Environmental and economic assessment of RAP multi-recycling in bituminous mixtures

A case study of a road rehabilitation in Portugal

David Jonathan Gaby Roland Vandewalle

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Supervisor: Professor Doctor José Manuel Coelho das Neves
Supervisor (UGent): Professor Doctor Nele De Belie

Jury

Chairperson: Professor Doctor Maria do Rosário Maurício Ribeiro Macário
Supervisor: Professor Doctor José Manuel Coelho das Neves
Member of Committee: Professor Doctor Manuel Guilherme Caras Altas Duarte Pinheiro

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Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

Road assets, and more specifically their pavement, require high investments and generate high environmental impacts. Recent developments such as a rise in energy cost, environmental concerns and a common sustainability awareness, have led governments and agencies to attempting to lower the life cycle cost and the environmental impact. One rehabilitation technique that is reported to reduce these factors is the incorporation of reclaimed asphalt pavement (RAP) into new bituminous mixtures. Recycling and multi-recycling contribute to waste reduction and optimize the use of resources, both key elements in a circular economy approach. The main objective of this dissertation is to assess the environmental and economic impacts of RAP incorporation in bituminous mixtures. This study evaluates and quantifies the decrease in economic and environmental impact by performing a life cycle assessment (LCA) and life cycle cost analysis (LCCA) on the pavement of a Portuguese road section. In this case study, five construction, maintenance and rehabilitation scenarios were compared, each including different percentages of RAP: 0, 25, 50, 75 and 100 %. As expected, scenarios comprising RAP showed a clear decrease in life cycle cost and in all environmental impact categories e.g. human health, resources, ecological factors etc. The average decrease in environmental impact for the scenario using 50 % of RAP for example, was reported to be 22 % and 21 % in life cycle cost. Moreover, the results demonstrated that both the cost and environmental impact decrease are directly proportional to the percentage of RAP used in the mixture.

Keywords

Pavement, recycling, rehabilitation, reclaimed asphalt pavement (RAP), life cycle assessment (LCA), life cycle cost analysis (LCCA)

Resumo

Os ativos rodoviários e mais especificamente os pavimentos exigem avultados investimentos e têm grandes impactos ambientais. Recentemente, questões como o aumento do custo de energia, as preocupações ambientais e a consciência de sustentabilidade têm motivado os governos e as administrações a adotar medidas de redução do custo do ciclo de vida e do impacto ambiental. Uma dessas medidas é a reciclagem, nomeadamente a incorporação de misturas betuminosas recuperadas (RAP) em novas misturas. A reciclagem múltipla contribuirá ainda mais à redução e otimização da utilização de resíduos, essencial à economia circular. O principal objectivo desta dissertação é avaliar os impactos ambientais e económicos da incorporação de RAP em misturas betuminosas. Este estudo avalia e quantifica a diminuição do impacto económico e ambiental através da avaliação do ciclo de vida (ACV) e da análise do custo do ciclo de vida (LCCA) do pavimento de uma estrada em Portugal. Neste caso de estudo foram avaliados cinco cenários de reabilitação para diferentes incorporações de RAP: 0, 25, 50, 75 e 100 %. Como expectável, a incorporação de RAP levou à redução no custo total do ciclo de vida e em todas as categorias de impacto ambiental, como saúde humana, recursos, fatores ecológicos etc. A redução média no impacto ambiental e no custo do ciclo de vida, para o cenário de 50 % de RAP, por exemplo, foi 22 % e 21 % respetivamente. Além disso, foi constatado que o custo total e o impacto ambiental diminuíram e foram diretamente proporcionais à incorporação de RAP.

Palavres-chave

Pavimento, reciclagem, reabilitação, mistura betuminosa recuperada (RAP), avaliação do ciclo de vida (ACV), análise de custo de ciclo de vida (LCCA)

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List of Acronyms

APA	Asphalt Pavement Association
APOS	Allocation at Point Of Substitution
ARRA	Asphalt Recycling and Reclaiming Association
B/C	Benefit/cost (ratio)
CDW	Construction and demolition waste
CIR	Cold in-place recycling
DGM	Dense-graded macadam
EUAC	Equivalent uniform annual cost
FDR	Full depth reclamation
FHWA	Federal Highway Association
HIR	Hot in-place recycling
HMA	Hot mix asphalt
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
M&R	Maintenance and rehabilitation
NPV	Net present value
PAP	Performance analysis period
PM	Penetration macadam
RAP	Reclaimed asphalt pavement
SMA	Stone-mastic asphalt
US	United States
VOC	Vehicle operation Cosc
WMA	Warm mix asphalt
WMM	Wet-mix macadam
WZ	Work zone

1 INTRODUCTION

This chapter gives a brief overview of the work. Before establishing the aim and objectives of this dissertation, a problem statement is formulated. The chapter finishes with a short summary of the work structure of this study.

1.1 Problem statement

Relatively recent developments such as a rise in energy cost, environmental concerns and a common sustainability awareness, have led to a shift in focus when it comes to evaluating assets we procure and use. Governments are trying to minimize not only the life cycle cost of constructed assets but also consider lowering the environmental impact (Davis Langdon, 2007a).

One of those constructed assets are roads and more specifically their pavement. Roads often require high investments and generate high environmental impacts. The incorporation of reclaimed asphalt pavement (RAP) into new mixtures is reported to lead to a reduction in life cycle cost and environmental impact, in comparison to pavements which comprise exclusively virgin materials (Lee et al., 2010; Aurangzeb et al., 2014).

Recycling contributes to waste reduction and optimizes the use of resources, both key elements in a circular economy. The repeated reusing, or multi-recycling of RAP, together with an economic and environmental assessment combination as presented in Santos et al. (2017) form the main innovative subjects of this dissertation.

1.2 Objectives and methodology

The main goal of this dissertation is to assess the environmental and economic impact of RAP incorporation in bituminous mixtures. This aim is thus to provide a clear understanding on how RAP and multi-recycling of flexible pavements could not only affect the total cost of a road pavement but also the impact it has throughout its life-cycle on human health, resources, ecological factors, among others.

This dissertation has therefore two specific key objectives:

1. Firstly, to analyse how RAP incorporation affects the environmental impact of a road pavement unit by performing a life cycle assessment (LCA).
2. Secondly, to study the economic influence by carrying out a life cycle cost analysis (LCCA).

To evaluate the possible advantages of RAP incorporation, and multi-recycling in pavement rehabilitation an LCA and LCCA were performed on a section of a flexible road pavement in Portugal, representative for local conditions. The first assessment, the LCA, tries to address the impact of the pavement section on human health, ecological factors and resources. And, more importantly, how the incorporation of RAP could reduce this impact. The second, the LCCA, attempts to evaluate the costs associated with the pavement section throughout its life cycle. And, correspondingly to the LCA, how the use of RAP could potentially reduce these costs.

1.3 Thesis organisation

This thesis consists of seven chapters and two annexes. The diagram shown in Figure 1-1 represents the general structure. The first chapter –chapter 1– includes an introduction to the subject, the aim and objectives and the organisation of this dissertation. Chapters 2, 3 and 4 comprise an extensive literature review and each discuss existing literature on one component, namely flexible pavements (chapter 2), LCA (chapter 3) and LCCA (chapter 4).

Chapters 5 and 6, in combination with annexes A and B comprise a case study of a Portuguese highway flexible pavement section. Chapter 5 includes the LCA of the flexible pavement unit. The LCA, performed in the SimaPro software, evaluates the environmental impact induced by RAP incorporation by comparing five scenarios of a road pavement unit, each with a different percentage of RAP incorporation (0, 25, 50, 75 and 100 %). Chapter 6 then consists of the LCCA applied on the same five structure scenarios presented in chapter 5. The LCCA assesses the economic impact of RAP incorporation by comparing several cost aspects of these scenarios. Finally the last chapter –chapter 7– reviews the overall results presented in chapters 5 and 6, draws a general conclusion and makes suggestions for possible future analyses.

The included annexes A and B, respectively contain a number of calculations and background data. The calculations in annex A comprise conversions and calculations of primary data to be used as input for the LCA further described in chapter 5. The calculations in annex B provide the input for the LCCA presented in chapter 6.

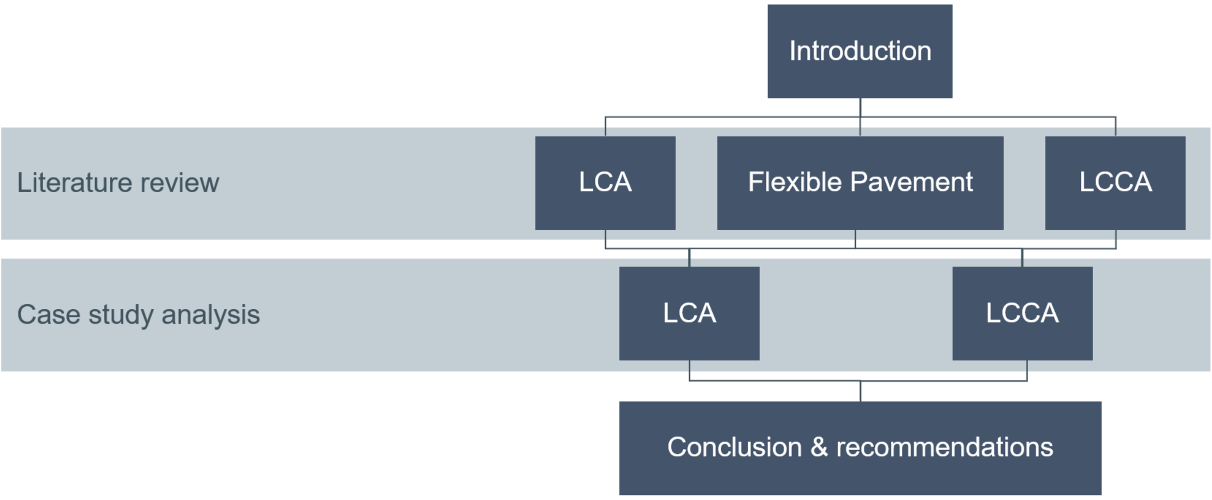


Figure 1-1 Thesis structure diagram

2 FLEXIBLE PAVEMENTS

Chapter 2 presents the first part of the literature review. It offers a small overview and review of existing literature regarding pavements and flexible road pavements in particular. Flexible pavement definition, properties, structure, failure, and rehabilitation methods are discussed in this chapter.

2.1 Introduction

A road is generally classified as a way used for travelling between places and hence accommodating one or multiple types of traffic. Depending on the type and amount of traffic a road can remain unpaved, as is sometimes the case in rural areas, though is often surfaced with a type of pavement. Unpaved roads consist of different types of material, such as gravel, sand, cobblestone, etc. Paved roads on the contrary, can be divided into two main types: flexible and rigid pavements (O'Flaherty, 2002). This paragraph mainly discusses the properties, use, construction, maintenance and rehabilitation methods of flexible pavements.

2.2 Definition and properties

A road pavement is a structure of overlaid layers or courses of selected and processed materials that is placed on the basement soil or subgrade (O'Flaherty, 2002). A typical pavement is assembled as follows: after the earthworks and the formation of a solid foundation, a subgrade layer is placed. The subgrade is then compacted with an optional subbase course consisting of aggregates (sand or crushed rock) on top of it. Once placed and the drainage is installed, the pavement layers are constructed. Which type of layers and their characteristics are discussed further in 2.3.

As mentioned in the introduction of this paragraph, two main types of pavements can be considered: flexible and rigid. It is internationally accepted that “a flexible pavement is any pavement other than a Portland cement concrete one”. This definition however, does not truly reflect the characteristics of the types of constructions masquerading as ‘flexible’ pavements. In practice, the classical flexible pavement has several unbound and/or bitumen-bound granular layers that are topped by a surface layer which, most commonly (but not exclusively), is bitumen-bound (O'Flaherty, 2002). Bituminous mixtures are composed of these bitumen-bound granular layers. There are several types of bituminous mixtures and asphalt concrete is one of the most current. Due to the presence of bituminous mixtures in those type of pavements, they are also designated bituminous pavements.

Regarding the bearing capacity, the difference between the two main types of pavement translates mostly in a difference in load distribution throughout the structure. Rigid pavements, because of the concrete’s strength and rigidity, tend to distribute the load over a wide area of subgrade as seen in Figure 2-1. The concrete slab itself supplies a major portion of a rigid pavement's structural capacity (ACPA, 2019). As the name implies, rigid pavement will almost not bend. The amount of flex is so small however, that they are considered rigid compared to flexible pavements. The rigidity of concrete allows the concrete surface layer to bridge small weak areas in the supporting layer through beam action. This allows the placement of rigid pavements on relatively weak supporting subgrade layers (SANRAL, 2019). The optional base and subbase courses are omitted in Figure 2-1, by way of clarification. In the case of flexible pavements, the intensity of a load is generally diminished as it is transmitted downwards from the surface by spreading it over an increasingly larger area (Figure 2-2). The material quality, or at least the degree of strength, can therefore gradually decrease throughout the structure (SANRAL, 2019). Flexible pavement, inherently built with different and less stiff material, does not spread loads as well as concrete. Therefore, flexible pavements usually require more layers and greater thickness for optimally transmitting load to the subgrade (ACPA, 2019).

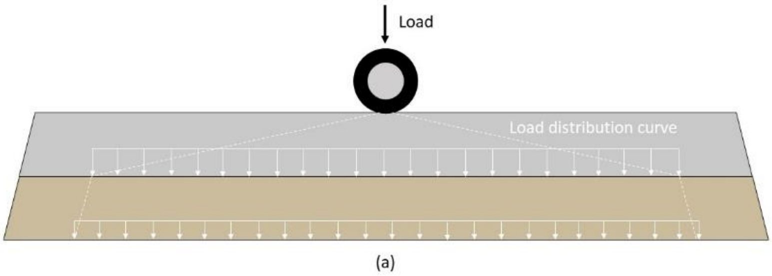


Figure 2-1 Rigid pavement load distribution (SANRAL, 2019)

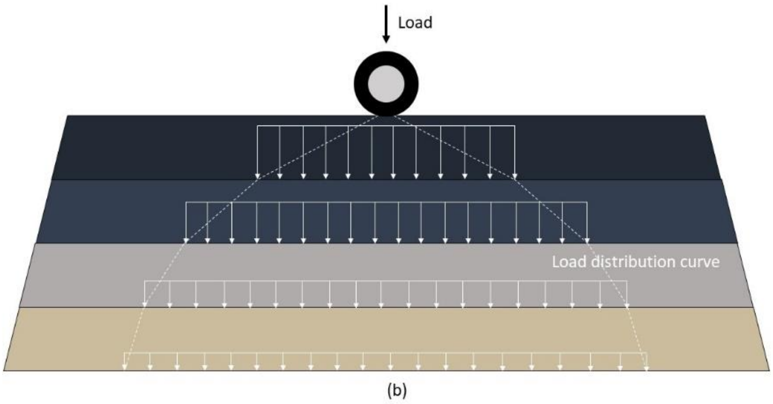


Figure 2-2 Flexible pavement load distribution (SANRAL, 2019)

Figure 2-3 provides an overview of flexible and rigid pavements most common in new structures. However, other types of pavement are classified as semi-rigid and combine characteristics of both types of pavement. O’Flaherty (2002) divides this third type into two subtypes: flexible composite pavement and rigid composite pavement. These two composite structures are formed with layers of bitumen- and cement-bound materials.

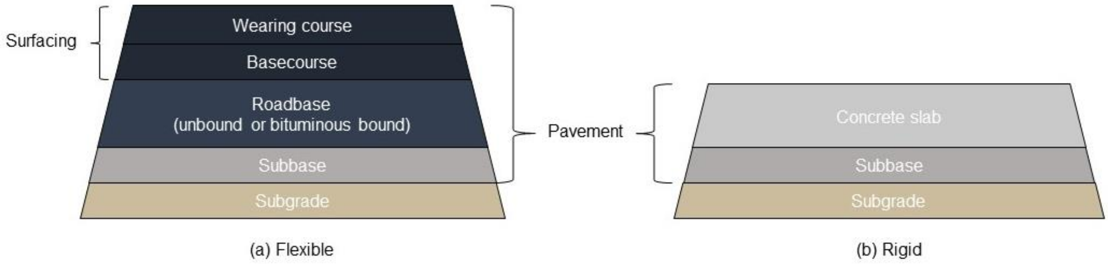


Figure 2-3 Basic elements of new flexible and rigid pavements (O'Flaherty, 2002)

2.3 Flexible pavement layers

The top layer of a flexible pavement is defined as the surface layer or surfacing in short. The functionality of this layer is twofold: it offers the road a safe, smooth and stable riding surface and contributes to the overall pavement stability by protecting it from natural elements. A surface layer composed of bituminous mixtures can either comprise a single homogeneous layer but more usually, however, comprises two distinct sublayers known as a wearing course (more commonly referred to as the surface course) and a basecourse (in mainland Europe and hence further on in this study referred to as binder course). Both are usually laid in separate operations (O'Flaherty, 2002).

The road base, often referred to as the base course, is considered as the main structural layer in a flexible pavement. These layers are designed to be dense, stable and resist both fatigue cracking and structural deformation (O'Flaherty, 2002).

The subbase layer, which is optional but commonly present in flexible pavements, can be used in different ways, depending on its intended function. It first distributes the loads from traffic further to the weaker subgrade layer. Secondly, a subbase is constructed to protect the subgrade layer, especially in the case of weak soil, during construction phase. Heavy construction equipment such as paving machines and hauling trucks might damage the subgrade if it is of poor quality. Other important functionalities of the subbase during construction involve the upward infiltration prevention of fine-grained subgrade soil into the base course and the downward frost action prevention (O'Flaherty, 2002).

Figure 2-4 presents the construction phase of the surface layer with a bituminous mixture overlay in the case of pavement rehabilitation.

Figure 2-4 Rehabilitation of a pavement surface layer with a bituminous mixture overlay

2.4 Bituminous mixtures

Previous paragraph discussed the structure and different layers of a typical flexible pavement. As mentioned before, these layers generally contain a bituminous mixture, which in turn usually consists of two main components: aggregate and a bituminous binder. These are combined (often with additives to enhance performance) in a certain ratio, according to the circumstances, specific situations or common practice (De Corte, 2017-2018).

The Asphalt Pavement Alliance (2019), divides bituminous pavements into three main categories, based on the sort of voids used in the mix:

a) **Dense-graded asphalt:**
   Dense-graded asphalt is the most common type of asphalt. The fundamental properties of this type of bituminous mixture are specified by EN 13108-1.

b) **Open-graded asphalt:**
   Open-graded asphalt is specifically designed to allow water to drain through. It is also defined as porous asphalt and specified in standard EN 13108-7.

c) **Stone-mastic asphalt:**
   Stone-mastic asphalt (SMA) is a gap-graded asphalt pavement designed to improve rut resistance and durability using a stable stone-on-stone skeleton held together by a rich mixture of asphalt cement, along with stabilizing agents such as fibres and/or asphalt modifiers. SMA is primarily used to pave high-volume interstates and highways, achieving high levels of rutting resistance and durability. In addition to improved durability and rutting resistance, SMA has very good friction characteristics. They have been shown to be effective in reducing road spray and traffic noise. SMA has also been successfully used on high-volume urban roadways with heavy bus and truck traffic (Asphalt Pavement Alliance, 2019). This type of bituminous mixture is specified in EN 13108-5.

Additional sections of EN 13108 include other types of bituminous mixtures, e.g. asphalt concrete for very thin layers (EN 13108-2), soft asphalt (EN 13108-3) and hot rolled asphalt (EN 13108-4). Depending on the temperature of production and compaction, bituminous mixtures can be classified as hot mix asphalt (HMA) or warm mix asphalt (WMA).

In general, bituminous mixtures are produced in asphalt plants (Figure 2-5a) and, after truck transportation, they are spread using an asphalt paver and, finally, compacted by wheel and roller compactors (Figure 2-5b).

Figure 2-5 Production (left) and application of a bituminous mixture (right)

The most important materials used in flexible pavement mixtures are bitumen and aggregates. Both materials and their properties will be discussed separately in following paragraphs. In other special bituminous mixtures, additives are added in small quantities, e.g. fibres or polymers, to modify the performance, the workability or the colour.

2.4.1 Aggregates

Aggregates in road construction are defined as hard, inert materials such as rocks (course aggregates), sand (fine aggregates) or another type of filler. Different types and sizes of material are often used to create beneficial characteristics. The most common aggregates used in road pavements are virgin materials such as natural rock materials, gravels and sands. More recently however, aggregates are replaced by recycled materials e.g. slag aggregates, reclaimed asphalt pavement (RAP), construction and demolition waste (CDW).

2.4.2 Bituminous binder

The bituminous binder, which only takes up around 5 % in asphalt concrete, consists mainly of a bitumen or a derivative. Bitumen is a complex material and contains mostly organic hydrocarbons (saturated and unsaturated aliphatic and aromatic compounds). Liquid asphalt forms naturally, such as at Pitch Lake in Trinidad, but most of the bituminous binder used is derived during the refinery distillation process that converts crude oil to fuel (Asphalt Pavement Alliance, 2019). This process includes condensation in a fractionating column. During the first distillation, which is carried out under 350°C, lighter fractions such as naphtha, gasoline and kerosene are removed. The ‘topped oil’ is then heated to collect the heavier diesel and lubricating oils. A bitumen residue remains (O'Flaherty, 2002).

Through the solution of the residue in hexane or heptane, a clear distinction can be made between asphaltenes (insoluble) and maltenes (soluble). Asphaltenes are high molecular weight species that are insoluble in these solvents, whereas maltenes have lower molecular weights and are soluble. Bitumens normally contain between 5 and 25 % by weight of asphaltenes and may be regarded as colloids of asphaltene micelles dispersed in maltenes (Freemantle, 1999).

Bituminous binder is classified as a thermoplastic material: it softens when heated and hardens when cooled. The material is also viscoelastic within a certain range of temperature according to Freemantle (1999): “it exhibits the mechanical characteristics of viscous flow and elastic deformation”. Although it can last for centuries within the crude oil, it doesn’t last when used for road pavement.

Nowadays, besides neat bitumen, modified bituminous binders with polymers, nanoparticles and other additives are used to improve bituminous mixtures’ performance and durability.

2.5 Pavement deterioration

To spend the -often large- budgets for road construction and rehabilitation wisely, it is imperative to consider pavement deterioration mechanisms, their cause and develop objective and consistent inspection methods. The accurate identification of a defect, i.e. including its cause, is considered important because even though the visual appearance of different defects may be similar, their cause and therefore the appropriate treatment (and treatment cost) can be substantially different (O'Flaherty, 2002). Several factors can influence the durability and performance of bituminous pavements. These factors are categorized by Haas (as cited by Nordfou, 2010) in Table 2-1.

Table 2-1 Pavement durability impact categories and factors (Haas, 2003)

Category	Impact factor	Category	Impact factor
Environment	Temperature	Maintenance	Treatment
	Moisture		Timing
	Radiation		Methods
	Freeze-thaw cycles		Quality
Traffic	Axle group	Structure	Layer thicknesses
	Loads		Layer types
	Tire types & pressures		Layer properties
	Axle spacing		Subgrade type
	Speed		Subgrade properties
	Repetitions		Variations in properties
Construction	Timing		
	Variance		
	As-built quality		
	Methods		

According to O’Flaherty (2002), the most common causes, traffic and climate, result in surface defects and/or structural deterioration. This typically includes:

- polishing of the stone in the surfacing, thereby reducing skidding resistance;
- loss of surface texture, also reducing skidding resistance;
- deformation of the surface due to traffic loading;
- oxidation of the binder, resulting in cracking and surface deterioration;
- fatigue of the bounded layers, which causes cracking and structural deterioration;
- deformation of the foundation, which causes rut and general structural deterioration.

2.6 Maintenance and rehabilitation

As stated earlier in this chapter, a flexible pavement surface will eventually fail in time due to weather conditions and traffic passage. It will thus, at some point, be the subject of one or multiple maintenance periods. According to Mallick and Kandhal (1997), there are three groups of rehabilitation methods: recycling, overlay and complete replacement (reconstruction). Which rehabilitation alternative is applied depends on several factors: the type and level of distress, the type of pavement, road requirements, availability of equipment and a skilful contractor, cost, impact on traffic, long-term maintenance cost, etc (Mallick & Kandhal, 1997).

Recently, the growing awareness about sustainability and environmental issues, have led decision-makers and technicians to correctly assess and correct resulting impacts from the manufacturing and application of bituminous mixtures (Botella et al., 2016). The authors also state that “the concept of sustainability has come to the field of bituminous mixtures with two main components: reducing emissions and consumption of raw materials and preserving resources for the future”.

Because of its clear advantages such as reduced cost, conservation of material, preservation of geometrics and environment and the conservation of energy, recycling sees a recent increase in use (Mallick & Kandhal, 1997). Both recycling and complete replacement of a bituminous pavement produce a considerable amount of Reclaimed Asphalt Pavement (RAP). RAP is defined as “asphalt reclaimed by milling of asphalt road layers, by crushing of slabs ripped up from asphalt pavements or lumps from asphalt slabs and asphalt from reject and surplus production” by the European standard EN 13108-8 (CEN, 2005).

RAP is obtained when asphalt pavements are removed for reconstruction, resurfacing of for gaining access to buried utilities. These pavement layers are removed by either milling or full-depth removal. The milling process, which can be seen in Figure 2-6, is done by a milling machine or miller. Milling machines today can be equipped with different types of cutter drum patterns. More teeth on the cutter drum produces finer patterns, yet production rates remain low. A lower number of teeth however, causes a courser surface but also higher production rates. Other parameters of the milling process include temperature of the pavement at the time of milling and the speed and depth of the milling. In some cases, for instance, courses are milled separately in order to isolate certain types of RAP (Antunes et al., 2019).

Figure 2-6: Milling of a flexible pavement

Full-depth removal on the other hand involves ripping and breaking the pavement. This is usually done by a rhino horn on a bulldozer and/or pneumatic pavement breakers. The broken material that's obtained from this operation is often subsequently transported to a central facility for processing. There, the RAP is crushed, screened, conveyed and then stacked (Antunes et al., 2019).

When properly crushed and screened, RAP consists of high-quality and well-graded aggregates coated by bitumen. This material can be processed and used to replace virgin aggregate and liquid bitumen in new bituminous mixtures (RAP mixtures). The Asphalt Recycling and Reclaiming Association (ARRA) (1992) establishes four different types of recycling methods that use RAP. The first method, hot recycling and RAP, uses a recycled mixture that is produced at a central processing plant, while the other methods adopt an in-situ methodology:

1. **Hot recycling and RAP**
   This recycling method uses RAP materials to produce new HMA, along with virgin materials. Both batch and drum type hot mix plants are used to produce recycled mixtures. The RAP material can be obtained by milling or ripping and crushing operations. The mixture placement and compaction equipment and procedures are the same as for regular HMA. Typically, 10 to 30 percent RAP is used in recycled hot mixes. The advantages of hot mix recycling include equal or better performance compared to conventional HMA, and capability to correct most surface defects, deformation, and cracking.
2. **Hot in-place recycling**
   According to the ARRA (1992), Hot in-place recycling (HIR) "consists of a method in which the existing pavement is heated and softened, and then scarified/milled to a specified depth. New HMA (with/without RAP) and/or recycling agent may be added to the scarified RAP material

during the recycling process. HIR can be performed either as a single pass or as a multiple pass operation.” The ARRA has identified three HIR processes (Asphalt Recycling and Reclaiming Association, 1992):

- Surface recycling: the existing surface is heated and subsequently scarified to a certain depth. The scarified material is then mixed with aggregate and/or recycling agent before being compacted.
- Repaving: this method combines the previous surface recycling with a simultaneous overlay of virgin HMA.
- Remixing: here, the RAP is mixed with virgin HMA and then paved as a single mix.

3. **Cold in-place recycling**

   In contrast to the previous technique, cold in-place recycling (CIR) uses no heat. The ARRA (1992) describes this method as follows: “the process includes pulverizing the existing pavement, sizing of the RAP, application of recycling agent, placement, and compaction. The use of a recycling train, which consists of pulverizing, screening, crushing and mixing units, is quite common. The processed material is deposited in a windrow from the mixing device, where it is picked up, placed, and compacted with conventional hot mix asphalt laydown and rolling equipment. Except for any recycling agent, no transportation of materials is usually required, and aggregate can be added, therefore hauling cost is very low. Normally, an asphalt emulsion is added as a recycling agent or binder.

4. **Full depth reclamation**

   Full depth reclamation (FDR) is defined by the ARRA (1992) as “a recycling method where all of the asphalt pavement section and a predetermined amount of underlying base material is treated to produce a stabilized base course”. The process is similar to a cold-mix recycling process with the addition of several additives to obtain an improved base (Asphalt Recycling and Reclaiming Association, 1992). The four main steps of this method are described by ARRA:

   - pulverization
   - introduction of additives
   - compaction
   - application of a surface course

According to Antunes et al. (2019), RAP mixtures have an economic and environmental advantage compared to mixtures that only incorporate virgin material. The environmental benefits are a direct consequence of a decrease in demand for raw material (aggregate and bitumen) and a reduction in emissions and energy. The application of RAP in new mixtures presents two main drawbacks however. The first can be described as a lack of confidence in RAP by several industry stakeholders due to studies that revealed certain weaknesses of the material when incorporated in new mixtures and the fact that in some cases virgin aggregates are cheaper than RAP. The second major drawback is due to a number of regulations that limit the incorporation of RAP in mixtures (Antunes et al., 2019).

3 LIFE CYCLE ASSESSMENT (LCA)

This chapter is the second part of the literature review. It offers an introduction into existing LCA practices, methodologies and software. Specific attention is spent on the application of LCA to flexible pavements.

3.1 Introduction

One of the most omnipresent constructed assets are road infrastructures. In fact, roads are not only an important part of a society's transportation network, they are often a public asset. Due to relatively recent developments such as a rise in energy cost, environmental concerns and a common sustainability awareness, there has been a shift in focus when it comes to evaluating assets we procure and use. According to Davis Langdon (2007a), governments are trying to minimize both the life cycle costs and environmental impact instead of simply considering lowest cost alone when it comes to achieving value from constructed assets.

According to Santos et al. (2017a) different stakeholders in the pavement sector have been seeking solutions for more sustainable pavement management and construction practices. The general approach for improving sustainability consists of reducing energy consumed, emissions generated, and virgin material used. This means implementing preventive maintenance, preferencing in-place recycling procedures, lowering the bituminous mixture heat and other eco-friendly pavement technologies (Santos et al., 2017a).

One of the most common methods to address these concerns and correctly quantify emissions, material and energy use is LCA (Said et al., n.d.). How and why this tool is used are the main subjects of following paragraphs.

3.2 Definition

According to Baumann and Tillman (as cited in Butt et al., 2014) LCA is a tool to investigate the environmental aspects of a product, a service, a process or an activity by identifying and quantifying the related input and output flows utilised by the system and its delivered functional output in a life cycle perspective. The LCA method should ideally be totally inclusive: assess the total environmental impact (Said et al., n.d.) and include all processes from a cradle-to-grave perspective (Butt et al., 2014). For a pavement LCA, this means that it starts with the acquiring of raw materials and ends with their disposal, considering a conventional linear economy. Several LCA methodologies and software tools include credits for substituted materials, but this remains not fully suitable for meaningful interpretation within a circular economy setting (Dieterle et al., 2018).

The LCA methodology was standardized by the International Organisation for Standardisation in the ISO 14040 series which divides the LCA framework into four steps (Butt et al., 2014):

1. Goal and scope definition (ISO 14040: 1997)
2. Inventory assessment (ISO 14040: 1997)
3. Impact assessment (ISO 14042: 2000)
4. Interpretation (ISO 14043: 2000)

Although above-mentioned standards were combined in EN ISO 14040: 2006, the general LCA framework described in this standard remains compiled of the same four stages. The methodology proposed in this study follows this general framework.

The first step, goal and scope definition, consists of pinpointing the purpose and boundaries of the study. This step also defines the audience, application of the exercise and the functional unit that will be used. The second step, the life cycle inventory (LCI), inputs (resources) and outputs (emissions) are compiled in relation to the functional unit. This step consists of collecting enough data to describe the whole life cycle of the product, process, service or activity. The third step, the life cycle impact assessment (LCIA), presents the link between the system described in the second step and the exterior; which kind of effect the system has on humans and the environment. Finally, in the fourth step, the results from the previous steps are interpreted and evaluated. To correctly make assumptions, improvements or recommendations, the results are analysed in relation to the first step. According to Van Dam et al. (2015) an LCA can be used for several purposes:

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle.
- Informing and guiding decision makers in industry, government, and non-governmental organizations for a number of purposes, including strategic planning, priority setting, product or process design selection, and redesign.
- Selecting relevant indicators of environmental performance from a system-wide perspective.
- Quantifying information on the environmental performance of a product or system (e.g., to implement an eco-labelling scheme, make an environmental claim, or produce an environmental product declaration statement).
- Differences in results from an LCA can guide decision makers into making choices that have lower or reduced environmental impacts.

3.3 Pavement life cycle

The life cycle of a pavement is usually divided into several phases. Table 3-1 presents the different pavement life cycle phases, according to three references:

1. Harvey et al. (2016), in correspondence with FHWA’s framework;
2. Santos et al. (2018)
3. Santero et al. (2010)

Table 3-1 Pavement life cycle phases

<table>
<tr><th>Ref.</th><th colspan="7">Life cycle phases</th></tr>
<tr><td>(1)</td><td>Material production</td><td>Design</td><td>Construction</td><td colspan="2">Maintenance/ preservation</td><td>Use</td><td>End-of-life</td></tr>
<tr><td rowspan="2">(2)</td><td colspan="4">Transportation of materials and mixtures</td><td></td><td>Use</td><td>Transportion of materials</td></tr>
<tr><td>Materials extraction</td><td>Bituminous mixtures production</td><td colspan="2">Construction and M&R</td><td>WZ traffic management</td><td>Use</td><td>End-of life</td></tr>
<tr><td>(3)</td><td colspan="2">Raw materials and production</td><td>Construction</td><td colspan="2">Maintenance</td><td>Use</td><td>End-of-life</td></tr>
</table>

Each phase comprises of several components or processes. A process represents an interaction between the pavement structure and the environment. According to Santero et al. (2010) these components “represent the direct processes by which pavement structures impact the environment; indirect and upstream processes are not shown, but would include the supporting processes for these components, such as electricity generation and fuel production.” Figure 3-1 shows a general pavement life cycle.

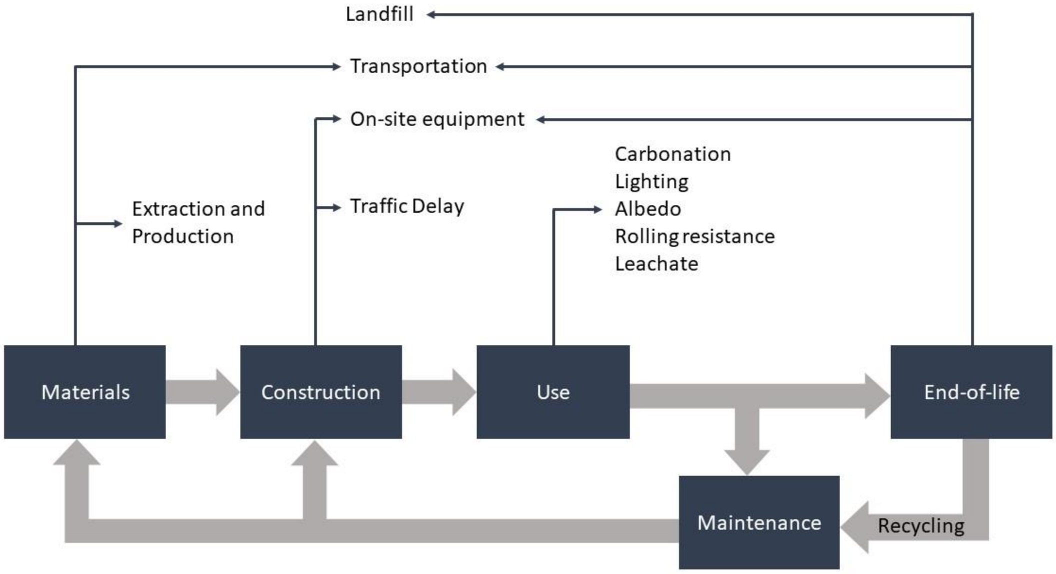


Figure 3-1 Phases and components of pavement life cycle (Santero et al., 2010)

3.4 Existent knowledge

Various studies and methods concerning pavement LCA have been published across different outlets including industry organizations, peer-reviewed journals and government reports. As mentioned before, the ideal procedure of an LCA is inclusive, which means that each phase or process in the product life cycle is discussed and nothing is omitted. Due to time, resource or data constraints, most studies fail to do so (Santero et al., 2010).

Santero et al. (2010) evaluated the then existent pavement LCA literature, consisting of fifteen studies, across four key methodological attributes; (1) functional unit comparability; (2) system boundary comparability; (3) data quality and uncertainty; and (4) environmental metrics. Although many more studies have been published since, the general remarks state by the authors and discussed in following paragraphs, are still significant.

1. **Functional unit comparability**
   One of the most important drawbacks for pavement LCA's in general, according to Santero et al. (2010), is the lack of consensus upon the proper functional unit. The functional unit of a pavement LCA is largely defined by two main parameters; the traffic and the analysis period. Santero et al. (2010) state that it is impossible to define a single, generally valid functional unit because of the large number of characteristics that define a pavement. Individual pavement LCAs will therefore need to establish a unique functional unit based on the goal and scope of the study. However, the basis for defining the functional unit "should address a standardized set of characteristics that accurately describe the pavement structure and its material properties, the performance standards for the pavement, and relevant exogenous variables, such as climate" (Santero et al., 2010).
2. **System boundary comparability**
   A second important point of comparison is the boundary or scope of pavement LCA studies. Santero et al. (2010) state that the purpose of every LCA should be to evaluate a product or process throughout its whole life cycle, including both direct and indirect impacts. Due to a lack of data and/or thoroughly understanding the system, accurately modelling and understanding each process or phase is inhibited. In neglecting to incorporate certain phases, LCA's not only use incomplete information, but valuable knowledge is also lost regarding ways to reduce the environmental impact. Moreover, research has shown that "the typically omitted phases and components are potentially large (or even dominant) contributors to the overall impact of a pavement (Santero et al. as cited in Santero et al., 2010).
   Probably the most significant omission from nearly all studies is that of the use phase. The use phase includes potentially influential components such as fuel consumption attributed to the roughness and structure of the pavement, the urban heat island effect, radiative forcing, concrete carbonatation, and leachate. Omissions like this can change the results of an LCA significantly and should therefore be well considered. As stated before, each project has its constraints (time, data availability…) so omissions of certain phases are insuperable. In these cases, "sensitivity analyses are a key tool to gain perspective on the potential influence of uncertain parameters" (Santero et al., 2010).
3. **Data quality and uncertainty**
   A third point of comparison is the quality of data used in the LCA. Almost every (pavement) LCA will, at some point, be confronted with data scarcity and reliability issues. In order to take this uncertainty and risk into account, it is prudent to perform sensitivity and uncertainty analyses to identify the robustness of the results (Santero et al., 2010).

4. **Environmental metrics**

   The LCI and LCIA scopes are the last factor of comparison presented by the authors. The last step of every LCA involves the evaluation of several alternatives based on their environmental performance. This performance however, can be measured through a wide range of different metrics.

   Santero et al. (2010) state that: “the focus on energy consumption and, to a lesser degree, conventional air pollutant and greenhouse gas emissions during the pavement life cycle, promotes a disproportionate amount of attention onto only a few environmental metrics. Water consumption, toxic releases, land use, and other indicators may be equally pressing environmental concerns, but are virtually non-existent in the existing pavement LCA literature”.

   Another important point of discussion is the feedstock energy of bitumen. Bitumen is a hydrocarbon and has therefore inherent energy that also should be accounted for. Since this feedstock energy is not really consumed energy, it should be treated or accounted for differently. Which technique should be used to calculate the feedstock energy is also a point of discussion amongst the different studies (Santero et al., 2010).

   ISO 14040 defines impact assessment as an LCA phase that is “aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts”. Most of the studies discussed in Santero et al. (2010) do not include a proper impact assessment. The paper also states that an impact assessment implies the use of weighting system in order to compare certain environmental impacts and combine them into a single score for the pavement variant. A weight-based approach however, holds an intrinsic subjectivity since the weights of different factors can be adapted to the goal of the study.

3.5 LCA tools

As mentioned in 3.2, an LCA should comprise four steps, according to the ISO14040:2006 standard:

1. Goal and scope definition
2. Inventory assessment
3. Impact assessment
4. Interpretation

To assist practitioners in performing these four steps efficiently, several types of tools and software were developed the past years and presented in this paragraph. According to Santos, et al. (2017b) there is a considerable variety of tools for conducting pavement LCA, and there are notable differences between them. Available tools cover different steps of LCA, consider different environmental issues and serve different purposes.

The first type of tools concern the databases which assist in the second step, the LCI, and are further discussed in 3.5.1. The second type are the impact methods that provide a framework to perform the third step, the life cycle LCIA, and are further discussed in 3.5.2. Lastly, presented and further discussed in 3.5.3, are the software packages which provide a user interface to perform the full LCA and often implement one or more databases and impact methods (Emami, et al., 2019).

3.5.1 LCI databases

The second stage of an LCA, the LCI, mainly consists of data collection. This data includes material inputs-outputs, extractions of resources, emissions of processes to air, water, and soil during the entire life cycle, etc. LCA is hence considered a data-intensive technique and data-availability can often form a problem for LCA-practitioners (Peereboom et al., 1999). Data is therefore often gathered from multiple sources, such as publicly available or commercial databases. Usually, two types of data are required (EC, JRC-IES, 2010):

- Primary data which is specific for the production processes for the product or service. Sources for primary data are the producers of goods and operators of processes and services, as well as their associations.
- Secondary data which presents generic and/or average data for the product or service studied. Secondary data sources which either give access to primary data (possibly after remodelling / changing the data) and to generic data are e.g. national databases, consultants, and research groups.

Data sources for secondary data are most often the above-mentioned commercial databases. These datasets commonly present distinctive features in terms of data sources, elementary flows inventoried and unit processes taken into account, technical, temporal and geographical representativeness. They can provide global, national or even regional or local data (Santos et al., 2017b).

Available tools cover different phases and processes of the pavement’s life cycle, take different environmental issues into account, and model with distinct levels of accuracy within chosen functional units and system boundaries. They can be global, national, or even regional or local. They have also been developed for different purposes, (e.g., research, consulting, and decision making), and their domain of applicability is tailored for different phases of a project’s life cycle, (e.g., planning, designing, construction and maintenance). Furthermore, they use different foreground and background generic or industry data. Also distinct is the level of interaction they allow with the user. While some of the tools are “black-boxes” in the sense that only the default processes and data can be used, others allow users to use their own data, to choose the database that best match the features of the case study, or even to modify the existing datasets (Santos et al., 2017b).

3.5.2 Impact assessment tools

Based on the data collected in the second step of an LCA, an LCI result table is usually produced. This table often contains hundreds of elementary flows which represent emissions and or extractions to and from the environment. The impact assessment which is subsequently performed based on the flows presented this table, comprises four elements which will be explained separately. According to the

ISO14040:2006 standard, only the first two (classification and characterization) are obligatory elements of every LCIA (Goedkoop et al., 2016):

- The first step, classification, consists of assigning each elementary flow to a certain impact category according to the substances' potential to contribute to this category. Impact categories include climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related), respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion (EC, JRC-IES, 2011).
- In the second step, characterization, the individual emissions from the elementary flows contributing to a single impact category are summed up. First however, they are converted into indicators using factors calculated by impact assessment models in order to account for their relative impact to a certain impact category (EC, JRC-IES, 2011).
- Normalization and weighting are often used to simplify the results from the previous two steps. They are however, regarded as optional in the ISO standards. Normalization provides insight into the extent an impact category indicator result has a relatively high or a relatively low value compared to a reference, e.g. the average annual impact of a European citizen in a specific year. Normalization also solves the incompatibility of units (Goedkoop et al., 2016).
- Weighting is the optional fourth and final step of the LCIA. It requires multiplying the normalization results with a weighting factor that expresses the relative importance of the impact category. As the normalization results, the weighted results all have the same unit and can hence be added up to create one single score for the environmental impact of a product or scenario. Weighting intrinsically means adding value to certain results and is therefore considered a subjective process. Although weighting and especially single score results may provide a clear and simple result, their representativeness is subject of debate (Brilhuis-Meijer, n.a.).

The choice of impact method will first of all strongly depend on the goal and scope of the LCA. The results from the LCIA should fulfil the goal and cover the scope described. Therefore, it should also be defined on beforehand what the targeted audience for the LCA will be and how this audience should be approached. It is imperative that the results presented at the end of the LCA are clear, objective and understandable for the people that they intend to reach. One of the defining factors in choosing the appropriate method is therefore the level of detail in which results are presented (Brilhuis-Meijer, 2014).

Many different methods are available to perform an LCIA. Although these methods differ in several aspects, one main distinction can be made between midpoint and endpoint methods. The principal difference between both methods is that they consider different stages in a cause-effect chain. Figure 3-2 presents an example of a cause-effect chain of a toxic chemical. In this example, a midpoint method would consider the increased chemical concentration in a lake, while an endpoint method would reflect on a more 'final' effect (Brilhuis-Meijer, 2014).

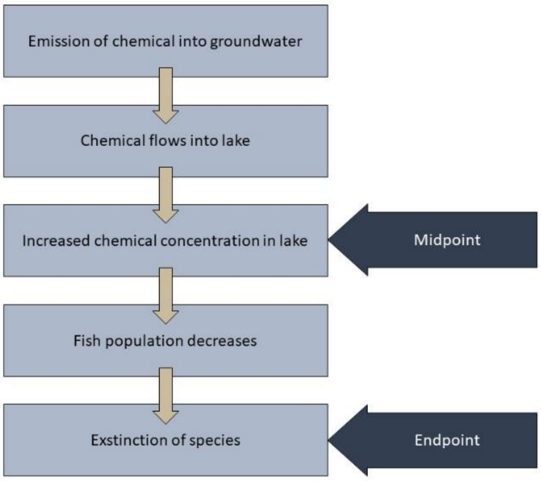


Figure 3-2 Example of a cause-effect chain with mid- and endpoint comparison (Brilhuis-Meijer, 2014)

Endpoint results are usually grouped and presented in three categories:

- Impact on human health
- Ecosystem quality
- Resource depletion

Although these results might prove more understandable for a wider audience, their statistical uncertainties are higher. Data gaps and assumptions accumulate along the cause-effect chain and will therefore cause endpoint results to be less certain (Brilhuis-Meijer, 2014).

3.5.3 Software packages

As mentioned before, there are several software packages that offer LCA-practitioners a user interface alongside access to one or more databases and impact methods. The last few years, many LCA tools have been developed for assisting specifically in pavement LCA's. In a recent study published by Santos et al. (2017b), a comparison was made between European and American tools to perform a pavement LCA. The set of pavement-specific LCA tools in the study included ROAD-RES, PaLATE V2.2, UK asphalt pavement LCA model, ROADEO, CMS RIPT, PE-2, CFET, ECORCE-M, DuboCalc, CO2NSTRUCT, VTTI/UC asphalt pavement LCA model, and Athena Impact Estimator for Highways.

Commercial LCA tools, despite being not specifically designed for pavement-specific LCA, have been used for that purpose since they are quite complete in terms of the elementary flows inventoried and unit processes taken into account, some of which are particularly applicable to the pavement domain (e.g., raw materials and equipment fuel combustion) (Santos et al., 2017b). Commonly used commercial LCA tools include OpenLCA, SimaPro, Gabi, Umberto, etc. (Osmani et al., 2017).

According to Santos' et al. (2017b), the analyst "should be careful when using a particular tool for conducting a pavement LCA, as even in the case of using the same stages, materials, and equipment the results can vary considerably. The impacts of road projects, the most-contributing processes and the scores for the different impact categories, will vary for any given project based on environmental burden associated with its life cycle stages, and material and processes therein.”

For a detailed description of these software tools and their functionalities, the reader is referred to specialized literature. The functionality of SimaPro, the tool used to perform the LCA presented in this study, is explained more in detail in chapter 5.

4 LIFE CYCLE COST ANALYSIS (LCCA)

This chapter is the third and final part of the literature review presented in this study. It discusses the existing literature on the definition, methodology and certain properties of LCCA. The chapter concludes with a short overview of existing LCCA software tools.

4.1 Introduction

As discussed in 3.1, Davis Langdon (2007a) states that "governments are trying to minimize both the life cycle costs and environmental impact instead of simply considering lowest cost alone when trying to achieve value from constructed assets such as roads." In this drive to acquire better value for money however, the LCCA still is an important tool for assessing the total cost performance of an asset over time. This includes the acquisition, operating, maintenance, and disposal costs.

The primary purpose of an LCCA is to evaluate different options for achieving a client's objectives, where those alternatives differ not only in their initial costs, but also in their subsequent operational costs (Davis Langdon, 2007a). This chapter provides a review of existing LCCA literature and discusses the definitions, methodologies and properties of LCCA according to multiple studies and reports.

4.2 Definition

A valuable definition of LCCA is given by Stanford University (as cited in Albuquerque e Castro, 2016):

> "Life cycle cost analysis is the process of evaluating the economic performance of an infrastructure over its entire life. LCCA balances initial investment with the long-term costs of owning and operating infrastructures. This analysis can explore alternative scenarios and can determine the time required for the different alternatives to achieve its payback. Maintenance, operation and use costs play an essential role in the total life cycle cost, representing a value almost the same order of its initial investment."

The analysis of life cycle costing, or LCCA, can thus be defined as a process to evaluate the economic performance of a physical asset throughout its life (Cortes Rezende, 2016). Despite the publication of international (ISO 15686-5) and European (EN 16627) standards on the topic of LCA and LCCA, these procedures must be adapted and interpreted according to the specific case they will be applied to. As stated in the Final Guidance (Davis Langdon, 2007a), an LCCA can be applied in a wide range of circumstances in construction, for example in a project to invest in:

- A single complete constructed asset
- An individual component within a constructed asset
- A portfolio comprising several assets

4.3 Methodology

Although multiple LCCA "procedures" can be found in the existing literature, the general methodology doesn't often differ. According to Davis Langdon (2007a), an LCCA should always comprise the following key steps:

1. Defining the objective of the proposed LCC analysis
2. Preliminary identification of parameters and analysis requirements
3. Confirmation of project and facility requirements
4. Assembly of cost and performance data
5. Carry out analysis, iterating as required
6. Interpreting and reporting results

The Federal Highway Administration (FHWA) in the U.S. defines a similar methodology for LCCA procedures (FHWA, 2002):

1. Establish design alternatives
2. Determine activity timing
3. Estimate costs (agency and user)
4. Compute life cycle costs
5. Analyse results

Another comprehensive methodology is presented by Babashamsi et al. (2016), which comprises the following 10 steps:

1. Define project scope
2. Establish LCCA framework
3. Develop alternative pavement strategies
4. Determine expected performance and M&R strategy
5. Estimate direct/owner costs
6. Estimate indirect/user costs
7. Develop expenditure stream diagram
8. Compute life cycle cost
9. Analyse result
10. Re-evaluate pavement strategies
11. Most economical strategy Identified?

    No? → Retake STEP 3

    Yes? → Selection of preferred strategies (Consideration of other factors?)

Probably the most followed and comprehensive LCCA procedure however, is the methodology based on the ISO 15686-5 and EN 16627 standards and presented in Davis Langdon (2007a). This methodology comprises of 15 steps, presented in Table 4-1.

Table 4-1 LCCA procedure steps (Davis Langdon, 2007a)

No.	Name	Outcome / achievement
1	Identify the main purpose of the LCCA	Statement of purpose of analysis Understanding of appropriate application of LCC and related outcomes
2	Identify the initial scope of the analysis	Understanding of: Scale of application of the LCC exercises Stages over which it will be applied Issues and information likely to be relevant Specific client reporting requirements
3	Identify the extent to which sustainability analysis relates to LCCA	Understanding of: Relationship between sustainability assessment and LCCA Extent to which the outputs from a sustainability assessment will form inputs into the LCCA Extent to which the outputs of the LCCA exercise will feed into a sustainability assessment
4	Identify the period of analysis and the methods of economic evaluation	Identification of the PAP and what governs its choice Identification of appropriate techniques for investment options
5	Identify the need for additional analyses (risk/uncertainty and sensitivity analyses)	Completion of preliminary assessment of risk/uncertainties Assessment of whether a formal risk management plan and/or register is required Decision on which risk assessment procedures should be applied
6	Identify project and asset requirements	Definition of the scope of the project and the key features of the asset Statement of project constraints Definitions of relevant performance and quality requirements Confirmation of project budget and timescales Incorporation of LCC timing into overall project plan
7	Identify options to be included in the LCC exercise and cost items to be considered	Identification of those elements of an asset that are to be subject to LCC analysis Selection of one or more options for each element to be analysed Identify which cost items are to be included
8	Assemble cost and time (asset performance and other) data to be used in the LCC analysis	Identification of: All costs relevant to the LCC exercise Values of each cost Any on-costs to be applied Time related data (e.g. service life / maintenance data)
9	Verify values of financial parameters and period of analysis	Period of analysis confirmed Appropriate values for the financial parameters confirmed Taxation issues considered Application of financial parameters within the cost breakdown structure decided
10	Review risk strategy and carry out preliminary uncertainty / risk analysis	Schedule of Identified risks verified Qualitative risk analysis undertaken – risk register updated Scope and extent of quantitative risk assessment confirmed
11	Perform required economic evaluation	LCC analysis performed Results recorded for use at step 14
12	Carry out detailed risk / uncertainty analysis (if required)	Quantitative risk assessments undertaken Results interpreted
13	Carry out sensitivity analyses (if required)	Sensitivity analyses undertaken Results interpreted
14	Interpret and present initial results in required format	Initial results reviewed and interpreted Results presented using appropriate formats Need for further iterations of LCC exercise identified
15	Present final results in required format and prepare a final report	Final report issued, to agreed scope and format Complete set of records prepared to ISO 15686 Part 3

4.3.1 Performance period and activity timing

One of the most important choices prior to the actual analysis is considered in step 4 of the methodology presented by Davis Langdon (2007a): identification of the period of analysis (Table 4-1). This is, in short, the timeframe over which the several strategies or in this case, rehabilitation techniques, will be considered. To decide on this matter, two main parameters are considered: the performance period (and how the pavement weakens over time) and the timing of maintenance or rehabilitation activities. Especially in the case of rehabilitation techniques it is important to consider these factors, to reflect the long-term costs associated with each technique, when deciding the period of analysis.

4.3.2 Analysis period

The minimum analysis period is, according to Walls & Smith (as cited in Antunes et al., 2016) 35 years. The Asphalt Pavement Alliance (APA) proposes a 40-year analysis period (as cited in Babashamsi et al. 2016). According to the APA, studies indicate that overlays last 15 years and some up to 20 years. Hence, a 40-year (or even 50-year) -analysis period should provide adequate information.

4.3.3 Sensitivity analysis & risk analysis

According to Davis Langdon (2007a), steps 10, 12 and 13 in Table 4-1 are not required, which is the reason why several sources speak of a 12-step methodology when it comes to LCCA. The implication of these three steps however, is subject of step 5. The choices made in this step determine the ultimate character of the LCCA, which can be deterministic or probabilistic. With a deterministic LCCA, discrete values are assigned to individual parameters. According to Babashamsi et al. (2016) however, a certain type of uncertainty lies within the input values of any given LCCA, which is according to Ang & Tang (as cited in Babashamsi et al., 2016) mainly due to four reasons:

- uncertainty is caused by randomness (measured or observed values would have different frequencies of occurrence and variation);
- regional construction variation;
- uncertainty across human factors (imperfect estimation or modelling);
- a lack of data.

Probabilistic LCCA allows the value of individual analysis inputs to be defined by a frequency (probability) distribution (FHWA, 2002). It uses various methods such as risk analysis and sensitivity analysis (steps 12 and 13 of the 15-step-method) to manage this uncertainty:

- A sensitivity analysis studies the effects of uncertainty of variables on the outcome; it is an evaluation of how much each input variable contributes to the uncertainty of the output.
- In the case of risk analysis, the probabilistic approach is utilized with input variables and computer simulation for the characterization of risk with the outcome (Babashamsi et al., 2016).

4.3.4 Cost assembly

Before assembling data it is imperative to decide which costs are relevant for the exercise and how these costs can be measured, calculated, or gathered from existing data. The costs included in an LCCA differ according to the case, but the division into life-cycle stages along with the main cost groups is a returning element in every LCCA of road structures. In general, the costs can be divided into two groups: the agency (or owner) costs and the user costs, both of which can be subdivided into smaller categories. A third group of costs proposed by Antunes et al. (2016) comprises of environmental costs. These last two groups however, are subject to discussion since there is simply not enough adequate, obtainable data in most cases. This impedes the possibility to compute them easily and correctly (Antunes et al., 2016).

The first group, the agency costs, often called the direct costs, are the costs supported by the owning administration or road agency over the life cycle of the project (Heuvinck, 2015). A non-exhaustive example of the costs that can be included in agency costs is given by Albuquerque e Castro (2016) in Table 4-2.

The second group of costs are the user costs. Although these user costs are not directly borne by the agency, they affect the agency's customers and the customers' perceptions of the agency's performance (FHWA, 2002). These costs are divided by Heuvinck (2016) into two large categories:

- Costs under normal operation: costs during periods free of construction, maintenance and/or rehabilitation. The pavement roughness is generally the dominant factor here.
- Work zone costs: costs that arise during periods of construction, maintenance and/or rehabilitation activities that restrict capacity.

As it is the case in agency costs, some elements of certain groups of costs are considered equal. Hence, these elements are not included in the equation. The most important cost-components that should be considered when calculating user-costs are (FHWA, 2002):

- Vehicle operating costs (VOC),
- User delay costs,
- Crash costs.

Table 4-2 Example of the different types and subtypes of road agency costs in LCCA (Albuquerque e Castro, 2016)

Type	Subtype
Pre-construction	Site costs
Product stage	Raw materials
	Transport
	Manufacturing
Construction	Transport
	Professional fees
	Temporary works
	construction
	Fit-out
	landscaping
	Taxes / subsidies / incentives
Use stage	Operation and maintenance
	Repair / replacement / refurbishment
	Energy & water
End-of-life stage	Deconstruction
	Waste transport & processing
	Disposal
After life stage	Revenue from disposal of interest of land
	Revenue from recycling

Although the consideration of these costs adds validity to the LCCA, it also provides a big challenge due to the uncertainty of its parameters. The value of user time, for instance, is one the main issues presented. Similarly, uncertainty exists about the effects of agency activities on crash rates and vehicle operating costs (FHWA, 2002).

4.3.5 Economic evaluation

Step 11 in the 15-step-method presented is the actual economic evaluation of the collected data. Many indices are available to perform this analysis such as the internal rate of return (IRR), equivalent uniform annual cost (EUAC), benefit/cost-ratio (B/C), Net Present Value (NPV) and others. According to Babashamsi et al. (2016), the level and context of analysis determine which indicator fits best. Developing nations for instance, due to the uncertainty of the discount rate, would benefit from the use of IRR as an indicator. The most used parameters however, are the NPV and EUAC. Equation 4.1 and 4.2 below show how these two parameters are calculated (Babashamsi et al., 2016):

$$NPV = Initial\ Cons. Cost + \sum_{K=1}^{N} Future\ Cost_K \left[\frac{1}{(1+i)^{n_K}}\right] - Salvage\ Value \left[\frac{1}{(1+i)^{n_e}}\right] \tag{4.1}$$

Where

N = number of future costs incurred over the analysis period,

i = discount rate in percent to calculate the time value of money,

n_K = number of years from the initial construction to the K^{th} expenditure,

n_e = analysis period in years.

$$EUAC = NPV \left[\frac{(1+i)^n}{(1+i)^n - 1}\right] \tag{4.2}$$

Where:

i = discount rate,

n = years of expenditure.

4.4 LCCA tools and software

To apply a certain type of methodology to execute a LCCA, software can provide a helpful tool. Several organizations have designed specialized computer programs for their LCCA approaches to assist with the analysis. An overview of some comprehensive packages is presented in Table 4-3 (Babashamsi et al., 2016). More general, flexible tools such as MS Excel also prove suitable for certain aspects of LCCA, as is discussed in chapter 6.

These models have some obvious limitations. For instance, user cost is excluded in several LCCA models as quantification is difficult and their definition disputable. These costs can incur delay costs, vehicle operating costs (fuel, engine oil, etc.), accident costs, etc. Another import limitation that LCCA models can suffer from is not considering preventive maintenance treatment within strategy formulation. Researchers argue that data is still insufficient for preventive maintenance which results in only a few models being able to quantify the long-term effectiveness of preventive maintenance treatment. It is commonly done with a service life extension or a performance jump. A third important factor of limitation is the nature of the input variables; most LCCA models treat the input variables discretely and compute a single deterministic result through the best-guess process of the fixed values for each input parameter. In contrast to most packages, the current FHWA package includes LCCA probabilistic approaches (Babashamsi et al., 2016).

Table 4-3 Overview of comprehensive American LCCA packages (Babashamsi et al., 2016)

Package	year	Life-cycle costs			
		Initial construction	Rehabilitation	User cost	Salvage value
DARWin	N/A	●	●		●
Texas DOT RPS/FPS	1968	●	●		●
HDM	1977	●	●	●	
LCCP/LCCPR	1987			●	
EXPEAR	1989	●	●		
PRLEAM	1991	●	●	●	●
LCCOST	1991	●	●	●	●
MicroBENCOST	1993	●	●		
ACPA LCCA	1993	●	●	●	●
CAL-B/C	2000	●	●	●	
REALCOST	2004	●	●	●	●
D-TIMS	2006	●	●	●	
IDAHO DOT LCCA	2008	●	●		
APA LCCA	2011	●	●	●	●

5 LCA APPLIED TO A CASE STUDY

This chapter covers the application of the LCA methodology on a specific case study of a flexible pavement unit. The chapter provides information regarding the LCA tools used in this dissertation, the specific methodology, the LCI, the LCIA and a discussion of the LCIA results.

5.1 Introduction

As mentioned earlier, the incorporation of RAP in bituminous mixtures holds a certain potential to improve the environmental and economic properties of a pavement. To quantify and evaluate the impact of rehabilitation methods which use RAP mixtures, both a comparative LCA and LCCA are applied to two construction, maintenance and rehabilitation (M&R) scenarios for a road section in Portugal.

- The first pavement scenario only comprises courses that use no recycled material and merely rely on virgin aggregates and binder for their mixture design.
- The second scenario however, was divided into four sub-scenarios, each involving courses which integrate a fixed percentage of RAP.

The first part of the analysis, the LCA, will be further discussed in this chapter. First, the specific LCA methodology used in this study is considered. The following parts of this chapter treat the actual LCA and describe the application of the methodology to the Portuguese road pavement section. This chapter concludes with an overview of the LCA results and associated remarks.

5.2 Methodology

As discussed in chapter 3, the LCA methodology was standardized by the International Organisation for Standardisation in the ISO 14040 series. These divided the LCA framework into four stages (Butt et al., 2014):

1. Goal and scope definition (EN ISO 14040: 1997)
2. Inventory assessment (EN ISO 14040: 1997)
3. Impact assessment (EN ISO 14042: 2000)
4. Interpretation (EN ISO 14043: 2000)

Although above-mentioned standards were combined in a new standard (EN ISO 14040: 2006), the general LCA framework described in this standard remains compiled of the same four stages. The proposed methodology in this study follows this general framework. To perform these four steps efficiently, numerous types of tools and software have been developed the past years, as discussed in 3.5. Especially the second and third step often require the use of specialized tools e.g. an extensive database and impact assessment methods.

The LCA presented in this study was performed through the SimaPro® software in combination with the Ecoinvent® database. This software-database combination is one the most widely spread LCA tools and provides the user with an interface, comprehensive environmental information databases and several methods to perform the impact assessment (Emami, et al., 2019). The software and database are discussed in following sub-paragraphs. The impact assessment method is further discussed in 5.5.

5.2.1 SimaPro 8

The first part of the software-database tool used in this study is the SimaPro software package. It was developed by PRé sustainability and it is considered to be one the most widely used software packages available (Emami, et al., 2019). The software first of all provides the user a clear interface to perform a full LCA, comprised of the four steps described in EN ISO 14040:2006.

The most important feature of the SimaPro software however, is the incorporation of one or more databases and impact assessment methods. There are several SimaPro licences available, which serve a variety of purposes. For this study, the multi-user classroom licence for the 8.5.2.0 version was used.

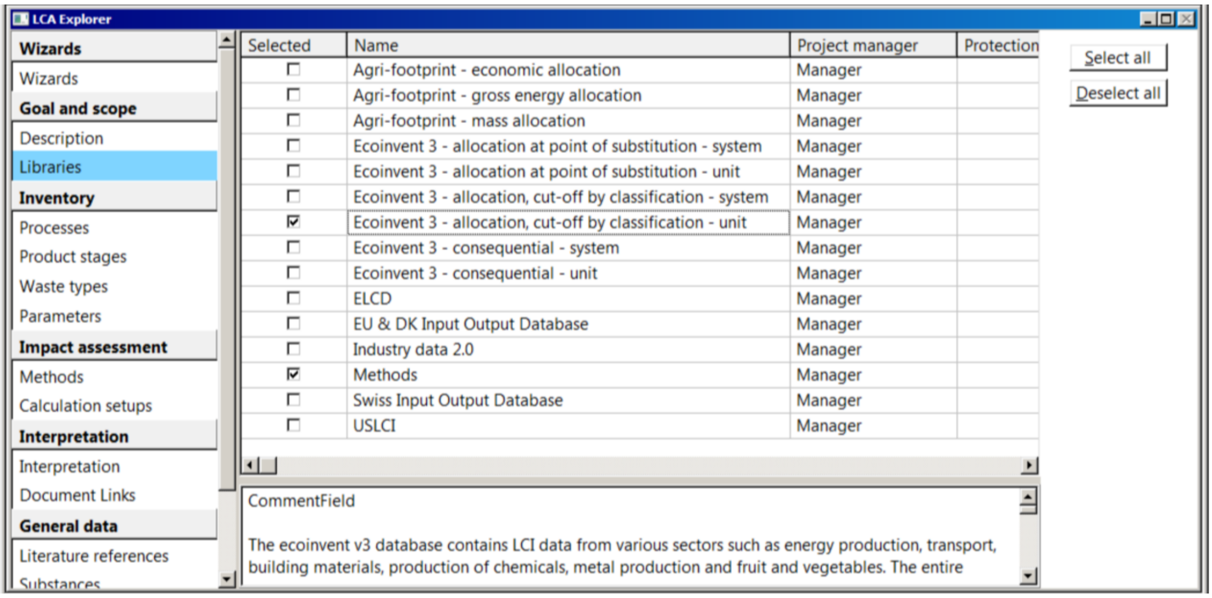
5.2.2 Ecoinvent database

One of the databases available in SimaPro, is the Ecoinvent database. As mentioned above, this database was selected because it is considered the most widely used database in the construction sector (Emami, et al., 2019). As shown in Figure 5-1, SimaPro provides six separate libraries that each contain all the processes that are found in the Ecoinvent database but use different system models and contain either unit or system processes. The three Ecoinvent system models are allocation at point of substitution, cut-off by classification and consequential (Ecoinvent, 2019). The difference between these three system models is defined as follows (Ecoinvent, 2019):

> “The system model 'allocation, recycled content′ or 'cut-off by classification' is based on the approach that primary production of materials is always allocated to the primary user of a material. If a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. The consequence is that recyclable materials are available burden-free to recycling processes and secondary (recycled) materials bear only the impacts of the recycling processes. Also, producers of wastes do not receive any credit for the recycling or re-use of products resulting out of any waste treatment.
>
> The system model 'allocation, default' or ‘allocation at point of substitution’ (APOS) contains two methodological choices: 1) it uses the average supply of products, as described in market activity datasets and 2) it uses partitioning (allocation) to convert multi-product datasets to single-product datasets. The flows are allocated relative to their 'true value', which is the economic revenue corrected for some market imperfections and fluctuations.
>
> The consequential system model handles the two methodological decisions used in both allocation system models differently: (1) it uses a constrained supply of products, based on

market activity data and on information about technology level; (2) it uses substitution (system expansion) to convert multi-product datasets into single-product datasets. In a constrained market, a change in demand does not result in a corresponding change in supply but instead in a change in consumption elsewhere. For example, by-product markets are constrained because their production volumes depend on the production volumes of the reference products, and it is the demand for the reference product that drives the production. This system model is intended to reflect the consequences of small-scale, long-term decisions by taking into account the constraints that apply at this scale and time horizon. Because of the constrained supply of products, the allocation of by-products is avoided by using substitution, and analyses a product which replaces or substitutes the by-product of the reference product. The emissions of that replacing product are then subtracted from the reference product emissions."

Both the attributional (default) and consequential databases are available in SimaPro using unit (gate-to-gate) and system (cradle-to-gate, aggregated LCI's) processes. Unit processes contain links to other unit processes, from which the inventory flows can be calculated by SimaPro. System processes contain the already calculated inventory flows and do not contain links to other processes (Ecoinvent, 2019). The system processes therefore present a more 'black box'-approach to LCI.



Selected	Name	Project manager	Protection
☐	Agri-footprint - economic allocation	Manager	
☐	Agri-footprint - gross energy allocation	Manager	
☐	Agri-footprint - mass allocation	Manager	
☐	Ecoinvent 3 - allocation at point of substitution - system	Manager	
☐	Ecoinvent 3 - allocation at point of substitution - unit	Manager	
☐	Ecoinvent 3 - allocation, cut-off by classification - system	Manager	
☑	Ecoinvent 3 - allocation, cut-off by classification - unit	Manager	
☐	Ecoinvent 3 - consequential - system	Manager	
☐	Ecoinvent 3 - consequential - unit	Manager	
☐	ELCD	Manager	
☐	EU & DK Input Output Database	Manager	
☐	Industry data 2.0	Manager	
☑	Methods	Manager	
☐	Swiss Input Output Database	Manager	
☐	USLCI	Manager	

CommentField

The ecoinvent v3 database contains LCI data from various sectors such as energy production, transport, building materials, production of chemicals, metal production and fruit and vegetables. The entire

Figure 5-1 Overview of the databases or libraries available in SimaPro

Another significant property of the Ecoinvent database is the distinction between market and transformation processes. The first type of processes includes inputs from the production in several countries or regions as well as inputs of transport processes. This type of process is preferred when the specific supplier is unknown. Transportation processes on the other hand contain all the inputs for making a product or service, except for transport, and all the associated emissions and resource extractions (Ecoinvent, 2019).

The database that was used in this study was the Ecoinvent 3 – allocation, cut-off by classification – unit database. The underlying philosophy of the cut-off approach is that a producer is fully responsible for the disposal of its wastes, and that he does not receive any credit for the provision of any recyclable materials (Ecoinvent, 2019).

5.3 Goal and scope definition

5.3.1 Goal

As discussed in the introduction of this chapter, the study presented in this dissertation tries to evaluate RAP-incorporation in bituminous mixtures by applying an LCA and LCCA to a flexible pavement section in Portugal. The main goal of the LCA is to quantify and evaluate the environmental performance of RAP-incorporation in bituminous mixtures compared to the use of virgin material. The focus hereby lies on three damage categories: human health (especially that of construction workers and people directly involved with the production process of flexible pavements), climate change and use of resources.

5.3.2 Functional unit

The functional unit of any type of LCA creates the basis of comparison between different structure scenarios with the same utility for the same function (Santos et al., 2018). Important to distinguish is the difference between a functional and a declared unit. If the precise function of the unit is not stated or known or when the LCA does not cover a full life cycle, the functional unit is replaced by the declared unit. Although the LCA in this study does not cover the full life cycle, the functional unit has a clear quantity, duration and quality and is hence further referred to as the functional unit (EeBGuide, 2012). In this case, this involves a unit of pavement that carries the same traffic over the same PAP. The functional unit presented in this LCA is a Portuguese national road section of 1-km length, composed of one independent roadway, with 2 lanes with an individual width of 3.5 m and a total PAP of 69 years, expanding from 1946 to 2015. The geometric characteristics, as well as the different mixtures used for each course are presented in Figure 5-2. This figure also displays the overall M&R strategy (tasks, courses and application timing) and the two main structure scenarios considered in this LCA.

Although the maintenance tasks and their timing are considered to be equal for both structure scenarios throughout their life cycle, the mixture composition of new courses is not:

- Maintenance three implies the milling of the asphalt concrete (AC) wearing course and replacing it with a new wearing course. In scenario A this course is comprised of a virgin AC, while in scenario B this course incorporates virgin AC as well as a certain amount of RAP which was obtained from the milling.
- Maintenance four implies the milling of both upper courses and replacing them with a new binder and surface layer respectively. In the case of scenario A these layers consist of SMA mixtures with virgin materials, while in the courses in scenario B a certain amount of RAP is incorporated along with virgin AC.

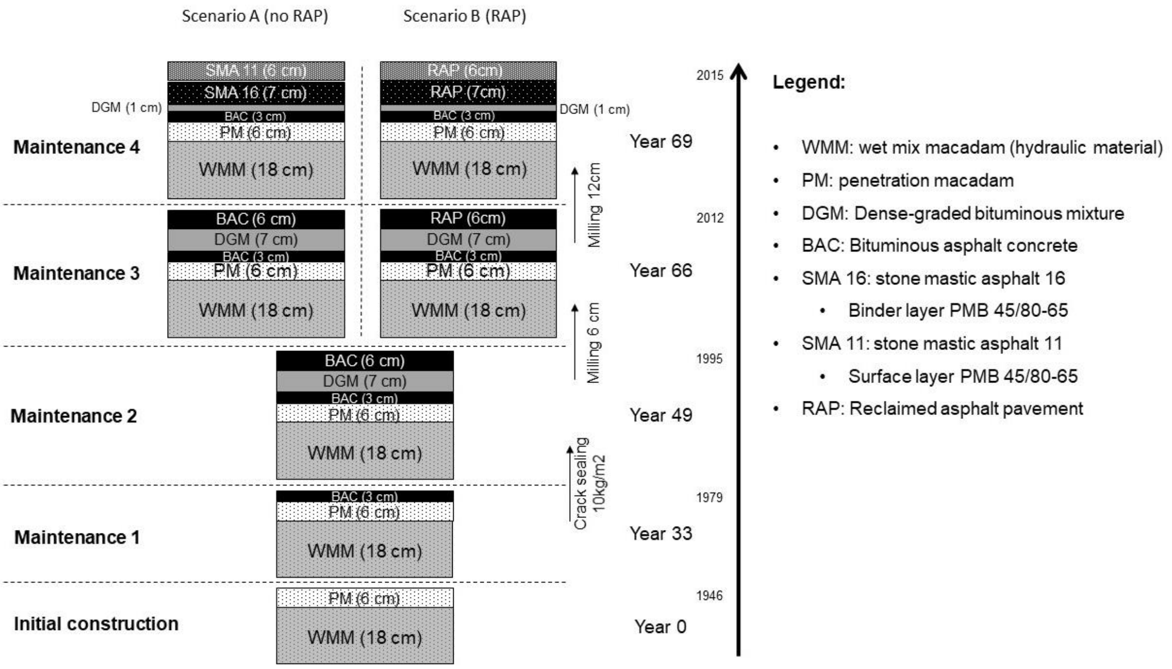


Figure 5-2 Geometric characteristics of the flexible pavement structure and M&R strategy scenarios

To evaluate the use of RAP material in bituminous mixtures, different percentages of incorporation were considered in this LCA. Scenario B was thus divided into 4 sub-scenarios, hereafter referred to as "structures", as can be seen in Table 5-1. Scenario A was subsequently renamed structure 0 to simplify comparison in the further course of the LCA.

Table 5-1 Scenario subdivision into structures by percentage of RAP incorporation

Scenario	Structure	RAP incorporation (% m/m)[a]
Scenario A	Structure 0	0
Scenario B	Structure 1	25
	Structure 2	50
	Structure 3	75
	Structure 4	100

[a] : mass percentage

5.3.3 System description and boundaries

The analysis boundaries of the road pavement section were set at the base and surface course. Due to the insufficient, and outdated data regarding the wet mix macadam (WMM) and penetration macadam (PM) course, these were not considered in the LCA. Given the comparative nature of the LCA and the fact these two courses are present throughout all scenarios; this omission has no relative impact on the LCA outcome. The boundaries subsequently include:

- The construction of all courses contained by the limits mentioned above and subsequent

M&R activities;
- The extraction of the materials needed to produce the mixtures used in those courses;
- The transportation of material between facilities, between facilities and work-site, and vice-versa.

Considering the system boundaries of RAP, the recycled material resulting from the milling process described in 5.3.2, a division is made between the pre- and post-processing of the RAP. A ‘cut-off’ allocation approach as described in Santos et al. (2017a), implies that only the post-processing of a recycled material such as RAP should be accounted for by the system. In this case, this would imply that any environmental impact resulting from the milling and hauling of RAP would be excluded from the system. These processes however, are already an inherent part of the considered M&R activities of the pavement and are therefore accounted for in the LCA. The pre-processing of the RAP is therefore attributed to the construction and M&R phase, while the post-processing is attributed to the mixture production phase.

5.3.4 Data sources and quality requirements

For an LCA study, usually two types of data are required (EC, JRC-IES, 2010):

- **Primary data** which is specific for the production processes of the product or service. Sources for primary data are the producers of goods and operators of processes and services, as well as their associations.
- **Secondary data** which presents generic and/or average data for the product or service studied. Secondary data sources which either give access to primary data (possibly after remodelling / changing the data) and to generic data are e.g. national databases, consultants, and research groups.

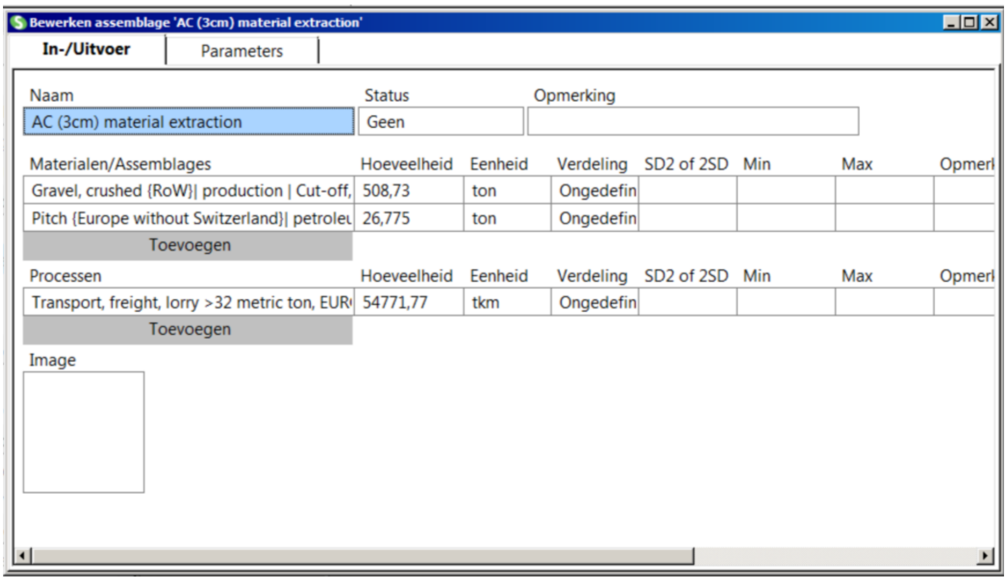
The primary data was selected to be as representative for Portuguese conditions during the PAP as possible. The sources for this data include following active construction companies and technical experts: Infraestruturas de Portugal, IP S.A., Alves Ribeiro Construção S.A., JJR Grupo and Estrela do Norte, Engenharia e Construção Civil, Lda. The secondary data on the other hand, is mainly related to the inventory analysis of raw materials extraction and production, fuels, construction and transportation vehicles and machines. This data was obtained primarily from the Ecoinvent database but modified whenever possible and suitable to approach Portuguese conditions. Both data types were combined in SimaPro to model the life cycles for the five different structures.

5.4 Life cycle inventory

The LCI stage consists of the actual data collection and modelling of the system. First, this paragraph briefly discusses the functionality and modelling features of SimaPro. Secondly, the data sources, the calculations that were performed to provide significant input and the modelling of the distinct phases of each structure in SimaPro are considered. And finally, the last sub-paragraph (5.4.7), renders an image of the final life cycle models of each structure. These steps, and especially the calculations, are addressed more in detail in Annex A.

5.4.1 SimaPro modelling

To fully comprehend how the final life-cycle models for each structure (presented in 5.4.7) were constructed, a brief summary of the modelling principles in SimaPro is provided in this sub-paragraph. Each model was built up of several assemblies of unit processes, which are linked to each other to create a network. As an example, a screenshot of the materials extraction phase assembly of the AC (3 cm) course is presented in Figure 5-3. The assembly in this figure consists of three processes: a gravel production process, a pitch production process and a transport process. Next to each process' definition, the amount and unit for the particular process is specified. These amounts are considered *primary data* and are hence provided by the user.



Naam: AC (3cm) material extraction
Status: Geen
Opmerking:

Materialen/Assemblages	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opmer
Gravel, crushed {RoW}| production | Cut-off,	508,73	ton	Ongedefin				
Pitch {Europe without Switzerland}| petroleu	26,775	ton	Ongedefin				

Processen	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opmer
Transport, freight, lorry >32 metric ton, EUR	54771,77	tkm	Ongedefin				

Figure 5-3 Assembly of the materials extraction phase of the AC (3 cm) course (SimaPro screenshot)

Each unit process in the network has various inputs (e.g. materials, fuels, electricity,…) and outputs (e.g. emissions to air, water, waste,…). Unit processes contain links to other unit processes, from which the inventory flows can be calculated by SimaPro. As an example, the unit process exchanges from the *Gravel, crushed {Rest of World}, production, cut-off* unit process are shown in Table 5-2. The amounts considered in this table, are provided by the Ecoinvent database and therefore labelled as *secondary data*.

A graphical representation of the input flows contributing to the *Gravel, crushed {RoW}, production, cut-off* unit process is shown in the network diagram in Figure 5-4. It should be noted however, that this representation was completed with a 6 % cut-off value. Unit processes contributing less than 6 % on a certain level, were therefore omitted. A 0 % cut-off value would actually display hundreds of unit processes, rendering the representation unclear.

Table 5-2 Unit process exchanges for the Gravel, crushed {RoW}, production, cut-off unit process (Lesage, Pascal, n.a.)

Name	Amount	Unit	Uncertainty	SD
Reference Products				
gravel, crushed	1	kg		
By-product/Waste				
municipal solid waste	2.12E-06	kg	Lognormal	1
waste mineral oil	2.50E-06	kg	Lognormal	1
To Environment				
Air				
Particulates, < 2.5 um	0.4E-09	kg	Lognormal	32.097
Particulates, > 10 um	5.6E-09	kg	Lognormal	17.607
Particulates, > 2.5 um, and < 10um	2.00E-09	kg	Lognormal	22.255
Water	0.00030659	m3	Lognormal	14.918
Water				
Water	0.00081756	m3	Lognormal	14.918
From Environment				
Natural resource				
Gravel, in ground	1.04	kg	Lognormal	12.214
Occupation, lake, artificial	6.27E-05	m2*year	Lognormal	20.567
Occupation, mineral extraction site	0.000288	m2*year	Lognormal	15.639
Transformation, from unspecified	3.51E-05	m2	Lognormal	20.567
Transformation, to lake, artificial	6.27E-06	m2	Lognormal	20.567
Transformation, to mineral extraction site	2.88E-05	m2	Lognormal	20.567
Water, unspecified natural origin	0.0011119	m3	Lognormal	12.214
From Technosphere				
Building, hall, steel construction	2.85E-06	m2	Lognormal	30.999
Conveyor belt	9.51E-08	m	Lognormal	32.097
Diesel, burned in building machine	0.0143	MJ	Lognormal	12.214
Electricity, medium voltage	0.00906	kWh	Lognormal	12.214
Gravel/sand quarry infrastructure	4.75E-11	unit	Lognormal	30.452
Heat, central or small-scale, other than natural gas	0.00491	MJ	Lognormal	12.214
Industrial machine, heavy, unspecified	9.51E-05	kg	Lognormal	30.999
Lubricating oil	2.5E-06	kg	Lognormal	12.214
Recultivation, limestone mine	1.27E-06	m2	Lognormal	20.567
Steel, low-alloyed, hot rolled	51.0E-06	kg	Lognormal	12.214
Synthetic rubber	4.0E-06	kg	Lognormal	12.214
Tap water	0.0122	kg	Lognormal	12.214

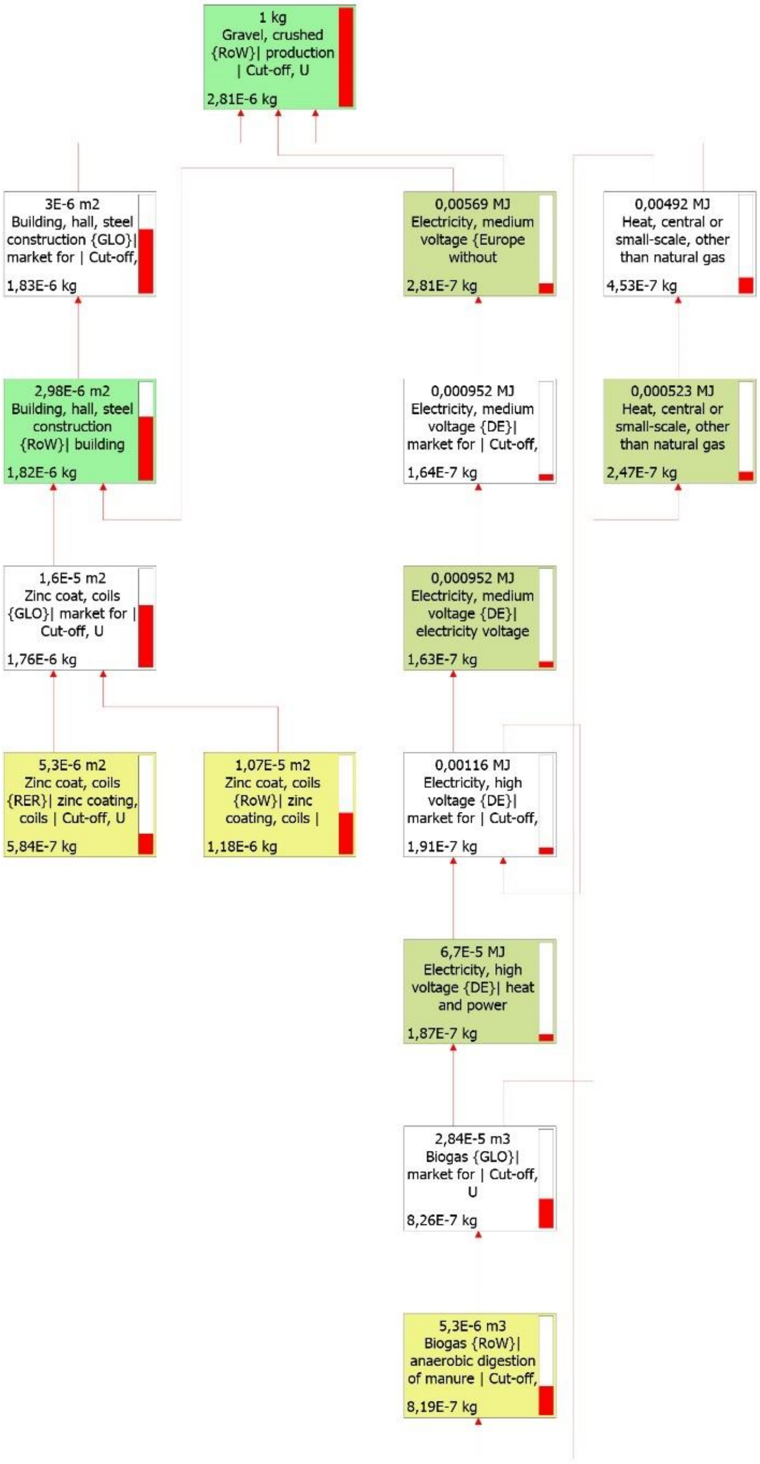


Figure 5-4 Graphical network representation of the Gravel, crushed {RoW}, production, cut-off unit process with a 6 % cut-off value (SimaPro screenshot)

The following sub-paragraphs each focus on one particular phase in the life cycle of the pavement structures; materials extraction, mixtures production, construction & M&R, work zone traffic management & use, and end-of-life. The last sub-paragraph however does not describe a single phase but provides an image of the total life cycle models.

5.4.2 Materials extraction phase

The first phase considered in the LCA contains the environmental impacts associated with the extraction and transportation of virgin materials. As discussed earlier, all bituminous mixtures are modelled as a combination of aggregates and bituminous binder, mixed together in a certain ratio. The impact of extraction or production of additives and rejuvenators is considered insignificant in this study so processes associated with these substances are hence omitted from the system.

The materials extraction phase consists of two subphases; the extraction of virgin materials itself, also referred to as materials production, and the transport of those materials. The final results presented here in Table 5-3 and Table 5-4 present the input numbers for the Ecoinvent unit processes selected in the SimaPro model. More detailed calculation results of both subphases can be found in A.1.1 of Annex A.

Table 5-3 Virgin aggregate and binder masses required per course

Structure	Course	Virgin aggregate mass (tonne)	Virgin binder mass (tonne)
All	AC (3 cm)	508.73	26.78
	AC (6 cm)	1,017.45	53.55
	DGM (1 cm)	169.58	8.93
	DGM (7 cm)	1,187.03	62.48
0	SMA 11 (6 cm)	1,001.39	69.61
	SMA 16 (7 cm)	1,168.28	81.22
1	AC (25 % RAP) (6 cm)	772.19	31.06
	AC + DGM (25 % RAP) (6 cm)	772.19	31.06
	AC + RAP (25 % RAP) (7 cm)	900.89	36.24
2	AC (50 % RAP) (6 cm)	513.54	21.96
	AC + DGM (50 % RAP) (6 cm)	513.54	21.96
	AC + RAP (50 % RAP) (7 cm)	599.14	25.61
3	AC (75 % RAP) (6 cm)	254.90	12.85
	AC + DGM (75 % RAP) (6 cm)	254.90	12.85
	AC + RAP (75 % RAP) (7 cm)	297.38	14.99
4	AC (100 % RAP) (6 cm)	0.00	10.71
	AC + DGM (100 % RAP) (6 cm)	0.00	10.71
	AC + RAP (100 % RAP) (7 cm)	0.00	12.50

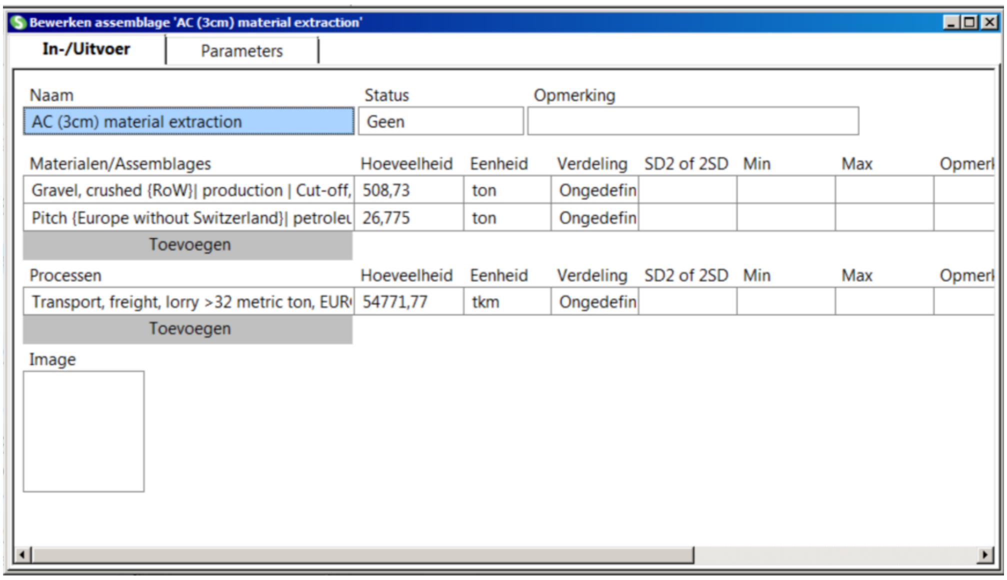
Table 5-4 Total required virgin material transport per course

Structure	Course	Required transport (tonne kilometer (tkm))
All	AC (3 cm)	54,888.75
	AC (6 cm)	109,777.50
	DGM (1 cm)	18,296.25
	DGM (7 cm)	128,073.75
0	SMA 11 (6 cm)	110,580.75
	SMA 16 (7 cm)	129,010.88
1	AC (25 % RAP) (6 cm)	81,877.95
	AC + DGM (25 % RAP) (6 cm)	81,877.95
	AC + DGM (25 % RAP) (7 cm)	95,524.28
2	AC (50 % RAP) (6 cm)	54,647.78
	AC + DGM (50 % RAP) (6 cm)	54,647.78
	AC + DGM (50 % RAP) (7 cm)	63,755.74
3	AC (75 % RAP) (6 cm)	27,417.60
	AC + DGM (75 % RAP) (6 cm)	27,417.60
	AC + DGM (75 % RAP) (7 cm)	31,987.20
4	AC (100 % RAP) (6 cm)	1,606.50
	AC + DGM (100 % RAP) (6 cm)	1,606.50
	AC + DGM (100 % RAP) (7 cm)	1,874.25

As mentioned above, Table 5-3 and Table 5-4 provide the input data for the structure modelling in the SimaPro software. The Ecoinvent unit processes associated with the production of virgin aggregate, the production of virgin bituminous binder and the transport of these materials by truck, are shown in Table 5-5. As an example, to clarify the modelling of this phase in SimaPro, a screenshot of the AC (3 cm) course materials extraction assembly is shown in Figure 5-5. The SimaPro screenshot shown in Figure 5-6 provides an overview of all materials extraction phase assemblies considered in the SimaPro model.

Table 5-5 Material extraction processes and corresponding SimaPro unit processes

Process definition	SimaPro unit process
The production of virgin aggregate	Gravel, crushed (RoW) | production
The production of virgin bituminous binder	Pitch (RoW) | petroleum refinery operation
Transport of aggregate and binder	Transport, freight, lorry > 32 metric tonne, EURO4 (GLO)

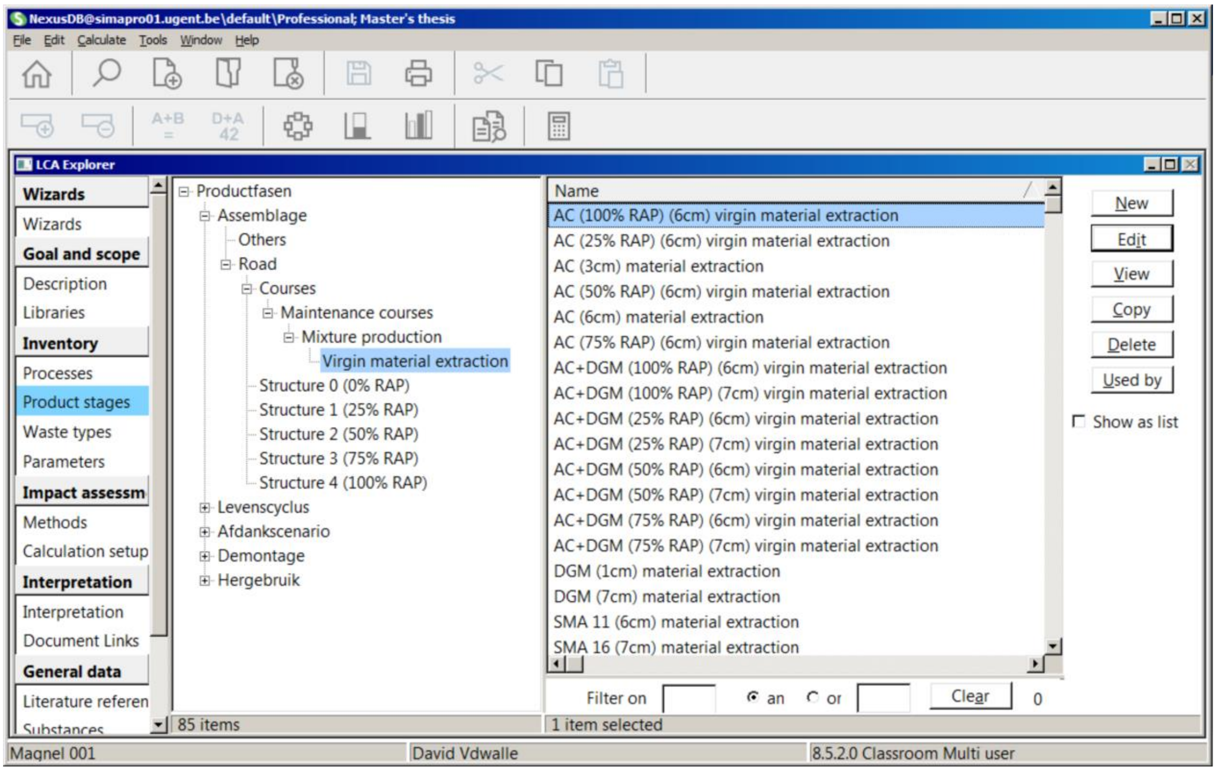


Naam	Status	Opmerking
AC (3cm) material extraction	Geen	

Materialen/Assemblages	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opmerl
Gravel, crushed {RoW}| production | Cut-off,	508,73	ton	Ongedefin				
Pitch {Europe without Switzerland}| petroleu	26,775	ton	Ongedefin				

Processen	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opmerl
Transport, freight, lorry >32 metric ton, EUR	54771,77	tkm	Ongedefin				

Figure 5-5 Assembly of the materials extraction phase of the AC (3 cm) course (SimaPro screenshot)



Name
AC (100% RAP) (6cm) virgin material extraction
AC (25% RAP) (6cm) virgin material extraction
AC (3cm) material extraction
AC (50% RAP) (6cm) virgin material extraction
AC (6cm) material extraction
AC (75% RAP) (6cm) virgin material extraction
AC+DGM (100% RAP) (6cm) virgin material extraction
AC+DGM (100% RAP) (7cm) virgin material extraction
AC+DGM (25% RAP) (6cm) virgin material extraction
AC+DGM (25% RAP) (7cm) virgin material extraction
AC+DGM (50% RAP) (6cm) virgin material extraction
AC+DGM (50% RAP) (7cm) virgin material extraction
AC+DGM (75% RAP) (6cm) virgin material extraction
AC+DGM (75% RAP) (7cm) virgin material extraction
DGM (1cm) material extraction
DGM (7cm) material extraction
SMA 11 (6cm) material extraction
SMA 16 (7cm) material extraction

Figure 5-6 List of all virgin material extraction assemblies included in the LCA (SimaPro screenshot)

5.4.3 Mixture production phase

The mixture production phase addresses the environmental impacts associated with the production of the different mixtures considered in the system. In accordance with the LCA study performed by Santos et al. (2018), all bituminous mixtures were assumed to be produced through a conventional heavy fuel oil (HFO)-fired batch mix plant. To account for variations in composition, mixing temperature, moisture content of aggregates and initial temperature of raw materials of the several types of mixtures, the thermal energy (TE) required to produce the different bituminous mixtures was determined. The final TE values for each course are presented in Table 5-6. The calculation however, is further discussed in detail in A.1.2.

Table 5-6 Thermal energy required to produce the courses studied

Course	TE (GJ)
AC (3 cm)	135.32
AC (6 cm)	270.64
DGM (1 cm)	45.11
DGM (7 cm)	315.74
SMA 11 (6 cm)	350.84
SMA 16 (7 cm)	409.32
AC (RAP) (6 cm)	270.64
AC + DGM (RAP) (6 cm)	270.64
AC + RAP (RAP) (7 cm)	315.74

The actual environmental impact resulting from the production of the bituminous mixtures was modelled through the SimaPro unit process *"heat production, heavy fuel oil, at industrial furnace 1MW* | *heat, district or industrial, other than natural gas* | *cut-off, U"* from the Ecoinvent database.

Besides the environmental impact resulting from the heating of the mixtures, the mixtures production phase of courses that consist of RAP mixtures also partly accounts for the impact of RAP processing. As described in 0, the RAP processing sub-phase was divided in pre-processing and post-processing. The pre-processing of the RAP is therefore attributed to the construction and M&R phase, while the post-processing is attributed to the mixture production phase. The post-processing of RAP consists of four activities (crushing, stacking, conveying and screening) and are considered to have a combined capacity of 184 tonnes per hour (Santos et al. 2017a). Table 5-7 presents the total time required to produce the RAP for each course that has a certain percentage of RAP incorporation.

To account for the environmental impact of RAP production in SimaPro, the four main RAP production activities mentioned above (crushing, stacking, conveying and screening) were modelled through the in SimaPro through different unit processes as shown in Table 5-8. The conveying and screening processes both were modelled through the *Machine operation, diesel, >= 74.57 kW, high load factor {GLO}*| *machine operation, diesel, >= 74.57 kW, high load factor* | *Cut-off, U* unit process from the Ecoinvent database. As this unit process is generally expressed in hour (hr), the total amount of hours required for the production for each course (displayed in Table 5-7), was thus used as input for both activities in SimaPro. The input data for the stacking and crushing unit processes (expressed in mass and volume) were also derived from Table 5-7.

Table 5-7 RAP production time per course

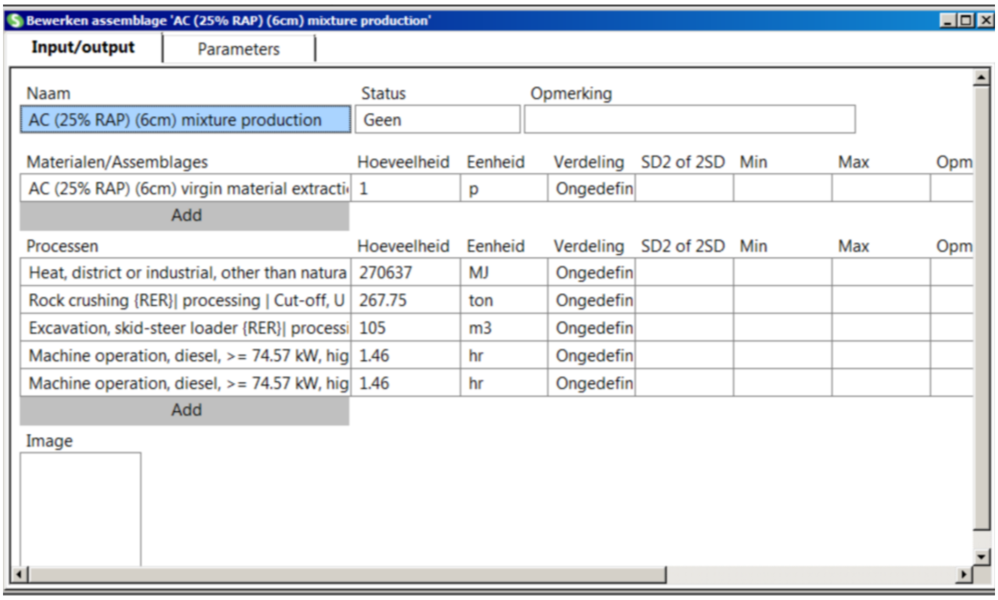
Structure	Course	RAP mass (tonne)	Efficiency (tph[a])	Total hours
1	AC (25 % RAP) (6 cm)	267.8	184	1.5
	AC + DGM (25 % RAP) (6 cm)	267.8	184	1.5
	AC + RAP (25 % RAP) (7 cm)	312.4	184	1.7
2	AC (50 % RAP) (6 cm)	535.5	184	2.9
	AC + DGM (50 % RAP) (6 cm)	535.5	184	2.9
	AC + RAP (50 % RAP) (7 cm)	624.8	184	3.4
3	AC (75 % RAP) (6 cm)	803.3	184	4.4
	AC + DGM (75 % RAP) (6 cm)	803.3	184	4.4
	AC + RAP (75 % RAP) (7 cm)	937.1	184	5.1
4	AC (100 % RAP) (6 cm)	1060.3	184	5.8
	AC + DGM (100 % RAP) (6 cm)	1060.3	184	5.8
	AC + RAP (100 % RAP) (7 cm)	1237.0	184	6.7

[a] tonnes per hour

Table 5-8 RAP processing SimaPro unit processes

Process definition	SimaPro unit process
Crushing of RAP by a crushing unit	Rock crushing {RER}| processing | Cut-off, U
Stacking of RAP by a wheel loader	Excavation, skid-steer loader {RER}| processing | Cut-off, U
Conveying of RAP on a conveyor belt	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}
Screening by a mobile screener	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}

As an example, a screenshot of the mixture production assembly for the AC+DGM (25 % RAP) (6 cm) course is shown in Figure 5-7. As can be seen from this figure, the mixture production assembly has two types of inputs; firstly, the materials extraction assembly of the associated course and secondly the processes related with RAP production and thermal heat production. Subsequently, Figure 5-8 displays a list of all mixture production assemblies included in the model.



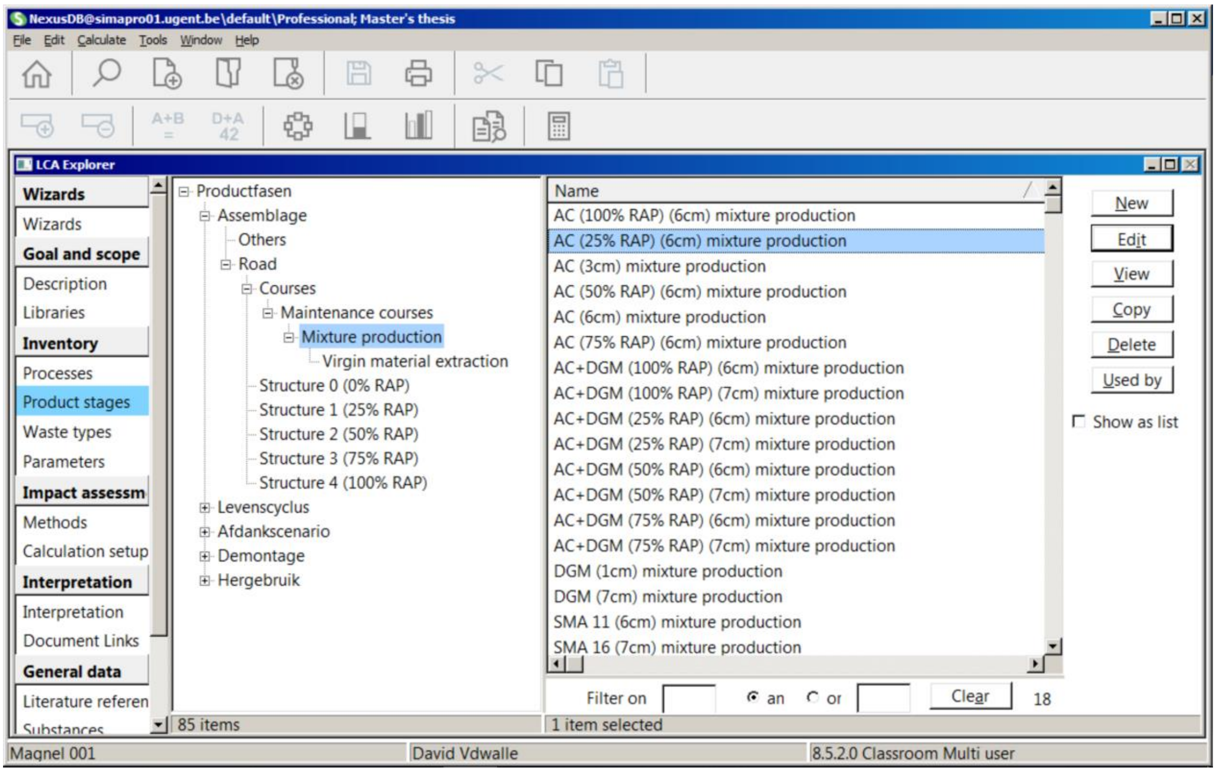
Bewerken assemblage 'AC (25% RAP) (6cm) mixture production'

Naam	Status	Opmerking
AC (25% RAP) (6cm) mixture production	Geen	

Materialen/Assemblages	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opm
AC (25% RAP) (6cm) virgin material extracti	1	p	Ongedefin				

Processen	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opm
Heat, district or industrial, other than natura	270637	MJ	Ongedefin				
Rock crushing {RER}| processing | Cut-off, U	267.75	ton	Ongedefin				
Excavation, skid-steer loader {RER}| processi	105	m3	Ongedefin				
Machine operation, diesel, >= 74.57 kW, hig	1.46	hr	Ongedefin				
Machine operation, diesel, >= 74.57 kW, hig	1.46	hr	Ongedefin				

Figure 5-7 Assembly of the mixture production phase of the AC+DGM (25 % RAP) (6 cm) course (SimaPro screenshot)



NexusDB@simapro01.ugent.be\default\Professional; Master's thesis

Name
AC (100% RAP) (6cm) mixture production
AC (25% RAP) (6cm) mixture production
AC (3cm) mixture production
AC (50% RAP) (6cm) mixture production
AC (6cm) mixture production
AC (75% RAP) (6cm) mixture production
AC+DGM (100% RAP) (6cm) mixture production
AC+DGM (100% RAP) (7cm) mixture production
AC+DGM (25% RAP) (6cm) mixture production
AC+DGM (25% RAP) (7cm) mixture production
AC+DGM (50% RAP) (6cm) mixture production
AC+DGM (50% RAP) (7cm) mixture production
AC+DGM (75% RAP) (6cm) mixture production
AC+DGM (75% RAP) (7cm) mixture production
DGM (1cm) mixture production
DGM (7cm) mixture production
SMA 11 (6cm) mixture production
SMA 16 (7cm) mixture production

85 items | 1 item selected

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Figure 5-8 List of all virgin mixture production assemblies included in the LCA (SimaPro screenshot)

5.4.4 Construction and M&R phases

This paragraph discusses the environmental impacts from the construction and M&R phases of the system. These impacts result namely from the machine operations involved in constructing the considered courses and the transportation of bituminous mixtures and milled material. A.1.3 in Annex

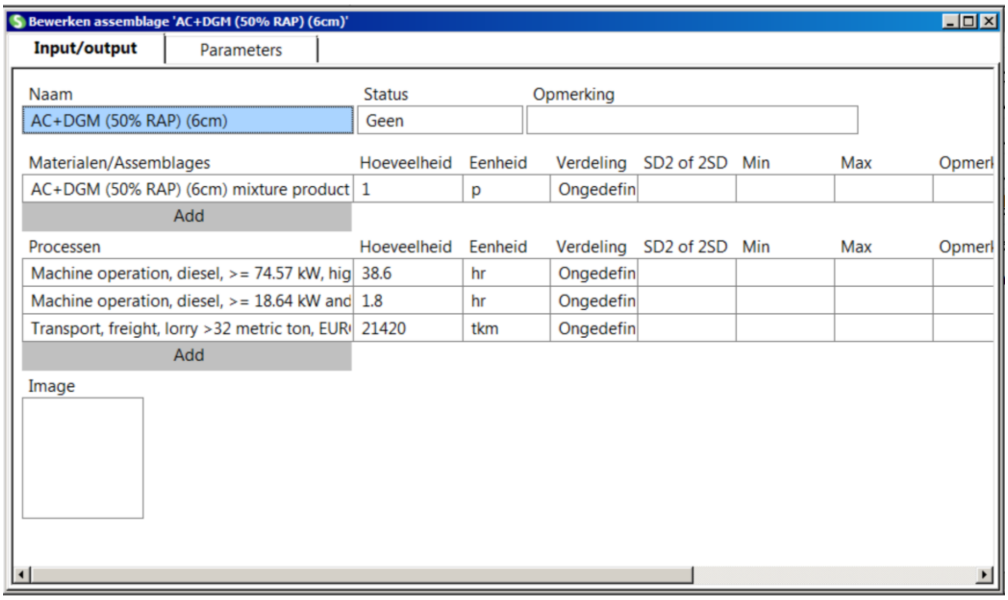
A. Table A-10 provides a full overview of the specific activities included in the maintenance and repair actions and the construction of each course. Moreover, the equipment efficiency of vehicles and machinery involved in these activities are specified as well. The primary data concerning the activities, efficiencies, costs, etc were based on available literature and interviews with contractors and road construction experts. Table 5-9 presents an overview of the unit process quantities for the construction and M&R phase for each course. The numbers in this table provided the input for the SimaPro unit processes included in the different structure models.

Table 5-9 Construction phase unit process quantities per course

Course or action	Truck transport (tkm[a])	Light machine operation (total h)	Heavy machine operation (total h)
AC (3 cm)	10710	0.9	29.7
AC (6 cm)	21420	1.8	38.6
DGM (1 cm)	3570	0.4	23.7
DGM (7 cm)	24990	2.6	41.6
SMA 11 (6 cm)	21420	1.8	38.6
SMA 16 (7 cm)	24990	2.1	41.6
AC + RAP (AC) (6 cm)	21420	1.8	38.6
AC + RAP (AC + DGM) (6 cm)	21420	1.8	38.6
AC + RAP (AC + DGM) (7 cm)	24990	2.1	41.6
1st milling	21420	2.1	14.7
2nd milling	42840	4.2	29.4

[a] Tonne-kilometre: unit of measure of freight transport which represents the transport of one tonne of goods over a distance of one kilometre.

In accordance with the methodology used by Santos et al. (2018), machine operations were modelled in SimaPro through two different unit processes from the Ecoinvent database, depending on the power of the machinery used. To describe the light machine operations, the SimaPro unit process '*Machine operation, diesel, >= 74,57 kW, high load factor*' was used. The heavy machine operations on the other hand, were modelled through the unit process '*Machine operation, diesel, >= 18,64 kW and < 74,57 kW, high load factor'*. For the transportation by truck, the '*Transport, freight, lorry > 32 metric tonne, EURO4* | *cut-off, U*' was chosen. To clarify, a screenshot of the AC+DGM (50 % RAP) (6 cm) course construction phase assembly is shown in Figure 5-9 as an example. Besides the three unit processes, the assembly also has the mixture production assembly of the associated course as input. And again, to put matters into perspective, an overview of all construction assemblies is provided in the screenshot in Figure 5-10.

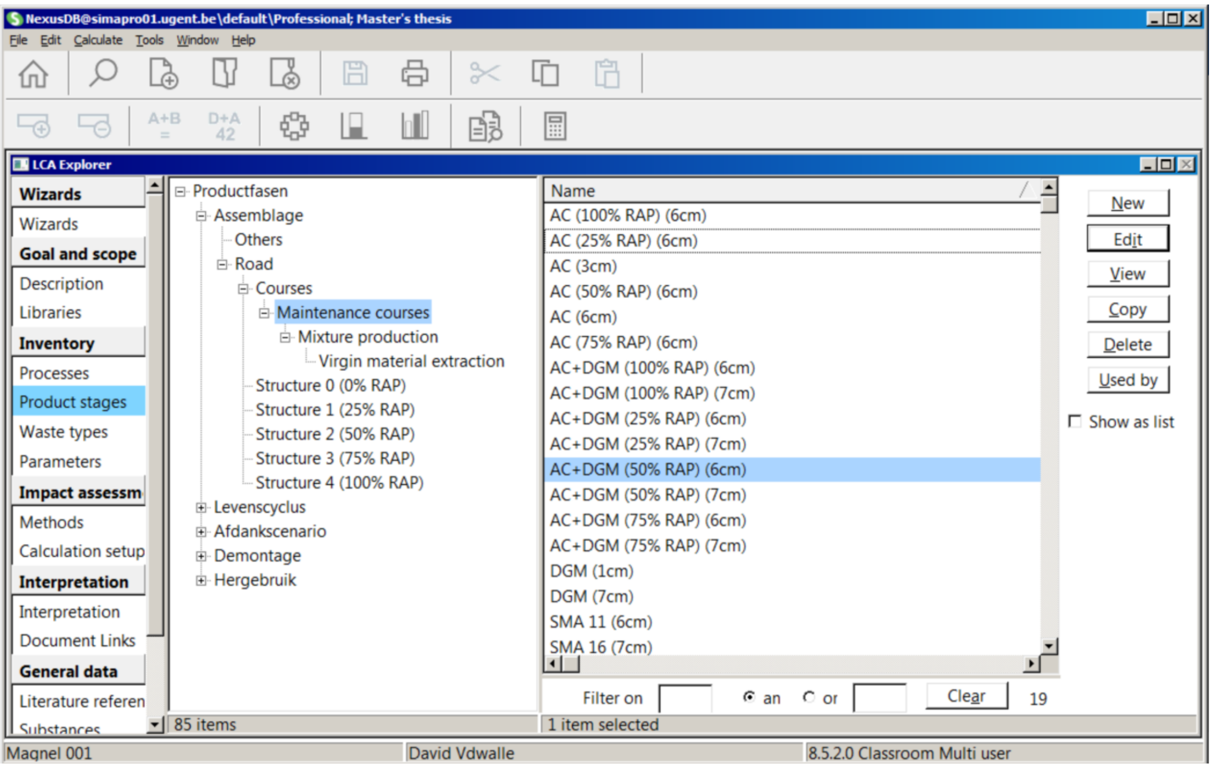


Naam: AC+DGM (50% RAP) (6cm)
Status: Geen
Opmerking:

Materialen/Assemblages	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opmerk
AC+DGM (50% RAP) (6cm) mixture product	1	p	Ongedefin				

Processen	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opmerk
Machine operation, diesel, >= 74.57 kW, hig	38.6	hr	Ongedefin				
Machine operation, diesel, >= 18.64 kW and	1.8	hr	Ongedefin				
Transport, freight, lorry >32 metric ton, EUR	21420	tkm	Ongedefin				

Figure 5-9 Assembly of the construction phase of the AC+DGM (50 % RAP) (6cm) course (SimaPro screenshot)



Productfasen
- Assemblage
  - Others
  - Road
    - Courses
      - Maintenance courses
        - Mixture production
          - Virgin material extraction
    - Structure 0 (0% RAP)
    - Structure 1 (25% RAP)
    - Structure 2 (50% RAP)
    - Structure 3 (75% RAP)
    - Structure 4 (100% RAP)
- Levenscyclus
- Afdankscenario
- Demontage
- Hergebruik

85 items

Name
AC (100% RAP) (6cm)
AC (25% RAP) (6cm)
AC (3cm)
AC (50% RAP) (6cm)
AC (6cm)
AC (75% RAP) (6cm)
AC+DGM (100% RAP) (6cm)
AC+DGM (100% RAP) (7cm)
AC+DGM (25% RAP) (6cm)
AC+DGM (25% RAP) (7cm)
AC+DGM (50% RAP) (6cm)
AC+DGM (50% RAP) (7cm)
AC+DGM (75% RAP) (6cm)
AC+DGM (75% RAP) (7cm)
DGM (1cm)
DGM (7cm)
SMA 11 (6cm)
SMA 16 (7cm)

19

1 item selected

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Figure 5-10 List of all course construction assemblies included in the LCA (SimaPro screenshot)

5.4.5 Work-zone traffic management and use phases

The first phase discussed in this paragraph, the work-zone traffic management phase, accounts for the marginal fuel cost and emissions released by on-road vehicles due to traffic perturbations caused by the different M&R events in comparison to those during normal road operation (Santos et al., 2018).

Due to a lack of data regarding traffic management during maintenance phases the environmental impacts of this phase were not included in this study.

The usage phase addresses environmental impacts resulting from the interaction of the pavement with the vehicles, environment and humans throughout its PAP (Santos et al., 2018). Santos et al. also mention several factors that have been subject of consideration during usage phase of the pavement such as;

- Pavement-vehicle interaction (PVI)
- Traffic flow
- Albedo
- Leachate
- Runoff
- Carbonatation
- Lighting

In this study however, the usage phase is not taken into account although the absolute contribution of this phase to the overall environmental impact of the pavement life cycle is potentially large (or even dominant) (Santero et al. as cited in Santero et al., 2010). The reason behind this omission lies again within the lack of well documented information regarding the case-study and consistent scientific background.

5.4.6 End-of-life phase

The end-of-life (EOL) phase of a pavement documents the destination of the pavement after its PAP. According to Santos et al. (2018), there are two main possible destinations for a given pavement: (1) remain in place, or; (2) be removed. In this study, the pavement is assumed to remain in place and to undergo maintenance 4 as described in 5.3.2. All environmental impacts of this phase are therefore considered in the materials extraction, mixture production and construction and M&R phase.

5.4.7 SimaPro final model

Before assessing the impact of each life cycle model in next paragraph, a brief impression is provided of the final SimaPro models. As mentioned before, each life cycle model consists of multiple assemblies which each in their turn comprise multiple, sometimes hundreds, unit processes. A graphical network representation of a whole life cycle is therefore considered irrelevant. However, to provide the reader a clear example of the final models, the life cycle of structure 2 was rendered and shown in Figure 5-11. To provide the reader a clear view, the image was rendered with a cut-off value of 4 %. Unit processes contributing less than 4% of the overall impact were hence omitted from the image but not from calculation.

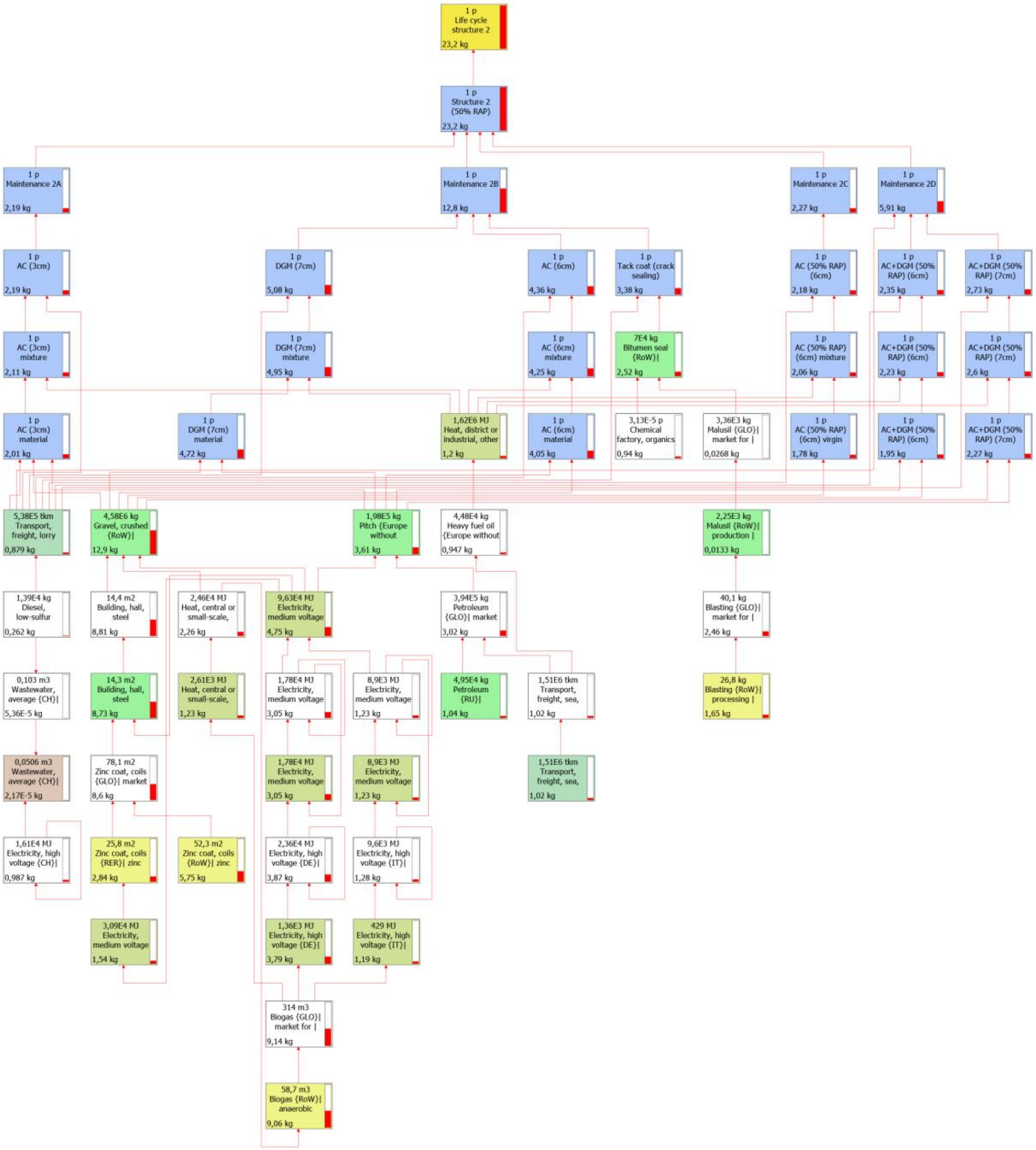

Figure 5-11 Network representation of life cycle structure 2 (SimaPro screenshot)

5.5 Life cycle impact assessment

As discussed in 3.5.2, the LCIA of an LCA presents the link between the system and the exterior; the impact it has on the environment, human health and resources. Presented in this paragraph, is the choice of method, characterization, damage assessment, normalization and the single score resulting from the LCIA. The five different life cycles of the sub-scenarios or structures considered in this study were defined in SimaPro as follows: Life Cycle Structure 0, Life Cycle Structure 1, and so forth. The results in this paragraph and in paragraph A.2 (Annex A) hence refer to the sub-scenarios as ‘LCS’s’.

5.5.1 Choice of method

As stated in 3.5.2, the choice should strongly depend on the targeted audience of the LCA. In this case, as defined in the goal and scope of the LCA, the aim of the study is firstly to evaluate a number of impacts of RAP incorporation, namely the impact on human health (mainly that of people closely related to the production or construction of the considered pavement), on resource depletion (and non-renewable resources) and on climate change (also referred to as global warming). Secondly, the results presented in this study are meant to reach a wide public consisting of different audiences. There should therefore not only be a large number of impact categories included in the method, but these categories should also be clearly defined and expressed in units that are easily recognized.

Considering these criteria, the method chosen for this study is the *IMPACT 2002+* method, provided in SimaPro. IMPACT 2002+ is a combination of four methods: *IMPACT 2002* (Pennington et al. 2005), *Eco-indicator 99* (Goedkoop & Spriensma, 2001), *CML* (Guinée, 2002) and *IPCC*. The motivation behind the selection of the IMPACT 2002+ method is threefold. The first reason is the large number of impact categories considered in this method (15), as well as their evident units. Secondly, the normalization in this method provides adequate and sufficient insight on three damage categories considered important in this study: human health, climate change and resources. Thirdly, IMPACT 2002+ is a European impact method, meaning its features are more closely related to Portuguese practice than for instance *ReCipe,* which is considered a global method.

5.5.2 Characterization

The first step of the LCIA is the classification, which consists of assigning each elementary flow to a certain impact category according to the substances' potential to contribute to this category. In the second step, characterization, the individual emissions from the elementary flows contributing to a single impact category are summed up. First however, they are converted into indicators using factors calculated by the IMPACT 2002+ model in order to account for their relative impact to a certain impact category. The impact categories and their units are shown in Table 5-10.

The characterization results, calculated in SimaPro, are discussed in detail and presented in table form in A.1.1 in Annex A. For each impact category, the results were converted to percentages of the maximum result (which proved to be the LC0 result in each impact category).

As an example, the characterization results of LCS0 and LCS2 are compared in Figure 5-13.

Table 5-10 IMPACT 2002+ LCIA method: impact categories and their units

Impact category	Unit	Unit definition
Carcinogens	kg C2H3Cl eq.	kg chloroethylene equivalents into air
Non-carcinogens	kg C2H3Cl eq.	kg chloroethylene equivalents into air
Respiratory inorganics	kg PM2.5 eq.	kg PM2.5 equivalents into air
Ionizing radiation	Bq C-14 eq.	Bq C-14 equivalents into air
Ozone layer depletion	kg CFC-11 eq.	kg CFC-11 equivalents into air
Respiratory organics	kg C2H4 eq.	kg ethylene equivalents into air
Aquatic ecotoxicity	kg TEG water	kg triethylene glycol equivalents into water
Terrestrial ecotoxicity	kg TEG soil	kg triethylene glycol equivalents into soil
Terrestrial acid/nutri	kg SO2 eq.	kg SO2 equivalents into air
Land occupation	m²org.arable	m² organic arable land
Aquatic acidification	kg SO2 eq.	kg SO2 equivalents into air
Aquatic eutrophication	kg PO4 P-lim.	kg PO4--- equivalents into a P-limited water
Global warming	kg CO2 eq.	kg CO2 equivalents into air
Non-renewable energy	MJ primary	MJ primary non-renewable
Mineral extraction	MJ surplus	MJ surplus

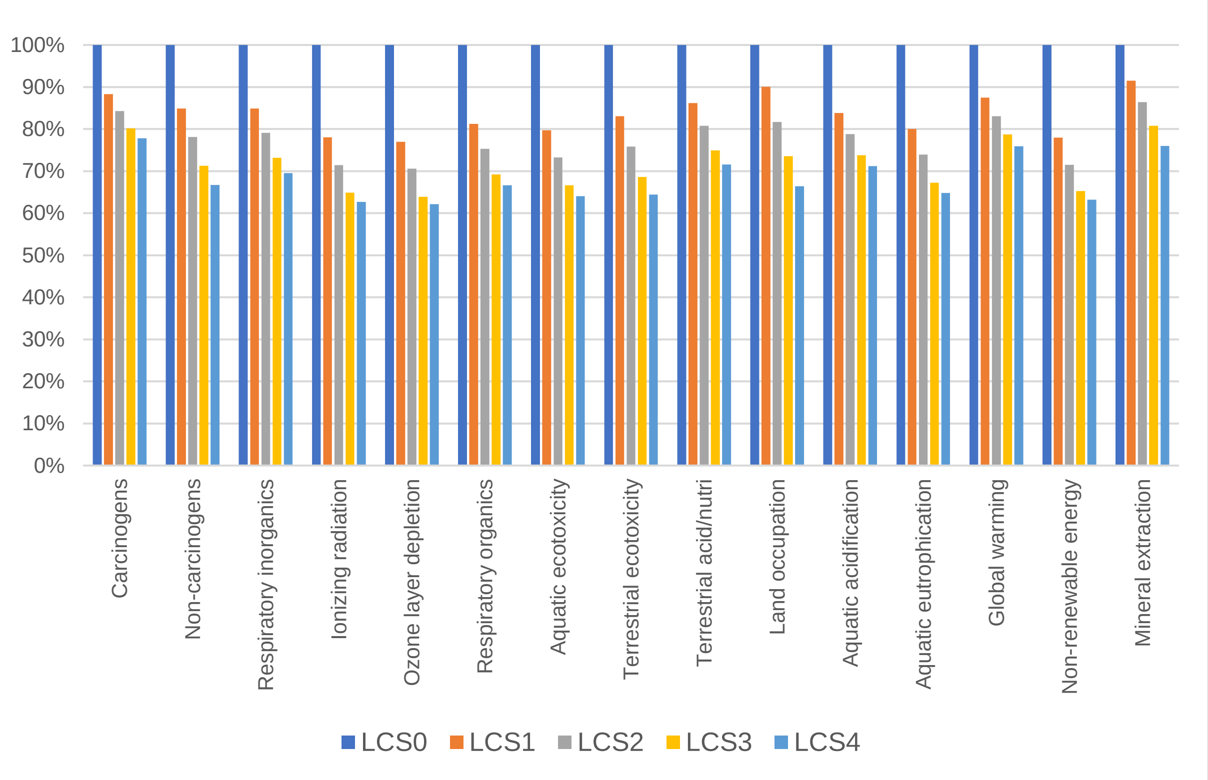

Figure 5-12 Characterization results (in percentages of the maximum per impact category)

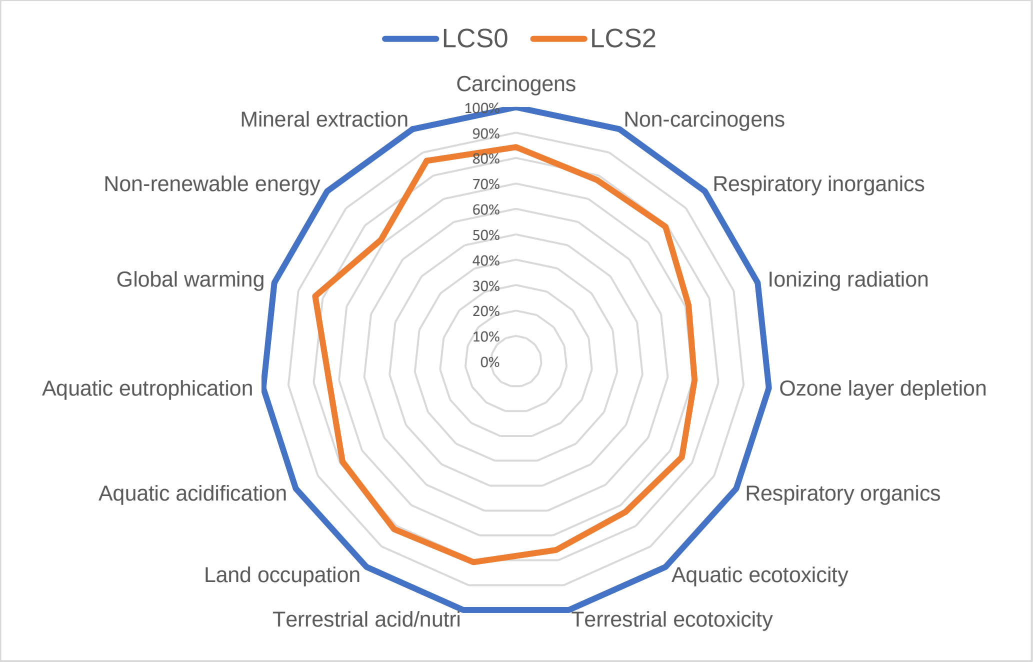

Figure 5-13 Characterization results comparison between LCS0 and LCS2

5.5.3 Damage assessment

The second part of the LCIA consists of a damage assessment. This step is optional for an LCIA and can be compared to the previous step. In the damage assessment however, the categories are defined from an endpoint approach in contrast to the midpoint approach used in the characterization step. Each damage category was thus compiled from several impact categories. For a more detailed explanation regarding the difference between mid- and endpoint the reader is referred to 3.5.

The damage categories provided by the IMPACT 2002+ method, together with their units, are displayed in Table 5-11. This table also presents the different impact categories assigned to each damage category.

5.5.4 Normalization

The third step, normalization, is according to the ISO standards also optional. Nonetheless, it can provide valuable insight into the extent an impact category indicator result has a relatively high or a low value compared to a reference. The damage factors reported in this study were normalized by dividing the impact per unit of emission by the total impact of all substances of the specific category for which characterization factors exist, per person per year (for Europe) (Humbert, De Schryver, Margni, & Jolliet, 2012). The resulting normalization numbers are shown in Table A-16 in Annex A (A.2.3). The graphical representation is shown in Figure 5-15. These numbers are ratio’s and normalization therefore also solves the incompatibility of units.

Table 5-11 IMPACT 2002+ damage categories (Humbert et al., 2012)

Impact category	Damage category	Unit	Unit definition
Carcinogens	Human health	DALY	Disability-adjusted life years: characterizes the disease severity, accounting for both mortality (years of life lost due to premature death) and morbidity (the time of life with lower quality due to an illness, e.g., at hospital)
Non-carcinogens			
Respiratory inorganics			
Respiratory organics			
Ionizing radiation			
Ozone layer depletion			
Aquatic ecotoxicity	Ecosystem quality	PDF*m²*yr	The Potentially Disappeared Fraction of species over a certain amount of m² during a certain amount of year.
Terrestrial ecotoxicity			
Terrestrial acid/nutri			
Land occupation			
Aquatic acidification			
Aquatic eutrophication			
Global warming	Climate change	kg CO_2 eq	kg CO_2 equivalents into air
Non-renewable energy	Resources	MJ primary	MJ primary non-renewable
Mineral extraction			

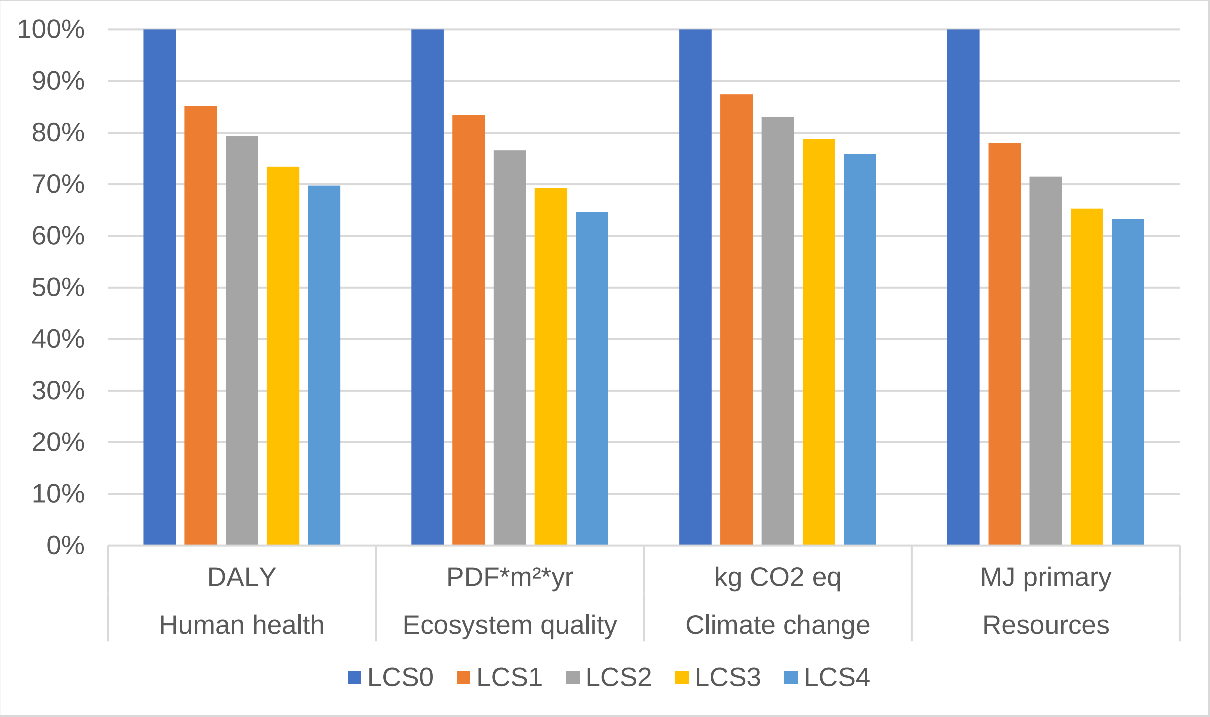

Figure 5-14 Damage assessment results (expressed in percentages of the maximum value per category): comparison for the 5 LCS's

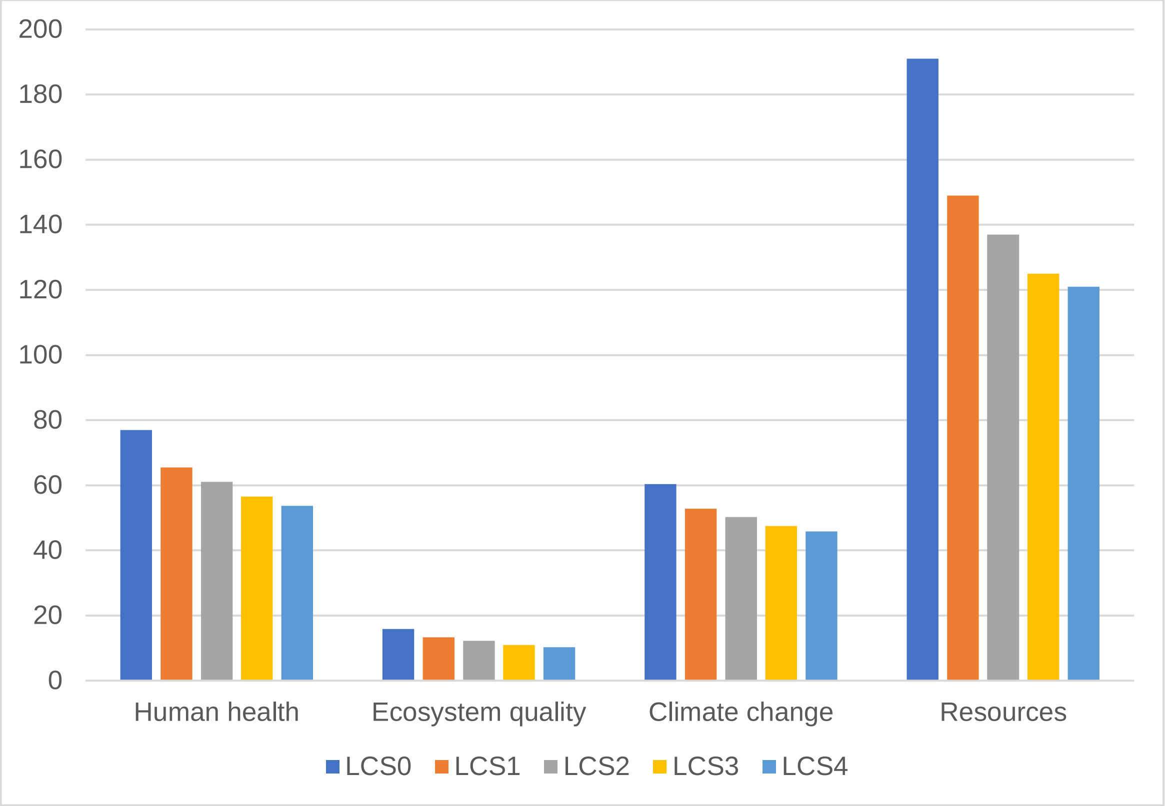

Figure 5-15 Normalization results

5.5.5 Weighting

Another optional step, weighting, was omitted from this study. Weighting of the normalization results implicates adding value to a certain damage category. Unless other social weighting values are available, the most commonly used weighting factors are 1:1:1:1, which are also the default values provided by SimaPro.

5.5.6 Single score

The last step, the single score, is calculated based on the weighting values. In this case, since weighting factors were considered 1:1:1:1, the weighting values were equal to the normalization results. To calculate the single score for each structure, the four normalization results were simply added up. The results from this step are displayed more in detail in Table A-17 in A.2.4 (Annex A). Although normalization and especially the single score mentioned in this sub-paragraph provide the reader a clear and perhaps more intuitive impression of the impact, it should be noted that these results are endpoint results and therefore imply multiple assumptions. Consequently, any conclusion which is drawn based on these steps should be handled carefully.

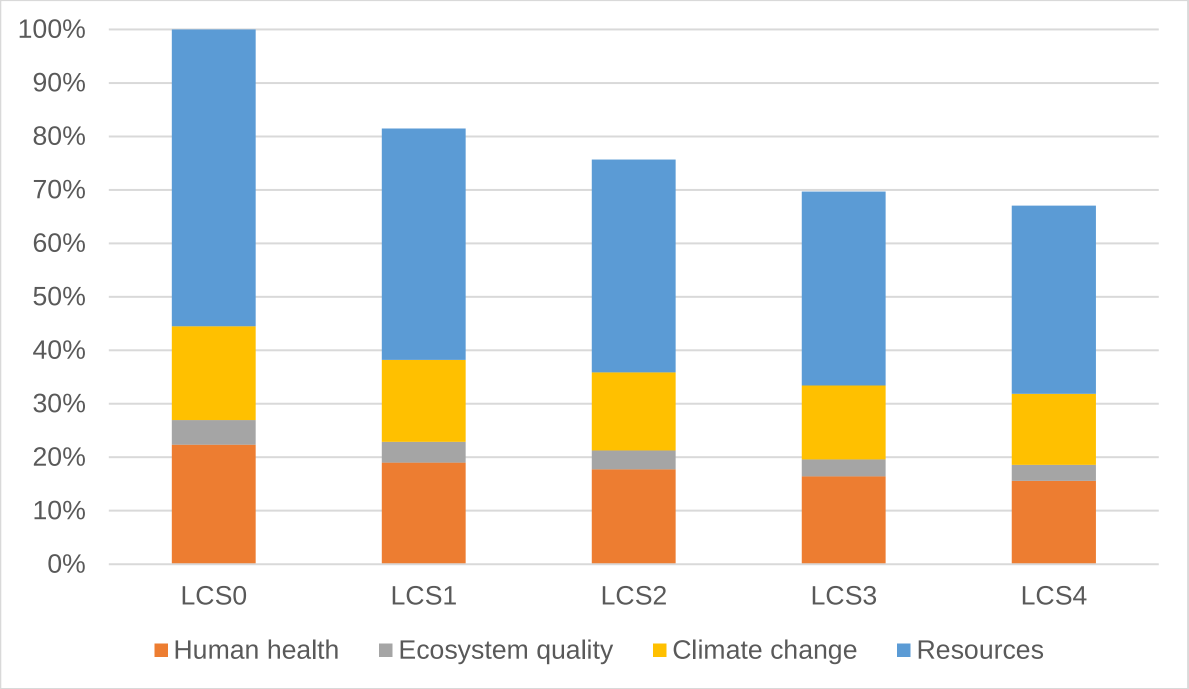

Figure 5-16 Single score values (expressed in percentages of the maximum single score value) for the five different structures considered in the LCIA

5.6 Results and discussion

The last paragraph of this chapter discusses the LCIA results presented in previous paragraph. First of all, it should be noted that any result from the LCIA presented in this study is to be interpreted cautiously. Throughout this LCA, several omissions and assumptions were made to simplify and streamline the work. All assumptions were done with care, considered justified through sufficient argumentation and all omitted elements were considered insignificant in light of the goal and scope of this study. The reader should however, take note of this when further analysing the results presented in this dissertation.

The first results discussed in this paragraph are the characterization results. The chart in Figure 5-12 displays a clear overall decrease in environmental impact with increasing percentages RAP incorporation. The results for each impact category, without exception, show that the higher the amount of RAP incorporation, the lower the environmental impact. For some categories, the decrease in impact for LCS4 (which has a theoretical RAP incorporation of 100 %) compared to LCS0 (which consists of virgin material only) is nearly 40 %.

The second part of LCIA, the damage assessment, demonstrates similar results as the characterization: an average damage category impact decrease around 15 % for LCS1 and even around 25 % for LCS4 can be observed in the chart presented in Figure 5-14.

The third LCIA step discusses the normalization and the single score. Although this step is optional and the normalization reference is arbitrary, it may provide valuable insight in the environmental impact of any flexible pavement. The chart in Figure 5-15 illustrates the same promising results for the LCS's that incorporate RAP in comparison to LCS0. The chart also shows a significant difference in impact between *resources* and the other categories. It may be clear that the environmental impact of the construction of a flexible pavement (with or without RAP incorporation) is mostly felt in this category. The same conclusion can obviously also be drawn from the single score chart presented in Figure 5-16. This chart may present a clear summary of the LCIA results, but a consideration that should be made regarding the normalization results, is the statistical uncertainty. As stated in 3.5.2, normalization results might prove more understandable for a wider audience, their statistical uncertainties are higher. Data gaps and assumptions accumulate along the cause-effect chain and will therefore cause endpoint results to be less certain. Although this may impact the results, the single score decrease from LCS0 to LCS4 is reported in Figure 5-16 to be more than 30 %, which should be considered significant

.

6 LCCA APPLIED TO A CASE STUDY

This chapter provides the second section of the case study analysis, the LCCA. This analysis consists of the methodology, goal & scope, the analysis requirements and the cost assembly. It concludes with the presentation of and discussion about the results.

6.1 Introduction

To analyse the overall impact of RAP incorporation in bituminous mixtures, both a comparative life cycle assessment (LCA) and life cycle cost analysis (LCCA) were applied to several construction, maintenance and rehabilitation (M&R) scenarios for a flexible pavement section in Portugal. The first part of the analysis, the LCA was the subject of previous chapter and covered the environmental impact of the considered pavement section alternatives. The second part, the LCCA, which is the main topic of this chapter, reports the economic impact of the different structure scenarios.

First, the methodology used to perform the LCCA is defined. Secondly, the goal & scope and analysis requirements are further explained. Next, is the cost assembly and finally, the results from this assembly will be presented and discussed.

6.2 Methodology

In chapter four, several procedures to perform an LCCA were presented. As mentioned, each procedure consists of several steps. Although the exact number and the definition of these steps may vary across the different procedures, the general methodology is considered equal for all procedures. The starting point for the LCCA procedure issued in this study was the methodology presented by Davis Langdon (2007a) shown in Table 6-1. This table also displays which steps were incorporated in this study and the related paragraphs in which they will be treated.

As discussed in paragraph 4.4, several organizations have developed specialized LCCA software to assist in this type of analysis. Due to some obvious limitations (Babashamsi et al., 2016) however, and a general lack of flexibility, the LCCA in this study was performed with MS Excel.

6.3 Goal and scope definition

6.3.1 Goal

The goal of the LCCA presented in this study is to evaluate the economic impact of RAP incorporation in bituminous pavements. More specifically, it should provide the reader an impression on how certain percentages of RAP incorporation in bituminous mixtures alters specific costs and could potentially decrease the overall cost of a bituminous pavement.

Table 6-1 Selection of LCCA procedure steps (Davis Langdon, 2007a)

No.	Definition	Associated paragraphs in this study
1	Identify the main purpose of the LCCA	Goal and scope
2	Identify the initial scope of the analysis	
3	Identify the extent to which sustainability analysis relates to LCC	
4	Identify the period of analysis and the methods of economic evaluation	Analysis requirements
5	Identify the need for additional analyses (risk/uncertainty and sensitivity analyses)	
6	Identify project and asset requirements	
7	Identify options to be included in the LCC exercise and cost items to be considered	Cost assembly
8	Assemble cost and time (asset performance and other) data to be used in the LCC analysis	
9	Verify values of financial parameters and period of analysis	
10	Review risk strategy and carry out preliminary uncertainty / risk analysis	
11	Perform required economic evaluation	
12	Carry out detailed risk / uncertainty analysis (if required)	
13	Carry out sensitivity analyses (if required)	
14	Interpret and present initial results in required format	Results and discussion
15	Present final results in required format and prepare a final report	

6.3.2 Scope

The functional unit analysed in this LCCA is considered the same as the functional unit presented in the LCA, discussed in 5.3.2. This means that the overall M&R scenario was considered equal and the same division into five sub-scenarios, or *structures*, was considered in the LCCA.

The scope for the LCCA in this study was largely based on the scope of the LCA, discussed in 0. The system boundaries for the LCCA also include the materials extraction, mixture production, construction and M&R phase and make the same assumptions in omitting the use phase from the equation. The end-of-life phase however, is partially considered in the LCCA, as opposed to the LCA. The milled material which results from the third and fourth maintenance, has two possible destinations: to be incorporated in new bituminous mixtures as RAP or to be used as landfill. In accordance with the environmental impact allocation in previous chapter, costs associated with the use of RAP material in this study solely originate from the RAP processing or transport, not from the procurement of the material itself. The costs associated with landfill however, will be accounted for in this LCCA. This landfill cost depends on the RAP incorporation percentage of each structure.

6.4 Analysis requirements

6.4.1 Project Analysis Period

The functional unit defined in 6.3.2 is considered the same as the functional unit used in the LCA in chapter five. It was defined as a unit of pavement that carries the same traffic over the same PAP. The total PAP of the unit of pavement is considered 69 years, expanding from 1946 to 2015.

6.4.2 Economic evaluation

Step 11 in the methodology presented by Davis Langdon (2007a) is defined as “Perform required economic evaluation”. As was mentioned in chapter 2, this evaluation can be performed through different indices. The most used parameters however, are the NPV and EUAC (calculated through respectively equations 4.1 and 4.2) (Babashamsi et al., 2016)

The NPV definition however, includes future costs and salvage value. The PAP of the functional unit considered in this study, however, ranges from 1946 to 2015 and is therefore already terminated. No future costs or salvage value should hence be considered and the NPV for each structure can simply be calculated as the overall sum of costs.

6.4.3 Risk/uncertainty and sensitivity analysis

The twelfth and thirteenth step in the LCCA methodology proposed by Davis Langdon (2007a) respectively comprise of a risk/uncertainty and a sensitivity analysis. As stated in chapter four, the choices made in this step determine the ultimate character of the LCCA, which can be deterministic or probabilistic. With a deterministic LCCA, discrete values are assigned to individual parameters. According to Babashamsi et al. (2016) however, a certain type of uncertainty lies within the input values of any given LCCA. Probabilistic LCCA allows the value of individual analysis inputs to be defined by a frequency (probability) distribution (FHWA, 2002). It uses various methods such as risk analysis and sensitivity analysis (steps 12 and 13 of the 15-step-method) to manage this uncertainty.

The primary data in this LCCA was provided by several companies and sector experts. For the bulk of the costs however, there was no clear frequency distribution or no sufficient values to assume a distribution available. A probabilistic LCCA with the available primary data therefore was not considered workable. The LCCA presented in this study thus is deterministic of nature and results should hence be interpreted with caution, which will be further discussed in the last paragraph of this chapter.

6.5 Cost assembly

The third step considered in this LCCA is the cost assembly. Before assembling data however, it is vital to decide which costs are relevant for the exercise and how these costs can be measured, calculated, or gathered from existing data. The costs included in an LCCA differ according to the case, but the division into life-cycle stages along with the main cost groups is a returning element in every LCCA of road structures. In general, the costs can be divided into two groups: the agency (or owner) costs and the user costs, both of which can be subdivided into smaller categories. A third group of costs proposed by Antunes et al. (2016) comprises of environmental costs.

These last two groups however, are subject to discussion since there is simply not enough adequate, obtainable data in most cases. This impedes the possibility to compute them easily and correctly (Antunes et al., 2016).

The first group, the agency costs, often called the direct costs, are the costs supported by the owning administration or road agency over the life cycle of the project (Heuvinck, 2015). A non-exhaustive example of the costs that can be included in agency costs is given by Albuquerque e Castro (2016) in Table 6-2.

Table 6-2 Example of the different types and subtypes of road agency costs in LCCA (Albuquerque e Castro, 2016)

Type	Subtype
Pre-construction	Site costs
Product stage	Raw materials
	Transport
	Manufacturing
Construction	Transport
	Professional fees
	Temporary works
	construction
	Fit-out
	landscaping
	Taxes / subsidies / incentives
Use stage	Operation and maintenance
	Repair / replacement / refurbishment
	Energy & water
End-of-life stage	Deconstruction
	Waste transport & processing
	Disposal
After life stage	Revenue from disposal of interest of land
	Revenue from recycling

The second group of costs discussed in 4.3.4 are the user costs. The most important cost-components that could be considered when calculating user-costs are (U.S. Department of Transportation: Federal Highway Administration's Office of Asset Management, 2002):

- Vehicle operating costs (VOC)
- User delay costs
- Crash costs

Although the consideration of these costs adds validity to the LCCA, it also provides a big challenge due to the uncertainty of its parameters. The value of user time, for instance, is one the main issues presented. Similarly, uncertainty exists about the effects of agency activities on crash rates and vehicle operating costs (U.S. Department of Transportation: Federal Highway Administration's Office of Asset Management, 2002). The LCCA presented in this study therefore does not include user costs. As mentioned previously however, a certain cost is attributed for the allocation of amounts of milled material to landfill.

6.6 Results and discussion

The sixth and last paragraph of this chapter presents and reviews the LCCA results. According to the 15-step LCCA methodology suggested by Davis Langdon (2007a), the economic evaluation step is performed through the calculation and comparison of indices such as NPV or EUAC. Whichever alternative generating the highest NPV or EUAC, would hence be considered the economically most viable option. As mentioned in 6.4.2 however, the economic evaluation in this study is simply done through a comparison of overall cost, i.e. the sum of all the costs that were taken into account. Table 6-3 gives an overview of these costs. Some of these costs were calculated based on primary data such as machine efficiencies, material unit costs etc. All calculations and subsequent results are disclosed in Annex B. More specifically, the conclusive, overall cost assembly is shown in paragraph B.2. in annex tables B-15, B-16, B-17, B-18, and B-19.

For analysis purposes however, the overall cost assembly tables did not prove suitable. All distinct cost factors where therefore grouped into seven categories; virgin material production, mixture production, transport, construction, RAP production, milling and landfill disposal. Although some minor nuances, these categories largely correspond with the life-cycle phases. Table 6-4 gives an overview of the total life cost per structure and per phase, divided into the seven categories. These categories correspond to the subtypes in Table 6-3, with exception of the transport category, which is the combination of virgin material transport, construction transport and waste transport subtypes.

Table 6-3 Overview of all cost factors considered in the cost assembly

Type	Subtype	Specific cost
Production stage	Virgin material production	Virgin aggregates
		Virgin binder
	Virgin material transport	Virgin aggregate transport
		Virgin binder transport
	Mixture production	Plant amortisation
		Diesel
		Fuel
		Emission costs
Construction and M&R	Construction transport	Mixture transport
		Milled material transport (for RAP production)
	Construction	Paving machine (own)
		Paving machine (rent)
		Bobcat equipped with brooms
		Tanker truck with water
		Light truck for cleaning
		Compressor
		Smooth wheel rollers 10 tonne
		Pneumatic rollers 12 tonne
	Milling	Milling machine with 2 ml drum (own)
		Milling machine with 2 ml drum (rent)
		Bobcat equipped with brooms
		Tanker truck with water
		Compressor
	RAP production	Crushing by crusher
		Screening plant
End-of-life	Waste transport	Transport of milled material (for landfill disposal)
	Disposal	Landfill cost

Table 6-4 Total life cycle costs

Phase	Structure 0 (€)	Structure 1 (€)	Structure 2 (€)	Structure 3 (€)	Structure 4 (€)
Virgin material production	251,982.41	163,470.57	142,749.35	122,028.13	111,500.92
Mixture production	65,577.09	65,577.09	65,577.09	65,577.09	65,577.09
Transport	35,642.86	31,528.57	28,442.86	24,928.57	21,671.43
Construction	161,483.87	161,483.87	161,483.87	161,483.87	161,483.87
Milling	10,451.70	10,451.70	10,451.70	10,451.70	10,451.70
RAP production	0.00	2,320.50	4,641.00	6,961.50	9,189.18
Disposal (landfill)	3,896.90	2,922.68	1,948.45	974.23	0.00
Total	**529,034.82**	**437,754.97**	**415,294.31**	**392,405.09**	**379,874.18**

The results from Table 6-4 are also displayed graphically in Figure 6-1 and Figure 6-2. The chart in Figure 6-1 shows the total life-cycle cost for each structure, in percentages of the maximum life cycle cost, which is that of structure 0. Moreover, the total costs in this chart are sub-divided into seven categories. The chart shown in Figure 6-2 expresses the costs in absolute numbers rather than relative percentages. Furthermore, it makes the same seven-category-distinction as the chart in Figure 6-1 but shows these costs separately for each structure.

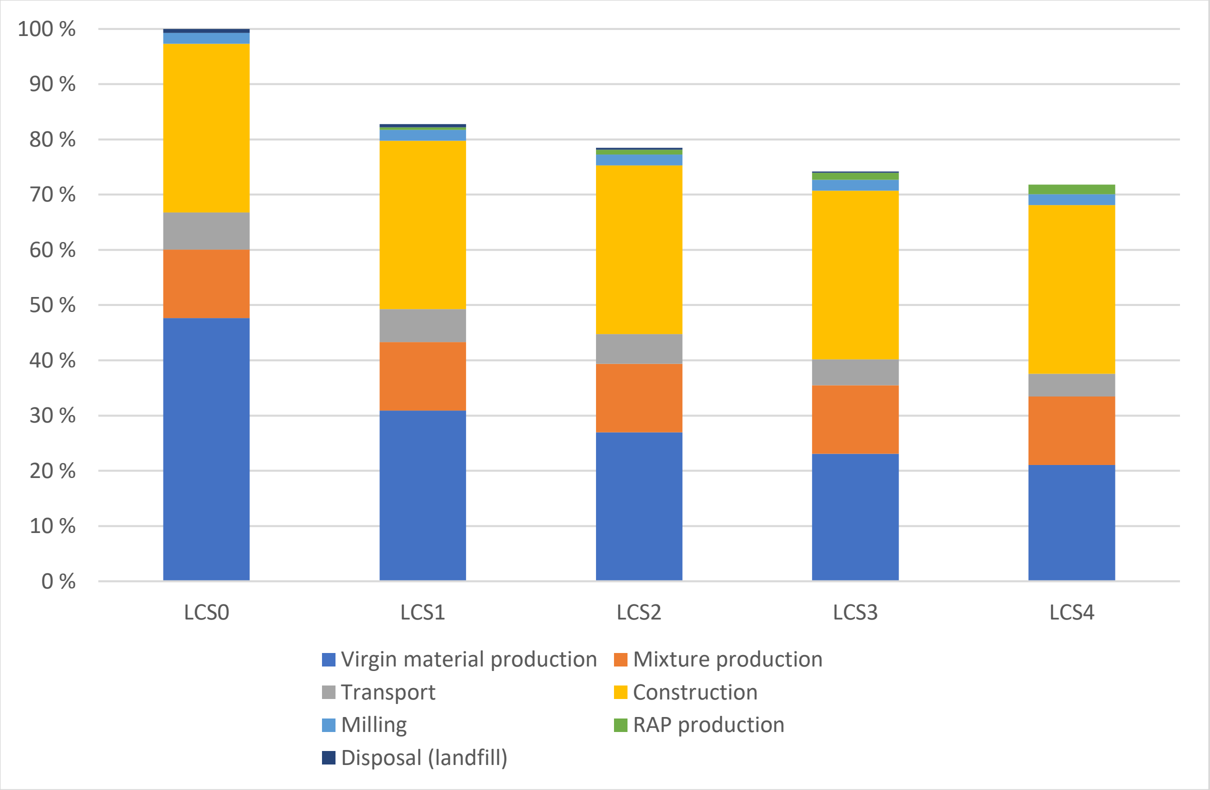

Figure 6-1 Total life cycle cost per structure, subdivided into the costs for the most significant life-cycle phases and expressed in percentages of the maximum total life cycle cost (structure 0)

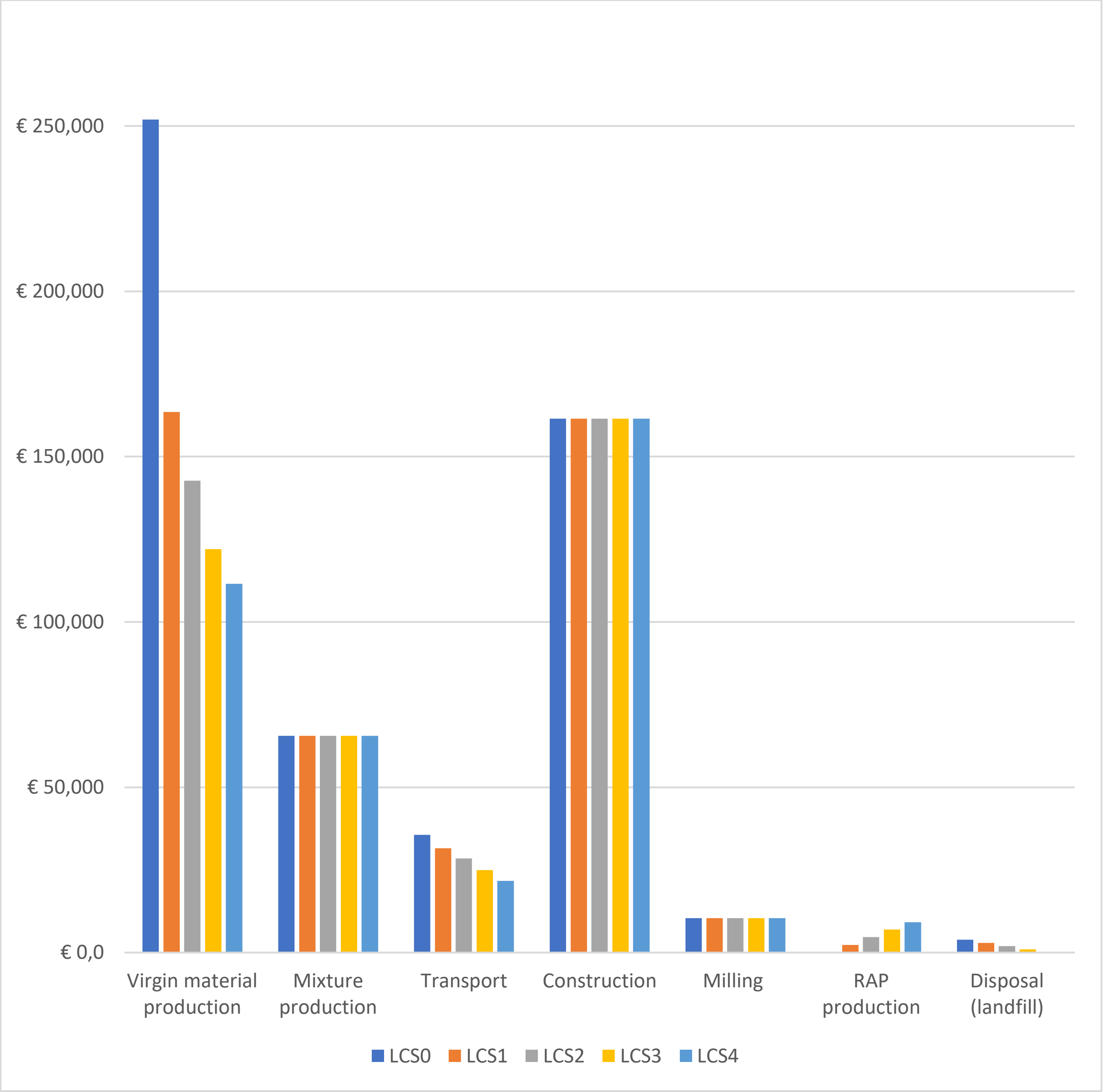

Figure 6-2 Total life cycle cost of the most significant life-cycle phases, displayed per structure

Both figures deliver valuable insights concerning the life cycle cost of a flexible pavement unit and the economic impact of RAP incorporation more specifically. The graph in Figure 6-1 for example shows a distinctive decrease in overall cost for structures 1 to 4 in comparison to structure 0. The difference between structure 0 and structure 1 for example, is more than 15 %.

The reduction in cost of virgin material contributes the most to this decrease, as can be seen in Figure 6-2. Other important life cycle cost categories that decrease with increasing RAP incorporation are transport and disposal (landfill). The reduction in transportation costs for RAP-incorporating structures is explained mainly through the cut in virgin material and the need for its transport. Another saving is reported by the costs of landfill disposal. These costs are obviously directly related to the amount of milled material from the maintenance actions that is not being reused. The more RAP is therefore incorporated, the less material will be directed to landfill. It should be noted that RAP incorporation also leads to a rise in one specific cost category which is the RAP production. Although this rise should be considered significant, it has a very limited effect on the overall cost.

7 CONCLUSION

This final chapter combines the results and discussions from chapters five and six to give the reader a summary and global analysis of the work. From this analysis, several conclusions are then drawn to formulate an answer to the problem stated in chapter 1. The final point of the chapter is an overview of a few recommendations for future work.

7.1 Summary and global analysis

To summarize, this study attempted to evaluate the impact of RAP incorporation and multi-recycling of bituminous mixtures in the case of flexible pavement rehabilitation. The impact was assessed, both from an environmental as an economic perspective, by performing an LCA and an LCCA case study. The functional unit of this case study comprised the flexible pavement of a Portuguese road section of 1 km length, 7 m width and a PAP of 69 years. The case study compared five M&R scenarios (referred to as 'structures') for the section, each with a different percentage of RAP incorporation in the bituminous mixtures: 0, 25, 50, 75 and 100 %.

The case study LCA findings are subject of the LCIA in paragraph 5.5, including characterization, damage assessment, normalization and single score results. The characterization step reveals the environmental impact of the five structure's life cycles across 15 impact categories. Throughout all categories, without exception, a general decrease of impact can be observed proportionate to the percentage of RAP used. As an example, the average decrease for structure 2 (which integrates 50 % of RAP) is 22 %. To provide the reader a more concise and comprehensible result, the impact category numbers were grouped into larger damage categories in the damage assessment, subsequently normalized in the normalization step and finally added in the single score step. Although being less accurate and certain, these results show the same trend as the characterization. In the case of structure 2 for example, a 22 % average decrease across the four damage categories (human health, resources, ecosystem quality and climate change) and a 24 % decrease in single score were observed. Moreover, the results suggest that the impact on the environment is linear correlated to the level or percentage of incorporation, which means a theoretical incorporation of 100 % RAP would be the most ecological advantageous option and, according to this case study, should reduce the overall impact on the environment by 33 %.

The case study LCCA comprised of a total life cycle cost comparison between the five structures. The total cost for each structure included costs of virgin material production, mixture production, transport, construction, milling, RAP production and landfill. The results of this comparison, introduced in 0, demonstrated a decrease in overall cost proportional to the percentage of RAP use. 50 % RAP incorporation for example, reduced the overall life cycle cost of the structure by 21 %. And, in correspondence with the LCA results, the economic impact was also directly proportional to the percentage of RAP used in the structure. The cheapest alternative in this case study was thus structure 5 which theoretically includes 100 % RAP and showed an overall life cycle cost decrease of 28 %.

The results from the case study LCA and LCCA completed in this study were both comprehensively discussed in chapters 5 and 6 respectively. For a more detailed analysis of these results, the reader is referred to the concluding paragraphs of these chapters.

7.2 Main conclusions

Multiple conclusions can be drawn from this study:

- The first main conclusion is the confirmation, as expected, that the incorporation of RAP in bituminous mixtures, and especially in a multi-recycling scenario, has lesser environmental impact than the use of virgin materials. The most important impact factors considered in this study were human health, natural resources and climate change or global warming. The case study LCA proved that across all factors, RAP incorporation is beneficial and reduces the impact significantly. Moreover, a linear correlation between the percentage of RAP included and environmental impact was demonstrated. This indicates that theoretically, when constructing or maintaining flexible pavement layers, a 100 % RAP incorporation (or the complete recycling and multi-recycling of materials) should be pursued.
- Secondly, the results from the LCCA case study even invigorate the environmental benefits of RAP incorporation by also proving their positive impact on the life cycle cost of a flexible pavement. As mentioned before, the overall cost reduction amounts 21 % for structure 2 which integrates 50 % of RAP. Furthermore, the same linear correlation also applies to the life cycle cost, signifying that a theoretical integration of 100 % also economically appears the ideal scenario.

Although these results may seem promising, it should be noted that this case study represents certain common Portuguese practices so they should be adapted for other construction and M&R scenarios, geographic regions or types of road pavements. Moreover, throughout the LCA and LCCA, several factors were considered irrelevant and omitted to simplify the calculation, e.g. the production of additives because they did not affect the relative comparison between solutions. Due to the comparative nature of the LCA and LCCA, the use phase cost and environmental for example, was considered equal across all structures and thus also not taken into account. It should also be pointed out that the primary data for this study was obtained through multiple active companies and experts to provide the most accurate and comprehensive input for the case study as possible. Minor fluctuations and inconsistencies were considered insignificant but due to external factors e.g. uncertainty, risk, and fluctuating prices however, this data may not be all-inclusive or fully accurate and should hence be treated cautiously.

In conclusion, the case study of a Portuguese flexible pavement section rehabilitation shows a clear decrease in environmental and impact when reclaimed asphalt pavement is reused (once or more than once) during maintenance phases. The multi-recycling of flexible pavement should therefore be favoured over using only virgin materials in new bituminous mixtures. Besides these environmental and economic benefits of RAP multi-recycling, significant worldwide research has also been carried on to confirm the mechanical and durability advantages of this technology with promising results.

7.3 Limitations and recommendations for future work

First of all, the LCA and LCCA applied to a case study in this dissertation supplied valuable insights regarding the multi-recycling of flexible pavement layers. Decision making in a pavement management context however, is a complex exercise. LCA and LCCA approaches should therefore be integrated into a multi-objective optimization framework that also includes the social dimension, structural objectives and constraints, etc (Santos et al., 2017a).

Secondly, in accordance with most (pavement) LCA's, this study was confronted with data scarcity and reliability issues. In order to take this uncertainty and risk into account, it is prudent to perform sensitivity and uncertainty analyses to identify the robustness of the results (Santero et al., 2010). Due to time constraints and the absence of statistical parameters, these analyses were not performed but could prove an important addition in future work to increase reliability.

Furthermore, as discussed in previous paragraph, during the LCA and LCCA several assumptions and omissions were made to simplify the calculation. Due to project constraints e.g. time, data availability etc, omissions are inevitable. Omissions like this can change the results of an LCA significantly and should therefore be well considered. Especially the omission of the use phase includes potentially influential components and should thus be subject of future work.

Finally, it should be noted that the choice of software tools to perform an LCA, e.g. SimaPro, the Ecoinvent database and the IMPACT 2002+ impact assessment method has a distinctive influence on the results. Another recommendation for future work is therefore to cross-examine the same functional unit across different tools.

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Annex A LCA CALCULATIONS

A.1 LCI data

A.1.1 Material’s extraction phase

The material’s extraction phase consists of the two subphases: the production and the transport of virgin materials. To calculate the required amount of virgin aggregate and virgin binder for each course, several calculations were performed. The starting point of these calculations was the primary data obtained from a variety of sources in combination with the characteristics of the functional unit; the length & width of the unit of pavement and the depth of each individual course.

First of all, to determine these amounts, a fixed binder-aggregate ratio of 95-5 was determined for all mixtures except the SMA mixtures (which have a 93.5-6.5 ratio). This implies that regardless of technical specifications, the majority of mixtures contains 95 % of aggregate and 5 % of binder. Furthermore, to derive the amount of virgin aggregate and binder from the total amount of material, the RAP incorporation for each specific course was determined.

Table A-1 presents these calculation properties for all the courses that have a 0 % RAP incorporation. As can be expected, the table shows no difference between the total and virgin quantities of aggregate and binder in these courses.

The second table presented in this paragraph, Table A-2, displays the calculation properties for the 25 % and 50 % RAP incorporation courses. Although the total aggregate to total binder ratio for these mixtures (and the 75 % and 100 % RAP incorporation courses as well) remains 95-5, the virgin material ratio’s do not abide by this rule. Instead, the virgin material amounts were determined based on the required virgin binder percentage for each percentage of RAP incorporation following laboratory tests. RAP incorporations of 25 % and 75 % respectively require a virgin binder mass percentage of 2.9 % and 1.2 % of the total mixture mass. For the 50 % RAP incorporation mixtures, a linear correlation was assumed between the percentage of RAP incorporation and the required virgin binder percentage. These mixtures therefore require 2.05 % of virgin binder mass percentage. The 100 % RAP mixtures though, were assumed to still need at least 1 % of virgin binder mass percentage instead of the expected 0 % as displayed in Table A-3.

Table A-1 Calculation properties for aggregate and binder quantities of 0 % RAP courses

Property	AC (3 cm)	AC (6 cm)	DGM (1 cm)	DGM (7 cm)	SMA 11	SMA 16
Width (m)	7	7	7	7	7	7
Length (km)	1	1	1	1	1	1
Thickness (cm)	3	6	1	7	6	7
Total volume (m^3)	210	420	70	490	420	490
Density (kg/m^3)	2550	2550	2550	2550	2550	2550
Total mass (tonne)	535.50	1071.00	178.50	1249.50	1071.00	1249.50
RAP content	0	0	0	0	0	0
RAP mass (tonne)	0.00	0.00	0.00	0.00	0.00	0.00
RAP volume (m^3)	0.00	0.00	0.00	0.00	0.00	0.00
Agg_density (kg/m^3)	2650	2650	2650	2650	2650	2650
Total_agg_content (% m/m)	0.95	0.95	0.95	0.95	0.935	0.935
Virgin_agg_content (% m/m)	0.95	0.95	0.95	0.95	0.935	0.935
Total_agg_mass (kg)	508725	1017450	169575	1187025	1001385	1168283
Virgin_agg_mass (kg)	508725	1017450	169575	1187025	1001385	1168283
Total_agg_vol (m^3)	191.97	383.94	63.99	447.93	377.88	440.86
Virgin_agg_vol (m^3)	191.97	383.94	63.99	447.93	377.88	440.86
Binder_density (kg/m^3)	1030	1030	1030	1030	1030	1030
Total_binder_content (% m/m)	0.05	0.05	0.05	0.05	0.065	0.065
Virgin_binder_content (% m/m)	0.05	0.05	0.05	0.05	0.065	0.065
Total_binder_mass (kg)	26775	53550	8925	62475	69615	81217
Virgin_binder_mass (kg)	26775	53550	8925	62475	69615	81217
Total_binder_vol (m^3)	26.00	51.99	8.67	60.66	67.59	78.85
Virgin_binder_vol (m^3)	26.00	51.99	8.67	60.66	67.59	78.85

Table A-2 Calculation properties for aggregate and binder quantities of 25 % and 50 % RAP courses

Property	**AC (25 % RAP) (6 cm)**	**AC (25 % RAP (6 cm)**	**AC + DGM (25 % RAP) (7 cm)**	**AC (50 % RAP) (6 cm)**	**AC (50 % RAP (6 cm)**	**AC + DGM (50 % RAP) (7 cm)**
Width (m)	7	7	7	7	7	7
Length (km)	1	1	1	1	1	1
Thickness (cm)	6	6	7	6	6	7
Total volume (m³)	420	420	490	420	420	490
Density (kg/m³)	2550	2550	2550	2550	2550	2550
Total mass (tonne)	1071.00	1071.00	1249.50	1071.00	1071.00	1249.50
RAP content (% m/m)	25	25	25	50	50	50
RAP mass (tonne)	267.75	267.75	312.38	535.50	535.50	624.75
RAP volume (m³)	105.00	105.00	122.50	210.00	210.00	245.00
Agg. density (kg/m³)	2650	2650	2650	2650	2650	2650
Total agg. content (% m/m)	95	95	95	95	95	95
Virgin agg. content (% m/m)	72.1	72.1	72.1	47.95	47.95	47.95
Total agg. mass (kg)	1017450	1017450	1187025	1017450	1017450	1187025
Virgin agg. mass (kg)	772191	772191	900890	513545	513545	599135
Total agg. volume (m³)	383.94	383.94	447.93	383.94	383.94	447.93
Virgin agg. volume (m³)	291.39	291.39	339.96	193.79	193.79	226.09
Binder density (kg/m³)	1030	1030	1030	1030	1030	1030
Total binder content (% m/m)	5	5	5	5	5	5
Virgin binder content (% m/m)	2.9	2.9	2.9	2.05	2.05	2.05
Total binder mass (kg)	53550	53550	62475	53550	53550	62475
Virgin binder mass (kg)	31059	31059	36236	21956	21956	25615
Total binder volume (m³)	51.99	51.99	60.66	51.99	51.99	60.66
Virgin binder volume (m³)	30.15	30.15	35.18	21.32	21.32	24.87

Table A-3 Calculation properties for aggregate and binder quantities of 75 % and 100 % RAP courses

Property	AC (75 % RAP) (6 cm)	AC (75 % RAP (6 cm)	AC + DGM (75 % RAP) (7 cm)	AC (100 % RAP) (6 cm)	AC (100 % RAP (6 cm)	AC + DGM (100 % RAP) (7 cm)
Width (m)	7	7	7	7	7	7
Length (km)	1	1	1	1	1	1
Thickness (cm)	6	6	7	6	6	7
Total volume (m^3)	420	420	490	420	420	490
Density (kg/m^3)	2550	2550	2550	2550	2550	2550
Total mass (tonne)	1071.00	1071.00	1249.50	1071.00	1071.00	1249.50
RAP content (% m/m)	75	75	75	99	99	99
RAP mass (tonne)	803.25	803.25	937.13	1060.29	1060.29	1237.01
RAP volume (m^3)	315.00	315.00	367.50	415.80	415.80	485.10
Agg. density (kg/m^3)	2650	2650	2650	2650	2650	2650
Total agg. content (% m/m)	95	95	95	95	95	95
Virgin agg. content (% m/m)	23.8	23.8	23.8	0.00	0.00	0.00
Total agg. mass (kg)	1017450	1017450	1187025	1017450	1017450	1187025
Virgin agg. mass (kg)	254898	254898	297381	0	0	0
Total agg. volume (m^3)	383.94	383.94	447.93	383.94	383.94	447.93
Virgin agg. volume (m^3)	96.19	96.19	112.22	0.00	0.00	0.00
Binder density (kg/m^3)	1030	1030	1030	1030	1030	1030
Total binder content (% m/m)	5.0	5.0	5.0	5.0	5.0	5.0
Virgin binder content (% m/m)	1.2	1.2	1.2	1.0	1.0	1.0
Total binder mass (kg)	53550	53550	62475	53550	53550	62475
Virgin binder mass (kg)	12852	12852	14994	10710	10710	12495
Total binder volume (m^3)	51.99	51.99	60.66	51.99	51.99	60.66
Virgin binder volume (m^3)	12.48	12.48	14.56	10.40	10.40	12.13

The results from these calculations, the virgin aggregate and binder masses for each course, provided the input in SimaPro and are shown in Table 5-3.

The second subphase of the material's extraction phase involved the transport of virgin material to the asphalt mixing plant. The selected unit process for transport by truck in SimaPro, *Transport, freight, lorry > 32 metric tonne, EURO4 (GLO),* has a default unit of tonne kilometre (tkm). To define this amount for each course, the total mass of transported material and the distance between the production site and mixing plant were calculated. The first number, the mass of virgin aggregate and binder were defined in the calculations above and displayed in Table A-1, A-2 and A-3. The second number, the distance between the quarry and the mixing plant on one hand, and the binder supplier and mixing plant otherwise, are considered 100 km and 150 km respectively. These values are estimated averages for Portuguese practice. The required virgin aggregate transport is presented in Table A-4, the required virgin binder transport in Table A-5 and the overall total required amounts of transport for each course are shown in Table A-6.

Table A-4 Required virgin aggregate transport per course

Structure	Course	Virgin aggregate mass (tonne)	One-way distance (km)	tkm
All	AC (3 cm)	508.73	100	50,872.50
	AC (6 cm)	1,017.45	100	101,745.00
	DGM (1 cm)	169.58	100	16,957.50
	DGM (7 cm)	1,187.03	100	118,702.50
Structure 0	SMA 11 (6 cm)	1,001.39	100	100,138.50
	SMA 16 (7 cm)	1,168.28	100	116,828.25
Structure 1	AC (25 % RAP) (6 cm)	772.19	100	77,219.10
	AC + DGM (25 % RAP) (6 cm)	772.19	100	77,219.10
	AC + DGM (25 % RAP) (7 cm)	900.89	100	90,088.95
Structure 2	AC (50 % RAP) (6 cm)	513.54	100	51,354.45
	AC + DGM (50 % RAP) (6 cm)	513.54	100	51,354.45
	AC + DGM (50 % RAP) (7 cm)	599.14	100	59,913.53
Structure 3	AC (75 % RAP) (6 cm)	254.90	100	25,489.80
	AC + DGM (75 % RAP) (6 cm)	254.90	100	25,489.80
	AC + DGM (75 % RAP) (7 cm)	297.38	100	29,738.10
Structure 4	AC (100 % RAP) (6 cm)	0.00	100	0.00
	AC + DGM (100 % RAP) (6 cm)	0.00	100	0.00
	AC + DGM (100 % RAP) (7 cm)	0.00	100	0.00

Table A-5 Required virgin binder transport per course

Structure	Course	Virgin binder mass (tonne)	One-way distance (km)	tkm
All	AC (3 cm)	26.78	150	4,016.25
	AC (6 cm)	53.55	150	8,032.50
	DGM (1 cm)	8.93	150	1,338.75
	DGM (7 cm)	62.48	150	9,371.25
Structure 0	SMA 11 (6 cm)	69.61	150	10,442.25
	SMA 16 (7 cm)	81.22	150	12,182.63
Structure 1	AC (25 % RAP) (6 cm)	31.06	150	4,658.85
	AC + DGM (25 % RAP) (6 cm)	31.06	150	4,658.85
	AC + DGM (25 % RAP) (7 cm)	36.24	150	5,435.33
Structure 2	AC (50 % RAP) (6 cm)	21.96	150	3,293.33
	AC + DGM (50 % RAP) (6 cm)	21.96	150	3,293.33
	AC + DGM (50 % RAP) (7cm)	25.61	150	3,842.21
Structure 3	AC (75 % RAP) (6 cm)	12.85	150	1,927.80
	AC + DGM (75 % RAP) (6 cm)	12.85	150	1,927.80
	AC + DGM (75 % RAP) (7 cm)	14.99	150	2,249.10
Structure 4	AC (100 % RAP) (6 cm)	10.71	150	1,606.50
	AC + DGM (100 % RAP) (6 cm)	10.71	150	1,606.50
	AC + DGM (100 % RAP) (7 cm)	12.50	150	1,874.25

Table A-6 Total required amount of virgin material transport per course

Structure	Course	Aggregate tkm	Binder tkm	Total tkm
All	AC (3 cm)	50,872.50	4,016.25	**54,888.75**
	AC (6 cm)	101,745.00	8,032.50	**109,777.50**
	DGM (1 cm)	16,957.50	1,338.75	**18,296.25**
	DGM (7 cm)	118,702.50	9,371.25	**128,073.75**
Structure 0	SMA 11 (6 cm)	100,138.50	10,442.25	**110,580.75**
	SMA 16 (7 cm)	116,828.25	12,182.63	**129,010.88**
Structure 1	AC (25 % RAP) (6 cm)	77,219.10	4,658.85	**81,877.95**
	AC + DGM (25 % RAP) (6 cm)	77,219.10	4,658.85	**81,877.95**
	AC + DGM (25 % RAP) (7 cm)	90,088.95	5,435.33	**95,524.28**
Structure 2	AC (50 % RAP) (6 cm)	51,354.45	3,293.33	**54,647.78**
	AC + DGM (50 % RAP) (6 cm)	51,354.45	3,293.33	**54,647.78**
	AC + DGM (50 % RAP) (7 cm)	59,913.53	3,842.21	**63,755.74**
Structure 3	AC (75 % RAP) (6 cm)	25,489.80	1,927.80	**27,417.60**
	AC + DGM (75 % RAP) (6 cm)	25,489.80	1,927.80	**27,417.60**
	AC + DGM (75 % RAP) (7 cm)	29,738.10	2,249.10	**31,987.20**
Structure 4	AC (100 % RAP) (6 cm)	0.00	1,606.50	**1,606.50**
	AC + DGM (100 % RAP) (6 cm)	0.00	1,606.50	**1,606.50**
	AC + DGM (100 % RAP) (7 cm)	0.00	1,874.25	**1,874.25**

A.1.2 Mixture production phase

To account for variations in composition, mixing temperature, moisture content of aggregates and initial temperature of raw materials of the several types of mixtures, the thermal energy (TE) required to produce the different bituminous mixtures was determined through an energy balance represented by Equation A.1((Santos et al., 2018).

$$TE = \begin{bmatrix} \sum_{i=0}^{M} m_i \times C_i \times (t_{mix} - t_0) + m_{bit} \times C_{bit} \times (t_{mix} - t_0) + \sum_{i=0}^{M} m_i \times W_i \times C_w \times (100 - t_0) \\ + L_v \times \sum_{i=0}^{M} m_i \times W_i + \sum_{i=0}^{M} m_i \times W_i \times C_{vap} \times (t_{mix} - 100) \end{bmatrix} \times (1 + CL) \tag{A.1}$$

The different parameters used in Equation (are further explained in Table A-7 below.

Table A-7 Equation 1 parameter definitions

Parameter	Definition
TE	Thermal energy (MJ/tonne mixture) required to produce one tonne of bituminous mixture
m_i	Mass of aggregates of fraction i
M	Total number of aggregate fractions
t_{mix}	Mixing temperature of a bituminous mixture
t_0	Ambient temperature
m_{bit}	Mass of bitumen
C_{bit}	Specific heat capacity coefficient of bitumen
W_i	Water content of aggregates in fraction i
C_w	Specific heat capacity coefficient of water
L_v	Latent heat required to evaporate water
C_{vap}	Specific heat capacity coefficient of water vapor
CL	Casing losses factor

Table A-8 Reference temperatures for mixtures with paving grade bitumen

Paving grade of bitumen	Reference temperature (°C)		Paving grade of bitumen	Reference temperature for mixtures of types other than mastic asphalt (°C)
	Mixtures of types other than mastic asphalt	Mastic asphalt mixtures		
20/30 PEN	180	250	250/330 PEN	130
30/45 PEN	175	240	330/430 PEN	125
35/50 PEN	165	230	500/650 PEN	120
40/60 PEN	155	220	650/900 PEN	115
50/70 PEN	150		V12000	115
70/100 PEN	145		V6000	110
100/150 PEN	140		V3000	100
160/220 PEN	135		V1500	90

Table A-9 Equation (1) parameter values

Parameter	Definition	Value	Unit
t_0	Ambient temperature	15	°C
$t_{BAC,0\,\%\,RAP}$	Mixing temperature of AC, 0 % RAP mixture	165	°C
$t_{BAC,25\,\%\,RAP}$	Mixing temperature of AC, 25 % RAP mixture	165	°C
$t_{BAC,50\,\%\,RAP}$	Mixing temperature of AC, 50 % RAP mixture	165	°C
$t_{BAC,75\,\%\,RAP}$	Mixing temperature of AC, 75 % RAP mixture	165	°C
$t_{BAC,100\,\%\,RAP}$	Mixing temperature of AC, 100 % RAP mixture	165	°C
t_{DGM}	Mixing temperature of DGM	165	°C
$t_{SMA\,11}$	Mixing temperature of SMA 11	230	°C
$t_{SMA\,16}$	Mixing temperature of SMA 16	230	°C
$t_{BAC+DGM,25\,\%\,RAP}$	Mixing temperature of AC+DGM, 25 % RAP mixture	165	°C
$t_{BAC+DGM,25\,\%\,RAP}$	Mixing temperature of AC+DGM, 50 % RAP mixture	165	°C
$t_{BAC+DGM,25\,\%\,RAP}$	Mixing temperature of AC+DGM, 75 % RAP mixture	165	°C
$t_{BAC+DGM,25\,\%\,RAP}$	Mixing temperature of AC+DGM, 100 % RAP mixture	165	°C
C_{agg}	Specific heat of virgin aggregates	0.74	kJ/kg/°C
W_{agg}	Water content of aggregates	3	$\%/m_{agg}$
C_{RAP}	Specific heat of RAP	0.74	kJ/kg/°C
C_w	Specific heat of water at 15°C	4.1855	kJ/kg/°C
L_v	Latent heat of vaporization of water	2256	kJ/kg
C_{vap}	Specific heat of water vapor	1.83	kJ/kg
C_{bit}	Specific heat of bitumen	2.093	kJ/kg/°C
CL	General casing losses factor	27	%

The casing losses (CL) factor mentioned in Table A-7 is defined as the thermal energy that is ‘lost’ by heating plant iron (e.g. the shell of the drum) and subsequently radiated to the atmosphere, rather than being used to heat mixture components (West, et al., 2014). This factor was considered the same for all mixtures presented in this study and based on findings presented in Santos et al. (2018). According to Santos. et al. (2018), the 27 % value for the casing losses is in accordance with findings in research studies existing in literature (West, et al., 2014).

The different parameter values presented in Table A-9 were based on literature, average values in real practice and findings presented in Santos et al. (2018). The mixing temperatures of each bituminous mixture considered in this study, are based on the EN 12697-35 standard presented in All bituminous mixtures studied are considered to have a paving grade of 35/50 pen. The SMA 11 and SMA 16 mixtures are classified as ‘mastic asphalt mixtures’ and are hence have a mixing temperature of 230°C. For all other bituminous mixtures, including those that incorporate a certain percentage of RAP, a mixture temperature of 165°C is considered.

Based on the values presented in Table A-9Table A-9 and Equation A.1, the thermal energy needed to produce each bituminous course was calculated and presented in Table 5-6. In this study however, several assumptions were made regarding the calculation of the required TE:

- Each mixture contains only fraction of aggregate;
- All virgin materials have the same initial temperature;
- All aggregates have the same water content;
- The total mass percentage of binder is equal (5 %) across all RAP mixtures, so therefore all courses with the same thickness that incorporate RAP require the same amount of thermal energy, disregarding the amount of RAP used in their mixture.

A.1.3 Construction phase

Table A-10 Construction activities and machine efficiencies

Activity	Equipment	Quantity	Efficiency	Unit	Processed material quantity	Unit	Total h	hours per equipment unit
1st Milling (6 cm)	Milling machine with 2 ml drum (own)	1	50	m^3/h	210	m^3	4.2	4.2
	Milling machine with 2 ml drum (rent)	1	50	m^3/h	210	m^3	4.2	4.2
	Truck for milled material (RAP) transport	10	36	m^3/h/truck	420	m^3	11.7	1.2
	Bobcat equipped with brooms	3					2.1	0.7
	Tanker truck with water	1					2.1	2.1
	Compressor	2					4.2	2.1
2nd Milling (12 cm)	Milling machine with 2 ml drum (own)	1	50	m^3/h	420	m^3	8.4	8.4
	Milling machine with 2 ml drum (rent)	1	50	m^3/h	420	m^3	8.4	8.4
	Truck for milled material (RAP) transport	10	36	m^3/h/truck	840	m^3	23.3	2.3
	Bobcat equipped with brooms	3					4.2	1.4
	Tanker truck with water	1					4.2	4.2
	Compressor	2					8.4	4.2
DGM (1 cm) course	Paving machine (own)	2	120	tonne/h	178.5	tonne	1.5	0.7
	Truck for the transport of bituminous mixture	10	27	m^3/h/truck	70	m^3	2.6	0.3
	Bobcat equipped with brooms	2					0.4	0.2
	Tanker truck with water	1					0.4	0.4
	Light truck for cleaning	1					0.4	0.4
	Compressor	2					0.7	0.7
	Smooth wheel rollers 10 tonne	2	675	m^2/h/machine	7000	m^2	10.4	5.2
	Pneumatic rollers 12 tonne	2	675	m^2/h/machine	7000	m^2	10.4	5.2
DGM (7 cm) course	Paving machine (own)	2	120	tonne/h	1249.5	tonne	10.4	5.2
	Truck for the transport of bituminous mixture	10	27	m^3/h/truck	490	m^3	18.1	1.8
	Bobcat equipped with brooms	2					2.6	1.3
	Tanker truck with water	1					2.6	2.6
	Light truck for cleaning	1					2.6	2.6
	Compressor	2					5.2	5.2
	Smooth wheel rollers 10 tonne	2	675	m^2/h/machine	7000	m^2	10.4	5.2
	Pneumatic rollers 12 tonne	2	675	m^2/h/machine	7000	m^2	10.4	5.2
AC (3 cm) course	Paving machine (own)	2	100	tonne/h	357	tonne	3.6	1.8
	Paving machine (rent)	1	100	tonne/h	178.5	tonne	1.8	1.8
	Truck for the transport of bituminous mixture	14	27	m^3/h/truck	210	m^3	7.8	0.6
	Bobcat equipped with brooms	2					0.9	0.4
	Tanker truck with water	1					0.9	0.9
	Light truck for cleaning	1					0.9	0.9
	Compressor	1					1.8	1.8
	Smooth wheel rollers 10 tonne	3	675	m^2/h/machine	7000	m^2	10.4	3.5
	Pneumatic rollers 12 tonne	3	675	m^2/h/machine	7000	m^2	10.4	3.5
AC (6 cm) course	Paving machine (own)	2	100	tonne/h	714		7.1	3.6
	Paving machine (rent)	1	100	tonne/h	357		3.6	3.6
	Truck for the transport of bituminous mixture	14	27	m^3/h/truck	420	m^3	15.6	1.1
	Bobcat equipped with brooms	2					1.8	0.9
	Tanker truck with water	1					1.8	1.8
	Light truck for cleaning	1					1.8	1.8
	Compressor	1					3.6	3.6
	Smooth wheel rollers 10 tonne	3	675	m^2/h/machine	7000	m^2	10.4	3.5
	Pneumatic rollers 12 tonne	3	675	m^2/h/machine	7000	m^2	10.4	3.5
Wearing course (6 cm)	Paving machine (own)	2	100	tonne/h	714	tonne	7.1	3.6
	Paving machine (rent)	1	100	tonne/h	357	tonne	3.6	3.6
	Truck for the transport of bituminous mixture	14	27	m^3/h/truck	420	m^3	15.6	1.1
	Bobcat equipped with brooms	2					1.8	0.9
	Tanker truck with water	1					1.8	1.8
	Light truck for cleaning	1					1.8	1.8
	Compressor	1					3.6	3.6
	Smooth wheel rollers 10 tonne	3	675	m^2/h/machine	7000	m^2	10.4	3.5
	Pneumatic rollers 12 tonne	3	675	m^2/h/machine	7000	m^2	10.4	3.5
Binder course (7 cm)	Paving machine (own)	2	100	tonne/h	833	tonne	8.3	4.2
	Paving machine (rent)	1	100	tonne/h	416.5	tonne	4.2	4.2
	Truck for the transport of bituminous mixture	14	27	m^3/h/truck	490	m^3	18.1	1.3
	Bobcat equipped with brooms	2					2.1	1.0
	Tanker truck with water	1					2.1	2.1
	Light truck for cleaning	1					2.1	2.1
	Compressor	1					4.2	4.2
	Smooth wheel rollers 10 tonne	3	675	m^2/h/machine	7000	m^2	10.4	3.5
	Pneumatic rollers 12 tonne	3	675	m^2/h/machine	7000	m^2	10.4	3.5

Table A-11 Unit processes used to model each construction activity

Equipment	Process
Paving machine	Heavy machine operation
Milling machine	Heavy machine operation
Tanker truck with water	Heavy machine operation
Compressor	Heavy machine operation
Light truck for cleaning	Heavy machine operation
Smooth wheel rollers 10t	Heavy machine operation
Pneumatic rollers 12t	Heavy machine operation
Bobcat equipped with brooms	light machine operation
Truck for mixture transport	Truck transport
Truck for milled material transport	Truck transport

A.2 LCIA

A.2.1 Characterization

Table A-12 Characterization results for the five life cycle structures (LCS) with IMPACT 2002+ method

Impact factor	Unit	LCS0	LCS1	LCS2	LCS3	LCS4
Carcinogens	kg C2H3Cl eq	8.22E+03	7.26E+03	6.93E+03	6.59E+03	6.40E+03
Non-carcinogens	kg C2H3Cl eq	8.29E+03	7.04E+03	6.48E+03	5.91E+03	5.53E+03
Respiratory inorganics	kg PM2.5 eq	709	602	561	519	493
Ionizing radiation	Bq C-14 eq	1.28E+07	9.99E+06	9.14E+06	8.31E+06	8.02E+06
Ozone layer depletion	kg CFC-11 eq	3.30E-01	2.54E-01	2.33E-01	2.11E-01	2.05E-01
Respiratory organics	kg C2H4 eq	4.26E+02	3.46E+02	3.21E+02	2.95E+02	2.84E+02
Aquatic ecotoxicity	kg TEG water	7.56E+07	6.03E+07	5.54E+07	5.04E+07	4.84E+07
Terrestrial ecotoxicity	kg TEG soil	2.36E+07	1.96E+07	1.79E+07	1.62E+07	1.52E+07
Terrestrial acid/nutri	kg SO2 eq	1.30E+04	1.12E+04	1.05E+04	9.74E+03	9.31E+03
Land occupation	m2org.arable	1.31E+04	1.18E+04	1.07E+04	9.64E+03	8.70E+03
Aquatic acidification	kg SO2 eq	4.20E+03	3.52E+03	3.31E+03	3.10E+03	2.99E+03
Aquatic eutrophication	kg PPO4 P-lim	1.65E+02	1.32E+02	1.22E+02	1.11E+02	1.07E+02
Global warming	kg CO2 eq	5.98E+05	5.23E+05	4.97E+05	4.71E+05	4.54E+05
Non-renewable energy	MJ primary	2.91E+07	2.27E+07	2.08E+07	1.90E+07	1.84E+07
Mineral extraction	MJ surplus	1.18E+04	1.08E+04	1.02E+04	9.53E+03	8.97E+03

Table A-13 Characterization results (in percentages relative to the maximum per impact factor) for the five life cycle structures (LCS) with IMPACT 2002+ method

Impact factor	Unit	LCS0	LCS1	LCS2	LCS3	LCS4
Carcinogens	kg C2H3Cl eq	100 %	88 %	84 %	80 %	78 %
Non-carcinogens	kg C2H3Cl eq	100 %	85 %	78 %	71 %	67 %
Respiratory inorganics	kg PM2.5 eq	100 %	85 %	79 %	73 %	70 %
Ionizing radiation	Bq C-14 eq	100 %	78 %	71 %	65 %	63 %
Ozone layer depletion	kg CFC-11 eq	100 %	77 %	71 %	64 %	62 %
Respiratory organics	kg C2H4 eq	100 %	81 %	75 %	69 %	67 %
Aquatic ecotoxicity	kg TEG water	100 %	80 %	73 %	67 %	64 %
Terrestrial ecotoxicity	kg TEG soil	100 %	83 %	76 %	69 %	64 %
Terrestrial acid/nutri	kg SO2 eq	100 %	86 %	81 %	75 %	72 %
Land occupation	m2org.arable	100 %	90 %	82 %	74 %	66 %
Aquatic acidification	kg SO2 eq	100 %	84 %	79 %	74 %	71 %
Aquatic eutrophication	kg PPO4 P-lim	100 %	80 %	74 %	67 %	65 %
Global warming	kg CO2 eq	100 %	87 %	83 %	79 %	76 %
Non-renewable energy	MJ primary	100 %	78 %	71 %	65 %	63 %
Mineral extraction	MJ surplus	100 %	92 %	86 %	81 %	76 %

A.2.2 Damage assessment

Table A-14 Damage assessment results for the five life cycle structures (LCS) with IMPACT 2002+ method

Damage category	Unit	LCS0	LCS1	LCS2	LCS3	LCS4
Human health	DALY	0.546	0.465	0.433	0.401	0.381
Ecosystem quality	PDF*m²*yr	2.18E+05	1.82E+05	1.67E+05	1.51E+05	1.41E+05
Climate change	kg CO2 eq	5.98E+05	5.23E+05	4.97E+05	4.71E+05	4.54E+05
Resources	MJ primary	2.91E+07	2.27E+07	2.08E+07	1.90E+07	1.84E+07

Table A-15 Damage assessment results (in percentages relative to the maximum per damage category) for the five LCS with IMPACT 2002+ method

Damage category	Unit	LCS0	LCS1	LCS2	LCS3	LCS4
Human health	DALY	100 %	85 %	79 %	73 %	70 %
Ecosystem quality	PDF*m²*yr	100 %	83 %	77 %	69 %	65 %
Climate change	kg CO2 eq	100 %	87 %	83 %	79 %	76 %
Resources	MJ primary	100 %	78 %	71 %	65 %	63 %

The results from Table A-15 provide the input for the graphical representation in 5.5.3 (Figure 5-14).

A.2.3 Normalization

Table A-16 Normalization results for the five LCS with IMPACT 2002+

Damage category	LCS0	LCS1	LCS2	LCS3	LCS4
Human health	77	65.5	61.1	56.5	53.7
Ecosystem quality	15.9	13.3	12.2	11	10.3
Climate change	60.4	52.8	50.2	47.5	45.8
Resources	191	149	137	125	121

A.2.4 Single score

Table A-17 Single score value for each structure life cycle based on the normalization results

Damage category	LCS0	LCS1	LCS2	LCS3	LCS4
Human health	77	65.5	61.1	56.5	53.7
Ecosystem quality	15.9	13.3	12.2	11	10.3
Climate change	60.4	52.8	50.2	47.5	45.8
Resources	191	149	137	125	121
Total (Single score)	**344.3**	**280.6**	**260.5**	**240**	**230.8**

Table A-18 Single score value (expressed in percentages of the maximum single score) for each structure life cycle based on the normalization results

Damage category	**LCS0**	**LCS1**	**LCS2**	**LCS3**	**LCS4**
Human health	22 %	19 %	18 %	16 %	16 %
Ecosystem quality	5 %	4 %	4 %	3 %	3 %
Climate change	18 %	15 %	15 %	14 %	13 %
Resources	55 %	43 %	40 %	36 %	35 %
Total (single score)	**100 %**	**81 %**	**76 %**	**70 %**	**67 %**

Annex B LCCA CALCULATION

This annex addresses in detail the calculations that were made to determine the values that served as input for the LCCA performed in chapter six. These calculations entail the processing of primary data, such as unit costs, machine efficiencies, etc to determine the total life cycle cost of the five structures considered in this study.

B.1 Cost assembly calculations

B.1.1 Materials extraction phase

First, the cost of virgin aggregates is calculated. The three main components of which the virgin aggregates considered in this study are comprised are granitic aggregates, limestone powder and filler. Tables B-1, B-2, B-3 respectively provide the costs associated with granitic aggregates, limestone powder and filler.

Table B-1 Granitic aggregate cost calculation per course

Structure	**Course**	**Granitic aggregate (%m)**	**Granitic aggregate mass (tonne)**	**Unit price (€/tonne)**	**Granitic aggregate cost (€)**
All	AC (3 cm)	68	345.93	12.00	4,151.20
	AC (6 cm)	68	691.87	12.00	8,302.39
	DGM (1 cm)	68	115.31	12.00	1,383.73
	DGM (7 cm)	68	807.18	12.00	9,686.12
Struc-ture 0	SMA 11 (6 cm)	94	941.30	12.00	11,295.62
	SMA 16 (7 cm)	94	1098.19	12.00	13,178.23
Structure 1	AC (25 % RAP) (6 cm)	53	539.25	12.00	6,470.98
	AC + DGM (25 % RAP) (6 cm)	53	539.25	12.00	6,470.98
	AC + RAP (25 % RAP) (7 cm)	53	629.12	12.00	7,549.48
Structure 2	AC (50 % RAP) (6 cm)	35	356.11	12.00	4,273.29
	AC + DGM (50 % RAP) (6 cm)	35	356.11	12.00	4,273.29
	AC + RAP (50 % RAP) (7 cm)	35	415.46	12.00	4,985.51
Structure 3	AC (75 % RAP) (6 cm)	17	172.97	12.00	2,075.60
	AC + DGM (75 % RAP) (6 cm)	17	172.97	12.00	2,075.60
	AC + RAP (75 % RAP) (7 cm)	17	201.79	12.00	2,421.53
Structure 4	AC (100 % RAP) (6 cm)	0	0	12.00	0.00
	AC + DGM (100 % RAP) (6 cm)	0	0	12.00	0.00
	AC + RAP (100 % RAP) (7 cm)	0	0	12.00	0.00

These tables show how much of each component is used in each course as well as the specific unit price and the cost per course. Secondly, in Table B-4, a similar calculation is presented for the cost of virgin bituminous binder per course.

Table B-2 Limestone powder cost calculation per course

Structure	Course	Limestone powder (%m)	Limestone powder mass (tonne)	Limestone powder unit price (€/tonne)	Limestone powder cost (€)
All	AC (3 cm)	29	147.53	3.50	516.36
	AC (6 cm)	29	295.06	3.50	1,032.71
	DGM (1 cm)	29	49.18	3.50	172.12
	DGM (7 cm)	29	344.24	3.50	1,204.83
Struc-ture 0	SMA 11 (6 cm)	0	0	3.50	0.00
	SMA 16 (7 cm)	0	0	3.50	0.00
Structure 1	AC (25 % RAP) (6 cm)	22	223.84	3.50	783.44
	AC + DGM (25 % RAP) (6 cm)	22	223.84	3.50	783.44
	AC + RAP (25 % RAP) (7 cm)	22	261.15	3.50	914.01
Structure 2	AC (50 % RAP) (6 cm)	15	152.62	3.50	534.16
	AC + DGM (50 % RAP) (6 cm)	15	152.62	3.50	534.16
	AC + RAP (50 % RAP) (7 cm)	15	178.05	3.50	623.19
Structure 3	AC (75 % RAP) (6 cm)	8	81.40	3.50	284.89
	AC + DGM (75 % RAP) (6 cm)	8	81.40	3.50	284.89
	AC + RAP (75 % RAP) (7 cm)	8	94.96	3.50	332.37
Structure 4	AC (100 % RAP) (6 cm)	0	0	3.50	0.00
	AC + DGM (100 % RAP) (6 cm)	0	0	3.50	0.00
	AC + RAP (100 % RAP) (7 cm)	0	0	3.50	0.00

Table B-3 Filler cost calculation per course

Structure	Course	Filler (%m)	Filler mass (tonne)	Filler unit price (€/tonne)	Filler cost (€)
All	AC (3 cm)	3	15.26	17.50	267.08
	AC (6 cm)	3	30.52	17.50	534.16
	DGM (1 cm)	3	5.09	17.50	89.03
	DGM (7 cm)	3	35.61	17.50	623.19
Structure 0	SMA 11 (6 cm)	6	60.08	17.50	1,051.45
	SMA 16 (7 cm)	6	70.10	17.50	1,226.70
Structure 1	AC (25 % RAP) (6 cm)	0	0	17.50	0.00
	AC + DGM (25 % RAP) (6 cm)	0	0	17.50	0.00
	AC + RAP (25 % RAP) (7 cm)	0	0	17.50	0.00
Structure 2	AC (50 % RAP) (6 cm)	0	0	17.50	0.00
	AC + DGM (50 % RAP) (6 cm)	0	0	17.50	0.00
	AC + RAP (50 % RAP) (7 cm)	0	0	17.50	0.00
Structure 3	AC (75 % RAP) (6 cm)	0	0	17.50	0.00
	AC + DGM (75 % RAP) (6 cm)	0	0	17.50	0.00
	AC + RAP (75 % RAP) (7 cm)	0	0	17.50	0.00
Structure 4	AC (100 % RAP) (6 cm)	0	0	17.50	0.00
	AC + DGM (100 % RAP) (6 cm)	0	0	17.50	0.00
	AC + RAP (100 % RAP) (7 cm)	0	0	17.50	0.00

Finally, the total virgin aggregate cost for each course was calculated by adding the cost for granitic aggregate, limestone powder and filler. The total structure costs were calculated by adding the total course costs of the courses they comprise of. The total virgin aggregate costs and total binder costs per structure are displayed in Table B-5.

Table B-4 Virgin binder cost calculation per course

Structure	**Course**	**Total virgin binder mass (tonne)**	**Bitumen unit price (€/tonne)**	**Bitumen cost (€)**
All	AC (3 cm)	26.78	450.00	**12,048.75**
	AC (6 cm)	53.55	450.00	**24,097.50**
	DGM (1 cm)	8.93	450.00	**4,016.25**
	DGM (7 cm)	62.48	450.00	**28,113.75**
Structure 0	SMA 11 (6 cm)	69.61	630.00	**43,857.45**
	SMA 16 (7 cm)	81.22	630.00	**51,167.03**
Structure 1	AC (25 % RAP) (6 cm)	31.06	450.00	**13,976.55**
	AC + DGM (25 % RAP) (6 cm)	31.06	450.00	**13,976.55**
	AC + RAP (25 % RAP) (7 cm)	36.24	450.00	**16,305.98**
Structure 2	AC (50 % RAP) (6 cm)	21.96	450.00	**9,879.98**
	AC + DGM (50 % RAP) (6 cm)	21.96	450.00	**9,879.98**
	AC + RAP (50 % RAP) (7 cm)	25.61	450.00	**11,526.64**
Structure 3	AC (75 % RAP) (6 cm)	12.85	450.00	**5,783.40**
	AC + DGM (75 % RAP) (6 cm)	12.85	450.00	**5,783.40**
	AC + RAP (75 % RAP) (7 cm)	14.99	450.00	**6,747.30**
Structure 4	AC (100 % RAP) (6 cm)	10.71	450.00	**4,819.50**
	AC + DGM (100 % RAP) (6 cm)	10.71	450.00	**4,819.50**
	AC + RAP (100 % RAP) (7 cm)	12.50	450.00	**5,622.75**

Table B-5 Total virgin aggregate and virgin binder cost per structure

Structure	**Total Aggregate cost (€)**	**Total binder cost (€)**
Structure 0	**64,584.18**	**187,398.23**
Structure 1	**50,935.24**	**112,535.33**
Structure 2	**43,186.51**	**99,562.84**
Structure 3	**35,437.78**	**86,590.35**
Structure 4	**27,962.92**	**83,538.00**

B.1.2 Mixture production phase

The mixture production phase cost was considered to consist of the following costs:

- The amortisation of the mixing plant (€150/h)
- The cost of diesel (€0.60/tonne mixture)
- The cost of fuel (€3.60/tonne mixture)
- The emissions cost of the mixing plant (€1,060/year or €0.12/h)

The global efficiency of the mixing plant is noted to be 600 tonnes/day. Tables B-6, B-7, B-8 and B-9 respectively provide the total costs for the plant emissions, amortisation, diesel and fuel, per course. The last table in this sub-paragraph (Table B-10) presents these totals per structure.

Table B-6 Plant emissions cost calculation

Structure	**Course**	**Total mixture mass (tonne)**	**Plant efficiency (tonnes/day)**	**Hours**	**Plant emissions unit cost (€/h)**	**Plant emission cost (€)**
All	AC (3 cm)	535.5	600	21.4	0.12	2.66
	AC (6 cm)	1071.0	600	42.8	0.12	5.31
	DGM (1 cm)	178.5	600	7.1	0.12	0.89
	DGM (7 cm)	1249.5	600	50.0	0.12	6.20
Struc-ture 0	SMA 11 (6 cm)	1071.0	600	42.8	0.12	5.31
	SMA 16 (7 cm)	1249.5	600	50.0	0.12	6.20
Structure 1	AC (25 % RAP) (6 cm)	1071.0	600	42.8	0.12	5.31
	AC + DGM (25 % RAP) (6 cm)	1071.0	600	42.8	0.12	5.31
	AC + RAP (25 % RAP) (7 cm)	1249.5	600	50.0	0.12	6.20
Structure 2	AC (50 % RAP) (6 cm)	1071.0	600	42.8	0.12	5.31
	AC + DGM (50 % RAP) (6 cm)	1071.0	600	42.8	0.12	5.31
	AC + RAP (50 % RAP) (7 cm)	1249.5	600	50.0	0.12	6.20
Structure 3	AC (75 % RAP) (6 cm)	1071.0	600	42.8	0.12	5.31
	AC + DGM (75 % RAP) (6 cm)	1071.0	600	42.8	0.12	5.31
	AC + RAP (75 % RAP) (7 cm)	1249.5	600	50.0	0.12	6.20
Structure 4	AC (100 % RAP) (6 cm)	1071.0	600	42.8	0.12	5.31
	AC + DGM (100 % RAP) (6 cm)	1071.0	600	42.8	0.12	5.31
	AC + RAP (100 % RAP) (7 cm)	1249.5	600	50.0	0.12	6.20

Table B-7 Plant amortisation cost calculation

Structure	**Course**	**Total mixture mass (tonne)**	**Plant efficiency (tonnes/ day)**	**Hours**	**Plant amortisation unit cost (€/h)**	**Amortisation cost (€)**
All	AC (3 cm)	535.5	600	21.4	150.00	3,213.00
	AC (6 cm)	1071.0	600	42.8	150.00	6,426.00
	DGM (1 cm)	178.5	600	7.1	150.00	1,071.00
	DGM (7 cm)	1249.5	600	50.0	150.00	7,497.00
Structure 0	SMA 11 (6 cm)	1071.0	600	42.8	150.00	6,426.00
	SMA 16 (7cm)	1249.5	600	50.0	150.00	7,497.00
Structure 1	AC (25 % RAP) (6 cm)	1071.0	600	42.8	150.00	6,426.00
	AC + DGM (25 % RAP) (6 cm)	1071.0	600	42.8	150.00	6,426.00
	AC + RAP (25 % RAP) (7 cm)	1249.5	600	50.0	150.00	7,497.00
Structure 2	AC (50 % RAP) (6 cm)	1071.0	600	42.8	150.00	6,426.00
	AC + DGM (50 % RAP) (6 cm)	1071.0	600	42.8	150.00	6,426.00
	AC + RAP (50 % RAP) (7 cm)	1249.5	600	50.0	150.00	7,497.00
Structure 3	AC (75 % RAP) (6 cm)	1071.0	600	42.8	150.00	6,426.00
	AC + DGM (75 % RAP) (6 cm)	1071.0	600	42.8	150.00	6,426.00
	AC + RAP (75 % RAP) (7 cm)	1249.5	600	50.0	150.00	7,497.00
Structure 4	AC (100 % RAP) (6 cm)	1071.0	600	42.8	150.00	6,426.00
	AC + DGM (100 % RAP) (6 cm)	1071.0	600	42.8	150.00	6,426.00
	AC + RAP (100 % RAP) (7 cm)	1249.5	600	50.0	150.00	7,497.00

Table B-8 Plant diesel cost calculation

Structure	**Course**	**Total mixture mass (tonne)**	**Plant efficiency (tonnes/day)**	**Hours**	**Diesel unit cost (€/tonne mixture)**	**Diesel cost (€)**
All	**AC (3 cm)**	535.5	600	21.4	0.60	321.30
	AC (6 cm)	1071.0	600	42.8	0.60	642.60
	DGM (1 cm)	178.5	600	7.1	0.60	107.10
	DGM (7 cm)	1249.5	600	50.0	0.60	749.70
Structure 0	**SMA 11 (6 cm)**	1071.0	600	42.8	0.60	642.60
	SMA 16 (7 cm)	1249.5	600	50.0	0.60	749.70
Structure 1	**AC (25 % RAP) (6 cm)**	1071.0	600	42.8	0.60	642.60
	AC + DGM (25 % RAP) (6 cm)	1071.0	600	42.8	0.60	642.60
	AC + RAP (25 % RAP) (7 cm)	1249.5	600	50.0	0.60	749.70
Structure 2	**AC (50 % RAP) (6 cm)**	1071.0	600	42.8	0.60	642.60
	AC + DGM (50 % RAP) (6 cm)	1071.0	600	42.8	0.60	642.60
	AC + RAP (50 % RAP) (7 cm)	1249.5	600	50.0	0.60	749.70
Structure 3	**AC (75 % RAP) (6 cm)**	1071.0	600	42.8	0.60	642.60
	AC + DGM (75 % RAP) (6 cm)	1071.0	600	42.8	0.60	642.60
	AC + RAP (75 % RAP) (7 cm)	1249.5	600	50.0	0.60	749.70
Structure 4	**AC (100 % RAP) (6 cm)**	1071.0	600	42.8	0.60	642.60
	AC + DGM (100 % RAP) (6 cm)	1071.0	600	42.8	0.60	642.60
	AC + RAP (100 % RAP) (7 cm)	1249.5	600	50.0	0.60	749.70

Table B-9 Plant fuel cost calculation

Structure	Course	Total mixture mass (tonne)	Plant efficiency (tonnes/day)	Hours	Fuel unit cost (€/tonne mixture)	Fuel cost (€)
All	AC (3 cm)	535.5	600	21.4	3.60	1,927.80
	AC (6 cm)	1071.0	600	42.8	3.60	3,855.60
	DGM (1 cm)	178.5	600	7.1	3.60	642.60
	DGM (7 cm)	1249.5	600	50.0	3.60	4,498.20
Structure 0	SMA 11 (6 cm)	1071.0	600	42.8	3.60	3,855.60
	SMA 16 (7 cm)	1249.5	600	50.0	3.60	4,498.20
Structure 1	AC (25 % RAP) (6 cm)	1071.0	600	42.8	3.60	3,855.60
	AC + DGM (25 % RAP) (6 cm)	1071.0	600	42.8	3.60	3,855.60
	AC + RAP (25 % RAP) (7 cm)	1249.5	600	50.0	3.60	4,498.20
Structure 2	AC (50 % RAP) (6 cm)	1071.0	600	42.8	3.60	3,855.60
	AC + DGM (50 % RAP) (6 cm)	1071.0	600	42.8	3.60	3,855.60
	AC + RAP (50 % RAP) (7 cm)	1249.5	600	50.0	3.60	4,498.20
Structure 3	AC (75 % RAP) (6 cm)	1071.0	600	42.8	3.60	3,855.60
	AC + DGM (75 % RAP) (6 cm)	1071.0	600	42.8	3.60	3,855.60
	AC + RAP (75 % RAP) (7 cm)	1249.5	600	50.0	3.60	4,498.20
Structure 4	AC (100 % RAP) (6 cm)	1071.0	600	42.8	3.60	3,855.60
	AC + DGM (100 % RAP) (6 cm)	1071.0	600	42.8	3.60	3,855.60
	AC + RAP (100 % RAP) (7 cm)	1249.5	600	50.0	3.60	4,498.20

Table B-10 Total mixture production costs (amortisation, diesel, fuel and plant emissions) per structure

Structure	Total amortisation cost (€)	Total diesel cost (€)	Total fuel cost (€)	Total plant emissions cost (€)
Structure 0	38,556.00	3,855.60	23,133.60	31.89
Structure 1	38,556.00	3,855.60	23,133.60	31.89
Structure 2	38,556.00	3,855.60	23,133.60	31.89
Structure 3	38,556.00	3,855.60	23,133.60	31.89
Structure 4	38,556.00	3,855.60	23,133.60	31.89

B.1.3 Construction phase

Table B-11 Construction activities with machine efficiencies and costs for each course type

Activity	Equipment	Equipment quantity	Cost (€/h)	Efficiency	Unit	Material quantity	Unit	Total h	h/ equipment unit	Total cost (€)
1st Milling (6 cm)	Milling machine with 2 ml drum (own)	1	340	50	m^3/h	210	m^3	4.2	4.2	1,428.00
	Milling machine with 2 ml drum (rent)	1	420	50	m^3/h	210	m^3	4.2	4.2	1,764.00
	Truck for milled material (RAP) transport	10	60	36	m^3/h/truck	420	m^3	11.7	1.2	700.00
	Bobcat equipped with brooms	3	40					2.1	0.7	84.00
	Tanker truck with water	1	65					2.1	2.1	136.50
	Compressor	2	17					4.2	2.1	71.40
2nd Milling (12 cm)	Milling machine with 2 ml drum (own)	1	340	50	m^3/h	420	m^3	8.4	8.4	2,856.00
	Milling machine with 2 ml drum (rent)	1	420	50	m^3/h	420	m^3	8.4	8.4	3,528.00
	Truck for milled material (RAP) transport	10	60	36	m^3/h/truck	840	m^3	23.3	2.3	1,400.00
	Bobcat equipped with brooms	3	40					4.2	1.4	168.00
	Tanker truck with water	1	65					4.2	4.2	273.00
	Compressor	2	17					8.4	4.2	142.80
DGM (1 cm) course	Paving machine (own)	2	150	120	tonne/h	178.5	tonne	1.5	0.7	223.13
	Truck for the transport of bituminous mixture	10	60	27	m^3/h/truck	70	m^3	2.6	0.3	155.56
	Bobcat equipped with brooms	2	40					0.4	0.2	14.88
	Tanker truck with water	1	65					0.4	0.4	24.17
	Light truck for cleaning	1	50					0.4	0.4	18.59
	Compressor	2	17					0.7	0.7	12.64
	Smooth wheel rollers 10 tonne	2	50	675	m^2/h/machine	7000	m^2	10.4	5.2	518.52
	Pneumatic rollers 12 tonne	2	55	675	m^2/h/machine	7000	m^2	10.4	5.2	570.37
DGM (7 cm) course	Paving machine (own)	2	150	120	tonne/h	1249.5	tonne	10.4	5.2	1,561.88
	Truck for the transport of bituminous mixture	10	60	27	m^3/h/truck	490	m^3	18.1	1.8	1,088.89
	Bobcat equipped with brooms	2	40					2.6	1.3	104.13
	Tanker truck with water	1	65					2.6	2.6	169.20
	Light truck for cleaning	1	50					2.6	2.6	130.16
	Compressor	2	17					5.2	5.2	88.51
	Smooth wheel rollers 10 tonne	2	50	675	m^2/h/machine	7000	m^2	10.4	5.2	518.52
	Pneumatic rollers 12 tonne	2	55	675	m^2/h/machine	7000	m^2	10.4	5.2	570.37
AC (3 cm) course	Paving machine (own)	2	150	100	tonne/h	357	tonne	3.6	1.8	535.50
	Paving machine (rent)	1	200	100	tonne/h	178.5	tonne	1.8	1.8	357.00
	Truck for the transport of bituminous mixture	14	60	27	m^3/h/truck	210	m^3	7.8	0.6	466.67
	Bobcat equipped with brooms	2	40					0.9	0.4	35.70
	Tanker truck with water	1	65					0.9	0.9	58.01
	Light truck for cleaning	1	50					0.9	0.9	44.63
	Compressor	1	17					1.8	1.8	30.35
	Smooth wheel rollers 10 tonne	3	50	675	m^2/h/machine	7000	m^2	10.4	3.5	518.52
	Pneumatic rollers 12 tonne	3	55	675	m^2/h/machine	7000	m^2	10.4	3.5	570.37
AC (6 cm) course	Paving machine (own)	2	150	100	tonne/h	714		7.1	3.6	1,071.00
	Paving machine (rent)	1	200	100	tonne/h	357		3.6	3.6	714.00
	Truck for the transport of bituminous mixture	14	60	27	m^3/h/truck	420	m^3	15.6	1.1	933.33
	Bobcat equipped with brooms	2	40					1.8	0.9	71.40
	Tanker truck with water	1	65					1.8	1.8	116.03
	Light truck for cleaning	1	50					1.8	1.8	89.25
	Compressor	1	17					3.6	3.6	60.69
	Smooth wheel rollers 10 tonne	3	50	675	m^2/h/machine	7000	m^2	10.4	3.5	518.52
	Pneumatic rollers 12 tonne	3	55	675	m^2/h/machine	7000	m^2	10.4	3.5	570.37
Surface course (6 cm)	Paving machine (own)	2	150	100	tonne/h	714	tonne	7.1	3.6	1,071.00
	Paving machine (rent)	1	200	100	tonne/h	357	tonne	3.6	3.6	714.00
	Truck for the transport of bituminous mixture	14	60	27	m^3/h/truck	420	m^3	15.6	1.1	933.33
	Bobcat equipped with brooms	2	40					1.8	0.9	71.40
	Tanker truck with water	1	65					1.8	1.8	116.03
	Light truck for cleaning	1	50					1.8	1.8	89.25
	Compressor	1	17					3.6	3.6	60.69
	Smooth wheel rollers 10 tonne	3	50	675	m^2/h/machine	7000	m^2	10.4	3.5	518.52
	Pneumatic rollers 12 tonne	3	55	675	m^2/h/machine	7000	m^2	10.4	3.5	570.37
Binder course (7 cm)	Paving machine (own)	2	150	100	tonne/h	833	tonne	8.3	4.2	1,249.50
	Paving machine (rent)	1	200	100	tonne/h	416.5	tonne	4.2	4.2	833.00
	Truck for the transport of bituminous mixture	14	60	27	m^3/h/truck	490	m^3	18.1	1.3	1,088.89
	Bobcat equipped with brooms	2	40					2.1	1.0	83.30
	Tanker truck with water	1	65					2.1	2.1	135.36
	Light truck for cleaning	1	50					2.1	2.1	104.13
	Compressor	1	17					4.2	4.2	70.81
	Smooth wheel rollers 10 tonne	3	50	675	m^2/h/machine	7000	m^2	10.4	3.5	518.52
	Pneumatic rollers 12 tonne	3	55	675	m^2/h/machine	7000	m^2	10.4	3.5	570.37

Table B-12 displays the RAP processing cost calculation for each course containing RAP. The processing of RAP consists of four main steps: wheel loading, conveying, crushing and screening. Because the transport by wheel loader and conveying are activities related to not only RAP but also virgin aggregates, they are discarded from the calculation. The RAP process unit cost was hence calculated as the combination of screening and conveying unit costs. According to Brock et al. (2016), this cost is estimated to be around $3. To account for currency conversion, inflation and price fluctuation, a conservative value of €4 was considered in this study.

Table B-12 RAP processing costs per course

Structure	Course	RAP mass (tonne)	RAP process unit cost (€/tonne)	RAP processing cost (€)
Structure 1	AC (25 % RAP) (6 cm)	267.8	4.00	**1,071.00**
	AC + DGM (25 % RAP) (6 cm)	267.8	4.00	**1,071.00**
	AC + RAP (25 % RAP) (7 cm)	312.4	4.00	**1,249.50**
Structure 2	AC (50 % RAP) (6 cm)	535.5	4.00	**2,142.00**
	AC + DGM (50 % RAP) (6 cm)	535.5	4.00	**2,142.00**
	AC + RAP (50 % RAP) (7 cm)	624.8	4.00	**2,499.00**
Structure 3	AC (75 % RAP) (6 cm)	803.3	4.00	**3,213.00**
	AC + DGM (75 % RAP) (6 cm)	803.3	4.00	**3,213.00**
	AC + RAP (75 % RAP) (7 cm)	937.1	4.00	**3,748.50**
Structure 4	AC (100 % RAP) (6 cm)	1,060.3	4.00	**4,241.16**
	AC + DGM (100 % RAP) (6 cm)	1,060.3	4.00	**4,241.16**
	AC + RAP (100 % RAP) (7 cm)	1,237.0	4.00	**4,948.02**

B.1.4 End-of-life phase

Table B-13 First milling landfill costs per structure

Structure	First milling total volume (m³)	Landfill (m³)	Landfill unit cost (€/m³)	Landfill cost (€)
Structure 0	420	420	2.93	**1,230.60**
Structure 1	420	315	2.93	**922.95**
Structure 2	420	210	2.93	**615.30**
Structure 3	420	105	2.93	**307.65**
Structure 4	420	0	2.93	**0.00**

Table B-14 Second milling landfill costs per structure

Structure	**Second milling total volume (m³)**	**Landfill (m³)**	**Landfill unit cost (per m³)**	**Landfill cost (€)**
Structure 0	910	910.0	2.93	**2,666.30**
Structure 1	910	682.5	2.93	**1,999.73**
Structure 2	910	455.0	2.93	**1,333.15**
Structure 3	910	227.5	2.93	**666.58**
Structure 4	910	0.0	2.93	**0.00**

B.2 Cost assembly results

Table B-15 Overall cost assembly (1/5)

Stage	LCS0 (€)	LCS1 (€)	LCS2 (€)	LCS3 (€)	LCS4 (€)
Production stage	**345,502.35**	**252,876.23**	**229,069.30**	**204,833.79**	**191,049.44**
Raw material extraction					
Aggregate production	64,584.18	50,935.24	43,186.51	35,437.78	27,962.92
Virgin binder production	187,398.23	112,535.33	99,562.84	86,590.35	83,538.00
Virgin material transport					
Virgin aggregate transport	22,285.71	19,714.29	16,628.57	13,885.71	10,628.57
Virgin binder transport	5,657.14	4,114.29	4,114.29	3,342.86	3,342.86
Mixture production					
Plant amortisation	38,556.00	38,556.00	38,556.00	38,556.00	38,556.00
Diesel	3,855.60	3,855.60	3,855.60	3,855.60	3,855.60
Fuel	23,133.60	23,133.60	23,133.60	23,133.60	23,133.60
Emission costs	31.89	31.89	31.89	31.89	31.89
Maintenance 1	**37,616.74**	**37,616.74**	**37,616.74**	**37,616.74**	**37,616.74**
Maintenance 2	**44,986.23**	**44,986.23**	**44,986.23**	**44,986.23**	**44,986.23**
Maintenance 3	**44,559.09**	**45,322.44**	**46,085.79**	**46,849.14**	**47,569.65**
Maintenance 4	**56,370.41**	**58,024.34**	**59,678.26**	**61,332.19**	**62,893.29**
Total	529,034.82	438,825.97	417,436.31	395,618.09	384,115.34

Table B-16 Overall cost assembly (2/5)

Stage	LCS0 (€)	LCS1 (€)	LCS2 (€)	LCS3 (€)	LCS4 (€)
Production stage	**345,502.35**	**252,876.23**	**229,069.30**	**204,833.79**	**191,049.44**
Maintenance 1	**37,616.74**	**37,616.74**	**37,616.74**	**37,616.74**	**37,616.74**
M1 transport					
AC (3 cm) mixture	466.67	466.67	466.67	466.67	466.67
M1 Construction costs					
Assembly and disassembly of the site, including the landscaping of the occupied area after disassembly.	25,000.00	25,000.00	25,000.00	25,000.00	25,000.00
Facilities including supply and maintenance of offices, residences, and consumables required for its operation.	7,500.00	7,500.00	7,500.00	7,500.00	7,500.00
Implementation of environmental monitoring of the contract, including human resources, materials & equipment.	2,500.00	2,500.00	2,500.00	2,500.00	2,500.00
AC (3cm) Construction					
Paving machine (own)	535.50	535.50	535.50	535.50	535.50
Paving machine (rent)	357.00	357.00	357.00	357.00	357.00
Bobcat equipped with brooms	35.70	35.70	35.70	35.70	35.70
Tanker truck with water	58.01	58.01	58.01	58.01	58.01
Light truck for cleaning	44.63	44.63	44.63	44.63	44.63
Compressor	30.35	30.35	30.35	30.35	30.35
Smooth wheel rollers 10 tonne	518.52	518.52	518.52	518.52	518.52
Pneumatic rollers 12 tonne	570.37	570.37	570.37	570.37	570.37
Maintenance 2	**44,986.23**	**44,986.23**	**44,986.23**	**44,986.23**	**44,986.23**
Maintenance 3	**44,559.09**	**45,322.44**	**46,085.79**	**46,849.14**	**47,569.65**
Maintenance 4	**56,370.41**	**58,024.34**	**59,678.26**	**61,332.19**	**62,893.29**
Total	529,034.82	438,825.97	417,436.31	395,618.09	384,115.34

Table B-17 Overall cost assembly (3/5)

Stage	LCS0 (€)	LCS1 (€)	LCS2 (€)	LCS3 (€)	LCS4 (€)
Production stage	**345,502.35**	**252,876.23**	**229,069.30**	**204,833.79**	**191,049.44**
Maintenance 1	**37,616.74**	**37,616.74**	**37,616.74**	**37,616.74**	**37,616.74**
Maintenance 2	**44,986.23**	**44,986.23**	**44,986.23**	**44,986.23**	**44,986.23**
M2 transport					
AC (6 cm) mixture	933.33	933.33	933.33	933.33	933.33
DGM (7 cm) mixture	1,088.89	1,088.89	1,088.89	1,088.89	1,088.89
M2 Construction costs					
Assembly and disassembly of the site, including the landscaping of the occupied area after disassembly.	25,000.00	25,000.00	25,000.00	25,000.00	25,000.00
Facilities including supply and maintenance of offices, residences, and consumables required for its operation.	7,500.00	7,500.00	7,500.00	7,500.00	7,500.00
Implementation of Environmental Monitoring of the contract, including human resources, materials and equipment.	2,500.00	2,500.00	2,500.00	2,500.00	2,500.00
AC (6 cm) Construction					
Paving machine (own)	1,071.00	1,071.00	1,071.00	1,071.00	1,071.00
Paving machine (rent)	714.00	714.00	714.00	714.00	714.00
Bobcat equipped with brooms	71.40	71.40	71.40	71.40	71.40
Tanker truck with water	116.03	116.03	116.03	116.03	116.03
Light truck for cleaning	89.25	89.25	89.25	89.25	89.25
Compressor	60.69	60.69	60.69	60.69	60.69
Smooth wheel rollers 10 tonne	518.52	518.52	518.52	518.52	518.52
Pneumatic rollers 12 tonne	570.37	570.37	570.37	570.37	570.37
DGM (7 cm) construction					
Paving machine (own)	1,561.88	1,561.88	1,561.88	1,561.88	1,561.88
Bobcat equipped with brooms	104.13	104.13	104.13	104.13	104.13
Tanker truck with water	169.20	169.20	169.20	169.20	169.20
Light truck for cleaning	130.16	130.16	130.16	130.16	130.16
Compressor	88.51	88.51	88.51	88.51	88.51
Smooth wheel rollers 10 tonne	518.52	518.52	518.52	518.52	518.52
Pneumatic rollers 12 tonne	570.37	570.37	570.37	570.37	570.37
Crack sealing					
Tack coat to place between bituminous layers with a modified bituminous emulsion	1,610.00	1,610.00	1,610.00	1,610.00	1,610.00
Maintenance 3	**44,559.09**	**45,322.44**	**46,085.79**	**46,849.14**	**47,569.65**
Maintenance 4	**56,370.41**	**58,024.34**	**59,678.26**	**61,332.19**	**62,893.29**
Total	529,034.82	438,825.97	417,436.31	395,618.09	384,115.34

Table B-18 Overall cost assembly (4/5)

Stage	LCS0 (€)	LCS1 (€)	LCS2 (€)	LCS3 (€)	LCS4 (€)
Production stage	**345,502.35**	**252,876.23**	**229,069.30**	**204,833.79**	**191,049.44**
Maintenance 1	**37,616.74**	**37,616.74**	**37,616.74**	**37,616.74**	**37,616.74**
Maintenance 2	**44,986.23**	**44,986.23**	**44,986.23**	**44,986.23**	**44,986.23**
Maintenance 3	**44,559.09**	**45,322.44**	**46,085.79**	**46,849.14**	**47,569.65**
M3 transport					
Milled material	700.00	700.00	700.00	700.00	700.00
AC + RAP (6 cm) mixture	933.33	933.33	933.33	933.33	933.33
M3 construction costs					
Assembly and disassembly of the site, including the landscaping of the occupied area after disassembly.	25,000.00	25,000.00	25,000.00	25,000.00	25,000.00
Facilities including supply and maintenance of offices, residences, and consumables required for its operation.	7,500.00	7,500.00	7,500.00	7,500.00	7,500.00
Implementation of Environmental Monitoring of the contract, including human resources, materials and equipment.	2,500.00	2,500.00	2,500.00	2,500.00	2,500.00
Subsidies					
1st milling					
Milling machine with 2 ml drum (own)	1,428.00	1,428.00	1,428.00	1,428.00	1,428.00
Milling machine with 2 ml drum (rent)	1,764.00	1,764.00	1,764.00	1,764.00	1,764.00
Bobcat equipped with brooms	84.00	84.00	84.00	84.00	84.00
Tanker truck with water	136.50	136.50	136.50	136.50	136.50
Compressor	71.40	71.40	71.40	71.40	71.40
RAP production					
Total RAP production cost	0.00	1,071.00	2,142.00	3,213.00	4,241.16
AC + RAP (6 cm) construction					
Paving machine (own)	1,071.00	1,071.00	1,071.00	1,071.00	1,071.00
Paving machine (rent)	714.00	714.00	714.00	714.00	714.00
Bobcat equipped with brooms	71.40	71.40	71.40	71.40	71.40
Tanker truck with water	116.03	116.03	116.03	116.03	116.03
Light truck for cleaning	89.25	89.25	89.25	89.25	89.25
Compressor	60.69	60.69	60.69	60.69	60.69
Smooth wheel rollers 10 tonne	518.52	518.52	518.52	518.52	518.52
Pneumatic rollers 12 tonne	570.37	570.37	570.37	570.37	570.37
Waste costs					
Landfill cost	1,230.60	922.95	615.30	307.65	0.00
Maintenance 4	**56,370.41**	**58,024.34**	**59,678.26**	**61,332.19**	**62,893.29**
Total	529,034.82	438,825.97	417,436.31	395,618.09	384,115.34

Table B-19 Overall cost assembly (5/5)

Stage	LCS0 (€)	LCS1 (€)	LCS2 (€)	LCS3 (€)	LCS4 (€)
Production stage	**345,502.35**	**252,876.23**	**229,069.30**	**204,833.79**	**191,049.44**
Maintenance 1	**37,616.74**	**37,616.74**	**37,616.74**	**37,616.74**	**37,616.74**
Maintenance 2	**44,986.23**	**44,986.23**	**44,986.23**	**44,986.23**	**44,986.23**
Maintenance 3	**44,559.09**	**45,322.44**	**46,085.79**	**46,849.14**	**47,569.65**
Maintenance 4	**56,370.41**	**58,024.34**	**59,678.26**	**61,332.19**	**62,893.29**
M4 transport					
Milled material	1,400.00	1,400.00	1,400.00	1,400.00	1,400.00
DGM (1 cm) mixture	155.56	155.56	155.56	155.56	155.56
Binder course (7 cm) mixture	1,088.89	1,088.89	1,088.89	1,088.89	1,088.89
Wearing course (6 cm) mixture	933.33	933.33	933.33	933.33	933.33
M4 construction costs					
Assembly and disassembly of the site, including the landscaping of the occupied area after disassembly.	25,000.00	25,000.00	25,000.00	25,000.00	25,000.00
Facilities including supply and maintenance of offices, residences, and consumables required for its operation.	7,500.00	7,500.00	7,500.00	7,500.00	7,500.00
Implementation of Environmental Monitoring of the contract, including human resources, materials and equipment.	2,500.00	2,500.00	2,500.00	2,500.00	2,500.00
2nd milling					
Milling machine with 2 ml drum (own)	2,856.00	2,856.00	2,856.00	2,856.00	2,856.00
Milling machine with 2 ml drum (rent)	3,528.00	3,528.00	3,528.00	3,528.00	3,528.00
Bobcat equipped with brooms	168.00	168.00	168.00	168.00	168.00
Tanker truck with water	273.00	273.00	273.00	273.00	273.00
Compressor	142.80	142.80	142.80	142.80	142.80
RAP production					
Total RAP production cost	0.00	2,320.50	4,641.00	6,961.50	9,189.18
DGM (1 cm) construction					
Paving machine (own)	223.13	223.13	223.13	223.13	223.13
Bobcat equipped with brooms	14.88	14.88	14.88	14.88	14.88
Tanker truck with water	24.17	24.17	24.17	24.17	24.17
Light truck for cleaning	18.59	18.59	18.59	18.59	18.59
Compressor	12.64	12.64	12.64	12.64	12.64
Smooth wheel rollers 10 tonne	518.52	518.52	518.52	518.52	518.52
Pneumatic rollers 12 tonne	570.37	570.37	570.37	570.37	570.37
Binder course (7 cm) construction					
Paving machine (own)	1,249.50	1,249.50	1,249.50	1,249.50	1,249.50
Paving machine (rent)	833.00	833.00	833.00	833.00	833.00
Bobcat equipped with brooms	83.30	83.30	83.30	83.30	83.30
Tanker truck with water	135.36	135.36	135.36	135.36	135.36
Light truck for cleaning	104.13	104.13	104.13	104.13	104.13
Compressor	70.81	70.81	70.81	70.81	70.81
Smooth wheel rollers 10 tonne	518.52	518.52	518.52	518.52	518.52
Pneumatic rollers 12 tonne	570.37	570.37	570.37	570.37	570.37
Wearing course (6 cm) construction					
Paving machine (own)	1,071.00	1,071.00	1,071.00	1,071.00	1,071.00
Paving machine (rent)	714.00	714.00	714.00	714.00	714.00
Bobcat equipped with brooms	71.40	71.40	71.40	71.40	71.40
Tanker truck with water	116.03	116.03	116.03	116.03	116.03
Light truck for cleaning	89.25	89.25	89.25	89.25	89.25
Compressor	60.69	60.69	60.69	60.69	60.69
Smooth wheel rollers 10 tonne	518.52	518.52	518.52	518.52	518.52
Pneumatic rollers 12 tonne	570.37	570.37	570.37	570.37	570.37
Waste costs					
Landfill cost	2,666.30	1,999.73	1,333.15	666.58	0.00
Total	529,034.82	438,825.97	417,436.31	395,618.09	384,115.34