Reviewing the variability in product category rules for asphalt pavements – A quantitative evaluation of methodological framework differences for environmental product declarations

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Abstract

The road construction industry is exploring the use of environmental product declarations (EPDs) as a communication tool and their implementation in green public procurement (GPP). Currently, several product category rules (PCRs) specific to asphalt mixtures exist. Consequently, it is important to assess the similarities and differences between these PCRs to avoid comparing EPDs derived from inconsistent methodological frameworks. This research revealed similarities in requirements for data quality, exclusion of inputs and outputs, and allocation procedures. However, it also showed major differences in the use of system boundaries, reference service life (RSL), functional unit (FU), and end-of-life (EOL) modelling. A quantitative evaluation of the variability of the PCRs showed that an RSL in its current form only provides information about the expected performance but does not alter environmental impacts in the final EPDs. Therefore, it is advised to recalculate the results into impacts per year. Furthermore, it was found that the use of a cut-off can influence EPD results greatly. Finally, if an EPD uses a cradle-to-grave or cradle-to-cradle scope, relocating the EOW does not affect the total impact but only triggers a shift of impacts between the EOL and material modules. However, if EPDs limit their scope to cradle-to-gate, the total result is notably impacted. In general, it is concluded that the selection of a specific PCR for asphalt mixtures does influence the EPD results. Therefore, it is important that procurement procedures define the PCR to be used to avoid unfair comparison of results when using different PCRs.

Highlights:

- PCRs do not cite the CEN/ISO sustainability assessment frameworks for civil works.
- System boundaries should be selected on a product- vs project-specific level.
- RSLs without impacts per year do not take durability into account in EPDs.
- The EOW state of RAP is in most cases modelled inconsistently within the same PCR.
- EPDs using a different PCR cannot be compared, harmonisation of PCRs is needed.

Keywords: Asphalt pavements, Product category rules, Environmental product declarations, Life cycle assessment, Green public procurement

Abbreviations: Green Public Procurement (GPP), Life Cycle Assessment (LCA), Environmental Product Declaration (EPD), Product Category Rule (PCR), Program Operator (PO), Functional Unit (FU), Subcommittee (SC), Technical Committee (TC), Service Life (SL), Reference Service Life (RSL), National Asphalt Pavement Association (NAPA), Life Cycle Impact Assessment (LCIA), European Asphalt Pavement Association (EAPA), European Committee for Standardization (CEN), End-of-Life (EOL), Reclaimed Asphalt Pavement (RAP), Declared Unit (DU), End-of-Waste (EOW), Warm-Mix Asphalt (WMA), Hot-Mix Asphalt (HMA), Equivalent Standard Axle Loads (ESALs), Polymer Modified Bitumen (PMB), Global Warming Potential (GWP)

1 Introduction

Green public procurement (GPP) can help to increase the sustainability level in the construction sector by purchasing products and services with lower life-cycle environmental impacts than their typically procured counterparts (Durão et al., 2020; Hernando et al., 2022; Rangelov et al., 2021; Roberts et al., 2020; Sariola and Ilomäki, 2016; Zokaei Ashtiani and Muench, 2022). GPP relies on a combination of life cycle assessment (LCA) and eco-labels as means of proof to communicate that products or services have lower environmental impacts (Del Borghi et al., 2020; Sönnichsen and Clement, 2020; Toniolo et al., 2019).

Literature highlights a few gaps related to GPP. Currently, ambiguous regulatory frameworks exist as public authorities define their GPP criteria primarily through political and national targets (He et al., 2022; Jelse and Peerens, 2017). Furthermore, there is a lack of knowledge about the environmental criteria that play an important role in environmental performance (Kadefors et al., 2021; Soto et al., 2020). Additionally, the practical integration of LCA during procurement is identified as limited, which has led to evaluation methods that poorly capture the environmentally relevant dimensions during procurement (Cheng et al., 2018; Scherz et al., 2022). Consequently, GPP is still in its infancy as a policy tool (Ng et al., 2013; Santos et al., 2015; Sönnichsen and Clement, 2020).

Notwithstanding, the interest of the construction sector in communicating the environmental performance of their products using environmental labels has increased (Božiček et al., 2021; Del Borghi et al., 2020; Passer et al., 2015). In the US, for example, the Buy Clean California Act now requires environmental product declarations (EPDs) from contractors of infrastructure projects (Kadefors et al., 2021; Rangelov et al., 2021). EPDs are considered the most reliable type of labels as they provide quantified and independently verified environmental information over the life cycle of a product (Cobut et al., 2013; Galindro et al., 2020; Gelowitz and McArthur, 2017; Minkov et al., 2015; Rangelov et al., 2021; Sariola and Ilomäki, 2016). They are regulated by product category rules (PCRs) to generate them in a more harmonised way (Anastasio et al., 2016; Mattinzioli et al., 2022a). PCRs provide detailed information regarding system boundaries, data sources, and environmental indicators to be used (Biswas et al., 2017; Dias et al., 2020).

However, there are no restrictions on who can develop PCRs. Additionally, there has been insufficient coordination amongst program operators (POs) working on overlapping PCRs in different locations, which raises questions about the consistency and comparison of EPDs for very similar products (Azarijafari et al., 2021; Cruz Juarez and Finnegan, 2021; Gelowitz and McArthur, 2016; Passer et al., 2015; Rangelov et al., 2021; Schmincke, 2013; Welling and Ryding, 2021). Consequently, EPDs with inconsistent LCA methodologies and different assumptions in terms of functional units (FUs), impact categories, and cut-off rules are available on the market (Achenbach et al., 2016; Azarijafari et al., 2021; Božiček et al., 2021; Dong et al., 2021; Galindro et al., 2020; Gelowitz and McArthur, 2017; Hossain and Thomas Ng, 2019). Some researchers even advise to have statements of non-comparability added on ecolabels to prevent confusion among users if different PCRs exist (Del Borghi et al., 2020).

Modifications in LCA studies can be associated with the local context of a case. If so, the modifications are normal and should be captured by the EPD. Examples of product-specific modifications are: differences in energy mix, transport distances, waste collection, sorting practices, and the disposal or recycling of materials (Del Rosario et al., 2021; Lützkendorf et al., 2012). Other modifications are due to methodological assumptions like FU, system boundaries, allocation methods, data sources, cut-off criteria, and impact categories (Gelowitz and McArthur, 2017; Papadopoulou et al., 2021). These modifications do not create a level playing field for LCA studies and should therefore be avoided. Harmonisation of PCRs can be seen as an absolute must for the consistent use of EPDs (Jelse and Peerens, 2017). Moreover, if they are harmonised and studies become more transparent, a healthier competition towards lowering the environmental performance of products can be created (Del Borghi et al., 2020).

The abovementioned highlights the willingness of the construction industry to use EPDs as communication tools and implementing them in procurement via GPP. However, it also exposes the main problem of the current practice, namely various EPDs with different methodological frameworks due to inconsistent PCRs. Even the slightest change in the framework for the calculation and/or communication of environmental footprints can prevent comparisons of products. Therefore, if EPDs are not aligned or made consistent, the practical implementation of EPDs in GPP as a decision-making tool in the construction sector will remain laborious.

2 Objectives and scope

The overall goal of this manuscript is to review and to quantitatively compare the existing normative frameworks and PCRs for determining the environmental profile of asphalt mixtures using EPDs. More specifically, the following objectives are defined:

- To provide an overview of the normative frameworks for the EPDs of asphalt pavements.
- To list existing PCRs specific to asphalt mixtures.
- To highlight the main methodological differences among these PCRs.
- To quantitatively evaluate the effect of the differences in PCRs using a scenario analysis.

3 Normative frameworks for the PCRs of asphalt mixtures

Figure 1 provides an overview of the interrelated normative frameworks to establish the environmental profiles of construction products and consequently, asphalt pavements. This normative background can be traced back to the work of five different subcommittees (SCs). In 1993, ISO technical committee (TC) 207 was created with a focus on environmental management. Their SC 5 concentrates on the standardization of LCA and related environmental management tools for products and organisations. Their most-known and often used outputs are the ISO 14040 and 14044 standards (CEN, 2006a, 2006b). These two standards form an important backbone for the other SCs.

Concurrently, ISO TC 207 SC 3 was created with the aim of producing standards in the field of communicating the environmental aspects of products. In general, ISO 14020 categorises environmental labels into three groups: ecolabels or type I (ISO 14024), self-declared claims or type II (ISO 14021), and EPDs or type III (ISO 14025) (CEN, 2023, 2018a, 2016a, 2010). This last category is often considered as the most detailed, transparent, neutral, and reliable of the three labels (Galindro et al., 2020; Gelowitz and McArthur, 2017; Rangelov et al., 2021; Sariola and Ilomäki, 2016). EPDs are comprehensive summary reports describing the environmental impact of products using LCA and should be formally verified by a third party before being made publicly available (CEN, 2010). However, like ISO 14040 and ISO 14044, ISO 14025 also fails to provide detailed guidance on preparing EPDs, which leaves room for interpretation. To increase the consistency of EPDs, the SC prepared ISO 14027 focussing on the development of PCRs (CEN, 2018b). PCRs provide guidance on how to accurately quantify the environmental impact of products, communicate the findings in a standardised and transparent way, and make the comparison of similar products possible (Ingwersen and Stevenson, 2012; Wu et al., 2014).

While TC 207 is focussed on environmental management in general, ISO TC 59 specifically concentrates on buildings and civil engineering works. Originally created in 1997, ISO TC 59 SC 14 targets the design life for construction works. This is an important SC as the selection of the service life (SL) is one of the most influential modelling choices in LCA (Huang et al., 2021; Marinković et al., 2021; Moins et al., 2022; Morales et al., 2021, 2020; Silva et al., 2022). They issued the ISO 15686 series which sets principles and frameworks for SL prediction procedures, reference service life (RSL) estimation, and performance evaluation for feedback on SL data from practice (ISO, 2017, 2012, 2011, 2008). Note that even though literature suggests that SL is one of the most influential parameters, and the framework of ISO TC 59 SC 14 is used as an input in ISO TC 59 SC 17 and CEN TC 350, none of these standards are directly cited by the specific PCRs for asphalt pavements.

In 2002, ISO TC 59 SC 17 applied sustainability principles to buildings and civil works using information from the three previously mentioned SCs. ISO TC 59 SC 17 provided standards on three different levels: frameworks, projects, and products (ISO, 2023a, 2023b, 2022a, 2022b, 2019a, 2019b). Simultaneously, CEN carried out the same exercise in TC 350 with a European scope, also considering the previously mentioned SCs and focussing on the same three levels (CEN, 2022, 2021a, 2021b, 2021c, 2021d, 2012). With ISO 21930 and EN 15804, ISO TC 59 SC 17 and CEN TC 350, respectively, published core PCRs for the development of EPDs for construction products. As they narrowed down the scope from generic LCA to LCA dedicated for construction products, conventions were established where ISO 14040 and ISO 14044 left room for interpretation (Achenbach et al., 2016; Cruz Juarez and Finnegan, 2021; Durão et al., 2020; Rasmussen et al., 2021). ISO 21930 and EN 15804, together with ISO 14040 and ISO 14044, form the backbone for any PCR or EPD related to construction products. CEN TC 350 and ISO TC 59 SC 17 decided to provide separate standards for the sustainability assessment of buildings and civil engineering works. However, ISO 21931-2 and EN 17472, which focus on the sustainability assessment of civil engineering works, were only published in 2019 and 2022, respectively. Therefore, they were not used as inputs in the development of ISO 21930 and EN 15804+A2. Consequently, none of the existing asphalt PCRs were developed considering the specific calculation methods for civil engineering works, which is clearly a gap in the state of the art of EPDs for asphalt pavements.

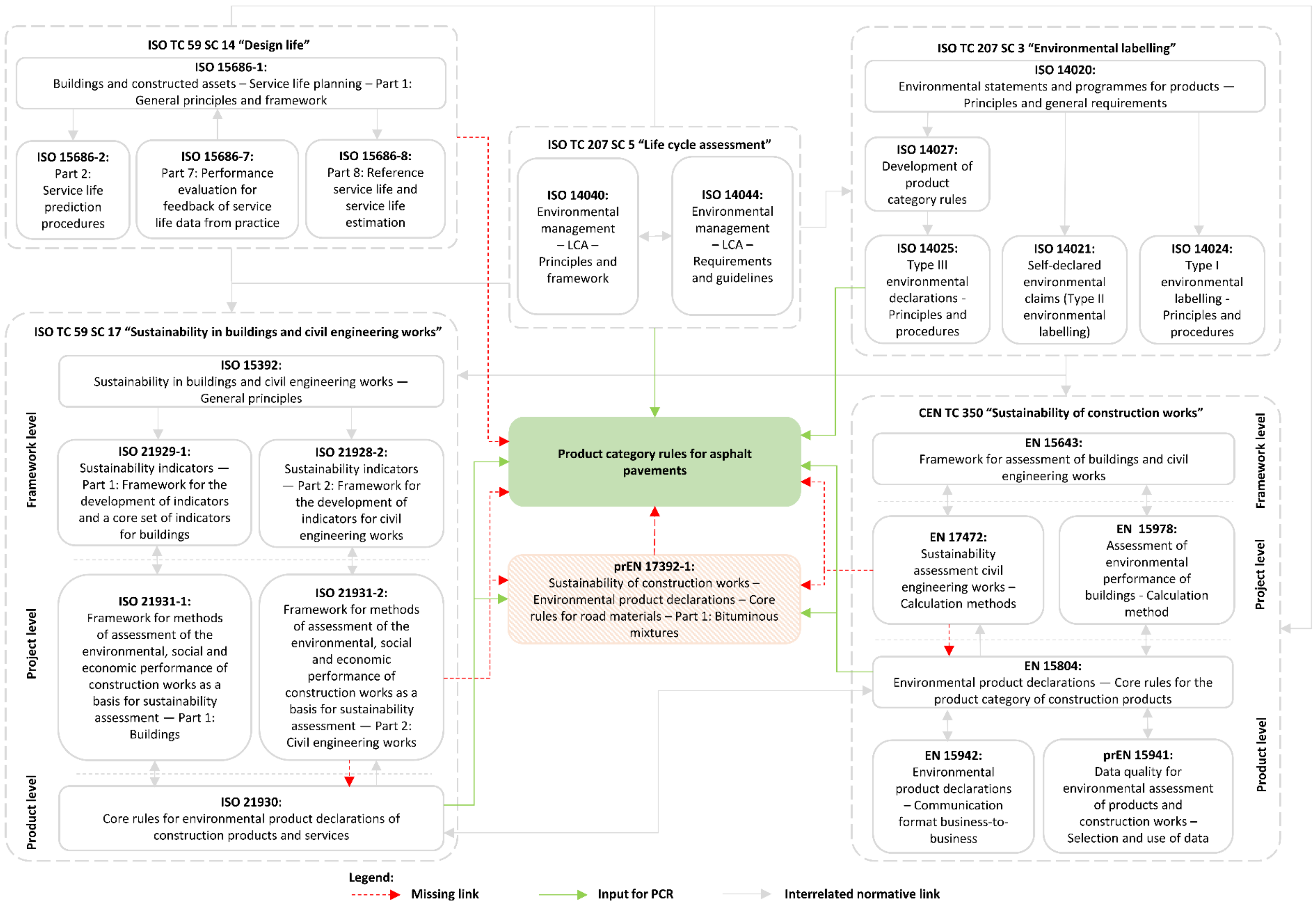


Figure 1 Overview of interrelated normative frameworks for the environmental profiles of asphalt pavements

4 Overview of PCRs specific to asphalt mixtures

Although EN 15804+A2 and ISO 21930 are a step forward for the construction industry when it comes to standardised environmental profiles, it must be noted that different construction products and/or industries often use different scopes, system boundaries, and impact categories. Since there is no core-PCR for asphalt pavements, stakeholders from the asphalt industry are individually developing more detailed PCRs. The first PCR for asphalt mixtures in the United States was developed by the National Asphalt Pavement Association (NAPA) (US-PCR) in 2016. During its development, stakeholders from the asphalt industry, public agencies, and private road owners were engaged (Rangelov et al., 2021). NAPA has issued a second version of their PCR which is valid until 2027. Some key changes between the first and second version are: ISO 21930 as core PCR instead of EN 15804, improved upstream datasets, requirements for portable asphalt plants, clarified system boundaries for secondary (recycled) materials, and enhanced reporting of life cycle impact assessment (LCIA) indicators based on foreground data (NAPA, 2022).

The European Asphalt Pavement Association (EAPA) published their guidance document in 2017 (EU-PCR) (EAPA, 2017). It was developed using relevant documentation from countries such as the US and Norway. It was later transformed into the draft PCR for EN 17392-1 (Rangelov et al., 2022); however, this draft PCR was rejected by the European Committee for Standardization (CEN). Therefore, its further development remains unclear. Its rejection can possibly be explained by the fact that EAPA used the original EN 15804 standard as a baseline while this standard has since been updated twice. Nevertheless, EAPA claims that their PCR complies with the latest EN 15804+A2:2019 version.

In addition to the US and the EU asphalt pavement associations, individual countries also developed (inter)national PCRs for asphalt mixture production. Norway was one of the first countries that published a specific PCR for asphalt production (NO-PCR). The Norwegian EPD Foundation (EPD-Norge) originally developed their PCR in 2016 together with a group of representatives from the asphalt industry and research institutes. EPD-Norge is aware of the work done by EAPA, so they stated that a revision of the Norwegian PCR should be considered to align both scopes once the new EN 17392-1 is published (EPD-Norge, 2022).

In 2018, EPD International released their specific PCR in the framework of the International EPD System for asphalt mixtures (SE-PCR). EPD International is based in Sweden; however, the geographical scope of their PCR is valid for the entire Europe. Since 2018, their PCR has been updated three times. The first two updates were only minor editorial changes. The most recent version, issued in 2019, included some extra editorial changes but also clarified the terms of use. Additionally, this PCR was used as a baseline to develop an Australian appendix (AU-PCR) in 2019 (EPD Australasia, 2019).

Lastly, the Netherlands published a PCR for asphalt mixtures in 2020 using the Dutch Environmental Performance Assessment Method for Construction Works as a baseline (NL-PCR). In 2022, the second version of the PCR was published. Note that the Dutch PCR is assigned to the Permanent Committee on Sustainability of the working group bituminous construction works. Their aim is to update the PCR annually to keep it in line with the latest developments. In their PCR they also briefly mention the rejected EN 17392-1 draft. However, they only refer to it as a concept because they do not expect a final version to be released in the next few years (Van der Kruk et al., 2022).

There is currently no specific PCR for asphalt pavements in Belgium; however, there is a national EPD program that started in 2016. The rules for the uptake of specific EPDs in a federal database were laid down in a legislative document prepared by the Federal Public Administration of Health and Environment; thus, there is no private PO in Belgium (Passer et al., 2015). Nevertheless, there is a national PCR for construction products using EN 15804+A2 as a starting point (Federal Public Service for Health Food Safety and Environment, 2022). Note that this PCR serves as the reference to discuss the LCA guidelines for the analysis of asphalt pavements in Belgium (BE-PCR) in this research.

5 Discussion of the PCRs' key differences

To understand how the selection of a specific PCR can influence the results, it is important to highlight the key differences in the state-of-the-art of asphalt pavement PCRs. The following section provides a detailed discussion of the listed PCRs, also considering the missing normative background frameworks. A summary of the key aspects of each PCR can be found in Table 1.

5.1 Mandatory life cycle phases

ISO and CEN's core PCRs for construction products provide a framework where the life cycle of construction products is divided into four life cycle phases: production phase (A1-A3), construction phase (A4-A5), use phase (B1-B7), and end of life (EOL) phase (C1-C4). Additionally, they provide an extra module D to address the net benefit and loads beyond the system boundary of the analysis. As a minimum, modules A1-A3, C1-C4, and D should be included in the EPD of construction products. Modules C1-C4 and D may be omitted if the product cannot be physically separated at the EOL, if it is no longer identifiable at the EOL because of a chemical or physical transformation process, and if it does not contain biogenic carbon (CEN, 2021d; ISO, 2023a). Of note, the milling of old pavements results in reclaimed asphalt pavement (RAP), which is a clean waste stream, so these conditions do not apply to asphalt mixtures.

Figure 2 provides an overview of the modules considered per PCR. EAPA and NAPA do not include the minimum set of modules as they limit their scope to mixture production only (A1-A3) (EAPA, 2017; NAPA, 2022). The SE-PCR and AU-PCR set their minimum scope as cradle to gate considering only A1-A3 like EAPA and NAPA. Therefore, their basic system boundaries are not compliant with the core PCRs. However, they also provide the option to broaden the scope including other modules, which makes their EPDs conform the standards (EPD Australasia, 2019; EPD International, 2022). The BE-PCR for construction products mandates the transport phase to the construction site (A4) in addition to A1-A3 required in EN 15804+A2 (Federal Public Service for Health Food Safety and Environment, 2022). The NO-PCR has two sets of system boundaries. Cradle-to-gate studies include modules A1-A4, C1-C4, and D. If the scope is broadened to a cradle-to-grave study, modules A5, B1, and B4 have to be included as well (EPD-Norge, 2022). The NL-PCR is currently the most comprehensive PCR when it comes to system boundaries. It requires all modules except B2 and B3; however, the client might request these as optional. For module B1, the NL-PCR provides a table with average leaching values; however, it only applies leaching to asphalt surface layers (Van der Kruk et al., 2022). Note that none of these PCRs cover modules B5-B7 as they are not considered to be of interest for asphalt pavements.

Based on the comparison, two key remarks emerge. First, the use phase in the core PCRs does not refer to the impact of the user, but to using the product itself. This means that the core PCRs provide room to include impacts related to leaching, maintaining, repairing, and/or replacing the pavement, but not for road user impacts. Thus, none of the specific PCRs include road user impacts even though literature describes this as a clear research gap in existing pavement LCA studies (Araújo et al., 2014; Gruber and Hofko, 2023; Santos et al., 2018a). This can be addressed when CEN EN 17472 calculation method for the sustainability assessment of civil engineering works is included in the PCR normative background because it includes an eighth submodule in the use phase for the impact of the user's utilization or consumables (CEN, 2022).

Table 1 Key aspects of PCRs for asphalt mixtures

	BE-PCR	US-PCR	EU-PCR	NL-PCR	NO-PCR	SE-PCR	AU-PCR
Origin	Belgium	United States	Europe	Netherlands	Norway	Sweden	Australia
PO	FPS	NAPA	EAPA	NMD	EPD-Norge	EPD International	EPD Australasia
Underlying standards	EN 15804+A2 ISO 21930	ISO 21930 ISO 14025	EN 15804 ISO 14025 ISO 14040 ISO 14044	EN 15804+A2 ISO 14040 ISO 14044	EN 15804+A2	EN 15804+A1 ISO 21930 ISO 14025 ISO 14040 ISO 14044	EN 15804+A1 ISO 14025 ISO 14040 ISO 14044
System boundaries	See Figure 2						
FU or DU[a]	1 tonne annual or 1 m^2 annual	1 tonne	1 tonne	1m^2 or 1 m^2 annual	1 tonne or 1 m^2	1 tonne or 1 m^2	1 tonne or 1 m^2
Use of RSL	Yes[b]	No	No	Yes	Yes[c]	Yes[b]	Yes[c]
Cut-off	1% by total mass or energy use[e]	1% by total mass or energy use[d,e]	1% by total mass or energy use[e]	1% by total mass or energy use[e]	1% by total mass or energy use[e]	1% by total mass or energy use[e]	1% by total mass or energy use[e]
Allocation	EN 15804+A2	ISO 21930	EN 15804+A2	EN 15804+A2	EN 15804+A2	EN 15804+A2	EN 15804+A2
Module D	Mandatory	Not included	Not included	Mandatory	Mandatory	Optional	Optional

Where PO = program operator; FPS = Federal Public Service for Health, Food Chain Safety, and Environment; NAPA = National Asphalt Pavement Association; EAPA = European Asphalt Pavement Association; NMD = Dutch Environmental Database; FU = Functional Unit; DU = Declared Unit; RSL = Reference Service Life; MKI = Environmental Cost Indicator

[a] If the functional or declared unit is expressed per tonne, this is per metric tonne.

[b] The PCR only requires an RSL for studies that include the use phase (B1-B7).

[c] The PCR only requires an RSL for studies that go beyond the A4 transport phase.

[d] Additives with a dosage superior to 0.01% by mass of mix and no available upstream data or proxy will be listed as data gap.

[e] The total sum of neglected input flows shall not exceed 5% of the energy usage and mass per phase (A1-A3, A4-A5, B1-B5, C1-C4 and D)

	Civil engineering works assessment information																	
	Civil engineering works life cycle information																	Information beyond the life cycle
	A1 – A3			A4 – A5		B1 – B8								C1 – C4				D
	Initial production			Initial construction		Use phase								End of life phase				Benefits and loads beyond the system boundary
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	C1	C2	C3	C4	D
	Raw material supply	Transport to production plant	Asphalt production	Transport to construction site	Pavement construction	Use (e.g., leaching)	Maintenance (e.g., sealing)	Repair (e.g., crack filling)	Replacement (e.g., mill & replace)	Refurbishment	Operational energy use	Operational water use	Users use (external)	Pavement deconstruction	Transport to processing site	Waste processing	Disposal	Reuse, recovery, recycling, potential
US-PCR	M	M	M															
EU-PCR	M	M	M															
NL-PCR	M	M	M	M	M	M	O	O						M	M	M	M	M
NO-PCR	M	M	M	M	O	O			O					M	M	M	M	M
SE-PCR	M	M	M	O	O	O	O	O	O					O	O	O	O	O
AU-PCR	M	M	M	O	O	O	O	O	O					O	O	O	O	O
BE-PCR	M	M	M	M	O	O	O	O	O					M	M	M	M	M

Figure 2 Overview of system boundaries for asphalt pavements using the ISO 21930, EN 15804+A2, and EN 17472 standards

Where M = Mandatory, and O = Optional

Secondly, there are no fixed agreements on the system boundaries to be considered, which also in literature is an important point of discussion. Some researchers state that unfair comparisons are made without considering the impact beyond the gate as pavements are generally designed for multidecade service lives (Rangelov et al., 2022; Strömberg et al., 2020). Others question the format of comprehensive EPDs, since a lot of information beyond the production phase is out of a product owner's control and is more likely to be known once a specific project is designed (Soust-Verdaguer et al., 2023; Strömberg et al., 2020; Wayman et al., 2014). Design-build projects are often a rarity; thus, in most cases asphalt producers have no influence over the inputs of the EPD beyond their production process as they are case-specific. For example, the durability of an asphalt layer does not depend only on the quality of the material production and construction processes but also on external factors like traffic, environmental conditions, and surrounding layers. Nevertheless, this information is important for policy makers and road agencies. Thus, the authors advise to have two sets of system boundaries for the pavement sector. For contractors, it is advised to only have product-specific EPDs that include modules A1-A3, C1-C4, and D. Additional information like the transportation distance to the construction site may be requested in the procurement process without being part of the product-specific EPD. Afterwards, road owners and academics can use these EPDs as building blocks to produce project-specific EPDs that also include modules A4-B8.

5.2 Use of a reference service life

For the authors, it is of utmost importance to consider the durability aspect of an asphalt mixture in EPD because a mixture can perform exceptionally well in a cradle-to-site analysis but have a very low performance once placed on the road. However, estimating the actual SL is a difficult task (Wayman et al., 2014). For EPDs covering the use phase, the core PCRs mandate the use of an RSL. The RSL describes a product's SL under a set of reference in-use conditions and can form the basis to estimate the SL under any other conditions (CEN, 2021d).

NAPA's and EAPA's PCRs only focus on modules A1-A3, so they do not consider any RSL (EAPA, 2017; NAPA, 2017). The BE-PCR, SE-PCR and AU-PCR provide room for multiple system boundaries, so the use of an RSL is not always mandatory. The BE-PCR and SE-PCR require an RSL if the EPD includes the use phase (EPD International, 2022; Federal Public Service for Health Food Safety and Environment, 2022). The AU-PCR requires an RSL once the study goes beyond the transport phase to the construction site (EPD Australasia, 2019). Interestingly, the SE-PCR and AU-PCR refer to an EAPA document for RSLs while EAPA's own PCR does not cite it. That document shows RSLs ranging between 10 and 25 years depending on the road and mixture category (EAPA, 2007). The NO-PCR follows the same approach as the AU-PCR, so it only includes an RSL if the study goes beyond delivery to the construction site. For the asphalt surface layer, the RSL varies between 4 and 17 years depending on the annual average daily traffic. Interestingly, the NO-PCR allows to deviate from this RSL if the value can be documented (EPD-Norge, 2022). Studies using the NL-PCR must include all life cycle phases, so an RSL is always mandatory. The NL-PCR has the most detailed information regarding RSLs with values ranging between 10 years for surface layers to 100 years for mixtures used in water works (Van der Kruk et al., 2022).

Again, some important observations emerge. Firstly, mechanical tests can show a difference in performance for mixtures that are categorised under the same FU as technical requirements contain only minimal required performance. When using a fixed RSL, the difference in quality will not be shown. Secondly, most EPDs are developed for only one life cycle and do not include an analysis period as more comprehensive LCA studies do. If studies consider the same number of maintenance interventions and only change the RSL, the difference in RSL will have no effect on the environmental impact. In other words, in their current form, EPDs include only to some extend mechanical performance; they only provide information regarding expected performance but do not account for it in the analysis. Some changes are proposed to capture the effect of mixture durability on the EPD results. Instead of using a fixed RSL per product category, it is suggested considering a quality index to obtain a variable RSL for product-specific EPDs, like the NO-PCR does (EPD-Norge, 2022). The quality index can then be used to adjust the RSL using the actual mechanical properties of the analysed mixture compared to the average properties of the mixture category. Furthermore, the results can be recalculated into impacts per year like the NL-PCR proposes. Another approach is to include a reference study period (RSP) as suggested in EN 17472. This will adjust the impacts for modules B1-B8 using the ratio of the RSP to the RSL. In other words, if the RSL is lower than the RSP, a higher use phase impact is taken into consideration. If the RSL is higher than the RSP, the use phase is considered only partially (CEN, 2022). Note that EN 17472 only applies this ratio to the modules of the use phase and not the impacts for the production, construction, and deconstruction phase. Following the system boundaries proposed in the previous section, this approach would only be of interest for project-specific EPDs. If detailed information is available, project-specific EPDs could also incorporate the mechanical performance estimated from mechanistic-empirical pavement design methods.

5.3 Functional or declared unit

LCA standards mandate the selection of an FU or declared unit (DU). An FU defines how a product's identified functions or performance characteristics are quantified. If an FU cannot unequivocally be described because multiple functions exist, or the precise function is unknown or not stated, a DU is used (CEN, 2021d, 2006a, 2006b). Note that EN 17472 does not refer to an FU or DU but a functional equivalent which represents the technical characteristics and functionalities of the civil engineering works (CEN, 2022).

EAPA and NAPA use the same DU, namely "1 metric tonne of asphalt mixture" (EAPA, 2017; NAPA, 2022). NAPA does not establish an FU because performance characteristics are inherently a function of the pavement design while their study only focusses on asphalt mixture production. The NL-PCR always requests a cradle-to-grave analysis, so their FU covers all impacts from phase A1 through D for 1 m² of paved mixture. They also allow the FU to be recalculated into an impact per m² per year (Van der Kruk et al., 2022). The NO-PCR provides three FUs depending on the system boundaries (EPD-Norge, 2022):

- Only modules A1-A3, C1-C4, and D are included: "1 tonne of manufactured asphalt mixture delivered to the construction site (A1-A4) including EOL treatment (C1-C4) and potential benefits/loads outside the product system (D)".
- Module A5 is also included: "1 m² of asphalt mixture that fulfils the specified quality criteria during the reference service life of the constructed pavement layer".
- Modules B1-B4 are also included: "1 m² of asphalt mixture that fulfils the specified quality criteria during the estimated service life of the entire asphalt pavement".

Both SE-PCR and AU-PCR have the same list of reference units consisting of four FUs/DUs in total. Three of them are like the NO-PCR. Their first part is identical; however, as they do not mandate modules C1-C4 and D, these modules are not specifically stated. The fourth DU is comparable with EAPA's and NAPA's DU: "1 metric tonne of manufactured asphalt mixture" (EPD Australasia, 2019; EPD International, 2022). The BE-PCR for construction products does not mandate a specific FU or DU. It does however provide a clear framework for defining an FU. An FU should include the function or services provided ("what"), a quantity ("how much"), an expected level of quality ("how well"), and the duration or lifetime of the product ("how long") (Federal Public Service for Health Food Safety and Environment, 2022).

It is found that the selection of an FU versus a DU is purely based on the system boundaries. If the analysis goes beyond the transport phase to the construction site (A4), the PCR specifies the reference unit as an FU while it is a DU if it does not go beyond this phase. Each asphalt mixture belongs to a certain mixture class and serves the function corresponding to that class. Therefore, the function of a mixture can influence the results (Gruber and Hofko, 2023; Mattinzioli et al., 2022b). Because of the effect of the function on the environmental impact, asphalt mixtures cannot always be cross compared. The use of a simple DU based on mass, length, area, or volume will not prevent this and thus, it should be avoided. Therefore, two sets of FUs are proposed by the authors: for the product-specific EPDs, the impacts can be analysed per tonne and year whereas for project-specific, EPDs can be reported per m² and year. The authors also propose to widen this FU with parameters like mixture function and traffic level to avoid unfair comparison (e.g., AC for base layers versus AC for surface layers, or AC for low traffic roads vs SMA for high traffic roads).

5.4 Allocation methods

Generally, all PCRs refer to EN 15804 for allocation procedures of their foreground processes (EAPA, 2017; EPD-Norge, 2022; EPD Australasia, 2019; EPD International, 2022; Federal Public Service for Health Food Safety and Environment, 2022; Van der Kruk et al., 2022). Only NAPA refers to ISO 21930 instead of EN 15804 for their baseline allocation procedures (NAPA, 2022). ISO 21930 and EN 15804+A2 follow the guidance given in ISO 14044; however, they refine the basic procedures and assumptions to reflect the goal and scope of their standards. In first instance, allocation should be avoided as far as possible by creating additional sub-processes. If this is not possible, co-product allocation is used. In general, EN 15804+A2 proposes co-product allocation based on economic values. However, if the share is less than 1%, the co-product may be neglected. Furthermore, if the difference in revenue from the co-products is low, allocation based on physical properties (e.g., mass or volume) is allowed. Allocation of reuse, recycling, and recovery depends on the end-of-waste (EOW) status. All impacts of waste processing during any of the modules in the product’s system are included in the corresponding module within the system boundary. Loads and benefits of secondary materials, secondary fuels, or recovered energy leaving the system boundary are assessed in module D, see section 5.6. Note that whenever the upstream data does not reflect these allocation principles, it should be clearly stated and justified in the PCR (CEN, 2021d).

The most discussed allocation procedure in the PCRs is linked to energy use to produce an asphalt mix. In general, there are three approaches:

- Divided equally across all mixtures using the plant’s annual energy consumption and total production quantity (EPD-Norge, 2022; EPD Australasia, 2019; NAPA, 2022). This also means there is no difference in energy consumption for the production of warm-mix asphalt (WMA) versus hot-mix asphalt (HMA) as clearly stated in the US-PCR (NAPA, 2022).
- Using measured energy consumptions. Note that the Netherlands only allows this if there is a minimum of five measurements of at least one hour for the specific mixture (Van der Kruk et al., 2022).
- Based on a thermodynamic model. The AU-PCR specifies the mixture consumption, specific heat capacity of the materials, moisture content, and the plant’s overall efficiency as inputs (EPD Australasia, 2019). The NL-PCR includes a more advanced energy-allocation model based on an energy balance analysis, which uses more detailed inputs: total energy use, binder heating system, type of asphalt plant, moisture contents, production quantities per mixture type, temperatures per mixture type, and RAP use per mixture type.

5.5 Data quality and exclusion of inputs and outputs

In general, there are two types of data: foreground and background data. Foreground or primary data are directly linked to the production and downstream processes of pavements. This data can be directly collected from the industry through measurements or observations. Background data is used to describe upstream processes that are not directly in the scope of observation. For background data, inventories or literature studies are often used (Bhat et al., 2021; Mattinzioli et al., 2021; Palumbo et al., 2020; Vandewalle et al., 2020). Representative datasets are crucial for the LCA of pavements as there is a direct relationship between data availability and accuracy of the results (Subedi et al., 2018). All PCRs use a cascade system to prioritise the use of data (EAPA, 2017; EPD-Norge, 2022; EPD Australasia, 2019; EPD International, 2022; Federal Public Service for Health Food Safety and Environment, 2022; NAPA, 2022; Van der Kruk et al., 2022):

- It is encouraged to use as much primary data as possible; however, it cannot be older than five years. Additionally, the data should be collected over a long enough period (the previous production year at a minimum).
- If not available, product or facility specific EPDs are advised.
- If not available, industry average EPDs are recommended.
- If not available, freely available public datasets (including critically reviewed LCA studies) that fulfil prescribed data quality characteristics for precision, completeness, and representativeness are suggested. Note that in this case national databases are preferred over international datasets.
- Finally, proxy data can be used if none of the above is available. Note that a detailed list with proxy data for commonly used additives is provided in the NL and US-PCR.

None of the PCRs, except for the BE-PCR for construction products, refers to CEN EN 15941 standard for the selection and use of data in EPDs. Also interestingly, the PCRs advise to use freely available public datasets over commercial databases (e.g., ecoinvent or Sphera, formerly known as GaBi) if no EPDs exist despite commercial databases being considered more comprehensive and data quality driven (Lu et al., 2017). This is because transparency, inclusiveness, and low cost are key in the context of GPP (Rangelov et al., 2022). Furthermore, pavement materials are often produced locally and commercial databases may not appropriately reflect local conditions (Rangelov et al., 2021). Note that they are only considered preferential over commercial databases if the quality of the data is not compromised.

In general, all PCRs apply the same cut-off for the exclusion of inputs and outputs in case of insufficient input data or data gaps, namely 1% of the total primary energy use and 1% of the total mass input, which is in line with EN 15804+A2. However, the total of neglected flows per module can only be 5%. Additionally, all PCRs state that materials which are considered environmentally relevant should always be included in the EPD, even when their mass is below the cut-off percentage. Examples of products that should be included are polymers for the modification of bitumen, pigments, liquid antistrips, recycling agents, warm-mix additives, emulsions, and fibres (EAPA, 2017; EPD-Norge, 2022; EPD Australasia, 2019; EPD International, 2022; NAPA, 2022; Van der Kruk et al., 2022).

5.6 Modelling the benefits and burdens of recycling

From a technical point of view, there are five possible EOL scenarios for asphalt pavements, all of which result in different processing techniques and loads/benefits beyond the system boundary (Gruber and Hofko, 2023; Santero et al., 2011; Santos et al., 2015; Vandewalle et al., 2020):

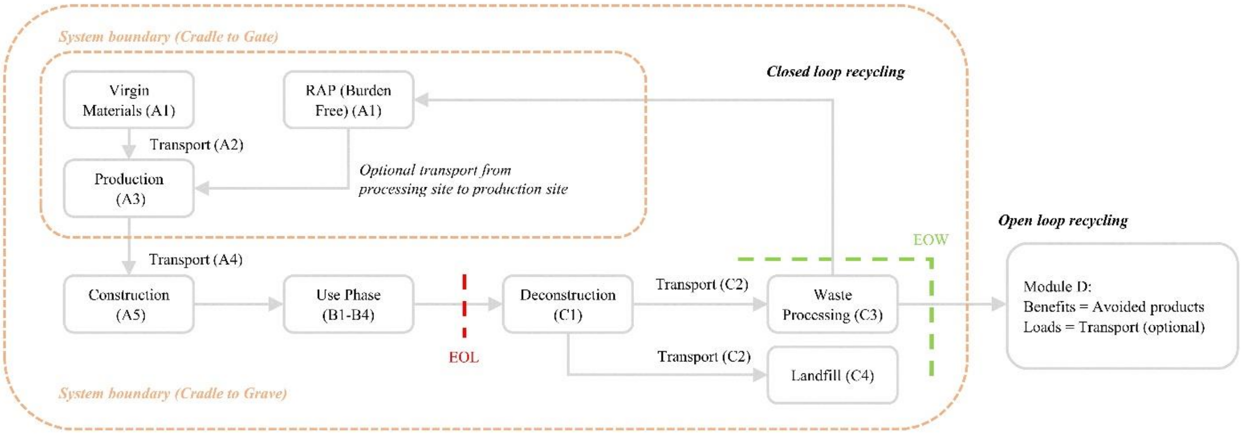
- It can remain in situ and serve as a support for a subsequent pavement structure.
- It can be demolished and recycled in new bituminous bound products. This is preferred as both virgin aggregates and bitumen can be substituted.
- It can be demolished and recycled in new unbound or cement bound products. This can be seen as downcycling because the binding action of bitumen is lost, and only virgin aggregates are substituted.
- It can be demolished and landfilled. Landfilling is a poor choice because RAP is typically considered to be 100% recyclable. Therefore, this scenario should only be modelled if there is specific reason to believe that RAP cannot or will not be recycled.
- Sometimes, a major waste treatment of RAP is needed if it contains hazardous materials like tar or pitch binders. In this case, it first must be thermally cleaned using temperatures up to 1000°C (Monir et al., 2020), which completely removes the tar-containing bitumen. Afterwards, the dust and aggregates can be recycled.

Data provided by the Belgian impartial body for the inspection of construction products (COPRO) showed that 51 ktonnes of RAP had to be thermally cleaned in 2022 because it contained tar. Considering the mass cut-off rule of 1%, it should be included in an industry average EPD as this was about 3% of the yearly RAP production rate. However, this comes from old construction sites and tar is no longer allowed in new asphalt production. Therefore, it is advised to only consider this scenario in project-specific studies encountering hazardous substances. Note that in this case, the entire scope of the study changes as the focus does not lie on the production and construction of a new pavement, but on the removal of an old one.

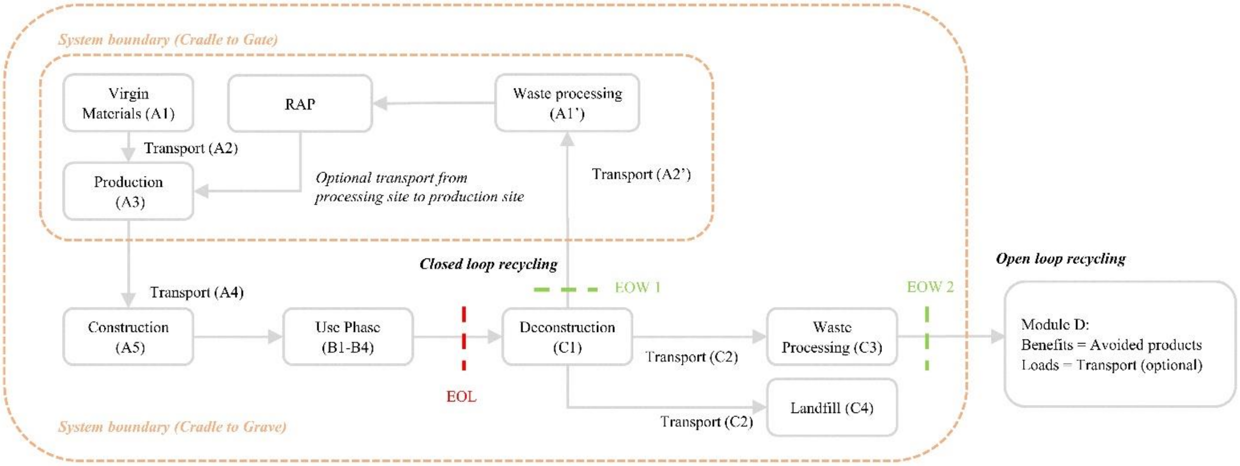
To determine the benefits and loads of recycling asphalt mixtures, it is important to determine the EOW status. The EOW criteria determine the point after which an asphalt mixture ceases to be waste and becomes RAP. The substitution effects in Module D are only calculated for the net output flows. This means there is a difference in modelling between closed or open loop recycling of RAP, see Figure 3. The quantity of RAP that can be reused for the reconstruction of the same pavement is modelled as closed loop recycling. This amount is allocated to the product system under the study and not module D. The amount of RAP stockpiled or recycled in a different product’s system is modelled as open loop (Bhat et al., 2021; Gruber and Hofko, 2023; Rangelov et al., 2022, 2021).

EN 15804+A2 refers to the EOW criteria of the European Commission. That document states that a product can only cease to be waste if it is commonly used for a specific purpose, a market for it exists, it fulfils technical requirements and meets existing legislation, and its use will not lead to overall adverse effects on the environment or human health (Delgado et al., 2008). This is interpreted in two different ways. The NL-PCR states that RAP must be processed into an aggregate before turning into a secondary material (Van der Kruk et al., 2022). Therefore, all impacts up to and including the crushing are allocated to the EOL of asphalt mixes. All subsequent impacts like transport or further processing are allocated to the next production process; however, most contractors use mobile crushers at their production plant eliminating those additional impacts. Therefore, this approach often models RAP as burden free when entering the production process (Moins et al., 2023), see Figure 3A.

A. End of waste = Processed RAP



B. End of waste = Milled RAP (incorrect modelling according to EN 15804+A2)



C. End of waste = Milled RAP (correct modelling according to EN 15804+A2)

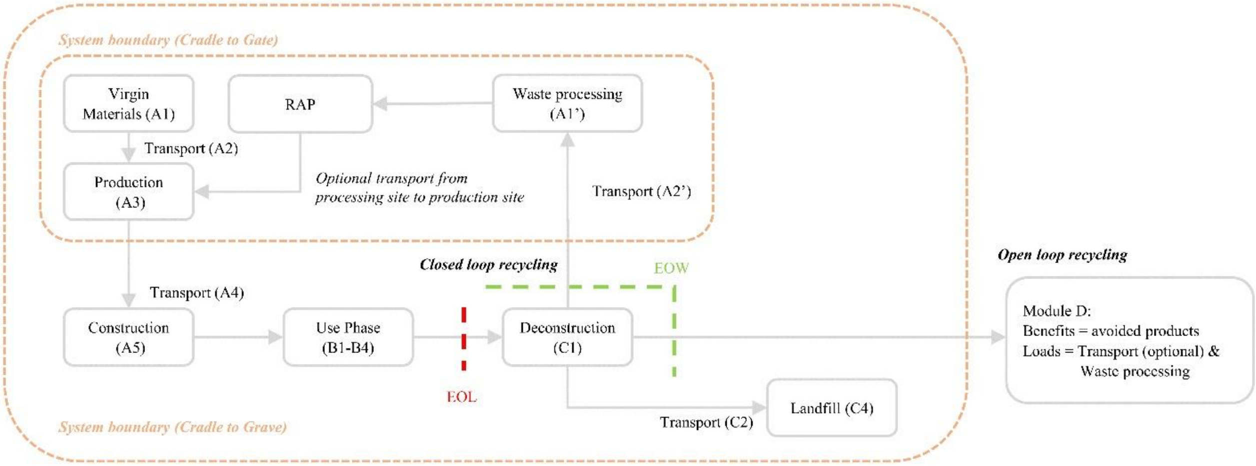


Figure 3 System boundaries with varying EOW locations

All other PCRs locate the EOW status once the milled RAP is loaded into a truck after deconstruction. They apply the polluter pays principle. If there is an inflow of secondary materials into the system boundaries (i.e., closed loop recycling), the transportation and waste processing of this quantity are considered under the initial production phase (modules A1-A3). However, if there is an outflow of secondary materials to recycling (i.e., open loop recycling), the transportation and waste processing of this quantity are considered at the EOL phase (modules C2 and C3) (EAPA, 2017; EPD-Norge, 2022; EPD Australasia, 2019; EPD International, 2022; NAPA, 2022), see Figure 3B. Of note, EN 15804+A2 clearly states that "*Any declared net benefits and loads from net flows leaving the product system that have passed the EOW state shall be included in module D"* (p.32, (CEN, 2021d)). Subsequently, if the PCRs locate their EOW directly after deconstruction in C1, it is not possible to have a C2 and C3 phase as this should be moved to module D, see Figure 3C. In other words, these PCRs use a double set of EOW criteria, which is clearly an inconsistency in their frameworks.

The above discussion clearly shows that there is no consensus among the PCRs on how to model the benefits and loads of recycling RAP. Furthermore, it is shown that within the same PCR, the system boundary can influence modelling the loads of recycling RAP, which creates inconsistencies in studies under the same PCR. Therefore, the difference in EOL modelling can be seen as one of the main factors why LCA studies of pavements may be hard to compare. The authors propose to follow EN 15804+A2 and the NL-PCR, i.e., to use the criteria proposed by the European Commission and locate the EOW after module C3.

6 Quantitative evaluation of methodological framework differences

The previous sections discussed the key differences between the existing PCRs. In summary, the biggest differences were the mandatory modules, the use of an RSL, the cut-off, and the location of the EOW status. To quantitively evaluate these differences, an LCA is carried out. First, an example is analysed using the PCRs in their present form to visualise the variance in environmental impacts. Afterwards, a scenario analysis is performed to evaluate the origin of the discrepancies in results more in depth.

6.1 LCA methodology

The following FU is selected: *"1 m² of paved surface layer including EOL treatment and benefits/loads outside the product system that fulfils the quality criteria during its RSL for a pavement with a traffic load lower than 16 million equivalent standard axle loads (ESALs)."*

Four different asphalt mixtures are selected using information from a previous research project (Moins et al., 2021). A detailed description of the mixtures is provided in Table 2. The LCA records can be found in Table 3. Note that Eurobitume's LCI for bitumen is used; however, an EPD for PMB is currently unavailable. A PMB record is modelled using information from a previous Eurobitume LCI report combined with the NL-PCR (Eurobitume, 2021, 2012; Van der Kruk et al., 2022). For all equipment types the same baseline LCA record is used, but their fuel consumption is adjusted using information from the US Environmental Protection Agency and a previous research project (Moins et al., 2023).

Primary data regarding transport distances were collected using the asphalt mixture technical datasheets: 138 km for crushed aggregate to plant by truck, 87 km for natural sand to plant by barge, 164 km for filler to plant by truck, 25 km for bitumen to plant by truck, 465 km for the cellulose fibres, and 210 km for WMA additive and rejuvenator to plant by truck. For the transport between the production plant and the work site (modules A4 and C2), a distance of 100 km is considered as suggested by the BE-PCR for construction products (Federal Public Service for Health Food Safety and Environment, 2022).

At this moment, there is no primary information available to determine the average energy consumption per mixture type in Belgium. Therefore, a thermodynamic model is used to calculate the energy consumption during production (Santos et al., 2018a; Vandewalle et al., 2020). However, instead of using a fixed heating temperature for all materials, it is assumed that the virgin aggregates are overheated to compensate for the lower temperatures for RAP and bitumen. Thus, the temperature of the aggregates is calculated using the formula provided in EN 12697-35 (CEN, 2016b). Rejuvenators are used to increase the recycling rates without having a negative effect on performance; however, a positive indirect effect is that the production temperature can also be decreased (Eltwati et al., 2023; Foroutan Mirhosseini et al., 2020; Jacobs et al., 2021). Hence, the AC10 50/70 RAP mix can also be produced at a lower temperature than the other two HMA mixes, see Table 2.

Table 2 Detailed description of mixtures for surface layers used in the scenario analysis.

	AC10 50/70 HMA	**AC10 50/70 RAP**	**AC10 50/70 WMA**	**SMA10 45/80-50 HMA**
Thickness (cm)	4	4	4	4
Bulk density (kg/m^3)	2307	2326	2307	2205
Mass per FU (tonne/m^2)	0.092	0.093	0.092	0.088
Traffic load (10^6 ESALs)	< 16	< 16	< 16	< 16
RSL (years)[a]	14	14	14	16
Crushed aggregate (%)[b]	75.7	47.6	75.7	86.9
Round aggregate (%)[b]	13.1	4.7	13.1	na
Added filler (%)[b]	5.4	0.4	5.4	6.8
RAP (%)[b]	na	43.8	na	na
Virgin binder (%)[b]	5.8	3.35	5.77	6.20
WMA additive (%)[b]	na	na	0.03	na
Rejuvenator (%)[b]	na	0.15	na	na
Cellulose fibres (%)[b]	na	na	na	0.05
Mixing temperature (°C)	180	160	140	180
Natural gas consumption (MJ/tonne)[c]	270.5	246.2	230.1	271.3
Electricity use (kWh/ton)	6.1	6.1	6.1	6.1
Net output of RAP (%)[d]	100	56.2	100	100
- **to asphalt (%)**[d]	61.8	34.7	61.8	61.8
- **to others (%)**[d]	38.2	21.5	38.2	38.2
- **Avoided bitumen (kg/m^2)**[d]	3.1	1.7	3.1	3.0
- **Avoided filler (kg/m^2)**[d]	5.6	3.2	5.6	5.4
- **Avoided aggregates (kg/m^2)**[d]	32.7	18.6	32.7	31.6
- **Avoided sand (kg/m^2)**[d]	45.3	25.7	45.3	43.8

[a] The RSLs were taken from the NL-PCR (Van der Kruk et al., 2022).

[b] By mass of asphalt mixture

[c] Determined using the model provided by (Santos et al., 2018a; Vandewalle et al., 2020).

[c] Based on primary data for 2022 from COPRO (neglecting RAP containing tar).

Table 3 Overview LCA records

	LCA Record	Source
Crushed aggregates	Belgian limestone, sandstone, and porphyry aggregates for use in mortar, concrete and bituminous or hydraulically bound mixtures	(Fediex, 2022)
Filler	Lime {Europe without Switzerland} | lime production, milled, loose | Cut-off, U	ecoinvent 3.9.1
Round aggregates	Sand {RoW}| sand quarry operation, extraction from riverbed | Cut-off, U	ecoinvent 3.9.1
Bitumen	Life-cycle inventory to produce 1 tonne of bitumen – with infrastructure	(Eurobitume, 2021)
PMB[a]	96.5% Life-cycle inventory to produce 1 tonne of bitumen – with infrastructure 3.5% Synthetic rubber {RER}| synthetic rubber production | Cut-off, U	(Eurobitume, 2021, 2012) ecoinvent 3.9.1
WMA additive	Anova® 1503 warm mix additive	(Cargill, 2021)
Rejuvenator	Anova® 1817 rejuvenator	(Cargill, 2022)
Cellulose fibres[b]	Cellulose fibre {RoW}| Cellulose fibre production | Cut-off, U	ecoinvent 3.9.1
Electricity	Electricity, medium voltage {BE}| market for | Cut-off, U	ecoinvent 3.9.1
Natural gas	Heat, district or industrial, natural gas {Europe without Switzerland} | market for heat, district or industrial, natural gas | Cut-off, U	ecoinvent 3.9.1
Diesel	Diesel, burned in building machine {GLO}| market for | Cut-off, U	ecoinvent 3.9.1
Transport	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U Transport, freight, inland waterways, barge {RER}| market for transport, freight, inland waterways, barge | Cut-off, U	ecoinvent 3.9.1
Equipment[c]	Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| machine operation, diesel, >= 74.57 kW, steady-state | Cut-off, U	ecoinvent 3.9.1

[a] Modelled using 96.5% regular bitumen, 3.5% SBS, 72 MJ/ton PMB of extra electricity for mixing the polymer into the PMB, and 500 km transport of the polymer to the refinery.

[b] Selected using the NL-PCR (Van der Kruk et al., 2022).

[c] This is the base dataset; however, consumptions were adjusted based on previous research (Moins et al., 2023).

In 2022, COPRO established that 662 ktonnes of RAP were recycled into cement- or unbound products, 1069 ktonnes were recycled into new asphalt mixtures, and 51 ktonnes had to be thermally cleaned because of the presence of tar. Neglecting the thermally cleaned RAP, this resulted in recycling rates into asphalt mixtures and other products of 61.8% and 38.2%, respectively. It is assumed that virgin filler and bitumen can only be substituted if RAP is recycled into new asphalt mixtures. If RAP is recycled in cement bound or unbound products, the binding action of these materials are lost. Furthermore, based on measurements, COPRO states that RAP in Belgium averagely consists of 5.4% bitumen, 9.9% filler, 35.5% fine aggregates, and 49.2% coarse aggregates. This information is used to determine the burdens and benefits beyond the product system in module D, see net output of RAP in Table 2.

Previous research has shown that global warming potential (GWP) is a good proxy for the overall environmental impact of asphalt mixtures (Hernando et al., 2022). Therefore, to simplify the discussion in this study, only the total GWP indicator of EN 15804+A2 is considered in the results and discussion section. However, to provide references for the other environmental indicators, the results using the full set of EN 15804+A2 indicators for the base scenario (impacts per year using the RSL including additives and EOW located after C3 are provided in Annex A: Environmental impact using EN 15804+A2 indicators for the base scenario.

6.2 Selection of scenarios

It is important to evaluate the origin of the discrepancies in results. Therefore, a scenario analysis is performed to quantitively evaluate the methodological framework differences. In addition to an example analysis of the PCRs in their current form, three parameters are selected using the findings from the previous sections:

1. The effect of using an RSL: one scenario will vary the RSL without expressing the results per year, while a second scenario will alter the RSL expressing the results per year.
2. The effect of using a cut-off: most additives that are used in asphalt mixtures fall under the cut-off limit of 1% by mass, although there may be a high environmental impact linked to them. Two scenarios will be modelled: one will neglect the cut-off and include the impacts of additives; another will apply the cut-off and neglect the environmental impact of additives.
3. The effect of locating the EOW: RAP needs to be crushed and sieved to meet technical requirements for its use in new asphalt mixtures. Therefore, according to the EOW criteria of the European Commission, the EOW should be located after the waste processing of RAP (module C3). Six scenarios will be analysed based on Figure 3: three EOW locations (fixed after C1, fixed after C3, varying between C1 and C3) with two different system boundaries (cradle to gate vs cradle to grave).

6.3 Results and discussion

Figure 4 was prepared as an example to visualise the variance in environmental impact caused by the selection of a specific PCR. Note that EN 15804+A2 states that the individual modules of a product's life cycle may not be added up into a total or sub-total of the life cycle stages except for modules A1, A2, and A3 (CEN, 2021d). However, to facilitate the discussion and to show the effects of the modelling framework, the total value was added. Focussing on the total impact, Figure 4a shows that only considering the mandatory modules results in three different groups with the same total result. Firstly, the US-PCR, EU-PCR, AU-PCR, and SE-PCR can be grouped as they only mandate modules A1-A3. Secondly, the BE-PCR and NO-PCR can be grouped as they mandate modules A1-A4 and C1-D. Finally, the NL-PCR provides the highest total result as it mandates most of the modules.

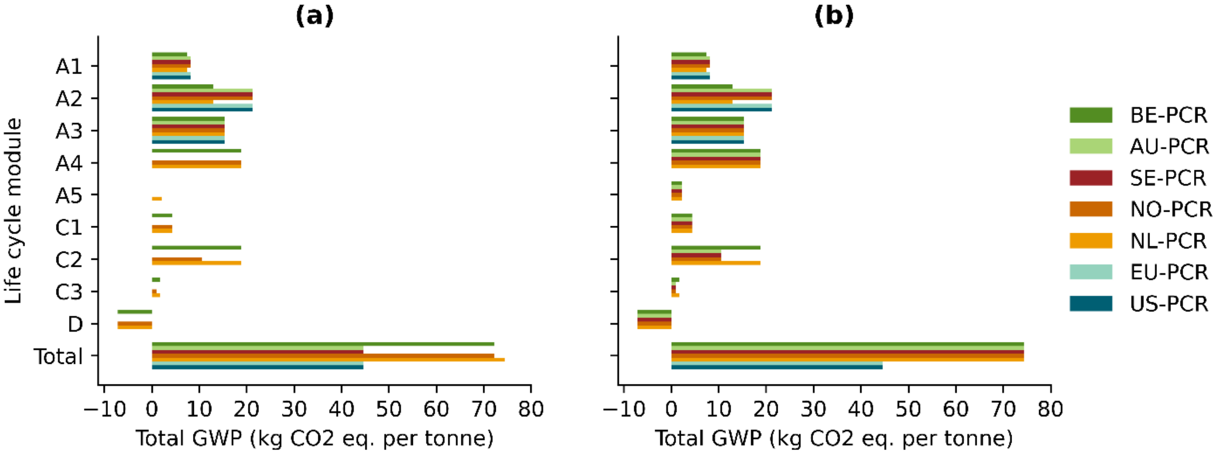


Figure 4 Total GWP per tonne of AC10 50/70 RAP using different PCRs; including only mandatory modules (a); and including optional modules as well (b)

Considering the optional modules as well, see Figure 4b, results in two groups as only the EU-PCR and US-PCR leave no room to go beyond the production gate and thus have no optional modules after module A3. However, focussing on individual modules, for example modules A1 and A2, it can also be concluded that selecting a different PCR will result in a different output even though the same mixture is analysed. In other words, at this moment the PCRs for asphalt pavements are not harmonised. A more detailed discussion of the source of these discrepancies follows next where four different asphalt mixes are compared using the proposed scenarios.

Figure 5a shows the GWP results of the scenario analysis per m² whereas Figure 5b recalculated these into impacts per m² and year using the RSL. As expected, Figure 5a shows that producing asphalt at lower temperatures or using RAP provides environmental benefits whereas using a PMB in the SMA increases the environmental load compared to a standard AC HMA mixture. Studies that focus on the environmental production impact of asphalt mixtures report the same findings (Araujo et al., 2022; Bizarro et al., 2021; Ma et al., 2019; Mattinzioli et al., 2022b; Moins et al., 2022; Oreto et al., 2021; Santos et al., 2021, 2018b, 2018a). Note that the benefit over the entire life cycle of producing asphalt at a lower temperature is only 3% compared to 16% if recycling is used. Previous research also states that the overall life cycle impacts do not change significantly if WMA mixes are used and that recycling has a larger effect on the overall results (Hasan et al., 2020; Santos et al., 2018a).

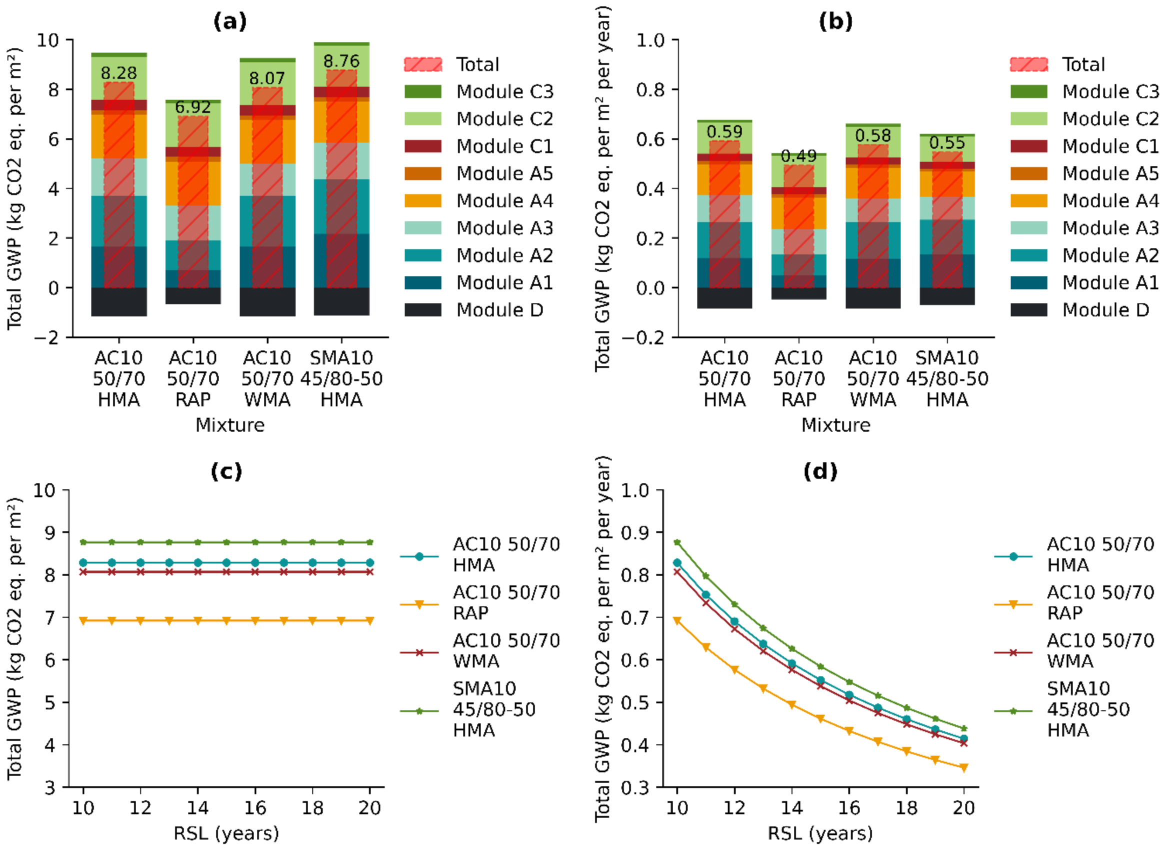


Figure 5 Effect of RSL on the total GWP; impact per m² for a fixed RSL (a); impact per m² and year for a fixed RSL (b); impact per m² for a variable RSL (c); and impact per m² and year for a variable RSL (d).

Literature also reports that if performance is considered in the analysis, the modification of mixtures by using a PMB could extend SL and entail considerable environmental benefits compared to conventional mixtures (Al-Hadidy and Tan, 2009; Al-Khateeb et al., 2020; Mokhtari and Nejad, 2013; Santos et al., 2018b). When the impact is expressed per year, Figure 5b illustrates that the SMA mixture has a lower environmental impact than the reference AC10 HMA mix due to the extended service life. In other words, even though both figures include the modules beyond the production phase, Figure 5a shows findings that are expected from a cradle-to-gate study whereas Figure 5b shows observations that are anticipated from a cradle-to-grave or cradle-to-cradle analysis.

Figure 5c and Figure 5d show the influence of the RSL on the environmental performance of asphalt mixtures. Assuming the current framework in EN 15804+A2, RSLs have no effect on the overall result (Figure 5c). Although this analysis does not consider maintenance or the use phase, EPDs typically consider only one repetition of the entire life cycle and routine maintenance is assumed (Cantisani et al., 2018; Trunzo et al., 2019). Therefore, maintenance interventions vary per pavement type but are kept constant for mixtures in the same category. In other words, asphalt EPDs typically consider the same number of processes per mixture category. Thus, varying the RSL only results in a shift in time but not in the number of processes to be included in the analysis. However, when calculating the impact per year, the influence of quality becomes apparent, see Figure 5d. Depending on the initial RSL, a one-year increase in RSL lowers the total GWP over the entire service life by 5% to 10%. Of note, lowering the production temperature by 40°C only lowers the full life cycle impact by 3%. Literature states that increasing the quality of an asphalt mixture will lead to higher SLs, which results in less resource use over longer periods and environmental savings. This makes SL one of the most important parameters in LCA (Anthonissen et al., 2015; Chiu et al., 2008; Landi et al., 2020; Siverio Lima et al., 2022). The discussion above proves clearly that it is important to consider quality in the EPD calculations of asphalt mixtures. However, as stated before and shown by the results, an RSL does not add any value to an EPD unless it is considered in the calculations by expressing the impacts per year.

The effect of using a cut-off on the total GWP of the asphalt mixtures is analysed in Figure 6. In total, four different additives were considered. The AC10 HMA mix has no additives, so there is no effect. Furthermore, the cut-off has a negligible effect on the AC10 WMA mix because of the very low dosage and production impact of the additive. Applying the cut-off increases the overall impact of the AC10 mix with RAP by 3% and decreases the impact of the SMA10 mix by 6%. When examining the individual modules, Figure 6 reveals that the effect is mainly measurable in module A1. If the focus narrows down to module A1 alone, the differences are +25% and -30% for the AC10 RAP mix and SMA10 mix, respectively. Literature provides comparable findings. The contribution of WMA additives to environmental scores typically remains under 10% depending on their type and system boundaries (Anthonissen et al., 2015; Ma et al., 2019). Furthermore, using additives for binder modification can change the impact of bitumen production by -80% to +20% (Nättorp et al., 2019; Praticò et al., 2020; Samieadel et al., 2018; Santos et al., 2021). Finally, the contribution of recycling agents in the overall environmental impact can range from negligible up to 26% (Hernando et al., 2022; Jahanbakhsh et al., 2020; Moins et al., 2022).

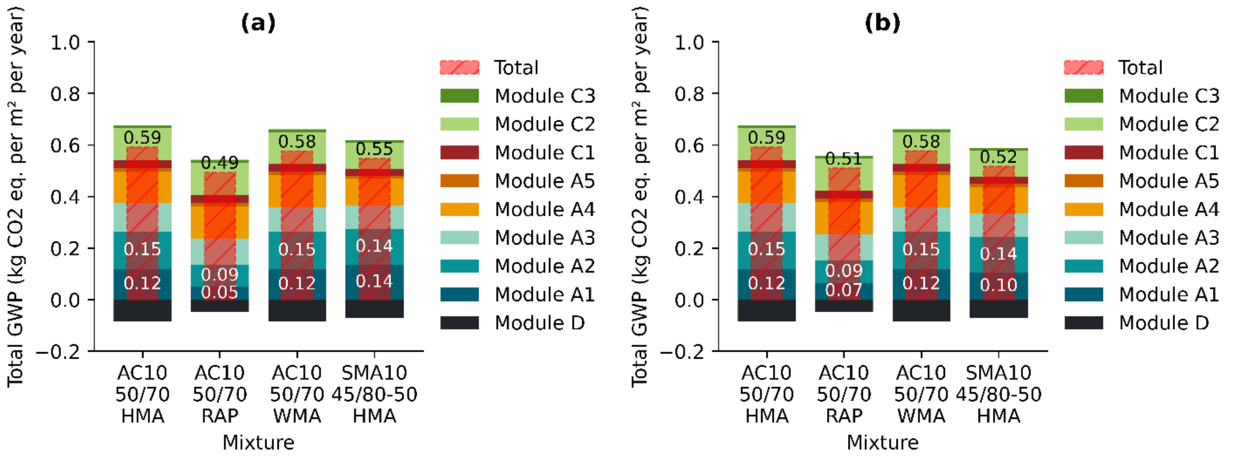


Figure 6 Effect of cut-off on the total GWP; impact per m² and year for a fixed RSL without a cut-off (a); and impact per m² and year for a fixed RSL with a cut-off (b).

Note that the results change in both directions, which is due to the type of additive. Biobased additives, like the rejuvenator used, typically have a negative GWP impact; thus, neglecting them in the analysis increases the results. Fossil-based additives have a positive GWP impact; therefore, applying a cut-off will lower the results. Another important remark involves the ranking of the mixtures. If no cut-off is applied, Figure 6a clearly shows that the AC10 mix with RAP has the lowest overall impact followed by the SMA10 mix. In this case, the SMA10 mix has an 11% higher impact; however, the difference drops to only 1% if the cut-off is applied (Figure 6b).

All available PCRs for asphalt mixtures state that if inputs are considered environmentally relevant, they should be included even though they fall under the cut-off limit (EAPA, 2017; EPD-Norge, 2022; EPD Australasia, 2019; EPD International, 2022; NAPA, 2022; Van der Kruk et al., 2022). However, none of the PCRs mention when an effect is considered significant. ISO 14044 and EN 15804+A2 both state that a change of +/- 10% in result can be considered significant and should be reported (CEN, 2021d; International Organization for Standardization, 2006). Therefore, based on the results of this study, it is concluded that a cut-off should not be applied to mixture additives.

The final scenario was designed to analyse the effect of the EOW criteria on module D and the overall results. Figure 7 shows three different EOW locations with total results for a cradle-to-gate (A1-A3) and cradle-to-cradle (A1-A5, C1-D) scope. The available PCRs for asphalt mixtures either locate their EOW after module C3 or use a different EOW for closed loop (C1) versus open loop recycling (C3), see Figure 7a and Figure 7b. Relocating the EOW partially after C1 transfers the impact of transporting (C2) and processing (C3) RAP for closed loop recycling to modules A1 and A2, see AC10 mix with RAP. In other words, locating the EOW partially after C1 lowers the impact of the EOL phase and increases the impact of the material phase. If the study uses a cradle-to-grave or cradle-to-cradle scope, this will have no effect on the total result. However, if the study uses a cradle-to-gate approach, the total production impact is increased as shown by the AC10 mix with RAP in Figure 7a and Figure 7b.

Having a double set of EOW opens the door for double counting. Therefore, the authors advise to either locate the EOW after C1 or after C3, independently of closed loop or open loop recycling. Relocating the EOW after C1 eliminates the impacts of modules C2 and C3 entirely and relocates it to either the material phase or module D. This results in a burden beyond the system boundary instead of a benefit as shown by Figure 7c. Note that this does not change the total results when compared to Figure 7b. However, compared to Figure 7a, the same conclusion applies with regards to the cradle-to-gate scope. In general, it is concluded that relocating the EOW influences modules A1, A2, C2, C3, and D. Furthermore, it does not affect the total impact if an EPD has a cradle-to-grave or cradle-to-cradle scope; however, if the EPD limits its scope to a cradle-to-gate study the total result is influenced.

7 Conclusions and recommendations

The road construction industry is exploring the use of EPDs as communication tools and their implementation in GPP. Currently, several associations and countries have issued their own PCR specific to asphalt mixtures: EAPA, NAPA, EPD Norge, the Netherlands, EPD International, and EPD Australasia. Consequently, it is important to assess the similarities and differences between these PCRs to avoid comparing EPDs with inconsistent methodological frameworks. An overview of the current normative framework for calculating EPDs showed that the PCRs either use EN 15804+A2 or ISO 21930 as their normative backbone. However, a clear reference to ISO 21931-2 and EN 17472, which cover the sustainability assessment of civil engineering works, is missing. Furthermore, interaction with the ISO 15686 series is lacking. As this series sets principles and frameworks for SL prediction procedures, RSL estimation, and performance evaluation for feedback on SL data from practice, it can be considered an important missing link.

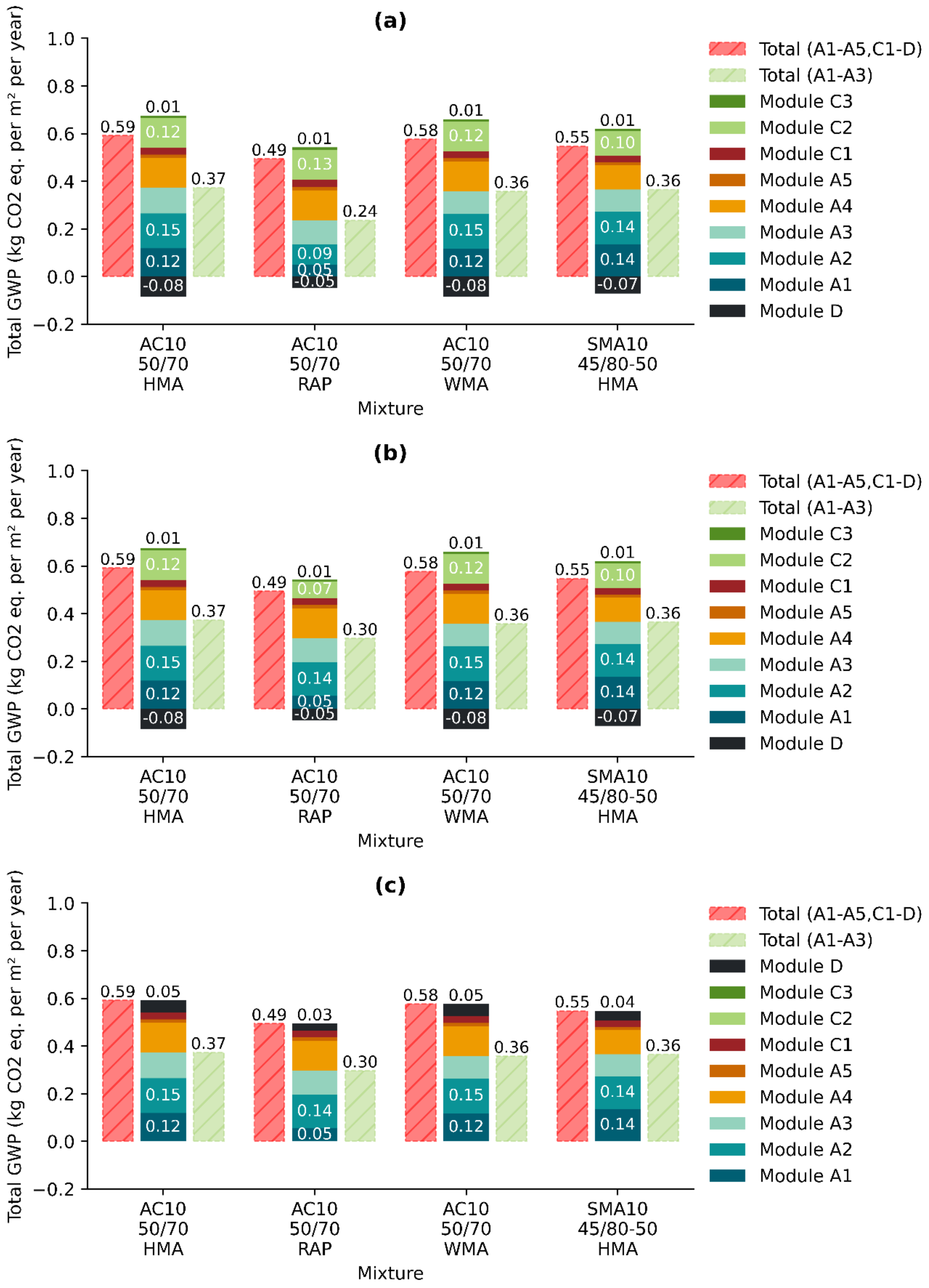


Figure 7 Effect of the EOW location on the total GWP; impact per m² and year for a fixed RSL with the EOW located after C3 (a); impact per m² and year for a fixed RSL with the EOW located after C1 for closed loop recycling and C3 for open loop recycling (b); and impact per m² per year for a fixed RSL with the EOW located after C1 (c)

The comparison of PCRs revealed similarities in requirements for data quality, exclusion of inputs and outputs, and allocation procedures. However, there were also some major differences regarding the use of system boundaries, RSL, FU or DU, and EOL modelling of loads and benefits beyond the system boundaries. For product-specific EPDs, the current PCRs lean more towards cradle-to-gate EPDs that use a DU instead of an FU. Conversely, EPDs for projects should broaden their scope to cradle-to-grave or cradle-to-cradle and use a FU. It was found that the selection of system boundaries is an important parameter as it also influences the selection of an RSL. Finally, it was concluded that PCRs use two different EOW modelling approaches. The NL-PCR locates the EOW after the waste processing of RAP in module C3 regardless of closed-loop or open-loop recycling. All other PCRs use a different EOW location for closed-loop versus open-loop recycling. If RAP enters or remains in the product's system, the EOW is located after C1, resulting in a production impact for RAP. When RAP leaves the system, the EOW is located after the waste processing in C3, making it burden free for the next cycle. This way, the latter approach opens the door for double counting; therefore, it is advised to fix the location of the EOW either after C1 or C3.

To quantitatively evaluate the effect of the differences in the PCRs, a scenario analysis was performed. Because of the lack of an analysis period, the use of an RSL in its current form only provides some information regarding expected performance but does not incorporate performance into the actual EPD calculation. Since performance is not incorporated, the current models only provide observations expected from a cradle-to-gate analysis regardless of the system boundaries considered. Therefore, it is advised to recalculate the results into impacts per year. Furthermore, the scenario analysis showed that using a cut-off for mixture additives can influence the results. Considering a cradle-to-cradle approach, the results only changed by +3% to -6% depending on the type of additive. However, if the focus is on module A1 alone, the differences varied between +25% and -30%. Additionally, the selection of a cut-off can have an impact on the ranking of the results. Consequently, it is concluded that a cut-off should not be applied to mixture additives. Finally, the effect of the EOW location was analysed. Relocating the EOW influences modules A1, A2, C2, C3, and D. If the EPD uses a cradle-to-grave or cradle-to-cradle scope, relocating the EOW does not affect the total impact but only triggers a shift in impacts between the EOL and material modules. Note that if the EPD limits its scope to a cradle-to-gate study, the total result will be influenced.

This research showed that some assumptions lead to subtle differences in EPD results such as a shift in impacts per module while maintaining the same total impact. Other assumptions, such as the use of impacts per year, can completely change the ranking of mixtures based on environmental performance. Therefore, it is generally concluded that the selected PCR will influence the findings. Furthermore, the comparison of results using different PCRs should be avoided. This may hamper the practical implementation of EPDs in GPP if the procurement procedures do not fix the PCR to be used.

It is important to note that the focus of this manuscript lies on the variability in methodological assumptions of the existing PCRs for asphalt mixture production. This manuscript did not address the variability in inputs such as mixture composition or transport distances nor did it consider the variability in LCA records for individual materials/processes. Additionally, it is worth noting that asphalt mixtures are used in downstream processes for larger infrastructure projects, which also use other products. Furthermore, upstream processes are used as inputs in asphalt mixture production. Therefore, the authors recommend broadening this discussion including all actors involved in infrastructure projects to harmonise all relevant PCRs. Otherwise, using material EPDs as building blocks for asphalt material production or calculating/comparing project specific EPDs will remain discouraged, because of potential inconsistencies in methodological frameworks. This can ultimately hinder the comparison of design alternatives using environmental statements and the future development and implementation of GPP in road engineering.

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Author contributions

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Annex A: Environmental impact using EN 15804+A2 indicators for the base scenario

Activity Browser (AB) was used to model the environmental impacts, which is an open source LCA software that builds on Brightway2 (Steubing et al., 2016). Table 4 provides an overview of the indicators considered by EN 15804+A2 with their corresponding abbreviation and unit. Table 5 to Table 8 present a detailed overview of the results per module per indicator per mixture for the base scenario.

Table 4 Overview environmental indicators using EF v3.1 EN 15804 LCIA and EN 15804 inventory indicators

Indicator	Abbreviation	Unit
Global Warming Potential total	GWP-total	kg CO2 eq.
Global Warming Potential fossil	GWP-fossil	kg CO2 eq.
Global Warming Potential biogenic	GWP-biogenic	kg CO2 eq.
Global Warming Potential land use and land use change	GWP-luluc	kg CO2 eq.
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11 eq.
Acidification Potential, Accumulated Exceedance	AP	mol H+ eq.
Eutrophication Potential, fraction of nutrients reaching freshwater end compartment	EP-freshwater	kg P eq.
Eutrophication Potential, fraction of nutrients reaching marine end compartment	EP-marine	kg N eq.
Eutrophication Potential, Accumulated Exceedance	EP-terrestrial	mol N eq.
Formation potential of tropospheric ozone photochemical oxidants	POCP	kg NMVOC eq
Abiotic Depletion Potential for non-fossil resources	ADP-m&m	kg Sb eq.
Abiotic Depletion for fossil resources potential	ADP-fossil	MJ, net calorific value
Water (user) deprivation potential, deprivation-weighted water consumption	WDP	m3 world eq. deprived
Potential incidence of disease due to PM emissions	PM	Disease incidence
Potential Human exposure efficiency relative to U235	IRP	kBq U235 eq.
Potential Comparative Toxic Unit for ecosystems	ETP-fw	CTUe
Potential Comparative Toxic Unit for humans	HTP-c	CTUh
Potential Comparative Toxic Unit for humans, non-cancer	HTP-nc	CTUh
Potential soil quality index	SQP	dimensionless
Total use of renewable primary energy resources	PERT	MJ, net calorific value
Total use of non-renewable primary energy resources	PENRT	MJ, net calorific value
Use of secondary materials	SM	kg
Use of renewable secondary fuels	RSF	MJ, net calorific value
Use of net fresh water	FW	m3
Hazardous Waste Disposed	HWD	kg
Non-Hazardous Waste Disposed	NHWD	kg
Radioactive Waste Disposed	RWD	kg
Materials for recycling	MFR	kg
Materials for energy recovery	MER	kg
Exported Electrical Energy	EEE	MJ, net calorific value
Exported Thermal Energy	ETE	MJ, net calorific value
Biogenic carbon content	BCC	kg C

Note, the following indicators could not be provided because they were not available in AB: Use of renewable energy excluding renewable primary energy resources, Use of renewable energy resources used as raw materials, Use of non-renewable primary energy resources excluding non-renewable energy resources used as raw materials, Use of non-renewable primary energy resources used as raw materials, Use of non-renewable secondary fuels, and Components for reuse

Table 5 Detailed results for AC10 50/70 HMA according to EN 15804+A2 per m^2 per year including additives with EOW located after C3

	A1	A2	A3	A4	A5	C1	C2	C3	D
GWP-total	1.18E-01	1.46E-01	1.09E-01	1.24E-01	1.43E-02	2.90E-02	1.24E-01	1.12E-02	-8.41E-02
GWP-fossil	1.18E-01	1.46E-01	1.09E-01	1.24E-01	1.43E-02	2.90E-02	1.24E-01	1.12E-02	-8.38E-02
GWP-biogenic	3.83E-04	1.32E-04	1.69E-04	1.08E-04	3.04E-06	6.31E-06	1.08E-04	2.46E-06	-2.88E-04
GWP-luluc	6.01E-05	7.66E-05	2.70E-05	6.01E-05	1.58E-06	3.28E-06	6.01E-05	1.28E-06	-4.15E-05
ODP	1.17E-08	3.16E-09	4.85E-09	2.69E-09	2.21E-10	4.70E-10	2.69E-09	1.85E-10	-6.61E-09
AP	9.71E-04	4.96E-04	1.07E-04	4.03E-04	6.99E-05	1.13E-04	4.03E-04	5.48E-05	-7.04E-04
EP-freshwater	1.50E-05	1.03E-05	2.76E-06	8.66E-06	4.34E-07	8.87E-07	8.66E-06	3.44E-07	-1.20E-05
EP-marine	2.75E-04	1.75E-04	3.93E-05	1.39E-04	3.09E-05	4.72E-05	1.39E-04	2.40E-05	-2.19E-04
EP-terrestrial	3.08E-03	1.85E-03	4.18E-04	1.47E-03	3.34E-04	5.06E-04	1.47E-03	2.58E-04	-2.43E-03
POCP	9.44E-04	7.38E-04	2.23E-04	6.03E-04	1.09E-04	1.75E-04	6.03E-04	8.53E-05	-7.38E-04
ADP-m&m	5.25E-07	4.72E-07	7.35E-08	4.07E-07	5.05E-09	1.04E-08	4.07E-07	4.04E-09	-3.18E-07
ADP-fossil	1.80E+01	2.07E+00	1.93E+00	1.77E+00	1.83E-01	3.90E-01	1.77E+00	1.53E-01	-1.06E+01
WDP	3.97E-02	1.02E-02	7.50E-03	8.66E-03	4.59E-04	9.47E-04	8.66E-03	3.68E-04	-4.96E-02
PM	1.03E-08	1.14E-08	8.11E-10	9.85E-09	1.08E-09	1.68E-09	9.85E-09	8.37E-10	-9.21E-09
IRP	1.24E-01	2.83E-03	1.61E-02	2.35E-03	8.74E-05	1.81E-04	2.35E-03	7.04E-05	-7.29E-02
ETP-fw	5.65E+00	1.01E+00	1.01E-01	8.59E-01	8.68E-02	1.84E-01	8.59E-01	7.26E-02	-3.32E+00
HTP-c	7.00E-11	6.92E-11	2.22E-11	5.86E-11	1.76E-11	2.49E-11	5.86E-11	1.36E-11	-4.72E-11
HTP-nc	1.17E-09	1.44E-09	1.94E-10	1.24E-09	4.86E-11	8.43E-11	1.24E-09	3.88E-11	-7.28E-10
SQP	6.30E+00	1.23E+00	7.60E-02	1.04E+00	1.23E-02	2.60E-02	1.04E+00	1.02E-02	-1.02E+01
PERT	7.79E-02	3.25E-02	3.98E-02	2.72E-02	1.05E-03	2.16E-03	2.72E-02	8.40E-04	-5.65E-02
PENRT	1.77E+01	2.08E+00	1.93E+00	1.77E+00	1.83E-01	3.90E-01	1.77E+00	1.53E-01	-1.04E+01
SM[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RSF[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
FW	1.14E-03	2.50E-04	1.84E-04	2.11E-04	9.89E-06	2.07E-05	2.11E-04	8.07E-06	-1.43E-03
HWD	2.49E-03	2.39E-08	6.70E-09	2.02E-08	1.43E-09	2.92E-09	2.02E-08	1.13E-09	-1.43E-03
NHWD	1.24E-02	5.80E-05	2.44E-05	4.91E-05	3.48E-06	7.11E-06	4.91E-05	2.76E-06	-7.02E-03
RWD	1.95E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.12E-04
MFR[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
MER[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EEE[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ETE[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BCC	-3.30E-05	-2.65E-05	-3.88E-05	-2.16E-05	-4.16E-07	-8.62E-07	-2.16E-05	-3.36E-07	3.59E-05

[a] All input records had a zero value for this indicator; thus, this indicator is zero for the asphalt mixture as well.

Table 6 Detailed results for AC10 50/70 RAP according to EN 15804+A2 per m^2 per year including additives with EOW located after C3

	A1	A2	A3	A4	A5	C1	C2	C3	D
GWP-total	4.92E-02	8.59E-02	1.02E-01	1.25E-01	1.45E-02	2.90E-02	1.25E-01	1.13E-02	-4.78E-02
GWP-fossil	7.71E-02	8.58E-02	1.01E-01	1.25E-01	1.45E-02	2.90E-02	1.25E-01	1.13E-02	-4.76E-02
GWP-biogenic	-2.81E-02	7.65E-05	1.68E-04	1.09E-04	3.07E-06	6.31E-06	1.09E-04	2.49E-06	-1.64E-04
GWP-luluc	2.42E-04	4.38E-05	2.65E-05	6.07E-05	1.60E-06	3.28E-06	6.07E-05	1.30E-06	-2.36E-05
ODP	7.87E-09	1.86E-09	4.50E-09	2.72E-09	2.24E-10	4.70E-10	2.72E-09	1.87E-10	-3.76E-09
AP	5.99E-04	2.87E-04	1.01E-04	4.08E-04	7.06E-05	1.13E-04	4.08E-04	5.54E-05	-3.99E-04
EP-freshwater	7.71E-06	6.03E-06	2.63E-06	8.75E-06	4.38E-07	8.87E-07	8.75E-06	3.48E-07	-6.78E-06
EP-marine	1.91E-04	1.00E-04	3.72E-05	1.41E-04	3.13E-05	4.72E-05	1.41E-04	2.43E-05	-1.24E-04
EP-terrestrial	1.98E-03	1.06E-03	3.95E-04	1.48E-03	3.37E-04	5.06E-04	1.48E-03	2.61E-04	-1.38E-03
POCP	5.37E-04	4.28E-04	2.08E-04	6.09E-04	1.10E-04	1.75E-04	6.09E-04	8.62E-05	-4.19E-04
ADP-m&m	9.02E-07	2.79E-07	7.07E-08	4.11E-07	5.10E-09	1.04E-08	4.11E-07	4.08E-09	-1.81E-07
ADP-fossil	1.06E+01	1.22E+00	1.82E+00	1.79E+00	1.85E-01	3.90E-01	1.79E+00	1.55E-01	-6.02E+00
WDP	-5.45E-03	6.02E-03	7.24E-03	8.76E-03	4.64E-04	9.47E-04	8.76E-03	3.72E-04	-2.82E-02
PM	6.31E-09	6.75E-09	7.83E-10	9.95E-09	1.09E-09	1.68E-09	9.95E-09	8.46E-10	-5.23E-09
IRP	7.18E-02	1.65E-03	1.62E-02	2.37E-03	8.84E-05	1.81E-04	2.37E-03	7.12E-05	-4.14E-02
ETP-fw	1.38E+01	5.93E-01	9.62E-02	8.68E-01	8.77E-02	1.84E-01	8.68E-01	7.34E-02	-1.88E+00
HTP-c	4.54E-11	4.07E-11	2.11E-11	5.93E-11	1.78E-11	2.49E-11	5.93E-11	1.38E-11	-2.68E-11
HTP-nc	8.46E-10	8.53E-10	1.85E-10	1.26E-09	4.91E-11	8.43E-11	1.26E-09	3.92E-11	-4.13E-10
SQP	6.66E+00	7.24E-01	7.47E-02	1.06E+00	1.24E-02	2.60E-02	1.06E+00	1.03E-02	-5.79E+00
PERT	4.20E-01	1.90E-02	3.97E-02	2.75E-02	1.06E-03	2.16E-03	2.75E-02	8.49E-04	-3.21E-02
PENRT	1.04E+01	1.22E+00	1.82E+00	1.79E+00	1.85E-01	3.90E-01	1.79E+00	1.55E-01	-5.90E+00
SM[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RSF[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
FW	8.32E-06	1.47E-04	1.79E-04	2.13E-04	1.00E-05	2.07E-05	2.13E-04	8.16E-06	-8.12E-04
HWD	1.46E-03	1.40E-08	6.28E-09	2.04E-08	1.44E-09	2.92E-09	2.04E-08	1.14E-09	-8.14E-04
NHWD	9.38E-03	3.41E-05	2.28E-05	4.97E-05	3.52E-06	7.11E-06	4.97E-05	2.79E-06	-3.98E-03
RWD	1.15E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-6.36E-05
MFR[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
MER[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EEE[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ETE[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BCC	1.04E-01	-1.54E-05	-3.88E-05	-2.19E-05	-4.20E-07	-8.62E-07	-2.19E-05	-3.40E-07	2.04E-05

[a] All input records had a zero value for this indicator; thus, this indicator is zero for the asphalt mixture as well.

Table 7 Detailed results for AC10 50/70 WMA according to EN 15804+A2 per m² per year including additives with EOW located after C3

	A1	A2	A3	A4	A5	C1	C2	C3	D
GWP-total	1.17E-01	1.46E-01	9.47E-02	1.24E-01	1.43E-02	2.90E-02	1.24E-01	1.12E-02	-8.41E-02
GWP-fossil	1.18E-01	1.46E-01	9.45E-02	1.24E-01	1.43E-02	2.90E-02	1.24E-01	1.12E-02	-8.38E-02
GWP-biogenic	-1.29E-03	1.32E-04	1.65E-04	1.08E-04	3.04E-06	6.31E-06	1.08E-04	2.46E-06	-2.88E-04
GWP-luluc	6.11E-04	7.67E-05	2.57E-05	6.01E-05	1.58E-06	3.28E-06	6.01E-05	1.28E-06	-4.15E-05
ODP	1.17E-08	3.16E-09	4.19E-09	2.69E-09	2.21E-10	4.70E-10	2.69E-09	1.85E-10	-6.61E-09
AP	9.77E-04	4.97E-04	9.56E-05	4.03E-04	6.99E-05	1.13E-04	4.03E-04	5.48E-05	-7.04E-04
EP-freshwater	1.51E-05	1.03E-05	2.49E-06	8.66E-06	4.34E-07	8.87E-07	8.66E-06	3.44E-07	-1.20E-05
EP-marine	2.82E-04	1.75E-04	3.51E-05	1.39E-04	3.09E-05	4.72E-05	1.39E-04	2.40E-05	-2.19E-04
EP-terrestrial	3.10E-03	1.85E-03	3.73E-04	1.47E-03	3.34E-04	5.06E-04	1.47E-03	2.58E-04	-2.43E-03
POCP	9.44E-04	7.38E-04	1.95E-04	6.03E-04	1.09E-04	1.75E-04	6.03E-04	8.53E-05	-7.38E-04
ADP-m&m	5.25E-07	4.72E-07	6.75E-08	4.07E-07	5.05E-09	1.04E-08	4.07E-07	4.04E-09	-3.18E-07
ADP-fossil	1.80E+01	2.08E+00	1.71E+00	1.77E+00	1.83E-01	3.90E-01	1.77E+00	1.53E-01	-1.06E+01
WDP	4.05E-02	1.03E-02	6.94E-03	8.66E-03	4.59E-04	9.47E-04	8.66E-03	3.68E-04	-4.96E-02
PM	1.04E-08	1.14E-08	7.50E-10	9.85E-09	1.08E-09	1.68E-09	9.85E-09	8.37E-10	-9.21E-09
IRP	1.24E-01	2.83E-03	1.60E-02	2.35E-03	8.74E-05	1.81E-04	2.35E-03	7.04E-05	-7.29E-02
ETP-fw	5.83E+00	1.01E+00	9.15E-02	8.59E-01	8.68E-02	1.84E-01	8.59E-01	7.26E-02	-3.32E+00
HTP-c	7.07E-11	6.92E-11	2.00E-11	5.86E-11	1.76E-11	2.49E-11	5.86E-11	1.36E-11	-4.72E-11
HTP-nc	1.20E-09	1.44E-09	1.75E-10	1.24E-09	4.86E-11	8.43E-11	1.24E-09	3.88E-11	-7.28E-10
SQP	6.29E+00	1.23E+00	7.26E-02	1.04E+00	1.23E-02	2.60E-02	1.04E+00	1.02E-02	-1.02E+01
PERT	1.01E-01	3.25E-02	3.89E-02	2.72E-02	1.05E-03	2.16E-03	2.72E-02	8.40E-04	-5.65E-02
PENRT	1.76E+01	2.08E+00	1.71E+00	1.77E+00	1.83E-01	3.90E-01	1.77E+00	1.53E-01	-1.04E+01
SM[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RSF[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
FW	1.17E-03	2.50E-04	1.72E-04	2.11E-04	9.89E-06	2.07E-05	2.11E-04	8.07E-06	-1.43E-03
HWD	2.48E-03	2.39E-08	5.88E-09	2.02E-08	1.43E-09	2.92E-09	2.02E-08	1.13E-09	-1.43E-03
NHWD	1.25E-02	5.80E-05	2.14E-05	4.91E-05	3.48E-06	7.11E-06	4.91E-05	2.76E-06	-7.02E-03
RWD	1.94E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.12E-04
MFR[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
MER[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EEE[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ETE[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BCC	9.64E-04	-2.65E-05	-3.81E-05	-2.16E-05	-4.16E-07	-8.62E-07	-2.16E-05	-3.36E-07	3.59E-05

[a] All input records had a zero value for this indicator; thus, this indicator is zero for the asphalt mixture as well.

Table 8 Detailed results for SMA10 45/80-50 HMA according to EN 15804+A2 per m^2 per year including additives with EOW located after C3

	A1	A2	A3	A4	A5	C1	C2	C3	D
GWP-total	1.35E-01	1.38E-01	9.17E-02	1.04E-01	1.20E-02	2.54E-02	1.04E-01	9.37E-03	-7.12E-02
GWP-fossil	1.35E-01	1.38E-01	9.16E-02	1.04E-01	1.20E-02	2.54E-02	1.04E-01	9.37E-03	-7.09E-02
GWP-biogenic	2.45E-04	1.20E-04	1.41E-04	9.06E-05	2.54E-06	5.52E-06	9.06E-05	2.06E-06	-2.44E-04
GWP-luluc	8.39E-05	6.68E-05	2.26E-05	5.03E-05	1.32E-06	2.87E-06	5.03E-05	1.07E-06	-3.52E-05
ODP	1.13E-08	2.99E-09	4.07E-09	2.25E-09	1.85E-10	4.11E-10	2.25E-09	1.55E-10	-5.60E-09
AP	9.84E-04	4.49E-04	8.99E-05	3.38E-04	5.85E-05	9.89E-05	3.38E-04	4.58E-05	-5.96E-04
EP-freshwater	2.33E-05	9.63E-06	2.31E-06	7.25E-06	3.63E-07	7.76E-07	7.25E-06	2.88E-07	-1.01E-05
EP-marine	2.58E-04	1.55E-04	3.30E-05	1.16E-04	2.59E-05	4.13E-05	1.16E-04	2.01E-05	-1.85E-04
EP-terrestrial	2.86E-03	1.63E-03	3.51E-04	1.23E-03	2.79E-04	4.42E-04	1.23E-03	2.16E-04	-2.06E-03
POCP	9.67E-04	6.70E-04	1.87E-04	5.04E-04	9.09E-05	1.53E-04	5.04E-04	7.14E-05	-6.25E-04
ADP-m&m	1.10E-06	4.52E-07	6.16E-08	3.40E-07	4.23E-09	9.09E-09	3.40E-07	3.38E-09	-2.69E-07
ADP-fossil	1.66E+01	1.97E+00	1.62E+00	1.48E+00	1.53E-01	3.41E-01	1.48E+00	1.28E-01	-8.98E+00
WDP	5.58E-02	9.63E-03	6.29E-03	7.25E-03	3.85E-04	8.28E-04	7.25E-03	3.08E-04	-4.20E-02
PM	1.09E-08	1.09E-08	6.80E-10	8.24E-09	9.02E-10	1.47E-09	8.24E-09	7.00E-10	-7.79E-09
IRP	1.15E-01	2.61E-03	1.35E-02	1.96E-03	7.32E-05	1.58E-04	1.96E-03	5.89E-05	-6.17E-02
ETP-fw	5.24E+00	9.55E-01	8.46E-02	7.19E-01	7.26E-02	1.61E-01	7.19E-01	6.07E-02	-2.81E+00
HTP-c	8.20E-11	6.52E-11	1.86E-11	4.91E-11	1.48E-11	2.18E-11	4.91E-11	1.14E-11	-3.99E-11
HTP-nc	1.43E-09	1.38E-09	1.63E-10	1.04E-09	4.07E-11	7.38E-11	1.04E-09	3.24E-11	-6.16E-10
SQP	3.92E+00	1.16E+00	6.37E-02	8.74E-01	1.03E-02	2.27E-02	8.74E-01	8.53E-03	-8.63E+00
PERT	1.22E-01	3.03E-02	3.33E-02	2.28E-02	8.79E-04	1.89E-03	2.28E-02	7.03E-04	-4.78E-02
PENRT	1.63E+01	1.97E+00	1.62E+00	1.48E+00	1.53E-01	3.41E-01	1.48E+00	1.28E-01	-8.80E+00
SM[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RSF[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
FW	1.45E-03	2.34E-04	1.55E-04	1.76E-04	8.28E-06	1.81E-05	1.76E-04	6.75E-06	-1.21E-03
HWD	2.15E-03	2.25E-08	5.63E-09	1.69E-08	1.20E-09	2.55E-09	1.69E-08	9.46E-10	-1.21E-03
NHWD	1.08E-02	5.46E-05	2.04E-05	4.11E-05	2.92E-06	6.22E-06	4.11E-05	2.31E-06	-5.94E-03
RWD	1.69E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-9.49E-05
MFR[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
MER[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EEE[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ETE[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BCC	2.68E-05	-2.41E-05	-3.25E-05	-1.81E-05	-3.48E-07	-7.55E-07	-1.81E-05	-2.81E-07	3.04E-05

[a] All input records had a zero value for this indicator; thus, this indicator is zero for the asphalt mixture as well.