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

A case study of a road rehabilitation in Portugal

EXTENDED ABSTRACT

David Jonathan Gaby Roland Vandewalle

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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. 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)

1 INTRODUCTION

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 recycled 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. Recycling and multi-recycling contribute to waste reduction and optimize the use of resources, both key elements in a circular economy (Antunes et al., 2019) .

To evaluate the possible advantages of RAP incorporation, and multi-recycling, a life cycle assessment (LCA) and life cycle cost analysis (LCCA) were performed on a section of flexible 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 (EC, JRC-IES, 2010).

2 METHODOLOGY

2.1 Functional unit

The functional unit of the LCA and LCCA creates the basis of comparison between different structure scenarios with the same utility for the same function (Santos et al., 2018). In this case, this involves a unit of pavement that carries the same traffic over the same performance analysis period (PAP). The functional unit in this study is a Portuguese national road section of 1-km length, composed of one independent roadway, with 2 lanes with an individual width of 3,5m 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 1. This figure also displays the overall maintenance and rehabilitation (M&R) strategy (tasks, courses and application timing) and the two main structure scenarios considered in the LCA and LCCA.

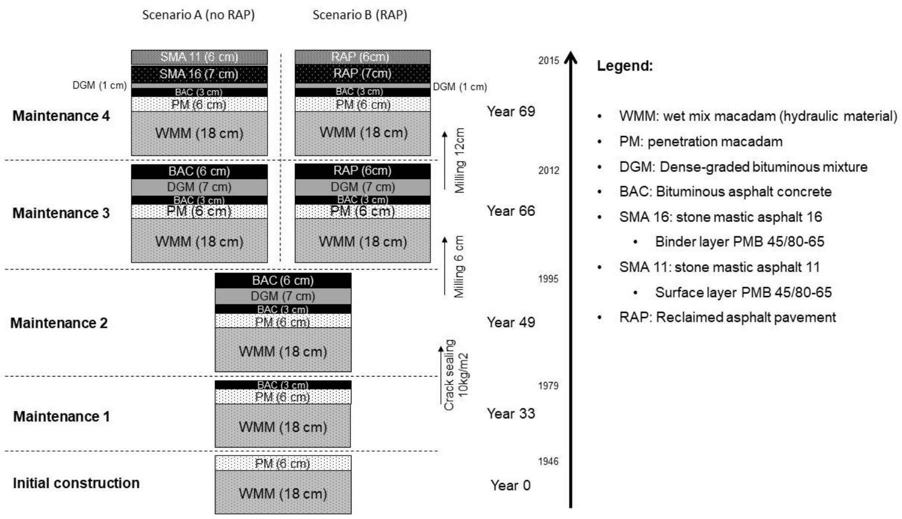

Figure 1 Geometric characteristics of the flexible pavement structure and M&R strategy scenarios

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.

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 1. Scenario A was subsequently renamed structure 0 to simplify comparison in the further course of the study.

Table 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

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.

2.2 LCA

The methodology to perform an LCA 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. 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 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 Intergovernmental Panel on Climate Change (*IPCC)*.

2.3 LCCA

The general methodology is considered equal for all existing LCCA procedures. The starting point for the LCCA procedure issued in this study was the methodology presented by Davis Langdon (2007a) shown in Table 2. This table also displays which steps were incorporated in this study and the according steps in this study.

Table 2 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	

3 RESULTS

This paragraph discusses the results from the LCA and LCCA performed on the presented case study. The first results are the LCA results which comprise the third step of the LCA, the life cycle impact assessment (LCIA). The second results are the LCCA results, comprising the output of the third step of the LCCA, the cost assembly. As mentioned above, this study compares five scenarios for a pavement section. Each scenario is referred to as a structure. The life cycle of each structure in following results subsequently, is referred to as life cycle structure (LCS) followed by the corresponding structure number e.g. LCS0, LCS1, etc.

3.1 LCA

The first LCA results, the first step in the LCIA, are the characterization results. The chart in Figure 2 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 %.

To provide 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. 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 3.

The third LCIA step includes the normalization. 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 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 et al., 2012). The normalisation results in Figure 4 illustrate 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 (the sum of normalisation results) chart presented in Figure 5. 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. Data gaps and assumptions accumulate along the cause-effect chain and will therefore cause endpoint results to be less certain (Brilhuis-Meijer, 2014). Although this may impact the results, the single score decrease from LCS0 to LCS4 is reported in Figure 5 to be around 33 %, which should be considered significant.

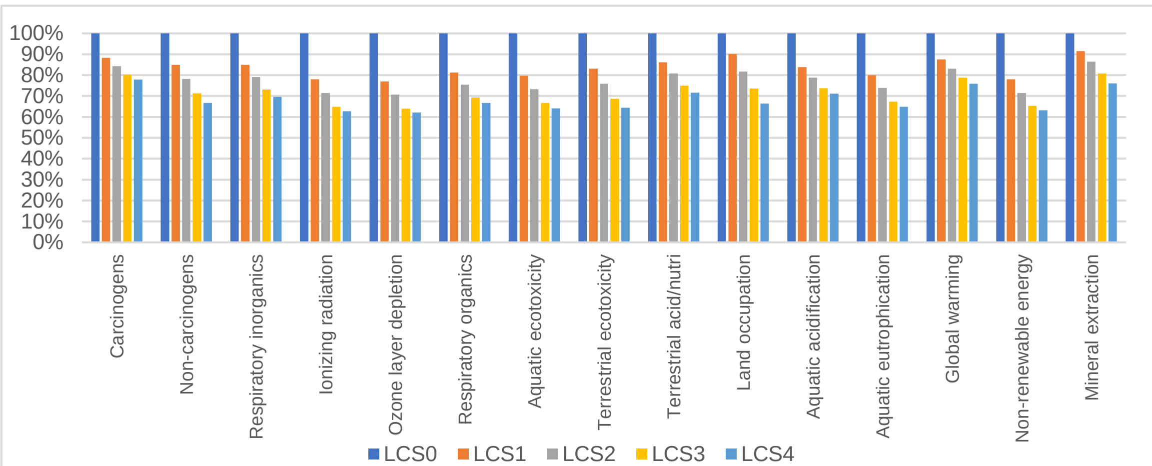

Figure 2 Characterization results (in percentages of the maximum per impact category

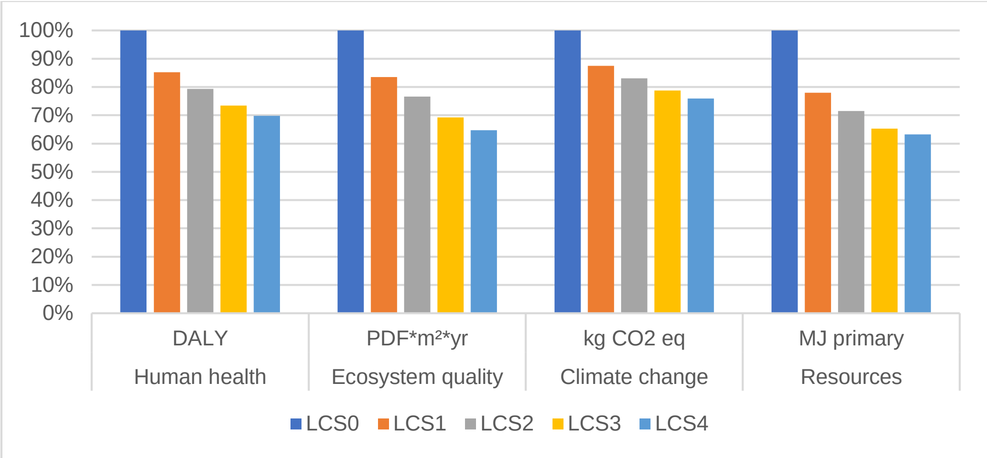

Figure 3 Damage assessment results (expressed in percentages of the maximum value per category): comparison for the 5 LCS's ([a] **DALY**: Disability-adjusted life years: characterizes the disease severity, accounting for both mortality (years of life lost due to premature death) and morbidity (the time of life with lower quality due to an illness, e.g., at hospital), [b] **PDF*m²*year**: The Potentially Disappeared Fraction of species over a certain amount of m² during a certain amount of year, [c] **kg CO2 eq**: kg CO2 equivalents into air, [d] **MJ primary**: MJ primary non-renewable)

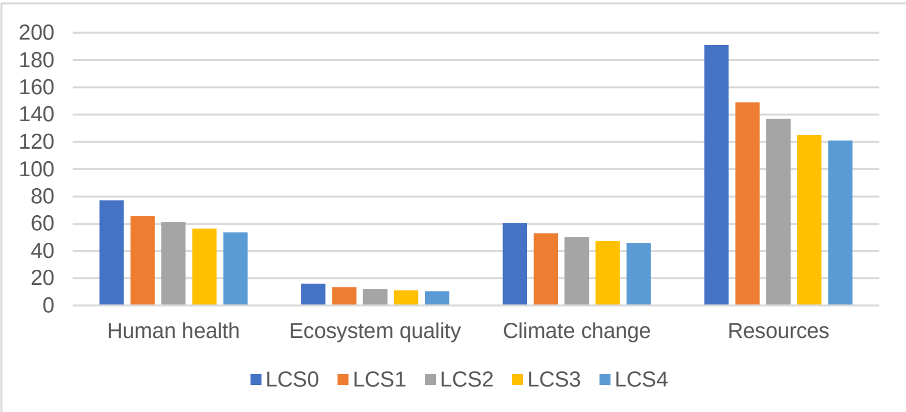

Figure 4 Normalization results

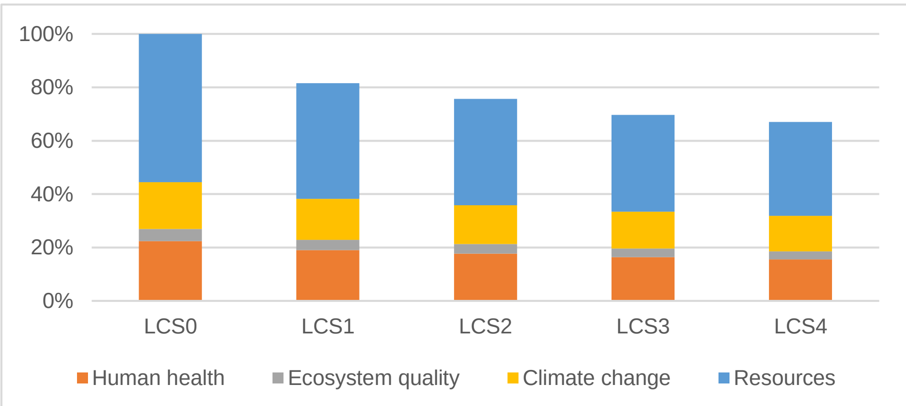

Figure 5 Single score values (expressed in percentages of the maximum single score value) for the five different structures considered in the LCIA

3.2 LCCA

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. The economic evaluation here however, is simply done through a comparison of overall cost, i.e. the sum of all the costs that were taken into account. Some of these costs were calculated based on primary data such as machine efficiencies, material unit costs etc.

For analysis purposes, 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 3 gives an overview of the total life cost per structure and per phase, divided into the seven categories.

Table 3 Total life cycle costs

Phase	LCS0 (€)	LCS1 (€)	LCS2 (€)	LCS3 (€)	LCS4 (€)
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 3 are also displayed graphically in Figure 6 and Figure 7. The chart in Figure 6 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 7 expresses the costs in absolute numbers rather than relative percentages. Furthermore, it makes the same seven-category-distinction as the chart in Figure 6 but shows these costs separately for each structure.

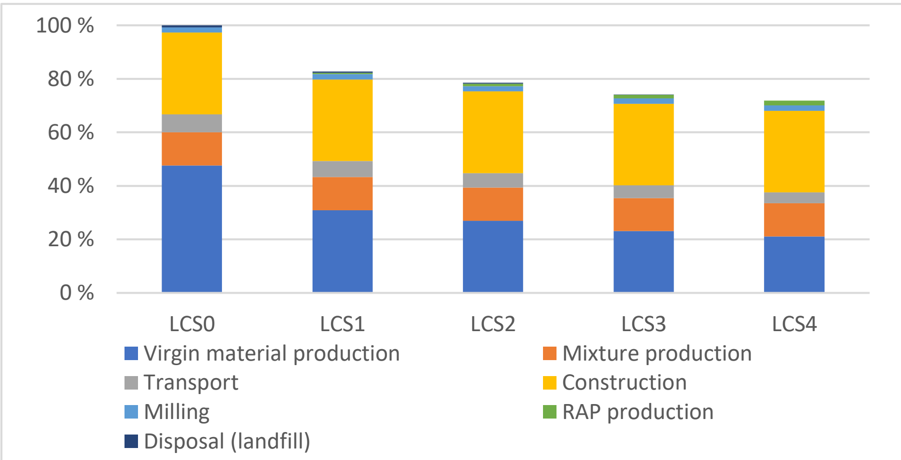

Figure 6 Total life cycle cost per structure, subdivided into the costs for the most significant life-cycle phases and expressed in percentages of the maximum total life cycle cost (structure 0)

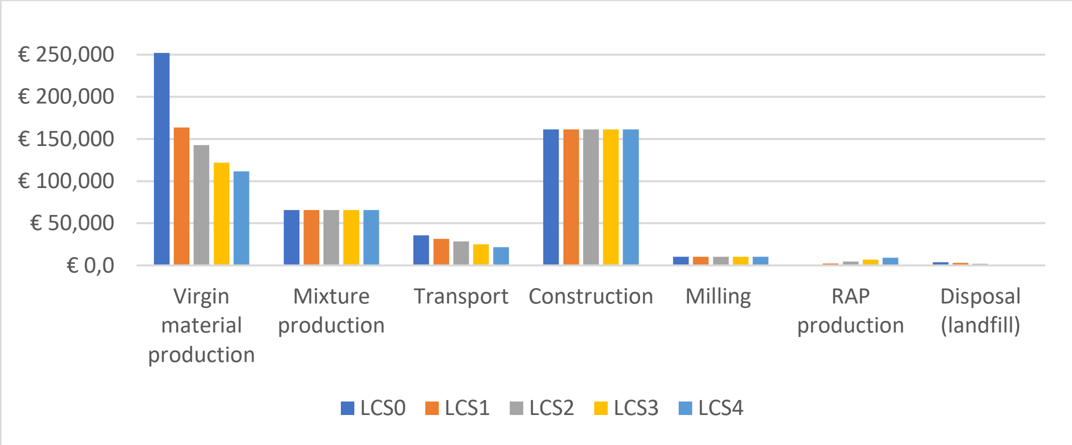

Figure 7 Total life cycle cost of the most significant life-cycle phases, displayed per structure

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 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 %. 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 reduction in cost of virgin material contributes the most to this decrease, as can be seen in Figure 7. 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.

4 CONCLUSION

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. 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). However, 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. 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.

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 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.

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

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.

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