Belgian Road Research Centre
Together for sustainable roads

Sustainability evaluation of asphalt mixtures

Dossier
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Content

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▶ 1 Context

1.1. Sustainability

The concept of sustainability is often explained with three pillars of sustainable development, namely the environmental, social and economic pillars (Figure 1.1). Sustainable development brings economic prosperity, is socially balanced (brings well-being) and is ecologically sustainable within the constraints of the planet we live on. It therefore means, among other things, consuming natural resources without depleting them and burdening the environment without exceeding its capacity for self-repair and without unduly disrupting natural processes. This requires economical use of finite resources and energy, less release of toxic substances to air, water and soil, and less waste generation. A development is sustainable if it is designed to continue indefinitely, not just for the present generation but for the benefit of all future generations (United Nations [UN], 1987).

Figure 1.1 – **Venn diagram** *of the three pillars of sustainability (adapted from Montanus, 2017)*

Sustainability is thus a broad concept, encompassing many aspects of our interaction with the environment (such as emissions, land use, biodiversity, energy, climate change, etc.) and also addressing social aspects of human development (meaningful work, fulfilment, safety, health, equality, etc.). This implies a broad view of human welfare, a long-term view of the consequences of our current actions, as well as social equality between generations and within the current generation.

Globally, the United Nations has further refined this theme, first through the Millennium Development Goals (period 2000-2015) and then the **Sustainable Development Goals** (SDGs, for the period 2015 – 2030) (UN, 2015). Figure 1.2 summarises the 17 categories of goals that the UN wants to work towards to make the world more sustainable by 2030. Together, this international frame of reference contains 169 economic, social and environmental goals (UN, 2020a).

Figure 1.2 – *Logos of the UN's 17 key Sustainable Development Goals (SDGS, 2022)*

Although this framework is mainly aimed at individual countries - UN member states - actions can also be taken at a lower level, and local governments, organisations, businesses or even individuals can take inspiration from it. Companies use (a selection from) these SDGs as a reference, inspiration or reporting framework to communicate to their stakeholders in an understandable way about their corporate social responsibility (CSR) efforts. This is how they try to justify their activities and impact on our living environment. They then focus on one or more of the 169 sub-objectives, namely those that best fit their activities. For their reporting, they can rely on the list of indicators prepared by the UN (UN, 2020b).

The construction industry also plays an important role in the pursuit of sustainable development. It is therefore necessary to work on a system for the sustainability assessment of construction works to provide a basis for the continuous improvement of environmental, social and economic performance. This then fits within the framework of a concrete contribution of the construction sector to achieving the United Nations' sustainable development goals.

1.2. Focus of the study

Recyclability is a major asset for asphalt. The reuse of reclaimed asphalt (RA) is associated with major benefits that are both economic and environmental. An important condition, of course, is to maintain the durability or performance of the corresponding asphalt mixtures, and this to ensure their service life. A principle here is that we reuse the materials at the end of their life - in this case of the road - while aiming for the highest added value. The deployment of RA in surface layers is a key challenge in this context. We also wish in this circularity that any depreciation or *downgrading* of RA during the recycling process is minimised. Hence, the issue of qualitatively and economically responsible handling of repeated reuse or *multiple recycling* of RA is also very topical. Specifically for asphalt where the raw material RA to be recycled has already lost a large part of its technical capabilities due to ageing processes, the use of rejuvenating agents (also called rejuvenators) can be a solution to improve recyclability or even just make it possible.

To maximise or deploy the above benefits in the context of a circular economy, it is necessary to have an objective assessment of the impact of reuse and rejuvenators on sustainability. Indeed, such an assessment allows an overall evaluation of sustainability to be made using a set of mostly quantitative indicators, which are at the environmental, economic and social level.

In this paper, we focus on sustainability evaluation in asphalt road construction, using as a case study an analysis of the sustainability of asphalt mixtures for top layers of road pavements, with and without recycling and whether or not combined with rejuvenators.

The result of a transparent evaluation also offers the road authority the opportunity to develop new forms of tendering in the future where, in addition to pricing, the aspect of sustainability is taken into account in an objective manner. This is referred to as 'green' procurement or *Green Public Procurement* (GPP) (European Commission, 2016).

BRRC – as a research centre for road construction and in line with its corporate slogan "*Together for sustainable roads*" – is also strongly committed to this topic, and has, for example, carried out a number of research projects on asphalt sustainability evaluation in recent years, in particular the EDGAR and Re-RACE projects (De Visscher et al., 2016; Vansteenkiste, 2021). The sustainability assessment detailed in this publication was part of the Re-RACE project. This used recent life cycle inventory (LCI) data of bituminous binders and rejuvenators (based on data made available by various suppliers or their federations).

Recycling activity by recovering RA as a raw material in new asphalt is driven by two main trends. On the one hand, there is the economic incentive of using cheaper-than-new raw materials in asphalt mixtures; on the other hand, there is the positive impact of RA reuse on the environment and, in particular, the reduction of the carbon footprint and counteracting scarcity of new raw materials (Vansteenkiste & Gonda, 2013). Both motivations fit perfectly into the aforementioned sustainability pillars. In a sustainability assessment of rejuvenators, the ecological and economic costs of adding the rejuvenator should be weighed against the ecological and economic benefits. If rejuvenants can have an impact on the amount of new materials/binding agent, the potential impact on this part of sustainability is clear.

1.3. Promoting sustainability through new form of procurement (*Green Public Procurement*)

In traditional tendering where only the offered cost price is decisive in the award of a work, service or product, sustainable solutions often have no chance of winning, because they are usually just more expensive than a non-sustainable variant. In that context, more sustainable solutions can only be promoted if certain elements of the sustainability analysis play a part in the award process, and are given a decisive contribution to it if necessary. We call this alternative method of procurement green or sustainable procurement (De Bock, 2021).

Contracting authorities have an important role to play in the transition to this alternative form of procurement, as the public authorities put important budgets for the procurement of products, services and works on the market, and can thus set an example for the rest of the companies in the economic chain. By writing specifications that promote and favour sustainability, it shows for all companies the direction to follow: that towards more sustainability. The international standard ISO 20400 (International Organisation for Standardisation [ISO], 2017) defines sustainable procurement as "harnessing purchasing power to maximise positive environmental, social and economic impact throughout the life cycle of products, services and works."

The importance of using an 'environmental score' is expected to gain further importance in the future, and primarily by road authorities in the context of GPP. In this context, reference can be made to the recent introduction of the CO2 performance ladder in a number of pilot projects (Scheldelaan, 2022). In an initial pilot project, the winning party – which could prove a "level 3" ambition level through certification – was given an award advantage of 3 % on the tender price (Onderhoud Scheldelaan, 2022; Scheldelaan, 2022; Stichting Klimaatvriendelijk Aanbesteden & Ondernemen, s.d.; Vlaamse Overheid, Agentschap Wegen en Verkeer [AWV], 2022).. The MKI or 'environmental cost indicator' is also an increasingly common concept in this regard, with which experience is currently being gained (from 2021 onwards) in the Netherlands (**Chapter 5**).

Belgium's approach to this is still evolving. Here the focus is rather towards a so-called "infra-TOTEM" (a version of the TOTEM-building tool adapted for road construction) (De Bock, 2020).

Or as expressed in the vision of AWV (Flemish government): "The holistic vision of environmentally conscious building in infrastructure then consists of 3 phases:

- in the design phase: choice of design options (materials, construction, execution, etc.) by evaluating the environmental impact using Infra-TOTEM;
- in procurement and implementation: CO_2 performance ladder & selection of building materials with lower environmental impact;
- on completion: As-Built calculation of real environmental impact after implementation" (De Winne, 2022).

This topic is clearly still evolving and also needs to enroll in a European framework, which is explained in more detail in a subsequent section.

2 Normative framework of sustainability assessment

2.1 Framework for the construction industry

A sustainability assessment means assessing the three pillars, which are collectively important for sustainability, especially environmental, social and economic aspects. The three pillars could possibly be defined separately, depending on the scope of the methodology.

Internationally, people have been working for many years to create a generally accepted (standards) framework to describe this sustainability analysis in a uniform way. This is done in Europe, for example, through CEN/TC 350 *Sustainability of Construction Works* and globally through ISO/TC 59/SC17 *Buildings and Civil Engineering Works*, *Sustainability* (Figure 2.1).

At the overarching level (*Framework level*, 1st row in Figure 2.1), there exists the new standard EN 15643 for the sustainability analysis of structures (buildings and civil engineering works). It integrates the previously existing five standards EN 15643-1 to EN 15643-5 (NBN 2010-2017). These covered respectively the general principles, environmental, social and economic aspects of the sustainability analysis of structures of the "buildings" type and on the other hand (in part 5) specific aspects of interest for structures of the "infrastructure works/civil engineering" type. In recent years, the revision of these standards has been carried out within CEN/TC 350 and this to transform the series of five substandards into one integrated standard, namely EN 15643 (NBN, 2021).

At project level (*Works level* in Figure 2.1), more detailed consideration is given to the situation of the structure in question, on the one hand for buildings (for residential, commercial or service activities, offices, etc.) and on the other for civil engineering works.

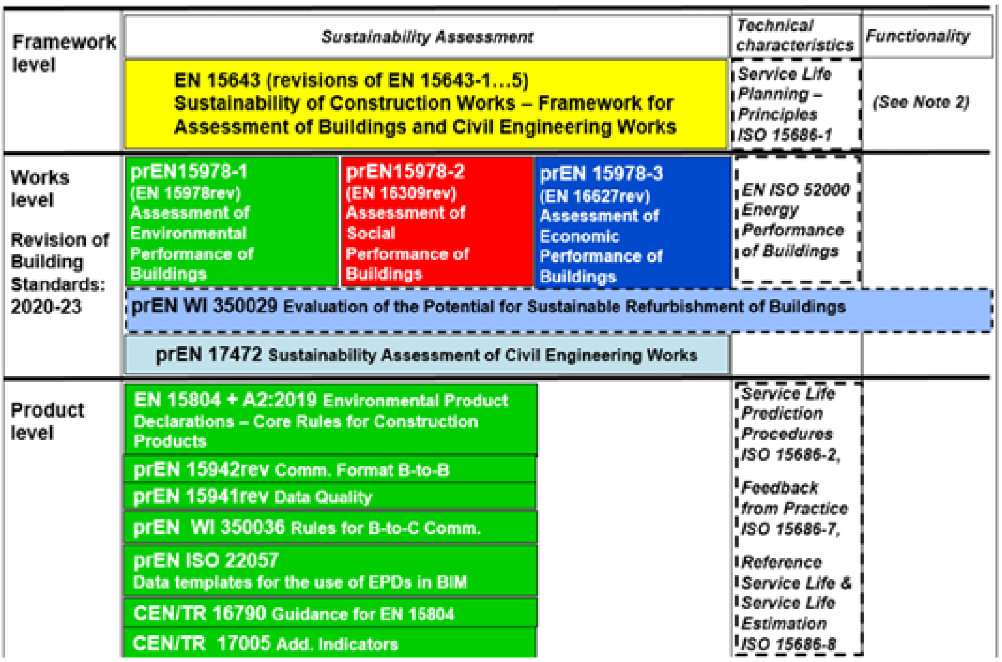

Figure 2.1 – *Coherence between standards for sustainability analysis of structures (Figure 2 – Work program of CEN/TC 350) (NBN, 2021)*

For the buildings sector, standardisation is already the most advanced: here, there are currently three different standards for assessing the sustainability of buildings (one for each pillar): EN15978rev (NBN, 2012) (environmental performance), EN16309rev (NBN, 2014) (social performance) and EN-16627rev (NBN, 2015) (economic performance). Again, CEN/TC 350 is working on a revision, and after the end of the current revision period for these standards (2020-23), these three standards will be merged into one standard consisting of three parts. Currently, these revisions are still in the draft stage: prEN 15978 (European Committee for Standardisation [CEN], 2021). At the same project level, a standard specific to infrastructure works/civil engineering has just been published (EN 17472, CEN, 2022).

At the level of individual building products (*Product level*, bottom 1st column Figure 2.1), standard EN 15804 (NBN, 2012+2019/2021) sets out the core rules for declaring the environmental performance of building products via EPDs (*Environmental Product Declarations*). Regarding the rules (PCR – *Product Category Rules*) that an EPD for asphalt materials must comply with, prEN 17392-1 (*Sustainability of construction works – Environmental product declarations – Core rules for road materials, Part 1: Bituminous Mixtures [CEN, 2020]*) due to still too many ambiguities in the draft text, no agreement for approval was reached during the consultation with the national members of CEN in June 2020.

This subject is clearly still evolving and BRRC is closely following developments, including as a member of the working groups for European standardisation (or their Belgian mirror group) such as CEN/TC 350 on *sustainability of construction works* and its subcommittee SC1 on "circular economy in the construction sector".

2.2 Assessment of a product

Evaluation methods are being developed to assess the sustainability of a product or service, and great attention is paid to the environmental pillar (and less to the economic and social pillars).

It is generally accepted that to determine (environmental) sustainability, one should apply the principle of *lifecycle thinking*. Here, all relevant aspects and effects (*impacts*) that occur over the course of the entire life cycle of a product, project, process or service, from the extraction of the basic raw materials to the waste treatment and eventual recycling phase after the end of the technical/economic life cycle, are considered.

The environmental impact is then analysed through a life cycle assessment (LCA), in which all relevant components and their input and output flows (such as energy, raw materials, land use, emissions, waste, recyclability, loss of usefulness, etc.) are analysed and calculated (Figure 2.2).

A life cycle analysis or LCA is a technique or calculation method that can be used to determine the environmental impact of a product, process or service in a reasonably uniform manner. The international standards ISO 14040 (NBN, 2006/2020a) and ISO 14044 (NBN, 2006/2020b) provide an accepted basis for how the LCA process can be carried out. In such a system, the total life cycle is represented with a division into three major phases (also called "information modules"), represented by the letters A (for the phase of raw material extraction, manufacturing of the product components, and construction at the building site), B for the (years of) use phase, and finally the letter C for the end-of-life phase (demolition and disposal of the waste materials). In addition, the letter D is used to symbolise all contributions (environmental costs and benefits) that lie outside the boundaries of the system under study (e.g. recycling of material components provides substitute savings on new raw materials for a subsequent system).

A full life cycle analysis covers all phases/information modules in the life cycle, including circularity, and is named *cradle-to-cradle*. In partial analysis, one is more likely to speak of from-cradle-to-gate, phases A1 to A3) or from-cradle-to-grave, phases A, B and C). For the system "asphalt road", an example of a system diagram then looks as shown in Figure 2.3.

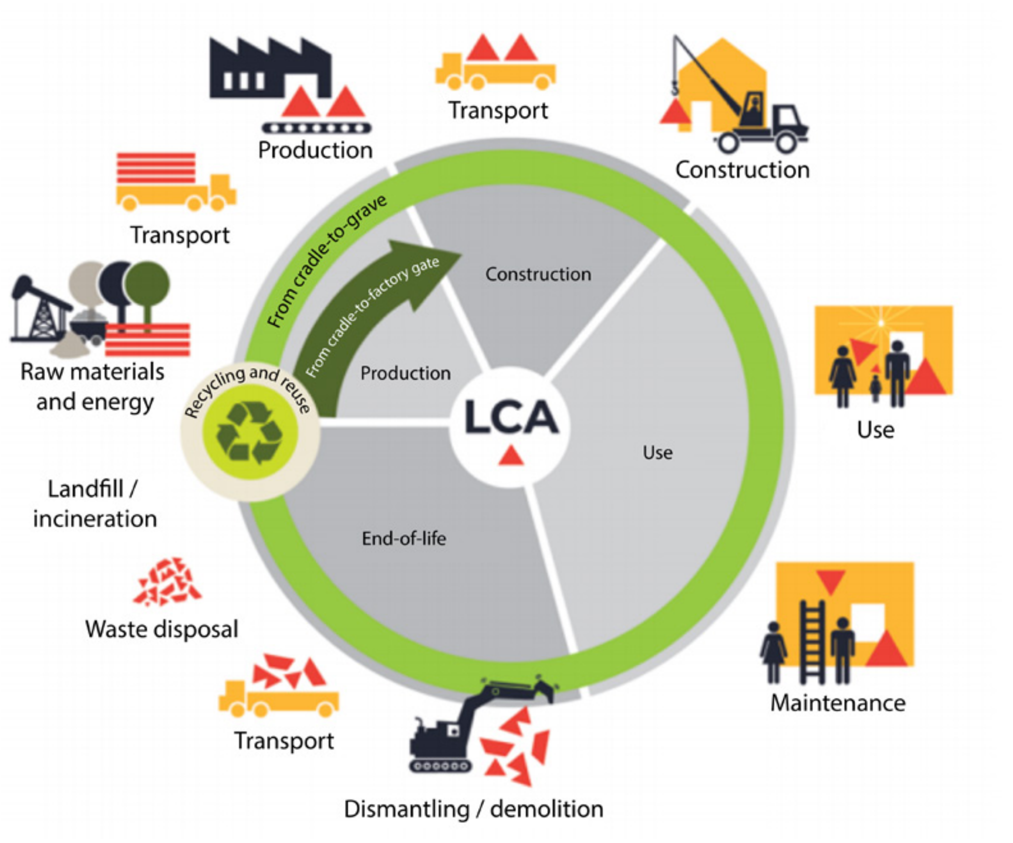

Figure 2.2 – *Life cycle analysis in construction (Source: Totem, 2018)*

It starts with the determination of a functional unit (exactly what is to be studied as a system, what should it do and what are the alternatives) and the delineation of system boundaries (what is included, what is not). From this follows a flow diagram of the process or product. Next, the inventory phase (LCIA = *Life Cycle Inventory Analysis*) finds out what raw materials and energy are used or consumed on the input side, what transformations take place and finally what wastes or emissions are generated on the output side, and this for each functional unit. Characterisation factors can then be used to convert quantities of materials and energy into certain categories of effects or impacts. These impacts are classified into certain relevant groups, such as contribution to climate change, contribution to acidification, etc.

Data of primary origin are preferably used for the inventory study. These are measured values from at the production site (such as the asphalt mixing plant) itself. If this is not possible, secondary data is used (e.g. for the transformation of raw materials such as petroleum, or for ready-to-use consumables for which a proprietary EPD is available). This study relied on the calculation method recommended in EN 17472 (CEN, 2022), which basically amounts to an aggregation of elementary matrix calculations, across all life stages (modules A, B, C and/or D). For each life stage (or module) i, a matrix calculation is done where the matrix for all material components contains the contribution of a given environmental indicator for that material component at that stage.

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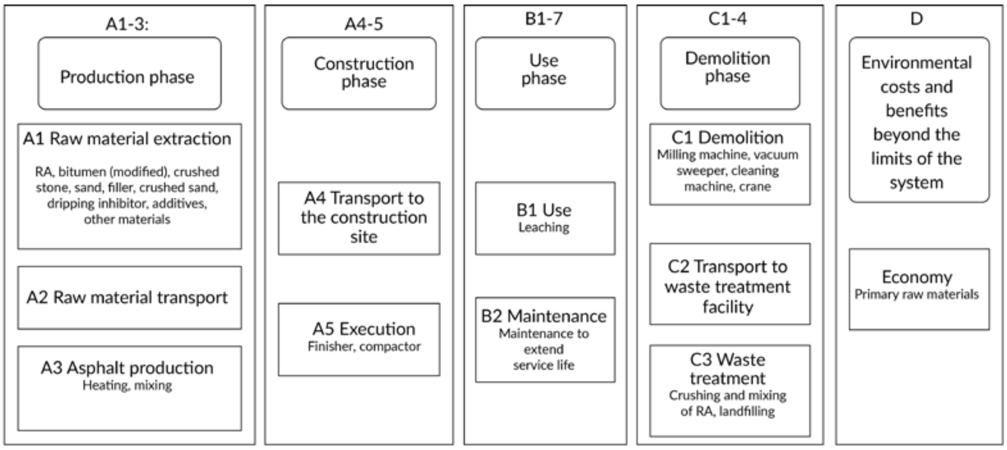

Figure 2.3 – *Example of a system diagram showing life cycle of an asphalt mixture and its associated information modules A/B/C/D (adapted from van der Kruk et al., 2022))*

3 Sustainability analysis – Method of approach

As can be seen from the discussion of the normative framework above, it is not yet clear how an analysis of the sustainability of a product, process or structure should be approached in concrete terms. This topic is still evolving.

Meanwhile, some proposals of more elaborate methodologies exist, for example:

- the SEVE method (used in France);
- the MKI method (environmental cost indicator, used in the Netherlands);
- the methodology based on the EDGAR project, which we outline further in this publication.

Here, we briefly discuss the approach of the other two methods (SEVE and MKI), before we will elaborate on the EDGAR method that we will continue to use in this paper.

3.1 SEVE

SEVE is the abbreviation of *Système d'Evaluation des Variantes Environnementales*, and is a calculation method (software, *éco-comparateur*) developed on behalf of the federation of the road construction industry in France (Routes de France). SEVE's objective is to be able to compare different road construction solutions or road maintenance schemes on a number of indicators. SEVE uses nine indicators, as summarised in Figure 3.1.

These include two qualitative or explanatory indicators (management of water and taking biodiversity into account) and seven quantitative indicators (energy consumption (in MJ), greenhouse gas emissions (in tonnes of CO_2 equivalents), amount of transport (in tonne-kilometres) and protection of natural resources (four components, in tonnes: consumption of aggregates of natural stone aggregate, consumption of reclaimed asphalt, application of recycled materials, amount of excavated soil reused on site)). SEVE results in a score for each of the nine indicators, without balancing each of them into an overall score.

Figure 3.1 – *The indicators of the SEVE software (Eco comparateur/SEVE, s.d.)*

3.2 MKI

MKI (in Dutch language) is the abbreviation of environmental cost indicator. It is an indicator linked to the costs associated with the environmental damage associated with a particular product or system and a way of aggregating results from different environmental indicators into a single indicator.

The MKI method applies monetisation to environmental impacts: environmental impacts are converted from an abstract unit (different for the various environmental impacts) to a comparable unit, namely a monetary value. It is a way of quantifying the results of different potential environmental impacts in a single score, in order to easily compare variants. It relies on the result of a full life cycle assessment (LCA) with 11 different indicators (in line with the Dutch interpretation of the first version of the European standard EN 15804 [NBN, 2012+2019/2021]). These different indicators are weighted by attaching a monetary weighting factor to each indicator and summing them to a single indicator expressed in a monetary value (euros).

The 11 environmental indicators (eight + three related to ecotoxicity) of the LCA integrating the MKI are:

- ✓ depletion of abiotic resources (excluding fossil energy carriers);
- ✓ depletion of fossil fuels;
- ✓ climate change;

- ✓ ozone layer depletion;
- ✓ photochemical oxidant formation;
- ✓ acidification;
- ✓ eutrophication;
- ✓ human toxicity;
- ✓ ecotoxicity: freshwater environment, marine environment and terrestrial environment.

The Belgian TOTEM method works in a similar way to the Dutch method of MKI: via monetisation and linking to weighting factors, the results of an LCA (consisting of several impacts or indicators with mutually different units) are combined into a single result expressed in the same (monetary) unit.

Two main points of difference between MKI and TOTEM do exist: on the one hand, the weighting factors differ (in terms of the size of the monetary value per impact, being the assumed shadow costs / environmental damage factors per unit of LCA impact), and on the other hand, the number of indicators is different (11 LCA indicators in the Dutch model (based on the first version of the standard EN15804), and 17 in the Belgian model (based on the second version of the standard EN15804) (NBN, 2012+2019/2021)).

Currently, the TOTEM tool only works for building-type structures (housing, offices and other non-residential buildings) and not yet for infrastructure works such as roads, but this is an expansion track with a lot of potential (De Bock, 2020; De Winne, 2022).

For more info on the MKI methodology, see chapter V and **Annex 4**.

3.3 EDGAR

For sustainability, both the SEVE and MKI methods only consider the environmental pillar and do not include indicators for the economic or social pillar.

Therefore, BRRC itself started looking for a suitable approach, which it has developed through the EDGAR (*Evaluation and Decision process for Greener Asphalt Roads*) project. In that research project commissioned by CEDR, BRRC, in collaboration with European partners, built up experience and knowledge and developed a methodology to perform a sustainability assessment of a material and/or (production) process specifically for asphalt (Anastasio et al., 2016; De Visscher et al., 2016; Wayman et al., 2016).

Feedback received from the accompanying steering committee and consultation with relevant stakeholders from road management practice have confirmed the methodology's deployability in practice.

The EDGAR approach uses a limited number of indicators relevant to asphalt roads (Table 3.1). This set of 11 indicators is less comprehensive than the full set of LCA impact categories, but an attempt has been made to integrate as many aspects as possible in a limited set for practical and clear reasons.

These include five indicators related to the environmental pillar (climate change, resource scarcity, recyclability, air pollution and leaching), two indicators related to technical performance (skid resistance and long-term technical suitability), one indicator related to the economic pillar (financial cost) and three parameters linked to both the social and environmental pillars (noise pollution, traffic congestion and responsible purchasing policy).

Impact / Indicator	Description
Climate change	the contribution to global warming from greenhouse gas emissions
Depletion of abiotic resources	the contribution to the depletion of non-renewable primary raw materials
Air pollution	the contribution to air pollution (acidifying emissions and smog)
Leaching	the potential for leaching of harmful chemical substances to soil and groundwater
Noise pollution	noise production due to tyre-road interaction
Recyclability	the evaluation of the future recyclability of the asphalt when the end of the service life will have been reached
Skid resistance	roughness determined by the surface characteristics of the asphalt, as an essential indicator of road safety (relevant for surface layers)
Responsible purchasing	evaluates the responsibility for social and environmental impacts in the purchasing process, by all actors in the production process
Cost	the financial cost over the entire life cycle (construction, maintenance milling and recycling)
Traffic congestion	the evaluation of the impact of construction and maintenance (as a function of technology) on road user mobility
Performance, technical durability	combination of performance indicators (fatigue and rutting resistanceresistance, water sensitivity) related to expected service life

Table 3.1 – *Set of sustainability indicators (EDGAR methodology)*

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4 Analysis by EDGAR method

In this section, we aim to illustrate the approach of the EDGAR method by concretely working out this method for a well-defined type of asphalt mixture.

4.1 Selected asphalt variants

This evaluation was carried out on a number of variants of asphalt mixtures intended for use as surface layers in road pavements, specifically of the AC10 surf mixture type, combining recycled RA with or without the addition of a rejuvenating agent.

The impact of RA recycling was evaluated by including variants with a relatively low recycling rate (20 %) on the one hand and a relatively high RA content (50 %) on the other hand. Consequently, the following five variants were compared:

- a classic asphalt mixture for top layer pavement focusing on an AC10 surf mixture (= reference);
- AC10 surf mixture with 20 % RA without rejuvenator;
- AC10 surf mixture with 20 % RA and with rejuvenator;
- AC10 surf mixture with 50 % RA without rejuvenator;
- AC10 surf mixture with 50 % RA and with rejuvenator.

The high recycling rate of 50 % in surface layers is not yet a reality in the practice of asphalt road construction (it is in mixtures for base layers), but is included here because it reinforces the differences in the comparison and thus highlights the future potential for more sustainable mixtures.

In this comparison, the AC10 surf mixtures were formulated so that all variants are fully comparable in terms of binder and mineral skeleton ratio: same total binder content (new bitumen + old binder from RA) as well as equal particle size distribution for the mineral aggregates (including those from the RA). A similar exercise can also be made for other types of asphalt for surface layers, e.g. type AC10 surf. This shows that the final results differ little from the current exercise, as these mixture types are quite similar in composition. The five variant AC10 surf mixture compositions are summarised in Table 4.1.

All AC10 surf mixtures include 59 kg of binder and 941 kg of mineral constituents per tonne of asphalt. The dosage of the rejuvenator was experimentally optimised to a ratio of 3.5 % of the mass of the old binder in the RA (Vansteenkiste, 2019).

In this calculation, it was assumed for simplification purposes that new bitumen and rejuvenator can be replaced in a one-to-one basis. For the variant with 50 % RA (which, in the case without rejuvenator, contains 26.4 kg of old bitumen per tonne of asphalt in addition to 32.6 kg of new bitumen), this dosage amounts to 0.92 kg of rejuvenator. In this case, the dosage of new bitumen is reduced by about 1 kg.

Composition AC10 surf mixture	Reference	With 20 % RA recycling		With 50 % RA recycling	
		Without rejuvenator	With rejuvenator	Without rejuvenator	With rejuvenator
Crushed stones	565	485	485	367	367
Broken sand	245	188	188	85	85
Round sand	56	33	33	14	14
Added mineral filler	75	47	47	5	5
Recovered minerals in RA	-	188	188	471	471
Recovered binder in RA	-	11	11	26	26
Bitumen (50/70)	59	48	48	33	32
Rejuvenator			0,4		1
Total	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**

Table 4.1 – *Overview of the mixture compositions of the AC10 surf mixture variants evaluated in the sustainability study (all quantities in kg per tonne of asphalt)*

4.2 Sustainability analysis – Calculation and results

For each parameter (indicator of potential environmental impact), an analysis was made according to the EDGAR methodology, focusing on the contribution of RA reuse, whether or not combined with rejuvenators.

4.2.1 Climate change (global warming potential)

Greenhouse gas (GHG) emissions are a good indicator of the contribution to the climate change problem. This impact on our global ecosystem is represented through the *Global W* arming Potential or GWP, and expressed as a mass of CO_2 equivalents (in kg).

So, the studied system comprises an asphalt surface layer. Calculating the impact of the entire system can be done by first taking an inventory on the input side of the materials used/consumed, and then multiplying for each material type the quantity used (mass) by the corresponding conversion factor, and summing across all material types according to the formula:

GHG emission total = **Σ** (across all material types j) **mass** $_j$ **x EF** $_{j,}$ **(Formula 1**)
with EF $_j$ the **emission factor** (for GHG) for material j expressed in kg CO_2-eq.
per unit mass.

Thus, to calculate the GWP contribution for a product or process, in the present case an asphalt mixture with a given mixture composition, a calculation must be made over the whole of all modules in the life cycle (or just the ones that seem most relevant to us or about which we have reliable information) by making the product of the row matrix of all material-specific emission factors with the column matrix of all corresponding material quantities in the asphalt mixture.

4.2.1.1 Module A1 (extraction of materials)

The first step was to calculate the contribution to climate change (as GWP value) caused by making available all the materials needed to produce the asphalt mixture. So that includes only the extraction and basic processing of raw materials from their extraction site to the gate of the manufacturer, who then offers the raw material commercially on the market. In the life-cycle approach, this corresponds to module A1 (Figure 2.3).

Assuming the mass composition of the asphalt mixtures included in this equation, the GWP conversion factors are thus needed for the following materials: coarse aggregates (crushed stone), fine aggregates (crushed sand and/or round sand), supply filler, road bitumen, RA and the rejuvenator.

Here we can note that different sources or databases can be used for this purpose, sometimes differing significantly from each other. We refer to **Annex 1** for more details on the data sources and their influence on the (variation and spread of the) emission factors in the calculation method. For bitumen, for example, the two sources from Eurobitume on the one hand and the US *Asphalt Institute* on the other give as a result a global warming emission factor (GWP) that differs from each other by a factor of 3! In contrast, for the material fraction 'aggregates', the variation in emission factors is rather small.

The collection of the unit emission factors further used in this study for the environmental indicator GWP for the set of raw materials is summarised in Table 4.2.

	Crushed stone	Sand	Filler	RA	Bitumen	Rejuvenator
Emission factor (GWP_i) (kg CO_2-eq/tonne)	4.3	3.0	32	1.5	208	- 1,220

Table 4.2 – *Unit emission factors of raw materials for the GWP (climate change) parameter*

In this table, the very large number with a negative value for the rejuvenator component stands out, namely minus 1,220 kg CO_2-eq per tonne, as revealed by the supplier's LCI sheet (KRATON Corporation, 2018; University of Antwerp & BRRC, 2021. The negative figure has to do with the origin of the rejuvenator. It is an oil of vegetal origin (this is called bio-based or bio-sourced material), produced in a biorefinery from CTO (*crude tall oil*) - a by-product from a pine processing process to produce cellulose fibres for paper (pulp). During their natural growth, trees extract CO_2 from the atmosphere (and therefore this is counted in as a negative number) and store that carbon in the wood structure. This CO_2 is called biogenic CO_2.

These data clearly show that per unit mass, especially the rejuvenator (negative value) and bitumen and, to a lesser extent, filler have significantly higher emission factors compared to aggregates (sand and crushed stone score similar emission factors).

Then, for each of the asphalt mixture variants to be compared, the GWP value was calculated by multiplying the row matrix for the emission factors with the column matrix of the mixture composition in accordance with Formula 1. Table 4.3 shows the results for the five asphalt mixture compositions. Figure 4.1 illustrates this graphically, broken down by variant and primary resource component.

The reference mixture (without recycling) shows a contribution to global warming potential per tonne of asphalt, of 18 kg CO_2 equivalent.

		20 % RA		**50 % RA**	
GWP score *(module A1 only)* **in kg CO2-eq per tonne of asphalt**	**Reference (no RA)**	Without rejuvenator	With rejuvenator	Without rejuvenator	With rejuvenator
Crushed stones	2.45	2.11	2.11	1.60	1.60
Sand	0.88	0.65	0.65	0.29	0.29
Filler	2.41	1.51	1.51	0.15	0.15
RA	-	0.30	0.30	0.75	0.75
New bitumen B50/70	12.2	10.1	10.0	6.8	6.6
Rejuvenator	-	-	- 0,45	-	-1.13
Total	**18.0**	**14.6**	**14.1**	**9.6**	**8.2**

Table 4.3 – *Climate change potential or GWP score (Module A1) for the five asphalt mixture variants and by raw material component*

Sustainability evaluation of asphalt mixtures

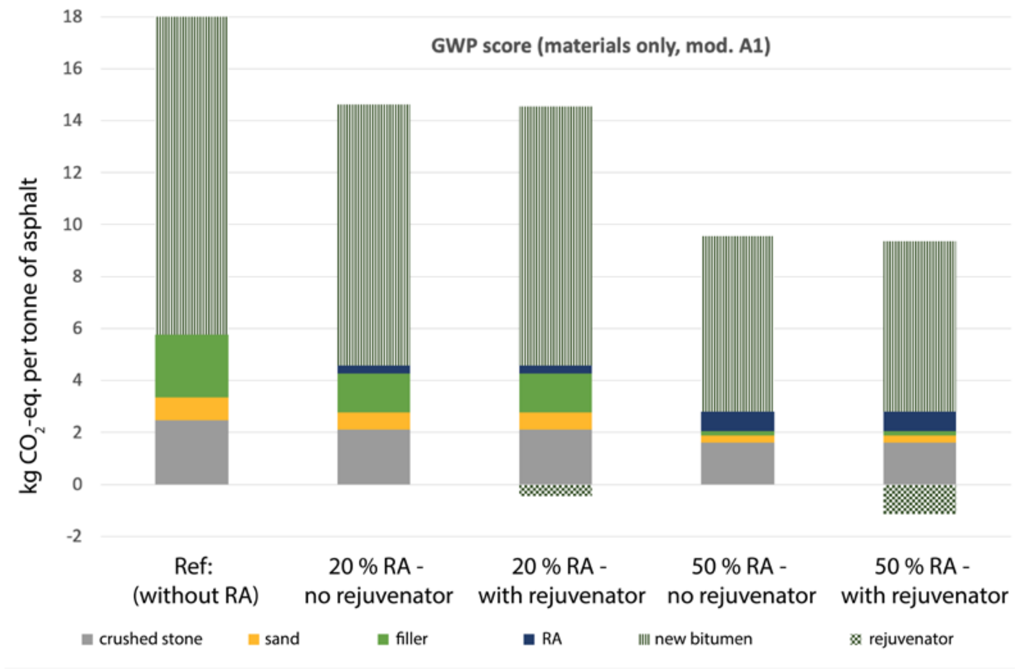


Figure 4.1 – *Climate change potential (module A1 section only) for the five asphalt mixtures, broken down by raw material component*

Furthermore, these results show the large gain in terms of climate score (for the module A1 section) that can be achieved by recycling RA (enhanced when using the *bio-based* rejuvenator): the asphalt mixture with 20 % RA has a 19 % (without rejuvenator) to 22 % (with rejuvenator) better (lower) material-specific GWP score than the reference mixture. The asphalt mixture with 50 % RA increases that gain to a score that is 47 % (without rejuvenator) to 55 % (with rejuvenator) lower than the reference.

The biggest contribution to this improvement is obtained firstly from lower (fresh) bitumen consumption and secondly from lower filler consumption.

The *bio-based* rejuvenator proportionally improves the GWP score due to its individual negative emission factor. However, the latter observation may change if a different type of rejuvenator were to be used, e.g. petroleum-based. Then, for resource extraction, there will not be a negative number for the climate change parameter, but a positive value (i.e. a worse score for greenhouse gas emissions). This is the case, for example, for rejuvenators type aromatic oil fractions and naphthenic oils from crude oil/petrochemicals (De Bock et al., 2020).

Usually, these rejuvenators are new products that are highly protected as business innovations. Thus, few details are known regarding its exact composition and environmental profile. In this respect, data uncertainty or unavailability is certainly a barrier to assessing its sustainability. Thus, for the various rejuvenators already on the market, we could not find officially published data on their environmental profile, and certainly not in the form of an EPD sheet. The unavailability of (environmental) data means that the calculations could not be made for this type of rejuvenators.

4.2.1.2 Module A2 (transport supply of asphalt raw materials)

A second step in calculating the contribution to climate change concerns the contribution caused by the transport of raw materials to the asphalt mixing plant. This involves what is referred to as "information module A2" in the life cycle of the asphalt product.

This calculation often can no longer rely on available data (e.g. from EPDs of individual commodities), but has to work with generic data and certain assumptions on how this transport takes place and what distance has to be covered.

The details for these assumptions are summarised in table 4.4, as well as (on the last row) the emission factor for greenhouse gas emissions per tonne of the respective feedstock calculated from them. The average transport distances and choice of corresponding means of transport for each commodity (1st and 2nd rows in the table) are own estimates. As a data source for the emission factors of the different transport modes, we use these from the website **www.co2emissiefactoren.be** (cf. section page on goods transport, based on Klein et al., 2021). If more specific data were available (e.g. because the exact transport distances and fuel consumption are known), it would be best to use them.

Raw material ▶	**Crushed stones**	**Broken sand**	**Natural sand**	**Filler**	**RA**	**Bitumen**	**Rejuvenator**	
Assumed average transport distance (km)	75	75	250	150	50	100	1,000	100
Transport	truck (tractor-trailer heavy; 29 tonnes bulk cargo)		barge (Kempenaar, 1,600 tonnes of bulk cargo)	truck (tractor-trailer heavy; 29 tonnes of bulk cargo)			ocean-going vessel (coastal shipping, containerised cargo 20 tonnes)	truck (tractor-trailer heavy; (20-tonne container)
Emission factor of the transport device (kg CO_2-eq per tonne.km)	0.088	0.088	0.042	0.088	0.088	0.088	0.032	0.121
Emissions per landing per tonne (kg CO_2.eq.)	6.6	6.6	10.5	13.2	4.4	8.8	32	12.1

Table 4.4 – *Scenarios and emission factors for module A2 (transport of raw materials to the asphalt mixing plant) for the different raw materials*

In the same way as in module A1 (see **Formula 1**), we calculate the contribution from transport in terms of CO_2 emissions per asphalt mixture. We do this by multiplying the row matrix of the emission factors (bottom row of Table 4.4) by the column matrix of the mass composition of each asphalt mixture (columns in Table 3.1). The results are shown by asphalt composition in Table 4.5, including the breakdown by material component.

GWP score *(module A2)* in kg CO_2-eq per tonne of asphalt	Reference (no RA)	20 % RA		50 % RA	
		Without rejuvenator	With rejuvenator	Without rejuvenator	With rejuvenator
Crushed stones	3.7	3.2	3.2	2.4	2.4
Broken sand	1.6	1.2	1.2	0.56	0.56
Natural sand	0.59	0.35	0.35	0.15	0.15
Filler	1.0	0.62	0.62	0.06	0.06
RA	-	0.87	0.87	2.2	2.2
New bitumen 50/70	0.52	0.43	0.42	0.29	0.29
Rejuvenator	-	-	0.02	-	0.04
Total	**7.4**	**6.7**	**6.7**	**5.7**	**5.7**

Table 4.5 – *Transport emissions (module A2) in kg CO_2-eq. per tonne of asphalt for the different components of the five AC10 surf mixture variants*

Transporting the raw materials for the reference asphalt mix, from their extraction site to the asphalt mixing plant, contributes 7.4 kg CO_2 equivalents per tonne of asphalt to the global warming potential. Rather, the differences between the five asphalt mixtures can be considered limited: a 10 % lower transport emission for the two mixtures with 20 % RA recycling and a 23 % lower transport emission for the mixtures with 50 % recycling, with a very minor contribution due to the application of a rejuvenator.

4.2.1.3 Module A3 (production of asphalt)

Module A3 in the life cycle refers to the activities at the asphalt mixing plant itself, namely the production of asphalt mixtures starting from the mineral raw materials, bitumen and (possibly) additives. In particular, this module A3 calculates the GWP score (of greenhouse gas emissions) directly associated with the energy consumption of the machinery and various parts of the asphalt production plants. This mainly concerns the natural gas or fuel oil consumption for the drying drum (drying and heating the stones and sand), the electricity needed in the heating of bitumen and the electric motors of the mixing plant (such as mixer, conveyors, fans and pumps, weighing equipment, etc.) and the diesel for the loading shovel motor.

See **Annex 3** for more details of this calculation, which shows that the asphalt production processes at the asphalt mixing plant itself generate around 23 to 24 kg of CO_2 emissions per tonne of asphalt.

Whether or not RA recycling is used affects the energy requirement in asphalt production. The latter relies on about 10 % higher energy (gas) consumption at the high recycling rate of 50 % RA compared to no RA application. A value of 23 kg CO_2-eq. is therefore further calculated for an AC10 surf mixture without recycling, and a value of 24 kg CO_2-eq. per tonne of asphalt for a low recycling ratio (20 % RA). Finally, a greenhouse gas emission value of 25.3 kg CO_2-eq. per tonne of asphalt is used when producing an asphalt mixture with high recycling ratio (50 % RA).

4.2.1.4 Sum of modules A1, A2 and A3

Bringing together 'from cradle to factory gate' the 3 modules A1 to A3 (extraction of the raw materials, transport to the asphalt mixing plant and production of the asphalt) gives the result as presented in Figure 4.2 and Table 4.6.

GWP score (kg CO_2-eq.) per tonne of asphalt	**Reference (without RA)**	**20 % RA - no rejuvenator**	**20 % RA - with rejuvenator**	**50 % RA - no rejuvenator**	**50 % RA - with rejuvenator**
From resource extraction	18.0	14.6	14.1	9.6	8.2
From transporting raw materials to asphalt mixing plant	7.4	6.7	6.7	5.7	5.7
From asphalt production	23	24	24	25	25
Total (A1 + A2 + A3)	**48**	**45**	**45**	**41**	**39**
Relative to the reference mixture without recycling	100 %	94 %	93 %	84 %	81 %

Table 4.6 – *Scores for contribution to climate change (for modules A1 to A3) for the five asphalt mixture variants*

For the whole of the first three modules of the life cycle (A1, A2 and A3), the reference AC10 surf mixture makes a potential contribution to global warming of about 48 kg CO_2 equivalent per tonne of asphalt (being the sum of 18 + 7 + 23 kg for the three respective modules). Recycling RA, with or without the addition of a rejuvenator, has a positive impact on environmental performance in terms of the GWP score (measure of climate change). An increasing recycling ratio from 20 % to 50 % RA in the mineral aggregate results in an improvement of 6 to 7 % and 16 to 18 %, respectively, with the biggest gain each time for AC10 surf mixture blends to which a rejuvenator was also added. This is because the addition of this rejuvenator makes only a negligible contribution in terms of additional transport and energy consumption, but does help reduce carbon intensity due to its biogenic carbon footprint in raw material extraction (with a negative GWP value for the bio-based product).

Sustainability evaluation of asphalt mixtures

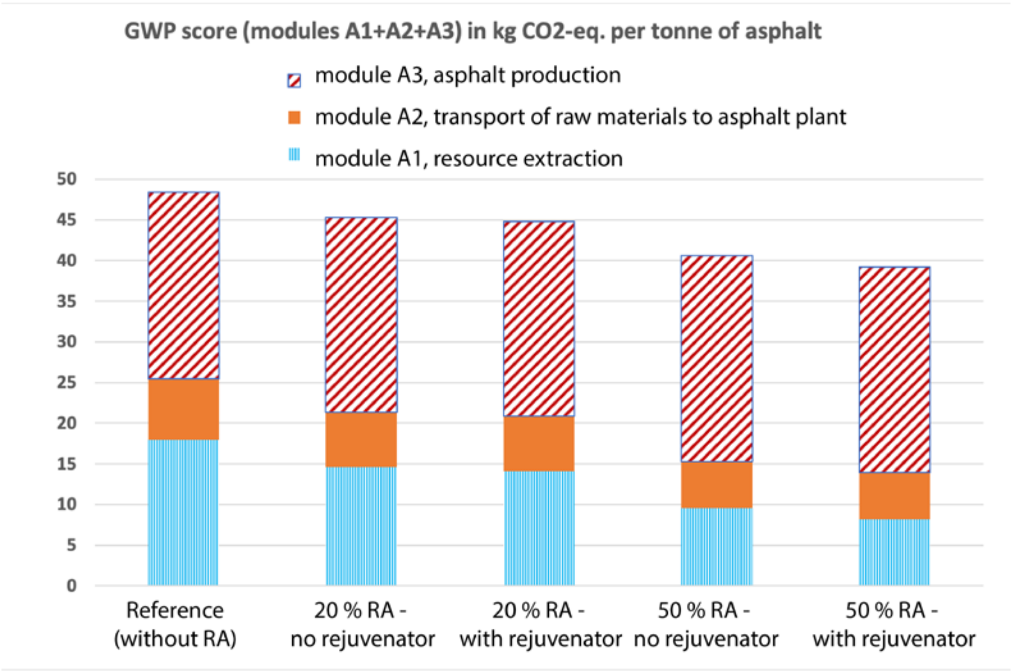


Figure 4.2 – *GWP scores for contribution to climate change (for modules A1 to A3) for the five AC10 surf mixture variants*

For the other modules in the life cycle of the asphalt road (modules B, C and D), which come after the asphalt production phase (transport to the construction site, laying of the asphalt mixture on the road, use of the asphalt road and, finally, the scenarios for the possibilities in the end-of-life phase (demolition and recycling again as RA), no significant differences (in GWP score) are expected between an AC10 surf mixture without RA on the one hand and with RA and/or rejuvenator on the other. For this reason, these modules are not discussed further in this analysis.

4.2.2 Depletion of non-renewable resources

Consuming some of the finite (non-renewable) resources available on our planet is a major constraint for sustainable development, as it may compromise availability for future generations. This impact is estimated in the LCA approach by the ADP (*Abiotic resource Depletion Potential*) parameter.

The ADP parameter is further divided into two parts, on the one hand into ADPm (consumption of materials/elements, using the metal antimony - chemical symbol Sb - as a reference and converting other materials to a mass of Sb equivalents), and on the other hand into ADPe which represents the consumption of energy from fossil energy sources (expressed in MJ).

Similarly to the GWP value, the result for the ADPm and ADPe parameter is calculated for the five AC10 surf mixture variants (module A1).

The results are summarised in table 4.7 and presented in figure 4.3.

		20 % RA		50 % RA	
Score per tonne of asphalt (from-cradle-to-factory-gate)	**Reference (no RA)**	**Without rejuvenator**	**With rejuvenator**	**Without rejuvenator**	**With rejuvenator**
ADPm (kg Sb-eq)	7.9 E-05	6.7 E-05	6.6 E-05	4.8 E-05	4.7 E-05
ADPe (MJ)	2,777	2,284	2,275	1,544	1,521

Table 4.7 – *Result of the calculations for "depletion of abiotic resources" (materials and fossil energy) for the different components of the five AC10 surf mixture variants*

For the ADPm (depletion of materials) parameter, this shows a result that is 15 % and 39 % better for the asphalt mixtures with 20 % and 50 % RA, respectively, compared to the reference asphalt mixture without recycling. Here, the rejuvenator has only minimal influence. By the way, it is noted that these are small number values in each case. Here, the largest contribution (74 % and 70 % and 60 % respectively) comes from the fresh bitumen. This confirms the sense that mineral aggregates are definitely not critical elements in global resource consumption.

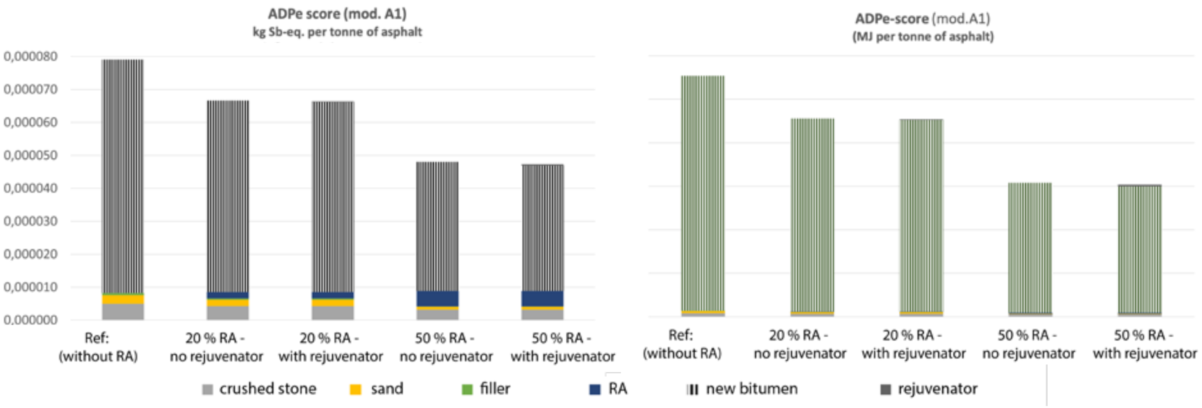


Figure 4.3 – *Score for abiotic resource depletion potential (left for elements = ADPm, right for fossil energy = ADPe) for the five AC10 surf mixture variants including the contribution per asphalt component*

For the ADPe (fossil energy) parameter, almost the entire contribution to this parameter comes from the new bitumen part. Thus, a result that is 18 % and 44 % lower for the asphalt mixtures with 20 % and 50 % RA, respectively, is achieved compared to the reference mixture (neither recycling nor rejuvenating agent). The use of the rejuvenator leads to an additional very small reduction of 0.3 to 0.8%.

4.2.3 Air pollution

Key indicators of the air pollution problem include tropospheric ozone depletion *(Ozone Depleting Potential or* ODP), formation of photochemical smog in the lower atmosphere *(Photochemical Ozone Formation Potential or* POP) and emissions of acidifying gases, especially sulphur dioxide *(Atmospheric Acidification Potential or* AP). Besides these impacts on different parts of the atmosphere itself, the environmental indicator 'fertilisation' or eutrophication *(Eutrofication Potential or* EP) of soil and aquatic systems, through the emission to air of nitrogen (oxides) and phosphorus (phosphate), also plays an important role.

Again, we should point out the large variation in emission factors between raw materials, with clearly larger emission factors belonging to the bitumen (and rejuvenator) part compared to the mineral aggregates. For bitumen, the two data sources (the inventory studies by Eurobitume (Ducreux et al., 2020) and Asphalt Institute (Wildnauer et al., 2019), see also Appendix 1), however, also conflict in terms of emission factor size or use different units. For example, for the parameter 'ozone layer depletion', according to Ducreux et al., 2020, the emission factor of 1 tonne of bitumen is 1.75 x10^{-5} kg CFC-11 equivalent, while Wildnauer et al., 2019 converted gives an emission factor of 2.55 x10^{-8} kg CFC-11 equivalent per tonne of bitumen, which is remarkably lower. For 'acidification' as well as for 'smog formation' we use the data from Wildnauer et al., 2019, since Ducreux et al., 2020 uses different units and does not provide a value for 'eutrophication'. The latter will be improved in the Eurobitume LCI study update at the end of October 2022 (European Bitumen Assocation [Eurobitume], 2022).

Given the dominant role of bitumen (and rejuvenator) in these impact calculations, similar conclusions can be drawn for the 'air pollution' component as for 'depletion of non-renewable resources', namely that recycling RA has a positive impact on environmental performance and that the addition of a rejuvenator only partially cancels out this environmental gain.

Table 4.8 summarises the results for the impact category 'air pollution' for the five AC10 surf mixtures. For each of these parameters (as was done in the earlier figures), the result can also be presented in a figure with a breakdown of the contribution by commodity component. Figure 4.4 shows an example for the parameter 'acidification potential (AP)'.

	Reference (no RA)	**20 % RA**		**50 % RA**	
Score per tonne of asphalt (from-cradle-to-factory-gate)		**Without rejuvenator**	**With rejuvenator**	**Without rejuvenator**	**With rejuvenator**
AP (kg SO_2-eq) (Wildnauer et al., 2019)	0.111	0.093	0.094	0.065	0.069
EP (kg PO_4^{3-}-eq) (Wildnauer et al., 2019l)	0.038	0.031	0.031	0.022	0.022
POP (kg ethene-eq) (Wildnauer et al., 2019)	0.026	0.021	0.022	0.014	0.016
ODP (kg CFC11-eq) (Wildnauer et al., 2019)	6.7 E-07	5.9 E-07	5.9 E-07	4.7 E-07	4.7 E-07
ODP (kg CFC11-eq) (Ducreux et al., 2020)	1.7 E-06	1.4 E-06	1.4 E-06	1.0 E-06	1.0 E-06

Table 4.8 – *Result of air pollution calculations for the AC10 surf mixture variants (per tonne of asphalt)*

4.2.4 Leaching to soil and groundwater

This indicator is not usually covered in the usual framework of indicators within LCA studies. In the EDGAR methodology, this indicator was added as road structures are built into a surrounding environment of soil and the groundwater within it, so there may be a potential risk regarding component leaching (contamination).

The AC10 surf mixture variants with recycling of RA and without rejuvenator contain no raw materials other than the reference mixture without RA, except for the RA fraction. The latter fraction includes already used raw materials (after application during the first life cycle), for which any consequences in terms of leaching have long since expired. Therefore, no changes with negative impact on leaching behaviour are expected. Indeed, it is generally accepted that the hydrophobic nature of bitumen leads to very low emissions (via leaching through contact with water). For the variants with rejuvenator, this could possibly be influenced by properties of the rejuvenator itself. However, no information/data is currently available on this.

Sustainability evaluation of asphalt mixtures

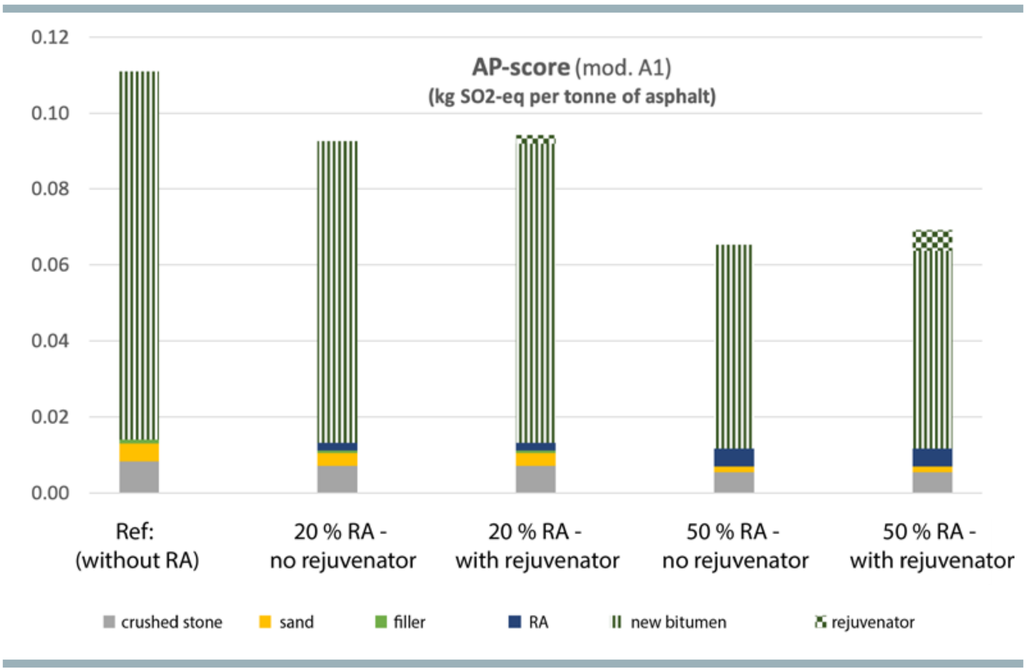


Figure 4.4 – *Score for acidification potential (AP) for the five AC10 surf mixture variants with contribution by feedstock*

4.2.5 Noise pollution

The variant mixture compositions with recycling of RA and with or without rejuvenator are used to produce the same type of asphalt mixture, namely AC10 surf mixture (with the same calibres and grain size distribution). Under the assumption that both the old and new bitumen and the rejuvenator occur in a homogeneous phase, no difference in the thickness of the binder coating around the aggregates is also expected. Consequently, no significant influence on the noise performance of the variant AC10 surf mixtures is postulated.

A possible influence on the noise performance between the AC10 surf mixture variants could potentially still occur due to changes in longer-term behaviour or occurring damage patterns: aggregate loss by ravelling, fraying or changes in road surface characteristics. Here, the percentage of voids may also play a role. We refer here to recent results of a sensitivity study conducted as part of the activities of the BRRC *Reclaimed Asphalt Steering Committee* where very similar results were determined for all AC10 surf mixture variants (Tanghe et al., 2023).

4.2.6 Skid resistance

For skid resistance, similar remarks can be made as in § 4.2.5 with regard to noise and this with regard to the mixture composition and surface characteristics (grain size, bitumen film, etc.) of the AC10 surf mixture variants. For other parameters that may play a role in skid resistance such as the (uniformity in the) finish quality of the surface layer, little information is currently available (is beyond the scope of this research project).

4.2.7 Recyclability *(circular economy potential)*

In the EDGAR project (De Visscher et al., 2016), a flow chart was created as a tool to estimate the potential for recyclability with a *recyclability* score. Knowing that asphalt can and will be recycled multiple times, recyclability - the reusability of End of Life (EOL) materials after the end of their useful life - is crucial for innovative, green techniques and in *sustainability* assessment.

With the experience and knowledge gained, the reuse of asphalt mixtures with rejuvenating agents does not seem to pose any additional problem compared to conventional asphalt mixtures. This applies both in terms of the legal framework and risks in terms of milling, sieving or stockpiling, as well as reheating in the dryer. However, it should be noted that there is currently little practical experience/know-how on the recyclability of asphalt mixtures where rejuvenators have already been applied.

In this context, it can be indicated that a series of aspects are still unclear (and consequently result in uncertainties and/or risks regarding recyclability) such as:

- Does all the added rejuvenating agent actively contribute to the softening of the recycled binder, or do (chemical) changes potentially occur that could negatively impact the (efficient) performance of the respective rejuvenator?
- Is there an impact, if any, of the rejuvenator on the asphalt's resistance to ageing?
- When dosing the rejuvenator for a new cycle, should the rejuvenator already added in the previous cycle be taken into account?

There is no reason to believe that the EOL product is not fully recyclable, but also the conditions to ensure such recyclability multiple times have not been fully identified today.

4.2.8 Responsible procurement policy

A responsible *sourcing* policy pays attention to sustainability aspects in the supply chain of the goods (and services) purchased, in this case including the origin of the rejuvenators. Traceability, the presence of a global *policy*, a quality management system, an energy and waste management system, employment and training are also included (ISO, 2017).

Specifically for the *bio-based* rejuvenator as applied in this project, in this context, the *policy* endorsed by the supplier's company should identify and weigh the required land use of the trees underlying the *bio-based* rejuvenator against the use of these lands for alternative purposes (e.g. farming for nutritional needs). However, there is no information available within this project to objectively assess these aspects.

4.2.9 Cost

The raw materials are a dominant factor in the total cost of producing an asphalt mixture. The bitumen content is particularly important. It is assumed that bitumen determines at least 40 % to 50 % of the total cost of an asphalt mixture. Consequently, partially replacing primary materials by using RA significantly lowers the cost price of the asphalt mixture. For an asphalt mixture with a high recycling rate of 50 % RA, this means a saving of ± 35 % (Leyssens et al., 2013).

Permanent availability of sufficient and homogeneous RA, while also controlling its possible fluctuations, is therefore a major asset for any asphalt producer. The cost of the rejuvenator has a negative impact here, but is relatively limited given the low usual dosage. Moreover, the cost of a rejuvenator can be expected to decrease in the future as the 'market' grows.

However, it is clear that a further increase in RA reuse in the future, such as in asphalt mixtures for surface layers, is particularly attractive from a financial and therefore economic point of view. In this context, the application of rejuvenators offers prospects.

4.2.10 Traffic congestion

Any impact of a particular technique or alternative material on the score on this indicator may be there as a result of a changed construction time or a diversion via a route with lower traffic capacity. In the case of the use of RA, whether in combination with rejuvenators or not, these changed circumstances are not the case. Hence, for this indicator, there is no impact on the assessment of the sustainability of the use of rejuvenators in asphalt roads.

4.2.11 Technical quality

Besides sustainability from a social and environmental point of view, technical sustainability *(durability)* also plays an important role in the whole sustainability story. A product or system that can reach its intended or longer (technical) lifetime and does not need to be replaced prematurely - this is a durable product - is the prerequisite for achieving high sustainability. Therefore, sustainability requires above all good technical quality. The performance requirements for the various asphalt mixtures (with or without recycling of RA and/or rejuvenator) are of course identical, given that they are always AC10 surf mixtures (same application domain).

Based on the results of preliminary studies carried out (initial type testing or ITT) both in the Re-RACE project and in the complementary RejuveBIT project, it appears that these performance requirements are also met by asphalt mixtures with recycling whether or not in combination with various rejuvenators (Piérard et al., 2020; Tanghe et al., 2020; University of Antwerp, EMIB & OCW, 2021; Vansteenkiste, 2021; Vansteenkiste et al., 2021) ITT tests include the determination of compactability by gyratory tests (% voids), determination of water sensitivity (ITSR value expressed in %), track formation resistance (LPD expressed in %, after 30,000 cycles). In addition to the tests provided during the ITT study, resistance to ravelling was also determined.

It can therefore be stated that these observations from both the laboratory study and practice give no indication about an altered (in a negative or positive sense) performance of asphalt mixtures type AC10 surf mixture for surface layers with RA, whether or not in combination with a rejuvenating agent. Consequently, a similar lifespan can be assumed at this time.

4.3 Summary of the results of the sustainability analysis using the EDGAR method

Table 4.9 summarises the analysis for asphalt toplayers of type AC10 surf mixture with a (high) percentage of RA (20 % or 50 %), whether or not combined with a bio-based rejuvenator.

For some indicators, the variants with or without recycling and/or rejuvenation agent score the same and there is no difference, but for some other important indicators such as climate change potential, resource depletion, air pollution and financial cost, there is a clear difference in favour of the asphalt mixtures with RA recycling. In this case, the considered rejuvenator further increases the benefit to a very slight extent.

In general, it is clear that technical durability aspects, such as maintenance or extension of technical lifespan and demonstrable increased performance, could also be decisive in a final sustainability assessment of the studied AC10 surf mixture variants. However, no such data is currently available.

Indicator	AC10 surf mixture with 20 % / 50 % RA relative to reference mixture (no RA)	Additional influence of the *(bio-based)* rejuvenator
Climate change	**6 % / 16 % improvement**	Additional improvement of 1 to 3 % (biogenic character)
Depletion of abiotic resources **- materials** **- fossil energy carriers**	**Improvement of 15 % / 39 %** **Improvement by 18 % / 45 %**	Additional improvement with 1 to 2 %
Air pollution	**Improvement by 15 % / 40 %**	Negative impact of 3% to 7% (for acidification)
Leaching	No information available	No difference
Noise pollution	No difference assumed	
Recyclability	No difference assumed	
Skid resistance	No difference assumed	
Responsible purchasing policy	No difference	
Traffic congestion	No difference	
Performance, technical durability	No difference	
Cost	**Improvement of 15 % / 35 %**	Minimal (but less good due to cost of rejuvenator)

Table 4.9 – *Overview of sustainability assessment for the various indicators*

5 Comparison between EDGAR and MKI methods in terms of sustainability assessment

5.1 A closer look at the MKI methodology

MKI is the Dutch language abbreviation of Environmental Cost Indicator. It is an indicator of the costs related to the **environmental damage** associated with a particular product or system. Above all, it is a way of bringing together different environmental indicators into a single indicator.

Indeed, impacts on the environment, such as climate change through greenhouse gas emissions or acidification of soil or water bodies through sulphur oxide emissions, have a cost (Drissen & Vollebergh, 2018; Van Harmelen et al., 2004).

This cost is not directly included in the economic market price; it is a so-called externality, a shadow cost. The shadow cost or price is the cost of the environmental damage caused by the product in question. This is an additional cost that is not included in the market price of the product, but is passed on to society (Figure 5.1).

Figure 5.1 – *The environmental cost as a supplement (externality, shadow cost) to the market price (Wat zijn schaduwkosten?, 2021)*

The shadow cost can be seen as the economic cost that would be required to avoid or depollute this environmental damage: the shadow price is the highest allowable cost level per unit of emission reduction. The lower the MKI value, the less harmful environmental impacts are associated with it.

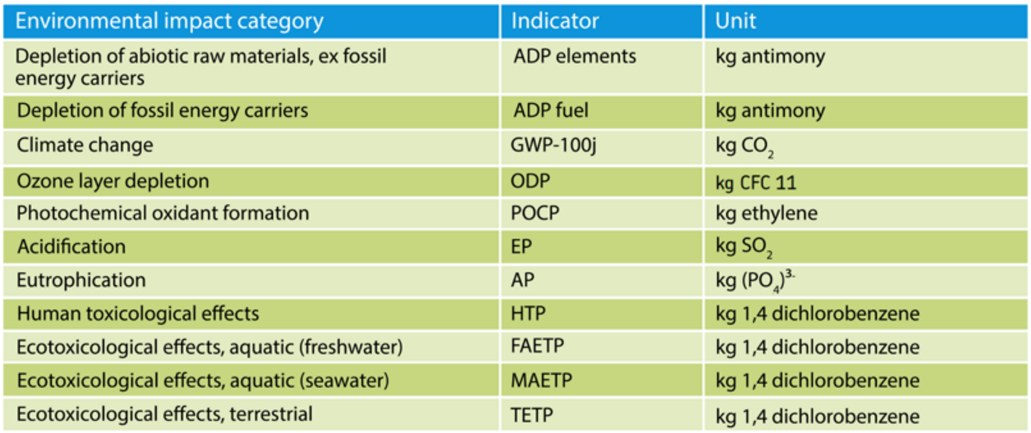
The MKI method applies monetisation to environmental impacts: environmental impacts are converted from a scientific unit (different for the various environmental impacts) to a comparable unit, namely a monetary value. It is a way to quantify in a single score the impact of different potential environmental impacts, in order to easily compare variants. It relies on the result of a full life cycle assessment (LCA) with 11 different indicators (in accordance with European standard EN 15804 [NBN, 2012+2019/2021]). It achieves a trade-off of these different indicators by attaching a monetary weighting factor to each indicator and summing them to a single indicator with a single score expressed in a monetary value (euros).

> A simple example to illustrate this: suppose variants A and B are compared for two parameters, namely 'climate change' and 'acidification'. Variant B scores twice as well for climate, but only half as well for acidification. So which of the two variants is the best (because most sustainable) solution?
> It depends on the weighting factors used to calculate an overall score.
> Suppose on the one hand a unit price of EUR 0.05 per kg CO_2 equivalent is used for climate change and on the other hand a unit price of EUR 4 per kg SO_2 equivalent for acidification, then in this simplified calculation example, variant A with an individual score (per m^2 of road surface) of, say, 500 kg CO_2-eq. for climate and 10 kg SO_2 equivalent for acidification, will have a total MKI score of (500 x 0.05 + 10 x 4 =) EUR 65, while variant B with an individual score (per m^2 of road surface) of, say, 250 kg CO_2 equivalent for climate and 20 kg SO_2 equivalent for acidification obtains an MKI score of (250 x 0.05 + 20 x 4 =) EUR 93. Variant A is then preferable, as the environmental cost indicator for it is the lowest.

In a less simplified representation, this way of calculating can be extended to all environmental indicators.

Of course, the size of this cost in terms of environmental damage may be subject to debate, and advancing insight may allow these weighting factors to evolve. Figure 5.2 shows these weighting factors as part of the current MKI methodology; they are based on the report entitled "Toxicity has its price" (Van Harmelen et al., 2004).

5.2 Calculation of the MKI value



Environmental impact category	Indicator	Unit
Depletion of abiotic raw materials, ex fossil energy carriers	ADP elements	kg antimony
Depletion of fossil energy carriers	ADP fuel	kg antimony
Climate change	GWP-100j	kg CO_2
Ozone layer depletion	ODP	kg CFC 11
Photochemical oxidant formation	POCP	kg ethylene
Acidification	EP	kg SO_2
Eutrophication	AP	kg $(PO_4)^{3-}$
Human toxicological effects	HTP	kg 1,4 dichlorobenzene
Ecotoxicological effects, aquatic (freshwater)	FAETP	kg 1,4 dichlorobenzene
Ecotoxicological effects, aquatic (seawater)	MAETP	kg 1,4 dichlorobenzene
Ecotoxicological effects, terrestrial	TETP	kg 1,4 dichlorobenzene

Figure 5.2 – *Weighting factors (for the 11 environmental impact categories) to determine the MKI (Stichting Nationale Milieudatabase, 2020, p. 39)*

The MKI value is calculated from the LCA results by multiplying the value (in equivalent units) for each environmental impact category by the monetary weighting factor, then summing across all impacts.

To present the calculation method in simple terms, we have included in **Annex 4** worked out a simple example.

5.3 Practice in the Dutch asphalt industry

To do a full calculation of environmental impacts, specialised software as found in (commercially developed) LCA packages is needed. For example, GaBi, SimaPro or OpenLCA. Because these LCA packages work generically (for all types of products and materials, not specifically for asphalt), they have to be combined with the product-specific national product category rules (PCR) rules (for Dutch asphalt, an update 2 came in early January 2022). The same applies to the package which the private company EcoChain Technologies (https://www.ecochain.com/nl/) has created for the Dutch asphalt sector, at the request of the sector itself. This is EcoChain's Environmental Impact Assessment (EIA) model, which simulates a virtual Dutch asphalt mixing plant. By entering the concrete issues of the specific project in this spreadsheet, it can be calculated.

Just about all Dutch asphalt mixing plants have purchased a licence to use this model from EcoChain. Because the asphalt industry sponsored the development cost of this model, the licence cost is fairly limited (a few thousand euros at most).

All asphalt contractors in the Netherlands make a new calculation of the MKI each time changes are made to the composition of their asphalt mix, based on EcoChain's LCA calculation software. For this, they do not need specialised LCA knowledge, but they do need training in using the EcoChain tool.

For future changes in the MKI method, including the transition from 11 to 19 indicators (according to EN 15804 + A2 [NBN, 2012+2019/2021]) that are measured in a Dutch LCA, and the associated weighting factors (how many euros of environmental cost are associated with those new (and possibly updated old) indicators per unit?), for now it is still waiting for the final publication (by the research institute CE Delft). The 'climate change' parameter remains dominant in it, but, for example, 'water use' would be given greater weight.

5.4 Extensible to Belgium?

It is remarkable that the Netherlands is a forerunner in Europe with this methodology, and in doing so can have an EPD (based on a complete LCA study) of asphalt variants used uniformly by the various contractors, such that they make an adjusted calculation for all their mixtures each time, etc. This is said to be due to the consensus among contractors, who got their sector organisation (Technical Committee at VBW Asphalt) to work with TNO to jointly draw up and adopt the PCR rules, something that has not succeeded in other European countries. On the contrary, Dutch contractors sensed that their main client, Rijkswaterstaat, would make a strong commitment to this: in the coming years, every project would be tendered with inclusion of the Environmental Cost Indicator in the award requirements (just as the CO_2 performance ladder is becoming a common tool).

Given that the calculation tool from the Dutch firm EcoChain was made specifically for the Dutch asphalt sector - developed at the request of and with financial support from their asphalt sector federation and available to all members through a licensing model - and is also being promoted as a tool on the demand side by the largest clients of asphalt road construction works (Rijkswaterstaat plus local authorities) in the Netherlands, this approach looks set to take off well in the coming years.

The situation in Belgium is different. For example, we do not have a national PCR for asphalt mixtures in Belgium, and registration and certification are also very different from those in the Netherlands. In our country, the focus seems to be more towards the so-called infra-TOTEM method. For the TOTEM software, the three regional authorities joined forces to come up with a common building-focused calculation method for the environmental impacts of building products and structures (http://www.totem-building.be/). For the road construction sector, Flanders (through AWV) seems to want to opt for an adaptation of the TOTEM tool to make it also applicable for the more environmentally friendly/more sustainable design of road constructions (De Winne, 2022).

5.5 Sustainable procurement with the MKI

The MKI method has an interesting advantage, namely its seemingly simple result. Through monetisation, the method succeeds in simply aggregating the wide variation of individual scores for 11 abstract environmental impacts into a single score, namely the environmental Euros for the shadow cost price. Different solutions can be easily compared based on their MKI score, which is not the case with an LCA table (expressed in multiple units).

By making shadow costs visible in the environmental cost indicator, the MKI can help in sustainable procurement (GPP). By including the MKI as a shadow price (e.g. by adding them to the market price of the good), those externalities are integrated into the true total price (economic cost + environmental social cost). In this way, a more sustainable solution (because with a lower MKI) can ultimately be accepted as the most advantageous solution despite a higher economic cost and thus be awarded to the most environmentally friendly bidder. For more info and a simple example, see **Annex 4.**

The MKI allows the contracting authority to incentivise and reward (monetarily compensate) the contractor for the extra effort (and extra cost) to offer a more sustainable solution in its bid. This compensation can be done on a one-to-one basis (one euro award advantage per euro gain on the MKI) or leveraged (more than 1 euro award advantage per euro lower MKI) in order to further commit to sustainability.

5.6 Comparison with the EDGAR method

A full calculation of the AC10 surf mixture type asphalt mixtures used in this publication as a case study for the surface layer of asphalt pavements, and this according to the Dutch method of MKI mentioned above, is not possible in practice, as we do not have the specific Dutch software package. On the other hand, such a calculation is also of little relevance to the Belgian situation, which is not comparable to the situation in the Netherlands.

Sustainability evaluation of asphalt mixtures

An interesting point that emerges from the sample calculation of MKI of the Dutch type mixtures for surface layers is the relative importance (as part of the total MKI) of the different environmental impact categories (Schwarz et al., 2020). In descending order of importance, these are: the potential for climate change, acidification, human toxicity effects, and the other eight impacts (Figure A4.2 in **Annex 4**). The first three categories of impacts account for about 80 % of total environmental costs, and thus deserve the most attention in reduction strategies.

Elements such as 'depletion of abiotic resources (elements)', 'ozone layer depletion' or 'ecotoxicological effects (terrestrial; aquatic (freshwater))' are of minimal importance in the overall MKI score for this type of asphalt mixture.

For the EDGAR approach, this could mean that the environmental impacts to be included would indeed not have to be the full 19 (or even 11) impact categories, but would be limited to a few, as is already the case today. Thereby, it would possibly be more relevant to replace the indicator 'depletion of abiotic resources' by 'human toxicological effects', and to limit the impact category 'air pollution' to only the potential to 'acidification', if the results from the Dutch example should also valid for other situations.

We further note that the MKI method (as is also the case for the LCA method on which it relies) only addresses parameters of the 'environment' pillar, and does not include elements of the 'social' pillar, nor the 'economy' pillar. In contrast, the EDGAR methodology does deliberately seek to bring together certain elements of the three pillars in the concept of sustainable development. In our view, that is a better approach.

6 Conclusion

In this paper, we explained the approach to achieve an objective assessment of the sustainability of an asphalt road surface.

In Chapter 1, we explained the context of sustainability as well as the focus on asphalt mixtures for wearing courses in this document, and the importance of including the results of a sustainability evaluation with the ultimate aim of arriving at improved procurement forms that contribute to the realisation of sustainable development.

In Chapter 2, we took a closer look at how the normative framework for sustainability assessments is evolving in an international context, and outlined the idea of life-cycle thinking of systems.

The method developed (Chapter 3) builds on the insights developed in recent BRRC research projects (EDGAR and Re-RACE), and goes further with a concrete application of it for an asphalt mixture for surface layers, including the recycling of reclaimed asphalt and the possible addition of a rejuvenator. For information, reference is also made to other methods in our neighbouring countries, such as SEVE in France or MKI in the Netherlands, or methods developed for buildings (TOTEM).

The EDGAR method relying on some eleven indicators was then concretely applied in chapter 4 and calculated in detail for a typical asphalt mixture. As the basis of the data for the environmental indicators, this relies on the information given in the environmental product declarations of the raw materials and processes used (EPDs). This also points to the complexity that exists in that context of getting coherent data available, or only having data that is difficult to compare.

Based on the *sustainability* assessment described here, conclusions can be drawn in general terms of positive or negative impact on the various indicators considered. A summary of the quantified results for five asphalt mixtures for surface layers of type AC10 surf mixture, with a (high) percentage of RA (20 % or 50 %) whether or not in combination with a *bio-based* rejuvenator, is presented.

For some indicators, the variants with or without recycling and/or rejuvenation agent score the same and there is no difference, but for some other important indicators such as climate change potential, resource depletion, air pollution and financial cost, there is a clear difference in each case in favour of the asphalt mixtures with RA recycling. The plant-based rejuvenator considered here increases the benefit to a very slight extent.

In general, it is clear that technical durability aspects, such as maintenance or extension of technical lifespan and demonstrable increased performance, could also be decisive in a final sustainability assessment of the studied AC10 surf mixture variants. However, no such data is currently available.

Finally, in Chapter 5, we explained more about the alternative method of the Environmental Cost Indicator (MKI), and the differences between the approach based on the MKI and the EDGAR method. A full calculation of the asphalt mixtures used as case studies in this publication according to the Dutch MKI method is not possible in practice and of little relevance, as the specific Dutch software package is not available here and is not adapted to the Belgian situation.

Sustainability evaluation of asphalt mixtures

However, the sample calculation of MKI of the Dutch type mixtures for surface layers does show an interesting indication of the relative importance (as part of the total MKI) provided by the different environmental impact categories: in descending order of importance, these are the potential for climate change, acidification, human toxicological effects, and the other eight impacts. The first three categories of impacts account for about 80% of total environmental costs, and thus deserve the most attention in reduction strategies.

An important observation regarding the alternative method of MKI is that the environmental cost indicator - as is also the case for the LCA method on which it relies - only addresses parameters from the environmental pillar, and does not include elements from the social or economic pillars of the concept of sustainability. In contrast, the EDGAR methodology does deliberately seek to bring together certain elements of the three pillars in the concept of sustainable development. In our view, that is a better approach.

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Abbreviations

ADP	Abiotic resource Depletion Potential
RA	Reclaimed asphalt
AP	Acidification potential
AC10 surf	Asphalt with Performance Requirements for Surface layers
GHG	Greenhouse gases
CEDR	Conference of European Directors of Roads
CEN	European Committee for Standardisation
COPRO	Impartial institution for the Control of construction products
CTO	Crude Tall Oil
EDGAR	Evaluation and Decision process for Greener Asphalt Roads
EOL	End of Life
EP	Eutrophication Potential
EPD	Environmental product declaration
GPP	Green Public Procurement
GWP	Global Warming Potential
ISO	International Organization for Standardization
ITS(R)	Indirect Tensile Strength (ratio)
ITT	Initial Type Testing
LCA/LCI(A)	Life Cycle Analysis / Life Cycle Inventory (Analysis)
MMG	Environmental Material Performance of Building Elements
ODP	Ozone Depleting Potential
PIARC	Permanent International Association of Road Congresses
PmB	Polymer modified bitumen
POP	Photochemical Ozone formation Potential
RILEM	International Union of Laboratories and Experts in Construction Materials, Systems and Structures
SBS	Styrene-butadiene-styrene block copolymer
SDG(s)	Sustainable Development Goals(s)
TRA	ApplicabilityRegulation

Annex 1

Emission factors for raw materials, where to find them and how to interpret them

A1.1 General methodology

To correctly analyse the potential environmental impact of asphalt (and the differences between asphalt mixtures) via a life cycle analysis, an LCA calculation relies on the interpretation of data spread across the various processes within the system boundaries. For asphalt, Figure A1.1 below gives a schematic representation of these processes and the physical flows of materials, energy and emissions involved, at least for the product phases (module A1 for the supply of raw materials – with blue background, and module A2 with the transport movements of those raw materials to the asphalt mixing plant – with red background, and module A3 with the asphalt production in the asphalt mixing plant – with green background).

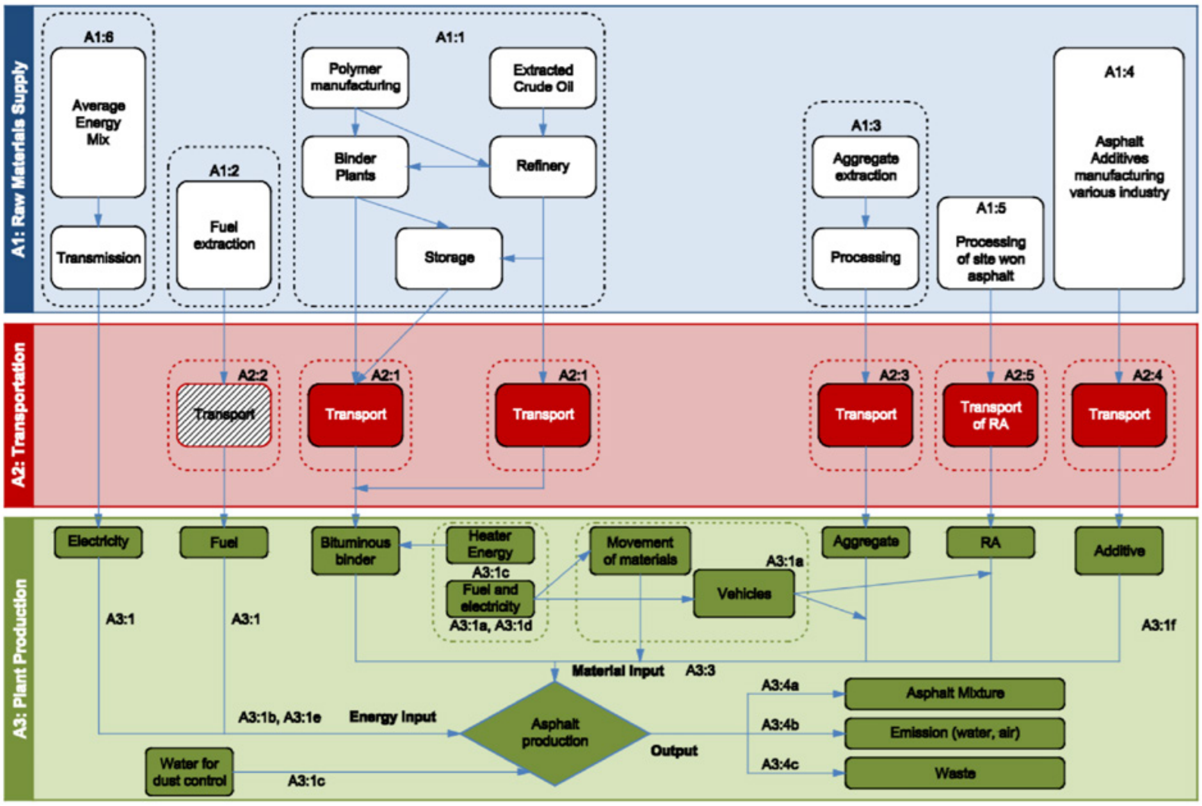

Figure A1.1 – *Diagram of system boundaries, processes and data types for asphalt at the product stage (from cradle to factory gate: information modules A1 – A3) (CEN, 2020, Figure 3)*

For each of the processes, the inputs (raw materials, energy) and outputs (intermediate or final products, other energy form, emissions) must then be determined and how much those emissions contribute to the different impact categories under consideration. For this, it is possible to rely on so-called **emission factors**, which quantify emissions for a standard quantity for each process component. Taking the impact category "global warming" (via GWP) as an example, in the raw material supply chain (module A1) we need to determine the GWP contribution of both aggregates, reclaimed asphalt or RA processing, bituminous binder and additives. These elements are represented in the figure above as data types A1:3 (quarry with aggregate extraction), A1:5 (RA processing), A1:1 (oil refinery and polymer plant) and finally A1:4 (manufacturing of additives, such as rejuvenators, and filler), respectively.

Information on these emission factors is given in so-called environmental product declarations or EPDs. These are prepared for a given product with preferably the most specific information possible - provided by an individual manufacturer or supplier - or with more generic (average) values provided by a group of manufacturers or an industry federation.

Although there are international standards that determine how an LCA should be carried out and how an EPD should be drawn up, it is very difficult to find an unambiguous value for the emission factors for a certain product (raw material, intermediate product or combined into e.g. an asphalt mixture). Moreover, results evolve over time as new processes are introduced at manufacturers or new technologies come into play. Also, the authors of these studies use different software and calculation models, and get their data from different databases, which may or may not have the same evolutions after a new update. Figure A1.2 outlines these causes of variability in EPDs.

In Belgium, the FPS Environment and Health has created a database for EPDs, accessible via the website www.b-epd.be, where on the one hand manufacturers (or federations) can declare the LCA

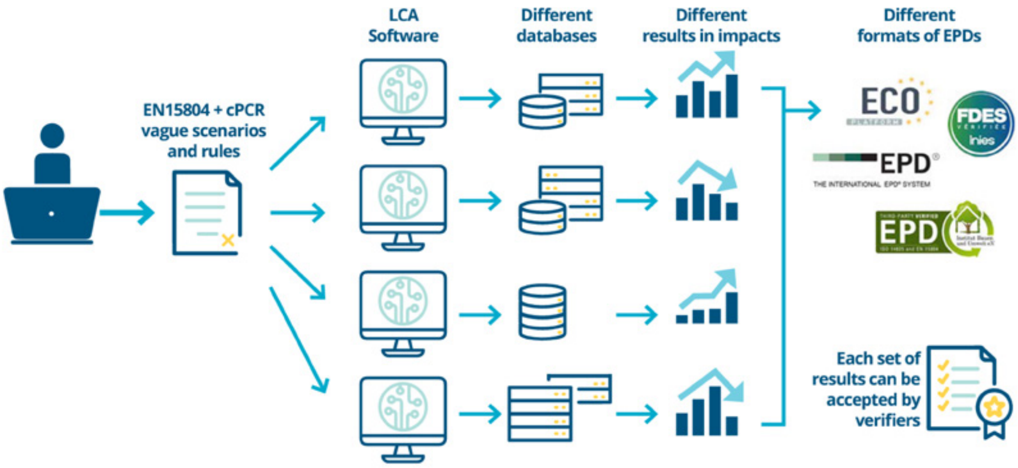

Figure A1.2 – *Challenges on EPDs and their variability (source: interview with Baijia Huang, ROCKWOOL International [Toth & Volt, 2021])* and EPD for their product and on the other hand citizens and companies can consult and further use those EPDs in their sustainability analyses (Federal Public Service [FPS] Public Health, Food Chain Safety and Environment, s.d.).

In the following sections, we elaborate on where this information can be found, and interpret it in terms of interpretation of the data or their variability. We mainly deal with the EPDs of bitumen, aggregates, RA, filler and rejuvenator.

A1.2 Emission factors for climate change potential

A1.2.1 Bitumen

The Federation of European Bitumen Producers published an inventory study (*life cycle inventory*) for bitumen production (cradle-to-factory gate) in 2012 (Blomberg et al., 2011). Such generalised sector-specific data are readily useful if data are not available for the specific bitumen used in the asphalt mixture.

Regarding the GWP (contribution to climate change) parameter, that study calculates a value of 0.191 kg CO_2 equivalent per kg of bitumen (*straight-run*), and a value of 0.323 kg CO2-eq per kg for polymer-modified bitumen (with 3.5 % SBS).

Meanwhile, this study was updated to a new version published in 2020 (Ducreux et al., 2020). This study would be representative of road bitumen production at a European refinery, as it takes into account average data from several European refineries in terms of crude oil origin and supply lines, technologies and conversion efficiencies from crude oil to bitumen. Figure A1.3 shows an outline of the system boundaries of bitumen production.

The flow chart of the (petroleum-to-bitumen) refinery is as follows:

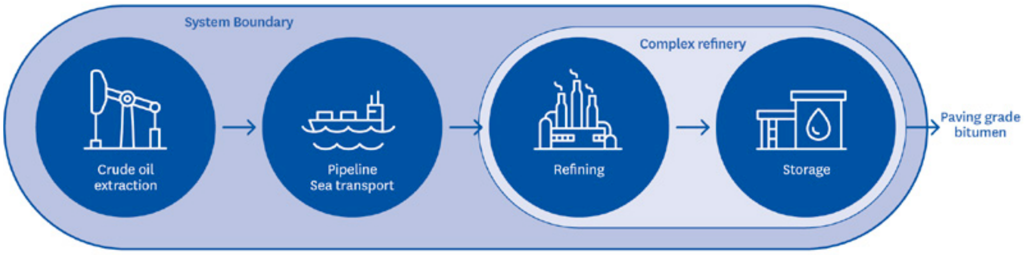

Figure 1. System boundaries for the bitumen LCI (cradle-to-refinery gate approach)

Figure A1.3 – *Delineation of system boundaries in the LCI (inventory study) of bitumen (source: Ducreux et al., 2020, Figure 1)*

This LCI may further distinguish whether it is with or without the "infrastructure". "With infrastructure" means that, in addition to the impacts of the actual process of bitumen production itself - from extraction of the petroleum over transport of the oil via pipeline or sea vessel to processing in the refinery - the additional flows associated with building the infrastructure (installations and machinery) needed to extract, transport and refine the crude oil are also taken into account: not only the energy consumed to drive the oil tanker is taken into account, but also the energy and raw materials required to build the vessel itself, in proportion to its contribution in the transport of that one tonne of oil, and so for all parts of the infrastructure.

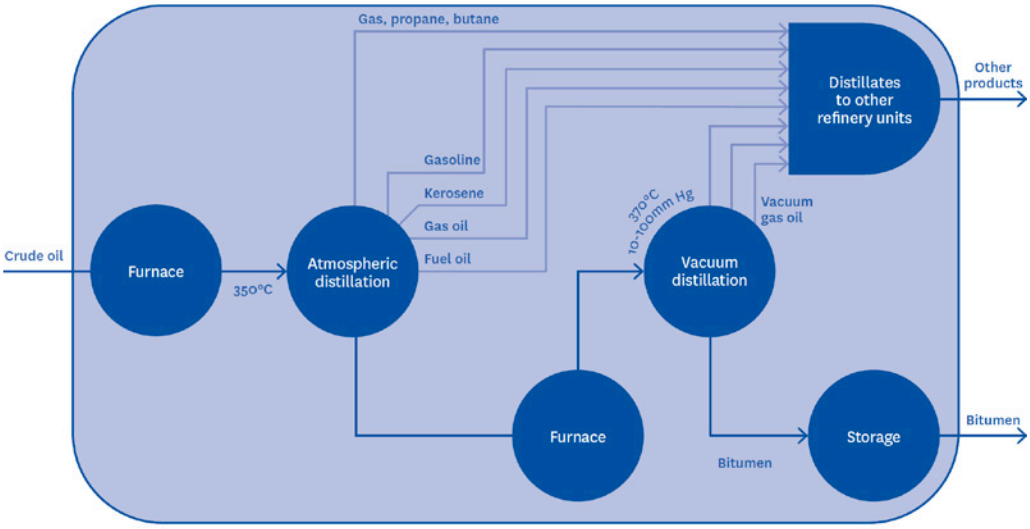

Figure 6. Schematic diagram of the refinery process

Figure A1.4 – *Flow diagram bitumen production in oil refinery (source: Ducreux et al., 2020, Figure 6).*

In this inventory study, Eurobitume analyses all *input* and *output* flows associated with the most relevant parts of the bitumen production process chain, as there are: consumption of crude oil (partly as a material, partly as an energy source for many process components), consumption of natural gas (as an energy source), emissions to air of gaseous pollutants such as carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen oxides (NO_x), methane (CH_4) and non-methane volatile organic compounds (NMVOC). Because of this, Eurobitume believes that the LCI provides useful data for the analysis of well-defined environmental impact indicators such as:

- depletion of abiotic resources/non-renewable fossil energy;
- climate change potential;
- ozone depletion;
- acidification;
- photochemical oxidation (smog formation).

The authors themselves state that the LCI study is less useful for the analysis of toxicity and ecotoxicity indicators (no results were reported on these). Note that this inventory study therefore does not conform to the standardised requirements for an EPD. N/A: After finishing this publication, Eurobitume published an update (Eurobitume, 2022) in a supplement to the 2020 study at the end of October 2022. That new document does now include all the environmental impact indicators of EN 15804+A2 (NBN, 2012+2019/2021).

Eurobitume's LCI report calculates the global warming potential of producing 1 tonne of road bitumen from a European refinery (excluding the "infrastructure") as being 150 kg CO_2 equivalent; including the infrastructure, this works out to a potential of 208 kg CO_2 equivalent per tonne of bitumen.

For comparison purposes, we also refer here to the similar study conducted in 2019 by the US *Asphalt Institute* as a federation of bitumen producers. In their LCA study (Wildnauer et al., 2019), they report their life cycle assessment of the asphalt binder representative of the North American market. Their focus is on oil refinery operations (data collected from 12 refineries in the US and Canada) and subsequent bitumen depots (data collected from 11 terminals), i.e. a cradle-to-factory approach similar to that used by their European counterparts. As a result for the impact analysis LCIA, Wildnauer et al, 2019 gives for the "climate change" parameter (GWP_{100}) a value of 0.637 kg CO_2 equivalent per kg of asphalt binder, or 637 kg CO_2-eq per tonne of bitumen. The calculation is done with the exclusion of "infrastructure elements" *(capital goods, infrastructure, human labour and employer transport*) because their results are considered of little relevance.

The model used for the LCA calculations was the *GaBi software system for life cycle engineering* , developed by the German firm thinkstep RA. In addition to the primary data (for refineries and terminals) provided by a survey of Asphalt Institute members, the inventory relied also on the secondary data from the GaBi LCI database, with the whole model of how crude oil is extracted and brought to refineries.

The differences in terms of GWP score between the US and European studies are thus significant. Comparing these 2 reports, the American LCA reports a far greater emission factor for greenhouse gasses than the European one, more than 3 times worse. The major differences are in both upstream (petroleum extraction) and downstream activities (temperature storage in bitumen depots), as illustrated in Table A1.1, which breaks down the total figure by main activity.

Study ▶ Activity group ▼	(Ducreux et al., 2020) without infrastructure	(Ducreux et al., 2020) with infrastructure	(Wildnauer et al., 2019)
extraction and preparation of crude oil	102	146	403
transport of crude oil	22	35	23
operations in oil refinery	19	20	77
transport of refinery to bitumen depots	7	7	33
activities in bitumen depot			101
Total figure for GWP (kg CO_2-eq)	**150**	**208**	**637**

Table A1.1 – *Total GWP figure (in kg CO2-eq. per tonne of bitumen) broken down by main activity in the bitumen production chain (data from Ducreux et al, 2020 & Wildnauer et al, 2019)*

Part of the difference between the results in the two LCA studies can probably be explained by differences in characteristics (physicochemical and geographical) of the petroleum mix (e.g. significant proportion of Canadian oil sands in the AI study) and the consequent differences in efforts required for exploitation and transport from the oil well to the refineries and subsequently the energy consumption for refining itself: in Eurobitume (Ducreux et al, 2020) mainly involves crude oil from the Middle East and Russia, while the AI situation involves crude oil that is 44 % derived from oil sands (tar sands in the Canadian province of Alberta). AI (Wildnauer et al., 2019) reports an origin distribution as being 53 % from Canada, 26 % from the US, 12 % from the Middle East and 8–9 % from South America.

The large differences in the operation of bitumen depots are also striking; in the AI study, this is probably an overestimate since these 11 bitumen depots are all located *off-site* with respect to the oil refinery (which necessitates long-distance transport and reheating of the bitumen). In Europe, this may be different as refinery and terminal are more often integrated on the same site, as is the case at the port of Antwerp, for example).

The AI study (Wildnauer et al., 2019) indicates that 4.98 kg of crude oil mix eventually leads to 1 kg of bitumen as end product from the refining process after allocation. In the Eurobitume study (Ducreux et al., 2020), this fact is not clear.

In his *critical review statement* (enclosed as an annex to the Eurobitume study [Ducreux et al., 2020]), the Swiss specialist Dr. Jungbluth's evaluated that the study did conform to current standards, but in many respects the results show a much more positive balance than is usual in specialised LCA databases. On climate change, among other issues, he estimates this to be an underestimate by a factor of 2. This would mainly be due to the underestimation of the importance of the escape (venting) of methane during petroleum extraction. There is also an apparent underestimation for other impact categories.

We note that there is significant variation in the baseline data, and this is so in many sources of LCA studies. With further calculations using these varying figures, the final results may also show a wide spread. However, it is not okay to simply fabricate an average figure. We therefore prefer to continue working with the value of **208 kg CO_2-eq per tonne of bitumen** (cf. Eurobitume with infrastructure [Ducreux et al., 2020]).

A1.2.2 Mineral constituents (crushed stone, sand and filler)

A similar approach can be taken for the mineral components in the raw material mix for asphalt, namely the filler, sand and stones.

If specific data is available, it is appropriate to use it. For example, if the asphalt mixing plant is located next to a quarry and all stones, sand and filler always come exclusively from this quarry, it is obvious to work with the very specific data from the EPD sheet of this quarry.

Currently, there are few EPD sheets available in the Belgian database of environmental product declarations (Service Public Fédéral Santé Publique, Sécurité de la Chaîne Alimentaire et Environnement, s.d.) regarding materials relevant to the road construction sector.

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In the absence of an EPD sheet, the quarry could make approximate calculations by reporting, on an annual basis, the energy consumption for all plant and machinery responsible for crushing, screening and crushing rock, calculating by emissions of equivalent amounts of greenhouse gases and dividing this by the annual output of the mineral aggregates.

In the absence of specific environmental information for a particular crushed stone type, generic data can be used, as for example reported in the *Inventory of embodied carbon and energy* (ICE) database of the University of Bath (UK), which collects data on the greenhouse gas intensity of building products (Hammond et al., 2011). The data in this database were collected in the cradle-to-factory gate scenario. It involves so-called *embodied carbon*, the sum of all direct and indirect carbon emissions, from material extraction (from quarry or mining) to finished product at the factory gate. This ICE database tries to take data from lots of sources into account and process them into a statistical mean value, and also gives a score to the reliability of that data.

In its most recent version, the ICE database (Circular Ecology, 2019) gives the following value for the material type "aggregates and sand" as the statistical mean value of all crushed rock and sand *(general, virgin aggregates, 89 % land won and 11 % marine won aggregate, bulk, loose)*: 4.93 kg CO_2-eq. per tonne. It is noted that these are average values with a wide spread in individual data, and more specific data should be used if possible.

More specific data can be found, for example, in EPD declarations from individual producers. As an example, we mention here the environmental information available in the EPD sheet of two European aggregate producers, on the one hand a quarry from Norway where the rock mass is crushed via explosives and on the other hand an Italian quarry where sand and gravel are extracted via dredging. As a third example, we also look at the sectoral EPD sheet of Fediex's Belgian quarries, which was published very recently.

- In Norway's national EPD database (http://www.epd-norge.no), we find, for example, the EPD sheet of crushed stone extracted from the quarry of Norwegian producer *Franzefoss Pukk AS* at Bondkall (Oslo), which operates a syenite-type natural stone quarry there (a coarse-crystalline igneous rock from the granite and basalt family). The sheet documents the environmental data of the quarry's various crushed stone products, broken down as a function of the number of steps required in the crushing and screening process (Figure A1.5).

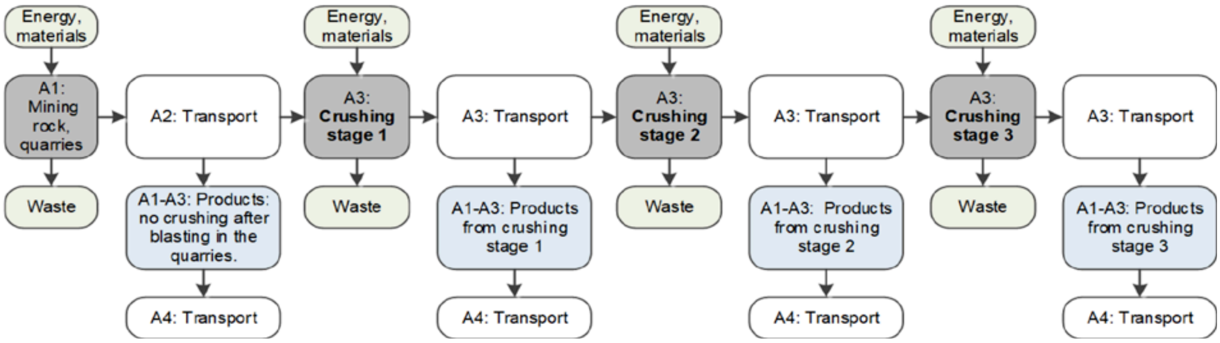


Figure A1.5 – *Schedule of inputs and outputs and products (crushed rock) by module in the quarry (source: Franzefoss Pukk, 2018)*

- This sheet states a GWP value of 3.40 kg CO_2 equivalent per tonne of crushed rock obtained after three steps in the crushing and screening process (e.g. for aggregate fractions 4/8, 8/11 or 8/16 used in asphalt applications) and a value of 2.79 kg CO_2 equivalent for crushed sand fraction 0/4 (which requires only two steps in the crushing and screening process).
- The figures in the EPD above are for a cradle-to-factory gate approach, from the quarry to the gate of the crushed stone factory (module A1 to A3 according to EN15804 [NBN, 2012+2019/2021]). The fiche notes that it does not include the contribution of explosives to detonate the rock massifs.
- In addition, the EPD sheet also provides the environmental information for module A4, transport from the crushed stone production site to the processing site (e.g. construction site, concrete plant or asphalt mixing plant in the nearby city). This additional transport to the customer has been modelled for a distance of 12.5 km one way, where a truck with engine emission efficiency class EURO 5 and payload category 16/32t drives a full load (13 tonnes of crushed stone on average) out and back empty, consuming 5 litres of diesel (corresponding to a specific consumption of 0.031 litres per tonne.km. The resulting GWP value is 1.57 kg CO_2 equivalent per tonne.
- Note that this bulk transport to the construction site is a relatively important contributor to the global warming potential: extrapolating to double the transport distance of 25 km one way would correspond to the same order of magnitude as the contribution of the entire operation of the quarry and the various processing steps to arrive at the product crushed stone fraction.
- In Italy's national EPD database (http://www.epditaly.it) we find the EPD sheet of sand and gravel extracted from the quarry of Italian producer *Gruppo Bassanetti* at Piacenza (Emilia-Romagna), which operates a wet quarry of natural sand and gravel there near the Po river. The sheet documents the environmental data of both sand and gravel for eight cases, determined by the type of granulate and the type of packaging (in bulk, in big bags for 1,500 kg or for 25 kg in plastic bags). We recall a GWP value of 2.67 kg CO_2-eq. per tonne of wet sand or gravel, in bulk (Gruppo Bassanetti, 2020).
- Concerning the production of crushed stone starting from solid rock and representative of the French market, the Environmental Data Sheet prepared by the French Granulate Producers Union (www.UNPG.fr) gives a GWP value of 2.6 kg CO_2-eq per tonne of crushed stone (module A1: *du berceau à la sortie de l'usine*). No further detail is given by calibre of aggregate fraction produced. On average, the input in terms of rock type consists of 50 % eruptive rocks, 30 % metamorphic rocks and 20 % limestone rocks (Union Nationale des Producteurs de Granulats [UNPG], 2017c).
- Regarding the production of aggregates of the gravel and sand type representative of the French market starting from non-massive rocks (*roches meubles*, sedimentary rocks of various origins: marine, fluvial, fluvio-glacial, aeolian, etc.), the environmental information sheet (EPD) prepared by the French association of aggregates producers gives a GWP value of 2.75 kg CO_2-eq per tonne of aggregates (module A1: *du berceau à la sortie de l'usine*). No further detail is given by calibre of gravel or sand produced. On average, the input in terms of rock type per tonne of aggregates consists of 984 kg of siliceous rocks or sands and 115 kg of alluvial rocks (UNPG, 2017d).

The above examples clearly show that there is some spread in the figures from the different sources, and that the specific data from the recent EPD sheets are generally slightly more favourable than the generic data from, for example, the ICE database.

- In the Belgian database for EPD information (http://www.b-epd.be), no information was available on aggregates from Belgian crushed rock or sand producers until the end of 2021. In early 2022, Fediex (Belgian Association of Mining Companies) placed an EPD sheet in the Belgian database covering a mix of Belgian limestone, sandstone and porphyry aggregates (Fédération de l'Industrie Extractive [FEDIEX], 2022). As usual in the Belgian EPD rules, at least the information modules A1 to A4 must be declared, i.e. from-cradle-to-factory-gate (A1-A3) supplemented by a standard transport scenario (A4). In this EPD, the result for the environmental impact category GWP (total) is a figure of 4.35 CO_2-eq. per tonne for the total production process (where modules A1 and A2 are actually integrated into A3). This is an industry average result (based on 20 Fediex members, corresponding to 58 % of the production of all Fediex members in 2019), for a mix of Belgian limestone, sandstone and porphyry aggregates, in different calibres, washed and unwashed. The relative proportions of the crushed rock types are not given verbatim in the EPD, but the accompanying information in the database sheet shows that they are (on a mass basis) on average about 77 % limestone, 4 % sandstone and 19 % porphyry as source rock types. Still remarkable: with regard to module A4 (the transport of aggregates in bulk according to a Belgian standard scenario), this EPD sheet mentions a value for global warming potential of 16.3 kg CO_2-eq. per tonne of aggregates. This value is 3.75 times what is charged for mining/production itself of these aggregates. This also implies that it makes more sense to look for improvement potential in transport rather than in raw material extraction itself.

Thus, the EPD sheets for aggregates in Europe discussed above do show some variability, but overall this is rather limited, as summarised in Table A1.2.

Author (year)	Geographic scope	Type of aggregate (possibly mix)			
		crushed stone	crushing sand	round sand/gravel	filler
(Hammond et al., 2011)	Europe (UK)	4.93			32
(UNPG, 2017a-d)	France	2.6 and 2.75			-
(Franzefoss Pukk, 2018)	individual quarry in Norway	3.40	2.79	-	-
(Gruppo Bassanetti, 2020)	individual quarry in Italy	-	-	2.67	-
(FEDIEX, 2022)	Belgium	4.35		-	-
Selection for this study		4.35	3	3	32

Table A1.2 – *Emission factor for aggregates from various sources (GWP, in kg CO_2-eq. per tonne of aggregate)*

We further calculate with a value of 4.35 kg CO_2-eq for the crushed stone fractions and 3 kg CO_2-eq for the sand fractions.

For factory produced filler (also called "supply filler"), only the value for the CO_2 emission factor for limestone flour (*ground limestone* in the *miscellaneous section;* data from version 2.0 of 2011) is available in Bath University's ICE: 32 kg CO_2 per tonne of limestone flour. ICE does not provide further details of the calculation, and makes the comment that it only concerns CO_2 as a greenhouse gas, so no CO_2-eq. (Hammond et al., 2011).

A1.2.3 Reclaimed asphalt

Regarding the reclaimed asphalt (from site-won asphalt pavement) processed as raw material for the production of new asphalt with reuse of both the mineral components (crushed stone fractions, sand and filler) and the bituminous binder - the reasoning is sometimes followed that an emission factor should not be charged for this, because those emissions belong to the life cycle of the previous product (in particular the processing at the end of the original asphalt road's life cycle, see Module C3). That would be so if a full LCA of that asphalt road is determined, from cradle-to-grave or cradle-to-rebirth.

In many exercises, and so here, only limited analysis is done, e.g. from-cradle-to-factory-gate. In that case, however, it is important to consider the extraction of reclaimed asphalt as is the case with the extraction of other aggregates.

The French granulate producers' union, for example, has drawn up an environmental information sheet (EPD) for the production of recycling granulates obtained from the treatment (sorting, crushing and screening) of construction and demolition debris. This explicitly states that these activities can actually be split into two parts (and are therefore published in two complementary sheets) (UNPG, 2017a-b). On the one hand, a part that belongs to the previous life (waste treatment of the building or structure being demolished; this is actually information module C3 in the end-of-life section; *du sortie de l'usine à la tombe*) and, on the other hand, a part that can be attributed to the new life (production of recycled aggregates starting from construction and demolition debris; this then falls within module A1; *du berceau à la sortie de l'usine*).

Climate change emission factor (GWP) figures for the production of 1 tonne of recycled aggregates from construction and demolition debris, representative of the French market, indicate a value of 1.5 CO_2-eq for module A1 and a value of 1.3 kg CO_2-eq for module C3 (UNPG, 2017b). The UNPG notes that by splitting off in the combined value of 2.79 kg CO_2-eq per tonne of recycled aggregates the part of module C3 (because it actually belongs to the end-of-life phase of the previous construction), and only counting with the 1.5 kg CO_2-eq for module A1, recycled aggregates thus get a lower GWP value than the one that applies to the production of aggregates of primary/natural origin, which is beneficial in the context of promoting the circular economy.

We assume that this reduced value of 1.5 kg CO_2-eq per tonne as an average for all types of recycled aggregates is also valid for the particular species that interests us here, namely reclaimed asphalt. This value therefore only applies to the activities of crushing and screening asphalt debris into reclaimed asphalt (module A1-A3), and therefore not to the activities of demolition (chipping) and disposal to the debris processing plant (items belonging to modules C1 - C3 in the end-of-life phase of the old asphalt road).

A1.2.4 Additives (other than rejuvenators)

No information; not present in our reference mixture nor in the alternatives.

A1.2.5 Rejuvenators

There is little data available in the literature on the 'Life Cycle Inventory' (LCI) of rejuvenators. We further use here the data from the environmental data sheet of one of the rejuvenators used in this project. According to the manufacturer, this product is suitable for use at high RA recycling rates, or when reusing an aged hard bitumen.

The LCI sheet gives a result for the GWP of -1.22 kg CO_2-eq per kg of product, which, to be more comparable with the other emission factors, we can also write as -1,220 kg CO_2-eq per tonne of rejuvenator (KRATON Corporation, 2018 via University of Antwerp, EMIB & BRRC, 2021).

This is indeed a (very large) negative number, as the rejuvenator is largely composed of an oil of plant origin (*bio-based*): CTO (*crude tall oil*) derived as a waste or by-product from processing of pine trees to produce cellulose fibres for paper (pulp). The exact composition of the rejuvenator is not revealed in the sheet (due to trade secrets; however, it does reveal that as a polyolester, it is a combination of two components, one of which is supplied by an external partner and the other produced by the manufacturer itself from CTO). During their natural growth, trees withdraw (which is why this is counted in as a negative number) CO_2 from the atmosphere and store that carbon in the wood structure; this CO_2 is called biogenic CO_2 (Figure A1-6).

Specifically for products of plant origin, biogenic CO_2 is of great importance, especially since it is a negative emission (a so-called *removal*). The calculation rules for carbon intensity (cf. EN 17472 [CEN, 2022]) explicitly take biogenic CO_2 into account, and provide that for the climate change potential GWP a total value is determined taking into account the greenhouse gases (GHG) from all sources: fossil carbon sources, biogenic sources, from land use or from land use transformations. This is both for emissions and *removals* as taken up by plants during their growth phase.

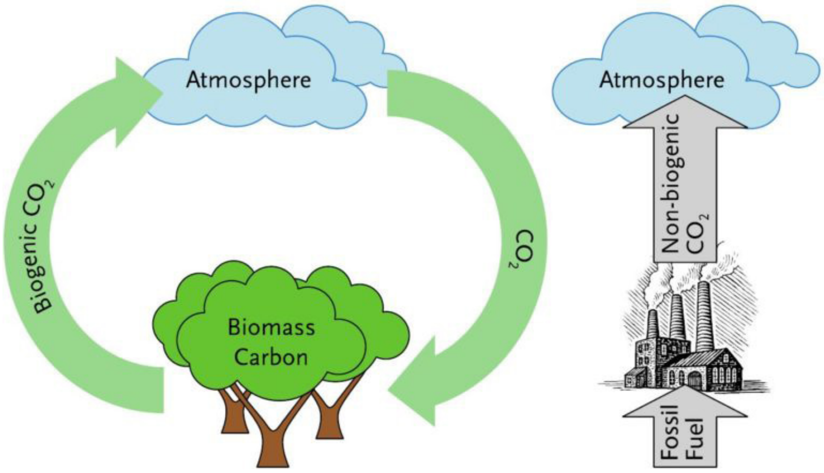


Figure A1.6 – *Schematic representation of biogenic CO_2 cycle (IEA Bioenergy, 2022)*

The production process of this *bio-based* product also generates greenhouse gases, of course, due to energy consumption in the process of reprocessing, chemical modification (e.g. esterification) and all transport activities, but these remain (at least under a cradle-to-factory approach) net lower than the large negative value caused by CO_2 absorption during the plant growth phase. This observation could perhaps be extended to numerous *bio-based* rejuvenators, as opposed to additives based on petroleum fractions.

ICE notes for the category of wood products that in terms of *carbon storage* , many EPD declarations do indeed factor in this carbon uptake, and thus arrive at a negative figure, but that this is only relevant for *sustainable sourced timber*, i.e. only timber from forests whose cleared trees are replanted with saplings. If not, an EPD that is only from-cradle-to-factory-gate is not correct, it should then be from-cradle-to-rebirth, where it is vital that the end-of-life phase (module C) is included in the calculations. The latter usually results in the negative figure (of CO_2 uptake) being adjusted to a positive figure (of CO_2 emissions). For information, the statistical average of all 211 data points concerning wood products in the ICE database gives a cradle-to-factory gate value of -1.03 kg CO_2-eq per kg of wood product (including carbon uptake), of which 0.493 kg CO_2-eq for regular emissions (excluding carbon uptake) and -1.52 kg CO_2-eq carbon uptake (Hammond et al., 2011).

According to publications ERG, Franklin Associates, 2013 and Cashman et al, 2016 by the American Federation of Processors of Pine Products, the greenhouse gas emissions of the average crude *tall oil* (CTO) refinery product mix in a cradle-to-factory pathway analysis (from management of mature pine forests to just after processing of the CTO at the biorefinery) are broadly equivalent to 1,171 kg CO_2-eq. per tonne of CTO distillate, calculated as the weighted average of the US (with 1,466 kg CO_2-eq. per tonne) and European (with 740 kg CO_2-eq. per tonne) pine oil processing chains.

This explicitly does not include carbon storage in the growing trees and thus in all derived products, to be more comparable with the alternative products and biodiesel (as was the aim of that study). In this total figure, a large contribution of CO_2 emissions comes from the pulping process (from log to *kraft* wood pulp), as well as from the distillation process and forestry activities to grow and harvest the pine trees.

The major differences between the European and US production chains lie mainly in the fact that the European plants (pulping and biorefinery) do rely to a large extent on closed-loop processes (where wood waste and intermediate and final products from the biorefinery are used as biofuel to provide energy for the other processes) and the US does not. Because these energy carriers come from biomass for which a zero CO_2 emission value is then factored in when burned, they reduce carbon intensity compared to the (US) process chain where fuels are more carbon intensive.

Further process steps to get from the CTO distillation products (such as *tall oil fatty acid, tall oil rosin, distilled tall oil, pitch*) to, among other things, the rejuvenator of interest to us here, obviously still generates additional greenhouse gases, so this figure of 740 kg CO_2-eq. per tonne of product for the European chain of CTO is certainly a lower limit if we were to consider them as indicative values for the rejuvenator, excluding biogenic carbon uptake. As already described above, we will still take biogenic CO_2 absorption into account in the further calculation and thus the negative figure of -1,220 kg CO_2-eq. per tonne) for GHG emissions.

A1.2.6 overview

The collection of all unit emission factors for the environmental indicator "climate change potential"

(GWP) is summarised in Table A1.3. For the other parameters (of air pollution), Table A1.4 summarises the relevant emission factors and their sources.

	Crushed stones	Sand (crushed)	Sand (unbroken)	Filler	RA	Bitumen	Rejuvenator
Emission factor (GWPi) (kg CO_2-eq/tonne)	4.35	3	3	32	1.5	208	-1,220

Table A1.3 - *Unit emission factors for parameter GWP (climate change, partim module A1)*

These data clearly show that per unit mass, especially the rejuvenator (negative value because *bio-based*) and bitumen, and to a lesser extent the filler, have significantly higher emission factors compared to aggregates (sand and crushed stone score similar emission factors). This means that the bitumen parameter plays a more important role in the GHG footprint than the mineral components, and that this should be the main focus to achieve a more sustainable asphalt mixture.

A1.3 Emission factors for air pollution parameters

Key indicators of the air pollution problem are tropospheric ozone layer depletion *(Ozone Depleting Potential or ODP*), formation of photochemical smog in the lower atmosphere *(Photochemical Ozone formation Potential or POP*) and emissions of acidifying gases, especially sulphur dioxides (atmospheric Acidification Potential or AP). Many EPDs also report "eutrophication" or *eutrophication potential* (EP) as an environmental indicator. Although this pollution arises primarily through emissions to air of gaseous elements (mainly phosphates and nitrogen oxides), it primarily impacts the aquatic environment (pollution of surface water, leading to excessive algae growth and loss of oxygen concentrations - necessary for aquatic life) and less on the environmental compartment "air".

Table A1.4 lists the emission factors relevant to air pollution and their sources.

Source of data ▶	(FEDIEX, 2022)	(UNPG, 2017c)	(Gruppo Bassanetti, 2020)	(UNPG, 2017b)	(Wildnauer et al., 2019)	(Ducreux et al., 2020)	(Kraton Corporation, 2018)
Emission factors (unit, per tonne of material)	crushed stone and sand	crushed stone	unbroken sand	RA	bitumen	bitumen	rejuvenator
Acidification (kg SO_2-eq.)	- (0.0318 mol H+ equiv.)	0.0147	0.0199	0.0096	1.64	- (2,18 mol H+-eq.)	5.84
Smog formation (kg ethylene-eq.)	- (0.0331 kg NMVOC equiv.)	0.00071	0.00056	0.00005	0.424	- (1,790 kg NMVOC-eq.)	2.73
Eutrofication (kg phosphate-eq.)	- (EP marine, 0.011 kg N-equiv.)	0.00308	0.00509	0.00206	0.585	-	1.00
Ozone layer-impairment (kg CFC-11-eq.)	7.07E-07	5.83E-07	3.31E-07	2.70E-07	2.55E-08	1.75E-05	6.98E-08

Table A1.4 - *Air pollution emission factors, by asphalt raw material, as used in this study*

The overview of these emission factors (for some air pollution parameters, per tonne of material, Table A1.4) should be accompanied by the observation that the 2020 Eurobitume LCI inventory study (Ducreux et al., 2020) does not report a result for the impact category "*eutrophication*", and for the indicators "acidification" and "smog formation" it uses different reference units, which are not comparable with the EPD data from the other sources. N/A: After finishing this publication, Eurobitume published an update in a supplement (Eurobitume, 2022) to the 2020 study at the end of October 2022; that new document does now include all the environmental impact indicators of EN 15804+A2 (NBN, 2012+2019/2021). We therefore continue to work with the data from the US AI study for these four indicators of environmental impacts.

In this table, it is striking that the emission unit factors for acidification, smog formation and eutrophication due to both bitumen and rejuvenator are again dominant, being much larger than the corresponding factors for the mineral components of asphalt. Only for the parameter "ozone layer depletion" is the emission factor due to the rejuvenator a factor of 4 to 8 smaller than that of the mineral components.

In turn, the emission factor due to bitumen is very different between the two data sources for this parameter: the Americans (Wildnauer et al., 2019) give a factor of 6 to 10 times smaller (compared to the minerals) while according to Eurobitume (Ducreux et al., 2020) it is given a value 30 to 60 times more important than that of the mineral components.

Furthermore, it is interesting to take a look at the difference in the unit emission factors of bitumen on the one hand and rejuvenator on the other: in each case, the unit factor (i.e. per kg of material) for the rejuvenator is several times higher than the value for bitumen, which is an indication that the rejuvenator (even a bio-based product based on a vegetable feedstock as in our example) is more harmful to the environment than a petroleum derivative such as bitumen.

Appendix 2

Overview of environmental impact categories according to EN 15804 (NBN, 2012+2019/2021)

IMPACT CATEGORY	INDICATOR	UNIT
Depletion of abiotic resources, e.g. fossil fuels	ADP-elements	kg antimony
Depletion of fossil fuels	ADP-fuel	kg antimony
Climate change	PRG-100j	kg CO_2
Depletion of the ozone layer	ODP	kg CFC_{11}
Photochemical oxidant formation	POCP	kg ethene
Acidification	EP	kg SO_2
Eutrophication	AP	kg $(PO4)^{3-}$
Human toxicity	HTP	kg 1.4 dichlorobenzene
Ecotoxicity, aquatic (freshwater)	FAETP	kg 1.4 dichlorobenzene
Ecotoxicity (seawater)	MAETP	kg 1.4 dichlorobenzene
Ecotoxicity, terrestrial	TETP	kg 1.4 dichlorobenzene

IMPACT CATEGORY	INDICATOR	UNIT
Climate change - total	GWP-total	kg CO_2 equiv.
Climate change - fossil fuels	Fossil GWP	kg CO_2 equiv.
Climate change - biogenic	Biogenic GWP	kg of CO_2 equiv.
Climate change - land use and land use change	PRG-luluc	kg of CO_2 equiv.
Depletion of the ozone layer	ODP	kg CFC_{11} equiv.
Acidification	AP	mole of H + equiv.
Eutrophication of fresh water	EP-freshwater	kg PO4 equiv.
Marine aquatic eutrophication	EP-marine	kg N equiv.
Eutrophication on land	EP-terrestrial	mole of N equiv.
Smog formation	POCP	kg NMVOC equiv.
Depletion of abiotic mineral and metal resources	ADP-minerals & metals	kg Sb equiv.
Depletion of abiotic resources Fossil fuels	ADP-fossil	MJ, net cal. value
Water requirements	WDP	m3 world eq. deprived
Fine particle emissions	Illness caused by fine particle emissions	Incidence of disease
Ionising radiation	Human exposure	kBq U235 equiv.
Ecotoxicity (freshwater)	CTU ecosystem	CTUe
Human toxicity, carcinogenic effects	Human CTU	CTUh
Human toxicity, non-carcinogenic effects	Human CTU	CTUh
Impact related to land use / soil quality	Potential soil quality index	Dimensionless

Figure A2.1 - *Transition from the old (top of the figure) to the new set of environmental impact categories (The Determination Method, 2021)*

Annex 3

Energy consumption and related greenhouse gas emissions at the asphalt mixing plant

Lifecycle information module A3 refers to the activities in the asphalt mixing plant itself, namely the production of the asphalt mixtures starting from the mineral raw materials, bitumen and (if it is the case) additives. In particular, this module calculates the GWP score (GHG emissions in mass CO_2 equivalents) directly associated with the energy consumption of the machinery and the various plant components.

This mainly concerns the natural gas or fuel oil consumption for the drying drum (drying and heating the stones and sand), the electricity needed in the heating of bitumen and the plant's electric motors (such as mixer, conveyor belts, fans and pumps, weighing equipment, etc.) and the diesel for the loading shovel motor. Thus, we do not consider GHG emissions more broadly associated with infrastructure and capital assets (construction and maintenance of the plant itself or replacement parts).

As a source of primary figures, we refer to the publication of Ascovil's asphalt mixing plant *(joint venture* between the firms Aswebo/Willemen and Colas) in Villers-le-Bouillet, one of the few asphalt mixing plants in Belgium to be certified under the EMAS environmental management system, which requires them to periodically and publicly communicate progress in their environmental performance. Such data is sometimes regarded as confidential business information, so little disclosure is made. In its statement dated May 2020 for the 2019 operating year, Ascovil reported that CO_2 emissions averaged 0.017 tonnes (i.e. 17 kg) of CO_2 per tonne of asphalt (ASCOVIL, 2020).

As these are data from a primary source, they are highly representative of the asphalt mixing plant in question itself. However, other asphalt production plants may record (more or less) different figures, as these depend on the local organisation of the plant such as fuel type, energy efficiency of the plant, use of under-roof storage areas, modernity of the entire plant and of the operating vehicles, etc.

The figures given by the asphalt producer are averages over the entire asphalt production of the year in question, i.e. for both surface layer mixtures and underlayer mixtures, both with and without recycling. In this case, this refers to an annual production of 225,498 tonnes of asphalt, divided into 38 % surface layer mixtures (without recycling RA and with an average bitumen content of 6.3 %), and 62 % base layer mixtures (60 % are mixtures with recycling at a rate of about 50 % RA and addition of 2 to 2.5 % new bitumen, and 2 % are base layer mixtures without RA and with an average bitumen addition of 4.4 %). The publication reports total CO_2 emissions of 3 801 tonnes of CO_2 in 2019. Converted per tonne of asphalt (for an annual production of 225 498 tonnes of asphalt), this would equate to specific CO_2 emissions from the asphalt mixing plant of 16.9 kg CO_2 per tonne of asphalt.

No details on emission factors are described, but the publication does detail the following data on gas, electricity and diesel consumption:

- The burner for the drying drum(s) for drying and heating the minerals (and the RA) is the biggest energy consumer at an asphalt mixing plant. In this case, it involves a burner fed with natural gas as fuel, which is the best choice of all fossil fuels from an emissions point of view and preferable to fuel oil or lignite fuel (Leyssens et al., 2013). Elements such as sufficient insulation of the drying drum, limiting the water content by storing aggregates and RA under cover, continuous production rhythm instead of many stops/start-ups also help establishing the (energy) efficiency of asphalt production. Gas consumption was 1.82 million Nm^3, with a cumulative energy value of 20,845 MWh, corresponding to a specific energy consumption per tonne of asphalt of 7.13 Nm^3 per tonne of asphalt or 92 kWh per tonne of asphalt.
- Electricity consumption for the various electric motors, the control room and the lab was 1,275 MWh, equivalent to 5.66 kWh per tonne of asphalt.
- The diesel consumption of the loading shovels was 41,715 litres in 2019, representing a specific consumption of 0.185 litres of diesel per tonne of asphalt.

Made based on website emission factors www.CO2emissiefactoren.be (EnergieID & CO2logic, s.d.) (which are calculated more broadly because not only *tank-to-wheel* but also *well-to-tank*, i.e. including the greenhouse gases generated in the extraction, processing and transport of the energy carrier) itself, we obtain the results shown in Table A3.1.

Energy carrier ▶	**Natural gas**	**Electricity**	**Diesel**	**Total**
Unit	kWh	kWh	litres	
Energy consumption (units)	20,845,000	1,275,357	41,475	
Emission factor (kg CO_2-eq. per unit)	0.244	0.205	3.25	
Total calculated emissions (kg CO_2-eq.)	5,074,096	261,448	134,794	5,399 tonnes CO_2-eq.
Tonnes of asphalt on an annual basis				225,498
Specific emissions (kg CO_2-eq. per tonne of asphalt)	22.5	1.16	0.60	24.3

Table A3.1 - *Example calculation of specific GHG emissions for an existing asphalt mixing plant in Belgium (to ASCOVIL, 2020)*

In terms of electricity, the emission factor for so-called "grey" electricity has been calculated here, which for Belgium anno 2021 consists on average of 53 % nuclear generation and 47 % natural gas-fired electricity generation. An improvement potential for the sector here lies in enabling more electricity generation based on renewable energy sources such as wind and solar power, which have a much lower emission factor than fossil sources. This is especially important due to the Belgian electricity generation transition path in the near future, where all (low-carbon) nuclear capacity will be shut down at the latest in 2025, and replaced mostly by new gas-fired electricity production.

The calculation in Table A3.1, using the emission factors according to the aforementioned website and applied to the example plant, clearly gives a higher total GHG emission than stated in the publication, namely a specific emission of 24.3 kg CO_2-eq. per annual average tonne of asphalt produced instead of 16.9 kg as stated.

Working further with this calculated value, we now try to further clarify if there is any influence of whether or not RA is recycled.

Is there a difference in energy requirement (and thus associated emissions) in production for a mixture on the one hand without RA and on the other hand with RA (and possibly rejuvenator), and if so, how much is that difference?

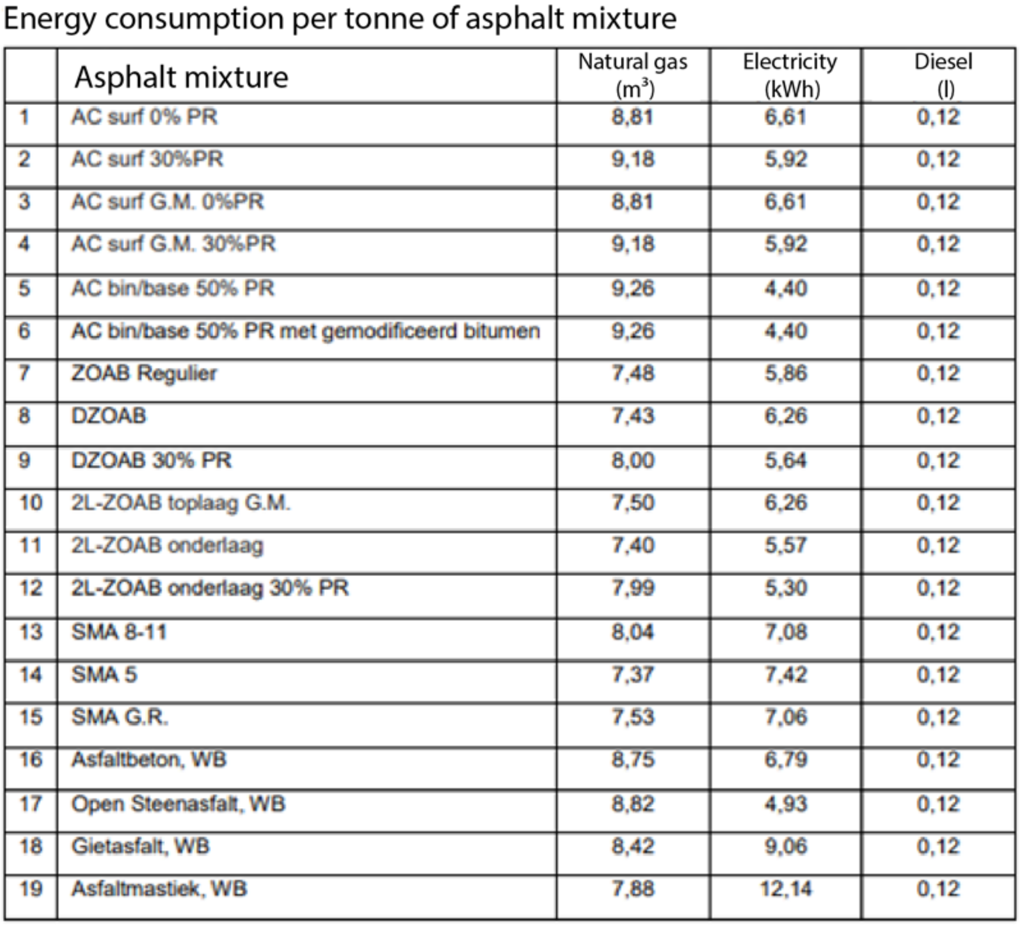
This is difficult to calculate and few sources from the literature are available. Assume for simplicity that we already know the answer: due to the fact that there are two dryers (one for the virgin materials and one for the RA), each causing a certain heat loss factor, and that in recycling the superheating of the virgin minerals required to reach thermal equilibrium also involves a certain energy inefficiency, there is a disadvantage in terms of energy requirements in the case of recycling. We estimate this disadvantage as follows: energy consumption and associated CO_2 emissions are 10 % higher for recycling at a very high recycling ratio of 50 % RA, and there is a 4-5 % difference to the disadvantage of recycling at a moderate recycling ratio of 20 % RA. In terms of electricity consumption, on the other hand, there may be savings in the case of recycling, as fresh bitumen is needed and therefore there is a saving in electricity consumption to keep that smaller amount of bitumen at temperature in the bitumen stocking tanks.

This energy difference estimate is confirmed by the data in the Netherlands study underlying their national PCR report. Publication (Schwarz et al., 2020) estimates the energy consumption for asphalt production (life cycle module A3) for the average situation in the Netherlands for 19 different types of asphalt mixtures (Table A3.2).

This shows that the use or non-use of RA recycling affects the energy demand in asphalt production: in the specific energy consumption per tonne of asphalt between mixtures without recycling RA on the one hand and comparable mixtures with RA on the other, there is always an increase in terms of natural gas consumption and at the same time a reduction in terms of electricity consumption for the mixtures with recycling compared to without recycling.

The differences for gas consumption average + 6 %, i.e. + 4.2 % between mixture types 1 and 2 and 3 and 4, + 7.7 % between mixture types 8 and 9, and + 8.0 % between mixture types 11 and 12, each using 30 % RA or no RA (an extrapolation to 50 % recycling of RA would then amount to about + 10 % gas). For electricity consumption, the savings are of the order of magnitude of - 9 %, namely on average - 11.4 % between mixture types 1 and 2 and 3 and 4, - 10.0 % between mixture types 8 and 9, and - 4.8 % between mixture types 11 and 12 (for a recycling ratio of 30 % RA; an extrapolation to 50 % recycling would then amount to about minus 16 % electricity). We assume that these

Sustainability evaluation of asphalt mixtures



Energy consumption per tonne of asphalt mixture

	Asphalt mixture	Natural gas (m^3)	Electricity (kWh)	Diesel (l)
1	AC surf 0% PR	8,81	6,61	0,12
2	AC surf 30%PR	9,18	5,92	0,12
3	AC surf G.M. 0%PR	8,81	6,61	0,12
4	AC surf G.M. 30%PR	9,18	5,92	0,12
5	AC bin/base 50% PR	9,26	4,40	0,12
6	AC bin/base 50% PR met gemodificeerd bitumen	9,26	4,40	0,12
7	ZOAB Regulier	7,48	5,86	0,12
8	DZOAB	7,43	6,26	0,12
9	DZOAB 30% PR	8,00	5,64	0,12
10	2L-ZOAB toplaag G.M.	7,50	6,26	0,12
11	2L-ZOAB onderlaag	7,40	5,57	0,12
12	2L-ZOAB onderlaag 30% PR	7,99	5,30	0,12
13	SMA 8-11	8,04	7,08	0,12
14	SMA 5	7,37	7,42	0,12
15	SMA G.R.	7,53	7,06	0,12
16	Asfaltbeton, WB	8,75	6,79	0,12
17	Open Steenasfalt, WB	8,82	4,93	0,12
18	Gietasfalt, WB	8,42	9,06	0,12
19	Asfaltmastiek, WB	7,88	12,14	0,12

Table A3.2 - *Average energy consumption per tonne of asphalt for nineteen mixture types in Dutch asphalt mixing plants (Schwarz et al., 2020))*

differences can be linearly scaled up to higher recycling ratios (as in our case here to 50% RA). No difference is taken into account for diesel consumption.

Given that heat energy is much more important than electricity demand and diesel consumption (see table A3.1), the disadvantage in terms of (natural gas) fuel is the determining factor in this comparison. Therefore, we further calculate with this worst-case estimate (10 % more energy (gas) consumption at the high recycling rate of 50 % RA compared to no RA), which converts to a value of 23 kg CO_2-eq. for a mixture without recycling, and a value of 24 kg CO_2-eq. per tonne of asphalt for a low recycling rate (of 20 % RA) and a GHG emission value of 25.3 kg CO_2-eq. per tonne for the production of an asphalt mixture with high recycling rate (of 50 % RA).

Annex 4

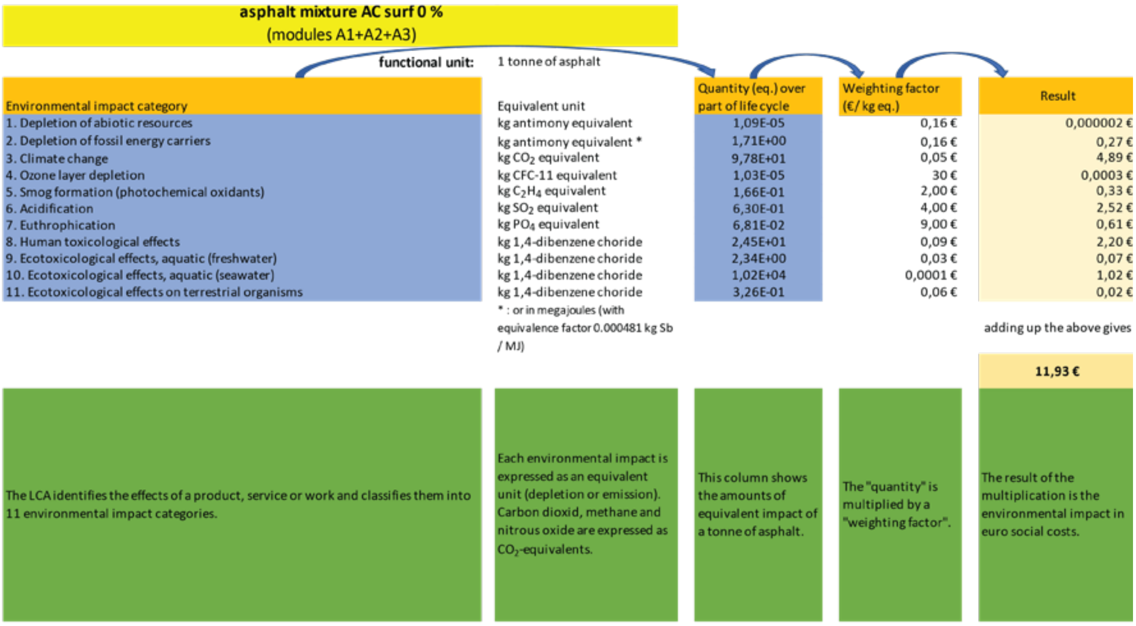
Explanation of the MKI methodology

MKI is the Dutch language abbreviation of Environmental Cost Indicator. It is an indicator of the costs related to the **environmental damage** associated with a particular product or system. Above all, it is a way of bringing together different environmental indicators into a single indicator.

The monetisation applied to environmental impacts in the MKI method is a way of quantifying the impact of different potential environmental impacts in a single score, in order to easily compare variants. It relies on the result of a full life cycle assessment (LCA) with 11 different indicators (in accordance with European standard EN 15804 [NBN, 2012+2019/2021]). It achieves a trade-off of these different indicators by attaching a monetary weighting factor to each indicator and summing them to a single indicator with a single score expressed in a monetary value (euros).

Of course, the size of this cost in terms of environmental damage may be subject to debate, and advancing insight may allow these weighting factors to evolve.

A4.1 Example of calculation of MKI value



asphalt mixture AC surf 0 %
(modules A1+A2+A3)

functional unit: 1 tonne of asphalt

Environmental impact category	Equivalent unit	Quantity (eq.) over part of life cycle	Weighting factor (€/ kg eq.)	Result
1. Depletion of abiotic resources	kg antimony equivalent	1,09E-05	0,16 €	0,000002 €
2. Depletion of fossil energy carriers	kg antimony equivalent *	1,71E+00	0,16 €	0,27 €
3. Climate change	kg CO_2 equivalent	9,78E+01	0,05 €	4,89 €
4. Ozone layer depletion	kg CFC-11 equivalent	1,03E-05	30 €	0,0003 €
5. Smog formation (photochemical oxidants)	kg C_2H_4 equivalent	1,66E-01	2,00 €	0,33 €
6. Acidification	kg SO_2 equivalent	6,30E-01	4,00 €	2,52 €
7. Euthrophication	kg PO_4 equivalent	6,81E-02	9,00 €	0,61 €
8. Human toxicological effects	kg 1,4-dibenzene choride	2,45E+01	0,09 €	2,20 €
9. Ecotoxicological effects, aquatic (freshwater)	kg 1,4-dibenzene choride	2,34E+00	0,03 €	0,07 €
10. Ecotoxicological effects, aquatic (seawater)	kg 1,4-dibenzene choride	1,02E+04	0,0001 €	1,02 €
11. Ecotoxicological effects on terrestrial organisms	kg 1,4-dibenzene choride	3,26E-01	0,06 €	0,02 €
	* : or in megajoules (with equivalence factor 0.000481 kg Sb / MJ)			adding up the above gives
				11,93 €
The LCA identifies the effects of a product, service or work and classifies them into 11 environmental impact categories.	Each environmental impact is expressed as an equivalent unit (depletion or emission). Carbon dioxid, methane and nitrous oxide are expressed as CO_2-equivalents.	This column shows the amounts of equivalent impact of a tonne of asphalt.	The "quantity" is multiplied by a "weighting factor".	The result of the multiplication is the environmental impact in euro social costs.

Figure A4.1 – *Example of calculation method for MKI (source: own calculation based on the data from (Schwarz et al., 2020) and by analogy with (Prinssen & Rademaker, 2020, Figure 3))*

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The MKI value is calculated from the LCA results by multiplying the value (in equivalent units) for each environmental impact category by the monetary weighting factor, then summing across all impacts. As explained in Chapter 5, the MKI approach is mainly applied in the Netherlands, not in other countries.

To simply introduce the calculation method, we have worked out an example below. Figure A4.1 shows, using an example calculation for 1 tonne of asphalt (from a Dutch type mixture), the steps to get from an LCA environmental profile (in this example, from-cradle-to-factory gate modules A1 to A3) to a MKI.

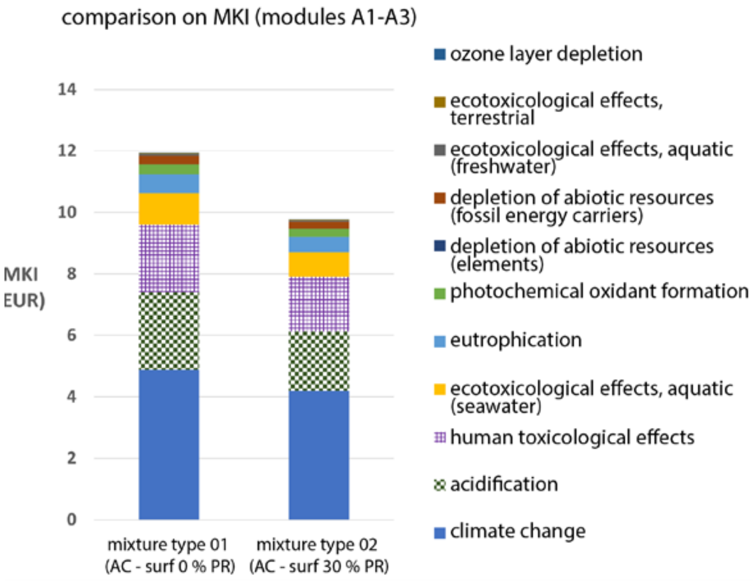


Figure A4.2 – *Sample MKI with influence of recycling (cradle-to-factory gate analysis of the Dutch type mixture for surface layers) (own calculation based on the data of (Schwarz et al., 2020))*

For this example, we used the results of the LCA study prepared for an average (virtual) asphalt mixing plant in the Netherlands, for the type mixture 'asphalt for surface layers, without recycling', calculated over part of the life cycle (modules A1 to A3) (Schwarz et al., 2020). Here, the environmental cost indicator MKI is €11.9 per tonne of asphalt mixture.

In this example, the largest contribution (about 45 %) to the total MKI comes from the environmental impact "climate change", followed by "human-toxicological effects" (20 %) and "acidification" (17 %). "Ecotoxicological effects on marine environment" counts for almost 8%, "eutrophication" counts for almost 5 %, "smog formation" and "depletion of fossil energy carriers" count for about 2 % each. The environmental effects "depletion of abiotic resources", "ozone layer depletion", "ecotoxicological effects on freshwater organisms" and "ecotoxicological effects on terrestrial organisms" each contribute less than 1 % to the total MKI.

This is clearly illustrated by Figure A4.2, which, for the standard surface layer mixture (on the one hand without recycling and on the other hand with 30 % RA recycling), breaks down the contribution to the overall Environmental Cost Indicator as the sum of the 11 different environmental impact categories.

Note: due to the future entry into force of Annex 2 for EN 15804 (NBN, 2012+2019/2021), the categories of environmental impacts to be taken into account will be expanded from a set of 11 indicators to a set of 19 indicators. See **Annex 2** for a listing of these sets of environmental indicators. As a result, the LCA calculation will also become more extensive, and more difficult to compare with past calculations. This new, broader set of indicators also requires new unit prices as weighting factors, as they are different environmental impacts. There is currently no consensus on these new unit prices.

A4.2 Sustainable procurement with the MKI

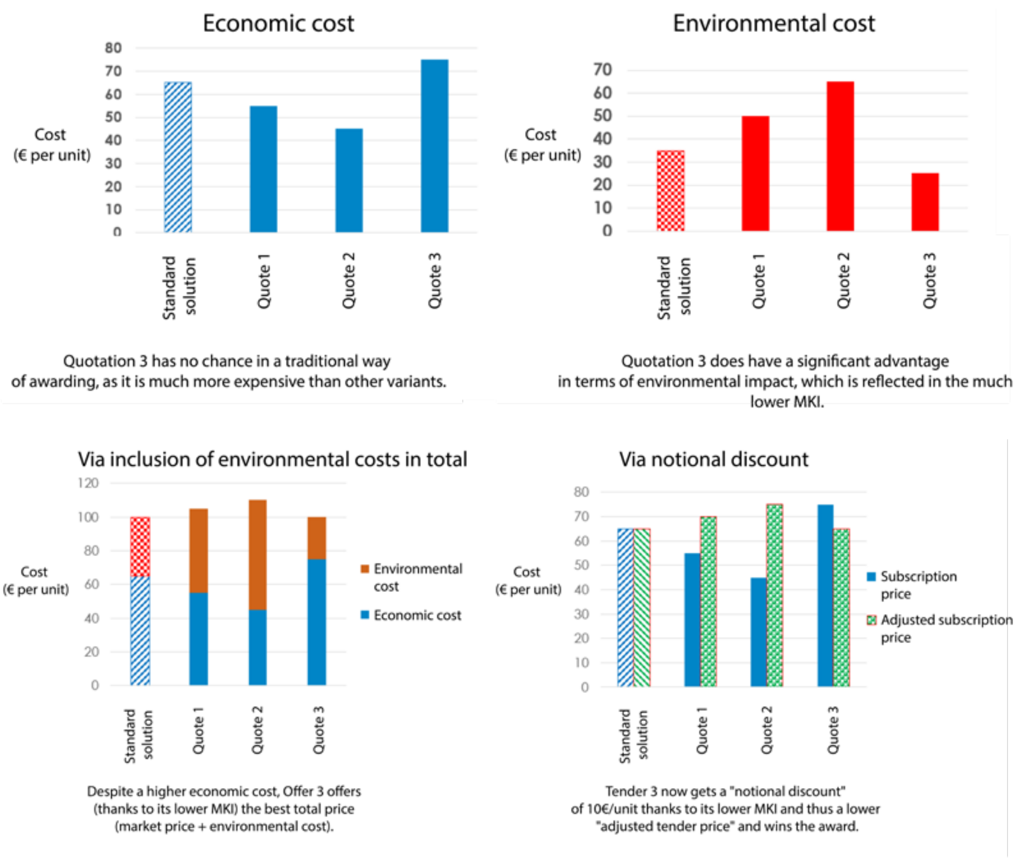
The MKI method has an interesting advantage, namely its seemingly simple result. Through monetisation, the method succeeds in simply aggregating the wide variation of individual scores for 11 abstract environmental impacts into a single score, namely the environmental Euros for the shadow cost price. Variant solutions can be easily compared based on their MKI score, which is not the case with an LCA table (expressed in multiple units).

By making the shadow costs visible in the environmental cost indicator, the MKI can help in green public procurement (GPP): by including the MKI as a shadow price inclusive (e.g. by adding it to the market price of the good), those externalities are integrated into the real total price (economic cost + social environmental cost). In this way, a more sustainable solution (because with a lower MKI) can ultimately be accepted as the most advantageous solution despite a higher economic cost and thus be awarded to the more environmentally friendly bidder. Figure A4.3 shows a simplified example of such an approach.

In this example, tender 2 has the lowest economic cost, but at the same time suffers from the highest environmental cost. Quotation 3 has a significantly higher economic cost, but a lower environmental cost. In a classical tender, offer 2 is the most economically advantageous solution. In contrast, in the sustainability-based approach, offer 3 has the lowest total cost. The contracting authority that really values a sustainable solution (with a low MKI) can, through this way of working, integrate sustainability into its procurement policy (GPP) and award the bidder of quotation 3 the work, as it offers the most interesting solution in bringing together economic and environmental costs.

The MKI allows the contracting authority to incentivise and reward (monetarily compensate) the contractor for the extra effort (and extra costs incurred) to offer a more sustainable solution in its bid. This compensation can be done one-to-one (one euro award advantage for every euro gain on the MKI) or leveraged (more than 1 euro award advantage for every euro lower MKI) in order to further commit to sustainability.

Sustainability evaluation of asphalt mixtures



Quotation 3 has no chance in a traditional way of awarding, as it is much more expensive than other variants.

Quotation 3 does have a significant advantage in terms of environmental impact, which is reflected in the much lower MKI.

Despite a higher economic cost, Offer 3 offers (thanks to its lower MKI) the best total price (market price + environmental cost).

Tender 3 now gets a "notional discount" of 10€/unit thanks to its lower MKI and thus a lower "adjusted tender price" and wins the award.

Figure A4.3 – *Example of a bid comparison with inclusion of the MKI (De Bock, 2022)*