to be stored and the storage does not require energy. Therefore, RAP is not re-used or recycled in a way that involves aggregate substitution. Rather, it is stored in different locations since it was not clear if the RAP was being re-used or landfilled.

Transportation
All assumptions about transportation is gathered in table 3.4. If the locations were known within one country transportation were assumed to be by truck and distances were found by road distances on maps. All transportation between countries were assumed to be via ship and distances found were aerial distances. If the locations were not known (connected to the actual location of the road) they were estimated. The transportation is also gathered in table B.4 and partly repeated in table B.5 in appendix B.

Table 3.4 Assumed transportation distances for the two scenarios, connected to the traditional and plastic waste enriched roads

Transportation	**Road type**	
	Traditional [km]	**Plastic waste additives [km]**
Aggregate from mine to asphalt production	30	30
Bitumen from production to asphalt production	11100	11100
Bitumen from port to asphalt prodution	20	20
Plastic wate from Gufunes to Gothenburg, SE	2000	-
Plastic waste from Gothenburg, SE to recycling in Bredaryd, SE	150	-
Plastic waste from Gothenburg, SE to incineration in Sävenäs in Gothenburg, SE	10	-
Plastic waste from recycling Bredaryd to Sävenäs, SE	140	-
Plastic waste from Gufunes to asphalt production	-	20
Recoverd asphalt to storage	52	52

3.2.2 Plastic Waste in the Capital Region of Iceland

The collection of the plastic waste is not considered important in this study and the focus will be on the residential source separated plastic that arrives at Gufunes, the waste reception and classification center of the capital region of Iceland. The waste reception is handled by a company named SORPA bs. There are mainly three sources of plastic waste; from households, from collection containers and from recycling stations. The plastic from households and collection containers are mainly plastic packaging (more than 80%). The packaging plastics are highly valuable to SORPA. On the other hand, plastic collected at recycling stations falls into a category of having less than 20% plastic packaging which is less valuable to SORPA. All of the differently sourced plastic waste however are sent to Sweden for recycling (Björnsdóttir (2016)).

Plastic waste from households

When the plastic has reached the reception facilities it is separated by a air classifier, packaged and made ready for shipment. The air classifier's electricity use will be left out of both scenarios. This is done because it is unnecessary to account for its electricity use since it is identical in both scenarios.

Plastic waste from collection containers
The plastic waste does not have to be separated when it reaches the reception facilities and is immediately packaged. The baling of plastic is assumed to use 11.4 kWh/ton plastic waste (Liljenroth (2014)).
The fractions of different types of plastics in a sample collected by ReSource International ehf in February 2018 can be seen in table 3.5. It is assumed that plastic waste coming from households and collection containers have the same fractions as are shown in table 3.5, i.e. containing more than 80% plastic packaging.

Table 3.5 The fractions of different types of plastic from two sources of residential source separated plastic waste from the capital region of Iceland, sampled by ReSource International ehf in February 2018.

	Households*		Collection Containers**		Total	
	kg	%	kg	%	kg	%
PET	2.38	10.60%	4.50	18.53%	6.88	14.72%
HDPE	3.72	16.54%	3.58	14.75%	7.30	15.61%
PVC	0.00	0.00%	0.12	0.47%	0.12	0.25%
LPDE	3.56	15.85%	5.68	23.40%	9.24	19.77%
PP	5.93	26.37%	4.51	18.58%	10.44	22.33%
PS	2.08	9.25%	1.23	5.07%	3.31	7.08%
Other plastics	2.06	9.16%	1.91	7.85%	3.96	8.48%
Non-plastics	2.75	12.23%	2.75	11.34%	5.50	11.77%
Total	22.48	100.00%	24.26	100.00%	46.74	100.00%

*Household source separated plastic waste from Reykjavík (græna tunnan) **Collection containers collecting residential source seperated plastic waste from Reykjavík (grenndargámur)

From table 3.5 it is evident that PP, LDPE, HDPE and PET make up the largest part (73%) of the plastic waste sample collected followed by non-plastic items. The non-plastic impurities are for example missorted items or paper labels.

Plastic waste from recycling stations
The plastic waste in this case is bailed on site and the fractions of plastic types from this source is unknown (Hjarðar (2018)). It is likely however that the actual plastic fractions coming from recycling stations are different than from households and collection containers shown in table 3.5. For this study however, it is assumed to be the same since there does not exist data on the plastic fraction collected via recycling stations.

The waste reception and classification center of the capital region of Iceland (managed by SORPA bs.) received approximately 900 tons of sorted plastic in 2016 (Björnsdóttir (2016)). Of those 900 tons, 494 tons were collected from recycling stations which receives plastic that falls under the category of having <20% plastic packaging (Björnsdóttir

(2016)). When SORPA bs. sends plastic waste to be recycled they receive payment from a company called Úrvinnslusjóður according to a tariff. Plastic waste that has <20% plastic packaging has the least value according to the tariff and therefore it could be obtained from SORPA bs (SORPA (2018b)). The plastic will either be obtained for free, for a low price or it would be possible to obtain compensation for eradicating the waste.

Plastic Recycling in Sweden

When all plastic has been collected and bailed the plastic waste is shipped to Gothenburg (approximately 2300 km) to IL Recycling in Sweden. Il Recycling is a subsidiary of Stena recycling in Sweden and categorises the waste into either recyclable plastic or non-recyclable plastic. It is assumed that of the total plastic waste input, 70% is recycled and 30% is incinerated. The recyclable plastic waste is next transported via a truck (approx. 150 km) to Swerec in Bredaryd. There it is pre-washed before it is sent through a Near infrared (NIR) sorting machine and finally mechanically recycled (Liljenroth (2014)). The washing is expected to use 78 L water/kg, 10.9 MJ/kg (for 40 °C) and 0.5 kWh/ton waste plastic. The NIR technology can sort PET, HDPE, PVC, LDPE, PP and PS and is estimated to use 27kWh/ton waste plastic (Ren (2012)). The mechanical recycling considers shredding (24 kWh/ton) and extrusion (270kWh/ton) with a 2% material loss (Liljenroth (2014)). The aforementioned companies were not contacted in the making of this study and literature values were considered sufficient in addition to information from SORPA bs (i.e. Ren (2012) and Liljenroth (2014)).
The fractions which are discarded from the recycling process is incinerated. Incineration is assumed to take place in Sävenäs in Gothenburg (owned by Renova) which is the closest incineration plant from the port which receives the plastic waste from Iceland. Plastic has a high calorific value and the energy required when plastic is burned is either used for the local district heating system or for the electricity grid. According to Renova's website 87% of the recovered energy is used for the district heating and 13% is used to generate electricity. Bottom ash and fly ash collected from the incineration process is used to fill up old mines and where it is assumed that it substitutes gravel. It is assumed that Renova's incineration plant performs as an average danish incineration plant since Renova's specific air pollution control and other data was not available. The substitution possibilities are therefore in heat, electricity, plastic and aggregate. Recycled plastic is often credited for virgin plastic albeit the declined quality characteristics.

Villanueva and Eder, 2014 discusses that there are two basic distinct ranges of recyclate output currently marketed in the EU: Type 1 and 2. According to those categories the sample described in table 3.5 would be an example of Type 2 recyclate output where the non-plastic impurities falls within the range of 5-15%. Type 2 recyclate outputs are traded to a limited extent due to their low value or about 200-50 EUR/tonne (decreasing value proportional to the amount of non-plastic impurities) (Villanueva and Eder (2014)). Because of all of the known limitations of traditional recycling of plastic waste it can be concluded that the recycling of the Icelandic plastic waste taking place in Sweden is less environmentally and economically profitable than some might believe. Hence, there is reason to believe that recycling a sample such as the one in table 3.5 will lead to a low quality product. To compensate for this the recycled product is not credited as virgin plastic of the same amount. Recycled PE and PP substitutes for 80% virgin plastic of the same type and recycled PS and PET substitutes for 30% virgin plastic.

3.2.3 Other Energy Considerations

For scenario 2 plastic waste needs to be cleaned and pelleted before it can be used for road construction. It is assumed that the washing requires the same amount of water, electricity and heat as in the recycling station in Sweden with the difference of using energy derived from Iceland. The pelletizer can make pellets from any type of plastic and its estimated energy consumption is 380 kWh/ton (Liljenroth (2014)).
The energy derived from Iceland is assumed to be hydro from reservoir in a non-alpine region and deep geothermal. In 2014 Sweden's electricity consumption was 42% based on hydro power, 41% based on nuclear power and the remaining 17% was based on other power sources (Energi (2016)). Electricity derived from Sweden is assumed to be nuclear, specifically pressure water reactor although it is a mixture of power sources. Furthermore, the electricity substitution due to the incineration of plastic waste in Sweden is also assumed to be nuclear. On the other hand, heat produced in the incineration plant is assumed to substitute heat and power co-generation from natural gas from a conventional power plant. All of the data on energy originates from Ecoinvent database.
Fuel used for the construction, use and disposal of road was assumed to be diesel. Furthermore, all fuel consumption related to these stages were quantified and an external process was used from Ecoinvent that accounts for the production and combustion of the fuel. The database was chosen because of its unspecific nature since it was difficult to approximate machinery used, their age, condition and emission filters. The database states that the diesel is burnt by a truck from 1998.
Additionally, the amount of energy used in production of asphalt using plastic waste is assumed to be the same as for a traditional road.

3.2.4 Road Improvements Effecting Longevity

It is assumed that 8% of plastic waste by the weight of bitumen can be added to the road mixture in scenario 2. The values found in literature on this subject range from 2-15% plastic waste to the weight of bitumen. Therefore, 8% was chosen as an average. Moreover, the PCA method could lead to an increase in surface roughness which would change the rolling resistance of the road consequently effecting the fuel consumption of the vehicles driving on the road. Nonetheless, weighing all the results of the literature found on plastic additives in road construction there seemed to be an harmonious positive results and it is therefore assumed that overall there are positive benefits for the road quality with the addition of plastic waste.
Although the effects of mixing different types of plastic is uncertain the following table 3.6 was constructed as a general, non-specific, way to assume quality improvements. An average lifetime of 7 years was assumed for a traditional wearing course for the purpose of conducting an environmental assessment. The average lifetime of a wearing course is actually on the scale of 2-14 years dependent on its location, traffic load and quality that

was achieved (Efla (2013)).

Table 3.6 Lifetime of the two alternative roads are different and calculated by the assumed parameter improvements; Abrasion, Wheel track formation, Fracturing

Quality property	Road type		Comment
	Traditional	Plastic waste additives	
Abrasion	1	1.3	30% improvement
Wheel track formation	1	1.25	25% improvement
Fracturing	1	1.3	30% improvement
Lifetime	7	8.5	years

As is indicated in table 3.6 it is assumed that abrasion can be improved by 30%, wheel track formation by 25% and fracturing by 30% between the two alternative roads. Collectively these improvements enhance the lifetime of the road in scenario 2 from 7 to 8.5 years.

3.3 Critical Assumptions

Most assumptions have already been mentioned in the subsection above so the only the most critical ones will be emphasized.
The most critical assumption is the lifetime of the plastic enriched road. The lifetime is based on a number of other assumptions such as; (i) the implementation of the plastic will have no effect on the energy used in the asphalt production, (ii) will not require additional machinery in the construction stage, (iii) will improve road quality as tested in laboratories, (iv) will suit Icelandic climate to the same degree as experienced in warmer climate, (v) the skid resistance will not be affected over time etc. These assumptions however stem from the fact that a plastic road has not been paved in Iceland and the modelling can only be improved by acquiring measured data.
This environmental assessment cannot quantify the effects of excessive use of salt, road paint, the leaching of plastic additives due to degradation nor the effects of microplastics due to abrasion. Microplastics are a severe problem for aquatic ecosystems. However, it can be argued that because of the increased rutting resistance by the addition of plastic in roads there will be less bitumen in the environment. As has been mentioned before, similarly to plastic, bitumen is a secondary product derived from crude oil. Conversely, an increased rolling resistance might increase the wear of tires which are thought to be heavily influential to the amount of microplastics currently in the ocean (Hartmann (2017)). Yet, given that the lifetime of a plastic enriched road would be extended there would be savings in asphalt production and demolition, savings in bitumen produced and aggregate extracted which, on a global scale, could compensate for the increased microplastic generation. Plastic additives and plastic degradation is discussed further in appendix A.
Albeit, there is room for improvement concerning inventory and data collection. (a) Data on the extraction of aggregate in Iceland, (b) fuel production and combustion in construction, use and demolition stages, (c) data on earthwork and road signs, (d) maintenance of road (e) recycling of RAP and (f) data on the specific plastic recycling facility that

handles Icelandic waste plastic are some of those processes. Several other assumptions were made which are show in table B.3 in appendix B.

Chapter 4

Life Cycle Assessment

4.1 Goal and Scope

The goal definition contains six sub chapters which are based on the ISO14040 standards (14040:2006 (2006) and 14044:2006 (2006)). These six aspects are; *Intended application of the study, Method assumptions and impact limitations, Decision context and reason for carrying out the study, Target audience, Comparison intended to be disclosed to the public and Commissioners of the study and other influential actors* (Hauschild et al. (2017)).
The scope definition declares the assessed product system and contains eight aspects; *Deliverables, Function, functional unit and reference flow, LCI modelling framework, System boundaries and completeness requirements, Representativeness of LCI data, Basis for impact Assessment, Requirements for comparative studies and Critical review needs* (Hauschild et al. (2017)).

4.1.1 Goal Definition

Intended Applications

This study aims to make a life cycle analysis from cradle-to-grave of a wearing course constructed in Iceland. Two scenarios will be compared; Sc1 - traditional composition used for the construction of wearing course as well as the current method of disposing residential source separated plastic waste in Iceland and Sc2 - residential source separated plastic waste used as additive in wearing course construction in Iceland. The comparison will therefore illustrate the consequence, on an environmental basis, of using locally sourced plastic waste in road construction in Iceland.
Scenario 2 is theoretical since no road has been paved using plastic waste additives in Iceland. However, there is an abundance of literature investigating the use of plastic waste in road construction which has been discussed in chapter 2 and will be used as validation for assumptions made in the study.

Method Assumptions and Impact Limitations

This study quantifies the consequential life cycle impact of two different types of roads following the EU-recommended practice for characterization modelling. In other words, consequential life cycle impact assesses the impacts that can be expected as a consequence of choosing one alternative over another.
The impacts of individual technologies are not the items of assessment and the upstream impacts of machinery used is neglected. The study is geographically framed to Icelandic conditions and situations and should be applied with caution to other geographical areas. Normalization was done to relate impact scores to European societal activity. Normalisation factors of toxicity related impact categories are thought to be underestimated which results in an overestimation of normalised impact scores for freshwater ecotoxicity and human toxicity.

Decision Context and Reason for Carrying out the LCA study

The results of the study will aid the Road Administration of Iceland (Vegagerðin) in the decision making of whether or not to use waste plastic in road construction. Vegagerðin wishes to improve its economical and environmental sustainability as well as improving road quality and customer service. Vegagerðin's decision will result in structural consequences since it will partly affect plastic recycling in Iceland, energy generation in Sweden and the global market for recycled plastic. Therefore the decision context is situation B (see ILCD guideline Commission (2010)) where multifunctionality will be solved by a mix of long term marginal processes and the LCI modelling framework is consequential.

Target Audience

The design department at Vegagerðin is the target audience of this study. The company uses life cycle concepts and is familiar with LCA.

Comparisons Intended to Be Disclosed to the Public

This consequential LCA study is not intended to be disclosed to the public.

Commissioner of the Study and Other Influential Actors

This study is commissioned by Vegagerðin. The author of the LCA is a student studying environmental engineering at Denmark's Technical University (DTU). Furthermore, the study is done in collaboration with the company ReSource International ehf. and is a part of a master thesis at DTU. ReSource Inernational ehf. is a consultant company specializing in environmental engineering in Iceland.

4.1.2 Scope Definition

Deliverables

The deliverables include a life cycle inventory, a life cycle impact assessment in characterized and normalized form and an interpretation of the results.

Function, Functional Unit, and Reference Flows

Function. The two types of roads are made of different materials with different proportions. The location of the roads should be a high traffic road located in a close proximity of the capital region of Iceland. The location of the two roads are assumed to be identical. Their main function (obligatory property) is to provide a bound surface on which vehicles can drive safely. The safety standard and road markings are set by the road designers at Vegagerðin (Vegagerðin and Gatnamálastofa (2004)).
Positioning properties are also set by Vegagerðin and carried out by asphalt paving companies. Positioning properties are those who are dependent on the desires of the buyer. Those properties are e.g. aggregate size, bitumen hardness, cost, quality and lifetime (see table 4.1).

Table 4.1 Obligatory and positioning properties of roads

Obligatory properties	**Positioning properties**
-Provide a bound surface for vehichles to drive	-Aggregate size, colour and country of origin
-Safety standards	-Bitumen properties and country of origin
-Road markings according to laws	-Eco-friendly
-Withstand traffic load	-Cost
	-Quality
	-Lifetime

Functional Unit. The two roads are compared on the basis of the functional unit: "Provide 1 km of confined and bound asphalt based surface on which vehicles can drive and is durable for a high traffic load every day for 7 years in Iceland. A high traffic load is defined by the Icelandic guidelines on bound asphalt, set by the road administration of Iceland (Vegagerðin (2017)), as >8000 ÁDU, average daily traffic in a year on two lanes."

Reference Flow. A wearing course; 1km long, 6m wide and 4.5 cm thick.

The average lifetime of a wearing course is between 2-14 years in Iceland (Efla (2013)) but in this case the traditional road is assumed to have a lifetime of 7 years. The two types of roads are generally different quality wise which has an effect on lifetime. The quality of roads is based on several parameters as mentioned in chapter 2. Four parameters were chosen and in table 3.6 the aforementioned properties have been given reference numbers that together effect the lifetime. Abrasion is assumed to be improved by 30%, wheel track formation by 25%, fracturing by 30% and lastly surface resistance is assumed to remain unchanged between the two alternative roads. It is assumed that these improvements can enhance the lifetime of the wearing course in scenario 2 from 7 to 8.5 years. This is assumed to give a relatively conservative estimation on the lifespan improvement possibilities of the plastic enriched road compared to what has been found in literature (see basis of the assumptions made in chapter 2). The impact scores of the plastic road will be scaled down for the two alternatives to be comparable from a lifespan perspective, i.e. the environmental emissions of the plastic road is 1 - 1.5 years/ 7 years = 78.6% that of a traditional road.

LCI Modelling Framework

The introduction of the plastic waste in road construction will partly affect structural changes on the market. It would have the effect that part of the plastic waste collected in Iceland would need to be cleaned and pelletized instead of being packaged and sent by ship to Sweden. Moreover, it has an effect on road construction in Iceland. The scale of change made on the plastic waste management and road construction is dependent on the decision makers at Vegagerðin.
Nonetheless, if 8% of plastic waste to the weight of bitumen is added to a 1 km wearing course it gives approximately 2.5 tonnes plastic waste. In 2006 there were 13,034 km of roads in Iceland, 32% of which are bound wearing courses (Vegagerðin (2006)). Which means 10,430 tonnes of plastic waste would accommodate the wearing courses of Iceland in 2006. The source separated plastic waste received at SORPA in 2016 were 900 tonnes (Björnsdóttir (2016)).
Thus, the decision context is macro-level, i.e. situation B in the ILCD Guideline (Commission (2010)), suggesting that the consequential principle is to be chosen as LCI modelling framework. Multifunctionality was solved through system expansion using marginal processes and some through crediting.

System Boundaries and Completeness Requirements

System boundaries. The life cycle analysis includes all life cycle stages of a wearing course from cradle-to-grave and the plastic waste management of Iceland for source separated residential plastic waste from grave-to-cradle. Grave-to-cradle means that the life cycle of plastic waste starts after it has been collected and ends when it has become a new product.
Processes that were included in the life cycle of the wearing course are raw material extractions of aggregate and bitumen which includes mining, drilling, distillation and transportation. The construction stage includes the production and paving of asphalt. The use stage includes snow removal, sweeping, pothole filling, painting and measurements preventing ice-skidding (using salt or gravel). At the end of life the pavement is demolished and transported to storage, until it is 100% recycled (re-used in the sub-bases of a road). For further information see chapter **??**.
Completeness requirements. Although this is not a hotspot analysis, most of the construction, use and recycling stages were included into the assessment because of the different quality and lifetimes of the two road types. Yet some processes were excluded:

- (i) Earthwork needed before wearing course can be laid was excluded.
- (ii) Road signs and other additional work during the construction stage was not included .
- (iii) Road work due to road accidents were not included in the maintenance stage.
- (iv) Capital equipment such as buildings and manual labor waste generation is excluded and therefore the design stage of the road is also excluded.

- (v) The emissions of vehicles related to the use of the road.
- (vi) Microplastics and leaching due to plastic waste could not be quantitatively added into the LCA.
- (vii) The environmental effects of salt and road paint could not be included into the LCA.
- (viii) The re-use of the reclaimed asphalt is assumed to be stored in the road's base layer and is therefore excluded.

Representativeness of LCI Data

Technological representativeness
The LCI data represents the technology currently used for production and construction of roads in Iceland. The technology used in the plastic recycling processes in Sweden is represented by literature values reported by Ren (2012). Other data used in the foreground processes is primarily from the companies; Vegagerðin, Malbikunarstöðin Hlaðbær Colas or - Höfði, SORPA and Swerec AB in Bredaryd.
Data for background processes, such as production of bitumen and properly sized aggregate is represented by the average technology currently used globally. Data from generic databases are thought to be sufficient for these processes.

Geographical representativeness
The geographical representativeness of the energy use was carefully examined as well as the amount of maintenance and service needed due to the extreme weather conditions in Iceland. The marginal energy substituted by the incineration of plastic was geographically framed to Swedish energy system (see table 4.2). Moreover, in the case of using plastic waste in road construction, the pre-processing of the plastic waste would be done using energy from Iceland.

Table 4.2 Geographical scope for life cycle stages in the study of using plastic waste in road construction in Iceland

Stage	**Road type**		**Plastic waste**	
	Traditional	**Plastic waste additives**	**Disposed**	**Pelleted**
Materials	Bitumen: Venezuela - Sweden - Iceland		Plastic waste: Iceland	
	Aggregate: Iceland			
Manufacturing	Asphalt production: Iceland		Pre-processing : Sweden	Iceland
	Earthwork: Iceland		Recycling: Sweden	-
	Road construction: Iceland		Incineration: Sweden	-
Use	Iceland	Iceland	Global	Iceland
Disposal	Iceland	Iceland	Credited: Sweden	-

Temporal representativeness
The development stage of the road was not considered to be important (assumed to be half a year). The manufacturing processes should be representative to the time frame 2018-2023, i.e. 5-year time frame.

The use and recycling stages, on the other hand, should be representative from 2018 to 2032, i.e. about 14 years (see figure 4.1).

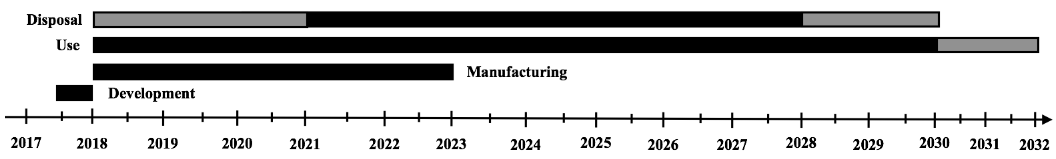

Figure 4.1 Temporal scope of the study. Manufacturing starts in 2018 and continues for 5 years. The use stage is assumed to last 7 years after the end of the manufacturing but could last for 2 years longer (expressed by the grey area). The disposal/demolition stage might start as soon as the manufacturing commences and is assumed to end 2 years after the use stage.

4.1.3 Basis for Impact Assessment

The life cycle impact assessment method includes characterisation modelling recommended by the ILCD (Commission (2010)). All characterisation factors in any life cycle impact assessment (LCIA) method used are associated with uncertainties. These uncertainties are inherent and stem from the differently modelled elementary flows and processes which consequently lead to variable uncertainties across impact categories. However, these uncertainties will be tested by comparing results of two different LCIA method. The life cycle impact assessment method used is ILCD recommended with normalisation factors found by the PROSUITE project conducted by the EU. The impact categories, their units and normalisation factors of the ILCD recommended LCA method can be seen in table B.1 in appendix B.
The modelling was done in EASETECH, and the impact categories "Ionizing radiation", "land use" and "resource depletion, water" were not added to EASETECH although presented in ILCD. The aforementioned impact categories were not implemented because of strong uncertainties, geographical dependence or due to method uncertainties. Moreover, the results from the impact categories "Human toxicity, cancer effects", "Human toxicity, non-cancer effects" and "Ecotoxicity freshwater" should be interpreted with caution because there is still need for improvement in the scientific knowledge about chemical toxicity.

Requirements for Comparative Studies

When a comparative study is to be disclosed to the public the comparison should be fair, i.e. the systems/processes compared should be of the same quality, based on the same quality data. Moreover, if processes are excluded then there should be an identical exclusion in both systems/processes. This comparative study is not intended to be disclosed to the public. However, the case study has been done using the same functional unit, same system boundaries, similar data quality and excluded processes are equally influential to both systems.

Critical Review Needs

Since this study is not intended for public disclosure there is no obligation for an external critical review. However, this study is a master thesis project which will be analyzed by an external examiner.

4.2 Life Cycle Inventory Analysis

4.2.1 LCI Model at System Level

Flow diagrams show the system model flow of the two scenarios (Figures 4.2 and 4.3). When comparing the two flow diagrams it is clear that many processes are the same, e.g. material stages, construction, use and recycling stages. However, the magnitudes of flows are different and because of the adjustments needed to be made in order for the roads to have comparable longevity all of the processes need to be included. It is also evident that the handling and recycling of the plastic waste is the main difference between the two flow diagrams.

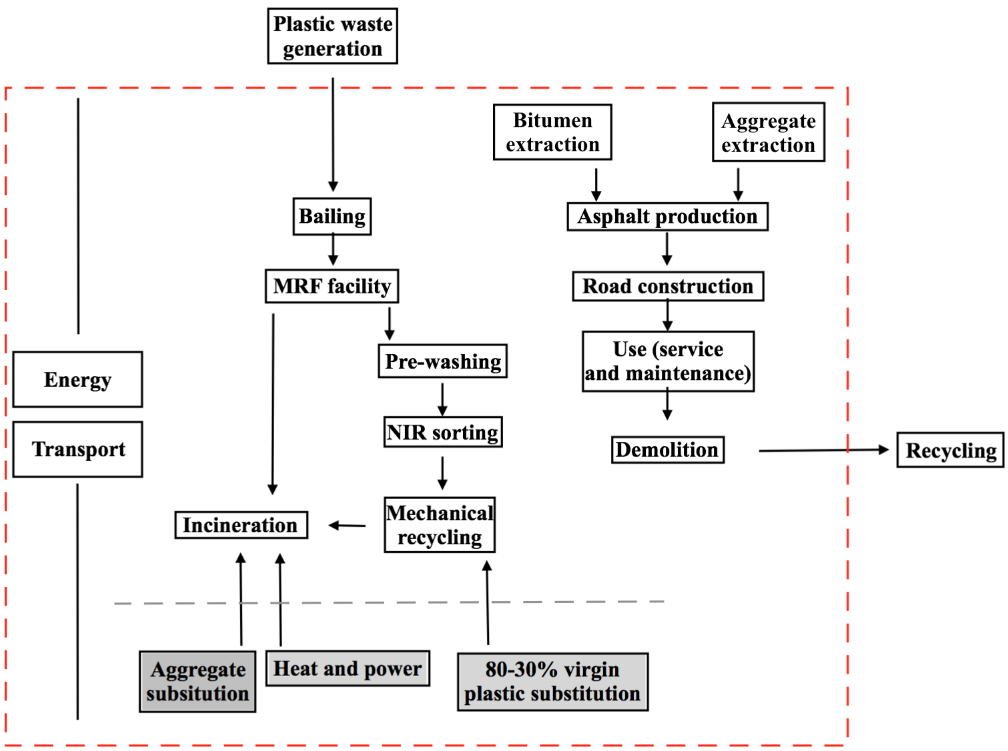

Figure 4.2 System model flow of *Scenario 1* which includes a *Traditional road's life cycle* and the current *Plastic waste management of Iceland* of source separated residual waste which mostly takes place in Sweden. Note that the traditional road has an expected lifetime of 7 years. The red dotted line indicates the system boundaries and below the grey dotted lines are the avoided production of products.

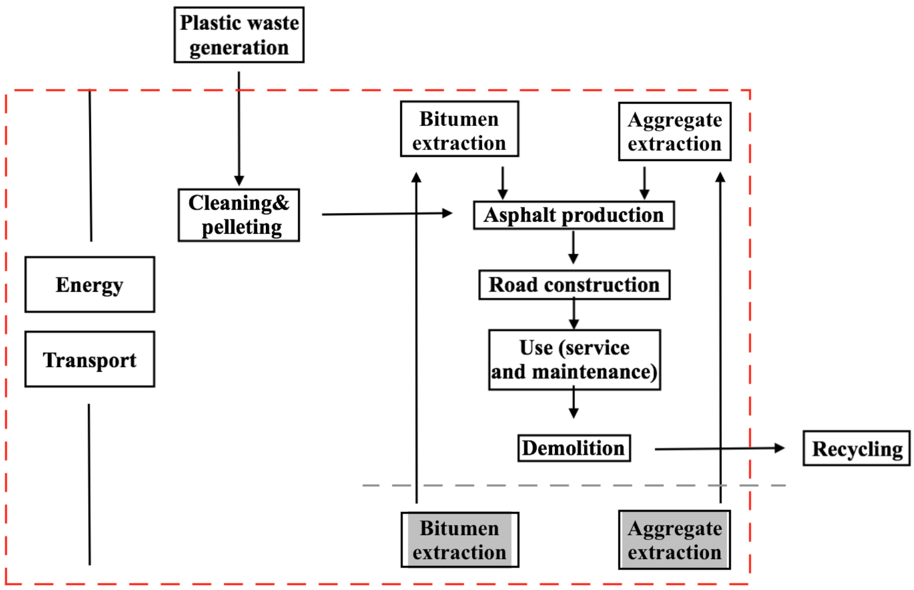

Figure 4.3 System model flow of *Scenario 2* which includes a *Plastic enriched road's life cycle* and the *pre-processing of the plastic waste*. Note that the plastic enriched road has an expected lifetime of 8.5 years. The red dotted line indicates the system boundaries and below the grey dotted lines are the avoided production of products.

Figure 4.4 shows the consequential system model flow. This diagram expresses the differences of the two alternative scenarios. The consequential system flow can therefore be compared to business-as-usual. Business-as-usual expresses if no change were to made to the system. In fig. 4.4 there would be a 100% avoidance of the plastic waste recycling, its energy use, the transportation needed and its virgin material substitution. Moreover, there is a 21.4% avoided impacts of a road's life cycle. This is due to the lifetime difference of the two alternative roads (8.5y - 7y) / 7y = 21.4%. Lastly, there is an added impact due to the pre-processing needed before plastic waste can be added to the asphalt mixture. This process includes cleaning and pelleting of the plastic waste.

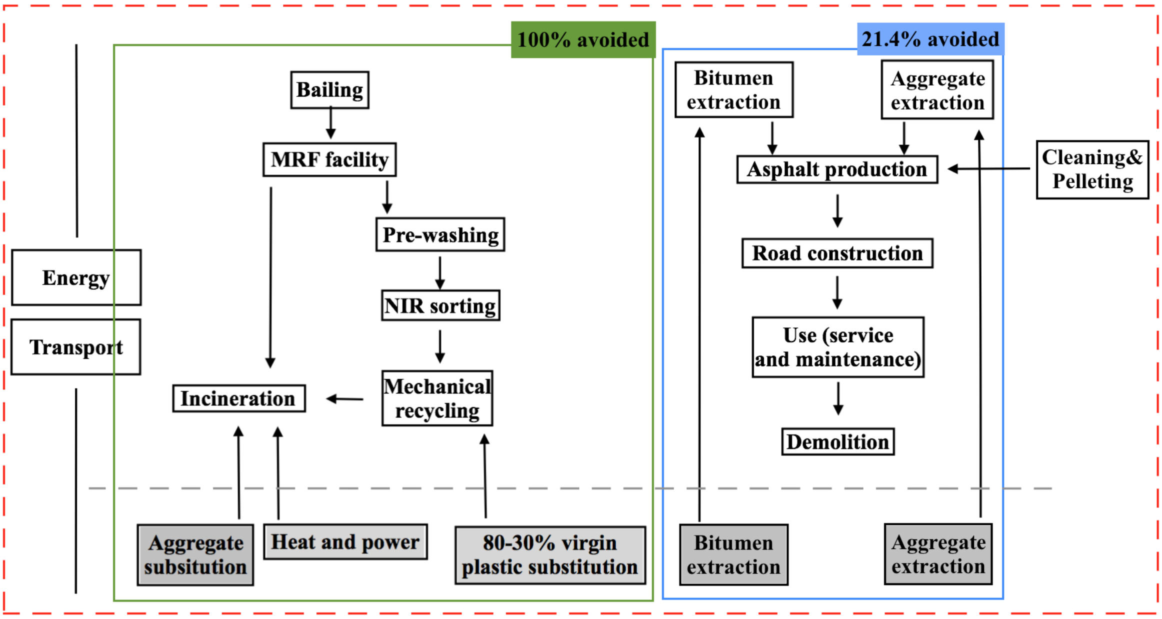

Figure 4.4 Consequential system model flow by adding *Plastic waste additives* in road construction to business-as-usual in Iceland. There is a 100% avoidance of the plastic waste management system including the substitution of virgin material and some energy and transportation. Note that the avoided road life cycle is due to the difference in lifetime of the two alternative roads in the two scenarios. Red dotted line indicates the system boundaries and below the grey dotted lines are the avoided production of virgin material.

Yet, it should be noted that when comparing the two road alternatives there is an exaggerated influence on the results due to the savings in bitumen and aggregate. The amount of bitumen needed in the plastic enriched road was found to be 89.5% of the weight needed for the traditional road and likewise the amount of aggregate was found to be 99.5% of the weight. To explain the exaggerated influence lets imagine that "a" is any process within the life cycle of a road, "x" is the amount of aggregate and "y" is the amount of bitumen:

$$a - 0.786a = 0.214a \tag{4.1}$$

$$x - 0.786 * (0.995x) = 0.218x \tag{4.2}$$

$$y - 0.786 * (0.895y) = 0.296y \tag{4.3}$$

However, what equations 4.1, 4.2 and 4.3 show is considered realistic. The savings in the amount of bitumen and aggregate used has an effect that less amount of material requires less fuel during construction and recycling stages.

4.2.2 Data Collection

Collection of data for the life cycle inventories were mainly from (i) Vegagerðin, who provided primary data about the lifetime, maintenance and service of the roads (ii) Malbikunarstöðin Hlaðbær Colas, who provided primary data related to the production and construction stages of the roads, (iii) SORPA, who provided data on the recycling facility of plastic waste in Sweden and (iv) Ecoinvent database from which aggregate and bitumen extraction processes were retrieved as well as the environmental effects of the energy systems, both in Iceland and Sweden. In addition to this, some data was collected via an internet search at websites of relevant companies or average data found for specific processes. The data collected is organized in appendix B in tables B.5,B.6 and B.7. However, data quality assessment is presented in table 4.4. The data specificity categories (very high – very low) are explained in table 4.3.

Table 4.3 Classification of data specificity categories are inspired by Wenzel et al. (2000)

Very high	Measured directly at specific process site or scaled from measurement
High	Derived from measurements at specific process site via modelling
Medium	LCI database process or data from literature specific to actual process
Low	Generic LCI database process or data from literature
Very low	Judgment by expert or LCA practitioner

The quality assessment category "very high" specificity indicates that the data has been measured directly at specific process site or scaled to fit the system/process which is examined. These quality assessment categories are inspired by Wenzel et al. (2000).

Table 4.4 Data quality assessment of the data used for the two scenarios. This specificity table is inspired by Wenzel et al. (2000)

Process	**Specificity**					**Type**	**Source**	**Access**
	Very high	High	Medium	Low	Very low			
Materials								
Bitumen		x				Amount	Calculated	Functional unit
Aggregate		x				Amount	Calculated	Functional unit
Plastic waste			x			Amount	Publications	Literature
Plastic waste	x					Composition	Measured by company	Email from company
Manufacturing								
Production of bitumen				x		Process	LCI database	Online search
Production aggregate				x		Process	LCI database	Online search
Plastic recycling				x		Process, Emissions, Efficiency	Publications from company	Online search
Plastic Incineration				x		Process, Emissions, Efficiency	Publications	Online search
Production of asphalt	x					Process	Measured by company	Direct dialogue
Paving of asphalt	x					Process	Measured by company	Email
Use								
Maintenance					x	Process, Emissions, Amount	Assumed	Online search
Service	x					Process, Emissions, Amount	Measured by company	Email with company
Disposal				x		Process, Amount	Publications	Online search
Transportation					x	Process, Emissions, Amount	Judgment	Online search and assumptions

The differences in data quality between the two scenarios are mostly related to the low quality data used for the plastic waste management in scenario 1 and the low quality data assumed to be connected to the cleaning and pelleting of plastic waste in scenario 2. However, it is not thought to have a large impact on the overall LCA results since the environmental effects of the road construction is considerably larger in comparison.

4.2.3 System Modelling Per Life Cycle Stage

Information about data collection, treatment and major assumptions is crucial for the interpretation of the results. The data collection is explained in great detail in the Inventory chapter. This sub chapter shortly summerises the information already stated in the Inventory. Additionally, a list of all minor and major assumptions can be found in appendix B in table B.3 and B.4.

Materials stage. The activities required to produce a road is given in appendix B in tables B.5, B.6 and B.7 and the amount of material required for the two alternative roads can be found in appendix B, table B.2. It is assumed that the aggregate is mined in the same fashion as is practiced in Europe and bitumen goes through the same process as is recorded as the average global production (data provided by Ecoinvent). Moreover, the upstream impacts of the plastic waste is cut off. The data shows that there is a difference of 3312 kg of bitumen and 3078 kg of aggregate for one kilometer of road. This is due to the fact that when 2520 kg of plastic waste (8% of weight of bitumen) is added to the road which occupies space in the asphalt mixture.

Manufacturing stage. Data on electricity used in the manufacturing of asphalt and construction of road comes from Hlaðbær Colas and is considered of high quality. The process and electricity used for the recycling of plastic waste in Sweden was adjusted from values reported by Ren (2012). This data is not considered of high quality. The major assumptions made in the manufacturing stage is (i) The mixing of asphalt will be optimum, (ii) Loss of material during production is neglected and (iii) Upstream impact and maintenance of the machinery used in the manufacturing stage is not considered.

Use stage. Data on maintenance and service was given by Vegagerðin and is considered of high quality. Nevertheless, several assumptions were made; (i) Transportation of maintenance to desired location is cut off, (ii) Effects of micro-plastics, road paint and excessive salt on the environment was cut off, (iii) Upstream impacts of road paint and material for pothole filling not considered, (iv) Emissions due to traffic on road is also cut off.

Disposal stage. Demolition of the two road alternatives are assumed to require identical amount of energy and is assumed to be executed with a cold asphalt miller and a dumping truck as reported by Wirtgen (2008). The recovered asphalt is then assumed to be transported 52 km to storage. The disposal strategy used in Iceland is to re-use the RAP in one of the sub layers (other than wearing course) of a new road. However, construction waste in Iceland seems to be an untapped resource and therefore the RAP could be used as a filler elsewhere. Because it was not clear if the reclaimed asphalt was re-used or landfilled it was decided that it would be defined as storage.

Transportation. Transportation distances are assumed in most cases and are considered uncertain. All distances between countries were calculated in aerial distances and the transportation between countries was assumed to be via ship. The age of the machinery and their standards relating to emissions was not accounted for.

4.2.4 Basis for Sensitivity and Uncertainty Analysis

Sensitivity analysis is made to see how assumptions influence the results of the LCA. In addition, an uncertainty and variability analysis was made.

Basis for perturbation analysis
Sensitivity Ratios (SR) were calculated for a variety of parameters to identify which were the most influential for the results of the LCA. The equation for SR is as follows 4.4:

$$SR = \frac{\frac{\Delta Result}{Initial Result}}{\frac{\Delta Parameter}{Initial Parameter}} \tag{4.4}$$

There is a limitation to the SR which is when the overall results are close to zero. This limitation refers to the mathematical problem of eq. 4.4 (this limitation was not encountered in this study). A parameter is considered to have a medium or large sensitivity if either one of the following statements are fulfilled (see equations 4.5 and 4.6):

$$Max|SR| \geq 0.3 \tag{4.5}$$

$$Max|SR| \geq 0.5 \tag{4.6}$$

The Sensitivity Coefficient (SC), on the other hand, is an important element of estimating measurement uncertainty and is used to convert uncertainty components to units of measure and magnitude relative to the uncertainty analysis. SC has the following equation 4.7:

$$SC = \frac{\Delta Result}{\Delta Parameter} \tag{4.7}$$

By finding the most influential parameters in the perturbation analysis the most critical assumptions can also be found. Due to the complexity of the system however, there are countless parameters that could be tested. Based on the contribution analysis, the following parameters were chosen for testing. The parameters tested were: the lifetime improvement of the plastic enriched wearing course, amounts of bitumen, aggregate and plastic waste, the efficiecies of the extraction of bitumen and aggregate, the fuel used in the construction and use stages, the transportation distance of bitumen to Iceland, the substitution percentages of the plastic waste to virgin plastic and the electricity use of cleaning and pelleting of plastic waste. All input parameters were perturbed by 10%. If a SR = 1 it means that a 10% increase of a parameter results in a 10% increase in the relevant impact score.

Basis for scenario analysis

A separate sensitivity check was performed where two parameters were changed at once. This is called a scenario analysis. These should not be mixed with the names of scenarios 1 and 2 and therefore they are called Scenario A1, B1 and C1 and Scenario A2, B2 and C2 (1 indicating scenario 1 and 2 indicating scenario 2). An overview of the scenarios is given in table 4.5.

In the analysis of scenario A the goal is to show the results of the study if the amount of bitumen and aggregate were not reduced by the addition of plastic in the asphalt. This scenario is expected to lower the difference in impact scores between the two scenarios.

Scenario B was made by changing the source of energy used for the plastic waste management system in Sweden and the electricity acquired from the incineration of plastic was credited for another type of electricity. In this scenario the energy used for MRF, pre-washing, NIR sorting and mechanical recycling was hydro power produced in Sweden. Additionally, the electricity generated in the waste-to-energy plant was credited for electricity produced burning hard coal in Sweden. Although the type of energy used is often highly influential in LCA results, in this case it is not assumed to have a large impact do to the results of the contribution analysis.

Scenario C was made to see the difference in ranking between the two scenarios compared to the base scenario due to LCIA method used. The ReCiPe impact method is used in Scenario C to calculate the results of the LCA. The specific impact method used is ReCiPe v.1.11, Midpoint (H) Hierarchist, Europe without long-term emissions. The impact categories presented by ReCiPe are; Climate change, Ozone depletion, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial eco-toxicity, Freshwater eco-toxicity, Marine eco-toxicity, Ionising radiation, Metal depletion and Fossil depletion. The impact categories, units and normalistaion factors of the ReCiPe LCIA method can be seen in table B.12 in appendix B, section Scenario analysis.

Table 4.5 Scenarios analyzed and corresponding model parameter changes from baseline scenario. In the LCIA methods w/o LT means without long-term emissions.

Sensitivity parameters	Baseline scenario		Sensitivity scenario					
			Scenario A		Scenario B		Scenario C	
	Sc 1	Sc 2	Sc A1	Sc A2	Sc B1	Sc B2	Sc C1	Sc C2
Bitumen [kg] Aggregate [kg]	3.2E+04 6.0E+05	2.8E+04 6.0E+05	3.2E+04 6.0E+05	3.2E+04 6.0E+05				
Electricity Sweden Heat substitution	Nuclear Natural gas	- -			Hydro Hard Coal	- -		
LCIA methodology	ILCD recommended, Global w/o LT						ReCiPe hierarchist Europe w/o LT	

Basis for uncertainty and variability analysis

In an analysis like this, the result will always contain some variance. The variance is either due to the parameter uncertainties or by the inherent variance of by unexpected occurrences. With less variance it is easier to make predictions to the actual results and therefore it will be easier to make valuable recommendations. The parameter uncertainty and variability was assessed by using a Monte Carlo simulation. Only parameters that were found to be important were assessed (medium to high sensitivity according to equations 4.5 and 4.6). Six parameters were considered. The amounts of material were assumed not to vary considerably, which is based on the quality of the data, and therefore it was estimated that the actual value would be within a 5% range of the default value. The lifetime of the plastic enriched road, efficiencies of the extraction processes and fuel consumption parameters were assumed to be within a 10% range of the default which was also estimated from the data quality, see table 4.6. These percentages of deviance from the default values should be considered when analyzing the Monte Carlo results.

Table 4.6 Uncertain or variable parameters and their relative standard deviation of 5 or 10% used for the Monte Carlo simulations

Uncertain or variable parameter	Mean (relative standard deviation)		Unit
	Scenario 1	Scenario 2	
Lifetime	1 (0%)	0.786 (10%)	fraction of a 7 year lifetime
Amount of bitumen	31.7 (5%)	28.4 (5%)	tonnes
Amount of aggregate	601.5 (5%)	598.4 (5%)	tonnes
Bitumen extraction	1 (10%)	1 (10%)	process efficiency
Aggregate extraction	1 (10%)	1 (10%)	process efficiency
Fuel in use stage	0.00962 (10%)	0.00962 (10%)	kWh

It was assumed that all parameters follow a normal distribution pattern. Differences in impact scores were considered significant if the ranges of the impact scores from 10 thousand iterations did not overlap.

4.2.5 Calculated LCI Results

The calculated LCI results can be seen in table B.5 in appendix B.

4.3 Life Cycle Impact Assessment

Characterised results

The characterised impact scores of all impact categories are listed in table 4.7. The two scenarios give positive impact scores of the same order of magnitude which is expected and scenario 2 has lower environmental impacts in all impact categories.

Table 4.7 Characterised impact scores for the 14 impact categories represented by the ILCD recommended LCA method. Red indicates a higher impact score of the two scenarios.

Impact category	Unit	Scenario 1	Scenario 2
Climate change	kg CO2-Eq	7.13E+04	5.56E+04
Ozone depletion	kg CFC-11 Eq	2.29E-02	1.63E-02
Human toxicity, ce	CTUh	2.73E-04	2.14E-04
Human toxicity, nce	CTUh	1.37E-02	1.04E-02
Particulate matter	kgPM2.5-eq	3.26E+01	2.48E+01
Ionising radiation human health	kBq U235 eq	7.44E+03	5.35E+03
Photochemical ozone formation	kg NMVOC	6.73E+02	5.14E+02
Terrestrial acidification	mol H+ eq	6.41E+02	4.83E+02
Eutrophication Terrestrial	mol N eq	2.21E+03	1.70E+03
Eutrophication Freshwater	kg P eq	5.31E-01	4.13E-01
Eutrophication Marine	kg N eq	1.97E+02	1.52E+02
Ecotoxicity freshwater	CTUe	2.18E+04	1.66E+04
Depletion of abiotic resources, fossil	kg Sb eq	2.38E+06	1.79E+06
Depletion of abiotic resources, elements	kg antimony-eq	1.00E+00	7.71E-01

Table 4.7 portrays that scenario 2 has less negative environmental impact compared to scenario 1. Interestingly, scenario 2 has a lower impact score in the impact category "Depletion of abiotic resources, fossil & elements" which implies that the savings in aggregate and bitumen in scenario 2 has more influence than the savings in plastic production due to the recycling of plastic waste.

Normalised results

The normalised impact scores can be seen in figure 4.5. Similarly to the characterised impact scores, scenario 2 has lower impact scores in all impact categories. The unit in which normalised impact scores are presented is personal equivalents (PE). The impact scores are derived from the characterised results and scaled to normalisation factors that represent the annual impact of an average person in the European Union (EU27) in 2010 (see normalisation factors in table B.1 in appendix B). In other words, the value 1 PE is equivalent to the yearly environmental emissions of one average person in the EU within that impact category. The highest impact scores are found in the impact categories "Depletion of abiotic resources, fossil and elements", "Ecotoxicity freshwater", "Eutrophication Terrestrial" and "Eutrophication Marine".

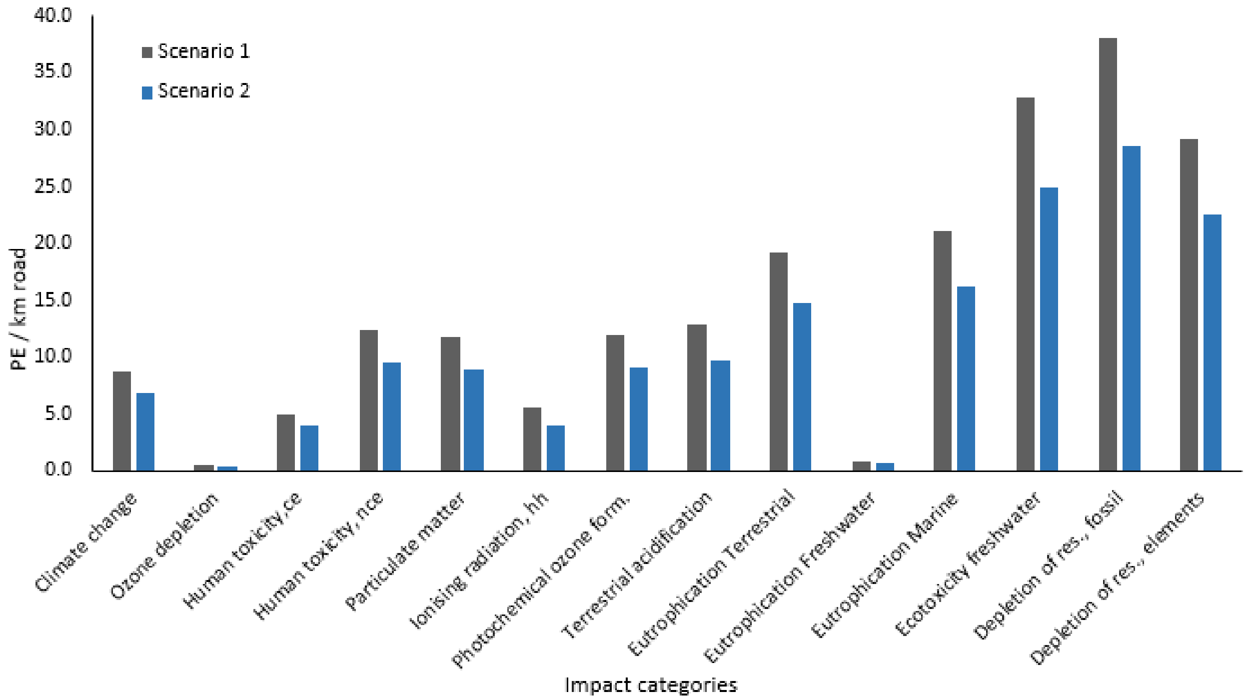

Figure 4.5 Normalised impacts scores in PE for the two scenarios, 7 years of operation

Figure 4.5 shows that scenario 2 has less negative environmental impact in every impact category. It is important to keep in mind that these results represent a 7 year lifetime of a 1 km of each road which is divided by an normalisation factor of PE/year and therefore the impacts seem to be high.

4.3.1 Interpretation

In order to provide final recommendations it is necessary to interpret the results of the LCA.

Process contribution of the two scenarios are identical because the processes bitumen extraction, aggregate extraction, construction, use and recycling stage make up 98-100% of the impacts in each category. Of course the process contributions of scenario 2 is not exactly the same as scenario 1 but it is not easily detectable from a figure. Therefore, it was deemed unnecessary to showcase both process contributions. Process contributions can be seen in figure 4.6.

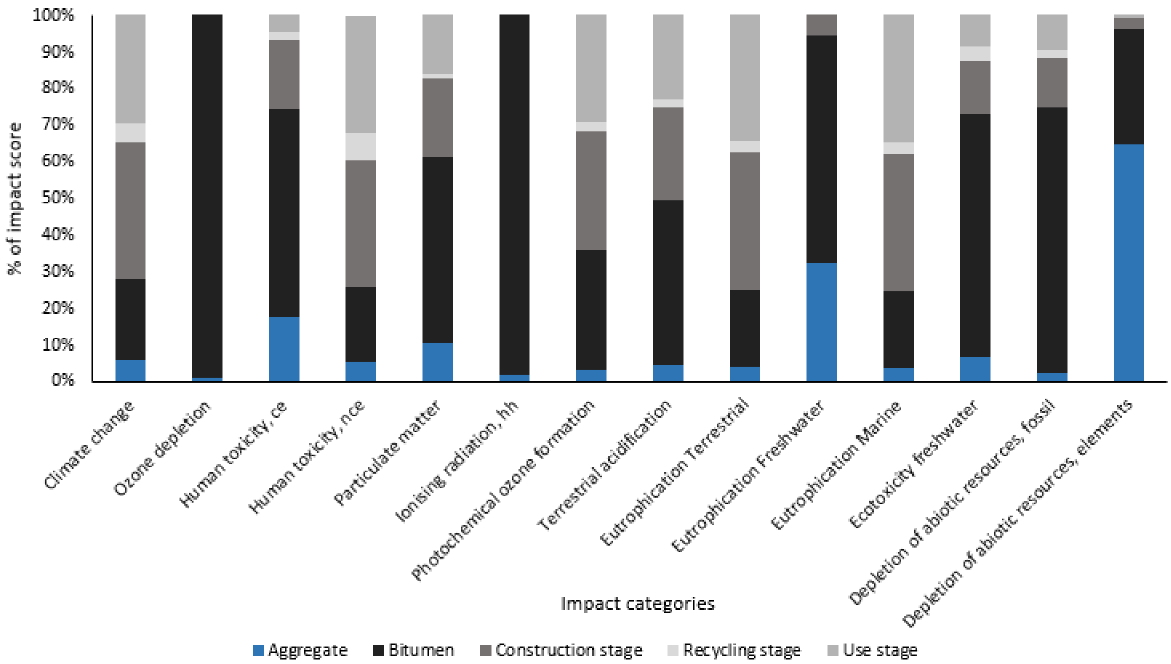

Figure 4.6 Process contributions of the impact scores within each impact category.

The process bitumen extraction includes the production of bitumen and transport via ship and truck. Aggregate extraction includes the transportation of aggregate. Construction- and use stage include use of electricity and the production and combustion of fuel. The recycling stage has negative environmental impacts since it only includes the fuel consumption of demolition and transportation to storage. The impacts of the recycling stage could be reversed in the case if reclaimed asphalt pavement (RAP) was crediting for aggregate extraction.
Figure 4.6 shows that bitumen extraction is the main driver of the environmental impacts in seven of the impact categories (Ozone depletion, Human toxicity (cancer effects), Particulate matter formation, Ionizing radiation (human health), Euthrophication freshwater, Ecotoxicity freshwater and Depletion of abiotic resources, fossil). Construction- and use stages have environmental impact in similar places which is expected since electricity and fuel consumption are the processes included in both stages. Lastly, the aggregate extraction has the largest impact on the depletion of elements which could also have been foreseen.

However, since the purpose is to compare the different scenarios it is important to investigate the non-identical processes in the scenarios. The processes that are different include the transportation, recycling and incineration of plastic waste in scenario 1, a 22% savings in impact scores due to lifetime differences of the two alternative roads and, finally, the cleaning and pelleting processes of plastic waste before it is used as additive in roads. Table 4.8 shows the summed characterised impact scores of aforementioned processes.

Table 4.8 Investigation of the characterised impact scores of the non-identical processes of the two scenarios. Column Plastic waste; SE refers to the bailing, shipping, recycling and incineration of plastic waste in Sweden. Column 21.4% of road impacts refers to the savings in impacts scores due to the increased lifespan of road alternative in sc2. Column Cleaning&pelleting refers to the impacts of the energy used to cleaning and pelleting plastic waste before it is used in road alternative in Scenario 2. Finally, "Cleaning&pelleting"-"21.4% of road impacts"-"Plastic waste; SE"="Difference".

Impact category	**Unit**	**Plastic waste; SE**	**21.4% of road impacts**	**Cleaning& pelleting**	**Difference**
Climate change	kg CO2-Eq	-1.3E+03	1.7E+04	5.0E+01	-1.6E+04
Ozone depletion	kg CFC-11 Eq	-2.0E-04	6.9E-03	4.7E-07	-6.7E-03
Human toxicity,ce	CTUh	-1.6E-05	7.5E-05	4.2E-07	-5.9E-05
Human toxicity, nce	CTUh	3.8E-05	3.2E-03	7.5E-07	-3.2E-03
Particulate matter	kgPM2.5-eq	-8.5E-01	8.6E+00	9.9E-03	-7.8E+00
Ionising radiation, hh	kBq U235 eq	-1.4E+02	2.2E+03	1.8E-01	-2.1E+03
Photochemical ozone form.	kg NMVOC	-6.7E+00	1.7E+02	2.5E-02	-1.6E+02
Terrestrial acidification	mol H+ eq	-5.9E+00	1.6E+02	2.3E-02	-1.6E+02
Eutrophication Terrestrial	mol N eq	-8.8E+00	5.2E+02	7.6E-02	-5.1E+02
Eutrophication Freshwater	kg P eq	-2.9E-02	1.5E-01	4.4E-04	-1.2E-01
Eutrophication Marine	kg N eq	-8.9E-01	4.6E+01	6.5E-03	-4.6E+01
Ecotoxicity freshwater	CTUe	-8.6E+02	6.1E+03	7.5E+00	-5.2E+03
Fossil depletion	kg Sb eq	-8.0E+04	6.7E+05	9.9E+01	-5.9E+05
Elements depletion	kg antimony-eq	-1.3E-02	2.5E-01	2.5E-04	-2.3E-01

The column "Difference" in table 4.8 is refers to the savings in characterised impact scores if scenario 2 was chosen over scenario 1. These savings are also shown in figure 4.7 in normalised form. The impact scores are negative to indicate that these values would be subtracted from the impact scores of Scenario 1 if Scenario 2 would be chosen.

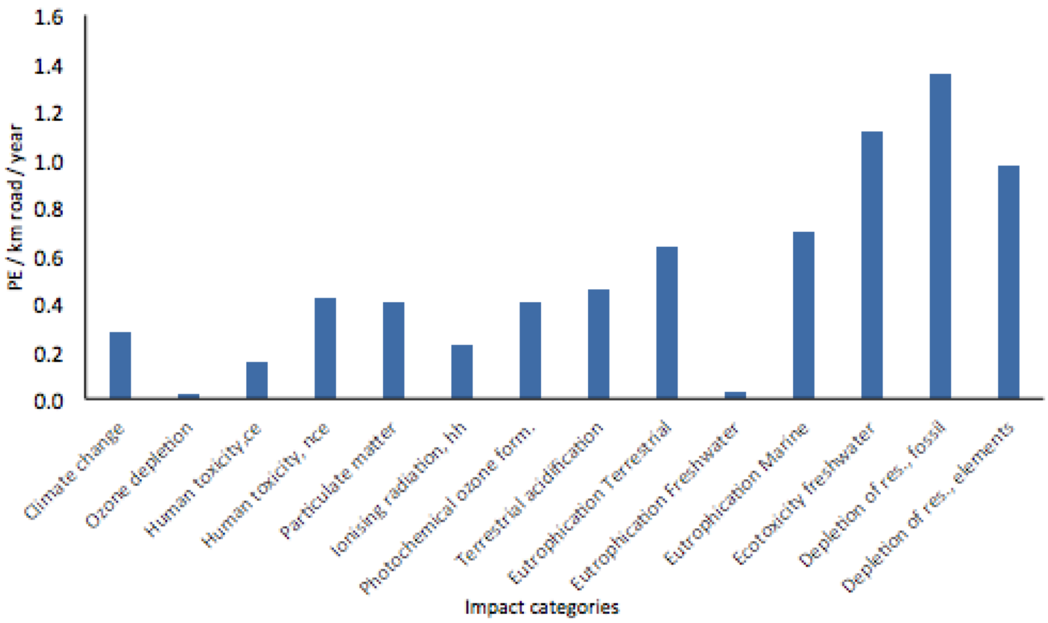

Figure 4.7 Investigation of the normalised impact scores of the non-identical processes of the two scenarios. Savings in PE by choosing to build roads with plastic waste additives shown for each impact category for each year of operation

Figure 4.7 illustrates that building roads with plastic waste additives in Iceland would greatly reduce environmental impacts, especially those related to the depletion of abiotic resources, ecotoxicity of freshwater and euthrophication of the sea and terrain. Furthermore, it was calculated that in order for there to be no savings in PE scores, the lifetime of the plastic road would have to be in the range of 6.5 to 6.8 years.

4.3.2 Sensitivity and uncertainty analysis

The assumptions made during the modelling of the two scenarios have influenced the results of the LCA. The extent of the influence will be determined by investigating result sensitivity due to data collection and quality, individual parameter change and multiple parameters change.
Sensitivity and uncertainty was analysed by performing a perturbation analysis, scenario sensitivity and uncertainty propagation. In the perturbation analysis, sensitivity ratios were calculated for different parameters (see figure 4.8). In the scenario sensitivity, three scenarios were built and compared to the baseline scenario (see figures 4.5 and 4.10 and table 4.9). Finally, in the uncertainty propagation, a Monte Carlo simulation was performed on sensitive parameters according to the perturbation analysis (see table 4.6).

Perturbation analysis
The aim of a perturbation analysis is to find the parameter that has the most influence on each scenario. From the process contribution analysis it is evident that the most influential processes to the results are bitumen, aggregate, construction- and use stage. Therefore, a perturbation analysis was performed on parameters concerning: amount and production efficiencies of bitumen and aggregate, amount and substitution efficiencies of

plastic, diesel use of machinery during construction- and use stage, electricity used during cleaning and pelleting and transoceanic transportation distances.
The results of the perturbation analysis can be found in table B.8, B.9 in appendix B. The most sensitive parameters for both scenarios were found to be the amount of bitumen and aggregate (BitAmount and AggrAmount) and the efficiencies of the bitumen and aggregate extraction (BitEff and AggrEff). This could be expected since the extraction of bitumen and aggregate were found to be heavily influential to the results (see figure 4.6) and the construction and use stages' fuel consumption are dependent on the amount that will be handled.

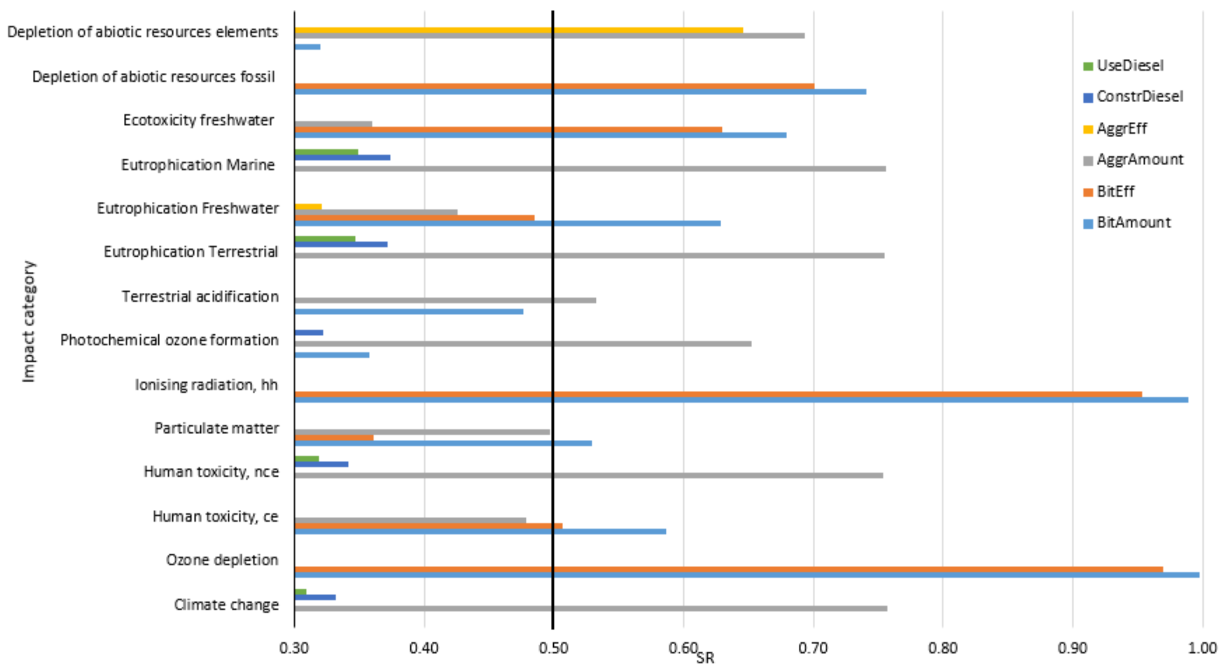

Figure 4.8 Sensitivity ratios of the most sensitive parameters plotted, scenario 1. Notice that the x-axis starts at SR = 0.3. All parameters represented by bars surpassing the black line are considered to have high sensitivity.

From figure 4.8 it is evident that two parameters have a medium sensitivity (ConstrDiesel and UseDiesel) and four have a high sensitivity (BitAmount, BitEff, AggrAmount, AggrEff). The sensitivity of bitumen amount and efficiecy is especially high, since a 10% increase in parameter values almost results in a 10% increase in impact scores for the impact categories "Ionising radioation human health" and "Ozone depletion". Of those two, the amount of bitumen has a high sensitivity in more impact categories. This is explained by the fact that BitEff only has an effect on the amount extracted of bitumen but BitAmount has an effect on the extraction of bitumen as well as the amount of fuel burnt in construction and use stages of the road. The same explanation can be used about the difference between AggrEff and AggrAmount. The impact categories "Depletion of abiotic resources, elements", "Eutrophication Marine", "Eutrophication Terrestrial", "Terrestrial acidification", Photochemical ozone formation", "Human toxicity (non-cancer effects)" and "Climate change" are all heavily influenced by the amount

of aggregate used. Together, the four high sensitive parameters influence all 14 impact categories.
Fuel consumption of the construction and use stage are found to have a medium sensitivity on 5 out of 14 impact categories. The results from scenario 2 are strikingly similar. Hence, figure 4.8 and tables B.10 and B.11 in appendix B are thought to be sufficient for its interpretation. The environmental savings connected to the difference of impact scores between the two scenarios are consequently affected to the same order of magnitude as shown in figure 4.8.
The amount of plastic used, the percentage of virgin plastic credited for, the electricity used for the cleaning and pelleting of plastic waste and transportation distances were shown to have low sensitivity.
Considering the data quality connected to these sensitivity results, there are improvements to be made on the robustness of the results by gathering information on the bitumen extraction efficiency and maintenance of the use stage. The perturbation analysis shows that there is considerable amount of bias connected to the results of the study.

Scenario analysis

The scenarios A, B and C were analyzed and compared to the baseline scenario. The results are presented in normalised form for each impact category (see table 4.9).

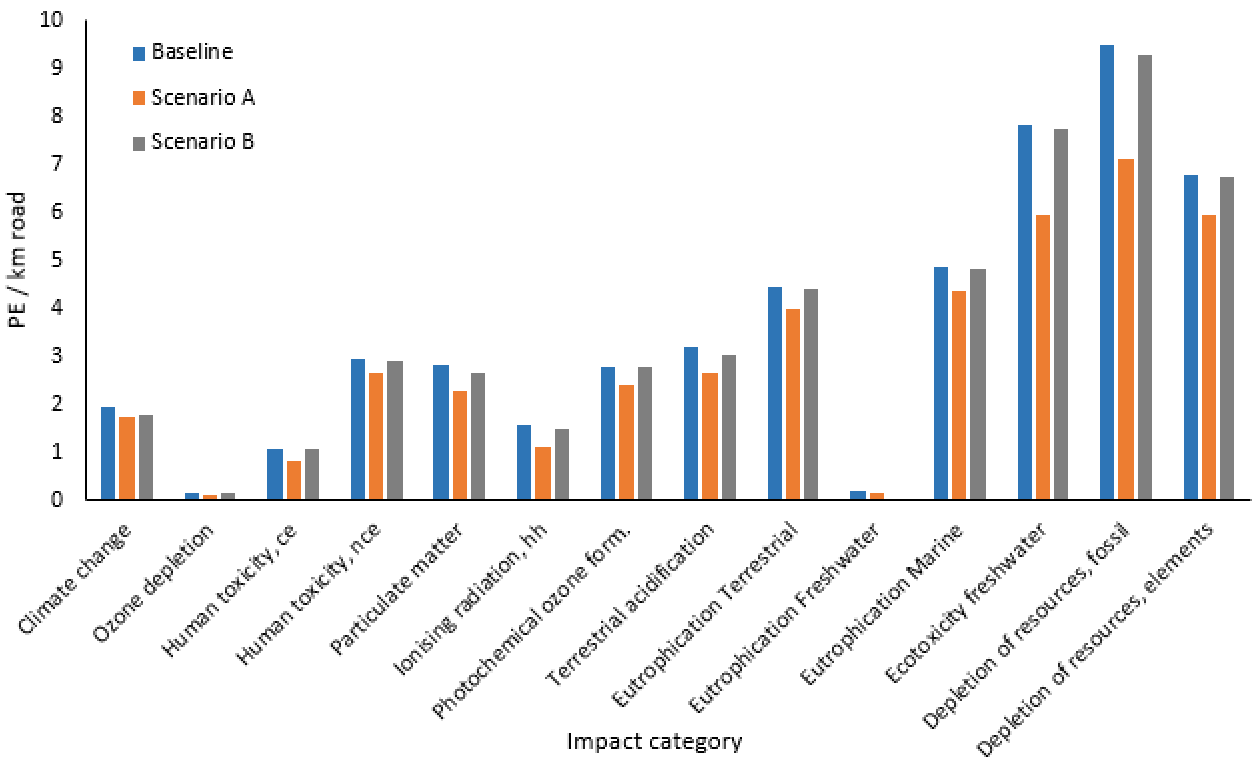

Figure 4.9 Sensitivity analysis of the consequential savings by choosing to build plastic enhanced roads over traditional roads in Iceland shown in normalised form. Scenario A represents if there were no savings in the amount of bitumen and aggregate with the addition of plastic in asphalt. Scenario B was made by changing the power source used in the plastic recycling and the source of the heat credited for in the incineration process of plastic waste. Scenarios A and B are compared to the baseline scenario for 7 years of operation.

Scenario A has lower savings in all impact categories compared to the baseline scenario and scenario B. This could be expected since, as has been shown in the perturbation analysis, the amount of bitumen and aggregate are highly sensitive parameters to the results. Nonetheless, it is clear that there are savings connected to every impact category. In Scenario B, small changes are observed in each impact category compared to the baseline scenario, all of which lower the consequential savings of choosing to build roads enhanced with plastic waste. However, these changes are not heavily influential to the final outcome of the LCA.

Scenario C could not be illustrated in the same figure as scenarios A and B because of the different impact categories presented by the ReCiPe LCIA method. The results of scenario C are shown in characterised form in table 4.9 and normalised form. The normalised results shown are the consequential savings due to choosing to build plastic enriched roads compared to business-as-usual, see figure 4.10.

Table 4.9 Characterised impact scores and their units using the ReCiPe LCIA method. Note that the impact categories and their units are different than those represented by the LCIA method recommended by the ILCD.

Impact category	Unit	Scenario 1	Scenario 2	Difference
Climate change	kg CO2 eq	7.13E+04	5.56E+04	-1.58E+04
Ozone depletion	kg CFC-11-Eq	2.29E-02	1.63E-02	-6.63E-03
Terrestrial acidification	kg SO2-Eq	4.88E+02	3.68E+02	-1.20E+02
Freshwater eutrophication	kg P-Eq	5.31E-01	4.13E-01	-1.18E-01
Marine eutrophication	kg N-Eq	2.32E+01	1.78E+01	-5.34E+00
Human toxicity	kg 1,4-DB eq	5.39E+03	3.94E+03	-1.45E+03
Photochemical oxidant form.	kg NMVOC	6.73E+02	5.14E+02	-1.58E+02
Particulate matter formation	kg PM10-Eq	1.71E+02	1.31E+02	-4.09E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	3.44E+01	2.39E+01	-1.05E+01
Freshwater ecotoxicity	kg 1,4-DB eq	6.15E+01	4.50E+01	-1.65E+01
Marine ecotoxicity	kg 1,4-DB eq	6.77E+01	4.96E+01	-1.81E+01
Ionising radiation	kg U235-Eq	7.43E+03	5.35E+03	-2.08E+03
Water depletion	m3	4.71E+05	3.77E+05	-9.43E+04
Metal depletion	kg Fe eq	1.98E+03	1.46E+03	-5.17E+02
Fossil depletion	kg oil eq	5.83E+04	4.36E+04	-1.47E+04

Similarly to results obtained by the ILCD LICA method, the characterised results of the ReCiPe LCIA method show savings in every impact category. However, there is a shift in focus, partly due to the differences in how the environmental emissions are categorized into impact categories and partly due to the differences in normalisation factors. Lastly, in some cases it is not possible to compare the results to the ILCD results due to the difference in units. All characterisation factors in any LCIA method are associated with uncertainties. These uncertainties are inherent and stem from the differently modelled elementary flows and processes which consequently lead to variable uncertainties across impact categories. These uncertainties are rarely known but they are expected to be of statistical significance for ecotoxicity and human toxicity impact scores. The elementary flows connected to climate change, acidifying and eutophying impact categories however, are similar between different impact assessment methods.

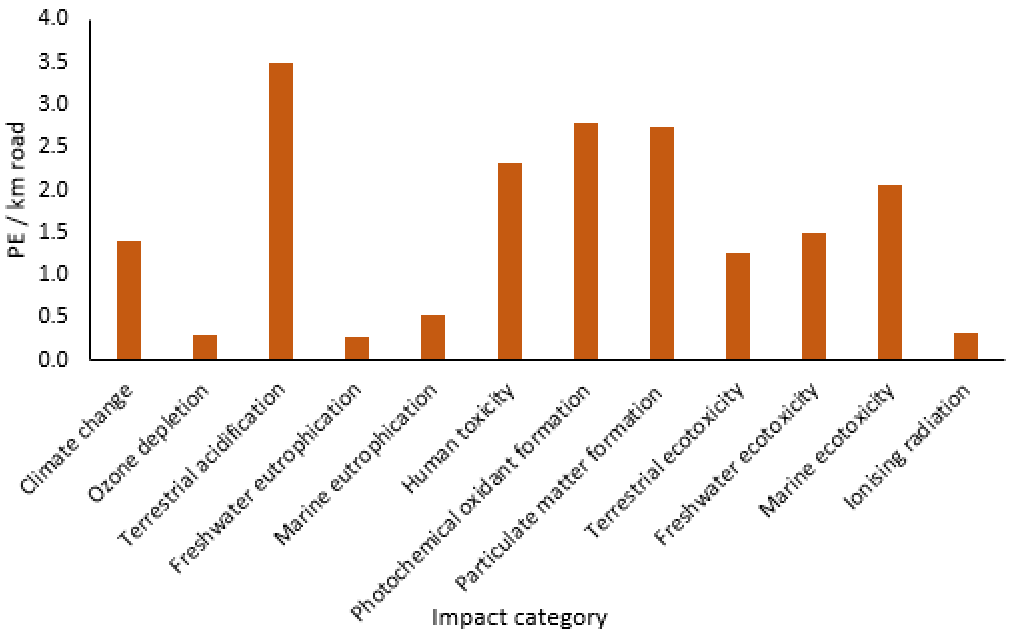

Figure 4.10 Normalised results for 7 years of operation; the consequential savings due to choosing to build locally derived plastic waste enriched roads compared to business-as-usual.

As can be seen from figure 4.10 there are savings connected to each impact category, yet there is a shift of focus and scale compared to the results of the ILCD method. These results emphasize the impacts of terrestrial acidification and do not show normalised results of water, fossil and elements depletion. Moreover, the ReCiPe LCIA method has low impact related to marine eutrophication.

Table 4.10 Normalisation factors of impact categories that have the same unit of two LCIA methods; ReCiPe Midpoint (H) Hierarchist and ILCD recommended method from 2013, PROSUITE project.

Impact categories	Unit	ReCiPe Midpoint (H) Hierarchist	ILCD recommended 2013
Climate change	kg CO2 eq/p/yr	1.12E+04	8.10E+03
Ozone depletion	kg CFC-11 eq/p/yr	2.20E-02	4.14E-02
Photochemical oxidant formation	kg NMVOC/p/yr	5.68E+01	5.67E+01
Freshwater eutrophication	kg P eq/p/yr	4.15E-01	6.20E-01
Marine eutrophication	kg N eq/p/yr	1.01E+01	9.38E+00

Table 4.10 illustrates the normalisation factors of the two impact methods which have the same units. The difference between the normalisation factors partly explains the differences in impact results found in figure 4.10 compared to the baseline scenario.
The scenario analysis shows that there are consequential savings connected to changing the mix of asphalt for every impact category, even though: (A) there would be no savings in the amount of bitumen and aggregate needed for a 1 km road, (B) the power sources of the Swedish energy systems are changed and (C) another LCIA method is chosen.

Uncertainty propagation

The uncertainty propagation was investigated using a Monte Carlo simulation. The parameters included were the lifetime change of the plastic enriched road, amount of bitumen and aggregate, the extraction efficiencies of bitumen and aggregate and the fuel consumption of the use stage (default values and relative standard deviations can be seen in table 4.6). The results; average values and their standard deviations can be seen in table 4.11.

Table 4.11 Results obtained from a Monte Carlo simulation. Average impact scores and their standard deviations are shown for all impact categories of scenarios 1 and 2

Impact category	**Unit**	**Scenario 1**		**Scenario 2**	
		Mean	**SD**	**Mean**	**SD**
Climate change	kg CO2-Eq	7.12E+04	1.37E+03	5.42E+04	1.40E+03
Ozone depletion	kg CFC-11 Eq	2.37E-02	2.07E-03	1.59E-02	1.53E-03
Human toxicity, ce	CTUh	2.80E-04	8.51E-06	2.10E-04	8.41E-06
Human toxicity, nce	CTUh	1.37E-02	2.52E-04	1.02E-02	2.72E-04
Particulate matter	kgPM2.5-eq	3.30E+01	6.18E-01	2.44E+01	7.76E-01
Ionising radiation, hh	kBq U235 eq	7.70E+03	6.54E+02	5.21E+03	4.88E+02
Photochemical ozone form.	kg NMVOC	6.73E+02	9.68E+00	5.02E+02	1.34E+01
Terrestrial acidification	mol H+ eq	6.44E+02	8.98E+00	4.73E+02	1.34E+01
Eutrophication Terrestrial	mol N eq	2.20E+03	5.07E+01	1.66E+03	4.85E+01
Eutrophication Freshwater	kg P eq	5.50E-01	1.77E-02	4.09E-01	1.87E-02
Eutrophication Marine	kg N eq	1.96E+02	4.56E+00	1.48E+02	4.35E+00
Ecotoxicity freshwater	CTUe	2.23E+04	1.01E+03	1.62E+04	8.41E+02
Fossil depletion	kg Sb eq	2.43E+06	1.32E+05	1.74E+06	1.05E+05
Elements depletion	kg antimony-eq	1.05E+00	4.07E-02	7.72E-01	3.25E-02

Three impact categories were chosen for representation on the basis that they had relatively the highest standard deviations. These impact categories are; "Ozone depletion", "Ionising radiation (human health)" and "Fossil depletion" and can be seen in figures B.2, B.6 and B.13. The columns represent the average value and the error bars represent two standard deviations. Since we assume that all parameters follow a normal distribution, 95% of the time the impact scores will be within the range of the error bars.

To examine what seem to be the crossing of error bars for Ozone depletion and Ionising radiation (human health) impact categories, probability distribution and cumulative distribution (figures 4.12 and 4.13) graphs were generated for these impact categories. The data used for the graphs were generated through the Monte Carlo simulation using parameters that were most influential to the respective impact category which were found by the perturbation analysis.

The most sensitive parameter (found by the perturbation analysis) is the lifetime of the plastic enriched road. Consequently, a separate Monte Carlo simulation was run using the same parameters and parameter variance where probability and cumulative distributions were made if there would be no lifetime improvement of the plastic enriched road. These graphs can be seen in appendix B and will not be discussed further in this section.

Unintentionally, the same two parameters had the most influence on both categories, namely bitumen amount and bitumen extraction process efficiency. For the sake of sim-

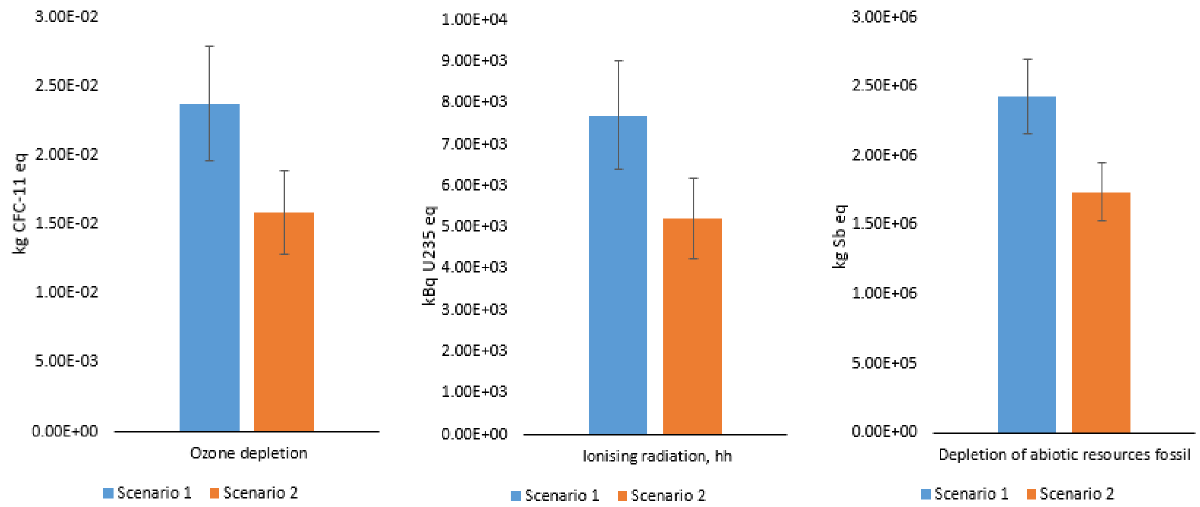

Figure 4.11 Monte Carlo sensitivity for Ozone depletion, Ionising radiation (human health) and Depletion of abiotic resources, elements impact category. The error bars represent two standard deviations and show the 95% certainty range of results for each impact category.

plicity, only one probability and cumulative distribution will be shown for each impact category.

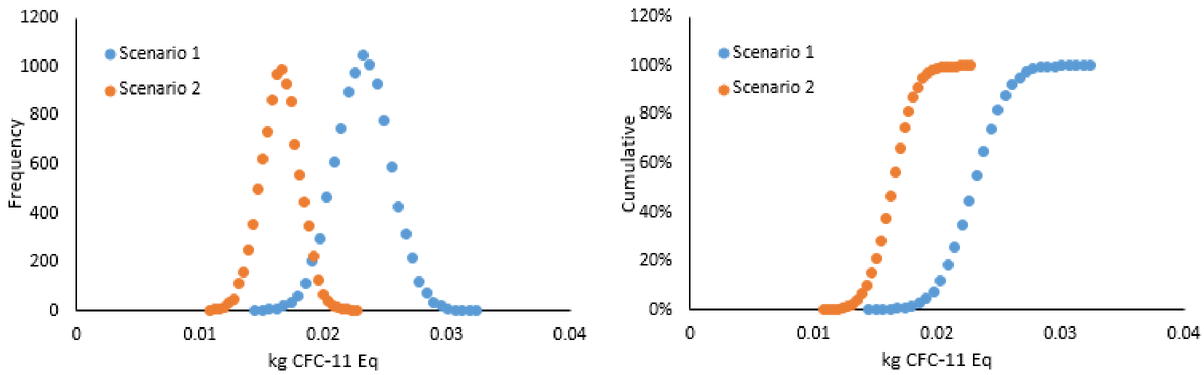

Figure 4.12 Probability and Cumulative distribution graphs of the Ozone depletion impact scores generated from the results of a Monte Carlo simulation (10 thousand iterations) for scenarios 1 and 2

The probability and cumulative distribution graphs for the Ozone depletion category show that both scenarios have a similar probability range by simulating a 10% range on the process efficiency of bitumen extraction. The probability distributions overlap at a frequency of 200 out of 10 thousand iterations, which is 0.02%. The cumulative distribution supports this and illustrates the cumulative scores of the overlap (figure 4.12, right). Moreover, because the impact category is influenced by bitumen process efficiency scenario 2 could not have higher influence on the ozone depletion category than scenario 1, given that the same bitumen extraction process provides the binder for both road options.

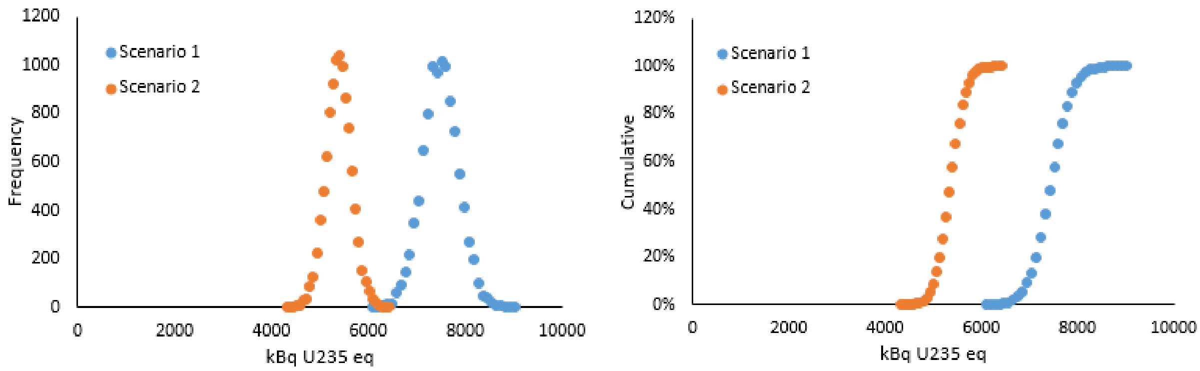

Figure 4.13 Probability and Cumulative distribution graphs of the Ionising radiation (human health) impact scores generated from the results of a Monte Carlo simulation (10 thousand iterations) for scenarios 1 and 2

The probability and cumulative distribution graphs for the "Ionising radiation (human health)" category show that the both scenarios have a similar probability range by simulating a 5% range on the amount of bitumen. The probability distributions in figure 4.13 seem to have a smaller overlap compared to figure 4.12 but that is because of the difference in variability ranges chosen for the different parameters. Also, unlike the bitumen process efficiency, the amount of bitumen used between the scenarios are not internally linked. In those cases where the amount of bitumen used in a traditional asphalt mixes is lower than the amount used for plastic enriched roads, an overlap may occur. The frequency cannot be read from figure 4.13 but it is 47 out of 10 thousand iterations and equals 0.005%. The cumulative distribution supports this and illustrates the cumulative scores of the overlap (figure 4.13, right).
The Monte Carlo simulation shows that there is a significant difference between the results of the two scenarios. No further uncertainty propagation was deemed necessary since there was negligible overlapping of the results.

Choice of representation

In this sub-section the choice of representation will be analyzed. Choice of representation regards to, the way in which the system boundaries and system model are defined in this study. This analysis is conducted because in fact there could be little difference in the use stages between the two scenarios in general. The processes included in the use stage such as pothole filling was assumed to be reduced along with other use related activities which were initially were thought to be important. The recycling of recovered asphalt (RAP) was, on the other hand not included in the study. The reason for this is that, in the process of collecting data it was understood that very little RAP is "recycled". However, in retrospect this process could be considered re-use and was not included because initially it was not thought to be important. The system boundaries and system model flow with the use stage cut-off and added recycling is illustrated in figure 4.14.

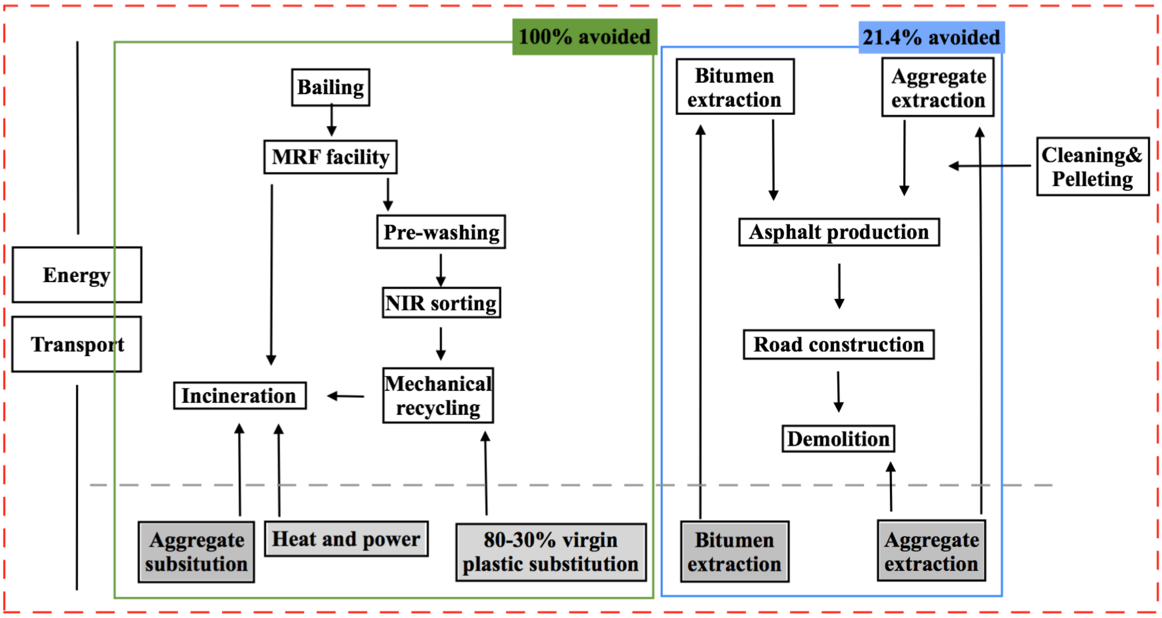

Figure 4.14 Consequential system model flow for the characterised and normalised results of the sensitivity sub-section "Choice of representation". Here the use stage has been cut-off and recycling stage has been added in comparison to the system model flow used in the rest of the study. The red dotted line indicates the system boundaries and the grey dotted line indicates the avoided production.

The analysis was done keeping the same functional unit, reference flow and intended application. In table 4.12 and figure 4.15 are the characterised and normalised results of the study if the use stage had been cut-off and if 1 kg of RAP would substitute 1 kg of aggregate.

Table 4.12 Characterised results of the study with different system model; no use stage and recycling of reclaimed asphalt pavement (RAP) substitutes the same amount of aggregate.

Impact category	Unit	Scenario 1	Scenario 2	Difference
Climate change	kg CO2-Eq	4.66E+04	3.62E+04	-1.04E+04
Ozone depletion	kg CFC-11 Eq	2.27E-02	1.61E-02	-6.58E-03
Human toxicity (cancer effects)	CTUh	1.96E-04	1.54E-04	-4.18E-05
Human toxicity (non-cancer effects)	CTUh	9.04E-03	6.82E-03	-2.22E-03
Particulate matter	kgPM2.5-eq	2.31E+01	1.74E+01	-5.66E+00
Ionising radiation human health	kBq U235 eq	7.25E+03	5.21E+03	-2.05E+03
Photochemical ozone formation	kg NMVOC	4.51E+02	3.41E+02	-1.10E+02
Terrestrial acidification	mol H+ eq	4.65E+02	3.46E+02	-1.20E+02
Eutrophication Terrestrial	mol N eq	1.38E+03	1.05E+03	-3.30E+02
Eutrophication Freshwater	kg P eq	3.33E-01	2.57E-01	-7.52E-02
Eutrophication Marine	kg N eq	1.23E+02	9.33E+01	-2.93E+01
Ecotoxicity freshwater	CTUe	1.81E+04	1.37E+04	-4.40E+03
Depletion of abiotic resources, fossil	kg Sb eq	2.04E+06	1.52E+06	-5.18E+05
Depletion of abiotic resources, elements	kg antimony-eq	3.05E-01	2.24E-01	-8.10E-02

There are substantial differences in characterised impact scores for each category compared to the baseline for each scenario. Nonetheless, these differences in characterised impact scores between the scenarios seem to be linear because there is not a significant difference in the consequential savings (see figure 4.15). From the characterised results in table 4.12, it is clear that there are consequential savings connected to every impact category if the representation of the system is changed by cutting off the use stages of the roads and crediting RAP for aggregate.

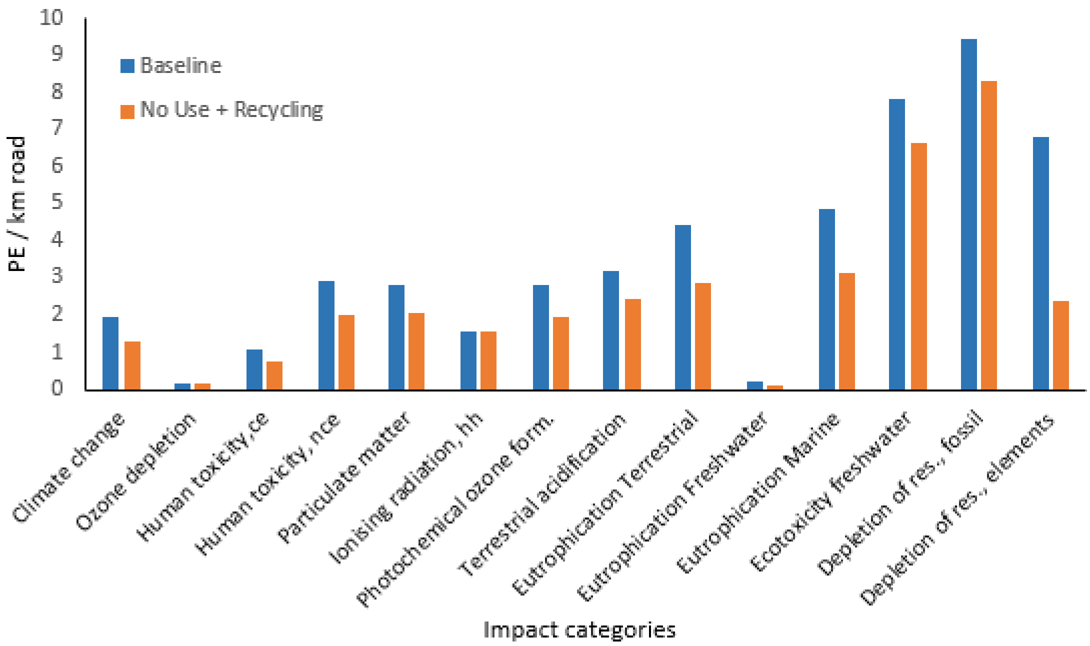

Figure 4.15 Normalised results of the consequential savings connected to building a plastic waste enriched road compared to business-as-usual. There is a change of representation of the system model shown in orange, here the use stage is not considered and the reclaimed asphalt is credited for aggregate. These results are compared with the baseline results

The normalised results of the new system model can be seen in figure 4.15. The figure shows the consequential savings are shifted and e.g. there are noticeable differences in scores connected to the impact categories eutrophication terrestrial and marine and element depletion. However as has been stated before, there are consequential savings connected to every impact category.
A Monte Carlo simulation was performed on scenarios 1 and 2 in the case of changing the system model. The average impact scores and their standard deviations for each impact category can be seen in table B.13 in appendix B. These results were obtained using the same parameters and parameter deviations as before which can be seen in table 4.6.

Completeness and Consistency Checks

Completeness check. The cut-off of processes has been consistently applied to both road alternatives in order to ensure completeness of the study. The processes that were cut-off

would increase the contribution of the construction and use stages of the two alternative roads to the overall results with the exception of the recycling stage (referring to the list of excluded processes (i) to (viii) in section "System Boundaries and Completeness Requirements"). These processes were left out, either due to difficulties in finding data or they were initially not thought to be important.
Firstly, earthwork and additional road work needed was cut-off, which is assumed to increase the fuel required in the construction stage and the amount of aggregate needed. The expected results are that there would be increased consequential savings in all impact categories except for ozonedepletion, ionising radiation (hh) and depletion of elements. Similarly, the vehicle emissions due to the use of road would increase the fuel produced and burnt in the use stage. These processes were expected to remain unchanged between the two scenarios. These assumptions as well as the aggregate substitution of RAP, were covered by the subsection 4.3.2.
The road work due to accidents that may occur on the road was excluded because of the difficulty of estimating their extent and because no evidence has been given that they would decrease with the enhanced quality of the road. Additionally, the microplastics and leaching due to plastic waste could not be quantitatively added to the model. Similarly, the reason being the difficulty of estimating their quantity, the knowledge gap of the amount of water percolating through the road layer and the variety of plastic additives present in different types of plastic. The contribution of this data is not expected to reduce the consequential savings with the exception of the leaching of plastic additives. The leaching is expected to have an effect on toxicity (human and freshwater) related impact categories and, as has been mentioned before, the toxicity related impact categories have an inherent uncertainty.
Overall, given that the assumptions made in the system models are correct it is estimated that the calculated consequential savings represent 70-85% of the actual total impacts.

Consistency check

The major source of inconsistency in data quality is the limited knowledge on the possible leachate formed due to the degradation of plastics and the quantity of microplastics formed due to the abrasion of the road. If this data were to be implemented there would also be a need for assessing the leachate formed in a traditional road and the chemicals found in bitumen. This inconsistency, however, is not assumed to change the conclusion of the study since the concentrations of the leachate and its effects are thought to be neglectable compared to the consequential savings found in the study.
Cut-off of processes and credits given to plastic waste management have been applied consistently to both scenarios as well as other assumptions, methods and data.

Chapter 5

Summary, Results and Discussion

5.1 Summary

Theory

The most relevant method of use to add plastic to asphalt mixtures was found to be polymer-coated aggregate (PCA) method. This is based on the fact that the method was found to be less energy intensive and have lower reported default rate in the application of the polymers to the asphalt mixtures compared to the polymer modified bitumen (PMB) method. Moreover, the PCA method has a better literature base than the plastic and aggregate mixture method.

A consensus was found among researchers that waste polymers could improve quality of wearing course by using the PCA method with the addition 3-15% of polymers to the weight of bitumen (Attaelmanan et al. (2011), Awwad and Shbeeb (2007), Vasudevan et al. (2012), Ahmadinia et al. (2011), Kalantar et al. (2012) and Al-Hadidy and Yi-Qiu (2009)). The aforementioned addition of plastic waste occupies space of the total mix which reduces the amount of bitumen needed for a good mix by about 0.5% of the total weight of the road (Vasudevan et al. (2012) and Al-Hadidy and Yi-Qiu (2009)). The five most common types of waste polymers were investigated in the context of being used for road construction as well as the polymer commonly used for bitumen modification, namely Styrene-Butadiene-Styrene (SBS). The five types of plastics investigated were; Polyethylene (PE; HDPE and LDPE), Polypropylene (PP), Polyvinyl Chloride (PVC), Polyethylene Terephthalate (PET) and Polystyrene (PS). Each plastic type had their pros and cons where thermoplastic elastomers tend to increase the elastic properties of binders, plastomers and reactive polymers help enhance stiffness and strength to heavy loads (Ahmadinia et al. (2011), Al-Hadidy and Yi-qiu (2009), Al-Hadidy and Yi-Qiu (2009) and Attaelmanan et al. (2011)). Most polymers provide better adhesion between aggregate and bitumen and decrease binder temperature susceptibility, which is favorable for hot climates (Al-Hadidy and Yi-Qiu (2009), Awwad and Shbeeb (2007) and Vasudevan et al. (2012)).

The literature review was used for the evaluation of the road parameters; Abrasion, Wheel track formation, Fracturing, Lifespan and Recycling. Although these parameters are inherently connected, they were evaluated separately. In order to identify the effects on these parameters the theoretical consequences of the test results of the different studies were used. It was assumed that: (i) abrasion would lessen due to the increased adhesion between bitumen and aggregate, (ii) wheel track formation would lessen due to the increased softening point of the asphalt mixture and (iii) fracturing was assumed to decrease due to the tensile strength, air void and Marshall test results of the various studies reviewed. The parameters mentioned, theoretically, have an effect of the lifespan of plastic waste enriched roads which is consequently assumed to increase. Lastly, the plastic waste additives should not have an effect on recycling possibilities of reclaimed asphalt pavements (RAP).

Inventory

The defined scenarios (scenarios 1 and 2) called for data collection that was listed in the inventory chapter and all data was quantified and referenced. The inventory chapter was divided into data concerning the life cycle of a road built in Iceland, plastic waste management taking place in Sweden, considerations on energy used and the lifetime improvements were quantified for the purpose performing a LCA.

Data concerning the life cycle of the road includes the material, manufacturing, use and disposal stage. The extraction processes of materials were collected from the database called ecoinvent although the amounts of materials were calculated. The manufacturing stage was based on data given by a asphalt manufacturing station (Malbikunarstöðin Hlaðbær Colas) located in the capital region of Iceland. Hlaðbær Colas gave an approximation of the average fuel burnt and electricity used for asphalt production and paving as well as an idea of the different types asphalt recipes. The data collected on the use stage of the road was given by the road administration of Iceland (Vegagerðin) which included an approximation of the fuel used during the service of a typical road for an average year. Data on the disposal stage was approximated via an online search and assumed to be a general process of demolition and transportation to storage. The re-use of the reclaimed asphalt was assumed to be equivalent to storage. All transportation distances were estimated by the help of maps and/or average distances.

Data on residential source separated plastic waste collected in the capital region of Iceland was either given by the waste collection company SORPA bs. or from a sample investigated by ReSource International ehf. The electricity use, process order and technology of the plastic waste management of Sweden was assumed to be the same as was reported by Liljenroth (2014). The report was given by SORPA bs as well as the fraction of plastic waste recycled vs. incinerated (a general assumption of 70:30). Next, the substitution possibilities of plastic waste to virgin plastic were assessed as well as electricity and heat credited due to the incineration of plastic.

Energy sources were considered to be a mixture of hydro and geothermal. The energy source of Swedish production was known to be a mixture but because an ecoinvent database was not found representing a mixture of energy nuclear was chosen as a baseline power source which was then analyzed in the LCA. The diesel production and consumption was represented by an ecoinvent database. The database was chosen because of its unspecific nature since it was difficult to approximate machinery used, their age, condition and emission filters. The database is therefore not technologically, geographically nor temporally specific.

The most critical assumption made was the increased longevity of the plastic enriched road. This assumption was made for the sole purpose of making an life cycle impact assessment and is the reason for the subject of the theory chapter and the extended sensitivity and uncertainty analysis of the LCA. The lifetime expectancy of the traditional road was assumed to 7 year and the plastic enriched road was assumed to have a lifetime of 8.5 years.

Life Cycle Assessment

This study was intended as a decision support tool for the Road Administration of Iceland (Vegagerðin) who are also the target audience. Because of the scale of the decision it was considered to be a macro-level situation which was solved using a consequential LCI modelling framework. The functional unit is: "Provide 1 km of confined and bound asphalt based surface on which vehicles can drive and is durable for a high traffic load every day for 7 years in Iceland. A high traffic load is defined by the Icelandic guidelines on bound asphalt, set by the road administration of Iceland (Vegagerðin (2017)), as >8000 ÁDU, average daily traffic in a year on two lanes". The reference flow was defined as a wearing course; 1 km long, 6 m wide and 4.5 cm thick.

The consequential system model flow includes an avoidance of the current plastic waste management system of Iceland, a partly avoided life cycle impact of a plastic waste enriched road due to a longer lifetime expectancy and the pre-processing of the plastic waste before it can be added to an asphalt mixture (all transportation and energy included).

5.2 Results

Scenario 2, including plastic waste enriched roads, has statistically lower impact scores than Scenario 1 connected to every impact category investigated by the LCA practitioner. According to the normalised results the biggest consequential savings of utilizing plastic waste for road construction in Iceland are connected to the impact categories; "Depletion of abiotic resources (fossil and elements)", "Eutrophication of terrain and marine" and "Ecotoxicity of freshwater".

The most influential processes to the impact scores of both scenarios are; Bitumen extraction, aggregate extraction, construction-, use- and recycling stages. Consequently, the amount of bitumen and aggregate used and the process extraction efficiency of bitumen and aggregate were found to be the second most sensitive parameters after the lifetime improvement of the plastic waste enriched road according to a perturbation analysis.

A scenario analysis was performed investigating the change in results if: (A) If there were no savings in bitumen and aggregate due to the addition of plastic waste to asphalt, (B) If a different power source is used for the plastic waste management in Sweden and heat generated by incineration of plastic was credited for a different power source and (C) Another impact assessment method were used to calculate the results. In all three cases the results were that, there are consequential savings related to each impact category by choosing to use plastic waste additives in road construction.

A Monte Carlo simulation was performed using the parameters found to be most sensitive to the outcome of the study according to the perturbation analysis with the addition of the amount of fuel burnt in the use stage. These parameters were assumed to deviate by 5-10% of their default values. The Monte Carlo simulation was run with 10 thousand iterations and gave average impact scores and standard deviations for each impact cate-

gory of the two scenarios. From those results it was concluded that it is 95% certain that scenario 2 has lower impact scores in every category compared to scenario approximately 99% of the time.
Choice of representation refers to the way in which the system boundaries and system model flow were defined. The system model flow was changed in this analysis by cutting off the use stage and crediting reclaimed asphalt pavement for aggregate but keeping the same functional unit, reference flow and intended application. The results of the analysis showed the consequential impact of using plastic waste in road construction compared to business-as-usual if there were no savings connected to the use stage and decreased savings due to the crediting of the reclaimed asphalt. The analysis showed that there are savings connected to every impact category. Normalised results of this analysis was compared to the baseline and as could be expected, there were less consequential savings when the use stage was cut-off and substitution added. The largest difference was connected to the impact category "Depletion of abiotic resources, elements".
Two additional Monte Carlo simulations were run and their results added to appendix B (B.8 and B.9). The sub appendix B.8 "Uncertainty propagation, no lifetime change", probability and cumulative distribution graphs were generated by running a Monte Carlo simulation (10 thousand iterations), using the same parameters and parameter variabilities as before. The results were tested if there were no lifetime change between the two alternative roads. The graphs therefore show the normal distribution of the results of each scenario if the only difference between the two road alternatives were the amount of bitumen and aggregate needed. The graphs show that there is some likelihood of consequential savings connected to impact categories "Ozone depletion" and "Ionising radiation (human health)".
The sub appendix B.9 "Choice of representation" shows the average impact scores of each impact category for both scenarios assuming a changed system model flow and system boundaries as was discussed earlier. The results were generated using a Monte Carlo simulation and the same parameters and parameter variance as before. The results show that there is a 90% certainty that there are consequential savings connected to all impact categories 100% of the time except for the impact category "Depletion of abiotic resources, elements".

The presentation of the normalised results should be noticed as the impact scores from the categorised results of 7 years operation are divided by normalisation factors of the average personal equivalence emission per year. The normalised savings results in the interpretation sub section however, presents the estimated savings per year of operation. If the functional unit of the study would assume an operation time of 1 year and we would assume the same proportional improvement of lifetime of the plastic enhanced road the normalised results would be similar to what was shown in sub section Choice of representation but for one year operation. Therefore, the results are scaled proportional to the lifetime change except for the environmental emissions of the plastic waste management which is only connected to the amount of plastic used.

5.3 Discussion and Limitations

Critical assumptions

As has been mentioned, the lifetime enhancement of the plastic waste enriched road is the most critical assumption made. Thereafter, it is worth to mention all assumptions made that influence the most sensitive parameters in the model. However, all these assumptions were tested for in the sensitivity analysis of the LCA. The sensitivity concluded that the impact scores are significantly lower for scenario 2 than for scenario 1 in all 14 impact categories.

Other assumptions

The application and mixing of the plastic waste is assumed to be optimum and is assumed that it will not require additional energy or machinery. The amount of bitumen needed in the plastic enriched road was found to be 89.5% of the weight needed for the traditional road and likewise the amount of aggregate was found to be 99.5% of the weight. The explanation is that the plastic waste occupies volumetric space in the mixture. However, these assumptions were tested for in the sensitivity and uncertainty analysis.

The PCA method implies that the influential polymer characteristics is melting temperature and in a mixed plastic waste composition there are several different melting temperatures. The PCA method has also been found to increase the roughness of the road and more efficiently bind the bitumen to the aggregates. An increased roughness of the road could decrease skidding and/or increase fuel consumption of vehicles and wear off tires. The grain size of the plastic makes a difference in outcome as Awwad and Shbeeb (2007) reported. In order to reduce grain size of the plastic more energy could be needed.

Data limitations

The literature review is not exhaustive from a civil engineering point of view. To increase the certainty of the possible quality improvements due to PMA that were addressed ideally measured data would be needed for Icelandic conditions. Alternatively, field measurements and literature data from India and various other countries near the equator was used for the literature review. Since a test road has not been paved in Iceland the lifetime expectancy of the plastic waste enriched road remains relatively uncertain for Icelandic conditions. In general, the amount and quality of literature data used for the study could also been improved by making sure there were no bias in the sense that the researchers did not research for the purpose to find improvements of road parameters.

The data used for the models could be improved. Influential processes such as aggregate extraction process specific to Icelandic conditions and more detailed information on the disposal process of the reclaimed asphalt pavements in Iceland should be improved. Additionally, the specific machinery used in the manufacturing stage of the roads, their age, emission rates, filters and other uncertain factors would reduce the uncertainties of the analysis. The aforementioned processes would however, inherently connected between the two scenarios.

Less influential data (but not connected between the scenarios) such as plastic waste recycling and incineration technologies, process and efficiencies specifically linked to Icelandic waste plastic could have been improved.

The effects of microplastics and leaching due to plastic additives and bitumen could not

be included in the study. The effects due to leaching could result in a lowered consequential savings by building plastic enriched road compared to business-as-usual in impact categories such connected to toxicity (human and freshwater) and possibly acidification of land.
Lastly, more relevant ecoinvent databases could have been used for the electricity used in Sweden and for the production and combustion of diesel fuel used in the construction, use and recycling stages. The changes in heat mix and heat demand in Iceland in the future was disregarded since heat supply is not assumed to change considerably within the time frame of the study.

Considerations

The waste hierarchy is a tool used where processes are evaluated in order to protect the environment. The hierarchy therefore evaluate processes and establishes preferred program priorities by categorizing processes into the most and least favorable actions based on sustainability. According to the waste hierarchy the most favorable action is to reduce the amount of waste produced and used. Less favorable are the acts of re-using, recycling and energy recovery and the least favorable is disposal.
The act of utilizing plastic waste in road construction could be considered recycling since the waste is re-purposed with a different function than initially intended. In other words, the polymeric properties of the plastic is used to enhance the roads longevity. At the same time the plastic waste is eradicated in a way that it is sequestered in the road layer. Contrarily, when plastic is incinerated there is a release of carbon dioxide into the atmosphere.
If however, the lifetime of the plastic enriched road is not extended the plastic waste is not being re-purposed. In those situations, plastic waste should not be used in road construction, rather the plastic waste should make use of the current waste management system of recycling and incinerating.
For asphalt mixtures, it is more ideal to use plastic waste that has gone through more than one life cycle to maximize the potential use of each plastic product. Therefore, if the same road performance can be achieved with high and low grade plastic waste pellets, it is preferable to use low grade plastic.
The difference between high and low grade plastic is essentially the amount of impurities and lessened strength. Therefore, there is a balance to be found in the amount of impurities without compromising environmental safety. Hence, before plastic waste is cleaned and pelleted there might be a need to make sure that unwanted items, e.g. batteries, will not make matters worse.
The results of the study should not be used to evaluate the environmental consequences of using virgin plastic in road construction. The reason being that in that case the upstream impacts of virgin plastic would need to be considered. Additionally, the results do not support the method of polymer modified bitumen (PMB) as there would be need to consider the energy used in the mixing and storage processes connected to that particular method.
If a plastic enriched road were to be made with a plastic enriched RAP it is important to keep in mind that when the amount of plastic is higher than 15% of the weight of binder the asphalt performance has been found to deteriorate. Therefore, the amount of plastic waste additives used in this case need to be re-scaled in order to maintain quality

performance of the wearing course.

For further investigation of plastic waste in road construction it would be feasible to research the possibilities of chemical exposure of the additives found in plastics. The research would then focus on the risk of chemical exposure of plastic additives into the environment via leaching through the wearing course layer. Additionally, a risk assessment of the chemicals themselves in this situation as well as a chemical assessment of the difference between a binder with and without plastic waste additives. The goal for this additional investigation would be to assess if plastic waste additives in road construction would create a relatively worse environmental toxicological outcome compared the current situation.

Chapter 6

Conclusion and Recommendation

Conclusions

I. Literature indicates hot asphalt mix properties will be enhanced by using 3-15% waste plastic using a polymer-coated aggregate (PCA) method.

II. The amount of bitumen needed in the plastic enriched asphalt was found to be 89.5% of the weight needed for the traditional road and likewise the amount of aggregate was found to be 99.5% of the weight. The explanation is that the plastic waste occupies volumetric space in the mixture.

III. An estimation was made of the possible lifetime enhancement of the plastic waste enriched wearing course for the purpose of making a life cycle assessment (LCA). A traditional asphalt mixture was assumed to have an average lifetime of 7 years and the plastic waste enriched alternative was assumed to have a lifetime of 8.5 years respectively.

IV. There are consequential savings connected to all 14 impact categories by choosing to build plastic waste enriched roads in Iceland compared to business-as-usual.

V. Processes of bitumen and aggregate extraction and fuel consumption of the construction, use and recycling stages contribute the most to the results of the LCA.

VI. The overall environmental performance difference between the two scenarios is due to the enhanced lifetime of the plastic enriched road. Savings in the amount of bitumen and aggregate used due to the addition of plastic which occupies space in the asphalt mixture is also greatly influential.

VII. The most critical assumptions made were connected to the most influential processes.

VIII. Transportation, the amount of plastic waste recycled and incinerated and plastic substitution was not heavily influential to the results of the study.

IX. Conclusion IV does not change even if; (A) there were no savings in the amount of bitumen and aggregate needed for the plastic waste enriched asphalt mixture, (B) energy sources of the plastic waste management are tested, (C) a different impact assessment method is used .

X. In order to reverse the results of the study a combination of factors would need to co-exist. Factors that could reverse the results are: (i) if there would be no lifetime enhancement of the plastic waste enriched road, (ii) no savings in amount of bitumen and aggregate, (iii) the mixing method of the PCA would be energy intensive

XI. The results do not support the use of virgin plastic nor the use of the polymer modified bitumen (PMB) method.

Recommendations
Recommendations are given to the commissioner of the study to support environmentally conscious design of a new hot asphalt mixture used for a wearing course utilizing plastic waste as additive for Icelandic conditions. The environmental evaluation was made considering the whole value chain and life cycle of plastic waste management currently used for Icelandic plastic waste:

I. To ensure a better environmental performance of wearing course the design should focus on optimizing lifetime enhancements of a new asphalt mixture.

II. The asphalt mixture should preferably consider using alternative material than bitumen and aggregate, which can enhance the cohesion between the two and/or enhance other road performance parameters.

III. The best environmental performance would be achieved by using alternative material that otherwise would be discarded (burnt or landfilled). Alternatively, a material can be chosen that has lower environmental positive effects by recycling than could be achieved by enhancing the lifetime of the bound surface layer.

IV. Utilizing residential source separated plastic waste from the capital region of Iceland is a environmentally feasible option for a new asphalt mix if there is a lifetime enhancement connected to its utilization.

V. In general, a better environmental performance can also be achieved by using bitumen and aggregate that have the best extraction process efficiency. Secondly, the fuel burnt in the manufacturing and demolition stages can be reduced.

VI. An enhanced recycling method of reclaimed asphalt pavements (RAP) has a positive affect on the environmental outcome.

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Appendix A

Theory appendix

A.1 Road Materials

Choice of material

Materials for road construction is chosen to fulfill quality standards and in Iceland those standards are the European technical guide EN13043. The standard includes demands on aggregate's mechanical characteristics such as strength and abrasion qualities. Additionally, the buyer/designer of the road will enforce standards on the physical characteristics of the road material such as aggregate size, shape and colour and the viscous properties of bitumen. The different quality of roads is depended on the designer's demands and also to the function of the road (high- or low traffic load).
The sub-base materials have less requirements to fulfill and therefore it is most common that local materials are chosen. As the layers are closer to the traffic the materials undergo more rigorous testing and the final wearing course will fulfill the highest of standards. Because of these standards it is common that the material used in the wearing course is transported longer distances to the building sites.
Aggregate gradation is one of the most common test on road aggregate which indicates the percentages of rock sizes in an aggregate mixture. The aggregate mixtures are named by the largest sized rocks such as the most common 5-8mm, 8-11mm and 16mm mixtures. In general the larger size mixture give a better resistance to spiked tires.

Aggregate

Rock material has physical- and mechanical characteristics. Physical characteristics include; mineral and chemical composition, colour, texture, grain size and shapes and lastly porosity. The mechanical characteristics include; strength-UCS, point load, Brazilian, hardness-schmidt hammer, Mohr's scale, brittle behaviour, violent failure, fracture mechanics, durability, plasticity and swelling potential (Singh and Goel (1999)).

Physical Characteristics
In Iceland, 90% of rock is solidified lava (mostly basalt) and the other 10% is weathered lava that has, under pressure and chemical reactions, reformed as rock. Basalt is an

extrusive rock, contains small crystals, is grey to black in colour, is rather alkaline and by definition contains less than 52% silicon dioxide (Sæmundsson et al. (1999)).
The crystallinity of rocks is determined by the elements of which it is composed of and the temperature and pressure at the time of formation. The more uniform the crystilline structure is the more resistant the rock is to abrasion. The crystallinity also has an effect on the shapes of the mineral since it has an effect on how the material breaks.
Permeability is the seepage of fluids or gases through interconnecting voids of porous material. The resistance to the flow depends on the geometry of the voids, type of rock and surface tension of water. Permeability is therefore a function of these parameters with the consideration of temperature (Singh and Goel (1999)).
Basalt has a grey to dark grey colour which causes the roads made with basalt to be dark. The colour of the roads are a factor of road safety regulations (which has given rise to the importation of lightly coloured Norwegian rock to Iceland for road construction (Elín Ásgerisdóttir, personal communication, February 9, 2018)).

Mechanical Characteristics
Basalt is considered to be medium strong to extremely strong in the classification of rock material based on unconfined uniaxal compressive strength (strength-UCS). This means that the rock materials have the strength of 25 MPa or higher of a point load.
There are multiple test described in "Efnisrannsóknir og efniskröfur" published by Vegagerðin (Vegagerðin (2017)). The mechanical characteristics of aggregate are tested by performing the following tests; grain distribution, moisture, humus, compression strength and rock quality (strength and resistance to weathering) and sometimes LA testing.The performance requirements of the aggregate are dependent on the assumed volume of traffic (for additional information see Vegagerðin (2017)).

Bitumen

Crude oil is a natural occurring resource extracted form the ground and distilled. From the distillation products such as fuel oils (e.g. gasoline and diesel) and bitumen are derived. The percentage weight of the products is dependent on the origin of the crude oil e.g. the Venezuela oil is found to be more enriched bitumen than the North Sea oil. Bitumen, also called heavy fuel oil (HFO) is a mixture of waste streams, unwanted distillates and residual oil and therefore it is a mixture of impure organic materials (Butt et al. (2014)).
Bitumen is a binder in asphalt and is typically about 5-6% by weight of the wearing course of a road (Magnusson et al. (2016)). Bitumen plays a large role in determining the road performance and can influence characteristics such as waterproofing, insulation, noise and bridge decking (Giavarini (1994) and Kalantar et al. (2012)). Bitumen is imported to Iceland. The company Nynas in Sweden sells Iceland the bitumen where the bitumen has been cleaned and refined even further than in the oil mining facilities. Nynas traditionally uses Venuzuela oil based bitumen although it could be a mixture of origins such as North Sea, Canada, Australia or Columbia (Nynas (2016)).
There are two main types of densities of bitumen used in Iceland, namely soft and hard bitumen. The stiffness of the bitumen is determined by a needle test and is named by the

distance the needle will get through the material in a certain amount of time at 25°C. Soft bitumen is therefore named 160/220 and hard bitumen 70/100. Soft bitumen is more commonly used in Iceland because the roads can be more easily paved in cooler climate. Hard bitumen is more commonly used in warmer climate since it has generally a higher melting temperature (Gísli Eymarsson, personal communication, February 12, 2018).
To ensure the quality of bitumen used it needs to be tested meet the demands of the Icelandic standards which includes measuring: injection depth, softening temperature, ignition temperature, solubility, dynamic viscosity, kinematic viscosity and fraas breakpoint (Vegagerðin (2017)).
Apart from this there can be several additives in bitumen such as softeners, dilutes or water. Some improvements in asphalt properties have been gained by bitumen modifications such as air blowing, fluxing agents or diluted oils or by any other emulsifying agent (Gísli Eymarsson, personal communication, February 12, 2018).

Asphalt specimen quality testing

Type testing (TT) should be done in the beginning and at a five year interval and the test should be performed by the standards of ÍST EN 12697-22, -16 and -12.
Wheel track formation is tested using a continuously rolling wheel over a asphalt layer. In a Prall test asphalt specimens are firstly submerged in water and then put into frames with 40 stainless steel ball bearings and pressed. Marshall test includes using a Marshall hammer to test void and compression characteristics of an asphalt sample. Generally, the Marshall test also tests the adhesion between aggregate and binder and a good adhesion reduces the likelihood of creeping. Low compression (≤2 mm) results in a crisp wearing course and could increase likelihood of cracking. High compression (≥4.5 mm) on the other hand can increase creeping (Vegagerðin (2017)). According to ÍST EN 13108-1 the lowest allowable air void content when performing a Marshall test is 1.0% for asphalt concrete AC and 1.5% for SMA. The highest allowable limit is similarly 3% for AC and 3.5% for SMA.

A.2 Plastic

Plastics are a wide range of synthetic and semi-synthetic organic compounds of mouldable polymers. The polymers are formed from chains of carbon atoms of high molecular mass. Plastics are traditionally made from petrochemicals but bioplastics have been produced from polyactic acid or cellulosics. Approximately one third of all plastic produced is used for packaging, another one third is used for the building sector and one third used for other applications such as cars, toys and furniture (Andrady and Neal (2009)).

Common Types of Plastic

Plastic is classified by; (i) Chemical structure, (ii) Chemical process, (iii) Physical properties or (iv) Product design characteristics. As all virgin plastics becomes waste they are all of concern when assessing their application feasibility to asphalt. However there will be a focus on the most commonly used plastics and the most toxic additives used in

plastic.
Thermoplastics and thermosets are subclasses of plastics that are classified by their product design characteristics. Thermosets can only be shaped once but thermoplastics of can be moulded multiple times and do not undergo chemical changes when heated. Thermoset plastics are made of liquid plastic whereas thermoplastic is typically made from 2-5mm plastic pellets. The pellets used are similar to powder (macro and microplastics) which tend to washed away during production which end up in the environment (Magnusson et al. (2016)).

Polyethylene (PE)
Polyethylene is a thermoplastic and is the most common plastic in the world. The chemical behavior of PE is similar to paraffin (kerosene) which can be found in candles and sometimes used as jet fuel or as additive in road construction. PE has a simple structure, is semi-crystalline, good chemical resistance and good fatigue and wear resistance (Awwad and Shbeeb (2007)). There are several subcategories of PE but the most common ones are high- and low density polyethylene (HDPE and LDPE).

HDPE - e.g. plastic bottles and piping

LDPE - e.g. plastic film, grocery bags and food containers (Hartmann (2017)).

Polypropylene (PP)
Polypropylene is also a thermoplastic and the second most common plastic. It can form a degree of crystallinity and is more resistant to creep than PE. PP is resistant to fatigue and is applied where those characteristics are needed. Therefore, PP is used in for example in chairs, labratory items, plastic yarns.

Polyvinyl Chloride (PVC)
Polyvinyl Chloride is also a thermoplastic and the third most common plastic. It is either rigid or flexible. PVC is made flexible with the addition of plasticizers and it is not uncommon for PVC to contain other additives such as heat stabilizers. PVC plastic is used in pipes, electrical cables, membership cards etc (Kaley et al. (2006) and Wypych (2016)).

Polyethylene Terephthalate (PET)
PET is the fourth most common plastic, also known as polyester and is mostly produced for synthetic fibers used in textiles but it is also used for bottles (Hartmann (2017)).

Polystyrene (PS)
PS is one of the most widely used plastics and is used for food containers (e.g. take away ice cream), plastic cutlery and CD holsters. Polystyrene food containers are better known as Styrofoam and does not biodegradable and is resistant to photolysis and therefore it has been banned in several countries and some states in the US (Wünsch (2000)).

Styrene-Butadiene-Styrene (SBS)
Although SBS is not a particularly common plastic it is the most common polymer used for modified bitumen. The reason for this is that SBS combines elastic and thermoplastic properties however the mixing of SBS and bitumen is considered complex (Airey (2003)).

There is a plethora of other types of plastic, many of which are specifically designed for airplanes or cars to be lightweight and strong and some of which have insulating or conducting properties for the electrical and building sectors.

Additives in Plastic

Plastic are either "pure" or have an addition of oxygen, nitrogen and/or sulfur. Pure plastic generally has low toxicity but additives such as phthalates can leach out of the plastic and have toxic effects. Additives are used to acquire certain product characteristics. Plastic additives can be stabilizers, fillers, pigments, flame retardants, fragrances, plasticizers etc. Stabilizers suppress degradation, fillers reduces the cost of a product or improves its performance and plasticizers are used to decrease the rigidity of plastics to mention a few. Some of these additives are toxic e.g. adipates, phthalates and bisphenol A. Plastics that include any of these toxic chemicals may be non-toxic however when they are heated some of the polymers in the plastic can decompose to monomers and the toxic chemicals can be released (Hartmann (2017)).

Degradation of Plastic

The degredation time of plastic can be months up to centuries dependent on the type of plastic. Molecular degradation of plastics can be caused by photo oxidation, thermal oxidation, biodegradation, other break-down of covalent bonds or hydrolysis. Degradation of plastic can also take place via chemical reactions where structural changes of the polymers lead to changes in the physical properties of the plastic. The physical abrasion leads to break down of plastics which results in nano-, micro- or macroplastics which, more often than not, lead to the ocean (Hartmann (2017)).

Recycled polymers

Recycling plastic can be problematic and when waste is collected commingled it is considered impossible to sort it into separate polymer streams (especially in an economical sense when comparing efforts to outcomes). However, the migration and chemical transformation of plastic additives during plastic's service life results in decreased quality compared to virgin plastics and therefore recycled plastic covers only a minor segment of the market demand (Jakobsen (2015)).

The recycling problems will occur when the sample is heterogeneous but also when it is homogeneous. When plastic is recycled even small polymeric impurities can radically change the properties of the recyclate. Most polymers are immiscible and their incompatibility is caused by the different polarity and melting points. When polymers are cross contaminated physical properties decline such as melt flow and impact strength and an heterogeneous mix can lead to weak chains in the polymer matrix (Jakobsen (2015)).

A.3 Life Cycle of Roads

Design Stage

The number of sub-layers, their thickness and material are defined in this stage as well as the width of the road and its road shoulders. These decisions are reflected in the length of the construction, lifetime of the road and its demolition. Moreover the strengthening parameters, water penetration and cost of the roads are affected. When the road has been designed the construction company will preform laboratory test to ensure that their material use and recipe fulfills the requirements of the buyer/customer (Gísli Eymarsson, personal communication, February 12, 2018). All test performed follow the ISO standards on laboratory experiments (Elín Ásgerisdóttir, personal communication, February 9, 2018).

Material and Manufacturing Stages

The activities related to the establishment of a road in a terrain are included in this stage and can be divided into sub-stages. The sub-stages are: (i) Excavation and preparation of road materials, (ii) Earthwork on terrain, (iii) Construction of pavement, (iv) Additional work.

(i) *Excavation and preparation of road materials*
Excavation of rocks differ from the purpose of the rock; Digging, ripping and blasting. The method chosen is dependent on the rock mass classification (Singh and Goel (1999)). When the gravel has been excavated it is moved with trucks to the asphalt factory. In Iceland, bitumen is imported from Gothenburg in Sweden. Bitumen is shipped to Iceland where it is transported to the asphalt factory and kept in tanks. The asphalt factories mix together aggregate and bitumen by demand each time according to a specific recipe that meets the demand of the buyer (see figure A.1). Aggregates are chosen by their properties and size according to the desired type of road (Gísli Eymarsson, personal communication, February 12, 2018).

The aggregate is heated up to 160-180°C (for hot mix asphalt) where the emissions go through several steps of flue gas cleaning and the particulate matter is collected in silos and used later in the mixture. When the aggregates have been heated they are mixed with bitumen and filler material. The filler material is fine particulate matter collected from the aggregates but sometimes concrete is imported and used. When the road mixture is ready it is loaded onto trucks that transport the material to the building site. There the material is spread onto the desired location and compressed. The compression has to take place before the mixture has cooled and if the materials need to be traveled long distances some additives are added to the asphalt mixture for the compression to take place under low temperatures. The additives are e.g. the product sasobit which is a synthetic hard wax (Gísli Eymarsson, personal communication, February 12, 2018 and Sasol (2017)).

(ii)*Earthwork and terrain*
When laying the ground for the road some earthwork is needed in different quantities

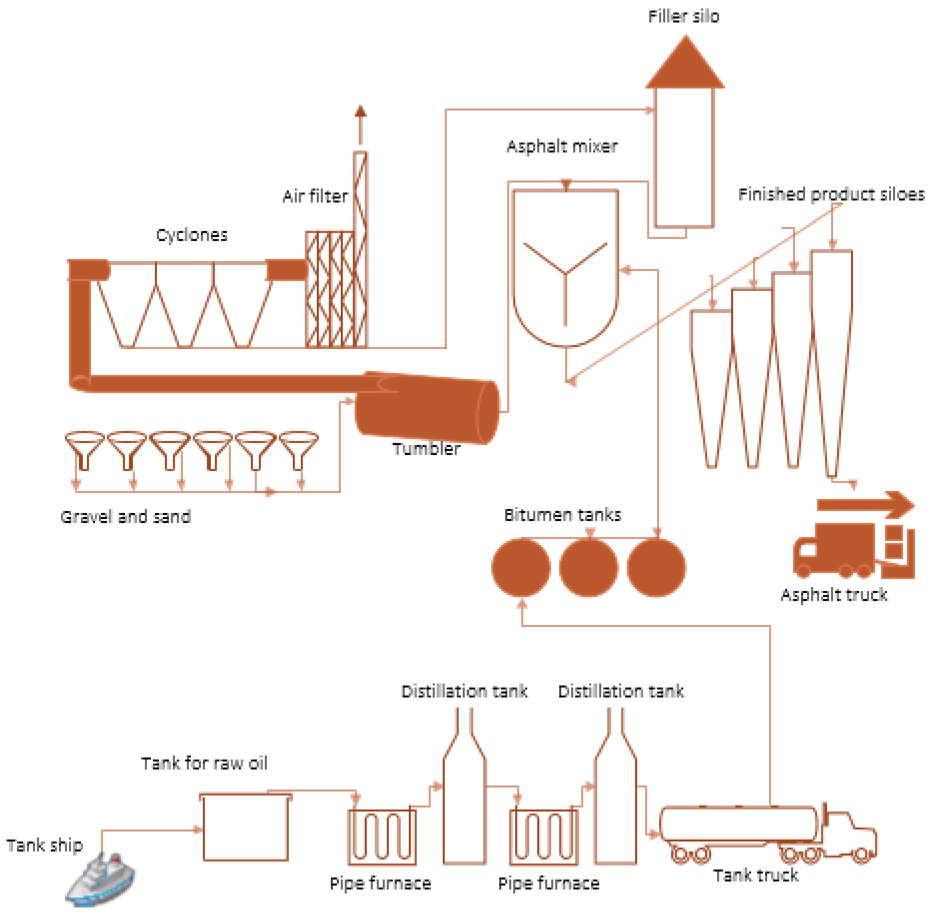

Figure A.1 Preparation and mixing processes of aggregates and bitumen for road construction in Iceland according to the location and gradient of the landscape. Different trucks such as bulldozers, excavators and loaders are used in the preparation of the area.

(iii) *Construction of pavement*
When the earthwork is finished the sub-base can be lain. The sub-base needs to be pressed and the upper layer of the sub-base needs to be tight in order for it to reach the appropriate carrying capacity and to minimize water penetration. The wedge ramps of the sub-base can be steeper than for other layers. The base course and wearing course are also compressed with a triple drum static (or other similar truck) after the asphalt material has been transported on site and the asphalt paver has lain it on the desired location. Sporadically there will be a filter layer between the different layers to prevent entwinement. However, if the aggregate gradation of the adjacent layers are reasonable this is not necessary.

(iv) *Additional work*
When the road has been paved a construction of an embankment is conducted including a drainage and water collection system. Thereafter, the road area is finalized with the addition of various road equipment such as road lighting, signs, safety- and noise cancelling fences etc.

The construction of roads in Iceland are conducted in the summertime form May to September. However it is heavily dependent on weather where roads will not be constructed on rainy days. During the winter months bitumen is stored in large tanks, hard and soft bitumen are kept in separate tanks and at about 18°C (Elín Ásgerisdóttir, personal communication, February 9, 2018).

Use Stage

The service life of a road will include the abrasion and wear of the road. Water in roads increases the maintenance of roads in countries like Iceland where the climate is constantly changing between frost and defrost. As the water percolates trough the layers, freezes and expands it forms potholes that need to be maintained. The maintenance includes crack filling and sealing. There are however other types of asphalt defects such as cracking, rutting and creeping that needs to be maintained. The most typical maintenance includes reshaping, sealing, stabilizing, pot hole patching and surface correcting.
During the winter in Iceland there is considerable service of shovelling and clearing snow off the streets which scrapes and can damage the road. There is also a considerable amount of gravel and salt used to prevent skidding. The amount of maintenance and service is mostly dependent on the location of the road, use and weather conditions. The distribution of salt for example is dependent on the traffic load and icing and is of concern because some research has shown that the salt can contaminate groundwater (Kaushal et al. (2005)). The salt (NaCl) is distributed onto the roads with a truck several times each winter and from there it is dissolved into the ice and runs off the roads to the drainage on the side of the roads. The salt will partly be blown away, dissolve into moisture or be shoveled to the side of the road. Approximately 50-80% of the salt will end up in the drainage or there close by. The rest (20-50%) can be carried as far as

40 m away from the road but 90% is assumed to be within the 20 m range (Blomqvist and Johansson (1999)). Salt will also increase pothole formation in the road as the salt crystals expand within small voids in the pavement (Vasudevan et al. (2012)).
Another way users prevent skidding is to use spiked tires which are currently (year 2018) allowed in Iceland from 1st of November to the 14th of April and are commonly used (Íslenskra Bifreiðaeigenda (FÍB) (2016)). The spiked tires increase the erosion of the road and create voids in the wearing course.

Recycling Stage

When a road needs to be demolished an asphalt miller is used which removes the wearing course and places it in a dumping truck. The asphalt is recycled in some cases however it is common in Iceland not to use more than about 5-10% recycled asphalt in the wearing course. The reason for this can be to assure quality of the new road but some older constructions can also contain hazardous chemicals. If reclaimed asphalt pavement (RAP) is added to a wearing course there are generally some steps taken to ensure the quality of the recycled asphalt such as burning and filtering (finding the source of the RAP and its aggregate gradient). The remaining 90-95% is collected and used in sub layers of the road (Jóakimsson (2018)).

Appendix B

LCA appendix

B.1 Life Cycle Impact Assessment Method and Normalisation Factors

The life cycle impact assessment method used is ILCD recommended with normalisation factors form the porsuit project. The impact categories, their units and normalisation factors of the ILCD recommended LCA method (Commission (2010))can be seen in table B.1.

Table B.1 Normalisation factors and impact categories of the ILCD - 2013 Prosuite Global NR

ILCD Impact Category	**Unit**	**PROSUITE Global (2010 or 2000)**
Climate change	kg CO2eq./PE/year	8.10E+03
Ozone depletion	kg CFC-11 eq. /PE/year	4.14E-02
Human toxicity, cancer effects	CTUh/PE/year	5.42E-05
Human toxicity, non-cancer effects	CTUh/PE/year	1.10E-03
Particulate matter/ Respiratory inorganics	kg PM2.5 eq. /PE/year	2.76E+00
Ionizing radiation, human health	kBq U235eq. (to air) /PE/year	1.33E+03
Photochemical ozone formation, human health	kg NMVOC eq. /PE/year	5.67E+01
Acidification	mol H+ eq. /PE/year	4.96E+01
Eutrophication terrestrial	mol N eq. /PE/year	1.15E+02
Eutrophication freshwater	kg P eq. /PE/year	6.20E-01
Eutrophication marine	kg N eq. /PE/year	9.38E+00
Land use	kg C deficit/PE/year	2.36E+05
Ecotoxicity freshwater	CTUe/PE/year	6.65E+02
Resource depletion water	m3water eq. /PE/year	2.97E+01
Resource depletion, mineral, fossils and renewables	kg Sb eq. /PE/year	3.13E-01
Resources, depletion of abiotic resources, fossil	MJ/PE/year	6.24E+04
Resources, depletion of abiotic resources (reserve base)	kg Sb eq. /PE/year	0.0343

B.2 Bill of Materials

Table B.2 Bill of material indicating the materials needed for the two alternative roads

Properties	Road type		Units
	Traditional	Plastic waste additives	
Wearing course - Depth	0.045	0.045	m
Width	6	6	m
Length	1000	1000	m
Aggregate	16-11	16-11	mm
	238.7	237.5	m^3
Basalt density	2520	2520	kg/m^3
	601493	598415	kg
	601.5	598.4	tonnes
Bitumen	31.7	28.3	m^3
Density of bitumen	1000	1000	kg/m^3
	31657.5	28346	kg
	32	28	tonnes
Plastic	-	2.74	m^3
Density of plastic	-	920	kg/m^3
	-	2520	kg
Total volume of wearing course	270	270	m^3
Total bulk density	2345	2333	kg/m^3
Total weight of wearing course	633.2	629.9	tonnes

B.3 List of Assumptions

Table B.3 List of assumptions made for the modelling of the LCA

Assumptions	**Road type**	
	Traditional	Plastic waste additives
The lifetime of the road in scenario 2 will improved by 21.5% compared to scenario 1		x
Aggregate is mined in the same fashion as is practiced in Europe	x	x
8% Plastic waste additives used by the weight of bitumen		x
0.5% weight of bitumen saved by the addition of plastic waste in roads		x
Bitumen goes through the same process as is recorded as the average global production	x	x
Bitumen assumed to be from Venezuela yet probably a mixture from S Korea, Iran and Venezuela	x	x
Bitumen production efficiencies are 100%	x	x
Energy of storing and keeping bitumen at 18°C is neglected	x	x
Upstream impacts of the plastic waste is neglected	x	x
Quality improvements of road assumed from literature values		x
Quality improvements of road only used to expand lifetime, not lower maintenance		x
Plastic waste mixture assumed to be the same as shown in table 3.5	x	x
Plastic waste Sweden, 70% recycled and 30% incinerated	x	
Processes and electricity used for the recycling of plastic waste in Sweden assumed to be as reported by Ren (2012)	x	
Loss of material during recycling is 2%	x	
Substitution of plastic is on the range of 30-80% virgin plastic	x	
Incineration institution assumed to be of the same quality as a danish incineration plant	x	
Incineration energy substitutes 83% heat and 17% electricity of nuclear power	x	
The mixing of asphalt will be at optimum conditions and lead to ideal quality	x	x

Table B.4 List of assumptions made for the modelling of the LCA

Assumptions	**Road type**	
	Traditional	Plastic waste additives
Loss of asphalt material during production is neglected	x	x
Upstream impact of the machinery used in the manufacturing stage is neglected	x	x
Maintenance of asphalt production machinery neglected	x	x
Transportation of asphalt from production to desired location is neglected	x	x
Transportation of maintenance to desired location is neglected	x	x
Effects of road paint and salt on the environment neglected	x	x
Effects of microplastics on the environment was neglected		x
Effects of plastic additives leaching into the environment is neglected		x
Upstream impacts of road paint and material for pothole filling neglected	x	x
Emissions due to traffic on road is neglected	x	x
Demolition stage is identical to that of the German cold mill used by Wirtgen (2008)	x	x
Energy used for the re-use of the demolished road is neglected	x	x
Emissions for machinery is assumed to follow European standards	x	x
Transportation of machinery to desired working location neglected	x	x
Transportation between countries via ship	x	x
Other transportation than between countries via trucks	x	x

B.4 Unit Process and LCI Results

Table B.5 Inventory and data sources for foreground processes for the two road alternatives

Parameter	**Road type**		**Unit**	**Note**	**Source**
	Traditional	**Plastic waste additives**			
Materials					
Bitumen	3.17E+04	2.83E+04	kg	Wearing course 270 m^3 which is 5% bitumen	Calculated
Aggregate	6.01E+05	5.98E+05	kg	Wearing course 270 m^3 which is 95% aggregate	Calculated
Plastic waste	-	2.52E+03	kg	Plastic waste is 8% of weight of bitumen	Calculated from data from literature
Manufacturing					
Electricity for production of bitumen	9.12E+03	8.16E+03	MJ	Electricity, medium voltage 0.08 kWh/kg * kg bitumen * 3.6 = MJ	Generic LCI database process
Electricity for production aggregate	1.62E+04	1.61E+04	MJ	(diesel + electricity + heat)*aggregate = (0.0147MJ + 0.00272kWh*3.6 + 0.00244)*kg	Generic LCI database process
Electricity for production of plastic recycling	2.14E+04	-	MJ	Includes all steps of recycling for 70% of 2520 kg plastic waste. Swedish energy system	Calculated from values reported by Ren, 2012
Electricity for incineration of plastic	-2.54E+03	-	MJ	Heat and energy substitution of incineration of MSW for 30% of 2520 kg plastic waste. Swedish energy system	Calculated from values reported by Renova incineration plant; SE - https://www.renova.se/in-english/about-us/
Electricity for production of asphalt	2.05E+05	2.04E+05	MJ	Measured by Hlaðbær Colas	Measured at specific process site
Oil burnt for production of asphalt	1.98E+05	1.97E+05	MJ	Measured by Hlaðbær Colas	Measured at specific process site
Oil burnt for road construction	9.95E+04	9.90E+04	MJ	Calculated by Hlaðbær Colas. Includes paving and transporting people, machinery and material to a location 52km away.	Measured average of a construction site

Table B.6 Inventory and data sources for foreground processes for the two road alternatives (continued)

Parameter	Road type		Unit	Note	Source
	Traditional	Plastic waste additives			
Use					
Oil burnt for road painting	2.22E+00	2.22E+00	L	Road painting is done 1 per year with speed of 12 km/hour burning 3.8 l/h for 7 years	Assumed
Oil burnt for pothole filling	7.35E+01	7.35E+01	L	Approximately 1 per year there will be 3 holes/km burning 3.5 l/hole for 7 years	Assumed
Oil burnt salting roads	2.10E+02	2.10E+02	L	Salt is distributed 85-100 times/year burning 0.3 l/km for 7 years	Skuli Thordarson, Dr.ing. Specialist, service department at Vegagerðin
Oil burnt sweeping	4.20E+00	4.20E+00	L	Sweeping 2 per year burning 0.3 l/km for 7 years	Skuli Thordarson, Dr.ing. Specialist, service department at Vegagerðin
Oil burnt rutting snow	4.90E+02	4.90E+02	L	Rutting is done 85-100 times/year burning 0.4-1 l/km for 7 years	Skuli Thordarson, Dr.ing. Specialist, service department at Vegagerðin
Disposal					
Oil burnt demolishing 1km road	2.43E+02	2.43E+02	L	Cold asphalt miller burns 0.9 l/m^3 and wearing course is 270 m^3, dumping truck uses 0.3 l/km	Calculated from values reported by Wirtgen milling company, 2008

Table B.7 Inventory and data sources for foreground processes for the two road alternatives (continued)

Parameter	Road type		Unit	Note	Source
	Traditional	Plastic waste additives			
Transportation					
Aggregate from mine to asphalt production	30	30	km	Lambafell Mosfellsbær to Hlaðbær Colas, 30 km	Assumed
Bitumen from production to asphalt production	11100	11100	km	Venezuela to Sweden, 9200 km. Sweden to Iceland, 1900 km	Assumed
Bitumen from port to asphalt production	20	20	km	From Reykjavík harbour to Hlaðbær Colas, 20 km	Assumed
Plastic waste from Gufunes to Gothenburg, SE	2300	-	km	Gufunes to Gothenburg, 2300 km	Assumed
Plastic waste from Gothenburg, SE to recycling in Bredaryd, SE	150	-	km	Gothenburg to recycling, 150 km	Assumed
Plastic waste from Gothenburg, SE to incineration in Sävenäs in Gothenburg, SE	10	-	km	Gothenburg to incineration, 10 km	Assumed
Plastic waste from recycling Bredaryd to Sävenäs, SE	140	-	km	Recycling to incineration, 140 km	Assumed
Plastic waste from Gufunes to asphalt production	-	20	km	Gufunes to Hlaðbær Colas, 20 km	Assumed
Recovered asphalt to storage	52	52	km	52 km from road location to Hlaðbær Colas	Assumed

B.5 Sensitivity Ratios and Coefficients

For sensitivity ratios (SR) and coefficients (SC) for scenario 1 see tables B.8 and B.9 and scenario 2 see tables B.10 and B.11.

Table B.8 Calculated sensitivity ratios and coefficients of each impact category for the amount of bitumen and aggregate as well as the efficiency of bitumen and aggregate extraction for scenario 1. All SRs ≥ 0.3 are coloured yellow indicating a medium sensitivity and SRs ≥ 0.5 are coloured red indicating a large sensitivity

Impact category	**BitAmount**		**AggrAmount**		**BitEff**		**AggrEff**	
	SR	**SC**	**SR**	**SC**	**SR**	**SC**	**SR**	**SC**
Climate change	2.61E-01	5.88E-01	7.57E-01	8.98E-02	1.68E-01	1.20E+04	3.48E-02	2.48E+03
Ozone depletion	9.97E-01	7.23E-07	1.14E-02	4.36E-10	9.69E-01	2.22E-02	9.72E-03	2.23E-04
Human toxicity, ce	5.87E-01	5.06E-09	4.78E-01	2.17E-10	5.06E-01	1.38E-04	1.72E-01	4.71E-05
Human toxicity, nce	2.43E-01	1.05E-07	7.54E-01	1.71E-08	1.94E-01	2.66E-03	1.79E-02	2.45E-04
Particulate matter	5.30E-01	5.45E-04	4.96E-01	2.69E-05	3.61E-01	1.18E+01	9.97E-02	3.25E+00
Ionising radiation, hh	9.89E-01	2.32E-01	2.98E-02	3.69E-04	9.53E-01	7.09E+03	1.95E-02	1.45E+02
Photochemical ozone formation	3.58E-01	7.61E-03	6.52E-01	7.29E-04	2.36E-01	1.59E+02	2.62E-02	1.76E+01
Terrestrial acidification	4.77E-01	9.66E-03	5.32E-01	5.67E-04	2.89E-01	1.85E+02	3.56E-02	2.29E+01
Eutrophication Terrestrial	2.49E-01	1.74E-02	7.55E-01	2.78E-03	1.10E-01	2.43E+02	2.88E-02	6.38E+01
Eutrophication Freshwater	6.29E-01	1.06E-05	4.26E-01	3.76E-07	4.85E-01	2.58E-01	3.22E-01	1.71E-01
Eutrophication Marine	2.48E-01	1.55E-03	7.56E-01	2.48E-04	1.08E-01	2.14E+01	2.79E-02	5.51E+00
Ecotoxicity freshwater	6.80E-01	4.69E-01	3.60E-01	1.31E-02	6.30E-01	1.37E+04	4.49E-02	9.80E+02
Depletion of abiotic resources fossil	7.40E-01	5.56E+01	2.93E-01	1.16E+00	7.01E-01	1.67E+06	1.55E-02	3.68E+04
Depletion of abiotic resources elements	3.20E-01	1.01E-05	6.93E-01	1.16E-06	2.99E-01	3.00E-01	6.45E-01	6.48E-01

Table B.9 Calculated sensitivity ratios and coefficients of each impact category for the amount and substitution of plastic, fuel consumption of construction and use stage and the transportation distance of bitumen for scenario 1. All SRs ≥ 0.3 are coloured yellow indicating a medium sensitivity

Impact category	**PlastAmount**		**PlastSub**		**ConstrDiesel**		**UseDiesel**		**BitTrans**	
	SR	**SC**	**SR**	**SC**	**SR**	**SC**	**SR**	**SC**	**SR**	**SC**
Climate change	-1.78E-02	-5.04E-01	-2.56E-02	1.66E+03	3.32E-01	2.30E+06	3.09E-01	2.29E+06	5.55E-02	3.57E+02
Ozone depletion	-8.89E-03	-8.09E-08	-5.30E-04	1.11E-05	3.72E-04	8.30E-04	3.47E-04	8.27E-04	2.83E-02	5.84E-05
Human toxicity, ce	-5.61E-02	-6.07E-09	-5.94E-02	1.47E-05	1.15E-01	3.06E-03	1.08E-01	3.06E-03	6.70E-02	1.65E-06
Human toxicity, nce	2.75E-03	1.49E-08	-2.90E-03	3.61E-05	3.42E-01	4.55E-01	3.19E-01	4.53E-01	1.06E-02	1.30E-05
Particulate matter	-2.60E-02	-3.36E-04	-2.96E-02	8.76E-01	1.98E-01	6.27E+02	1.85E-01	6.25E+02	1.48E-01	4.34E-01
Ionising radiation, hh	-1.88E-02	-5.55E-02	-4.70E-04	3.17E+00	4.52E-03	3.27E+03	4.22E-03	3.26E+03	3.53E-02	2.36E+01
Photochemical ozone formation	-1.00E-02	-2.67E-03	-1.14E-02	6.94E+00	3.22E-01	2.11E+04	3.01E-01	2.10E+04	8.93E-02	5.41E+00
Terrestrial acidification	-9.15E-03	-2.33E-03	-1.19E-02	6.92E+00	2.53E-01	1.58E+04	2.36E-01	1.57E+04	1.62E-01	9.35E+00
Eutrophication Terrestrial	-3.99E-03	-3.50E-03	-6.15E-03	1.24E+01	3.72E-01	8.02E+04	3.47E-01	7.99E+04	1.02E-01	2.03E+01
Eutrophication Freshwater	-5.50E-02	-1.16E-05	-7.58E-02	3.66E-02	3.81E-02	1.97E+00	3.56E-02	1.96E+00	1.39E-01	6.63E-03
Eutrophication Marine	-4.49E-03	-3.51E-04	-6.29E-03	1.13E+00	3.74E-01	7.19E+03	3.49E-01	7.16E+03	1.02E-01	1.81E+00
Ecotoxicity freshwater	-3.96E-02	-3.43E-01	-4.26E-02	8.45E+02	1.30E-01	2.77E+05	1.22E-01	2.76E+05	3.36E-02	6.60E+01
Depletion of abiotic resources fossil	-3.34E-02	-3.15E+01	-2.49E-02	5.37E+04	1.34E-01	3.09E+07	1.25E-01	3.08E+07	2.51E-02	5.38E+03
Depletion of abiotic resources elements	-1.30E-02	-5.17E-06	-1.24E-02	1.13E-02	1.80E-02	1.76E+00	1.68E-02	1.75E+00	1.79E-02	1.62E-03

Table B.10 Calculated sensitivity ratios and coefficients of each impact category for the amount of bitumen and aggregate as well as the efficiency of bitumen and aggregate extraction and lifetime improvement for the plastic enriched road for scenario 2. All SRs ≥ 0.3 are coloured yellow indicating a medium sensitivity and SRs ≥ 0.5 are coloured red indicating a large sensitivity

Impact category	BitAmount		AggrAmount		BitEff		AggrEff		LifeT	
	SR	SC	SR	SC	SR	SC	SR	SC	SR	SC
Climate change	2.35E-01	4.61E-01	7.60E-01	7.06E-02	1.51E-01	8.42E+03	3.49E-02	1.94E+03	9.95E-01	7.04E+04
Ozone depletion	9.87E-01	5.68E-07	1.26E-02	3.43E-10	9.59E-01	1.56E-02	1.07E-02	1.74E-04	1.00E+00	2.07E-02
Human toxicity, ce	5.23E-01	3.96E-09	4.73E-01	1.70E-10	4.51E-01	9.68E-05	1.69E-01	3.62E-05	9.96E-01	2.72E-04
Human toxicity, nce	2.24E-01	8.25E-08	7.72E-01	1.35E-08	1.79E-01	1.87E-03	1.83E-02	1.91E-04	9.96E-01	1.32E-02
Particulate matter	4.88E-01	4.28E-04	5.09E-01	2.11E-05	3.33E-01	8.27E+00	1.02E-01	2.54E+00	9.97E-01	3.15E+01
Ionising radiation, hh	9.67E-01	1.83E-01	3.24E-02	2.90E-04	9.32E-01	4.99E+03	2.12E-02	1.14E+02	1.00E+00	6.81E+03
Photochemical ozone form.	3.30E-01	5.98E-03	6.67E-01	5.73E-04	2.17E-01	1.12E+02	2.68E-02	1.38E+01	9.97E-01	6.52E+02
Terrestrial acidification	4.45E-01	7.59E-03	5.52E-01	4.46E-04	2.70E-01	1.30E+02	3.70E-02	1.79E+01	9.97E-01	6.13E+02
Eutrophication Terrestrial	2.28E-01	1.37E-02	7.68E-01	2.18E-03	1.01E-01	1.71E+02	2.93E-02	4.99E+01	9.96E-01	2.16E+03
Eutrophication Freshwater	5.70E-01	8.30E-06	4.29E-01	2.96E-07	4.39E-01	1.81E-01	3.24E-01	1.34E-01	9.98E-01	5.24E-01
Eutrophication Marine	2.27E-01	1.22E-03	7.69E-01	1.95E-04	9.90E-02	1.50E+01	2.84E-02	4.31E+00	9.96E-01	1.92E+02
Ecotoxicity freshwater	6.28E-01	3.68E-01	3.70E-01	1.03E-02	5.82E-01	9.68E+03	4.61E-02	7.66E+02	9.98E-01	2.11E+04
Fossil depletion	6.93E-01	4.37E+01	3.05E-01	9.10E-01	6.57E-01	1.17E+06	1.61E-02	2.88E+04	9.98E-01	2.27E+06
Elements depletion	2.93E-01	7.97E-06	7.06E-01	9.10E-07	2.74E-01	2.11E-01	6.58E-01	5.07E-01	9.99E-01	9.80E-01

Table B.11 Calculated sensitivity ratios and coefficients of each impact category for the amount of plastic, electricity use of cleaning and pelleting of plastic, fuel consumption of construction and use stage and the transportation distance of bitumen for scenario 2. All SRs ≥ 0.3 are coloured yellow indicating a medium sensitivity

Impact category	**PlastAmount**		**CPElec**		**ConstrDiesel**		**UseDiesel**		**BitTrans**	
	SR	**SC**	**SR**	**SC**	**SR**	**SC**	**SR**	**SC**	**SR**	**SC**
Climate change	4.66E-03	1.03E-01	8.68E-04	1.27E+02	3.33E-01	1.80E+06	3.12E-01	1.80E+06	5.02E-02	2.51E+02
Ozone depletion	3.90E-05	2.53E-10	2.39E-05	1.02E-06	4.09E-04	6.49E-04	3.83E-04	6.49E-04	2.80E-02	4.11E-05
Human toxicity, ce	3.56E-03	3.03E-10	1.62E-03	9.12E-07	1.12E-01	2.34E-03	1.05E-01	2.34E-03	5.75E-02	1.11E-06
Human toxicity, nce	3.92E-03	1.62E-08	5.45E-05	1.50E-06	3.50E-01	3.56E-01	3.27E-01	3.55E-01	9.74E-03	9.16E-06
Particulate matter	2.55E-03	2.52E-05	3.22E-04	2.10E-02	2.03E-01	4.91E+02	1.90E-01	4.90E+02	1.36E-01	3.05E-01
Ionising radiation, hh	9.20E-05	1.95E-04	2.38E-05	3.35E-01	4.92E-03	2.56E+03	4.60E-03	2.56E+03	3.45E-02	1.66E+01
Photochemical ozone form.	3.44E-03	7.01E-04	4.23E-05	5.72E-02	3.30E-01	1.65E+04	3.09E-01	1.65E+04	8.22E-02	3.81E+00
Terrestrial acidification	2.76E-03	5.29E-04	3.72E-05	4.73E-02	2.62E-01	1.23E+04	2.45E-01	1.23E+04	1.51E-01	6.58E+00
Eutrophication Terrestrial	3.94E-03	2.66E-03	3.78E-05	1.69E-01	3.79E-01	6.27E+04	3.54E-01	6.27E+04	9.30E-02	1.43E+01
Eutrophication Freshwater	1.62E-03	2.66E-07	5.88E-04	6.38E-04	3.84E-02	1.54E+00	3.59E-02	1.54E+00	1.25E-01	4.67E-03
Eutrophication Marine	3.95E-03	2.38E-04	3.65E-05	1.46E-02	3.80E-01	5.62E+03	3.56E-01	5.62E+03	9.31E-02	1.27E+00
Ecotoxicity freshwater	2.07E-03	1.36E-02	3.22E-04	1.40E+01	1.34E-01	2.16E+05	1.25E-01	2.16E+05	3.11E-02	4.65E+01
Fossil depletion	1.55E-03	1.10E+00	3.77E-05	1.77E+02	1.39E-01	2.42E+07	1.30E-01	2.42E+07	2.36E-02	3.79E+03
Elements depletion	5.74E-04	1.76E-07	2.48E-04	5.01E-04	1.84E-02	1.38E+00	1.72E-02	1.38E+00	1.64E-02	1.14E-03

B.6 Scenario analysis

Table B.12 Impact categories, units and normalisation factors of the ReCiPe v.1.11, Midpoint (H) Hierarchist, Europe LCIA method.

Impact category	Unit	ReCiPe, (H) Europe
Climate change	kg CO2 eq/p/yr	1.12E+04
Ozone depletion	kg CFC-11 eq/p/yr	2.20E-02
Terrestrial acidification	kg SO2 eq/p/yr	3.44E+01
Freshwater eutrophication	kg P eq/p/yr	4.15E-01
Marine eutrophication	kg N eq/p/yr	1.01E+01
Human toxicity	kg 1,4-DB eq/p/yr	6.27E+02
Photochemical oxidant form.	kg NMVOC/p/yr	5.68E+01
Particulate matter formation	kg PM10 eq/p/yr	1.49E+01
Terrestrial ecotoxicity	kg 1,4-DB eq/p/yr	8.25E+00
Freshwater ecotoxicity	kg 1,4-DB eq/p/yr	1.10E+01
Marine ecotoxicity	kg 1,4-DB eq/p/yr	8.73E+00
Ionising radiation	kg U235 eq/p/yr	6.26E+03
Agricultural land occupation	m2a/p/yr	4.52E+03
Urban land occupation	m2a/p/yr	4.07E+02
Natural land transformation	m2/p/yr	1.61E-01
Water depletion	m3/p/yr	0.00E+00
Metal depletion	kg Fe eq/yr	7.13E+02
Fossil depletion	kg oil eq/p/yr	1.56E+03

B.7 Uncertainty propagation

The uncertainty propagation was executed using a Monte Carlo simulation. The results of the Monte Carlo can be seen in figures; B.1, B.2, B.3, B.4, B.5, B.6, B.7, B.8, B.9, B.10, B.11, B.12, B.13 and B.14 for each impact category.

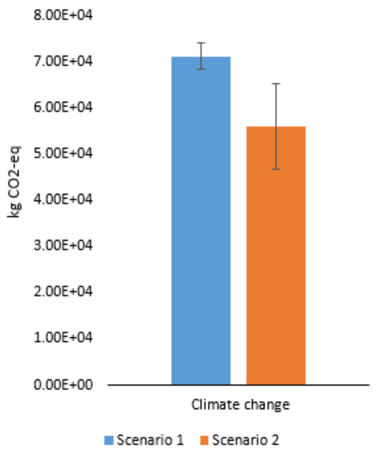

Figure B.1 Monte Carlo sensitivity for Climate change impact category.The error bars represent two standard deviations and show the results of this impact category with 95% certainty

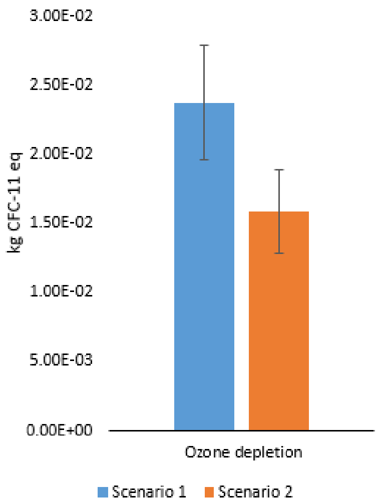

Figure B.2 Monte Carlo sensitivity for Ozone depletion impact category. The error bars represent two standard deviations and show the results of this impact category with 95% certainty

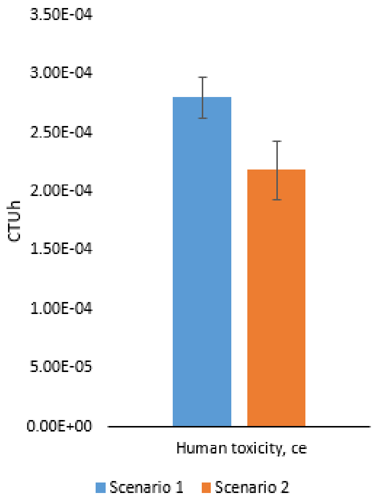

Figure B.3 Monte Carlo sensitivity for Human toxicity (cancer effects) impact category. The error bars represent two standard deviations and show the results of this impact category with 95% certainty

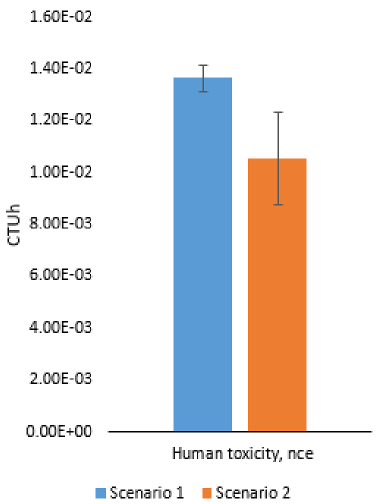

Figure B.4 Monte Carlo sensitivity for Human toxicity (non-cancer effects) impact category.The error bars represent two standard deviations and show the results of this impact category with 95% certainty

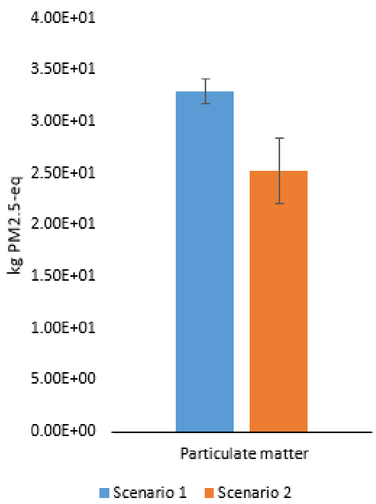

Figure B.5 Monte Carlo sensitivity for Particulate matter impact category. The error bars represent two standard deviations and show the results of this impact category with 95% certainty

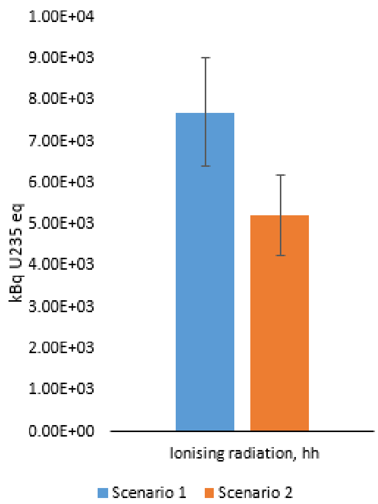

Figure B.6 Monte Carlo sensitivity for Ionising radiation (human health) impact category. The error bars represent two standard deviations and show the results of this impact category with 95% certainty

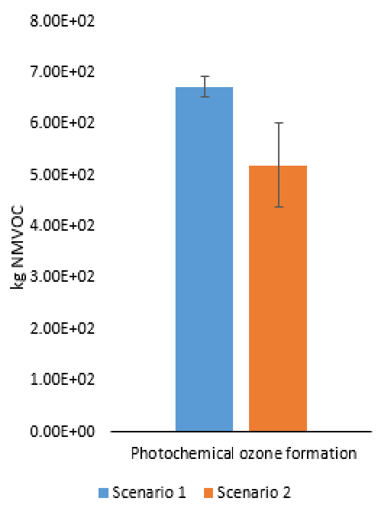

Figure B.7 Monte Carlo sensitivity for Photochemical ozone formation impact category.The error bars represent two standard deviations and show the results of this impact category with 95% certainty

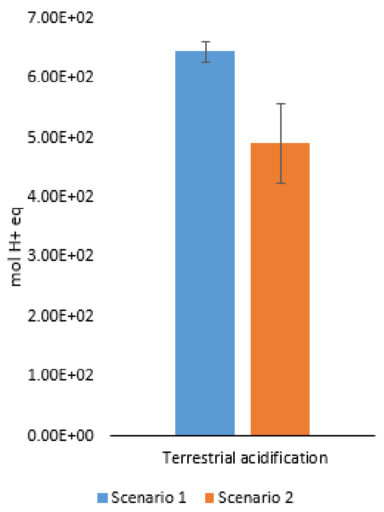

Figure B.8 Monte Carlo sensitivity for Terrestrial acidification impact category. The error bars represent two standard deviations and show the results of this impact category with 95% certainty

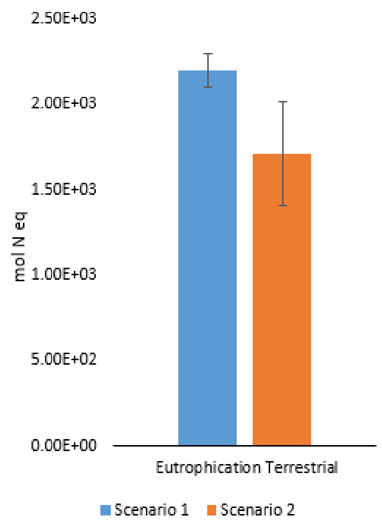

Figure B.9 Monte Carlo sensitivity for Eutrophication terrestrial impact category. The error bars represent two standard deviations and show the results of this impact category with 95% certainty

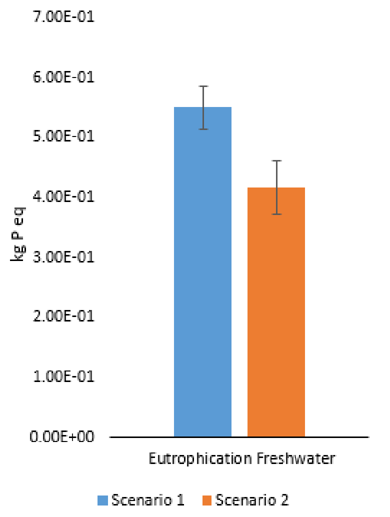

Figure B.10 Monte Carlo sensitivity for Eutrophication freshwater impact category.The error bars represent two standard deviations and show the results of this impact category with 95% certainty

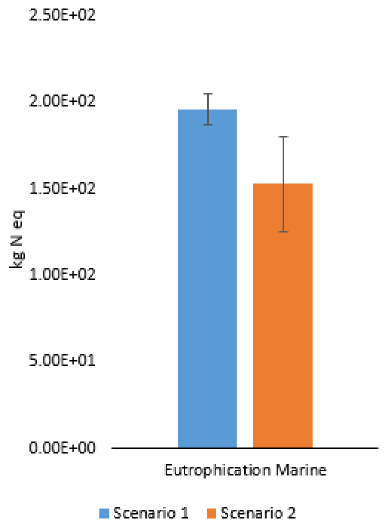

Figure B.11 Monte Carlo sensitivity for Eutrophication marine impact category. The error bars represent two standard deviations and show the results of this impact category with 95% certainty

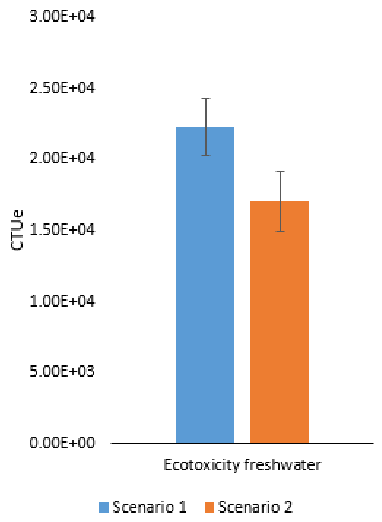

Figure B.12 Monte Carlo sensitivity for Ecotoxicity freshwater impact category. The error bars represent two standard deviations and show the results of this impact category with 95% certainty

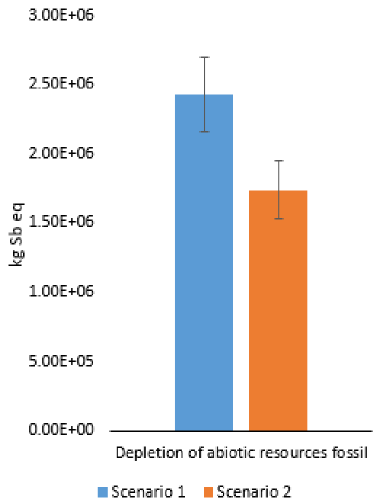

Figure B.13 Monte Carlo sensitivity for Depletion of abiotic resources, fossil impact category.The error bars represent two standard deviations and show the results of this impact category with 95% certainty

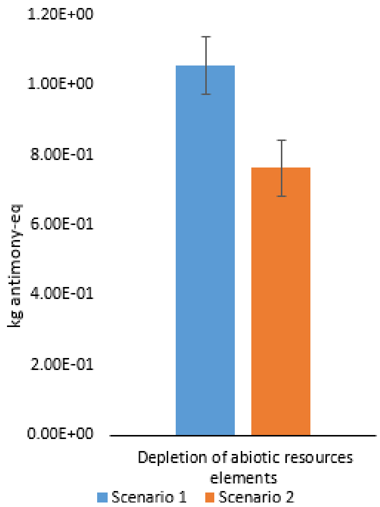

Figure B.14 Monte Carlo sensitivity for Depletion of abiotic resources, elements impact category. The error bars represent two standard deviations and show the results of this impact category with 95% certainty

B.8 Uncertainty propagation, no lifetime change

In this section are probability and cumulative distribution graphs generated by results of a Monte Carlo simulation assuming that there would be no difference in lifetime between the two road alternatives in scenarios 1 and 2. There parameters which were used for the analysis are the same as before (see table 4.6) and are mentioned in the captions of each figure pair (see figures B.15, B.16, B.17, B.18, B.19 and B.20).

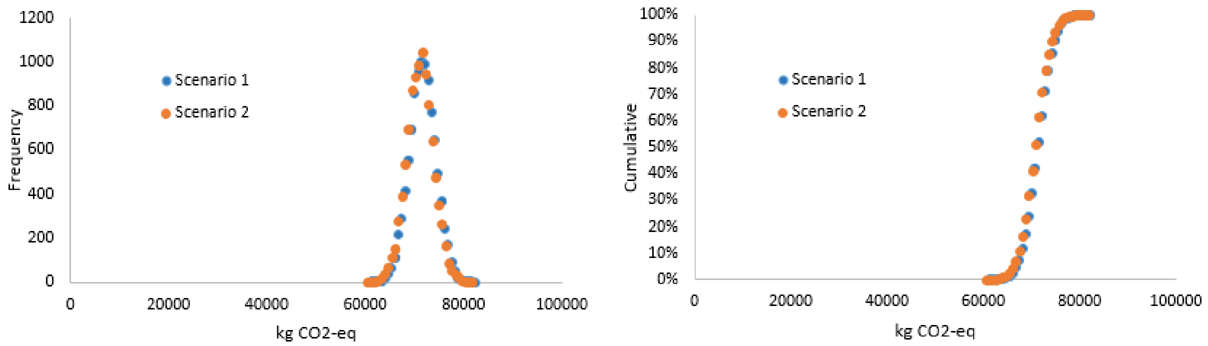

Figure B.15 Probability and Cumulative distribution graphs of the Climate change impact scores generated from the results of a Monte Carlo simulation run by assuming 5% variance of aggregate amount used (10 thousand iterations) for scenarios 1 and 2

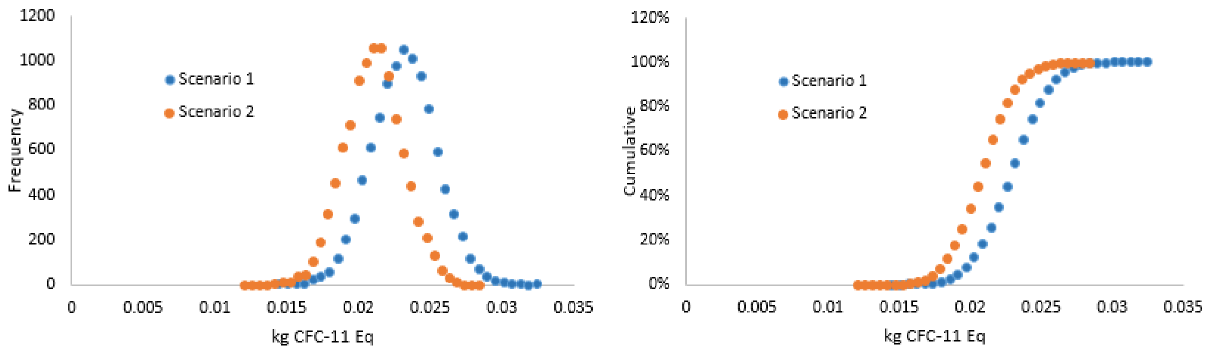

Figure B.16 Probability and Cumulative distribution graphs of the Ozone depletion impact scores generated from the results of a Monte Carlo simulation run by assuming 10% variance of bitumen extraction process efficiency (10 thousand iterations) for scenarios 1 and 2

The differences in scores between the scenarios are because of the bitumen and aggregate savings due to the addition of plastic waste. These probability and cumulative distributions show that even though there would not be an extended durability of the plastic enriched road there is some likelihood of savings connected to the impact categories shown.

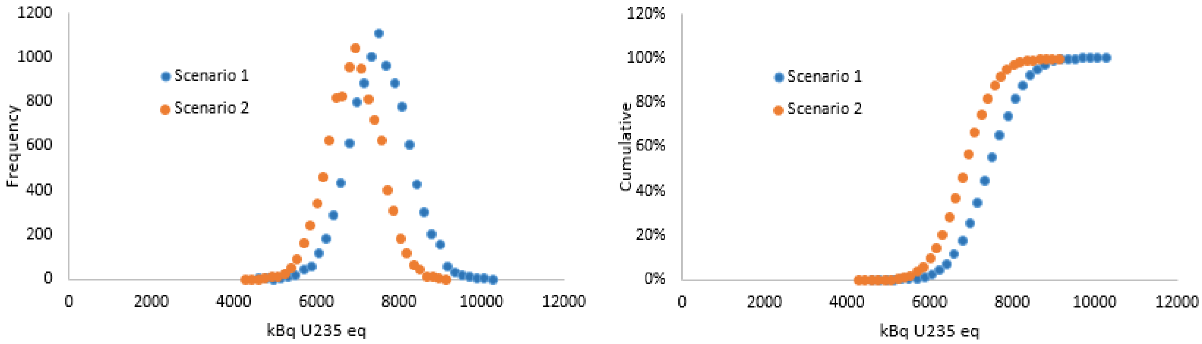

Figure B.17 Probability and Cumulative distribution graphs of the Ionising radiation (human health) impact scores generated from the results of a Monte Carlo simulation run by assuming 10% variance of bitumen extraction process efficiency (10 thousand iterations) for scenarios 1 and 2

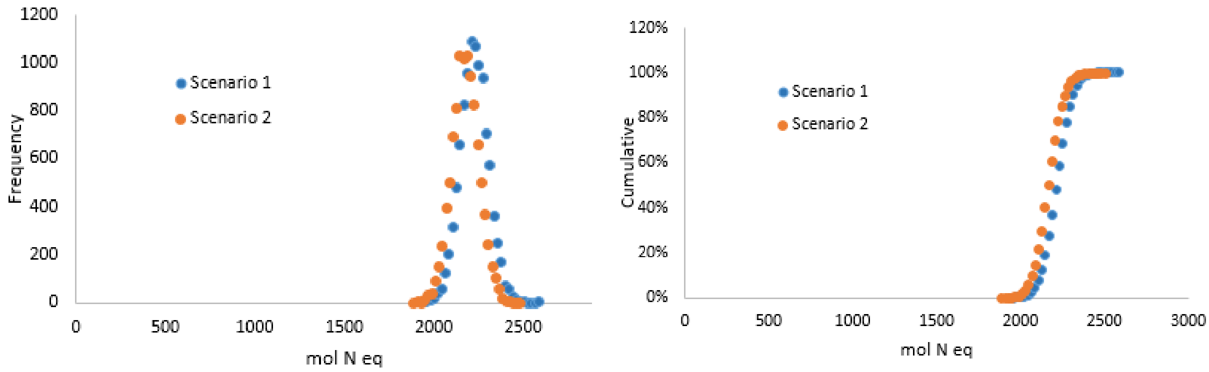

Figure B.18 Probability and Cumulative distribution graphs of the Eutrophication Terrestrial impact scores generated from the results of a Monte Carlo simulation run by assuming 10% variance of fuel consumption in the use stage (10 thousand iterations) for scenarios 1 and 2

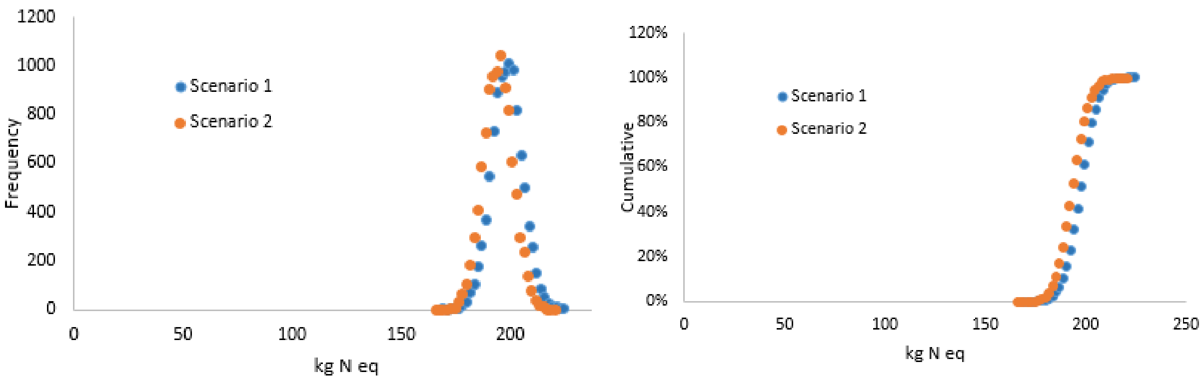

Figure B.19 Probability and Cumulative distribution graphs of the Eutrophication Marine impact scores generated from the results of a Monte Carlo simulation run by assuming 10% variance of fuel consumption in the use stage (10 thousand iterations) for scenarios 1 and 2

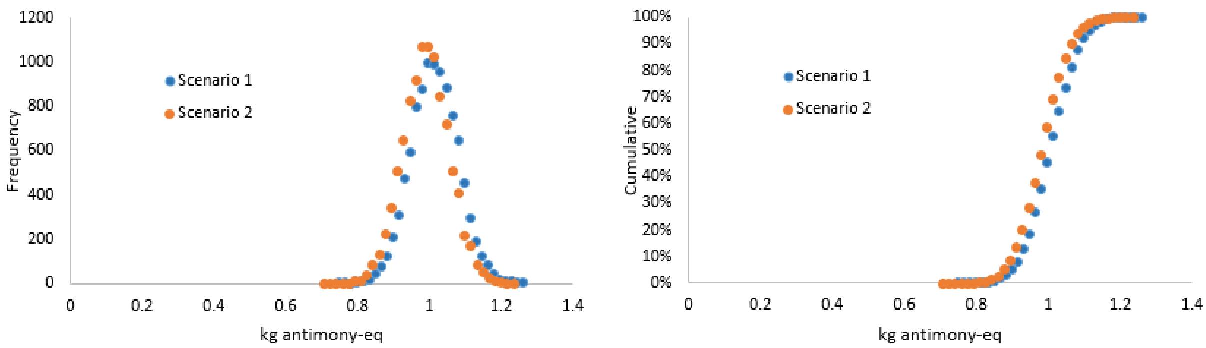

Figure B.20 Probability and Cumulative distribution graphs of the Depletion of abiotic resources, elements impact scores generated from the results of a Monte Carlo simulation run by assuming 10% variance of aggregate extraction process efficiency (10 thousand iterations) for scenarios 1 and 2

B.9 Choice of representation

A Monte Carlo simulation was performed on scenarios 1 and 2 in the case of changing the system model. The system model in this case; use stage cut-off and the crediting of RAP for aggregate (system model flow and system boundaries can be seen in figure 4.14). In table B.13 the average impact scores and their standard deviations obtained from the Monte Carlo simulation using the same parameters and parameter variations as before (see table 4.6).

Table B.13 Results obtained from a Monte Carlo simulation using a system model where use stage is cut-off and RAP is credited for aggregate. Average impact scores and their standard deviations are shown for all impact categories of scenarios 1 and 2. Red represents the highest relative uncertainty, yellow = medium relative uncertainty, green = some relative uncertainty, no color = >95% certain that scenario 2 has lower impact than scenario 1.

Impact category	**Unit**	**Scenario 1**		**Scenario 2**	
		Mean	**SD**	**Mean**	**SD**
Climate change	kg CO2-Eq	4.74E+04	2.40E+03	3.45E+04	2.99E+03
Ozone depletion	kg CFC-11 Eq	2.40E-02	2.30E-03	1.54E-02	1.82E-03
Human toxicity, ce	CTUh	2.04E-04	1.57E-05	1.47E-04	1.58E-05
Human toxicity, nce	CTUh	9.22E-03	4.72E-04	6.49E-03	5.66E-04
Particulate matter	kgPM2.5-eq	2.39E+01	1.44E+00	1.66E+01	1.63E+00
Ionising radiation, hh	kBq U235 eq	7.67E+03	7.36E+02	4.96E+03	5.85E+02
Photochemical ozone formation	kg NMVOC	4.64E+02	2.34E+01	3.24E+02	2.92E+01
Terrestrial acidification	mol H+ eq	4.80E+02	2.47E+01	3.29E+02	3.00E+01
Eutrophication Terrestrial	mol N eq	1.40E+03	6.46E+01	9.94E+02	8.68E+01
Eutrophication Freshwater	kg P eq	3.49E-01	3.11E-02	2.48E-01	3.05E-02
Eutrophication Marine	kg N eq	1.25E+02	5.75E+00	8.86E+01	7.73E+00
Ecotoxicity freshwater	CTUe	1.89E+04	1.48E+03	1.31E+04	1.36E+03
Depletion of abiotic resources fossil	kg Sb eq	2.14E+06	1.76E+05	1.45E+06	1.55E+05
Depletion of abiotic resources elements	kg antimony-eq	3.25E-01	5.94E-02	2.24E-01	4.88E-02