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Modelling the Environmental and Economic Life Cycle Performance of Maximizing Asphalt Recycling on Road Pavement Surfaces in Europe

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Abstract: The road pavement industry, worldwide, has often shown reluctance in quickly implementing innovative practices; however, in the case of raw material consumption, a cultural change is necessary and, in this sense, sustainability assessment could play a major role. Along these lines, this research study aims to provide evidence to all the involved stakeholders (material producers, pavement contractors, and road authorities) of how life cycle-based techniques can be crucial in evaluating whether the adoption of asphalt mixtures with high contents of reclaimed asphalt (RA) for wearing courses is actually a sustainable practice for major European roads. An evaluation framework composed of a life cycle assessment, to calculate the carbon footprint of both pavement materials and pavement activities, and a life cycle cost assessment, performed to determine the overall economic burden of the related road pavement surface courses and maintenance strategies over a sixty-year analysis period, is presented and applied to selected case studies. These were developed together with three major European national road authorities and include scenarios involving the construction of road surfaces with asphalt mixtures containing up to 90% RA. Results have shown that whenever high-content RA mixes do not under-perform against conventional mixtures, up to 50% CO_2eq savings can be registered and up to 60% economic cost reductions can be reported. The durability of road pavement layers remains a key parameter for any road pavement sustainability assessment exercises; therefore, in order to adapt the obtained results to other contexts, researchers should always consider conducting a sensitivity analysis of the reference service life and/or road authorities should somehow request road pavement durability as a pre-requisite within procurement practices.

Keywords: road pavement; reclaimed asphalt (RA); life cycle assessment (LCA); life cycle cost (LCC); carbon footprint (CF)

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1. Introduction

Asphalt recycling is becoming more common and is normally labelled a sustainable practice. Several studies on the sustainability assessment of road pavement have been published, both to assess new projects and maintenance activities. The volume of existing research proves that the life cycle approach is more and more widely used in road pavement industries [1], but there is still a limit, represented by several gaps in the methodology [2]. Conventional materials [1,3], as well as alternative mixtures [1,4,5], have been investigated. Reclaimed asphalt (RA) has already been demonstrated as a valid partial substitute for virgin aggregates, maintaining beneficial properties [6,7]. It can be deduced that decreasing the extraction of raw materials can lead to reductions in emissions and costs. All the existing studies report an improvement when RA is used, and the combination of reduced temperature and the use of RA is particularly beneficial [8,9]. Several studies investigate sustainability performance at the pavement level, while the assessment of the production of one-ton volumes of asphalt mixtures is less developed [8]. Some studies compare the use of RA with the use of a conventional mix [10] or other alternative materials [11,12], while others aim to assess environmental performance with increases in RA content [8,13,14]. In all cases, whatever the mixtures are (asphalt concrete, stone mastic asphalt, porous asphalt), the emissions of CO_2eq (the so-called carbon footprint (CF)) decrease with the decrease in virgin aggregate content, as reported in Table 1. With the exception of refs. [8,15], none of the existing research has investigated the sustainability performance of mixtures containing more than 50% RA. This is also true for studies performing life cycle cost (LCC) assessments, which are less developed than environmental analyses for RA mixtures. The studies report a linear reduction in costs as the RA content increases: reductions of 8%, 11%, and 14%, respectively, are due to 30%, 40%, and 50% RA contents [14] used in production and construction, while a reduction from 21% to 26% is, respectively, linked to an RA variation from 10% to 50%, also considering the maintenance and the end-of-life [13].

Table 1. CF and LCC application in RA case studies.

Author/Year	Stages Considered	Comparison of Mixtures with Different RA Content (y/n)	RA Content (%)	CF reduction (%)-Comparison with Conventional Mix	Cost Reduction (%)
Chiu et al., 2007 [11]	Material production, transport, construction	n	AC 45% RA	23% (not a CF, it is an avarage of environmental improvement)	/
Vidal et al., 2013 [4]	Material production, transport, construction, use, maintenance, EoL	y	HMA 15% WMA 15%	13% 13%	/ /
Aurangzeb et al., 2013 [14]	Material production, transport, construction	y	AC 30% RA AC 40% RA AC 50% RA	7% 10% 13%	8% 11% 14%
Araùjo et al., 2014 [16]	Material production, transport, construction	n	AC 50% RA	17%	/
Bloom et al., 2017 [10]	Material production, transport, construction	n	55%	39%	33%
Praticò et al., 2020 [9]	Material production, transport, construction, EoL	y	AC 45% RA AC 30% RA	8% 6%	/ /
Vandewalle et al., 2020 [15]	Material production, transport, construction, maintenance, EoL		AC 25% RA AC 50% RA AC 75% RA + rej SMA 100% RA	16% 22% 28% 31%	
Zhao et al., 2021 [13]	Material production, transport, construction, maintenance, EoL	y	HMA 10% RA HMA 20% RA HMA 30% RA HMA 40% RA HMA 50% RA	11% 13% 15% 17% 19%	21% 23% 24% 25% 26%
Bizarro et al., 2021 [8]	Material production	y	AC 50% RA SMA 71% SMA 93% RA WMA PA 71% RA Foam. Bit. PA 93% RA	35% 50% 55% 59% 64%	/

It is clear that the use of RA has great potential to reduce environmental impacts, but a gap in the research currently prevents us from understanding whether, and to what degree, it is still worth maximising RA content. At the same time, there are still too few studies demonstrating the long-term economic benefits of using this technology.

In the above-mentioned studies, some inconsistencies and differences can be found in terms of functional units, system boundaries, databases, and software, making it difficult to compare the results. Most of the researchers conducted sustainability assessment exercises by considering a portion of pavement, often 1 km of constructed road, and assessing the impacts of the production and installation of the pavement component [10,17–19]. However, the burdens related to the use and the end-of-life phases are very often disregarded, and even excluded some exceptions [11,16,17]. Some research assesses sustainability considering several indicators [4,10,17], while other research only calculates carbon footprints and/or energy consumption [14,16,19]. This highlights the need for widely accepted frameworks to perform sustainability assessment exercises in the road pavement sector. These frameworks must comply with the generalised standard procedures provided by the International Standards Organisation in ISO14040 [20] and ISO14044 [21] for environmental life cycle assessment (LCA) and ISO 15686-5:2017 [22] for the life cycle cost (LCC) assessment related to economic aspects. What is stated above is valid for any applications and sectors [23,24]; however, each industry/sector should achieve harmonised SA procedures by tailoring these techniques to each investigated field. Within the road pavement sector, for instance, a plethora of scientific papers have been presented, with efforts usually aiming at providing a mere application of the methodology [1,11,12,14]. However, for SA to be an effective tool for decision-making, each industry needs a general framework suggesting harmonised approaches to carry out LCA exercises (i.e., the Product Category Rules) and/or to understand common procedures for data gathering and/or the use of results. Along these lines, first the PavementLCA framework in the USA [25], and very recently the PavementLCM framework of the Conference of European Directors of Roads [26] have provided guidelines towards a harmonised SA of road pavement materials and road pavement construction/maintenance activities. The latter suggests assessing sustainability, considering different exercises for each involved stakeholder: the manufacturer, contractor, and road authority. Each exercise differs in terms of unit, analysis period, system boundaries, and impact indicators. Concerning these last ones, the framework presents a set of sustainability performance indicators mainly based on the use of LCA and LCC techniques. This SA framework can be applied to assess and/or compare the sustainability of promising practices at any level of the road pavement industry, from technology development to asset management.

Aim and Structure of the Study

This study aims to understand whether maximizing the re-use of asphalt mixtures within major European road pavement surfaces is an environmentally and economic sustainable option. In order to do so, the authors at first developed three case studies gathering primary data from three major European road authorities and considering scenarios involving the construction of road surfaces with six asphalt mixtures containing up to 90% RA. Then, a tailored SA framework involving LCA and LCC (Figure 1) was used for evaluating the sustainability potential of material manufacturing (asphalt producers), layer installation (contractors), and maintenance strategies over a sixty-year analysis period (road agencies).

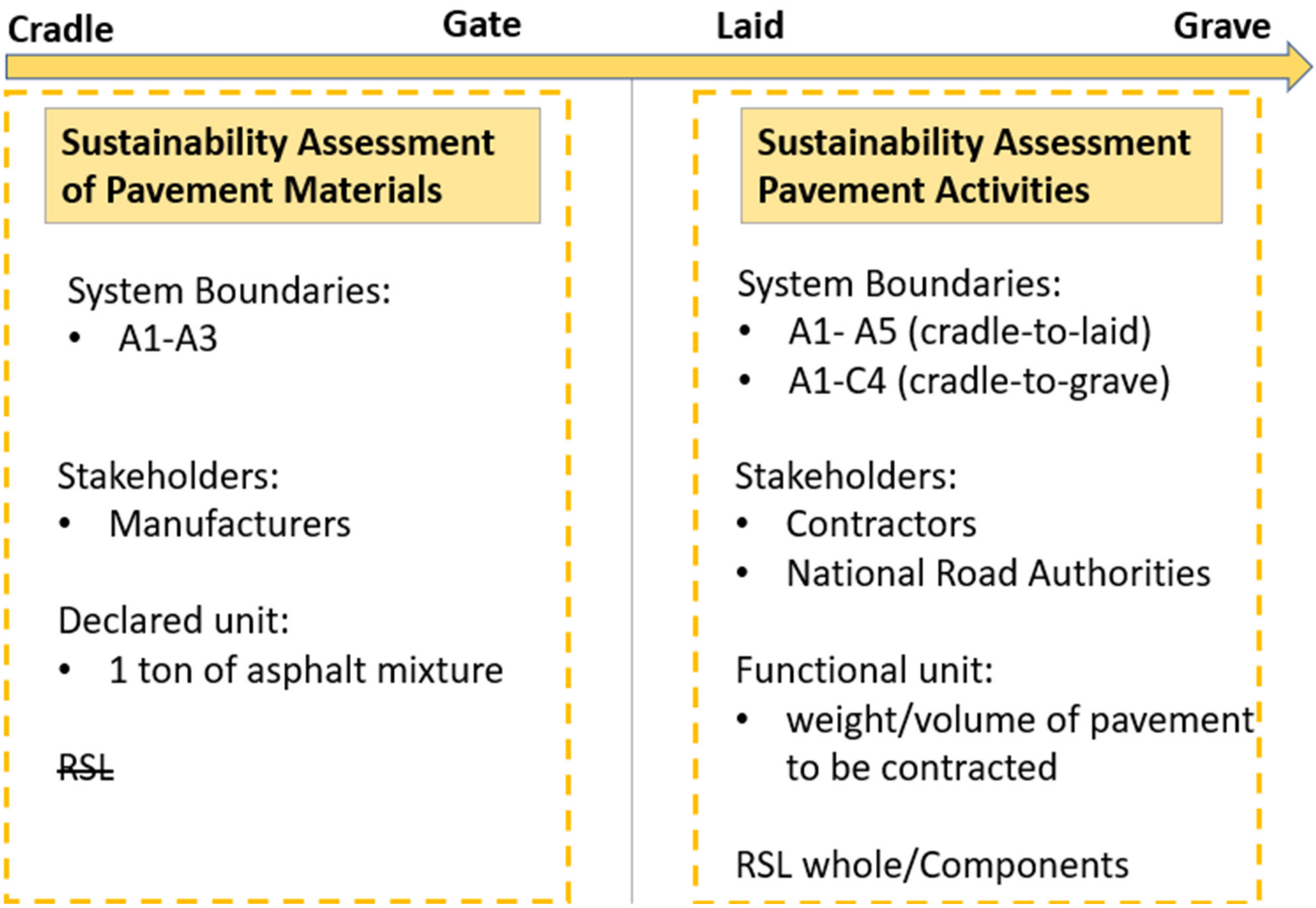


Figure 1. PavementLCM SA framework (adapted from PavementLCM, CEDR 2021, [26]).

This introduction provides the context and theoretical background necessary to better understand what is shown in the next paragraphs: Section 2, "Methodology" will describe the structure of the investigation and provide details on the selected case studies; then, Section 3, "Results and Discussion" will present the SA findings, which are summarised in Section 3.3 "Summary of Results"; last, Section 4, "Conclusions and Future Studies" will provide practical recommendations for practitioners and ideas for further development for the scientific community.

2. Methodology

In order to obtain practical recommendations representative of the whole Europe, three case studies were built as representative of different geographical European areas (North, Central, South), pavement structures, maintenance strategies, and traffic levels. In each case, the comparison assumed that either asphalt concrete (AC16) or stone mastic asphalt (SMA8) were used as paving material throughout the analysis period (60 years). Furthermore, it was assessed that AC16 could contain up to 90% RA and SMA8 could contain up to 60% RA.

Once the case studies were structured, a long and detailed data collection exercise was conducted by building tailored surveys filled by NRAs [27] and/or through collection of secondary data from literature and/or software databases referenced in each of the following sections. Sometimes data were obtained by simpler email exchanges and filling tailored data collection templates.

Then, an SA assessment phase was carried out by tailoring the framework shown in Figure 1 to allow each involved stakeholder to obtain the sustainability performances of materials (several asphalt mixtures with high RA content) and paving activities (tailored maintenance strategies) related to case studies built to be representative of Southern, Central, and Northern Europe. Environmental and economic impact assessments were carried out by means of life cycle assessment (LCA) and life cycle cost (LCC) assessment, respectively, according to European standards on SA [22], while considering existing international standards [20–22] and frameworks [25].

Figure 2 presents a summary of the organisation of the whole study. Details of the materials, case studies, data collection, and SA are presented in the next paragraphs.

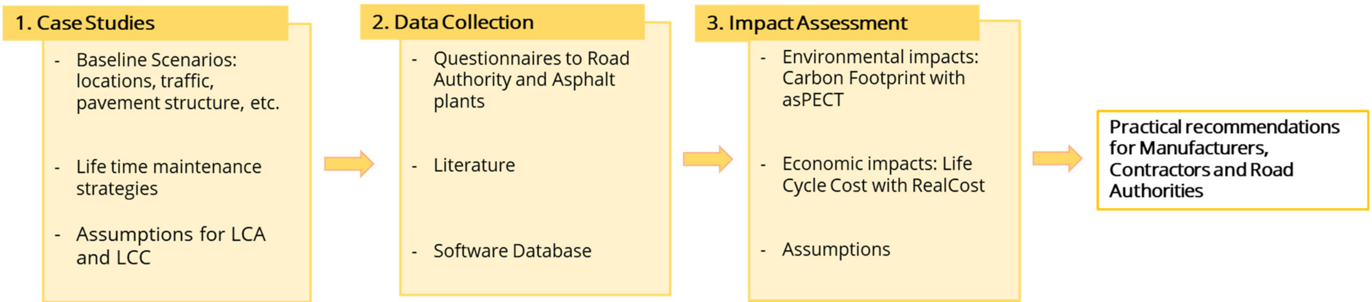


Figure 2. Sustainability performance assessment methodology: case studies, data collection, impact assessment.

2.1. Case Studies and Data Collection

2.1.1. Pavement Materials

As mentioned above, two mixes used for wearing courses were selected as the baseline materials for the comparison. These are the typical mixes used for major roads in Germany (SMA with polymer-modified bitumen) and in Italy (AC with paving bitumen). The study then considered several versions of both technologies, incorporating at least three levels of RA and sometimes additives (add) as follows:

- AC16 30% RA + add
- AC16 60% RA + add
- AC16 90% RA + add
- SMA8S 30% RA
- SMA8S 60% RA
- SMA8S 60% RA + add

The asphalt mixture technologies, both with and without RA, were adopted and/or developed within the Allback2Pave project [27]. This effort, for the AC16s, modified the typical mix design specified by Italian NRAs (ANAS) by incorporating 30%, 60%, and 90% RA. In contrast, for the SMA8s, typical recipes without RA used in Germany (BASt) were designed and produced with 30%, 60%, and 60% + additives. Table 2 provides the details of each mix design as provided by the previously mentioned specifications and by the Allback2Pave project. Within the project, durability was also investigated, and it was concluded that, with a correct mix design and a fractioned and characterised RA, high recycling rates in asphalt wearing courses do not cause worse performance.

Additionally, the study considered hypothetical scenarios where each of the mixtures was used in each case study, including the Northern European case in the UK. The mixtures were all compared to conventional mixtures to understand whether their use in replacing current asphalts reduces negative environmental impacts; in other words, this study assessed whether these new mixtures are more sustainable.

Table 2. Details of asphalt mixture baselines and mixes with high RA contents.

	South Europe Baseline	Central Europe Baseline	North Europe Baseline	AC16 30% RA + Add	AC16 60% RA + Add	AC16 90% RA + Add	SMA8S 30% RA	SMA8S 60% RA	SMA8S 60% RA + Add
Virgin aggregates (%)	86.9	86.2	87.4	63.84	33.77	3.9	61.59	35.62	35.62
Filler (%)	7.0	6.5	7.0	-	-	-	2.57	-	-
STA RA (%)	-	-	-	-	-	-	30	60	60
LTA RA (%)	-	-	-	31.4	62.8	93.5	-	-	-
Bitumen (%)	6.1	-	5.6	4.5	2.9	1.9	-	-	-
PMB (%)	-	7.0	-	-	-	-	5.54	4.08	3.48
Fibres (%)	-	0.3	-	-	-	-	0.3	0.3	0.3
STORBIT additive (%)	-	-	-	0.26	0.53	0.7	-	-	0.6

2.1.2. Case Studies

The above-mentioned asphalt mixtures were assumed to replace the current ones in three case studies representative of three geographical areas (South Europe (SE), Central Europe (CE), and North Europe (NE)), pavement structures, levels of course durability, and traffic levels (high, medium, and low). Each case study was crafted with the help of the interested NRAs and/or other available resources and was intended to be representative of "typical" inter-urban roads of the selected countries. The collection of primary data from asphalt production plants in Germany and Italy and tailored questionnaires completed by the interested NRAs were the sources of information on the key variables, such as the asphalt mix recipes, energy and fuel consumption, and transport distances. A summary of each case study is provided below together with screenshots of geography and locations (Figure 3), while details are presented in Table 3 and Figure 4 below and in Tables A1–A3 in Appendix A.2.

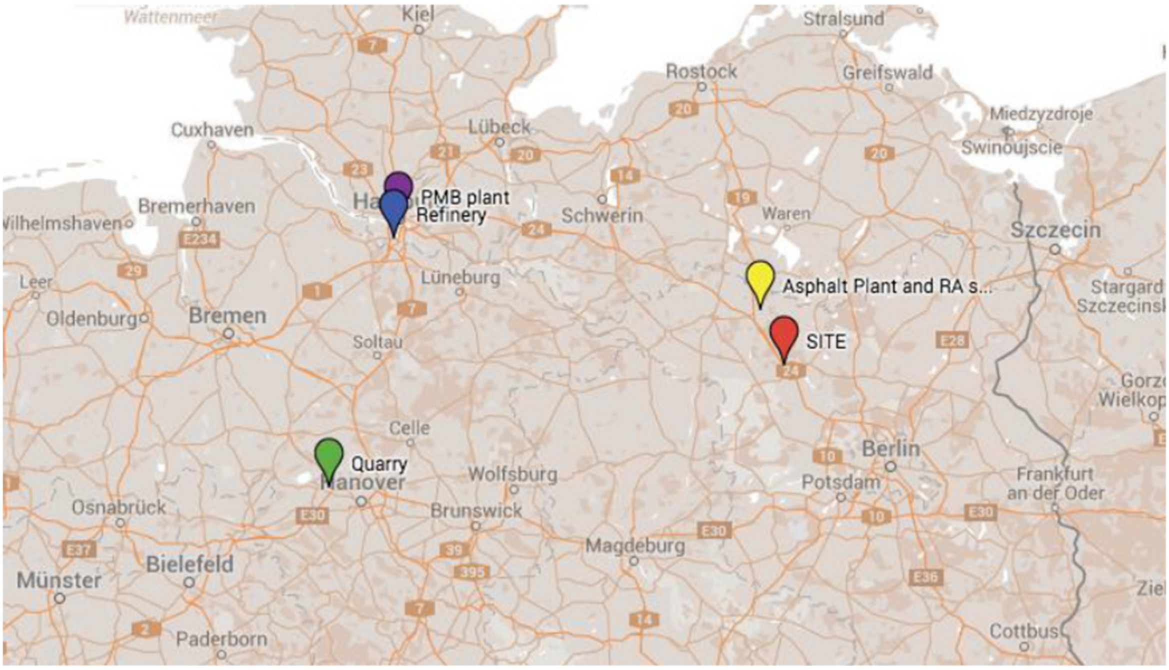
- South Europe: Italy: A repaving operation on a motorway (40,000 ADT) called A19-Palermo–Catania. The road consists of two separate carriageways in each direction that are structurally composed of 170 mm of asphalt (30 mm wearing course, 40 mm binder course, and 100 mm of base) and 300 mm of foundation cement-stabilised sand. The road section, the object of the intervention, is 9.50 m wide and 2000 m long. Usual maintenance of this type of pavement consists of five-year periodic inlay of the wearing course, mainly for skid resistance issues [28], while the binder course is substituted every thirty years.
- Central Europe: Germany: A repaving operation on an inter-urban highway called A24 and situated near Berlin with medium traffic volume (20.000 ADT). The structure is composed of 30 mm of wearing course, 80 mm of binder course, 140 mm of base course, 200 mm of unbound gravel base course, and 350 mm of unbound frost blanket. The road section, the object of the intervention, is 11.80 m wide and 800 m long. Usual maintenance for this type of pavement, realised with SMA mixture, consists of sixteen-year periodic inlay of the wearing course [29], while the binder course is substituted every thirty years.
- North Europe: UK: An inlay operation on an inter-urban road with low/medium traffic volume (10.000 ADT) consisting of a single carriageway. The structure is currently composed as follows: 40 mm of wearing course, 100 mm of binder course, and 50 mm of base course. The road section, the object of the intervention, is 11 m wide and 720 m long. The wearing course is realised with SMA mixture, and its maintenance

consists of ten-year periodic inlay [30], while the binder course is substituted every thirty years.

- Maintenance strategies: The maintenance strategies were considered similar for all of the case studies. These consisted of the milling and inlay of wearing courses (WCs) enhanced with binder course (BC) inlays and rehabilitation, considering an analysis period of 60 years. This assumption was made to account for the potential benefits, in terms of costs and emissions, linked to the use of RA, which implies reductions in the material stockpiled and the depletion of virgin materials. The maintenance plan was dependent on the reference service life of each pavement component, which was provided as primary data by European NRAs or estimated through laboratory tests [27]. The authors assumed that road pavement foundation and sub courses would not deteriorate and that the asphalt would not go under/over performance. The maintenance procedures consider the details shown below [27] and in Table 4:
    - Surface treatments involve the periodic inlay of wearing course and the occasional inlay of binder and base course.
    - Maintenance is undertaken on one carriageway (two lane) or one lane (single-lane road) at a time, with the traffic diverted onto the other carriageway/lane.
    - Work zones are extended for the whole length and the width of the full carriageway.
    - In the case studies with dual carriageways, maintenance events are considered only in one direction.

(a)

Figure 3. *Cont.*



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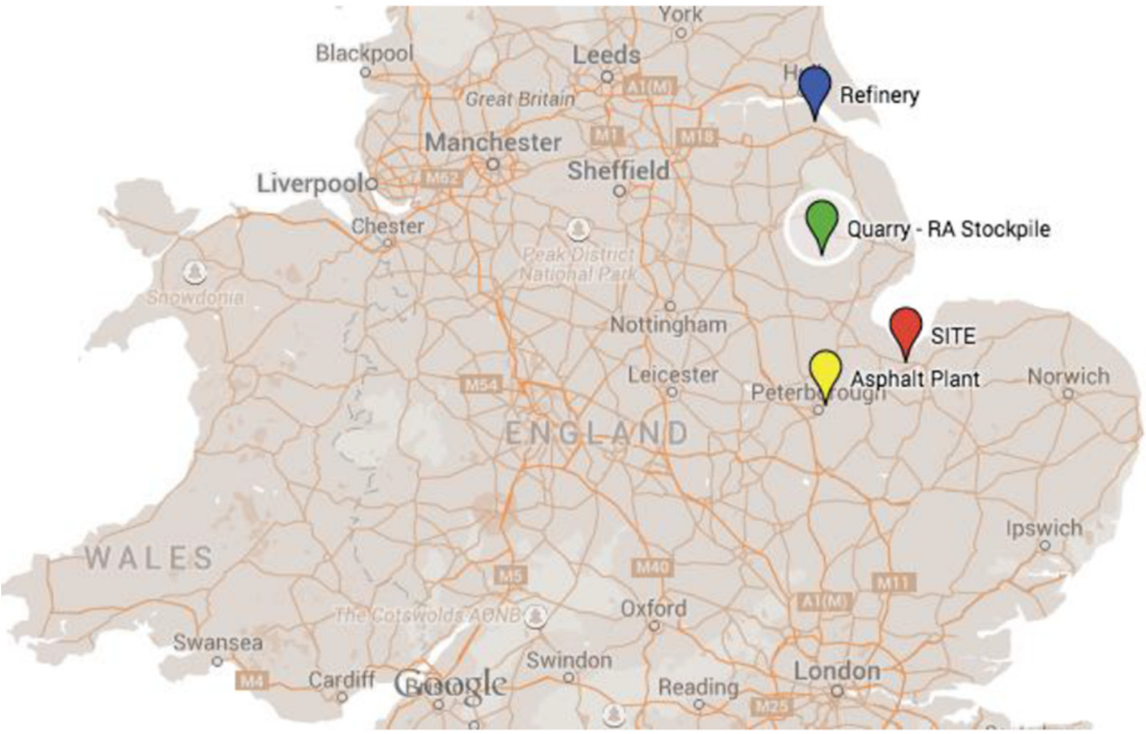

(**c**)

Figure 3. (**a**–**c**) Case studies: geography and locations. (**a**) South Europe case study–localisation; (**b**) Central Europe case study–localisation; (**c**) North Europe case study–localisation.

Table 3. Asphalt paving geometry and durability.

Pavement Course	South EU-IT (ANAS, 2015) [28]	Central EU-D (BASt, 2015) [29]	North EU-UK (Spray, 2014) [30]
Section width	9.50 m	11.80 m	11.00 m
Section length	2000 m	800 m	720 m
Foundation heights	Cement treated sand 300 mm	Unbound course gravel + frost blanket 350 mm	Cement treated limestone 258 mm
Traffic levels	High traffic	Medium traffic	Low traffic
Typical durability of wearing course	5 years (HMA)	16 years (SMA)	10 years (SMA)
Typical durability of binder course	25–30 years		
Typical durability of base course	50 years		

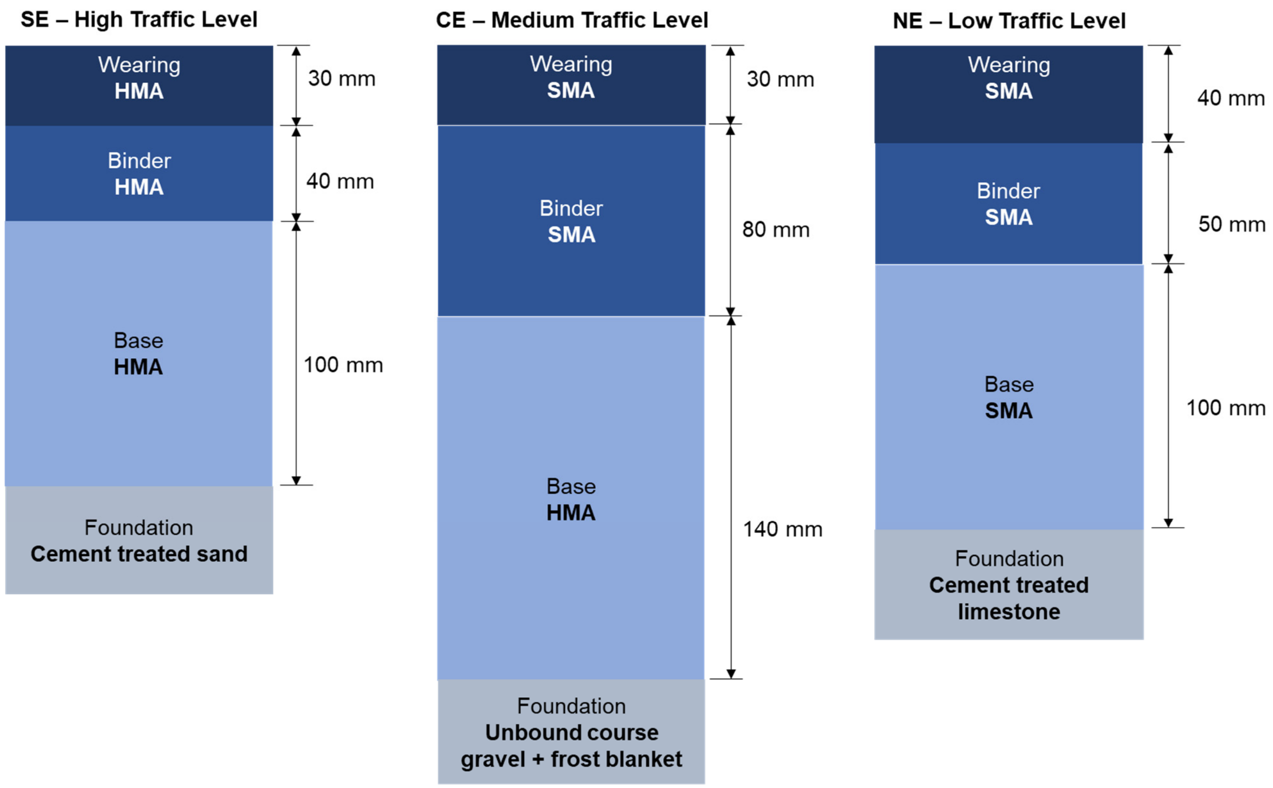

Figure 4. Case studies: pavement structures.

Table 4. Country-dependent maintenance strategy over 60 years.

Italy: (ANAS, 2015) [28]		Germany: (BASt, 2015) [29]		UK: (Spray, 2014) [30]	
Year	**Procedure**	**Year**	**Procedure**	**Year**	**Procedure**
0–5	Inlay WC + BC	0–15	Inlay WC + BC	0–10	Inlay WC + BC
5–10	Inlay WC	15–30	Inlay WC	10–20	Inlay WC
10–15	Inlay WC	30–45	Rehabilitation	20–30	Inlay WC + BC
15–20	Inlay WC	45–60	Inlay WC	30–40	Inlay WC

Table 4. *Cont.*

Italy: (ANAS, 2015) [28]		Germany: (BASt, 2015) [29]		UK: (Spray, 2014) [30]	
Year	**Procedure**	**Year**	**Procedure**	**Year**	**Procedure**
20–25	Inlay WC			40–50	Rehabilitat.
25–30	Inlay WC + BC			50–60	Inlay WC
30–35	Inlay WC				
35–40	Inlay WC				
40–45	Inlay WC				
45–50	Inlay WC				
50–55	Rehabilitation				
55–60	Inlay WC				

2.2. Environmental Impact Assessment by Means of LCA

As mentioned before, the chosen methodology to assess the environmental performance was LCA; specifically, a carbon footprint assessment was carried out. The CF assessment was performed using asPECT (Asphalt Pavement Embodied Carbon Tool) [31], a flexible and customisable tool which enabled the implementation of all the inputs and estimated CO_2eq emissions. The tool enables the calculation of greenhouse gas emissions throughout the life cycle of a road pavement, in compliance with ISO standards. It is flexible and customisable: it allows inserting and changing inputs and implementing new pavement designs. In order to estimate the CO_2eq of each case study and scenario, the selected approach considered the currently used asphalt mixes and maintenance practices as the "baseline"; these were replaced with asphalt mixes containing different contents of RA%, thus building up a series of comparable scenarios. EARN Deliverable 5 [32], together with standards and reputable data sources, was utilised to provide missing data such as emissions factors for fuels, transport, and embodied carbon values for constituent materials.

In order to assess the environmental impact for each stakeholder, three different SA exercises were implemented. In fact, as stated in a recent framework developed by the Conference of European Directors of Roads [26], SA exercises for road pavements can be differentiated in relation to the aim of the study and the type of involved stakeholders. In particular, as already shown, the SA exercise, including system boundaries (Figure 5), changes as follows:

1. Asphalt mixture producers: The assessment is related to the production of the asphalt mixtures (cradle-to-gate), and the declared unit is assumed to be one ton of asphalt mixture.
2. Pavement contractors: The evaluation concerns the installation of a pavement component(s) (cradle-to-laid), and the functional unit is the total weight of the pavement component(s) to be contracted, considering only a reference service (i.e., 10 years for a wearing course)
3. Road pavement agencies: The assessment relates to the comparison of the maintenance strategies (over a certain analysis period (laid-to-grave)), and the functional unit is a square meter of road pavement and/or the total weight of pavement component(s) to be contracted.

Details of the exercises have been grouped and presented in typical steps constituting an LCA study, namely: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation of results.

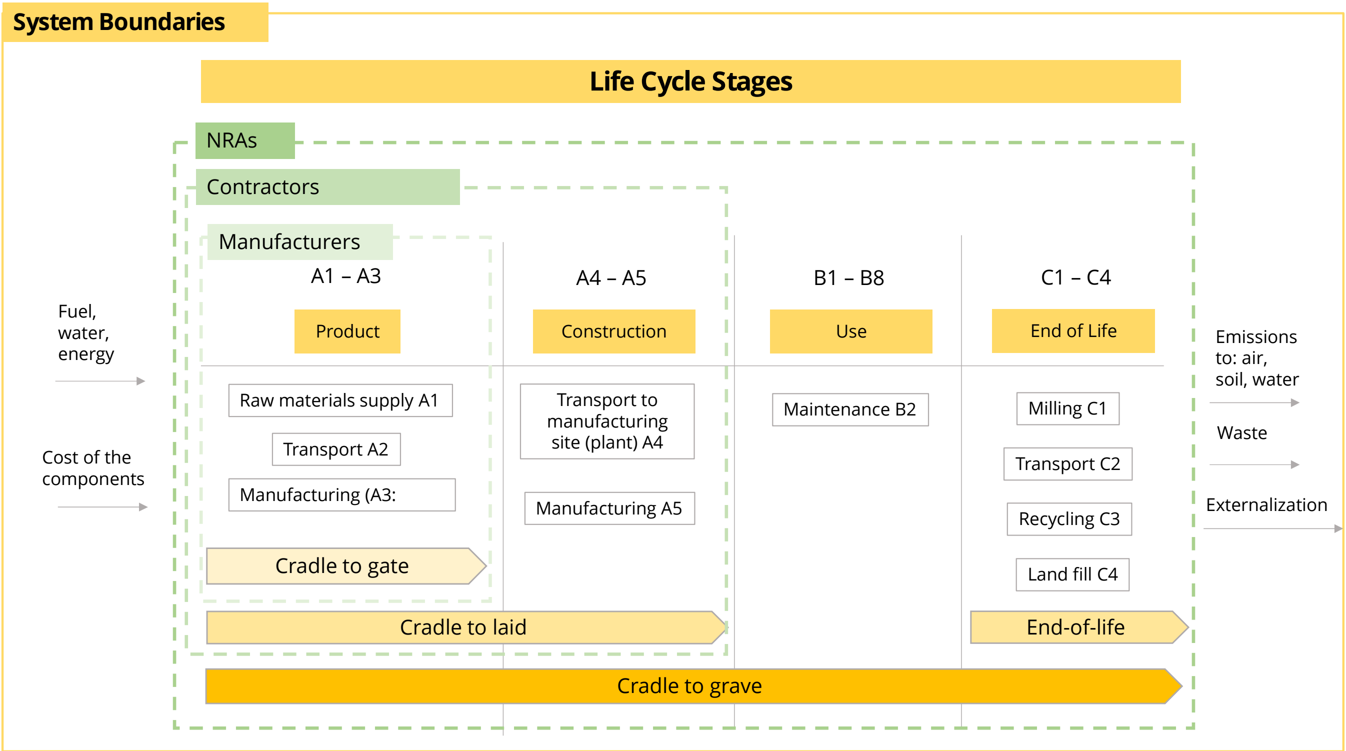

Figure 5. System boundaries for each SA exercise.

2.2.1. Goal and Scope Definition

The aim of this study is to calculate the environmental impacts related to the use of different mixtures throughout the pavement life cycle. The materials investigated include conventional hot asphalt mixtures (SMAs in Germany and ACs in Italy) and six mixtures with high contents of RA (AB2P mixtures).

The results of the study can be compared to understand how much less impactful using recycled asphalt is.

The intended applications of the study are:

- Understanding of the environmental benefits related to asphalt recycling.
- Understanding of the pros and the cons of using these new technologies when compared to current baselines.
- Support of more sustainable decision-making processes among asphalt mixture producers.

The study is directed to manufacturers, national road authorities, and academics to provide evidence of the environmental impact of maximizing RA for pavement roads.

The case studies have already been detailed in the previous section.

The system boundaries, as reported in Figure 5, are:

- A "cradle-to-gate" perspective for the pavement materials, considering only the production of the asphalt mixtures;
- A "cradle-to-laid" and a "cradle-to-grave" perspective were considered if the object of the assessment was pavement activities and therefore the wearing course. In the first case, the focus was on the production of the material and the installation of the layer; in the second case, all the necessary stages from the extraction to the end-of-life were considered.

A distinction between declared units and functional units is provided in the study: the former are used in assessments which do not cover the full life cycle, while the latter are used in other cases [33]. Hence, declared units are used for pavement material assessment and are defined as one ton of asphalt course, while functional units are considered for pavement activities and are assumed to be equivalent to the tons of asphalt to be replaced, calculated by multiplying the volume of each wearing course by an estimated density of 2.3 t/m^3.

Concerning the analysis period, for pavement activities it was assumed to be one reference service life in the exercise for contractors, otherwise it was 60 years in the exercise for NRAs.

With reference to cut-off rules, processes/activities that altogether did not contribute to more than 1% of the total environmental impact for any impact category were omitted from the inventory. The only allocation considered regards the RA entering the systems. It was assumed that it contains 0 kg of CO_2eq. Furthermore, RA recoverability is 95% (5% lost in transport, processing, etc.).

The only impact category is the global warming potential, while the considered characterisation factors are the latest Defra emission factors, as considered by the asPECT tool [31,32].

All the used data was primary, when possible, or taken from the literature when the former was not available.

2.2.2. Life Cycle Inventory (LCI)

In this second step, all the data required for the assessment were collected: they concern the inputs and outputs of the system in all the phases considered in the system boundaries. The inventory was modeled with asPECT. Data were directly provided by the partners/producers or taken from the database when missing (Table A4).

- Production phase (A1–A3)

The production phase consists of all inputs and outputs necessary for the extraction and transport of raw materials, plus the production of the asphalt mixtures:

- ○ Raw materials supply (A1): The inventories (Table 2) include all the information linked to the components used, such as aggregates, neat bitumen, polymer-modified bitumen, fibres, and the STORBIT PLUS Rejuvenator (which is a composition of high-viscosity second refinement known for its higher viscosity STORFLUX PLUS and Fischer Tropsch Wax; it has a solid state of aggregation at room temperature).
- ○ Transport (A2): This includes the distances between raw material suppliers and the asphalt plant. In this case study, all the constituents are locally sourced, excluding the additive imported from Germany (Table A5).
- ○ Manufacturing (A3): This includes energy consumption required in the plant and the typology of the fuel. Some data were directly provided (i.e., quantity of energy used), while other data was assumed and taken from the literature, including:
- ○ The consumption of electricity and fuel oil, taken from UK grid;
- ○ The activity of soluble binder in RA, which was fixed to 80% (partial blending) to have an average of the two extremes considered during the mix design (100% and 60%);
- ○ The content of soluble binder in the RA fraction;
- ○ An increase of 10% due to RA aggregate heating, considered to account for fuel consumption [34].
- Installation (A4–A5)

The inventory linked to this step includes the inputs and outputs necessary for the components' transport from the plant to the site (A4) and their successive installation (A5). The distances are all contained in Table A6. The installation includes laying and compaction of the asphalt courses plus a tack coat of bitumen emulsion. Data concerning A4 were directly provided, while those concerning A5 were taken from asPECT v4.0.

Furthermore, some assumptions were defined:

- ○ According to asPECT protocol, laying and compacting impacts were considered as 4.7 kg CO_2eq per ton of asphalt.
- ○ Tack coat bitumen emulsion is applied at a rate of 0.4 L/m^2 of laid asphalt [32].

  - ○ Unless otherwise stated, it is assumed that all the materials used at the site come from the asphalt plant.
- Use phase (B2)

This phase is included only if the system boundaries are extended to the maintenance activities.

In particular, within the use phase, only repair (B3) is part of the system boundaries. This is a step which corresponds to all the operations needed for course substitution (A1–A5 for the new course and C1–C3 of the one to be replaced).

Each maintenance activity consists of two steps:

  - ○ milling of the pavement course to be substituted, including 10 mm of regulating course.
  - ○ installation of new course, with the same inputs and outputs reported in A1–A5.
- End-of-Life (C1–C3)

Each maintenance activity has its own burden in terms of waste. Nevertheless, it has been decided that the milled pavement is transported and stockpiled in order to produce reclaimed asphalt for new mixtures.

The impacts related to this phase are due to milling, transport, and recycling. The data related to transport distances are presented in Table A7 in Appendix A.2.

2.2.3. Life Cycle Impact Assessment (LCIA)

This third step aims at calculating the potential impacts linked to the system. In this case, only an impact category was chosen and the methodology for calculation was strictly linked with the used tool (asPECT v4.0). No optional step (i.e., characterisation, grouping) was carried out. All the results are presented in Section 3.

2.2.4. Interpretation of Results

This fourth step consists in the interpretation of the obtained results and identification of the significant issues and the main relevant phases of the study. At the end, conclusions and recommendations are provided. This part is detailed and explained in Section 3.

2.3. Economic Impact Assessment by Means of LCC

The present economic impact was evaluated by using LCC using RealCost [35] software to calculate the net present value, which was limited to the cradle-to-gate approach (manufacturers) plus a basic estimate over the analysis period of 60 years. The assessment was carried out for production costs (cradle-to-gate), but also with a basic estimate of the costs over the analysis period of 60 years. The LCC was performed following the points described in the methodology.

1. Establish alternative pavement design strategies:

The conventional baseline will be replaced with high-content RA mixtures, as described in the sections above.

2. Determine performance periods and activity timing:

This LCC is a cradle-to-gate analysis, so it is limited to the costs of the production of asphalt mixtures, calculated for the sixty-year analysis period. According to the maintenance plan and the durability assigned to each infrastructure component, the number of interventions and tons of asphalt mixtures were calculated. In particular, the expected number of maintenances is fourteen (nine inlay WC, two inlay WC + BC, one rehabilitation) for SE, four (two inlay WC, one inlay WC + BC, one rehabilitation) for CE, and five (two inlay WC, two inlay WC + BC, one rehabilitation) for NE.

3. Estimate agency costs:

Once the pavement design strategies and performance period were selected, the data collection was carried out according to the inputs needed for RealCost life cycle cost analysis software [36]. In this case study, the agency costs correspond to the cost of asphalt mixes. Hence, they are obtained by multiplying the cost of each ton for total tons of asphalt to be replaced in each intervention in each case study. The costs to be collected and accounted for are related to the production phase, from the extraction of raw materials (A1) to their transport to asphalt plant (A2) up to the manufacturing process (A3) (Tables A8 and A9).

Concerning the costs related to A1–A2, they were mostly collected interviewing plants/contractors and material suppliers; for the SE case study, all data was provided by Ferrara, except for the cost of fibres from Iterchimica, while the NE and CE case study information was taken from the literature (i.e., [32]), excluding the costs of fibres [37] and the STORBIT PLUS additive [38]. They were assumed to be constant throughout the analysis period (60 years) for each intervention needed and previewed in the maintenance strategy. Concerning the costs linked to A3, they are given by the energy consumption used in the plant. Electricity and oil costs were taken from the literature [32] and some assumptions were made according to their consumption for the mixtures with a high content of RA. In fact, oil consumption was assumed to be 10% regardless of the amount of RA added, while the electricity amount was the same for all the alternatives.

4. Net Present Value

The net present value calculation was performed thanks to RealCost, a spreadsheet program made by FHWA. It performs a simulation on the basis of a discrete value (a fixed discount value because the deterministic approach was chosen) and computes an array of life-cycle costs (using a sampling of pre-defined costs or a probability distribution of costs). Each current baseline was compared with the six alternatives with RA; additionally, for each case study, the course's durability, maintenance, and rehabilitation plans were implemented. As mentioned earlier, the life cycle cost exercise was carried out through a deterministic approach which is based on the definition of a fixed discount rate. Fixing the discount rate at 0% means to state no time preference: the costs of today are weighted as benefits in the future. Nevertheless, in common practice, the discount rate for public works is never null and it depends on the country. For this reason, according to the literature [37], a value for each case study was used for the calculation, namely, 5% for South Europe, 3% for Central Europe, and 3.5% for the first 30 years and 3% for the remaining 30 years for North Europe.

3. Results and Discussion

3.1. Calculation of Environmental Performance

On the basis of the data collected and the assumptions made, the results of the assessment highlight the environmental benefit linked to the use of high amounts of RA for most of the case studies. The results are reported in the tables below.

- Pavement Material–Manufacturers (A1–A3)

The results of the first assessment are provided in Table 5 and Figure 6. They show the total quantity of CO_2eq emitted to produce one ton of asphalt mixture.

Table 5. CO_2eq emissions due to the production of one ton of asphalt mixture (A1–A3).

	Baseline	AC16-RA30add	AC16-RA60add	AC16-RA90add	SMA RA30	SMA RA60	SMA RA60add
SE [kg CO_2eq]	37.89	37.7	35.28	32.98	47.12	39.82	43.84
CE [kg CO_2eq]	88.3	65.01	51.14	37.72	73.99	57.25	60.25
NE [kg CO_2eq]	52.89	44.39	42.35	40.56	53.7	47.15	50.59

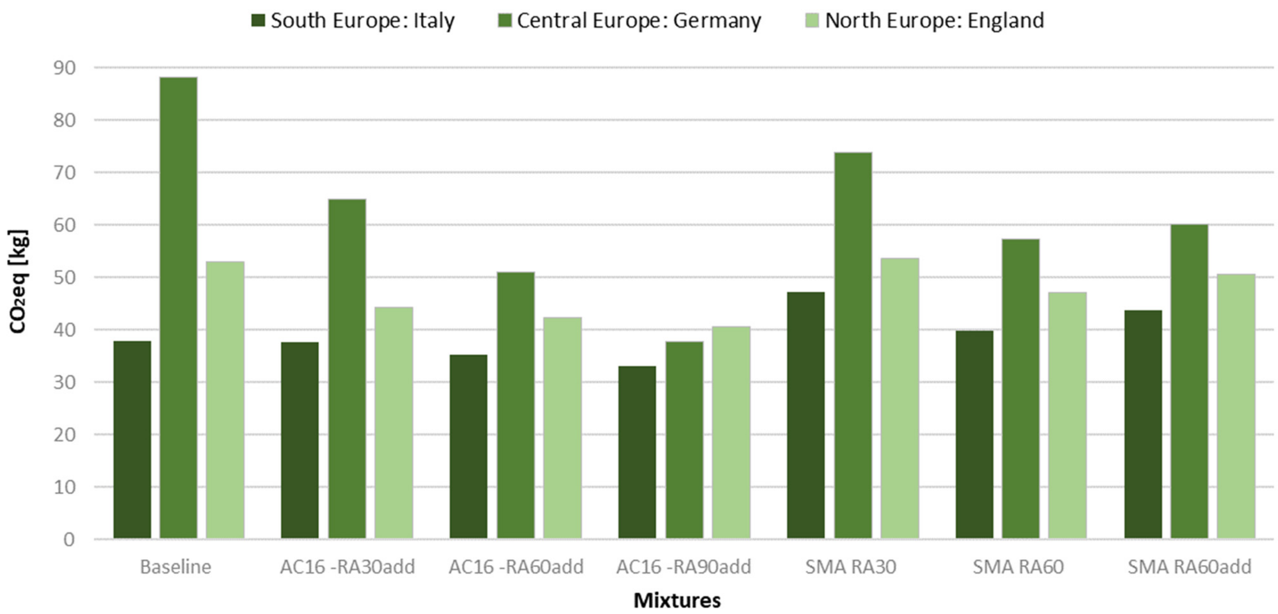

Figure 6. CO_2eq emissions due to the production of one ton of asphalt mixture (A1–A3).

Furthermore, to go deeper in the study, hotspot analyses were performed to assess the most impactful phases limited to the cradle-to-gate system (contribution > 50%).

The impacts related to production phase were divided into the three categories: 1. Raw material sourcing (A1); 2. Transport to plant (A2); 3. Heating and Mixing (A3). Looking at the results, generally, it can be stated that the contribution for manufacturing the mixtures increases proportionally with the increase in the amount of RA (due to the higher energy required by it). Instead, the impacts related to extraction of raw materials decrease.

In detail, concerning the SE case study, a hotspot always represented A3 while the impact of A2 was not significant (from 3% to 7%). The situation changed in the CE case study, where the impact of the A2 phase was much higher (from 16% to 46%), since transport distances were significantly longer. In NE case study, the only hotspot was obtained in A3 (53%) with the highest amount of RA (90%). Hence, for SE and NE, the heating and mixing (A3) phase were the most impactful, while in the CE, the transport to the plant (A2) provided the highest impact.

- Pavement Activities–Contractors (A1–A5)

The results of the assessment involving the contractors are provided below. Table 6 reports the total quantity of CO_2eq emitted for the production and installation of a pavement component (one course, i.e., wearing course).

Table 6. CO_2eq emissions due to the production and installation of one pavement course (A1–A5).

	Baseline	AC16-RA30add	AC16-RA60add	AC16-RA90add	SMA RA30	SMA RA60	SMA RA60add
SE [kg CO_2eq]	151.11	150.65	145.13	139.84	172.27	155.48	164.68
CE [kg CO_2eq]	242.19	169.74	137.77	106.95	190.44	152.03	158.93
NE [kg CO_2eq]	143.98	124.43	119.83	115.69	145.82	121.141	60.3

Figure 7 shows CO_2eq emissions due to the production and installation of one pavement course (A1–A5), showing a visible trend of reduction in CO_2eq when the amount of RA was higher, ensuring that the reduction in virgin material is environmentally friendly in a cradle-to-laid approach.

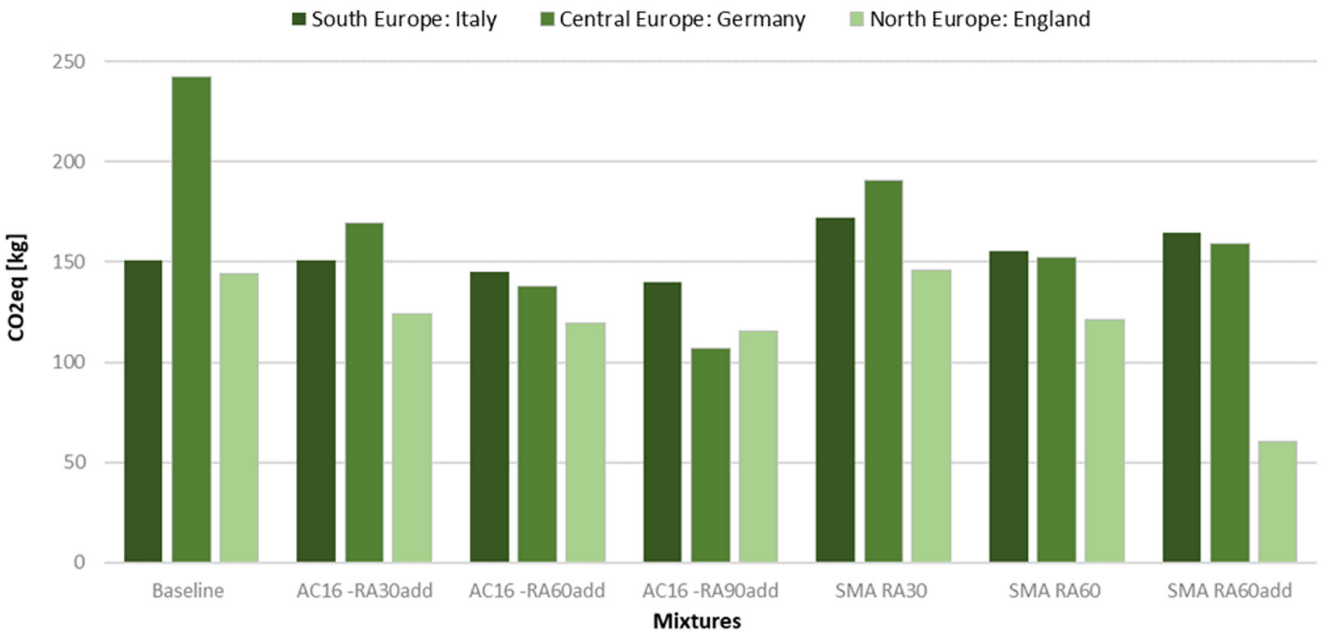

Figure 7. CO_2eq emissions due to the production and installation of one pavement course (A1–A5).

- Pavement Activities–NRAs (A1–C3)

Table 7 reports the total quantity of CO_2eq emitted throughout the analysis period (60 years) for all the interventions required. It was assumed that whenever the maintenance intervention involved binder and base courses, these mixes were considered the wearing course.

Table 7. CO_2eq emissions for all the operations required in 60 years (A1–C3).

	South Europe: Italy	Central Europe: Germany	North Europe: England
Baseline [CO_2eq]	2361	952.8	648.9
AC16-RA30add [CO_2eq]	2356	740.6	573.0
AC16-RA60add [CO_2eq]	2295	612.3	554.8
AC16-RA90add [CO_2eq]	2236	491.7	538.8
SMA RA30 [CO_2eq]	2595	822.5	656.1
SMA RA60 [CO_2eq]	2410	669.8	597.6
SMA RA60add [CO_2eq]	2512	697.2	628.3

Figure 8 shows a visible trend of reduction in CO_2eq when the amount of RA increases, demonstrating that a cradle-to-grave approach also shows good environmental performance by these mixtures.

3.2. Calculation of Economic Performance

The costs have been calculated on the basis of the data collected and following the steps described above. Tables 8–10 represent the calculations carried out considering the agency costs for a cradle-to-gate analysis (results represented in Figures A4–A6 in Appendix A.1), while Figure 9 presents the total cradle-to-gate costs over a sixty-year analysis period.

3.3. Summary of Results Amongst Case Studies

Due to the variety and number of results produced within the study, this section provides a summary of both environmental and economical assessment for each case study. With regards to the environmental performance, overall, it can be stated that using a high quantity of RA is useful to reduce emissions of CO_2eq. Nevertheless, there are some differences among the case studies.

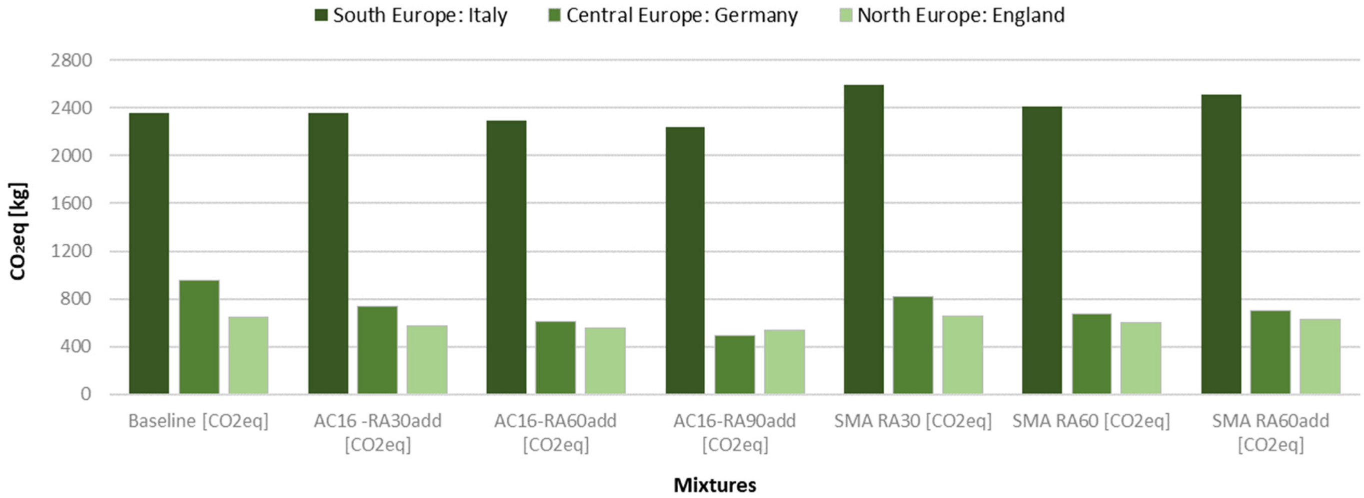

Figure 8. CO_2eq emissions for all the operations required in 60 years (A1–C3).

Table 8. SE case study: cradle-to-gate cost/ton of asphalt mixes (A1–A3).

	AC16 0% RA	AC16 30% RA + add	AC16 60% RA + add	AC16 90% RA + add	SMA 8S 30% RA	SMA 8S 60% RA	SMA 8S 60% RA + add
	€/t	€/t	€/t	€/t	€/t	€/t	€/t
Raw material acquisition	33.80	29.20	24.60	21.20	39.10	29.90	34.90
Transport to plant	0.40	0.30	0.30	0.20	0.30	0.20	0.40
Electricity	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Heating	1.18	1.30	1.30	1.30	1.30	1.30	1.30
TOTAL (€/t)	35.5	30.9	26.4	22.9	40.9	31.5	36.7

Table 9. CE case study: cradle-to-gate cost/ton of asphalt mixes (A1–A3).

	SMA 8S 0% RA	AC16 30% RA + add	AC16 60% RA + add	AC16 90% RA + add	SMA 8S 30% RA	SMA 8S 60% RA	SMA 8S 60% RA + add
	€/t	€/t	€/t	€/t	€/t	€/t	€/t
Raw material acquisition	69.1	46.7	38.5	32.7	57.0	45.0	48.7
Transport to plant	5.2	4.0	2.4	0.8	3.9	2.6	2.6
Electricity	0.136	0.136	0.136	0.136	0.136	0.136	0.136
Heating	1.18	1.30	1.30	1.30	1.30	1.30	1.30
TOTAL (€/t)	75.7	52.2	42.3	35.0	62.4	49	52.7

Table 10. NE case study: cradle-to-gate cost/ton of asphalt mixes (A1–A3).

	SMA UK 0% RA	AC16 30% RA + add	AC16 60% RA + add	AC16 90% RA + add	SMA 8S 30% RA	SMA 8S 60% RA	SMA 8S 60% RA + add
	€/t	€/t	€/t	€/t	€/t	€/t	€/t
Raw material acquisition	56.5	46.7	38.5	32.7	57.0	45.0	48.7
Transport to plant	1.2	1.3	1.3	1.3	1.2	1.2	1.3
Electricity	0.136	0.136	0.136	0.136	0.136	0.136	0.136
Heating	1.18	1.30	1.30	1.30	1.30	1.30	1.30
TOTAL (€/t)	58.9	49.4	41.2	35.5	59.7	47.6	51.4

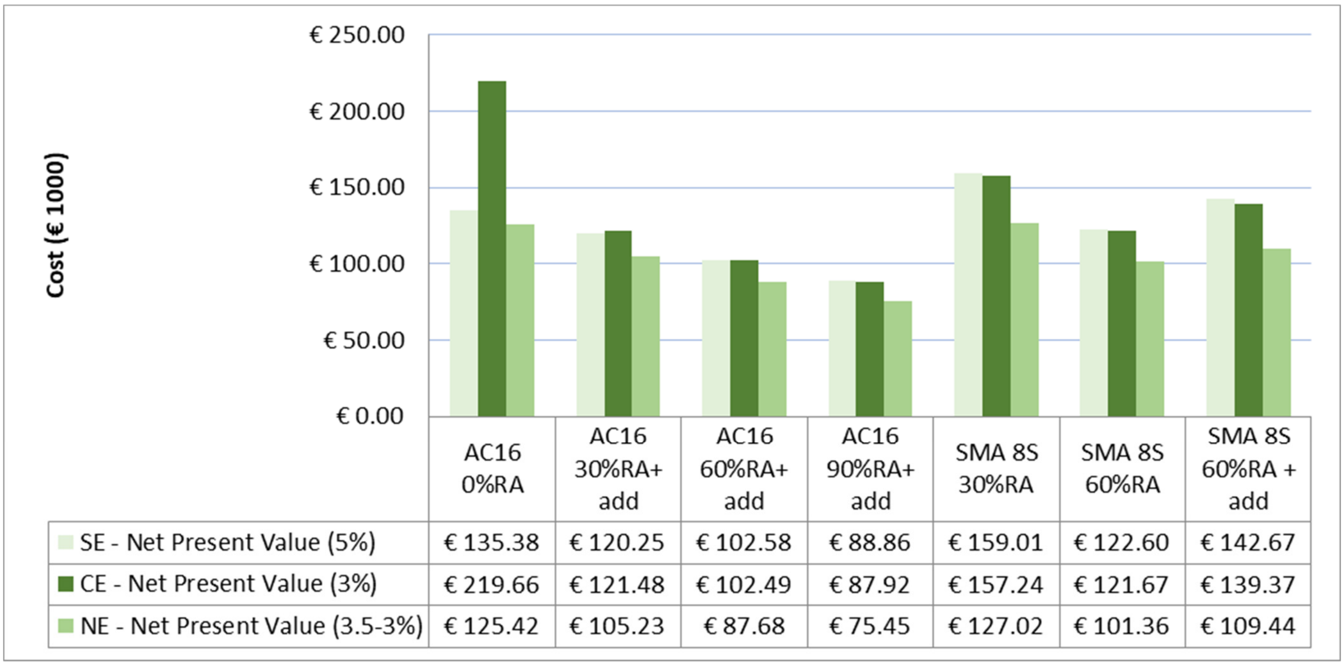

Figure 9. Economic impacts due to the production of asphalt mixture (agency costs) (A1–A3).

For material producers and contractors, it can be stated that:

- Using asphalt with RA in the CE case study provided the best results compared to the baseline (from −13.5% to −48%) because the distance of the virgin aggregate quarry from the asphalt plant was 10 times higher than the distance to the RA stockpile.
- The worst performance was recorded in Italy, where AC16 mixtures provided a reduction in CO_2eq (from −0.2% to −5.3%) while the use of SMA asphalts caused an increase in impacts (from 0.2% to 9.9%). These values can be explained because of the long distances from the plant to the site and from the site to the RA collection stockpile: on average, the distances were more than twice as high as the other cases.
- The additive used in this study allowed high recycling rates while keeping reasonable mixing and compaction temperatures. Since in all the case studies higher recycling rates enabled significantly lower transport of virgin material, overall, the additive helped indirectly lower the environmental impact.
- Considering that, for each case study, durability, maintenance strategy, and end-of-life were always assumed to be the same, the difference lies in the production phase (A1–A3). In particular, within the SE and NE case studies, using technologies and/or procedures enabling minimisation of emissions during A3 is recommended, while

minimizing these distances should provide important environmental benefits within the CE case study.

- Using SMA in the CE case study was more environmentally friendly than in the other countries because of the average shorter transport distances.

For road owners, looking at the entire life cycle, it can be stated that:

- Enhancing the durability of an asphalt course and decreasing the number of maintenance interventions is far more important than increasing the amount of recycled material incorporated in the mixtures. In fact, the best results are recorded for CE and NE case studies, where the interventions were significantly lower than in Italy (4–5 against 12).
- Incorporating high quantities of RA implies important benefits almost in each case study. Nevertheless, in Italy, where it was chosen to add polymer-modified bitumen and fibres in SMA8S, these mixes had a consequently higher footprint. It can be deduced, then, that any improvement in the lifetime of this course can bring significant benefits to the environment. Both in CE and in NE, significant improvements were recorded. In particular, in Germany, maximizing the use of RA in asphalt mixes significantly reduced carbon emissions when compared to the baseline. Additionally, in the UK, the trend was similar: up to a 15% reduction in emissions was recorded when the RA increased.

Concerning the economic aspects, it can be stated that:

- Independently of the case study, increasing the amount of RA implies significant economic benefits; when a 60–90% volume of RA is incorporated, a cost reduction between 25% and 60% is recorded.
- The production of SMA is always more expensive than the production of an AC16; this is due to the higher costs for the acquisition of raw materials used in the mixture, such as PMB, fibres, or additives.

4. Discussion and Conclusions

From the present study, it is evident that maximizing the re-use of reclaimed materials from wearing courses in European road pavement make sense both from an economic and an environmental perspective. Therefore, it is important to move towards high-content RA wearing courses, being aware that new pavement must not under-perform compared to conventional materials and that, being a key factor, the durability/reference service life of road pavement must be somehow assessed/ensured after its construction.

This was obtained through the analysis of three case studies selected and developed to be representative of European practices. Results were obtained with the main assumption that asphalt technologists are now able to engineer reclaimed asphalt mixtures with comparable performance to conventional ones. In turn, this enabled authors to consider the expected durability of wearing courses laid with high-content RA asphalt mixtures, having the same durability as wearing courses built with conventional materials (no recycling). Having this main assumption in mind, the main take away messages to consider when adapting these results to other contexts are as follows:

- Overall, maximizing the use of RA while maintaining the durability of road pavement component(s) is suitable from both an environmental and an economical perspective. This holds true regardless of the selected case studies, geographical location within Europe, traffic level, and road pavement structures.
- Concerning the environmental impact
    - In general, significant CO_2eq savings (up to almost 50%) can be observed for high-content RA asphalt mixtures when compared to the baselines. These savings derived primarily from the incorporation of a high percentage of recycled materials, as well as from average shorter transportation distances of RA compared to virgin aggregates. In fact, in Europe, the former is usually

stockpiled directly in the asphalt plant, while for the latter it is necessary to always add up emissions due to transport from quarries.

  - In all the selected case studies, the main parameter that governs the volume of emissions remains the durability. This result might be different with different values of reference service life; therefore, in order to adapt these conclusions to other case studies, the authors strongly suggest carrying out a case-by-case sensitivity analysis.
- Concerning the economic impacts:
  - LCC provided clear evidence of the economic savings due to the maximisation of the RA. In fact, the cost reduction ranged from 25 to 60% whenever the RA content ranged, respectively, from 60 to 90%.
- The adopted framework allows performing SA exercises for more informed decision-making by all stakeholders involved in the road pavement industry. It is evident that, in the current form, the framework provides estimates of economic costs and carbon footprints; therefore, the SA exercise can certainly be enriched with other environment-related impact categories. Currently, co-authors are also working towards improving the proposed approach by introducing indicators derived from social LCA.
- Durability of road pavement layers remains a main parameter for any road pavement sustainability assessment exercise; therefore, more research should focus on a detailed estimation of the reference service life of road pavements and/or each paved layer. In this sense, a collaboration between material manufacturers and pavement contractors aiming at obtaining/guaranteeing road pavement reference service lifespans is advisable as a pre-requisite within procurement practices.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviation

AADT	Average Annual Daily Traffic
AC	Asphalt Concrete
ANAS	Azienda Nazionale Autonoma delle Strade
BAST	Bundesanstalt für Straßenwesen (Federal Highway Research Institute in Germany)
BC	Binder Course
CE	Central Europe
CF	Carbon Footprint
EARN	Effects on Availability of Road Network
FHWA	Federal Highway Agency
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
LTA	RA Long-Term Aged Reclaimed Asphalt
NE	North Europe
NPV	Net Present Value
RA	Reclaimed Asphalt
RSL	Reference Service Life
PCR	Product Category Rules
PMB	Polymer Modified Bitumen
SE	South Europe
SMA	Stone Mastic Asphalt
STA RA	Short-Term Aged Reclaimed Asphalt
TUD	Technische Universität Dresden
WC	Wearing Course

Appendix A

Appendix A.1. Figures

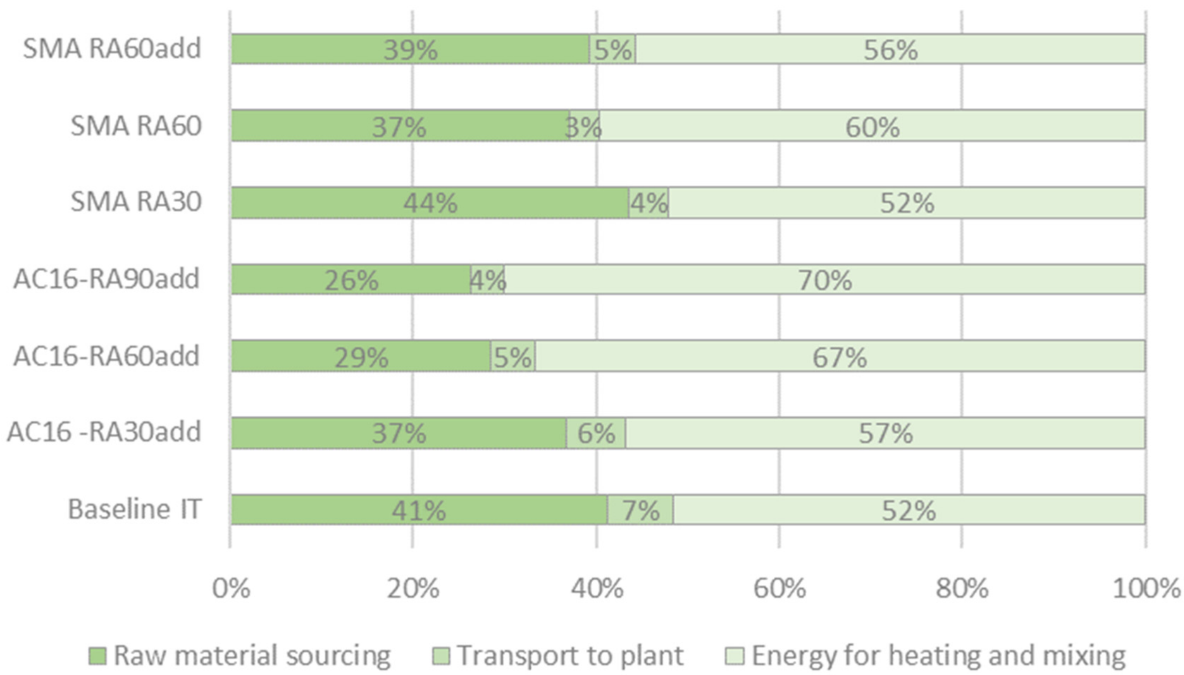

Figure A1. South Europe case study–hotspot analysis (A1–A3).

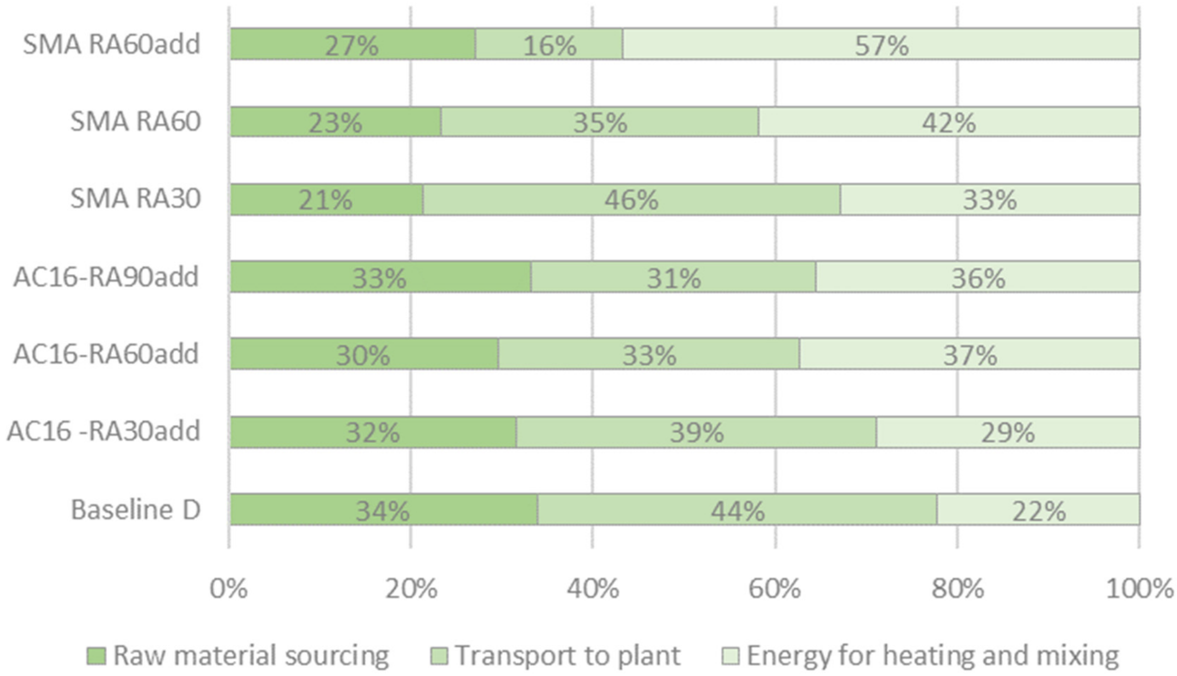

Figure A2. Central Europe case study–hotspot analysis (A1–A3).

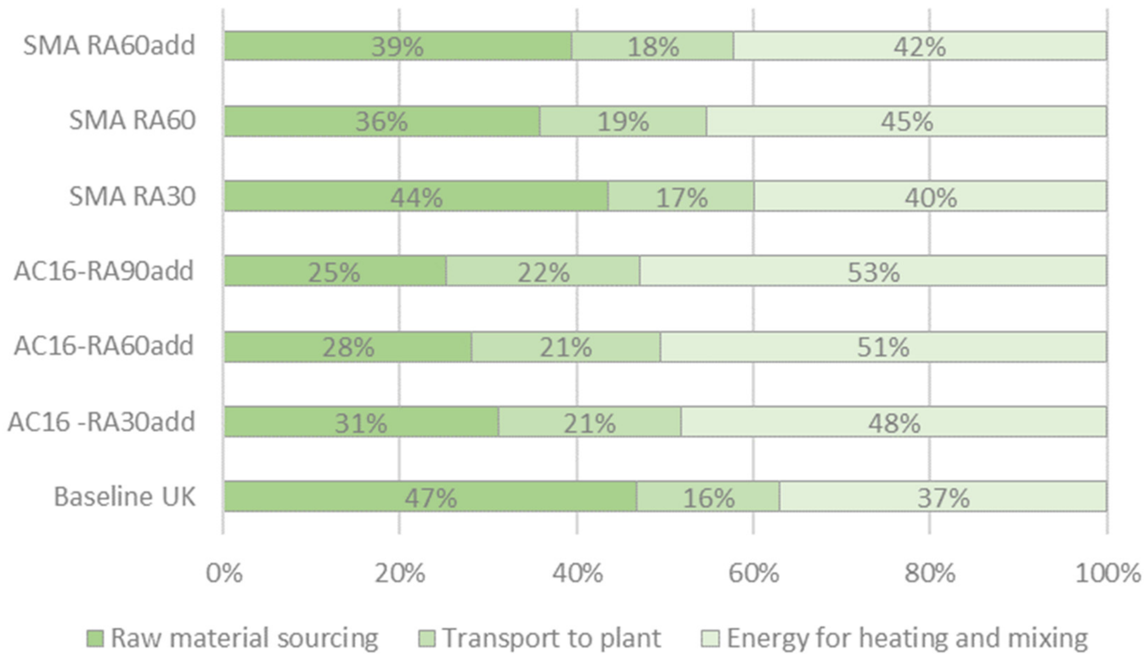

Figure A3. North Europe case study–hotspot analysis (A1–A3).

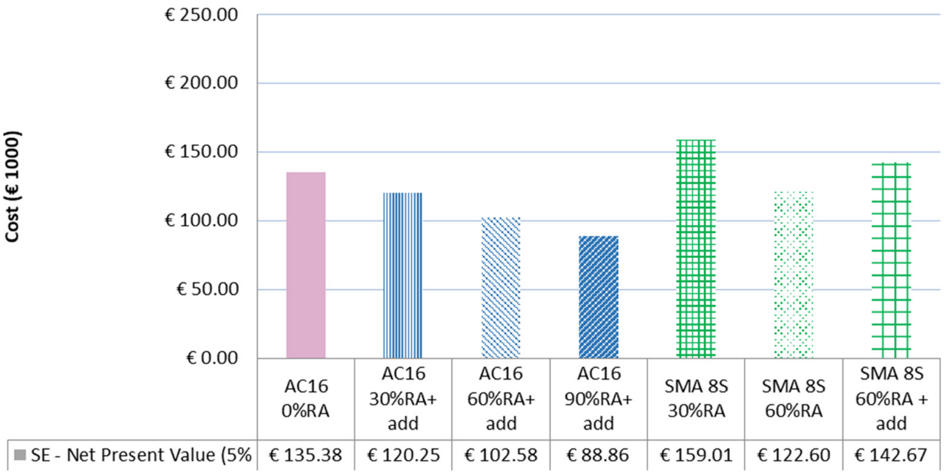

Figure A4. South Europe case study–cradle-to-gate cost of the production of the asphalt mixture (one ton) (A1–A3).

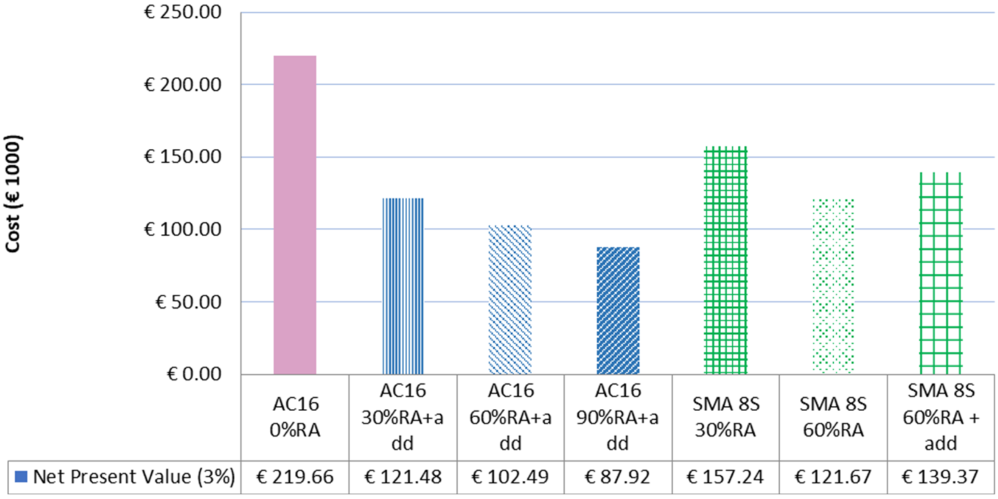

Figure A5. Central Europe case study–cradle-to-gate cost of the production of the asphalt mixture (one ton) (A1–A3).

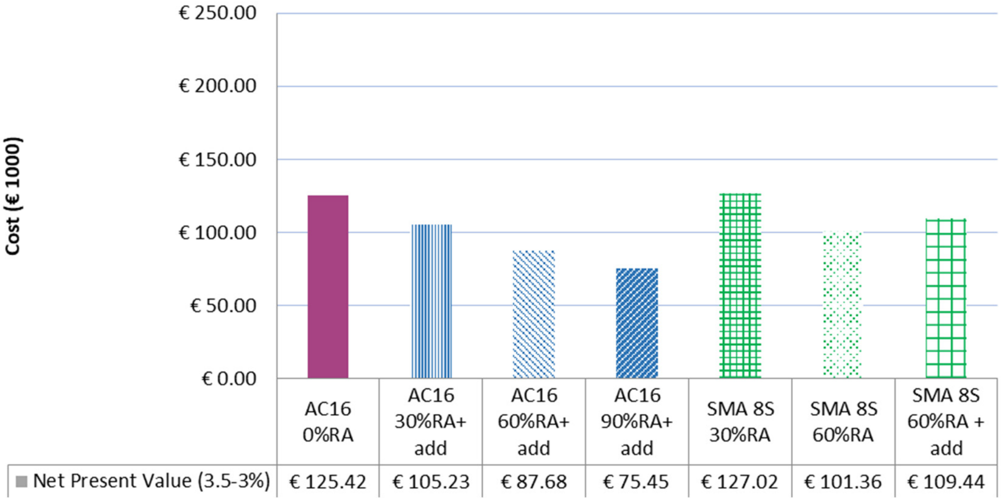

Figure A6. North Europe case study–cradle-to-gate cost of the production of the asphalt mixture (one ton) (A1–A3).

Appendix A.2. Tables

Table A1. South Europe case study: Information used to conduct the analyses.

GENERAL	
Section length	2000 m
Lane Width	Total carriageway width 9.50 m. Two lanes (3.5 m) plus shoulders (1.25 m)
Number of lanes	Dual carriageway road with two lanes
Traffic	HIGH VOLUME: 30,000 AADT vehicles/day
CURRENT PAVEMENT MATERIALS	
Mix specifications for all mixes used in the project. These should include (at the very least) aggregate type and content, asphalt content, and any modifiers used in the mix.	• Aggregate 86.9% • Filler 7% • Total binder content: 6.1% • Type of binder: Bitumen • No added fibres, additives, or modifiers
DESCRIPTION OF WORK Information about the milling, laying, and compaction processes used for each course, such as:	
Typical lift thickness used when laying each asphalt course	170 mm asphalt, 30 mm wearing course, 45 mm binder course, 100 mm base course, and 300 mm of stabilised sand with cement
TRANSPORT DISTANCES (km)	
From: Bitumen refinery/binder production To: Mixing Plant	35
From: Bitumen refinery/binder production To Work Site	233
From: Aggregate Quarry To: Mixing Plant	23
From: RA stockpile To Mixing plant	0
From: Equipment storage To Work Site	198
From: Mixing plant To Work Site	198
From: Work site To: RA Stockpile	198

Table A2. Central Europe case study: Information used to conduct the analyses.

GENERAL	
Section length	800 m
Lane Width (m)	Total carriageway width 11.80 m.
Number of lanes	Dual carriageway road with two lanes
Traffic	MEDIUM VOLUME: 20,000 AADT
CURRENT PAVEMENT MATERIALS	
Mix specifications for all mixes used in the project. These should include (at the very least) aggregate type and content, asphalt content and any modifiers used in the mix.	• Aggregate 86.2% • Filler 6.5% • Total binder content: 7% • Fibres: 0.3% • Type of binder: PMB • No additives or modifiers

Table A2. *Cont.*

DESCRIPTION OF WORK Information about the milling, laying, and compaction processes used for each course, such as:	
Typical lift thickness used when laying each asphalt course	30 mm wearing course, 80 mm binder course, 140 mm base course, unbound gravel base course 200 mm, unbound frost blanket 350 mm
TRANSPORT DISTANCES (km)	
From: Bitumen refinery To: Binder production (PMB)	29
From: binder production plant (PMB) To: Mixing Plant	189
From: Bitumen refinery/binder production To Work Site	-
From: Aggregate Quarry To: Mixing Plant	348
From: RA stockpile To Mixing plant	0
From: Equipment storage To Work Site	35
From: Mixing plant To Work Site	35
From: Work site To: RA Stockpile	35

Table A3. North Europe case study: Information used to conduct the analyses.

GENERAL	
Section length	720 m
Lane Width (m)	Total carriageway width 11 m
Number of lanes	Single carriageway with 2 lanes
Traffic	LOW VOLUME: 10,000 AADT
PAVEMENT MATERIALS	
Mix specifications for all mixes used in the project. These should include (at the very least) aggregate type and content, asphalt content and any modifiers used in the mix.	• Aggregate 92.0% • Filler 2.9% • Total binder content: 5.1% • Type of binder: Bitumen • No additives, fibres, or modifiers
DESCRIPTION OF WORK Information about the milling, laying, and compaction processes used for each course, such as:	
Typical asphalt wearing course thickness	190 mm asphalts: 40 mm wearing course, 100 mm binder course, 50 mm base course and 258 mm of stabilised sand with cement

Table A3. *Cont.*

TRANSPORT DISTANCES (km)	
From: Bitumen refinery/binder production To: Mixing Plant	160
From: Bitumen refinery/binder production To Work Site	130
From: Aggregate Quarry To: Mixing Plant	70
From: RA stockpile To Mixing plant	70
From: Equipment storage To Work Site	43
From: Mixing plant To Work Site	43
From: Work site To: RA Stockpile	56

Table A4. Data quality–parameters and emission factors for modelling.

Elements	**Source**	**Notes**
Costs	Wayman, 2014 [32], ITERCHIMICA [37], STORIMPEX [38]	Most of them were directly provided by the supplier, some of them coming from the literature
Durability	ANAS [28], BASt [29], Spray [30]	Durability should be subjected to sensitivity analysis
Discount rate	Vardakoulias, 2013 [39]	Discount rate should be subjected to sensitivity analysis (+ 1%)
Energy consumption–plant	Primary data. Temperature variations in hot and warm recycled mix collected from asphalt plant in Italy and Germany. Re-Road, 2012 [34]	Due to only slight variations in temperatures when using additives, the asphalt plant energy consumption was considered the same in all cases Heating increments should be subject to a sensitivity analysis to up 25% of increase
Laying and compacting energy consumption	asPECT v4.0 [31]	Review EARN and CEREAL outputs for relevance
Maintenance strategies	ANAS [28], BASt [29], Spray [30]	Strategies were adapted based on exchange of information with road authority engineers
Materials–additive	asPECT v4.0 [31], Mineral Products Association [38], STORIMPEX [38]	
Materials–mix recipes	ANAS [28], BASt [29], Spray [30], AllBack2Pave [27]	-
Planing energy consumption	asPECT v4.0 [31]	Review EARN and CEREAL outputs for relevance
Rolling resistance of materials in place	Reviewed published sources, no significant difference observed between asphalt with similar grading profiles	Assumed to be identical for all the considered asphalt mixes
Transport–distances	ANAS [28], BASt [29], Spray [30]	Distances should be subjected to sensitivity analysis
Transport–emission factors	[39]	-

Table A5. Case study-specific raw material transport distances to the plant (A2).

	Origins	Mode of Transport	One Way Distance (km)
South Europe–Catania, Italy			
Virgin aggregates 0.075–20 mm	Quarry	Rigid > 17 t, 20 t payload	46
Filler < 0.075 mm	Plant	-	0
RA Planings	RA stockpile	Rigid > 17 t, 20 t payload	32
Bitumen/PMB	Refinery	Rigid > 17 t, 20 t payload	215
Fibres	ITERCHIMICA Bergamo, IT	Articulated > 33 t, 24 t payload	1370
STORBIT PLUS additive	STORIMPEX Leipzig	Articulated > 33 t, 24 t payload	2250
Central Europe–Wittstock, Germany			
Virgin aggregates 0.075–20 mm	Quarry	Rigid > 17 t, 20 t payload	348
Filler < 0.075 mm	Plant	-	0
RA Planings	RA stockpile	Rigid > 17 t, 20 t payload	35
Bitumen/PMB	Refinery	Rigid > 17 t, 20 t payload	215
Fibres	Central Germany	Articulated > 33 t, 24 t payload	623
STORBIT PLUS additive	STORIMPEX Hamburg	Rigid > 17 t, 20 t payload	180
North Europe–Lincoln, UK			
Virgin aggregates 0.075–20 mm	Quarry	Rigid > 17 t, 20 t payload	70
Filler < 0.075 mm	Plant		0
RA Planings	RA stockpile	Rigid > 17 t, 20 t payload	70
Bitumen/PMB	Refinery	Rigid > 17 t, 20 t payload	160
Fibres	Central Germany	Articulated > 33 t, 24 t payload	375
STORBIT PLUS additive	STORIMPEX Hamburg	Articulated > 33 t, 24 t payload (overestimated by not including the rail freight channel tunnel)	1160

Table A6. Transport distances from plant to site (A4).

	Origin	Mode of Transport	One Way Distance (km)
South Europe–Palermo, Italy			
Asphalt mixes to site	Plant	Rigid > 17 t, 20 t payload	198
Bitumen emulsion for tack Coat	Plant	Rigid > 17 t, 20 t payload	233
Equipment	Plant	-	198
Central Europe–Wittstock, Germany			
Asphalt mixes to site	Plant	Rigid > 17 t, 20 t payload	35
Bitumen emulsion for tack Coat	-	Rigid > 17 t, 20 t payload	215
Equipment	-	-	35
North Europe–Lincoln, UK			
Asphalt mixes to site	Plant	Rigid > 17 t, 20 t payload	43
Bitumen emulsion for tack Coat	-	Rigid > 17 t, 20 t payload	160
Equipment	-	-	43

Table A7. Case study-specific excavated RA transport distances to the stockpile (C2).

Origin	Mode of Transport	One Way Distance (km)
South Europe–Palermo, Italy		
Excavated RA to stockpile	Rigid > 17 t, 20 t payload	198
Central Europe–Wittstock, Germany		
Excavated RA to stockpile	Rigid > 17 t, 20 t payload	35
North Europe–Lincoln, UK		
Excavated RA to stockpile	Rigid > 17 t, 20 t payload	56

Table A8. SE case study: cost of the asphalt mix constituents.

	Data Source	SE–IT [€/t]
Virgin aggregates 0.075–20 mm	Ferrara	10
Filler < 0.075 mm	Ferrara	10.50
RA Planings	Ferrara	4 *
Bitumen	Ferrara	400
Polymer modified bitumen	Ferrara	520
Fibres (glass) (0.90 €/Kg)	ITERCHIMICA	900
STORBIT PLUS additive	Ferrara	1350
Freight Transport (rigid > 17 t, 20 ton payload)	Ferrara	0.33

* RA cost in Italy is the cost of stockpiling and fractioning (4 €/ton). If it is considered the cost to bring the RA to landfill is 8 €/ton.

Table A9. CE and NE case study: cost of the asphalt mix constituents.

	Data Source	CE/D and NE/UK [€/t]
Virgin aggregates 0.075–20 mm	Wayman M [32]	16.75
Filler < 0.075 mm	as aggregate	16.75
RA Planings	Wayman M [32]	11.00
Bitumen	Rodriquez	650
Polymer modified bitumen	Wayman M [32]	730.87
Fibres (glass) (0.90 €/Kg)	ITERCHIMICA	900
STORBIT PLUS additive	STORIMPEX	1350
Transport–Rigid > 17 t, 20 ton payload	Wayman M [32]	1.03
Transport–Articulated > 33 t, 24 t payload	Wayman M [32]	1.03

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