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Pavement LCM Guidelines

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Executive summary

Figure a. Steps to set up a Sustainability Assessment tailored from EN 15978:2011

This D5.1a report focuses on the PavementLCM Guidelines to setup and perform the Sustainability Assessment (SA) of pavement materials/products, as well as pavement activities (pavement components and road pavement), as reported in the scheme in Figure a. This structure is specially tailored for road pavement and originally refers to buildings, as Sustainability of Construction Works: Assessement of Environmental Performance of Buildings – Calculation method (EN 15978:2011).

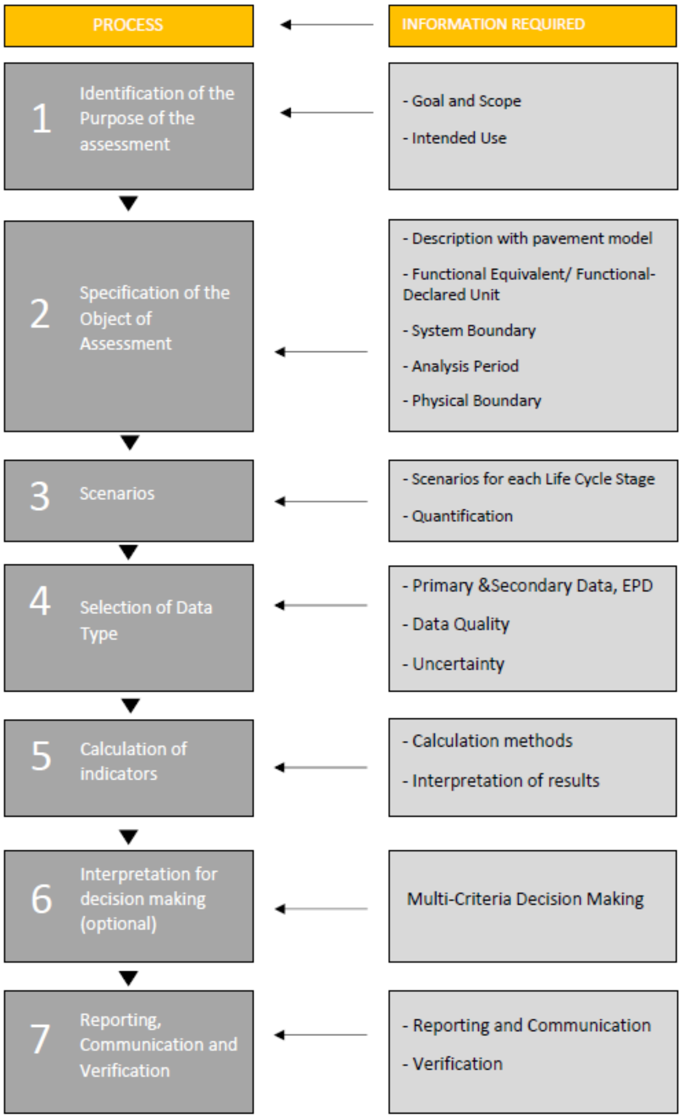

Figure a. Steps to set up a Sustainability Assessment tailored from EN 15978:2011

Each section of this step-by-step procedure is described in detail also with an example of its application [carried out in previous projects such as AllBack2Pave (CEDR, 2015) and CRABforOERE (CEDR, 2021)].

Due to the extent of information, four annexes and an addendum (D5.1b) have been created to provide NRAs with details on useful definition, Standards, Studies and Tools for the SA, LCA and LCC and performing decision making by using Multi-Criteria Decision-Making techniques.

Furthermore, to make the exercise easier to implement by NRAs and/or stakeholders, a dedicated template was prepared and will be provided within the Pavement LCM Tools

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1. Introduction

Life Cycle Management (LCM) is a business management approach that can be used by all types of organizations in order to improve their products and/or services while strenghtening their overall sustainability performance. Its purpose is to ensure more sustainable value chain management. LCM can be used to target, organize, analyze and manage product-related information and activities (Remmen et al,. 2007) towards continuous improvement along the product life cycle.

Along these lines, the PavementLCM project proposes the introduction of LCM practices for National Road Authorities (NRAs) by a systematic use of Sustainability Assessment (SA). On this basis, the Pavement LCM framework (D2.1) proposes a clear differentiation of the types of SA exercises that each industrial stakeholders should undertake.

First of all, it is suggested to differentiate the object of the assessment in two main areas, SA of pavement materials/products and SA of pavement activities; Secondly, within these two areas the framework proposes up to five possible exercises, as defined and explained below and shown in the figure:

Pavement materials/products, must be used to build, repair, replace and maintain road pavements and their components. The SA exercise for these products should be the responsibility of material/products manufacturers (i.e. asphalt manufacturer).

- Manufacturers: must perform the SA of each material and/or products supplied to Contractors and/or NRAs for the construction of a new road pavement and/or the maintenance of existing road pavements. Furthermore, manufacturers might be asked by NRAs to assess the sustainability of the proposed innovative materials/products.

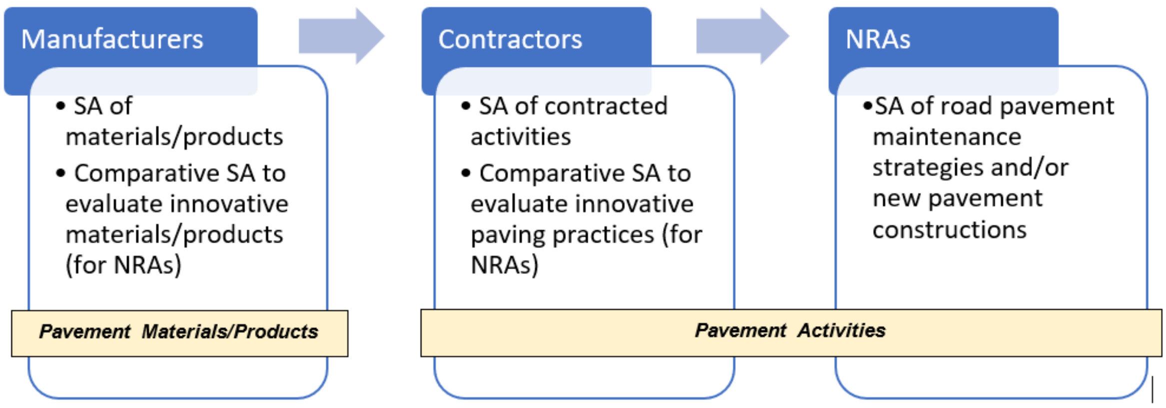


Figure 1 - SA exercises proposed by the Pavement LCM Framework

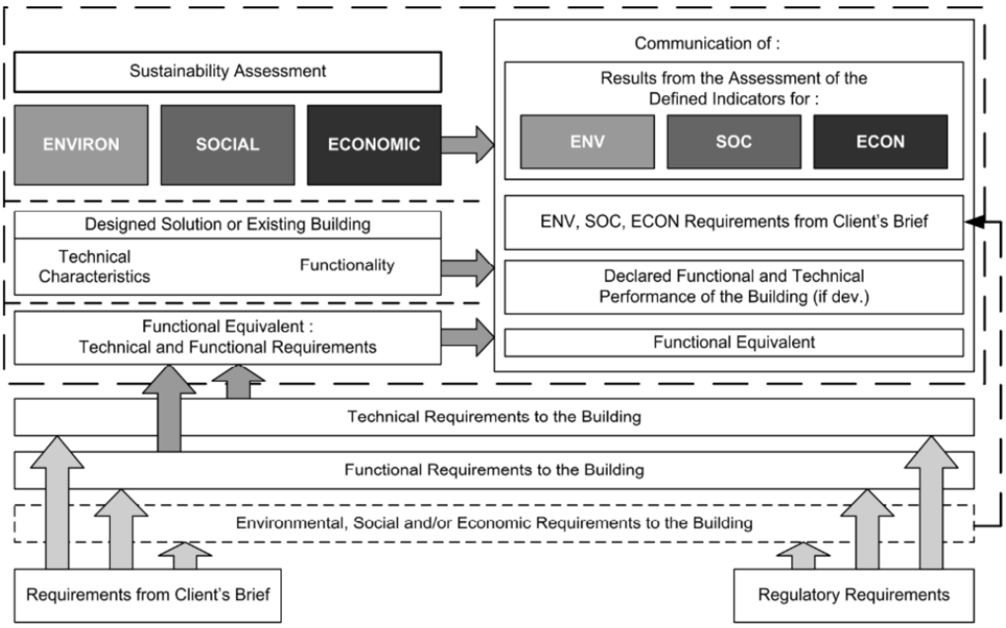
Pavement activities, must be carried out to build, repair, replace and maintain the functional and technical requirements of a road pavement and its components. The SA exercises for these activities should be the responsibility of paving contractors and road owners. In particular:

- Contractors: must perform the SA of the contracted activities, such as the construction of a new road pavement and/or the replacement of the road pavement component/element (i.e., wearing course). Furthermore, contractors might be asked by NRAs to assess the sustainability of proposed innovative technologies related to installations of road pavement components
- Road owners (i.e., NRAs): must support their decision-making process by performing the SA of selected maintenance strategies and/or projects to be procured or awarded related to the “flexible road pavement level” or at a “Part level” of the model (see 2.2.1 or the Framework).

Using the SA results to support decision-making is what is here defined as **Pavement Life Cycle Management**. This deliverable,“PavementLCM Guidelines“ (D5.1), provides knowledge, tools and resources to support NRAs‘ stakeholders responsible to request and/or carry out any of the above mentioned SA exercises. D5.1 has been defined according to the most recent european standard on Sustainability of Construction Works: Civil Engineering Works – Framework (EN 15643-5-2017) and Sustainability of Construction Works: Assessement of Environmental Performance of Buildings – Calculation method (EN 15978:2011).

1.1. Useful info from Pavement LCM State-of-the-art and Framework

SA is nowadays a standardised approach that has been clearly defined for buildings and it is being defined for the other civil engineering works by the group CEN/TC 350. This committee is focusing its effort on the development of standardized methods for the assessment of the sustainability aspects of new and existing construction works within the UN Sustainable Development Goals. As shown in the image below, a SA exercise takes under consideration all the pillars of sustainability (Environment, Society and Economy) of a project or an existing asset, whose impacts are assessed according to its characteristics (functional and technical), previously quantified to define the functional equivalent, used as basis for comparison.



The requirements are previously defined and striclty dependent on regulatory system and client's brief. Once the calculations are made, in relation with the chosen indicators of the three pillars, it is important to provide a detailed communication of what is defined and assumed (requirements, functional equivalent, etc) and the results of the assessment.

A general framework for the SA has been defined in the Deliverable 2.1, where the scope, the Objects of the Assessment and the indicators were defined.

In particular:

- the scope was defined as the pavement structure for motorways which are typically managed by NRAs in Europe, including only the aspects striclty related to pavement materials and activities.

- the objects of the assessment are distinguished in Pavement Materials and Products (manufacturers) and Pavement Activities (contractors and NRAs), each one with its own characteristics;

- the indicators, according to feedbacks receveid by the NRAs and further current studies and standards, were defined as follows in Table 1.

- The proposed Life Cycle Impact Assessment Methodology for the calculation of environmental indicators is Environmental Footprint (EF3.0) Life Cycle Impact Assessment, suggested by the ILCD-JRC. All the indicators proposed, the linked unit and description are linked to this methodology and taken from the reports published by the Joint Research Centre. Instead, the energy use and the secondary materials consumption can be directly deduced from the Life Cycle Inventory and they aren't linked to a specific methodology.

Table 1 – Indicators for the Sustainability Assessment of pavement materials and activities

Related to	SA Indicator	Object of assessment	Description
Environment	**Global Warming Potential (GWP- total)**	Pavement materials and activities	Generally accepted equivalent of greenhouse gas (GHG) accumulation.. It shall be expressed in kg CO_2 equivalent (see EN 15804). It refers to the midpoint impact category "Climate Change" of EF3.0 who indicator is Radiative forcing as global warming potential (GWP100). The GWP total <u>is the sum</u> of three different indicators that might be additional requested: - Global Warming Potential-Fossil fuels (GWP- Fossil fuels) - Global Warming Potential-Biogenic (GWP-biogenic) - Global Warming Potential-Land use and land use change (GWP-luluc)

Environment	**Acidification**	Pavement materials and activities	Includes a quantification of all acidifying compounds that causes a reduction in system's acid neutralising capacity. Generally, it is caused by air emissions of NH_3, NO2 and SO_X. It refers to the midpoint impact categories of EF3.0 "Acidification" whose indicator is Accumulated Exceedance (AE)
Environment	**Eutrophication**	Pavement materials and activities	It measures the enrichement of the environment with nutrient salts. It refers to three different midpoint impact categories of EF3.0 related to Eutrophication, as follows: - "Eutrophication terrestrial" Accumulated Exceedance (AE) - "Eutrophication acquatic freshwater", fraction of nutrients reaching freshwater end compartment (P) - "Eutrophication acquatic marine", fraction of nutrients reaching marine end compartment (N) -
Environment	**Natural resources consumption**	Pavement materials and activities	Includes a quantification of the consumption of natural resources linked to the activities. It refers to the four different midpoint impact categories of EF3.0: - "Water use", deprivation potential, deprivation-weighted water consumption (WDP) - "Land use" Potential Soil Quality index (SQP) - "Resources use, minerals and metals" - Abiotic depletion potential for non fossil resources (ADP-minerals&metals) - "Resources use energy carriers" Abiotic depletion for

			fossil resources potential (ADP-fossil)
Environment	**Air pollution**	Pavement materials and activities	Assessing pollution potential on the basis of air pollution (non-CO_2 emissions), evaluating particulate matter and photochemical oxidation potentials. It refers to two different midpoint impact categories of EF3.0: - "Particulate Matter", human health effect assocaited with the exposure to PM (PM) - "Photochemical ozon formation", Trophospheric Ozone Concentration increase
Environment	**Energy use**	Pavement materials and activities	Includes a quantification of the energy required during the life cycle of the object of assessment. The Energy use total <u>is the sum</u> of two different indicators - Energy from renewable resources - Energy from non-renewable These are both obtained from the Life Cycle Inventory
Environment	**Secondary materials consumption**	Pavement materials and activities	Includes a quantification of the material recovered from previous use or from waste which substitutes primary materials. It can be expressed by mass units or as percentage of recycled materials used related to the total consumption It can be obtained from the Life Cycle Inventory
Economy	**Cost** *This indicator differs for materials and activities:* - Cost	 Pavement materials	All costs related to the object of assessment during the product stage. All significant and relevant costs and benefits of the object of assessment, throughout life cycle,

	- Net Present Value/ Whole life cycle cost	Pavement activities	while fulfilling the performance requirements, see CWA 17089
Technical and functional requirements	**Tyre-pavement noise**	Pavement activities	The type of pavement used has an impact on the tyre/road noise level on a given road. This indicator is expressed as reduction of tyre-pavement noise level in dB compared to the reference pavement
Technical and functional requirements	**Durability**	Pavement activities	Reference Service Life of pavement components. P.S. suggestions on the topic are in WP4 of PavementLCM (D4.1)
Technical and functional requirements	**Optional indicators**	Pavement activities	This indicator is left customisable from each road authority on the basis of local priorities. (i.e. skid resistance, permeability, etc..)

2. Pavement Life Cycle Management: Setting up the Sustainability Assessment Exercise – Calculation methods

In order to carry out the SA of pavement materials and activities, the steps illustrated in Figure 3 shall be followed. These steps have being defined on the basis of the following series of standards for calculation methods for buildings:

- EN 15643-1:2010 Sustainability of construction works – Sustainability assessment of buildings – General Framework
- EN 15643-5:2010 Sustainability of construction works – Sustainability assessment of buildings and civil engineering works – Framework on specific principles and requirement for civil engineering works
- EN 15978:2011Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method
- EN 16309:2014 Sustainability of construction works - Assessment of social performance of buildings - Calculation methodology
- EN 16627:2015 Sustainability of construction works - Assessment of economic

performance of buildings - Calculation methods

- EN 15804:2012+A2:2019 Sustainability of construction works – Environmental product declaration- Core rules for the product category of construction products

The PavementLCM Framework and Guidelines aim at tailoring these standards for road pavement materials and activities.

The following sections provides guide through the development of each step including, in some cases, examples for pavement materials and pavement activities.

It must be mentioned that most of the studies found in literature target only one of the dimensions of sustainability, mainly environmental and economic. Therefore, the examples provided in the following sections may refer only to one pillar of sustainability, but the framework presented involves all of those explained in the framework.

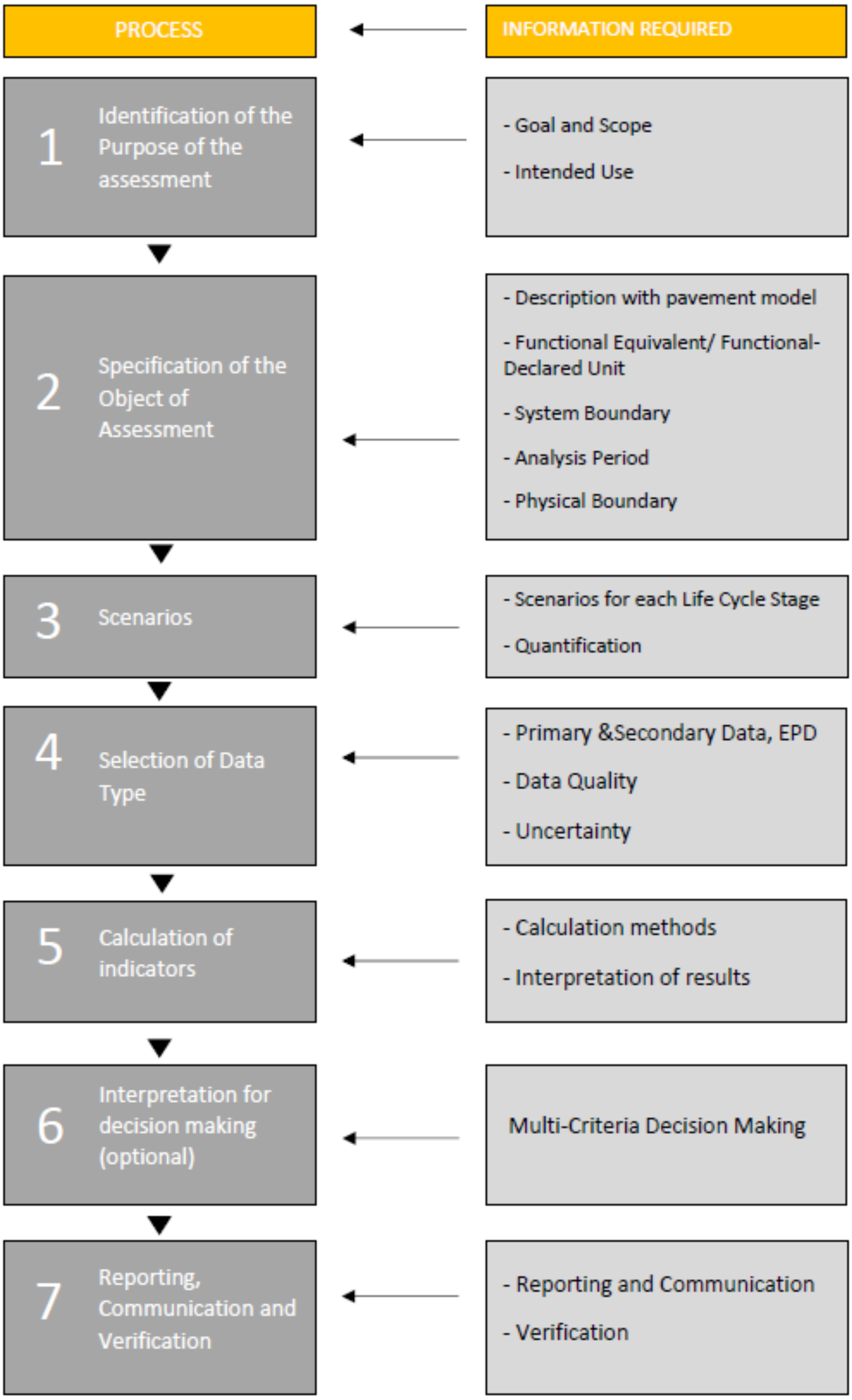
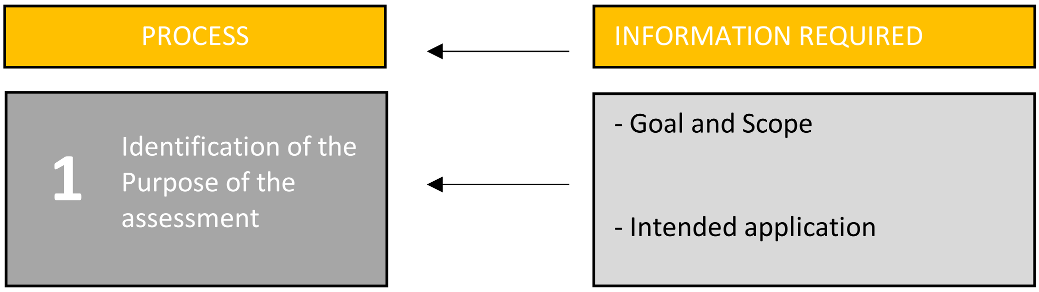


Figure 3 - Pavement LCM Guidelines to setup SA exercises

2.1 STEP 1 - Identify the purpose of the SA



According to PavementLCM proposed scheme, the purpose of the assessment (EN 15978:2001) is defined by:

- ✓ Goal
- ✓ Scope
- ✓ Intended application.

2.1.1 Goal and Scope

*The **goal** is to quantify the all the inputs and outputs of material flows and energy, calculate the indicators defined for the SA, and assess how these flows affect the environment. In other words, to quantify the environmental perfomance of the product/service of the assessment.*
*The **scope** is represented by what is included in the assessment according to the other point of the SA.*

2.1.2 Intended Application

*According to the ILCD Handbook (2010), the **intended application** can be divided into three different groups:*

- Product improvement
- Product comparison
- Communication

In particular, the intended application of the SA can be selected from the following:

1. Assistance in a decision-making process such as comparison of the sustainability performance of different design options, different maintenance strategies or identification of the potential sustainability performance improvements
2. Declaring the sustainability performance (such as environmental product declaration [EPD])
3. Documenting the sustainability performance of the system for use in certification, labelling or marketing
4. Support for policy development, such as identifying issues of some specific processes
5. Identifying product groups with the largest environmental impact
6. Identifying the hotspots

7. Evaluating improvement potentials from changes in product design Green Procurement

The purpose of the SA will determine the level of detail required of the data used in the calculation of the indicators. However, the calculation method remains the same.

2.1.3 Step 1 – Examples and Case studies

- Pavement material/product: Asphalt mixture (only environmental dimension of sustainability)

Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement – (Vidal, Moliner, Martínez, & Rubio, 2013)

"*The present study aimed to calculate the environmental impacts of different road pavements during their entire life cycle. The pavements investigated include HMA and zeolite-based WMA, both with and without RAP content. In this way, the results for the different asphalt pavements could be compared with each other to determine the best alternatives in environmental terms*."

Case study for Material/ Product – (CEDR, 2021)

The main **goal** is to calculate the environmental impacts of different mixtures during their product stage (cradle-to-gate (A1-A3)). The materials investigated include conventional hot asphalt mixtures (base course (AC32TS HMA) in Germany and the conventional binder course in San Marino) and cold asphalt mixtures derived from WP4 (Crab4Oere mixtures). These mixtures are produced with different manufacturing processes: in- situ, recycling for the german case study, in-plant recycling for the one produced in San MarinoThe **Scope** of the assessment is the asphalt mixtures production, from the extraction of raw materials to the material production.

The **Scope** are the Pavement Products, from the extraction of raw materials to the manufacturing of asphalt mixture.

The **intended applications** are:

- understanding the environmental benefits related with cold asphalt recycling;
- Understanding the pros and the cons of using the C4O technologies when compared to currently used construction methods
- Helping decision-making of asphalt mixture producers

- Pavement activity (only environmental dimension of sustainability)

Life Cycle Assessment of low temperature asphalt mixtures for road pavement surfaces: a comparative analysis – (Joao Santos, Bressi, Cerezo, Lo Presti, & Dauvergne, 2018)

"*The main goal of this study is to quantify the potential life cycle environmental impacts of a flexible road pavement section throughout its life cycle. The road pavement section studied involves the use of conventional and low-temperature asphalt mixes, with and without RAP content, in the construction, maintenance and rehabilitation (M&R) of wearing courses of the flexible road pavements. The comparative findings of this study are intended to be used by highway agencies and pavement practitioners to make more assertive judgments on the pros and contras associated with the use of emerging and commonly called sustainable strategies* *and practices for road pavement construction and M&R.”*

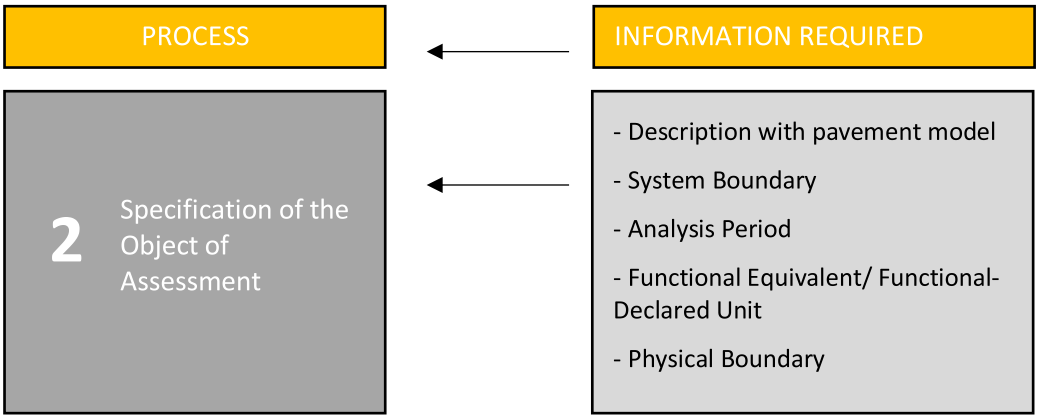
Case study for Activities – (CEDR, 2015)

The main **goal** of the study is to evaluate the environmental and economic impacts (performance) of asphalt mixtures (the baselines and six mixes with high content of recycled material) to be used within inlay procedures for three case studies representative of typical management of Italian, German and English motorways.

The **Scope** of the assessment is the pavement system, considered as the structure constructed above the native undisturbed subgrade soil, typically constructed in distinct layers and including compacted or stabilized subgrade, bound or unbound subbase(s) and the wearing course. Not included in the assessment are painting, signals, lightining, barriers and drainage structures. In particular in this case only the surface layers are considered.

The **intended use** is to assist NRAs in the decision-making process in order to choose the most sustainable alternative.

2.2 STEP 2 - Specification of the object of assessment



The specification of the object of assessment in PavementLCM Framework was detailed in Section 5 of D2.1, considering pavement materials and pavement activities, including:

- ✓ A description of the object. -> Pavement material/product or pavement activity
- ✓ System boundaries with area of influence (spatial boundary).
- ✓ Analysis period (if applicable)
- ✓ Functional equivalent, that can also be a Functional unit or Declared unit.
- ✓ Physical boundary (according to FHWA

2.2.1 Description of the object of the assessment

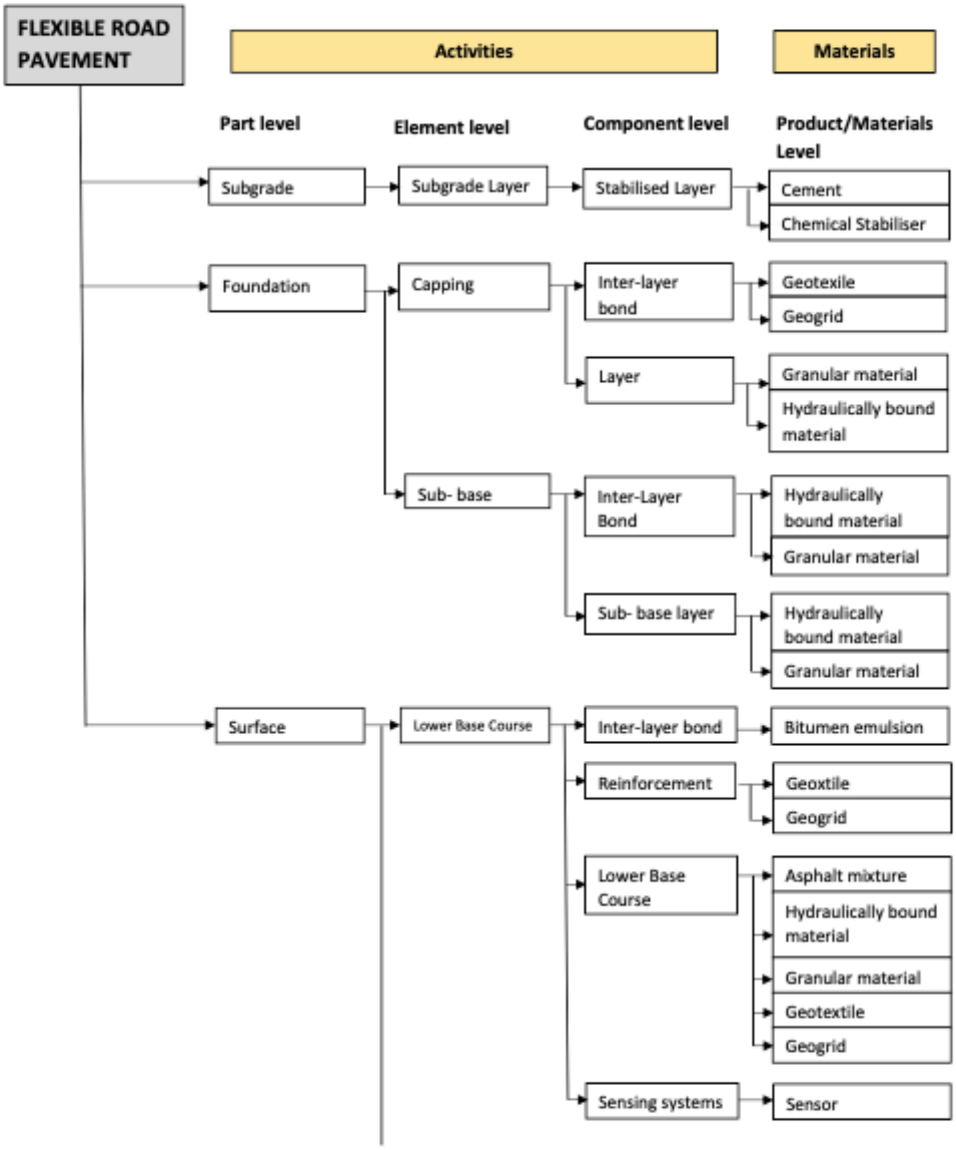
*The **object of the assessment** is the pavement material/product or the pavement activity over its life cycle. If the assessment is restricted to a part of it, this shall be* *documented, reported, and justified. The object shall be described in terms of its physical and time-related characteristics. To quantiy mass and flows, the EN15978 proposes the use of a building model, which decomposes the object in four levels.*

To facilitate the quantification a differentiation can be made between:

- Its constituent parts
- Related processes such as transport, construction, maintenance
- Operational use (water, energy)

The description of pavement activities should include the pavement construction and services and the used equipment.

It is important to select the Product(s), Component(s), Element(s) taken into consideration to facilitate the definition of quantities and data needed.


FLEXIBLE ROAD PAVEMENT
Activities
Materials
Part level
Element level
Component level
Product/Materials Level
Subgrade
Subgrade Layer
Stabilised Layer
Cement
Chemical Stabiliser
Foundation
Capping
Inter-layer bond
Geotexile
Geogrid
Layer
Granular material
Hydraulically bound material
Sub- base
Inter-Layer Bond
Hydraulically bound material
Granular material
Sub- base layer
Hydraulically bound material
Granular material
Surface
Lower Base Course
Inter-layer bond
Bitumen emulsion
Reinforcement
Geoxtile
Geogrid
Lower Base Course
Asphalt mixture
Hydraulically bound material
Granular material
Geotextile
Geogrid
Sensing systems
Sensor

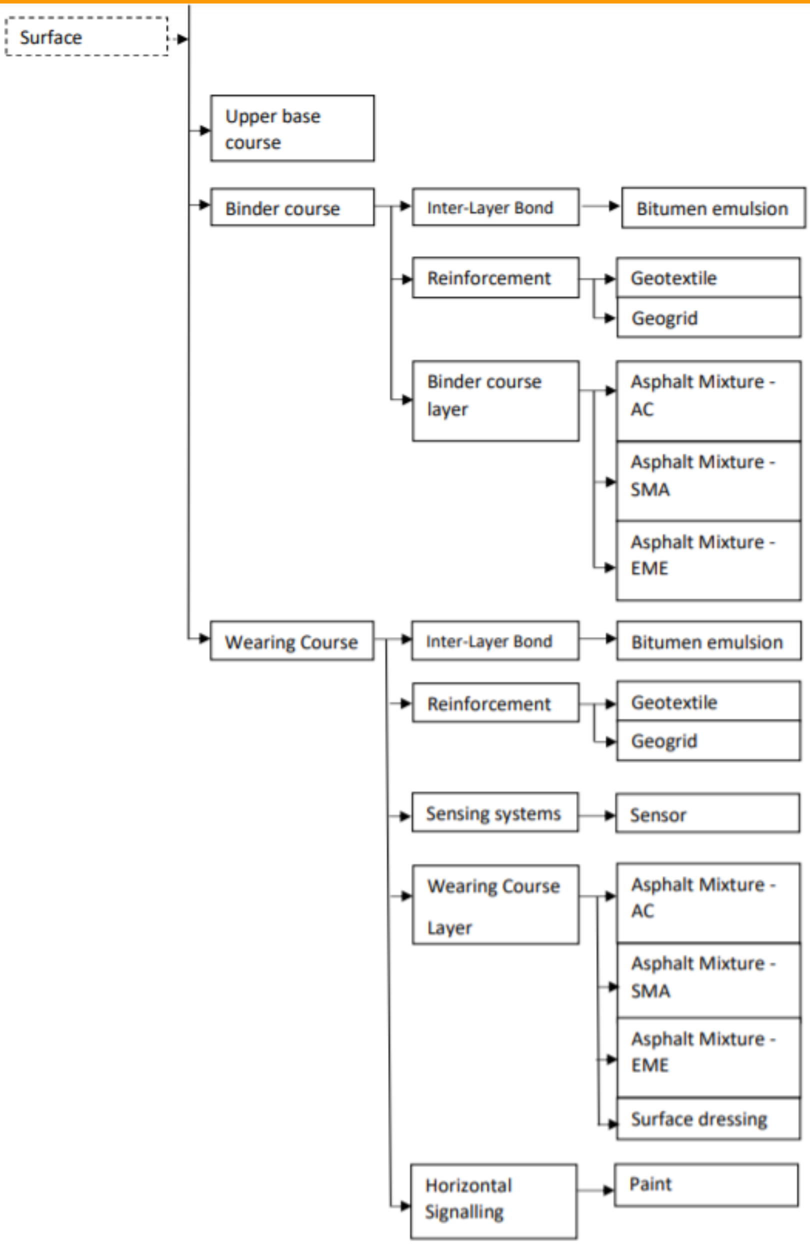


Figure 4 – PLCM Pavement Model, tailored from the buidling model of EN15643-5

2.2.2 System boundaries

*The **system boundaries** for the full life cycle assessment of pavement materials and activities are shown in Figure 5. As mentioned, depending on the purpose of the SA, different life cycle stages can be included or excluded based on the practitioner's choice. EN 15804 and EN 15643-5 call the life cycle stages "information modules" and assign a specific name to each of them, as reported in the figure 5. EN 15804 and EN 15643-5 call the life cycle stages "information modules" and assign a specific name to each of them, as reported in the figure 5*

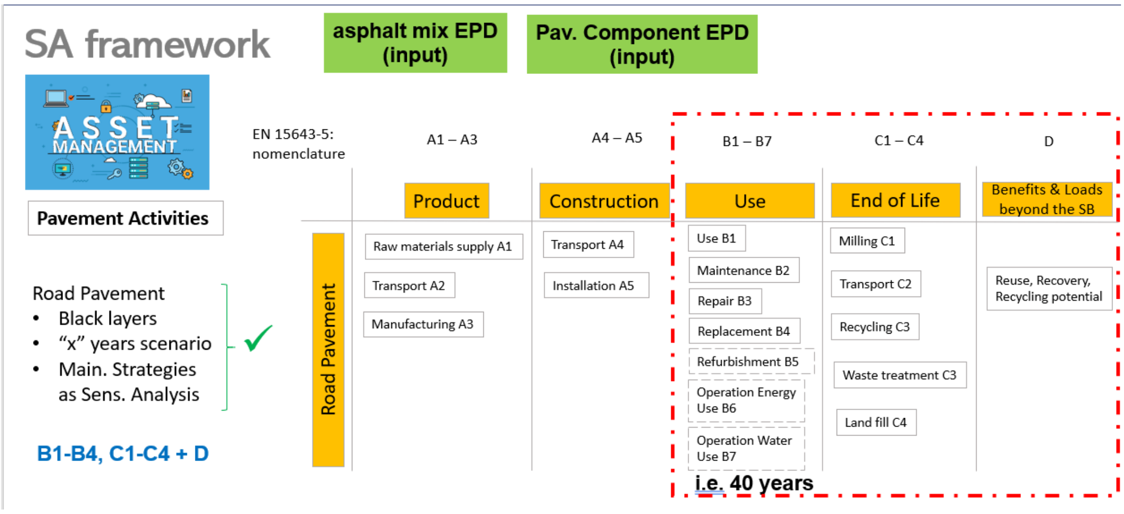


Figure 5 – System Boundaries

In more details:

a) <u>Product and construction stage</u> (Modules A1 to A5):

1) A1 to A3 represent the production stages (material extraction, transport, manufacturing and acquisition), including all impacts and costs linked.

2) A4 to A5 represent the construction stage including transportation of materials to site up to the point of final handover, including all impacts and costs linked.

b) Use stage (Modules B1 to B7):

The system boundary includes the use of construction products and services for protecting, conserving, moderating or controlling the object of assessment, and scenarios for maintenance. The assessment shall include impacts, costs and aspects of the pavement-integrated technical system. The system boundary for the assessment shall exclude impacts and aspects of the appliances, fixtures and fittings that are not pavement-related.

B1-B7 covers the use stage within the life cycle of the system.

1) B1 to B5 represent the impacts and costs that arise as a consequence of the civil engineering works being in place: where B1 represents Use, B2 Maintenance, B3 Repair, B4 Replacement, B5 Refurbishment.

Some examples:

- Maintenance (B2): ex: painting work, represtinate permeability of porous asphalts, etc..
- Repair (B3): ex. Repair a pothole
- Replacement (B4): ex. Replacement of a wearing course, a complete renewal including removal of existing parts. (it's the stage for pavement activities)

- Refurbishement (B5): A major change in the pavement functionality (i.e. from conventional pavement to porous pavement and/or a pavement with energy harvesting capabilities)

2) B6 to B7 represent operational energy and water flows of the civil engineering works and impacts from processes specific to civil engineering works asset and site in operation. In case of pavement activities these stages are linked with future pavement systems.

c) <u>End of life stage</u> (Modules C1 to C4):

1) C1 represents the impacts and costs from deconstruction or decommissioning of the civil engineering works;

2) C2 to C4 represent the impacts and costs from waste management process, including its transport from the deconstruction site to the point where end of waste state (final disposal) is reached.

d) Benefits and loads beyond the system boundary (Module D):

Components for reuse and materials for recycling and energy recovery are considered as potential resources for future use. Module D quantifies the net environmental benefits or loads from reuse, recycling and energy recovery resulting from the net flows of materials and exported energy exiting the system boundary.
Where a material flow exits the system boundary and has an economic value or has reached the end-of-waste status and substitutes another product, then the impacts may be calculated and shall be based on:

- average existing technology;
- current practice;
- net impacts, which are the impacts connected to the recycling process which substitutes primary production, minus the impacts producing the substituted primary product. For closed loop recycling only the net material flow exiting the system is used as the basis for calculating the avoided impacts

N.B. The applicable formula for the calculation of the loads and benefits beyond the system boundary per unit of output for module D calculated for each output flow leaving the system boundary is provided in the EN15804:2012 + A2: 2019

According with the two systems chosen, the system boundaries can be defined as follows:

<u>Pavement materials</u>:

The following lifecycle stages should be included in the system:

- Raw matrial supply (A1), primary data and/or derived from raw material supplier EPDs
- Transport to manufacturing plant (A2), if present
- Product manufacturing (A3)

Pavement Activities:

- Asphalt Contractors:
- Product (A1 – A3), derived from material manufactures‘EPDs
- Transport to site (A4)
- Installation of pavement components (A5)
- Use of the installed pavement components limited to the reference service life of the pavement components and including pavement-user/environment interaction (B1) maintenance of specific technical and functional requirements (B2) and Repair (B3).
- End-of-life activities to dismantle the road pavement components (C1 – C4)
- Possible recycling strategies (D)

- NRAs:
- Product (A1 – A3), derived from material manufactures' EPDs + data on economic and social indicators
- Transport to site (A4), derived from contractors'EPDs + data on economic and social indicators
- Installation of pavement components (A5) derived from contractors‘ EPDs+ data on economic and social indicators
- Use of the installed pavement components over the analysis period (B1)
- Maintenance, Repair, Replacement (B2, B3, B4) of the road pavement and its components
- End-of-life activities, if road pavement physical boundaries are limited to surface and base layer. If physical boundaries are extended to subgrade end-of-life might not exists or it can be considered only if the pavement changes functionality (C1 – C4)
- Possible recycling strategies (D)

Adapting the actual EN 15978 on calculation method about Buildings to our field, it follows that:

- New Construction: The system boundary can start from Product Stage (Module A) and all the required information have to be provided to NRAs by asphalt manufacturers and contractors (EPD and costs).

- Asset management of existing roads: The system boundary starts from the use stage (B1 – B7) and ends with the End of Life (C1-C4) + D.

According with the definition of information modules and knowing that inside each "B" stage, as said before, the burdens connected with the new materials/components are included, NRAs need EPDs and costs from manufacturers and contractors to perform the assessment.

The steps linked with the Product/Construction stage (A1-A5) are strictly connected with the materials and pavement components that will be used. That's why asphalt manufacturers and contractors have to provide EPDs, containing mandatory informations to calculate the environmental burdens.

2.2.3 Analysis period (if applicable)

*Assessments are carried out based on a chosen **analysis period** (called reference study period by EN15978). According to the framework, analysis period should be chosen only in the case of pavement activities, since it refers to the duration in which the inputs and outputs associated with the functional unit are inventoried (i.e. use stage); pavements in particular impose major challenges because initial construction and future maintenance and rehabilitation events often have different functional design lives. To make a reliable statement about the impacts of a product/service or to make a fair comparison between alternative systems that offer competing products/service, the functional unit needs to define an appropriate time horizon for analysis. Typically for pavements, the intention of setting the analysis period is similar to that used for life cycle cost analysis (LCCA): capture the performance of the initial product or service and its effect through the life of at least the next subsequent major rehabilitation treatment, and preferably through the lives of following rehabilitation treatments or the next full reconstruction (Harvey et al., 2016).*

Futhermore, the analysis period (usually defined between 40 and 60 years for pavement activities) not always corresponds with the estimated service life of used products. That's why a maintenance strategy is usually developed and composed of several interventions (see Scenario 2.3)

The following is also suggested in the FHWA report (2011):

- When different pavement design options are to be compared, the selected analysis period should be at least long enough to cover the life of the next major rehabilitation of the longest lasting system so that the effects of the current alternative on subsequent decisions are considered in the analysis.
- When one of the pavement systems or treatments in the LCA is extremely long lived, a maximum analysis period of 100 years is recommended.
- When the longest-lived pavement system in the LCA will receive only maintenance and preservation treatments then a minimum 35-year analysis period is recommended.
- When the object of the assessment is a pavement component, then the analysis period is equal to its estimated service life.

2.2.4 Functional Equivalent/ Functional/ Declared unit:

*The **functional unit** defines the way in which the identified functions or performance characteristics of the product are quantified. The primary purpose of the functional unit is to provide a reference by which material flows (input and output data) and any other information are normalized to produce data expressed on a common basis.*

The ***declared unit** is used instead of the functional unit when the precise function of the product or scenarios is not stated or is unknown.*

*The **functional equivalent** is a representation of the required technical characteristics and functionalities of the pavement. The major functional requirements shall be described together with intended use and the relevant specific technical requirements.*

This description allows the functional equivalency of different options and building types to be determined and forms the basis for transparent and unbiased comparison.

The following it is suggested:

- ✓ **For pavement materials**, 1 tonne of produced material is recommended as declared unit.
- ✓ **For pavement activities**, the exact volume (or weight) of the road pavement to be contracted and/or built as required at project-level or 1 m^2 of surfaced pavement, as recommended by PCRs, together with a clear description of the physical boundaries to account for the total volume of paved materials. Furthermore, the functional equivalent should specify the Estimated Service Life of the component, specifying capacity (e.g. number of vehicles per hour [veh/h]), and any other relevant technical and functional requirements (e.g., regulatory framework and client's specific requirements) and reference/estimated service life (according to The International EPD System 2017, The Norwegian EPD Foundation 2017, The international EPD System 2018)

→ Example of the definition of declared unit

- o Pavement material: Asphalt mixture

Guidance Document for preparing Product Category Rules (PCR) and EPD for Asphalt Mixtures - European Asphalt Pavement Association (EAPA) 2017
"1 metric tonne of asphalt mixture"

→ Example of the definition of functional equivalent/ functional unit

- o Pavement activity: construction of pavement structure

Environmental and economic assessment of pavement construction and 2 management practices for enhancing pavement sustainability – (J. Santos, Cerezo, Flintsch, & Ferreira, 2017)
"*The functional unit considered was defined as a 1km long one-way road pavement section of an Interstate highway in Virginia, USA, with 2 lanes, each of which is 3.66m wide. The project analysis period was 50 years, beginning in 2011 with the construction of the pavement structure. The annual average daily traffic (AADT) for the first year was 20,000 vehicles of which 25% were trucks (5% of the truck traffic consisted of single-unit trucks and the remaining percentage of combination trucks). The traffic growth rate was set equal to 3% per year.*" *

*Although this example does not follow the recommendation of this framework, it was chosen because of the level of detail it provides. "Length of road" is a very common functional unit for pavement activities. This is because the "lenght" of roads refers to a specific pavement structure.

2.2.5 Physical boundary

*The **physical boundaries** of the functional unit define the portions of the pavement structure to be considered part of the pavement system at the location(s) included in the study. The dimensions permit the determination of volumes, masses, surface areas and other quantities needed to perform the SA. If the goal of the LCA does not include the complete pavement system, then the system boundaries can be adjusted.*

→ Example:

Select the portion(s) included in the study:

- o Surface (Wearing course, Binder course, Base course)
- o Foundation (capping, sub-base)
- o Subgrade

2.2.6 Step 2 – Examples and Case studies

Case study for Material/ Product – (CEDR, 2021)

The **object of the assessment** are two CRABs mixtures compared with conventional hot asphalt mixtures, currently used for binder and abse course. Here are the details of each case study:

- German Case Study – in-situ recycling CRAB

The actual base AC32TS HMA, currently used, is a Hot Mix Asphalt and was studied in terms of environmental benefits when compared with the CRAB mixture provided by Germany. This CRAB is directly produced in-situ and was identified in this study as "CRAB_G". It's composed of 4% of cement, 4% of bituminous emulsion, 3.1% of water and contains a high percentage of RAP (936 kg).

- San Marino Case Study- in-plant recycling CRAB

The environmental burdens of conventional binder course was compared with a CRAB mixture whose recipe has been provided by the Road Authority of San Marino. This mixture, called CRAB_RSM, is produced in plant and then moved to the site. It is composed of 4.5% of bitumen emulsion, 2% of cement and contains a high percentage of RAP (845 kg).

The **system boundaries** chosen are A1-A3 (cradle-to-gate) which include raw material acquisition (A1), Transport (A2), Manufacturing (A3). The analysis period is not applicable since only the product stage is considered.

The **Declared unit** is 1 metric ton of asphalt mixture.

Case study for Activities – (CEDR, 2015)

The **object of the assessment** is the repaving work in Italy for a motorway with a high traffic volume with the average Annual Average Daily Flow that can be considered of about 30000 AADT (A19 Palermo- Catania). The section considered is 2-km-long and 9,50 m width and 170 mm thick (30 mm wearing, 40 mm binder, 100 mm base).

The **functional unit** is the quantity of asphalt mixtures to be manufactured and used during the inlay procedures of the case study, multiplying the volume of each wearing course for an estimated density of 2,3 t/m3. In this case it is calculated as:

SE case study:
m^3 of asphalt mixture needed= $2000 \times 9{,}50 \times 0{,}030 = 570\, m3$
f.u.= m^3 of asphalt mixture needed x density= 1311 t

CE Case Study:
m^3 of asphalt mixture needed= $800 \times 11{,}80 \times 0{,}030 = 283{,}2\, m3$
f.u.= m^3 of asphalt mixture needed x density= 651,36 t

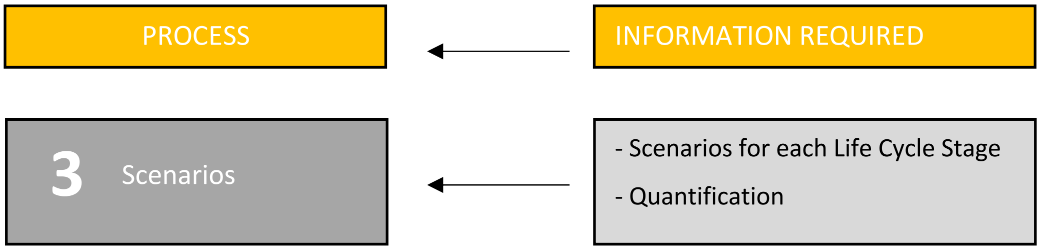
NE case study:
m^3 of asphalt mixture needed= $720 \times 11 \times 0{,}040 = 316{,}8\, m3$
f.u.= m^3 of asphalt mixture needed x density= 728,64 t

The **system boundaries** chosen include B3 + C1-C4 phases (informations on A module provided by contractors/manufacturers).

The **analysis period** is 60 years (as fort he LCC) and the physical boundaries chosen according to the pavement model are the wearing and binder courses (element level) and all the components and products linked to, such as:

- Part: Surface
- Element: Base course, binder course, wearing course
- Components: Lower base course layer;
  Binder course layer for the binder course;
  Wearing course layer for the wearing course.
- Products: Bitumen emulsion, Asphalt mixture,
  Bitumen emulsion, Asphalt mixture for the binder course;
  Bitumen emulsion, Asphalt mixture for the wearing course.

2.3 STEP 3 - Scenarios



2.3.1 Scenarios for each Life Cycle Stage

They are defined as the "collection of assumptions and information concerning an expected sequence of possible future events" (15978, 2011) shall be established to perform the SA on their basis. Scenarios are developed for the construction, use and end-of-life stages and therefore this step is only included in those SA going beyond cradle-to-gate, e.g., for pavement activities. The applied scenarios shall be described or referenced in the assessment report and made available for communication. The scenarios shall be realistic and representative and in accordance with the technical and functional requirements as given in the functional equivalence.

For pavement activities, scenarios must be developed about how the pavement will be constructed, used, maintained, replaced, dismantled and reused during the specific analysis period.

As specified in D3.1, the uncertainty inherent in developing scenarios can be divided into two types; 'scenario uncertainty' and 'model uncertainty'. For instance, predicting the durability of a pavement material in service, leads to examples of scenario uncertainty, such as future maintenance requirement and service life. This will generally require an estimate of performance at a predicted traffic flow. Where traffic growth or, for instance, emissions due to traffic delayed at work zones are predicted using models, these will be associated with model uncertainty in the results of the model or indeed, in the selection of alternative models or inputs to them.

Description of scenarios for each Life cycle stage:

a) Product and Construction stage (A1-A3 and A4-A5)

Environmental information for the product stage is defined in the product EPD. Scenarios in A1-A3 phases include information on theextraction of raw materials, asphalt plant (energy and fuel type and quantity), asphalt mix design, and distances/transport to plant.

Scenarios for the construction process (A4-A5) stage cover the period from the factory gate of the different construction products to the practical completion of the construction work. The scenarios shall define for any elementary operation described within the boundaries of the construction stage (ground works and landscaping; transport of materials, products, waste and equipment within the site; construction process; product installation.)

b) Use stage (B1-B7)

The scenarios for the use stage shall describe all activities with a relevant environmental impact arising from the operation of the pavement activity, including the pavement systems and pavement management activities associated with the object of assessment. Scenarios should be based on the existing regulations, client's requirements, or accepted code of practice. The scenarios that shall be included in an assessment of use stage of the building life cycle require consideration of the following:

- ✓ pavement management activities that include maintenance and repair;
- ✓ use of energy for operational use, if any;
- ✓ use of water for operational use;
- ✓ maintenance activities.

- Scenario related to use stage (except energy and water) - Module B1

The scenario shall define the internal and external conditions for the object of assessment. These conditions influence the impacts related to the characteristics of the products in their application (e.g. release of substances into the environment depends on pattern of use, humidity, air velocity, and temperature).

- Scenarios for maintenance, repair, replacement - Module B2, B3 and B4

These scenarios shall consider the following:

- ✓ client requirements as expressed in the brief (example: maintenance every five years or no maintenance);
- ✓ service life planning according to ISO 15686-1, -2, -7 and -8;
- ✓ requirements issued from EN 15804;
- ✓ manufacturers' information;
- ✓ pattern of use.

- Scenarios for operational water use - Module B6 and B7

The scenarios for energy and water use shall include (but not be limited to) energy consumed in the operational phase of pavement.

The scenario for module B6 shall specify per energy carrier the imported energy used to satisfy the specified demand and per energy carrier the energy that is exported.

Scenarios should consider both the water input and output flows for waste water treatment.

In particular, operational energy use and water use, could be taken into consideration only for "emerging" pavements such as those able to harvest energy.

c) Scenarios for the end-of-life stage (C1-C4)
Processes linked with deconstruction, transport (distances and fuel consumption), all waste treatement processes and disposal activities should be considered.

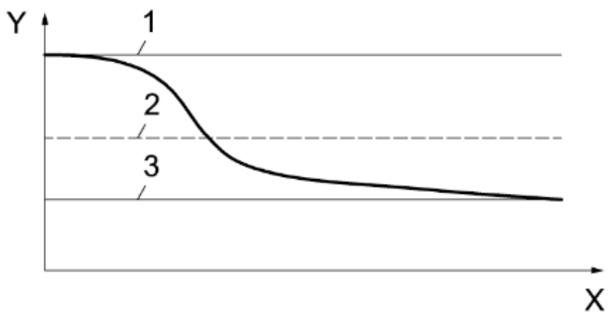
d) Scenarios for benefits and loads beyond the system boundaries (D)
The scenarios describe the processes that lead to future substitution of resources. The scenarios for reuse, recovery and recycling potentials outside of the system boundary of the object of assessment describe the processes that lead to future substitution of resources.

2.3.2 Quantification of the pavement and its life cycle

According to EN 15978:2011, it's the quantification of all materials and products determined on the basis of the design description of the object of assessment or with actual quantities and the scenarios for each module of their life cycle of the object of the assessment. It is helpful to use the Pavement Model introduced in Step 2.

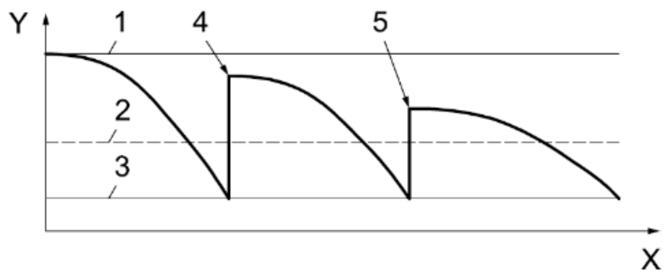
- ✓ **Gross amount.** The assessment shall take into account the gross amount of material and products used to form the object of assessment. Account shall be taken of the 'losses' that occur as a result of a number of factors such as loss/damage in transit, loss/damage on-site, losses in normal processing of products, materials components, etc. on site.

- ✓ **Net amount:** specified according to the design drawing and/or the as-built (and operated) situation, and corresponds to the net units of products, materials, components and elements that all together constitute the pavement.



Key

X RSL
Y functional performance
1 initial
2 average
3 minimum



Key

X	RSL
Y	technical and functional performance
1	initial
2	average
3	minimum
4	maintenance/ repair
5	maintenance/ repair

Figure 6 – *Type of Technical and Functional Performance and RSL (from EN 15804)*

- ✓ **Reference Service Life (RSL):** service life of a ***construction product*** which is known to be expected under a set of reference in-use conditions and which can form the basis for estimating the service life under other in-use conditions. (EN 15804)
  The RSL of a product can be based upon empirical, probabilistic, statistical data and shall always taking into account the intended use. The RSL is dependent on the properties of the product and specific in-use conditions. These conditions shall be declared together with a RSL and it shall be stated that the RSL only applies to these specific in-use conditions.

- ✓ **Estimated Service ife:** service life that a ***pavement or an assembled system*** (part of works) would be expected to have in a set of specific in-use conditions, determined from reference service life data after taking into account any differences from the reference in use conditions (EN 15978).

  It's possible to make a difference between:

  a) Components that will not be replaced under defined conditions
  No replacements are required when the Estimated Service Life (ESL) of the installed products, structural element(s) or component (foundations, column, beam), meets or exceeds the required service life of the pavement.

  b) Replaceable components and number of replacements
  For all components or elements that may be repaired or replaced, the ESL and information on processes for repair, replacement and disposal has to be defined.
  The number of replacements for products, components, elements, used in the pavement is directly linked to its ESL. To facilitate the quantification of number of replacement, the EN15978 provides a specific formula which takes into account both the estimated service life and the reference service life.

2.3.3 Step 3 – Examples and Case Studies

Case study for Material/ Product (CEDR, 2021)

Only a cradle-to-gate (A1-A3) is considered, so the information related to the scenarios are:

- type of raw materials
- informations on plant (type of energy and quantity);
- transport distances to plant;
- mix design.

The **Quantities** needed for 1 metric ton of asphalt mixture, according to the "mix design", are reported below:

	AC32TS	AC12	CRAB_G	CRAB_SM
Fine Aggregates	600 kg	505 kg	-	50 kg
Coarse Aggregates	295 kg	400 kg	-	-
Reclaimed Asphalt	-	-	936 kg	845 kg
Cement	-	-	40 kg	20kg
Binder	35 kg	55 kg	40 kg	45 kg
Filler	70 kg	40 kg	-	40 kg
Water	-	-	31 kg	5 kg

Case study for Actvities – (CEDR, 2015)

The activities taken into consideration for the asset management are detailed below:

- AB2P 2015 – South Europe case study

Project Information: Example of repaving work in Italy for a motorway with a high traffic volume with the average Annual Average Daily Flow that can be considered of about 30000 AADT

The case study is based on a repaving (inlay) operation on the road pavement of a 2-km-long section on A19 motorway, also named Palermo-Catania.

- AB2P 2015 – Central Europe case study

Project Information: Example of repaving work in Germany for an inter-urban highway with medium traffic volume with the average Annual Average Daily Traffic that can be considered of about 20000 AADT

The project consisted in repaving a section of 800 m x 11.8 m. Included is also the milling process.

- <u>AB2P 2015 – North Europe case study</u>

Project Information: Typical example of inlay work on an inter-urban road in the United

Project Information: Typical example of inlay work on an inter-urban road in the United Kingdom for low/ medium trafficked road with the average Annual Average Daily Flow (AADF) that can be considered of about 10000 AADT.
The case study analysed is a road section of single carriageway (typical width, 11 m).

- The activities can be summed up as:

- Management treatment:
- Surface treatments with periodic inlay of wearing course and occasional inlay of binder and base course
- Maintenance is undertaken in one carriageway (two lane), or one lane (single lane road) at a time, with the traffic diverted onto the other carriage/lane.
- Workzones are extended for the whole length and the width of the full carriageway.
- In the case studies with dual carriageway, maintenance event is considered only in one direction.

- Materials: The actual baselines will be compared with the six new mixes already mentioned.
- The following maintanainance strategies are foreseen:

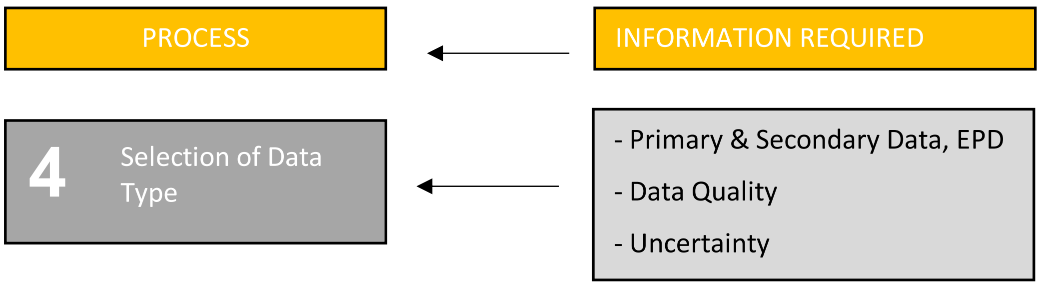
Analysis period	60 years					
Country dependent maintenance strategy	*Italy:* (ANAS 2015)		*Germany:* (BASt 2015)		*UK:* (Spray 2014)	
	year	*procedure*	*year*	*procedure*	*year*	*procedure*
	0 - 5	Inlay WC+BC	0 - 16	Inlay WC+BC	0 - 10	Inlay WC+BC
	5 - 10	Inlay WC	16 - 28	Inlay WC	10 - 20	Inlay WC
	10 - 15	Inlay WC	28 - 44	Rehabilitation	20 - 30	Inlay WC+BC
	15 - 20	Inlay WC	44 - 60	Inlay WC	30 - 40	Inlay WC
	20 - 25	Inlay WC			40 - 50	Rehabilitat.
	25 - 30	Inlay WC+BC			50 - 60	Inlay WC
	30 - 35	Inlay WC				
	35 - 40	Inlay WC				
	40 - 45	Inlay WC				
	45 - 50	Inlay WC				
	50 - 55	Rehabilitation				
	55 - 60	Inlay WC				

Quantification

In detail, the following quantities are needed, for each type of mixture, according to the considered section:

1) Baseline UK: Coarse Aggregates= 874 kg – Biitumen= 70 kg – Filler= 56 kg -
2) Baseline Germany: Coarse Aggregates= 862 kg – Biitumen= 70 kg – Filler= 65 kg- Fibres= 3 kg
3) Baseline Italy: Coarse Aggregates= 869 kg – Biitumen= 61 kg – Filler= 70 kg
4) AC16 30%RA+add RA= 314 kg – Coarse Aggregates= 638 kg – Biitumen= 45 kg t – Storbit Additive= 3 kg
5) AC16 60%RA+add RA= 628 kg – Coarse Aggregates= 337 kg – Biitumen= 29 kg - Storbit Additive= 5 kg
6) AC16 90%RA+add RA= 935 kg – Coarse Aggregates= 39 kg – Biitumen= 19 kg - Storbit Additive= 7 kg
7) SMA8 S30%RA RA= 300 kg t – Coarse Aggregates= 615 kg – Biitumen= 55 kg – Filler= 25 kg - Fibres= 3 kg
8) SMA8S 60%RA RA= 600 kg – Coarse Aggregates= 356 kg – Biitumen= 40 kg – Fibres= 3 kg
9) SMA8S 60%RA+add RA= 600 kg – Coarse Aggregates= 356 kg – Biitumen= 34 kg –- Fibres= 30 kg - Storbit Additive= 6 kg

2.4 STEP 4 – Selection of Data Type



2.4.1 Primary and Secondary Data, EPD (Data Collection)

Data *is the core of any SA, and their collection is one of the key steps in the process and it is expected to be the most time-consuming, resource-intensive part of the SA. The degree of confidence that can be placed on the results and in the assessment will depend upon the level of precision and detail provided in the data and the information used to represent the object of assessment. The choice of data type depends on (15978, 2011):*

- *the scope and intended use of the assessment*

- *when the object of assessment is assessed within the decision-making process*
- *the availability of information*
- *the importance of the data in relation to the overall importance of the study.*

Assessments should be made using data and information that most precisely represents the object of assessment and the time of the assessment. This information may be given in different forms:

- *Unit process: smallest element considered in the inventory analysis (e.g. bitumen)*
- *Aggregate process: larger element considered in which different unit processes have been aggregated (e.g. asphalt mixture)*

Informations can be given as aggregated data for aggregated processes or as product/material specific for unit process.

The options to collect data are (Harvey et al. 2016):

- Option 1 – Measured data from source (Primary Data**):** Source-specific primary data with direct measured data are considered as option 1. This is likely the most expensive and the most reliable data that can be collected for a unit process if the measurement conditions are representative.
- Option 2 - Process-Activity Data and Modelling with Emission Factors (Primary or Secondary Data): This option can be used for collecting primary and secondary data. The actual data collected are process-activity data, such as energy consumed, products, hours of operation, productivity, etc. Primary (Option 2A) or secondary (Option 2B) data can be collected as process-activity data. For example, for an asphalt plant, input data for Option 2A can be the energy sources and consumption for the specific plant producing the asphalt mixture used in the construction of pavement studied, while secondary process-activity data (Option 2B) can be average energy consumption for all counter-flow, drum-type asphalt plants in Europe. In general, process-activity data collected in Option 2A will be more representative than those collected in Option 2B. In general, the reliability and representativeness of the inventory results decreases from Option 1 to 2 and from Option 2A to Option 2B.

- Option 3 – Data from literature (Secondary Data): When process-activity data are not available to the initiator or the practitioner of the SA, data from the literature and publicly available databases and sources may be used. This may range from primary data reported in the databases to proxy data when only similar (but not identical) material or process data are available. However, special attention is needed when proxy data are used, as data sources should be checked for their representativeness and transparently reported with the inventory results.

- Option 4 – Use of EPD. According to what said before, manufacturers and contractors must provide EPDs of materials/components installed. These documents contain important information and data to be implemented.

Ideally, every practitioner should have as many primary data as possible for all the processes included in the system boundaries of their analysis. However, collecting this data is a very time consuming and expensive task and therefore, a number of commercial (i.e. GaBi, ecoinvent) or public databases (i.e. Okobaudat) are available for practitioners. In work package 5, PavementLCM will deliver a **"Sustainability Assessment Compass"** in which practitioners will be able to identify where secondary data can be found. In ordert o find it please look at the PavementLCM RESOURCES.

Data collection should include the following actions to ensure transparency and uniformity while minimizing misunderstanding (Harvey et al., 2016):

- Development of a data management plan documenting data-collection processes, inventory reporting and updates, internal data-quality-control procedures, and responsibilities.
- Development of process flow diagrams that outline all unit processes, including their interrelationships.
- Preparation of data-collection forms and templates.
- Listing of the units of the flows.
- Identification of types of data for each unit process following the guidance provided in the scoping phase.
- Description of the data collection and calculation techniques needed for all data.
- Documentation clearly identifying any special cases, irregularities, or other items associated with the data provided.

Data can also be represented by:

- generic data that is typical of the types of structure and materials used;
- average data combined from different manufacturers or production sites for the same product;
- collective data that is determined according to the requirements of EN 15804 and which will allow an EPD to be established for a type or a category of similar products;
- information that is specific to the manufacturers' components and/or products used in the construction;
- specific detailed information (i.e. a full bill of quantities, dimensions, etc.) for the actual products and components used and directly measured information for utilities and services (energy, water demand, waste, etc.) as built and operated.

Table 2 – Type of Data (EN15978)

Preferred data	Point of the time of the assessment				
	Inception/ Concept design	Detailed design	Construction	Use stage	End of life of the building
Generic data	X	X	X	X	X
Aggregated data	X	X			
Average data	X	X	X	X	X
Product collective data	O	x	x	X	x
Product average data	O	X	X	X	X
Product specific data	O	X	X	X	X
Model scenarios for use stage	X	X	X	X	
Measured data			X	X	X
Other data	O	O	O	O	O
NOTE Cross represents the preferred use of data - Circle represents alternative sources if available.					

2.4.2 Data Quality

It is linked to the quality of data used and data sources. ISO 14044 (2006) defines data quality as "characteristics of data that relate to their ability to satisfy stated requirements". The first step in the evaluation of the data quality is the development of scoring criteria. According to ISO 14044 (2006), the data quality requirements must be described in the assessment and cover the following 10 criteria:

1) time-related coverage: age of data and the minimum length of time over which data should be collected;
2) geographical coverage: geographical area from which data for unit processes should be collected to satisfy the goal of the study;
3) technology coverage: specific technology or technology mix;
4) precision: measure of the variability of the data values for each data expressed (e.g. variance);
5) completeness: percentage of flow that is measured or estimated;
6) representativeness: qualitative assessment of the degree to which the data set reflects the true population of interest (i.e. geographical coverage, time period and technology coverage);
7) consistency: qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis;
8) reproducibility: qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study;
9) sources of the data;
10) uncertainty of the information (e.g. data, models and assumptions).

The scoring criteria may change depending on the LCA application, but it should contain all or most of the data-quality indicators. For instance, specifics PCRs set their own data quality criteria. Once the criteria is set, in order to evaluate the appropriateness and the quality of the data used, they have to be scored against such aspects.

The EN 15804:2012+A2:2019 provides another approach to test data quality, however the authors considers the table provided in JRC Report (2016) more appropriate for this application. This matrix introduces five quality indicators to describe the quality of the data and to estimate the associated uncertainty; these are Completeness, Methodological appropriateness, Technological representativeness, Time-related representativeness and Geographical representativeness.

These indicators have been grouped and shown in Table 3.**Errore. L'origine riferimento non è stata trovata.** Each one of the indicators have a score from one to five, where one means the quality of the indicator is excellent, whereas a score of five means a poor degree. Furthemore, an example of data quality assessing is provided in Table 4.

Table 3 – Table for Data Quality Assessment (JRC, 2016)

			Data quality elements					
			Representativeness					
Quality level	Quality rating	Definition	Technological	Geographical	Time-related	Completeness	Methodological Appropriateness and Consistency	Parameter uncertainty
Very goo d	1	Meets the criterion to a very high degree, without need for improvement.	E.g. Process is same. For electricity from grid, average technology as country- specific consumption mix.	Country specific data	≤ 3 year s old data	Very good completene ss (≥ 90 %)	Full compliance with all requirements of the PEF guide	Very low uncertainty (≤ 7 %)
Goo d	2	Meets the criterion to a high degree, with little significant need for improvement.	E.g. average technology as country- specific consumption mix.	Central Europe, North Europe, representativ e EU 27 mix,	3-5 year s old data	Good completene ss (80 % to 90 %)	Attributional Process based approach AND following three method requirements of the PEF guide met: (1) Dealing with multi-functionality; (2) End of life modelling; (3) System boundary.	Low uncertainty (7 % to 10 %)
Fair	3	Meets the criterion to an acceptable degree, but merits improvement.	E.g. average technology as country- specific production mix or average technology as average EU consumption mix.	EU-27 countries, other European country	5-10 year s old data	Fair completene ss (70 % to 80 %)	Attribution Process based approach AND two of the following three method requirements of the PEF guide met: (1) Dealing with multi-functionality; (2) End of life modelling; (3) System boundary.	Fair uncertainty (10 % to 15 %)
Poor	4	Does not meet the criterion to a sufficient degree, but rather requires improvement.	E.g. average technology as country- specific consumption mix of a group of similar products	Middle east, North-America, Japan etc.	10-15 year s old data	Poor completene ss (50 % to 70 %)	Attributional Process based approach AND one of the following three method requirements of the PEF guide met: (1) Dealing with multi-functionality; (2) End of life modelling; (3) System boundary.	High uncertainty (15 % to 25 %)
Very poor	5	Does not meet the criterion. Substantial improvement is necessary.	E.g. other process or unknown, not available (n.a.)	Global data or unknown	≥ 15 year s old data	Very poor or unknown completene ss (< 50 %)	Attributional Process based approach BUT: None of the following three method requirements of the PEF guide met: (1) Dealing with multi-functionality; (2) End of life modelling; (3) System boundary.	Very high uncertainty (>25 %)

Table 4 - Example of Data Quality Assessment

Data set	Representativeness: Technological	Representativeness: Geographical	Representativeness: Time-related	Completeness	Parameter uncertainty	Methodological Appropriateness and Consistency	Resulting Data Quality Rating (DQR)
CH: building, hall, steel construction	1	3	3	1	3	4	2.50
CH: disposal, sludge from pulp and paper production, 25% water, to sanitary landfill	1	3	3	1	3	4	2.50
CH: disposal, steel, 0% water, to municipal incineration	1	3	3	1	3	4	2.50
DE: lignite briquettes, at plant	1	3	3	1	3	4	2.50
DE: maize starch, at plant	1	3	3	1	3	4	2.50
DE: potato starch, at plant	1	3	3	1	4	4	2.67
RER: AKD sizer, in paper production, at plant	1	2	3	1	3	4	2.33
RER: aluminium sulphate, powder, at plant	1	2	3	1	3	4	2.33
RER: building, multi-storey	1	2	3	1	3	4	2.33
RER: electricity, medium voltage, production RER, at grid	1	2	2	1	3	3	2.00
RER: facilities, chemical production	1	2	3	1	3	4	2.33
RER: heavy fuel oil, at regional storage	1	2	3	1	3	4	2.33

2.4.3 Uncertainty

Uncertainty *is a general term used to describe the spread of an observation and its distribution. Data uncertainty can result from several causes such as accuracy of equipment used, deficiencies in production, factors related to data quality including completeness and reliability of the data. According to what is defined in D3.1, the total uncertainty is the result of two different ones: basic and additional.*

It can be estimated based on the normal distribution properties using the following equation:

$$\sigma^2 = {\sigma^2}_{bu} + \sum_{n=1}^{5} {\sigma^2}_n$$

Where:

- ${\sigma}^2$ is the total variance in the data,
- ${\sigma^2}_{bu}$ is the basic uncertainty variance, and
- ${\sigma^2}_{n=1:5}$ are the additional uncertainty variances from the pedigree matrix.

2.4.3.1 Basic Uncertainty: It is used to describe uncertainty due to for example measurement inaccuracy; it highlights the fact that any observation can never be deterministic.

One of the most common way to measure is the Monte Carlo Simulation (MCS).

By this method, input parameters are defined by their probability distribution functions (PDF), then the model that links the inputs with the outputs is run for many times, every time a new set of inputs is randomly generated based on the input PDFs, and a new set of outputs is calculated and stored. In the ecoinvent method, a lognormal distribution is generally assumed to model this category of uncertainty.

Table 5 - Variance of the underlaying normal distribution of the basic uncertainty category, - D3.1

Input/ output group	**c**	**p**	**a**
demand of:			
thermal energy, electricity, semi-finished products, working material, waste treatment services	0.0006	0.0006	0.0006
	0.12	0.12	0.12
transport services (tkm)	0.3	0.3	0.3
Infrastructure			
resources:			
Primary energy carriers, metals, salts	0.0006	0.0006	0.0006
Land use, occupation	0.04	0.04	0.002
Land use, transformation	0.12	0.12	0.008
pollutants emitted to water:		0.04	
BOD, COD, DOC, TOC, inorganic compounds (NH4, PO4, NO3, Cl, Na etc.)		0.3	
		0.65	
Individual hydrocarbons, PAH			
Heavy metals			0.09
Pesticides			0.04
NO3, PO4			0.04
pollutants emitted to soil:		0.04	
Oil, hydrocarbon total		0.04	
Heavy metals			0.04
Pesticides			0.033
pollutants emitted to air:	0.0006	0.0006	
CO2			
SO2	0.0006		
NMVOC total	0.04		
NOX, N2O	0.04		0.3

Input/ output group	c	p	a
CH4, NH3	0.04		0.008
Individual hydrocarbons	0.04	0.12	
PM>10	0.04	0.04	
PM10	0.12	0.12	
PM2.5	0.3	0.3	
Polycyclic aromatic hydrocarbons (PAH)	0.3		
CO, heavy metals Inorganic emissions, others	0.65		
Radionuclides (e.g., Radon-222)		0.4	
		0.3	

The variance of the underlaying normal distribution of the basic uncertainty can be calculated based on the type of exchange and process involved, as shown in Table 3. This table shows that the variance can be estimated based on the process type whether it is combustion "c", process emissions "p", or agricultural emissions "a", and based on the exchange involved.

To simplify the calculation, the PavementLCM methodology proposes to filter the process contribution in order to isolate the most important processes, defined as the ones contribute the most to the impacts. The filtering rule was to set cut-off value of 1%; this threshold means that every process contributes to less than 1% of the impact total will not be counted as important process but its value will be considered in the "remaining processes".

To estimate the uncertainty level in these data, MCS analysis was run to every one of the important processes identified in this project. This step allows the estimation of the Coefficient of Variation (CoV) of every one of the important processes (D3.1)

2.4.3.2 Additional uncertainty: It is linked to the data quality, reported in the section above in Table 3. The table allows assessing a level of uncertainty related to each quality rating and within a range from 7% to 25%.

For completeness of information, assessing the uncertainty related to the quality of the collected data can also be carried out by using a Pedigree Matrix which is connected to each process. This methodology, highly specific and used in WP4, is included in some LCA inventory databases, such as Ecoinvent (Weidema et al. 2013). As a first approach to the issue, NRAs members are recommended to refers to Table 3.

2.4.3 Step 4 – Examples and Case Studies

Case Study for Activities – (CEDR, 2015)

All the information related to the asphalt mixtures production have been obtained through:

- **Primary Data**: Data collection at Asphalt Plant and Questionnaires to Road Authority
- **Secondary Data**: Other standard and reputable data sources were utilised to provide energy consumption during production, fuel, transport and embodied carbon values for constituent materials.
- **Data Quality** hasn't been calculated;
- **Uncertainty** hasn't been calculated.

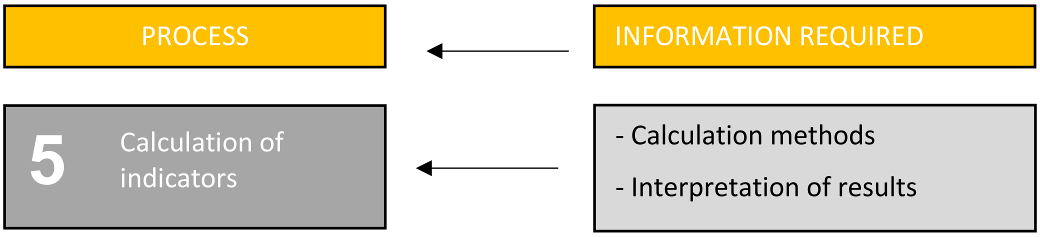
Case study for Material/ Product – (CEDR, 2021)

- **Primary Data**: Questionnaires for materials acquisition, processes and transportation, .
- **Secondary Data**: GaBi Database for extraction of raw materials.
- **Data Quality:** It consists of assigning a ranking, according to a table, to datas used for the assessment. In this case, the example is only for environmental assessment.

Data	Type	Source	Technological Representativ.	Geographical Representativ.	Temporal correl.	Completeness	Methodological Appropriateness and Consistency	Avarage
Aggregates	Secondary	GaBi	4	2	2	2	2	2.4
Filler	Secondary	GaBi	4	2	2	2	2	2.4
Bitumen	Secondary	GaBi	4	2	2	2	2	2.4
Cement	Secondary	GaBi	4	2	2	2	2	2.4
Reclaimed Asphalt (RA)	Secondary	GaBi	4	2	2	1	2	2.2
Gas Consumption in Asphalt Plant	Primary	Material Producer	1	2	2	1	2	1.6
Electricity Consumption in Asphalt Plant	Primary	Material Producer	1	2	2	1	2	1.6
Other resources use consumption : heating oil	Primary	Material Producer	1	2	2	1	2	1.6
Other resources use consumption: diesel for CRAB and for AC12	Primary	Material Producer	1	2	2	1	2	1.6
Transport Distances	Primary	Real Distances related to the specific case study	1	2	1	1	1	1.2
Transport Mean	Secondary	GaBi Database	4	2	2	2	2	2.4
						tot av.=		1.98

- **Uncertainty** hasn't been calculated.

2.5 STEP 5 - Calculation of indicators



2.5.1 Calculation methods

*Within PavementLCM Framework, the Sustainability Performance Indicators (SPIs) proposed for pavement materials and pavement activities are listed in Table 6**Errore. L'origine riferimento non è stata trovata.**, together with the methodologies and techniques to calculate them.*

*The calculation of each indicator in Table 6**Errore. L'origine riferimento non è stata trovata.** is detailed in the following sections for asphalt mixtures and pavement activities related to asphalted pavements due to the high relevance of in these materials for highways in Europe, where about 90% of all paved roads are paved with asphalt. There are 5 types of indicators:*

1. *Environmental impact*
2. *Economic impact*
3. *Social impact*
4. *Functional requirements*
5. *Technical requirements*

Table 6 - . Sustainability Performance Indicators (SPIs) for pavement materials and pavement activities.

Indicator	Sustainability pillar/category	Object of assessment	Methodology for calculation	Standards related
Global Warming Potential (GWP-total)	Environment	Pavement materials and activities	Life Cycle Assessment (LCA)	ISO 14040, ISO 14044, EN15804, CWA 17089, JRC Technical Reports (2018)
Acidification	Environment	Pavement materials and activities	Life Cycle Assessment (LCA)	ISO 14040, ISO 14044, EN15804, CWA 17089, JRC Technical Reports (2018)

Eutrophication	Environment	Pavement materials and activities	Life Cycle Assessment (LCA)	ISO 14040, ISO 14044, EN15804, CWA 17089, JRC Technical Reports (2018)
Natural resources consumption	Environment	Pavement materials and activities	Life Cycle Assessment (LCA)	ISO 14040, ISO 14044, EN15804, CWA 17089, JRC Technical Reports (2018)
Air pollution	Environment	Pavement activities	Life Cycle Assessment (LCA)	ISO 14040, ISO 14044, EN15804, CWA 17089, JRC Technical Reports (2018)
Energy use	Environment	Pavement materials and activities	Life Cycle Inventory (LCI)	ISO 14040, ISO 14044, EN15804, CWA 17089
Secondary materials consumption	Environment	Pavement materials and activities	Life Cycle Inventory (LCI)	ISO 14040, ISO 14044, EN15804, CWA 17089
Cost	Economy	Pavement materials & Pavement activities	Life Cycle Cost (LCC)	CWA 17089, EN 15686-5 EN 16627
Tyre-pavement noise	Technical and functional requirements	Pavement activities	Tests: • Statistical Pass-by method • Close Proximity method Any other covered in a national, European, or international standardisation document	CWA 17089
Durability	Technical and functional requirements	Pavement activities	Laboratory tests proposed, further definition in	EN 12697-22,EN 12697-24, EN 12697-12

			WP4 of PavementLCM	
Other optional indicators considered important for NRAs	Technical and functional requirements	Pavement activities	This indicator is left customisable from each road authority based on local priorities. (i.e., skid resistance, permeability, etc..)	

2.5.1.1 Environmental impact indicators (LCA)

The selected economic indicator is cost, calculated following a life cycle approach if applicable.

The calculation of the environmental indicators selected in PavementLCM SA Framework is performed using LCA. The principles and framework to perform an LCA of any system are established in ISO 14040 and the requirements and guidelines in ISO 14044. Furthermore, in Europe, the ILCD General guide for Life Cycle Assessment (JRC, 2010) is a useful tool which explains, step by step, how to perform an LCA exercise.

LCA methodology consist of four phases already briefly described in D2.1. These phases are related as shown in Figure 7, together with its direct applications. Further details and recommendations are provided in the following section for the calculation of the iimpact indicators proposed for pavement materials and activities.

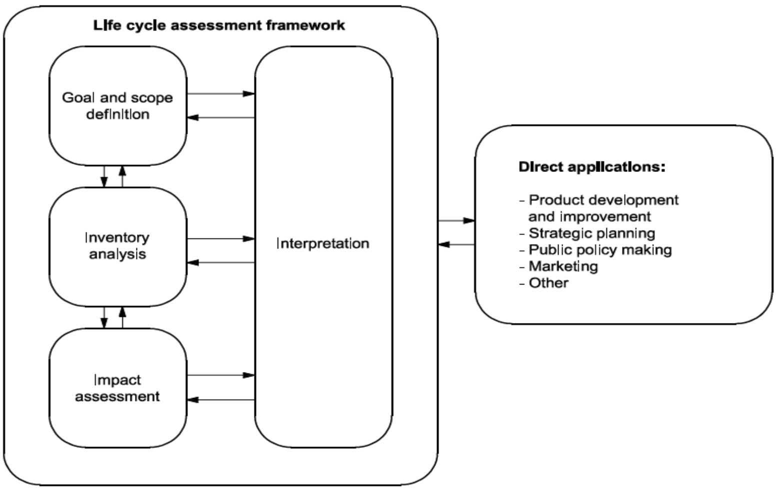


Figure 7 - LCA Phases (ISO 14040)

The principles, framework, guidelines and requirements in ISO standards are general for any system and any LCA should comply with them. However, they leave details and choices (e.g. system boundaries, impact assessment methodology, etc.) open to practitioners of each field. In this regard, in order to harmonise the LCA of the same products and systems and allow comparisons, PCRs are developed to set a common ground and provide guidance on how to carry out the assessment of the same products and systems, allowing also in that way the comparison of results. Therefore, one of the first steps before performing a LCA, is to check whether PCRs are available for the product or system to study and if that is the case, the LCA can be performed according to them. The available PCRs at the moment of this deliverable were presented in D2.1.

More details to perform an LCA are provided in the Annex C of this deliverable.

2.5.1.1.2 Step 5 – Examples and Case Studies for LCA

Case study for Material/ Product – (CEDR, 2021)

1) Goal and Scope

Some useful informations to perform an LCA have been already provided in the previous phases (description of the object of the assessment, declared unit, system and physical boundaries).

The points for each steps not described before are detailed here:

- **Cut-off rules**: no cut-off rules were applied in order to consider all materials' influence. All data was available and produced when necessary.

- **Allocation procedures**: No allocation was considered in this study, except the effect of Reclaimed Asphalt. RA is considered to bring zero emission into the considered system boundaries (EAPA, 2016)

- **Choice of Indicators to calculate**:

Impacts are calculated during the third part of LCA, so in the Life Cycle Impact Assessment (LCIA) with a specific methodology called EF2.0.

In details, the indicators taken into consideration are:

- Global Warming Potential (GWP) with total Climate Change considered as the sum of:
- Global Warming Potential-Fossil fuels (GWP- Fossil fuels)
- Global Warming Potential-Biogenic (GWP-biogenic)
- Global Warming Potential- Land use and land use change (GWP-luluc)

- Acidification

- Eutrophication, taking into consideration:
- "Eutrophication terrestrial", whose indicator is Accumulated Exceedance
- "Eutrophication acquatic freshwater", whose indicator is fraction of nutrients reaching freshwater end compartment
- "Eutrophication acquatic marine", whose indicator is fraction of nutrients reaching marine end compartment potential, fraction of nutrients reaching freshwater end

- Natural Resources, which refers to four midpoint impact categories:
- "Water use", whose indicator is deprivation potential, deprivation-weighted water consumption (WDP)
- "Land use", whose indicator is Potential Soil Quality index (SQP)
- "Resources use, minerals and metals", whose indicator is Abiotic depletion potential for non fossil resources (ADP- minerals&metals)

- "Resources use, minerals and metals", whose indicator is Abiotic depletion potential for non fossil resources (ADP- minerals&metals)
- "Resources use energy carriers", whose indicator is Abiotic depletion for fossil resources potential (ADP-fossil)

- Air pollution, which refers to:

- "Photochemical ozon formation", Trophospheric Ozone Concentration increase.

- Two other indicators were taken into account but direclty provided by the LCI. Hence, any LCIA methodology was applied and they are:

- Energy use (renewable and non renewable);
- Secondary materials consumption.

- **Assumptions and limitations of the study**

- Concerning the assumptions, according to EAPA no stack emissions have been used and default energy for crushing and processing has been considered 47 MJ/t.
- When used, RA stockpile and processing are located at the asphalt plant, therefore, transport distance of RA is zero.

2) Life Cycle Inventory

The asphalt mixtures were produced in the asphalt plant "Touraine Enrobes" (Tours, France).
Here in detail the data collection:

Asphalt mixtures components by weight

	AC32TS	AC12	CRAB_G	CRAB_SM
Fine Aggregates	600 kg	505 kg	-	50 kg
Coarse Aggregates	295 kg	400 kg	-	-
Reclaimed Asphalt	-	-	936 kg	845 kg
Cement	-	-	40 kg	20kg
Binder	35 kg	55 kg	40 kg	45 kg
Filler	70 kg	40 kg	-	40 kg
Water	-	-	31 kg	5 kg

A1 + A2- - Raw material acquisition + Transport

	AC32TS		AC12		CRAB_G		CRAB_RSM	
	Location	Distan.	Location	Distan.	Location	Distan.	Distances	Distan,
Fine Aggregates	Neumagen-Dhron	28 km	Forlì	65 km	-	-	Ravenna	65 km
Coarse Aggregates	Neumagen-Dhron	28 km	Castel Viscardo	235 km	-	-	-	-
Reclaimed Asphalt	-	-	-	-	In-situ (E-44 Trier)	0 km	In-plant	0 km
Cement	-	-	-	-	Allmendingen	392 km	Moselice	210 km
Binder	Niederlassung Bonn	163 km	Bologna	125 km	Niederlassung Bonn	163 km	Bologna	125 km
Filler	Neumagen-Dhron	28 km	Serra San Quirico	150 km	-	-	Gubbio	145 km
Water	In-plant	0 km	In-plant	0 km	Trier	2,9 km	In-plant	0 km

A3 - Production

	AC32TS	AC12	CRAB_G	CRAB_SM
Electricity	12 MJ/t	6,75 kwh/t	-	0,65 kWh/t
Natural Gas	-	10 m^3	-	
Water	2 MJ/t	-	-	
Diesel	-	0.042 kg	0,16 kg	0,17 kg
Other type of energy (heating oil)	420 MJ/t	-	-	

Secondary Data:

All the other data, such as the elementary flows of extraction of raw materials, have been taken from the Professional Database of Gabi ts by Thinkstep, a company of Sphera.

2.2 Data Calculation

All the collected data was introduced in GaBi ts software and Data Quality has been already provided.

3) Life Cycle Impact Assessment

		Conventional Binder	CRAB_RSM used for Binder
CLIMATE CHANGE	EF 2.0 Climate Change [kg CO2 eq.]	64.7	32.4
	EF 2.0 Climate Change (biogenic) [kg CO2 eq.]	0.115	0.0751
	EF 2.0 Climate Change (fossil) [kg CO2 eq.]	64.3	32.3
	EF 2.0 Climate Change (land use change) [kg CO2 eq.]	0.693	0.0396
	EF 2.0 Acidification terrestrial and freshwater [Mole of H+ eq.]	0.221	0.0694
EUTROP	EF 2.0 Eutrophication freshwater [kg P eq.]	0.000133	5.39E-05
	EF 2.0 Eutrophication marine [kg N eq.]	0.0899	0.0221
	EF 2.0 Eutrophication terrestrial [Mole of N eq.]	0.99	0.24
AIR POLL.	EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.]	0.227	0.0618
NATURAL RESOURCES	EF 2.0 Land Use [Pt]	328	143
	EF 2.0 Resource use, energy carriers [MJ]	3.02E+03	922
	EF 2.0 Resource use, mineral and metals [kg Sb eq.]	1.11E-05	5.56E-06
	EF 2.0 Water scarcity [m³ world equiv.]	4.38	0.765
ENERGY	Energy use (mJ)	6.57+25	5.78E+25
	- Non renewable	6.57E+25	5.78E+25
	- Renewable	2.22E+06	2.22E+05
	Secondary Materials Consumption (kg)	0	845

		Conv Base AC32Ts HMA	CRAB_G used for base
CLIMATE CHANGE	EF 2.0 Climate Change [kg CO2 eq.]	63.5	47.5
	EF 2.0 Climate Change (biogenic) [kg CO2 eq.]	0.116	0.0799
	EF 2.0 Climate Change (fossil) [kg CO2 eq.]	63.3	47.4
	EF 2.0 Climate Change (land use change) [kg CO2 eq.]	0.0947	0.0645
	EF 2.0 Acidification terrestrial and freshwater [Mole of H+ eq.]	0.194	0.0826
EUTROP	EF 2.0 Eutrophication freshwater [kg P eq.]	1.04E-04	6.28E-05
	EF 2.0 Eutrophication marine [kg N eq.]	0.0465	0.0272
	EF 2.0 Eutrophication terrestrial [Mole of N eq.]	0.512	0.296
AIR POLL.	EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.]	0.142	0.0762
NATURAL RESOURCES	EF 2.0 Land Use [Pt]	316	164
	EF 2.0 Resource use, energy carriers [MJ]	2.24E+03	881
	EF 2.0 Resource use, mineral and metals [kg Sb eq.]	6.91E-04	5.63E-06
	EF 2.0 Water scarcity [m^3 world equiv.]	5.2	1.99
ENERGY	Energy use (mJ)	5.01E+25	2.21E+25
	- Non renewable	5.01E+25	2.21E+25
	- Renewable	8.12E+14	2.22E+05
	Secondary Materials Consumption (kg)	0	936

✓ **Optional steps**

Standards identify some optional steps in order to deepen the results obtained.

1. Normalisation
No normalisation is proposed in this study because adjusting values measured on different scales to a notionally common scale is not necessary.

2. Weighting
In relationship to this case study, all the chosen impact indicators have the main importance: that's why no weight were attributed.

3. Grouping
No grouping was proposed.

4) Life Cycle Interpretation

In this section, the results of LCI and LCIA are summarised and discussed as a basis for further conclusions and recommendations in accordance with the goal and scope definition of the study.

4.1. Identification of significant issues

Paying attention on the table, it is possible to underline that:

- In both cases, the CRAB is more environmentally performant than the conventional hot mix, in any environmental impact category. This is mainly due to the fact that CRAB materials has got a very high quantity of reclaimed asphalt sourced from nearby and/or on-site location
- For Germany, the highest decreases in terms of impacts can be seen on the acidification (-57%), on Resource use- energy carriers (-61%) and Resource use- minerals and metals (-99%) and on energy consumption (-56%).
- For Republic of San Marino, the most negatevely affected impact categories are the Climate Change-land use change (-82%), the acidification (-73%), Eutrophication (-76% terrestrial, -75% marine), the photochemical ozone formation (-73%), the water scarcity (-83%) and the use of renewable energy (-90%).

The mixtures impacts results were compared and reported in the graphic here below.

- San Marino CRAB seems to be more environmental friendly compared with the German one for all the impact categories, except for the resource use-mineral and metals (-50% San Marino vs -99% Germany), and for Energy Use (-12% San Marino vs -56% Germany).
- Furthermore, German CRAB contains a higher quantity of reclaimed asphalt than the other cold mixture (936 kg vs 845 kg).

✓ **Hotspot Analysis**

It was studied the contribution of each LC stage for the two conventional mixtures and for CRAB_G and CRAB_SM. In all the four analyses, it's evident that raw materials acquisition is the most impactful stage, representing almost always a hotspot or a relevant step in the Life Cycle. In particular, for both the CRABs, A1 is always relevant or a hotspot (with contributions from 99% to 50%), except for Climate Change- land use change for CRAB-G (46%). Concerning CRAB_G, A1 average contribution is of 86%, A2 of 7% and manufacturing of 7%. Instead, for the cold mix producers in San Marino, A3 influences a bit more than in Germany (13%), while A1 is less impactful (79%) and A2 is almost the same (8%). For the conventional hot mixes, A1 is almost always a hotspot/relevant stage, but with the difference that contributions are more fairly distributed between the Raw Materials supply and the manufacturing steps. The transport influences in a very low percentage, as also showed in the sensitivity analysis reported below.

✓ **Sensitivity Analysis**

In order to understand how much the impacts are influenced by choices and parameters, two sensitivity analyses were performed and the following factors were considered:

Contribution of transport distances:

In two previous projects (Lo Presti et al., 2015 and Jimenez del Barco Carrion et al., 2018), the transport stage was found to have a high impact on the results and conclusions of LCA. For this reason, within this investigation, the transport of raw materials to the asphalt plant has been subjected to sensitivity analysis.

To answer this question, three scenarios have been created. In each scenario all the extracted materials (aggregates, bitumen, additives, etc) are sourced at the same transport distance from the asphalt plant and changed for each scenario. The distances considered are 50km, 100km and 200km. as distances increase, also impacts become bigger, even if the increase of emissions incidence is very low. In fact, the variation range changes from 1% to 5% according to the impact categories, even if the distances are assumed at 200 km.

From this it was deduced that transport doesn't affect in a huge way the impacts.

Contribution of mix design formula :

The results in terms of emissions might be affected by the composition of the CRAB materials. Therefore, in order to draw some conclusions, the presented case studies have been enriched also with other four CRABs formulas with varying ranges of cement, bitumen and water, as defined in WP4 o fthe same project. It was deduced that the recipes don't influence in a very specific way the impacts for all the categories: it's impossible to select a CRAB whose production implies a reduction of all chemical emissions.

4.2 Evaluation that considers completeness, sensitivity and consistency checks

In order to define the basis for conclusion and recommendations, it's necessary to evaluate the previous phases of LCA through the checks reported below.

✓ **Consistency Check**

According the actual standard, it is important to be sure that all the LCA carried out is consistent throughout.

First of all, the consistency with Goal and Scope is assured. In fact, for istance, we can state that the f.u. defined as 1 ton of asphalt mixture, the impact categories chosen following the Pavement LCM Guidelines and system boundaries as A1-A3 (cradle-to-gate) are all consistent with what stated in Goal and Scope.

Secondly, the consistency with the LCI phase is assured too thanks to the data provided by the parteners and specific for the case studies and responding to the requirements (see data quality). All the data were uploaded in GaBi database to perfom the assessment.

Thirdly, concerning the consistency for LCIA phase, the methodology and impact categories used are the same of those defined in Goal and Scope Definition. Furthemore, all the processes were included.

✓ **Completeness Check**

According to ISO 14040, it is important to ensure that all relevant information and data needed for the interpretation are complete and available. As stated in the Goal & Definition phase, any cut-off rule was applied.

In detail, it can be stated that:

- all the LCI unit process coverage and system modeling are complete. In fact, the model is exaclty created in GaBi according to the chosen system boundaries. Any process was excluded;
- Intermediate and elementary flow coverage are complete. The model is created with GaBi and all the unit processes contain the linked elementary flows.
- Life Cycle Impact Assessment phase is complete. In fact, the following evaluations were done:
- the selected impact categories are those one suggested by PavementLCM Framework, which is based on the actual suggestions by JRC and they cover the set of most relevant impacts potentially occuring.
- Completeness of the model's elementary flows recorded in the inventory is assured and no significant elementary flows are excluded in the impacts calculation, as checked in GaBi database.

✓ **Sensitivity Check with Uncertainty Analysis**
No Uncertainty Analysis was carried out

4.3 Conclusions, limitations and recommendations

As a result:

- The research shows that regardless of the manufaturing process, the environmental performance of all investigated CRABs was better than a conventional asphalt in almost all the impact categories.

- CRAB materials seems to be more environmental friendly than HMA, both for in-situ recycling (base course) and in-plant recycling (binder course) . In fact, all the impact categories, for both case studies with CRABs, have an environmental impact on average lower than 50%.

- The hotspot analysis showed that the most impactul stage is the acquisition of raw materials (A1) for CRAB (86% of totale missions for CRAB_G and 79% for CRAB_SM). Hence, in order to further reduce environmental impacts of this technology, CRAB material producers should focus on identify materials whose extraction and/or supply is less impactful.

- sensitivity analyses revealed that transport distances, related to material supply and CRAB manufacturing, do not play the same main role as they tipically have with the environmental impact of conventional asphalt mixtures.

- In general, appreciable emissions savings (almost 50%) can be observed for both CRAB as well as for the others whose mix design was provided by WP4. In fact, regardless of the manufacturing process and mix design formula, CRABs are less impactful than conventional mixtures.

Case Study for Activities – (CEDR, 2015)

As specified earlier, this LCA is a Carbon Footprint exercise, where only the quantity of CO_2 equiv, linked to the Climate Change indicator, is calculated.

The environmental impact is obtained considering the results of the LCA for each asphalt mixture object of the assessment and calculating for each design alternatives the quantity of CO_2 equiv emitted.

1) Goal & Scope Definition

Some useful informations to perform an LCA have been already provided in the previous phases (description of the object of the assessment, declared unit, system and physical boundaries).

The points for each steps not described before are detailed here:

- Cut-off rules: Processes/activities that altogether do not contribute to more than 1% of the total environmental impact for any impact category will be omitted from the inventory analysis.

- Allocation procedures: In order to reward recycling practices into the new mixture, 100:0 rule was adopted in favour of the recycled content method.

- Choice of impact categories: in this study, only the GWP [kg CO_2 equiv] was calculated.

- Assumptions and limitations: whenever the maintenance intervention involves also binder and base courses, it is assumed these asphalt mixes to be the same than the considered wearing course. In fact, it looks not realistic that future interventions will make use of RA only in wearing courses. Furthermore, the durability of all new technologies were considered the same of the baseline. Other assumptions, linked to LC stage, are reported below.
Only the Carbon Footprint is calculated, so the results obtained can't be used to claim a general "environmental friendship" of the considered mixtures.

2) Life Cycle Inventory

- A1- A3 (Product phase):

- Baseline asphalt mixture

	South EU - IT	*Central EU - D*	*North EU - UK*
Virgin aggregates (%)	86.9	86.2	87.4
Filler (%)	7.0	6.5	7.0
RA (%)	-	-	-
Binder (%)	6.1	7.0	5.6
Fibres (%)	-	0.3	-

- New mixtures Cradle-to-gate constituent CO2e values

	Data Source	kg CO2e/t
Virgin aggregates 0.075 – 20 mm	EARN	4.4
Filler <0.075 mm	EARN	0
RA Planings	EARN	0.31
Bitumen	asPECT v4.0	190
Polymer modified bitumen	EARN	370
Fibers	asPECT v4.0	0.78
STORBIT PLUS additive	STORIMPEX	875

- Case study specific raw material's transport distances to the plant

	Origin	Mode of transport	One way distance (km)
South Europe			
Virgin aggregates 0.075 – 20 mm	Quarry	Rigid>17t, 20t payload	46
Filler <0.075 mm	Plant	-	0
RA Planings	RA stockpile	Rigid>17t, 20t payload	32
Bitumen/PMB	Refinery	Rigid>17t, 20t payload	215
Fibers	ITERCHIMICA Bergamo, IT	Articulated >33 t, 24 t payload	1370
STORBIT PLUS additive	STORIMPEX Leipzig	Articulated >33 t, 24 t payload	2250
Central Europe			
Virgin aggregates 0.075 – 20 mm	Quarry	Rigid>17t, 20t payload	348
Filler <0.075 mm	Plant	-	0
RA Planings	RA stockpile	Rigid>17t, 20t payload	35
Bitumen/PMB	Refinery	Rigid>17t, 20t payload	215
Fibers	Central Germany	Articulated >33 t, 24 t payload	623
STORBIT PLUS additive	STORIMPEX Hamburg	Rigid>17t, 20t payload	180
North Europe			
Virgin aggregates 0.075 – 20 mm	Quarry	Rigid>17t, 20t payload	70
Filler <0.075 mm	Plant	-	0
RA Planings	RA stockpile	Rigid>17t, 20t payload	70
Bitumen/PMB	Refinery	Rigid>17t, 20t payload	160
Fibers	Central Europe (Re-Road 2012)	Articulated >33 t, 24 t payload	375
STORBIT PLUS additive	STORIMPEX Hamburg	Articulated >33 t, 24 t payload (overestimated by not including the rail freight channel tunnel)	1160

- Asphalt mixtures details

	AC16 30%RA+add	*AC16 60%RA+add*	*AC16 90%RA+add*	*SMA8S 30%RA*	*SMA8S 60%RA*	*SMA8S 60%RA+add*
Virgin aggregates (%)	63.84	33.77	3.9	61.59	35.62	35.62
Filler (%)	-	-	-	2.57	-	-
STA RA (%)	-	-	-	30	60	60
LTA RA (%)	31.4	62.8	93.5	-	-	-
Bitumen (%)	4.5	2.9	1.9	-	-	-
PMB (%)	-	-	-	5.54	4.08	3.48
Fibres (%)	-	-	-	0.3	0.3	0.3
STORBIT additive (%)	0.26	0.53	0.7	-	-	0.6

- <u>A4- A5 (Transport and Costruction phase)</u>:

- Case study specific asphalt mixes' transport distances to the site

	Origin	Mode of transport	One way distance (km)
South Europe			
Asphalt mixes to site	Plant	Rigid>17t, 20t payload	198
Bitumen emulsion for tack Coat	Plant	Rigid>17t, 20t payload	233
Equipment	Plant	-	198
Central Europe			
Asphalt mixes to site	Plant	Rigid>17t, 20t payload	35
Bitumen emulsion for tack Coat	-	Rigid>17t, 20t payload	215
Equipment	-	-	35
North Europe			
Asphalt mixes to site	Plant	Rigid>17t, 20t payload	43
Bitumen emulsion for tack Coat	-	Rigid>17t, 20t payload	160
Equipment	-	-	33

- C1-C4 (End-Of-Life phase)

  To complete the life cycle, cradle-to-grave, it is anticipated that for each maintenance intervention, the existing asphalt layers, plus 10 mm regulating course, will be milled and stockpiled at a specific site. This will be carried out for each specific intervention over the 60 year analysis period and the final CO2eq will be obtained by simply adding up the kg CO2 obtained from all the maintenance interventions.

  Case study specific excavated RA transport distances to the stockpile

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

- Assumptions in LCI:
  - RA recoverability: 95% (due to 5% losses during transport, processing, etc.)
  - Recycled benefit allocation – current recycling: 100%
  - Recycled benefit allocation – future recycling : 0%
  - UK grid as a default for electricity and fuel oil
  - Activity of soluble binder in RA was fixed to 80% (partial blending), to have an average of the two extremes considered during the mix design (100% and 60%)
  - Soluble binder from RA is included in the RA fraction
  - The total fuel consumption of the burner increased by 10% due to RA aggregate superheating and possible variation in RA moisture content (Re-Road 2012).
  - In line with the asPECT protocol, laying and compacting impacts were included at a rate of 4.7 kg CO2e per tonne of asphalt.
  - Tack coat bitumen emulsion is applied at a rate of 0.4 L/m2 of laid asphalt (Wayman M 2014)
  - it is assumed that all the materials (asphalt mixture, bitumen, emulsions and other additives used for the laying process) used at the site come from the Asphalt plant.
  - Excavations are only associated with interventions subsequent to initial installation at which point wearing course is replaced
  - CO2 waste disposal: not applicable because all excavated material is then stockpiled.
  - CO2 future RA processing (futproRAP): 1.0 kg CO2eq/t based on UK values (Wayman, Schiavi-Mellor and Cordell 2014)

3) Life Cycle Impact Analysis

On the basis of the data collected, assumptions and parameters, CF of the asphalt mixes were performed and the total contribution over the 60 years provided. Cradle-to-laid + EOL CF of the considered AB2P asphalt mixes for wearing course and variations with respect to the currently used mixes (baselines)

	South EU (Italy) (kgCO2e/t)		*Central EU (Germany)* (kgCO2e/t)		*North EU (UK)* (kgCO2e/t)	
Baseline	93.1	-	105.3	-	72.9	-
AC16 30%RA+add	92.9	-0.2%	82.1	-22.3%	64.4	-11.7%
AC16 60%RA+add	90.5	-2.8%	68.2	-35.2%	62.3	-14.5%
AC16 90%RA+add	88.2	-5.3%	54.8	-48.0%	60.5	-17.0%
SMA8S 30%RA	102.3	9.9%	91.1	-13.5%	73.7	1.1%
SMA8S 60%RA	95.0	0.0%	74.3	-29.4%	67.1	-8.0%
SMA8S 90%RA+add	99.0	0.2%	77.3	-26.6%	70.6	-3.2%

The tool used for this purpose was asPECT v4.0 (Wayman, Schiavi-Mellor and Cordell 2014).

Normalization of results: The results presented in the table above have been normalized using as reference unit 1 tonne of mixture.

Calculated CO2e footprints per tonne for the four mixtures (South EU case study)

Mixture	South EU Cradle-to-gate CO2e footprint (kgCO2e/t)	South EU Cradle-to-laid CO2e footprint (kgCO2e/t)	South EU Cradle-to-laid + EOL CO2e footprint (kgCO2e/t)
AC16 0%RA (baseline)	37.9	65.7	93.1
AC16 30%RA+add	37.7	65.5	92.9
AC16 60%RA+add	35.3	63.1	90.5
AC16 90%RA+add	33.0	60.8	88.2
SMA8S 30%RA	47.1	75.0	102.3
SMA8S 60%RA	39.8	67.7	95.0
SMA8S 90%RA+add	43.8	71.7	99.0

4) Interpretation of results

- Hotspots Analysis

A hotspot analysis was performed to understand which steps are the most influent in the Life Cycle, considered the phases mentioned above in the Sistem Boundary.

The relative values were cumulated for each phases (A1-A3, A4-A5 and C) of each mixture. In all the cases compared, the main difference in terms of CF was in credle-to-gate phase, due to the assumptions regarding the same durability

The figures below show the contribution for each phase and the last one, as example, present the differences between hotspots (contribution >50%) and relavant (contribution >80%).

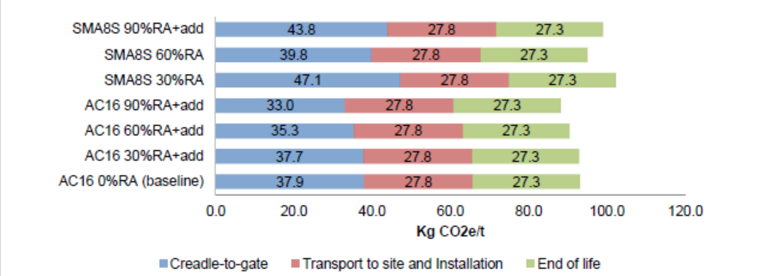


Figure 12: kg CO2e/t contribution of the life cycle steps to the overall footprints for the South EU case study

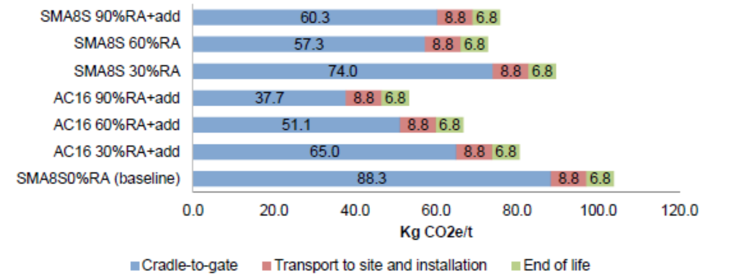


Figure 14: Contribution of the life cycle steps to the overall footprints (Central EU case study)

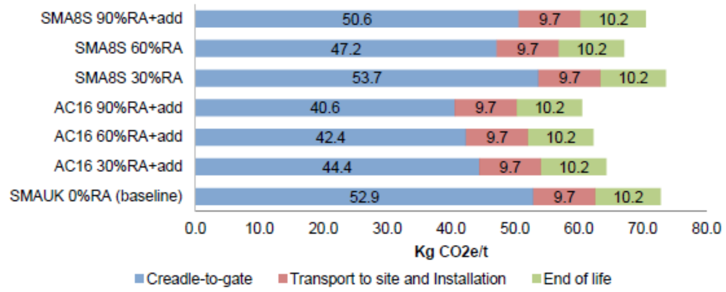
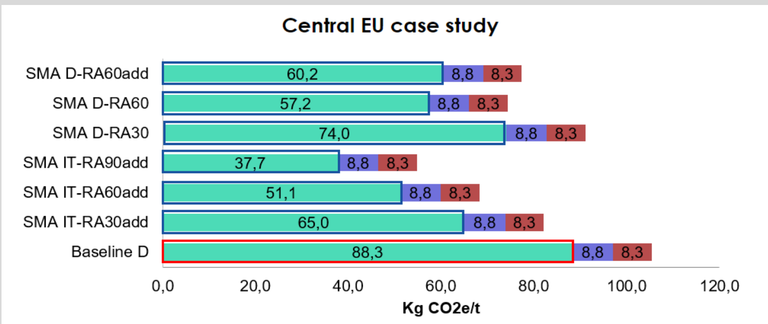


Figure 16: Contribution of the life cycle steps to the overall footprints for the North EU case study

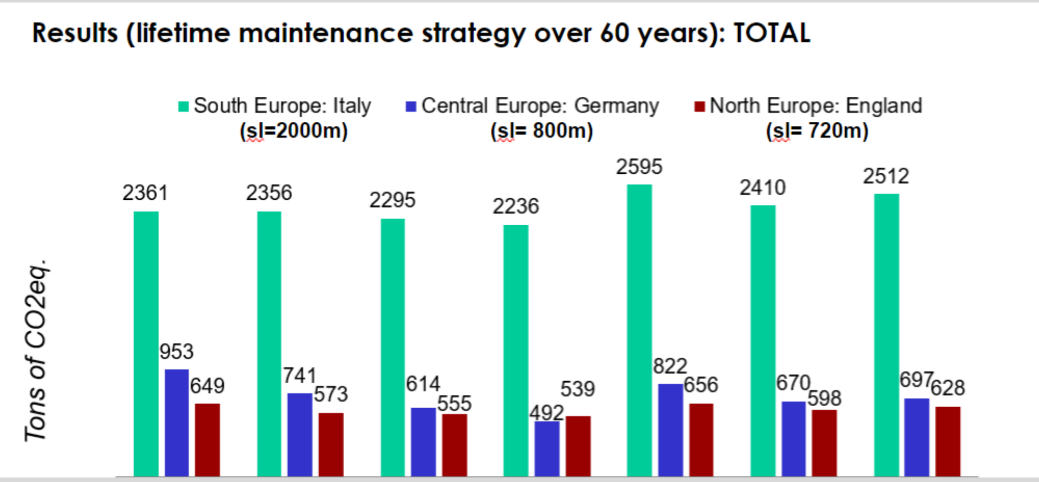


- **Conclusions and Recommendations**

"In the South Europe case study, the AC16 mixes bring an overall advantage in terms of CO2e footprint that is proportional to the amount of RA used in the mix. On the other hand, the SMA8S mixes have a higher footprint that is mainly dependent on the polymer modified bitumen embodied CO2e (almost double that of non-modified bitumen) and the fibres used in the mix: the trend in fact is similar to the SMA-IT AB2P (the more RA the less carbon footprint) except for the last mix where an additive is used. In both cases, with this maintenance strategy/wearing course durability, the effect of maximising the amount of recycled material seems to be minimal. It can be deduced then, that any improvement in the lifetime of this layer can bring significant benefits to the environment.

The Central EU case study shows that for both AC16 and SMA8S, a similar trend is followed: the overall carbon footprint decreases when the RA content increases. In fact, in this case study, the wearing course durability is the highest and therefore, more than the other case studies, the amount of recycled content plays a significant role. In fact, especially for the central EU scenario, maximising the use of RA in asphalt mixes, significantly reduces carbon emissions when compared to the baseline (almost half of the emissions with 90% RA).

In the North Europe case study the relative position of the AB2P mixtures is the same as the previous ones: the carbon footprint decrease with an increase in RA content and overall the AC16 have lower values. This happens again because the North Europe reference mixture, as the central EU one, uses PMBs but it has slightly lower total emissions due to the embodied CO2 of aggregates. In fact, in the North Europe baseline there is a significant amount of filler that doesn't need transportation to the asphalt plant, while the filler in the Central EU mix is included in the RA that needs to be transported to the plant. The North EU case study on average shows the lowest environmental impact despite it has more interventions than the Central EU case study. Furthermore, it shows up to 15% reduction of emissions due to increase of RA content and it is possible to conclude that there are no specific advices to improve the maintenance strategy for this case study.." (AB2P – D5.2)



2.5.1.2 Economical impact indicators (LCC)

The selected economic indicator is cost, calculated following a life cycle approach if applicable. If so, this calculation is performed using LCC. The principles and framework to perform an LCC of buildings and constructed assets are established in ISO 15686-5:2017.

Furthemore, the calculation of costs should be based on functional equivalent and pavement model as defined before, respecting the system boundaries previously defined.

For asphalt mixtures, the indicator includes all significant and relevant costs and benefits of the object of assessment during the product stage (A1-A3). This means that for asphalt mixtures, the indicator does not follow a life cycle approach. On the other hand, for pavement activities, it includes all significant and relevant initial and future costs and benefits of the object of assessment throughout all the life cycle, while fulfilling the performance requirements. LCC is the indicator proposed in CWA 17089 for pavement activities and therefore the one proposed in PavementLCM Framework.

NRAs, private operators and contractors and engineering companies might have their own LCC methodologies and calculation methods. If all the principles of the life cycle costing are followed, these methodologies and calculation methods are appropriate for using. If there is no particular methodology available, ISO 15686-5:2017 provides specific guidelines and information to quantify this LCC.

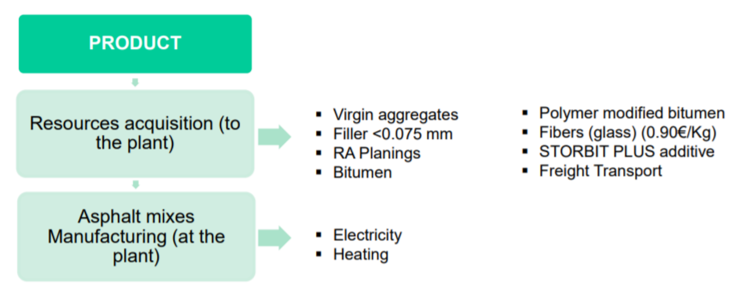
More details to perform an LCC are provided in the Annex D of this deliverable.

2.5.1.2.1 Step 5 – Examples and Case Studies for LCC

Case study for material/product- AB2P

N.B. The reported case study for the LCC of a material isn't the same used for the LCA.

An LCC was performed to understand the economic impacts, in a cradle-to-gate vision (A1-A3), of six new asphalt mixtures The materials taken into account are the same used in the LCA reported above and considering the three different geographic scenarios. In other words, the study was carried out to compare the several solutions' costs in relationship to the country where they have to be used.



In details the performed calculation is related only to "Product" life cycle stage (A1-A3) and composed of: raw material acquistion (A1), transport (A2), Manufacturing (A3), excluding therefore all the other related costs, such as agency costs (projects, administration, construction supervision and construction costs etc).

Costs are detailed below:

A1 + A2- Raw materials acquistion and Transport: Costs were collected with interviews to suppliers and contractors and, where missing, provided by literature.

- Cost of the asphalt mixes constituents for SE

	Data Source	SE – IT (Ferrara 2015) €/t
Virgin aggregates 0.075 – 20 mm	(Ferrara 2015)	10
Filler <0.075 mm	(Ferrara 2015)	10.50
RA Planings	(Ferrara 2015)	4*
Bitumen	(Ferrara 2015)	400
Polymer modified bitumen	(Ferrara 2015)	520
Fibers (glass) (0.90€/Kg)	(ITERCHIMICA 2015)	900
STORBIT PLUS additive	(Ferrara 2015)	1350
Freight Transport (rigid>17 t, 20 ton payload)	(Ferrara 2015)	0.33

Case Study for Activities – (CEDR, 2015)

- **CE and NE case study: cost of the asphalt mixes constituents**

	Data Source	CE/D and NE/UK €/t
Virgin aggregates 0.075 – 20 mm	(Wayman M 2014)	16.75
Filler <0.075 mm	as aggregate	16.75
RA Planings	(Wayman M 2014)	11.00
Bitumen	(Rodrquez 2015)	650
Polymer modified bitumen	(Wayman M 2014)	730.87
Fibers (glass) (0.90€/Kg)	(ITERCHIMICA 2015)	900
STORBIT PLUS additive	STORIMPEX	1350
Transport - Rigid>17 t,20 ton payload	(Wayman M 2014)	1.03
Transport - Articulated>33 t, 24 t payload	(Wayman M 2014)	1.03

A3 - Manufacturing: the asphalt mixtures vary for the RA content and, in relationship to it, the energy consumption used to heat the material changes.

Some assumptions were made in terms of energy costs (oil and gas values taken from literature) and of quantity consumptions.

- **SE case study: cradle-to-gate cost/ton of asphalt mixes**

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

- **CE case study: cradle-to-gate cost/ton of asphalt mixes**

	SMA 8S 0%RA	AC16 30%RA+ add	AC16 60%RA +add	AC16 90%RA+ add	SMA 8S 30%RA	SMA 8S 60%RA	SMA 8S 60%RA + add
	€/t	€/t	€/t	€/t	€/t	€/t	€/t
raw material acquisition	69.1	46.7	38.5	32.7	57.0	45.0	48.7
transport to plant	5.2	4.0	2.4	0.8	3.9	2.6	2.6
Electricity	0.136	0.136	0.136	0.136	0.136	0.136	0.136
heating	1.184	1.184	1.184	1.184	1.184	1.184	1.184
TOTAL (€/t)	**75.6**	**52.1**	**42.2**	**34.9**	**62.3**	**48.9**	**52.6**

- **NE case study: cradle-to-gate cost/ton of asphalt mixes**

	SMA UK 0%RA	AC16 30%RA+ add	AC16 60%RA+ add	AC16 90%RA +add	SMA 8S 30%RA	SMA 8S 60%RA	SMA 8S 60%RA + add
	€/t	€/t	€/t	€/t	€/t	€/t	€/t
raw material acquisition	56.5	46.7	38.5	32.7	57.0	45.0	48.7
transport to plant	1.2	1.3	1.3	1.3	1.2	1.2	1.3
Electricity	0.136	0.136	0.136	0.136	0.136	0.136	0.136
heating	1.184	1.302	1.302	1.302	1.302	1.302	1.302
TOTAL (€/t)	**58.9**	**49.4**	**41.2**	**35.5**	**59.7**	**47.6**	**51.4**

In all the cases, using RA implies economical benefits.

Case Study for Actvities – AB2P

An LCC cradle-to-gate of maintenance activities was performed, using the data collected and processed above and multiplying the total tons of asphalt to be replaced for each intervention.

The LCC was performed according to what said by FHWA and data collection was based on informations required by RealCost Life-Cycle Cost analysis software.

Only costs of materials (A1-A3) were taken into consideration, excluding B and C phases.
Furthemore, some assumptions were made such as:
- All materials and freight transport costs assumed to remain constant throughout the 60 years investigation period,
- Electricity and oil consumptions were considered the same for all design alternatives (1.6l/ton)
- Indirect costs and discount rates were considered constant for each case study (EU region)

The results for each case study are reported below:

- SE case study

	AC 16 0% RA	AC16 30%RA+add	AC16 60%RA+add	AC16 90%RA+add	SMA 8S 30%RA	SMA 8S 60%RA	SMA 8S 60%RA + add
	€	€	€	€	€	€	€
Inlay WC (1311 ton)	465 53	40558	34598	29970	53631	41352	48120
Inlay WC+BC (3059 ton)	108 624	94635	80729	69929	125138	96488	112279
Rehabilitat ion (7429 ton)	263 800	229828	196057	169828	303907	234329	272678

- CE case study

	SMA 8S 0%RA	AC1 6 30% RA+ add	AC16 60%RA+add	AC16 90%RA+add	SMA 8S 30%RA	SMA 8S 60%RA	SMA 8S 60%RA + add
	€	€	€	€	€	€	€
Inlay WC (651 ton)	4927 4	**3392 4**	27550 3	22731 1 40 2	40572 318 9	31819 3423 8	34238
Inlay WC+BC (2388 ton)	1086 24	9463 5	80729	69929	125138	96488	112279
Rehabilitati on (5428 ton)	1806 71	1243 90	100844	83347	148763	116670	125538

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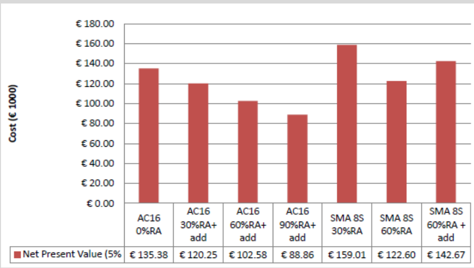
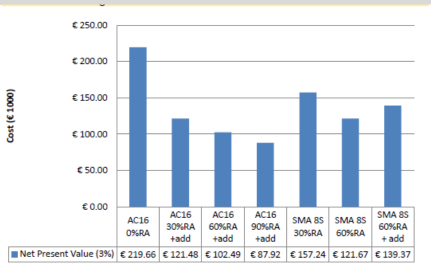
- NE case study

	SMA UK 0%RA	AC16 30%RA+add	AC16 60%RA+add	AC16 90%RA+add	SMA 8S 30%RA	SMA 8S 60%RA	SMA 8S 60%RA + add
	€	€	€	€	€	€	€
Inlay WC (729 ton)	42941	36028	30020	25833	43490	34703	37472
Inlay WC+BC (1639 ton)	96617	81063	67544	58124	97851	78081	84311
Rehabilitation (3461 ton)	203969	171134	142593	122705	206575	164838	177990

Using the free software RealCost, the Net Present Value (NPV) was calculated, applying some assumptions.





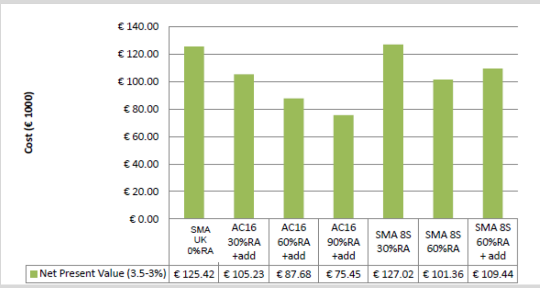


Image: SE, CE, NE Case Studies

In all the cases, using RA implies economical benefits and a 60 - 90% of RA causes a cost reduction of 25%- 60%.

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2.5.1.3 Social impact indicators

Social Life Cycle Assessment is starting to be adopted in other disciplines, however is at early stage and in this occasion the authors preferred not to identify any oft he S-LCA indicators and wait fort he development of the method.

The only selected indicator with a "social" impact is the tyre/pavement noise, its calculation is only applicable in the case of pavement activities and it is detailed amongst the technical and functional indicators

2.5.1.4 Technical and Functional Indicators

The indicators selected to take into account technical and functional requirements are related to:

- Durability
- Tyre-pavement noise
- NRA's specific

Durability is a property of pavement, and/or its components, understood as the "retention of a satisfactory level of performance over the structure's expected service-life without major maintenance for all the properties that are required for the particular road situation" (Nicholls, Mchale, & Griffiths, 2008). In the case of asphalt pavements, durability is dependent on several factors, consequently the prediction of the durability of a pavement, or its components, is a complex task. One of the factors it's certainly the the durability-related properties of asphalt mixtures, quantifiable by using laboratory tests. On this regard, EDGAR defined an indicator as a collection of properties to characterise:

- Resistance to rutting according to EN 12697-22
- Resistance to fatigue according to EN 12697-24
- Water sensitivity according to EN 12697-12

The determination of these properties is suggested in PavementLCM SA Framework as a starting point for the calculation of the indicator but further details are **provided in WP4**. WP4 will also report on how to consider uncertainty for these indicators.

Tyre-pavement noise refers to the capability of reduction of tyre-pavement noise level. This indicator is calculated in accordance to CWA 17089, proposing the following methods:

- Statistical Pass-by method
- Close Proximity method
- Any other covered in a national, European, or international standardisation document

It is also highlighted that the user should define the level of application and take into consideration that some characteristics of the pavement may change over time, revision frequency should also be defined by the user.

At last, one or more NRAs specific indicators can be chosen according to the priority of each local NRA (i.e. skid resistance, permeability, etc.)

2.5.1.4.1 Step 5 – Examples and Case Studies for Technical and Functional Indicators

Case Study for Activities – AB2P

In the reported case study durability was assumed to be the equal to the baselines of each scenario. In fact, this parameter is usually one of those which affects the most asphalt mixtures carbon footprint and to allow that these new future mixes can be environmentally-friendly, their service lifes have to be at least the same of an actual mix.

Data about baselines' durability was directly provided by NRAs and summed up below:

Pavement course	South EU - IT (ANAS 2015)	Central EU - D (BASt 2015)	North EU - UK (Spray 2014)
Typical Durability of wearing course	5 years (HMA)	16 years (SMA)	10 years (SMA)
Typical Durability of binder course	25-30 years		
Typical Durability of base course	50 years		

2.5.2 Interpretation of SA results

In order to facilitate the identification of the best choice or the comparison between the options previously studied, it's important to proceed with the interpretation of SA results. It means that all the obtained outcomes have to be looked all together and analysed under a common vision.

The interpretation can be done using some procedure already explained, such as

- Uncertainty and sensitivity analysis.
- Normalization of obtained results

The various sources of uncertainty in indicator assessment and in the weighting of indicators in multi-criteria decision analysis (MCDA) inherent in SA, mean that the sustainability of an asphalt mixture or pavement activity can only be estimated and the result of comparative assessments can only be expressed in terms of the likelihood of a decision leading to lower adverse impacts or greater sustainability. The types of sensitivity and uncertainty analysis described above will generate assessments that can be represented as the likelihood of a decision being more sustainable.

The NRAs undertaking assessments must decide how results should be presented to assist in decision making and in what level of likelihood will lead to a decision to make an alternative choice to current practice.

Some initial suggestions for reporting of results are (see
):

- Reduction in average impact (e.g. GWP) *n*, between two alternatives
- Probability of *x*% improvement
- Probability of 'regret' *r*

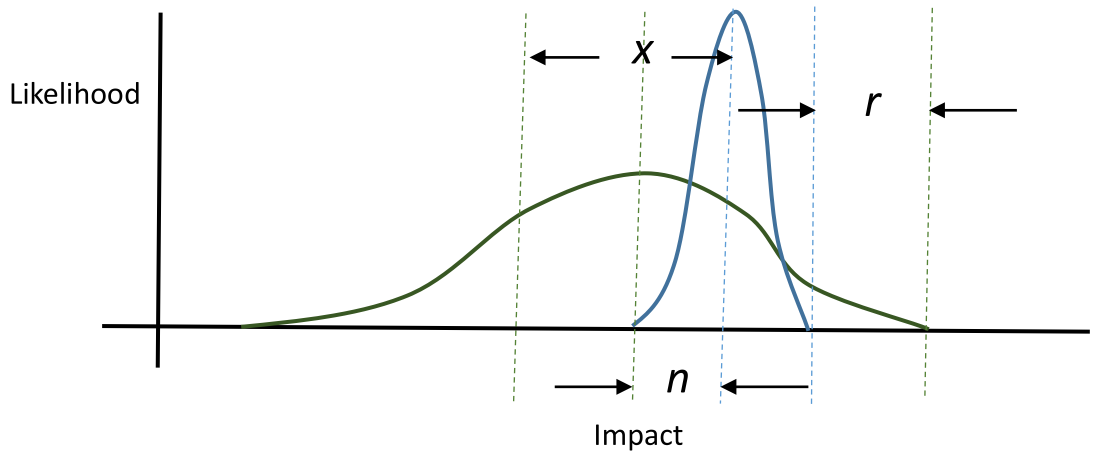


Figure 8 - Likelihood of impacts

The interpretation of results should finally lead to conclusions and recommendations.

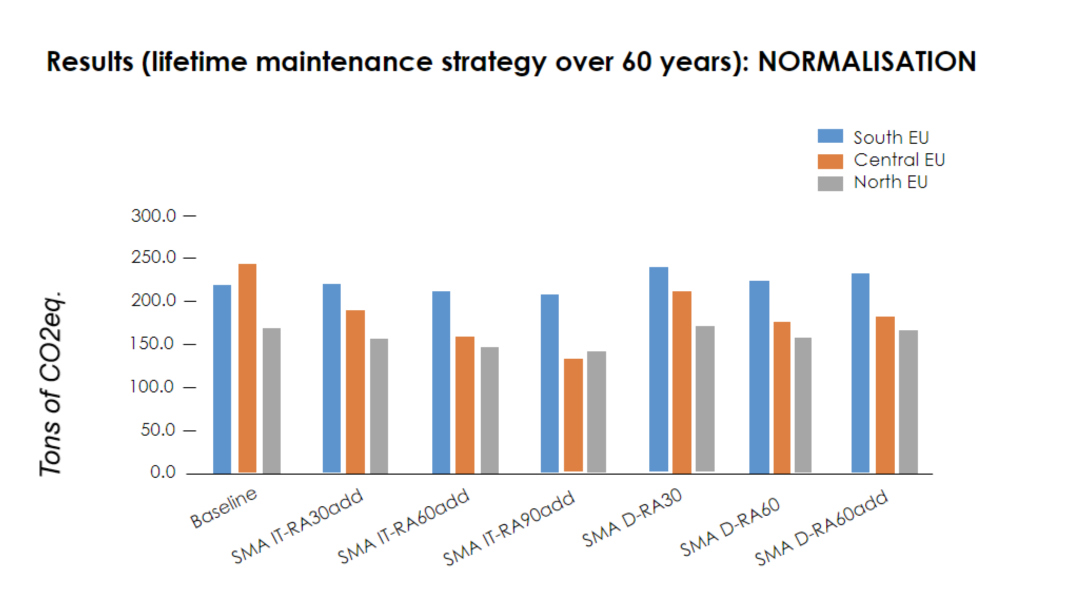
In EN15978 after the calculation of the indicators there is the phase of reporting and communcation with: - general information, assess results, data sources.

2.5.3 Step 5 – Examples and Case Studies for Intepretation of SA results

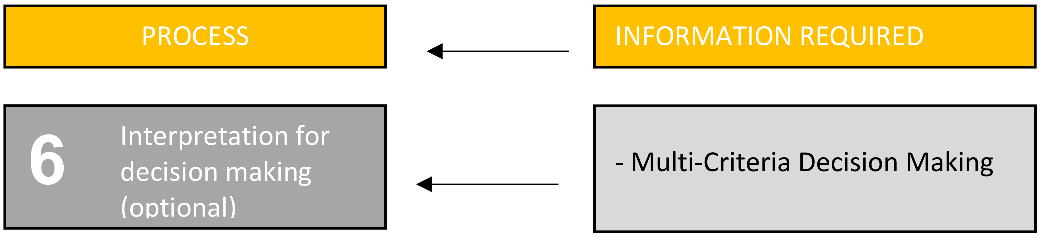
Case Study for Activities – AB2P

In the case study provided, no uncertainty was performed.

The normalization of the environmental results was calculated considering the impacts for 1 m3 of asphalt mixture, beyond the design section of the specific case study.



2.6 STEP 6 - Interpretation for decision making (optional)



2.6.1 Multi- Criteria Decision Making

Choosing the best sustainable alternative isn't easy, in particular when several aspects are taken into account and regard different aspects of Sustainability (Enviornment, Society, Economy). As reported in D5.1b, "the decision-making process involves assessing of the considered alternatives based on the selected evaluation criteria and identifying the best solution. Every solution will match the criteria to a certain extent; and the decision maker must identify the best solution that match the considered criteria to the largest extent. MCDM methods provide stepping-stones and techniques for finding a compromise solution."

In PavementLCM, amongst several multi-criteria decision making (MCDM) methods taken into consideration, PROMETHEE method has been chosen, described, and applied in D5.1b.
The method was developed by professor Brans in 1982 and it provides "an overall or net ranking for a set of alternatives based on the balance between the positive outranking, which shows how well an alternative is better than other alternatives, and the negative outranking which shows how bad an alternative is outscored by other alternatives" (D5.1b)

In the MCDA it's important to choose the weighting of indicators which reflect the importance assigned to each of them. This operation can be done according to three different methods (Entropy weighting method EWM, Avarage weight method AWN, User defined weights UDW).

An MCDM can be applied as follows:

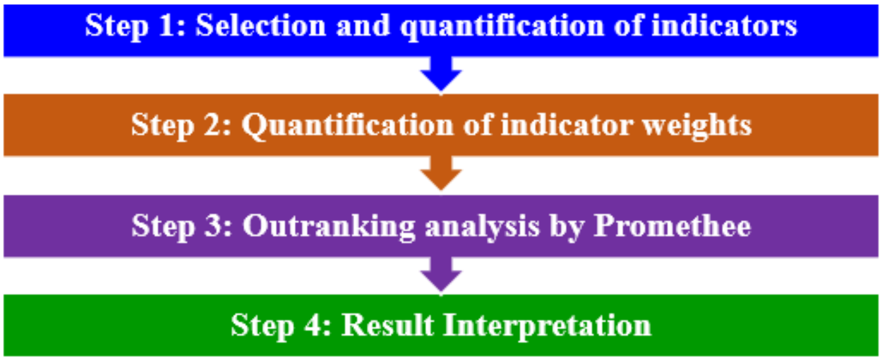


Figure 9 - Application steps of MCDM analysis by the PTOMETHEE method

Please refer to D5.1b for a more detailed explanation.

2.6.2 Step 6 – Examples and Case Studies

Case Study for Material/Product – Case study provided in D5.1b

The asphalt mixtures object of the assessment are the following ones:

- SMA 16 *; SMA 11* ; *SMA 8* ; *SMA 11 – LSL*; *PA 8* ; PA 16

Once they are defined, it's important to calculate the associated indicators to each asphalt mixtures as described in the prevous stages. The chosen indicators for the specific case study are linked to the pillar of Sustainability + the functional and technical requirements. They are: Global Warming Potential, Air pollution, Energy use, Secondary materials consumption, Cost €/ton of asphalt, Tyre-pavement noise reduction, Durability.

The indicator values have been calculated according to the functional unit and then for all the quantity necessary for the considered analysis period.

The next step is to assign the weights to each indicator, according to their importance. Here thee methods have been applied:

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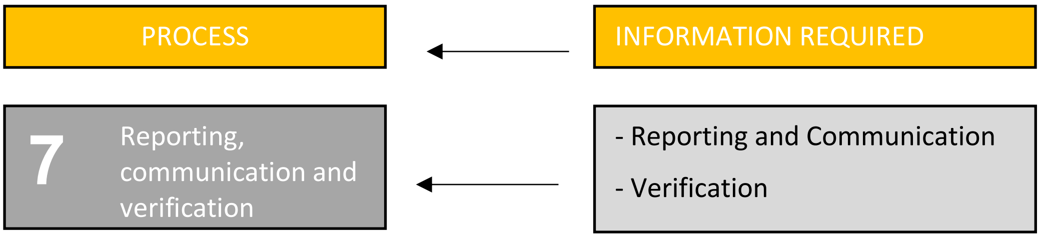
Indicator \ weight %	EWM	AWM	UDW
Global warming	0.93	14.29	8.83
Photochemical oxidation	0.50	14.29	11.27
Eutrophication indicator	2.31	14.29	11.27
Energy demand	0.58	14.29	9.16
Secondary materials consumption	51.51	14.29	13.24
Costs	0.43	14.29	13.08
Noise reduction	43.73	14.29	33.15
Total weight	100%	100%	100%

Once PROMETHEE is applied through a Matlab code, the MCDM results are as follows:

Mix Type	Q+	Q-	Net Q
SMA11 - LSL	0.536	0.251	0.284
PA16	0.586	0.333	0.253
SMA16	0.428	0.359	0.069
SMA8	0.520	0.472	0.055
PA8	0.331	0.589	-0.258
SMA11	0.231	0.635	-0.404

These results show that SMA11-LSL is the most sustainable alternative amongst other alternatives. The results are fully aligned or compatable with the values and the weights of the input indicators.

2.7 STEP 7 - Reporting, communication and verification



2.7.1 Reporting and communication

Reporting of the assessment should include the following information:

- ✓ *Purpose of the assessment*
- ✓ *Object of assessment*
- ✓ *Statement of boundaries and scenarios*
- ✓ *Data sources*
- ✓ *List of indicators and expression of results*
- ✓ *Interpretation of results*

The results of the assessment shall be reported and communicated according to the information groups, as defined by EN 15643-5:

- Aspects and impacts specific to civil engineering works asset and site during the life cycle of the works (modules A0-C4)- in Pavement Activities case studies modules B1-C4)
- Aspects and impacts specific to civil engineering works asset and site in operation (modules B6-B7), if any
- Aspects and impacts specific to user's utilization of the civil engineering works (**module B8). This is currently not suggested within the PAVEMENTLCM framework.**

In particular results can be organised following the tables below:

a) Regarding the environmental results, they can be reported as a structured list, according to the scenarios selected. (EN15978, 2011)

Table 7 – Civil Engineering Works Assessment Information

	CIVIL ENGINEERING WORKS ASSESSMENT INFORMATION					
	CIVIL ENGINEERING WORKS ASSESSMENT INFORMATION					SUPPLEMENTARY INFORMATION BEYOND THE CEW LIFE CYCLE
	BEFORE USE STAGE			USE STAGE	END of LIFE STAGE	D - Benefits and loads beyond the system boundary
Stage	PRE-CONSTRUCTION STAGE	PRODUCT STAGE	CONSTRUCTION STAGE			
Aspects and impacts specific to CEW and site during the life cycle works	A0 Results from the pre-construction stage	A1-A3 Results from the products stage (cradle to gate)	A4-A5 Results from the construction process stage	B1-B5 Results from the use stage excluding CEW in operation	C1-C5 Results from the end of life stage	Reuse-Recovery-Recycling potential
Aspects and impacts specific to CEW and site in operations				B6-B7 Results from the CEW in operation		
Aspects and impacts specific to users utilisation of the CEW				B8 Results of the users utilisation of the civil engineering works		

Table 8 – List to report the LCA results (EN 15978)

Indicators for environment al impacts	Unit Indicator	Modules A1 to A5		Modules B1 to B7 Use stage							Modules C1 to C4 End of life stage				Module D Benefits and loads beyond the system boundary
		Product stage (A1-3)	Construction Stage (A4-5)	Building in use					Energy use B6	Water use B7	Deconstruction / demolition	Transportation	Waste processing	disposal	Re-use Recycling Recovery potential
				Use of products B1	Maintenance B2	Repair B3	Replacement B4	Refurbishment B5							
Global warming potential, GWP	kg CO_2 equiv														
Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11 equiv														
Acidification potential of land and water; AP	kg SO_2 equiv														
Eutrophication potential, EP	kg $(PO_4)^{3-}$ equiv														
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg Ethene equiv														
Abiotic Resource Depletion Potential, ADP elements	kg Sb equiv														
Abiotic Resource Depletion Potential, ADP fossil fuels	MJ														

b) Regarding the results coming from an LCC, the expression of results, values shall be reported for each module of the life cycle. If a module is not assessed, it shall be stated as MNA 978 (Module Not Assessed) and reasons for omitting this information shall be given.

Table 9 - List to report the LCC results (adapted from EN 15978)

<table>
<tr><th>Costs and incomes</th><th>Unit indicator</th><th colspan="2">Information Modules A

Before use stage</th><th colspan="3">Information Modules B

Use stage</th><th>Information Modules C

End-of-life stage</th><th>Information Modules D

Costs and incomes beyond the system boundary</th></tr>
<tr><td>Non-annual costs</td><td>€ (or other currency)/ occurance Date of occurance</td><td colspan="2">Pre- construction (A0) and Construction (A1-A5)</td><td colspan="3">Maintenance
(B2)
Repair and replacement
(B3, B4)</td><td>Deconstruction, Transport, Waste processing and Disposal (C1-C4)</td><td>Re-use
Re-cycling
Recovery Potential</td></tr>
<tr><td>Non - annual income</td><td>€/ occurance (or other currency) Date of occurance</td><td colspan="2"></td><td colspan="3">Use (B1)</td><td></td><td>Re-use
Re-cycling
Recovery Potential
Land sale</td></tr>
<tr><td>Annual recurrent costs</td><td>Ref. Year €/year</td><td colspan="2"></td><td>Use and maintenance (B1 and B2)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Annual recurrent income</td><td>Ref. Year €/year</td><td></td><td></td><td>Use (B1)</td><td></td><td></td><td></td><td></td></tr>
</table>

The communication of results, based on the previous tables, may be simplified according to the following rules (EN 15978:2011 and EN 16627:2015) :

- the communication may be limited to a selection of indicators;
- results shall be presented separately for all the pavement life cycle stages and for module D;
- within each of the pavement life cycle stages, the results per indicator may be summed;
- provided that values for the indicator are determined for each module within that stage;

if values have not been determined for all modules of a life cycle stage, the results shall be presented separately for each module of that stage, and those modules for which no values are determined shall be shown as Module Not Assessed (MNA);

- if relevant information is provided at the product level on Module D, this information should be reported (environmental).

2.7.2 Verification

*The **verification process**, or critical review, is essential if the results of the SA are to become public. According to ISO 14040, the scope and type of critical review desired is defined in the scope phase of an LCA, which should be extended to a SA. The scope should identify why the critical review is being undertaken, what will be covered and to what level of detail, and who needs to be involved in the process Data sources*

In order to be verifiable, all information used, options, or decisions taken shall be presented in a transparent manner. If there is need for verification of the assessment, a verification procedure shall be applied. The verification shall include (but is not limited to) the following:

- ✓ consistency between the purpose of assessment and boundaries and scenarios used;
- ✓ traceability of data used for the products;
- ✓ conformity of data with requirements of standards, if applicable;
- ✓ consistency between the scenarios that apply at pavement level with those use for the product;
- ✓ completeness and justification of completeness for the quantification at the pavement level.

The competence of the verifier or reviewer shall be stated in the verification procedure.

In the particular case of LCA, ISO 14040 and ISO 14044 define two types of critical review:

- Critical review by internal or external expert. A critical review may be carried out by an internal or external expert. In such a case, an expert independent of the LCA shall perform the review. The review statement, comments of the practitioner and any response to recommendations made by the reviewer shall be included in the LCA report. A critical review by an external expert is recommended for pavement LCA studies that are intended (Harvey et al., 2016):
    - To recommend pavement design, construction, rehabilitation and maintenance, and end- of-life decisions or policy changes to or by NRAs.
    - For research purposes in support of advanced pavement-LCA methodologies and applications.
- Critical review by panel of interested parties. A critical review may be carried out as a review by interested parties. In such a case, an external independent expert should be selected by the original study commissioner to act as chairperson of a review panel of at least three members. Based on the goal and scope of the study, the chairperson should select other independent qualified reviewers. This panel may include other interested parties affected by the conclusions drawn from the LCA, such as government agencies, non-governmental groups, competitors and affected industries. The selection of review-panel members should consider their expertise in the scientific disciplines relevant to the important impact categories of the study, in addition to other expertise and interest

PavementLCM SA Framework recommends that the requirements established for an LCA verification or critical review are used when performing an SA.

The review statement and review panel report, as well as comments of the expert and any responses to recommendations made by the reviewer or by the panel, shall be included in the SA report.

3- Conclusions and Recommendations

This deliverable provides specific guidelines to perform a Sustainabilty Assessment exercise for pavement materials and pavement activities for NRAs, according to the series of EN standards dedicated to Sustainability in construction works. Furthermore, the guidelines take some other inspiration from ISO 15643-1/4 and FHWA framework,

PavementLCM SA Guidelines are based on the PavementLCM framework, already proposed in D2.1, which covers the assessment of the three pillars of sustainability (environmental, economic and social) as well as functional and technical requirements. For this, sets of sustainability performance indicators have been proposed together with a step by step procedure tailored specifically for allowing NRAs and stakeholders to perfomr the SA exercises for both pavement materials and pavement activities according to the EN standards.

PavementLCM SA defines the steps to set up a SA as:

1. Identification the purpose of assessment
2. Specification of the object of assessment
3. Definition of scenarios
4. Selection of data type
5. Calculation of indicators
6. Interpretation for decision- making
7. Reporting, communication and verification

Furthermore, to guide the practioners also a series of tools and resources are provided within the PavementLCM Package (http://pavementlcm.eu) to support with the implementation of these exercises.

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ANNEX A – Useful Definition

area of influence
area or combination of areas surrounding a civil engineering works that can be affected with changes to their economical, environmental or social conditions by the civil engineering works' operations throughout its life cycle

component
construction product (3.6) manufactured as a distinct unit to serve a specific function or functions

construction product
item manufactured or processed for incorporation in construction works

construction work

activities of forming a civil engineering works

declared unit
quantity of a construction product for use as a reference unit in an EPD for an environmental declaration based on one or more information modules

durability
ability to maintain the required technical performance throughout the service life subject to specified maintenance, under the influence of foreseeable action taken into account in the scenario

economic impact
any change to the economic conditions, whether adverse or beneficial, wholly or partially resulting from economic aspects

economic performance
performance related to economic impacts and economic aspects

environmental impact
change to the environment, whether adverse or beneficial, wholly or partially, resulting from environmental aspects

environmental performance
performance related to environmental impacts and environmental aspects

estimated service life
service life that a *building* or an *assembled system (part of works)* would be expected to have in a set of specific *in-use conditions*, determined from *reference service life data* after taking into account any differences from the *reference in use conditions*

functional equivalent
quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison

functional performance
performance related to the functionality of a civil engineering works or an assembled system (part of works), which is required by the client, users and/or by regulations

functional requirement
type and level of functionality of a building, civil engineering works or assembled system which is required by the client, users and/or by regulations

functional unit

quantified performance of a product system for use as a reference unit

impact category
class representing environmental issues of concern to which life cycle inventory analysis results may be assigned

impact category indicator
quantifiable representation of an impact category

information module compilation of data to be used as a basis for a type III environmental declaration, covering a unit process or a combination of unit processes that are part of the life cycle of a product

life cycle assessment - LCA
compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle

life cycle inventory analysis - LCI
phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle

maintenance
combination of all technical and associated administrative actions during the service life to retain a civil engineering works or an assembled system (part of works) in a state in which it can perform its required functions (i.e. painting work)

product category rules - PCR
set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories

repair
combination of all technical and associated administrative actions during the service life associated with corrective, responsive or reactive treatment of a construction product or its parts installed to return it to an acceptable condition in which it can perform its required functional and technical performance (i.e. repristinate permeability of porous asphalt)

replacement
combination of all technical and associated administrative actions during the service life associated with the return of a construction product to a condition in which it can perform its required functional or technical performance, by replacement of a whole construction element.(i.e. replacement of a component)

reference service life - RSL
service life of a construction product which is known to be expected under a set of reference in-use conditions and which can form the basis for estimating the service life under other in-use conditions

RSL data
information that includes the reference service life and any qualitative or quantitative data describing the validity of the reference service life

reference study period
period over which the time-dependent characteristics of the object of assessment are analysed

scenario
collection of assumptions and information concerning an expected sequence of possible future events

system boundary
interface in the assessment between a *building* and its surroundings or other product systems

technical performance
performance related to the capability of civil engineering works or an assembled system (part of works), which are required or are a consequence of the requirements made either by the client, users and/or by regulations

technical requirement
type and level of technical characteristics of a *construction works* or an assembled system (part of works), which are required or are a consequence of the requirements made either by the client, and/or by the *users* and/or by regulations.

ANNEX B – Standards, Studies and Tools for the SA

Process of SA	Information Required	Standards	Guidelines/ Previous Studies	Tools
1. IDENTIFY PURPOSE OF THE ASSESSMENT	Goal	- EN 15643-5		
	Intended use	- EN 15643-5		
2. SPECIFICATION OF THE OBJECT OF THE ASSESSMENT	Description	- EN 15643-5 - EN 15978 (for build)		
	Functional Equivalent	- EN 15643-5 - EN 15978		
	System boundaries	- EN 15643-5 - EN 15978 - EN 15804 - ISO 14040 - ISO 14044	ILCD Handbook- *General Guide for Life Cycle Assessment*	
	Analysis period	- EN 15643-5 - EN 15978 (Only in case of Pavement Activities)		PavementLCM tool (?)
3. SCENARIOS	Scenarios (only for SA going beyond cradle-to-gate)	- EN 15643-5 - EN 15978		PavementLCM tool

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4. SELECTION OF DATA	Primary and Secondary Data	- EN 15643-5	Harvey et al. 2016	PavementLCM Tool
	Data Quality	- EN 15643-5 - EN 15978	ILCD Handbook- *General Guide for Life Cycle Assessment*	Tables to assign a score to data
	Uncertainty		ILCD Handbook- *General Guide for Life Cycle Assessment*	
2 CALCULATION OF INDICATORS	LCA	- EN 15643-5 - EN 16627 - ISO 14040 - ISO 14044	- CWA17089 - ILCD Handbook- *General Guide for Life Cycle Assessment* - *Other ILCD Handbooks* - JRC - *Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods* - JRC- *Guide for interpreting life cycle assessment result* - *JRC- Development of a weighting approach for the Environmental Footprint*	Excel implemented files, softwares (i.e. Open LCA, Gabi, SimaPro)
	LCC	- ISO 15686-5	- CWA17089 - FHWA - *Life Cycle Cost Analysis Primer*	Excel implemented files, softwares
	S-LCA	Not ISO yet	- UNEP/SETAC – *Guidelines for Social Life Cycle Assessment of Products and Organizations 2020* - UNEP/SETAC - *The Methodological Sheets for Sub - Categories in Social Life Cycle Assessment (S-LCA)*	Excel implemented files, softwares (i.e. Open LCA)
	Technical Indicators			
	Sensitivity	- EN 15643-5	- ILCD Handbook- *General Guide for Life*	

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	Analysis		*Cycle Assessment* - JRC - *Guide for interpreting life cycle assessment result*	
3 **INTERPRETATION OF SA RESULTS**	Uncertainty	- EN 15643-5	- ILCD Handbook- *General Guide for Life Cycle Assessment* - JRC - *Guide for interpreting life cycle assessment result*	
	Normalization	- EN 15643-5	- ILCD Handbook- *General Guide for Life Cycle Assessment* - JRC - *Guide for interpreting life cycle assessment result*	
4 **REPORTING AND VERIFICATION**	The assessment results	- ISO 14044 - ISO 15392:2019 - ISO 15686-5 - EN 15643-5 - EN 15978		
	Verification	- EN 15643-5 - EN 15978		

Annex C – Life Cycle Assessment (LCA)

Here in detail the explanation of the four steps to perform an LCA.

1C. Goal and Scope definition

The first step in any LCA study is to define the study goal(s) and scope. A precise definition of the goal is needed to clearly identify system boundaries and the functional unit that will be used throughout the LCA study, including the subsequent phases of establishing the LCI, conducting impact analyses, and effectively interpreting and reporting the results. A well-defined goal helps to determine which processes and flows within the system boundaries are to be included or excluded from the study.

In PavementLCM Framework, the goal of performing LCA is to calculate the environmental indicators of pavement materials or activities as part of their Sustainability Assessment (SA), according to the set purpose of the assessment (see Section 2.1).

According to ILCD Handbook, **Goal Definition** is composed of the following steps:

Table 10 - LCA Goal definition

Element of LCA study	Definition
Intended application of the results	i.e. comparison of the sustainability performance of different design options or Declaring the sustainability performance For more details, see Section 2.1
Limitations due to methodological choices	Paying attention to results claimed, according to methodologies chosen for istance (EF is the suggested one) and to comparaisons made (i.e. materials compared and quantities needed for specific case studies)
Reasons for carrying out the study & decision context	Explanation of what a study does (i.e. Impacts associated with nation-wide recycling or incineration of used paper) and it's different from the intended applications, which explains why a study is made (i.e. support decision on governemental recommendations for preferred paper)

Target audience	To whom the results are intended to be communicated (policy makers, public audience, Road Authority staff, ..)
Comparative studies to be disclosed to the public	If the LCA study has to be disclosed to the public, the ISO standards specifies lots of requirements on the conduct and documentation of the study on the execution, documentation, review and reporting of the LCA (a critical review is needed)
Commissioner of the study	i.e. ex. Danish NRA

Having the goal of the LCA, the **Scope** should include the definition of the elements presented in Table 10. In other words, during this phase the object of the LCI/LCA study (i.e. the exact product or other system(s) to be analysed) is identified and defined in detail.
Some of these elements were already defined in PavementLCM Framework in previous sections, and therefore Table 10 refers to them.

Table 11. LCA Scope definition

Element of LCA study	Definition
Description of the product under study - Pavement material or - Pavement activity And its functions	See Section 2.2
Functional Equivalent/ Declared/functional unit	See Section 2.2
System boundaries and life cycle stages	See Section 2.2
Physical boundaries	See Section 2.2
Analysis period	See Section 2.2
Allocation procedures	See below
Cut-off rules	See below
Indicators to calculate	- Global Warming Potential (GWP) - Acidification - Eutrophication, fraction of nutrients reaching freshwater end compartment (EP-freshwater) - Eutrophication potential, fraction of nutrients reaching marine end compartment (EP-marine)

	- Eutrophication potential, Accumulated Exceedance (EP-terrestrial) - Water (user) deprivation potential, deprivation-weighted water consumption (WDP) - Potential soil quality index (SQP) - Abiotic depletion potential for non fossil resources (ADP- minerals&metals) - Abiotic depletion for fossil resources potential (ADP-fossil) - Human health effects associated with the exposure to PM - Trophospheric ozone concentration increase - Energy use - Secondary materials consumption,
Assumptions and limitations of the study	See below
Data requirements and data quality	See Section 2.4 and below
Type of LCI and LCA deliverables	- Life Cycle Inventory - Life Cycle Impact Assessment Results, including impact assessment and interpretation - Comparative Life Cycle Assessment Study
Type of Critical Review, if any	It can be made by Internal or External experts or by a panel of interested parties. See 2.7.2 and ISO 14040:2006

✓ **Allocation procedures**

For the definition of the scope, the allocation procedures that will be considered producing the life cycle inventory have to be specified.

Allocation is defined as “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO 14040). The use of allocation is often needed because few industrial processes yield a single output or are based on a linearity of raw material inputs and outputs. In fact, most industrial processes yield more than one product, and they recycle intermediate or discarded products as raw materials. Therefore, consideration should be given to the need for allocation procedures when dealing with systems involving multiple products and recycling systems.

The principles for allocation established in EN15804 must be followed. For co-production:

- Allocation shall be avoided as far as possible by dividing the unit process to be allocated into different sub-processes that can be allocated to the co-products and by collecting the input and output data related to these sub-processes.

- If it cannot be avoided:
    - Allocation shall be based on physical properties (e.g. mass, volume) when the difference in revenue from the co-products is low;
    - In all other cases allocation shall be based on economic values;
    - Material flows carrying specific inherent properties, e.g. energy content, elementary composition (e.g. biogenic carbon content), shall always be allocated reflecting the physical flows, irrespective of the allocation chosen for the process.

For reuse, recycling and recovery:

- The end-of-life system boundary of the construction product system is set where outputs of the system under study, e.g. materials, products or construction elements, have reached the end-of-waste state. Therefore, waste processing of the material flows (e.g. undergoing recovery or recycling processes) during any module of the product system (e.g. during the production stage, use stage or end-of-life stage) are included up to the system boundary of the respective module.

Currently, asphalt mixtures are incorporating many recycled materials. The recycled material most used in asphalt mixtures and asphalted pavement activities is Reclaimed Asphalt (RA). In addition to the requirements in EN15804, most PCRs present specific recommendations for dealing with recycled materials being all in agreement and as following (The International EPD System 2018: Product Category Rules for Highways (Except Elevated Highways), Streets and Roads v2.0):

- If there is an inflow of recycled material to the production system, the recycling process and the transportation from the recycling process to where the material is used shall be included.
- If there is an outflow of material to recycling, the transportation of the material to the recycling process shall be included.
- Impacts associated with the processes involved in preparing the recycled materials for use in the asphalt mixture are considered part of the system boundary.

✓ **Cut -off rules**

Cut-off rules are the criteria applied to exclude input and outputs in the LCA when producing the life cycle inventory. The rules used must be specified in the scope definition and be in accordance to EN15804 as following:

- All inputs and outputs to a (unit) process shall be included in the calculation, for which data are available. Data gaps may be filled by conservative assumptions with average or generic data. Any assumptions for such choices shall be documented;
- In case of insufficient input data or data gaps for a unit process, the cut-off criteria shall be 1 % of renewable and non-renewable primary energy usage and 1 % of the total mass input of that unit process. The total of neglected input flows per module, e.g. per module A1-A3, A4-A5, B1-B5, B6-B7, C1-C4 and module D shall be a maximum of 5 % of energy usage and mass. Conservative assumptions in combination with plausibility considerations and expert judgement can be used to demonstrate compliance with these criteria;

- Particular care should be taken to include material and energy flows known to have the potential to cause significant emissions into air and water or soil related to the environmental indicators of this standard. Conservative assumptions in combination with plausibility considerations and expert judgement can be used to demonstrate compliance with these criteria.

Regarding the last point, some PCRs include a list of materials that cannot be excluded (EAPA, 2017):

- Polymers in binder, broken down into two classes of chemicals: elastomers or rubbers, such as styrene-butadiene-styrene (SBS), and plastomers
- Liquid antistrips, recycling agents, and warm-mix chemical additives
- Fibres

✓ **Assumptions and limitations of the study**

Any assumptions and/or limitation of the study should be declared in the scope definition. Regarding the life cycle inventory or life cycle impact assessment phases, these may include (ISO 14040):

- limited development of the characterization models, sensitivity analysis and uncertainty analysis for the LCIA phase
- limitations of the LCI phase, such as setting the system boundary, that do not encompass all possible unit processes for a product system or do not include all inputs and outputs of every unit process, since there are cut-offs and data gaps
- limitations of the LCI phase, such as inadequate LCI data quality which may, for instance, be caused by uncertainties or differences in allocation and aggregation procedures
- limitations in the collection of inventory data appropriate and representative for each impact category

✓ **Data Requirements and Data Quality**

ISOs define a set of requirements that datas have to respect, provided in the table 3 in LCI paragraph. It's important to provide infos on data (sources, kind of data) and to specify if there are missing informations and to differentiate primary from secondary data.

✓ **Type of Critical Review** (if any)

The scope should identify why the critical review is being undertaken, what will be covered and to what level of detail, and who needs to be involved in the process.
The review should ensure that the classification, characterization, normalization, grouping and weighting elements are sufficient and are documented in such a way that enables the life cycle interpretation phase of the LCA to be carried out. Confidentiality agreements regarding the content of the LCA should be entered into as needed.

Critical review can be made by:
- internal or external expert , who should be familiar with the requirements of LCA and should have the appropriate scientific and technical expertise.
- a panel of interested parties. An external independent expert should be selected by the original study commissioner to act as chairperson of a review panel of at least three

members. This panel may also include other interested parties affected by the conclusions drawn from the LCA, such as government agencies, non-governmental groups, competitors and affected industries.

2C. Life Cycle Inventory (LCI) analysis

LCI is defined as "data collection and calculation procedures to quantify relevant inputs and outputs of a product system" (ISO 14040). The LCI results are the input to the subsequent LCIA phase. The process of conducting an inventory analysis is iterative. As data are collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goals of the study will still be met. Sometimes, issues may be identified that require revisions to the goal or scope of the study.

Briefly, the result of an LCI is a list of quantified elementary flows used as input for the Impact Assessment.

A Life Cycle Inventory work consists of two steps: data collection and data calculation.

✓ Data Collection

As mentioned in Section 2.4 of this report, data is the core of any SA and all the information provided there applies here. In LCA, the required data for each unit process within the systems boundary includes (ISO 14040):

- energy inputs, raw material inputs, ancillary inputs, other physical inputs,
- products, co-products and waste,
- emissions to air, discharges to water and soil

Data can be collected on site (primary data) or from secondary sources (i.e. literature).

✓ Data Calculation

According to ISO14040 this steps includes:

- Validation of data collected,
- the relating of data to unit processes, and
- the relating of data to the reference flow of the functional unit.

In other words, according to ISO14044, it's important to check data validity to confirm and provide evidence that the data quality requirements have been fulfilled. It's important that data represent all the chosen life cycle steps and a comparison of input and output flows entering and leaving the system is made (mass balance).

Useful questions:

- Does the unit process inventory include all relevant product, waste and elementary flows that would be expected?
- Are the amounts of the individual flows and of the chemical elements, energy and parts in the input and output in expected proportion to each other?

If only an LCA is being carried out, it can be helpful to assess the quality of data, using the table 3 of this deliverable.

For the calculation of the environmental indicators proposed in PavementLCM Framework, the following inventories should then be produced for any process:

- Energy consumption
- Greenhouse gas emissions. This requires the life cycle inventory of major greenhouse gas emissions, including CO_2, CH_4, and N_2O. In addition, NO_X, particulates (including black carbon), and other pollutants that are emerging as critical climate change factors should also be included as the scientific consensus develops on their effects and global warming potentials.
- Material flows, including fossil/non-renewable resource flows, and dividing in primary and secondary materials.
- Air pollutants, including NO_X, Volatile Organic Compounds (VOC), PM_{10}, $PM_{2.5}$, SO_2, CO, and lead.

A list of the processes to consider for the **LCA of asphalt mixtures** is presented here:

- Product Stage:
  - Material acquisition/production, including:
    - Aggregates
    - Bitumen
    - Filler
    - Modifiers
    - Additives
    - Reclaimed Asphalt
    - Rejuvenators
  - Mixing process
  - Feedstock energy of materials that are used as a fuel
  - Transport of materials to mixing plant / site (in the case of manufacturing onsite)

A list of the processes to consider for the **LCA of pavement activities** related to asphalt materials is presented here:

- Product Stage:
  - Material acquisition/production, including:
    - Aggregates
    - Bitumen
    - Filler
    - Emulsion
    - Modifiers
    - Additives
    - Reclaimed Asphalt
    - Rejuvenators
  - Mixing process
  - Feedstock energy of materials that are used as a fuel
  - Transport of materials to mixing plant / site (in the case of manufacturing onsite)
- Construction Stage:

- Transport of materials and equipment to site
- Equipment use at the site for all operations (i.e. laying, compaction, tack coat application)

- Use Stage:
  - Asset Management operations, including:
    - Material acquisition and production
    - Transport of materials and equipment from/to site
    - Equipment use at the site
    - Materials disposal
    - Processes for maintaining the functional and technical requirements, for reparing, for replacing
    - Waste management/ End of life of the removed part of the component
- End of Life Stage:
  - Equipment use at the site for all operations, including:
    - Deconstruction
    - Recycling or waste treatment
    - Disposal
  - Transport of materials and equipment from site to recycling place, treatment plant or landfill

3C. Life Cycle Impact Assessment

Impact assessment translates the inventory into meaningful indicators of a product or system's impact on the environment and human health. This is generally achieved by classifying inventory flows into impact categories and characterizing the inventory results through appropriate impact indicators, by means of characterisation factors. Therefore, ISO 14044 identifies some mandatory and optional steps.

In details, the three **mandatory steps** in LCIA are:

- ✓ selection of impact categories and indicators;
- ✓ classification of the LCI results to the selected impact category; (if a software to perform an LCA is used this step is authomatically done)
- ✓ selection of characterisation factors or LCIA methodology/model (if applicable).

The **optional steps** are:

- ✓ Normalisation
- ✓ Weighting
- ✓ Grouping

The mandatory steps answer the following questions:

1) Selection of impact categories, category indicators and characterisation models: "Which impacts do I need to assess?"
2) Classification: Assignment of LCI results to the selected impact categories. "Which impacts does each LCI result contribute to?"

3) Characterisation: Calculation of category indicator results. “How much does each LCI result contribute?“

In addition to the selection and calculation of indicators, as optional, the following elements can be present (i.e. they are optional) in the LCIA phase, depending on the goal and scope of the study (ISO 14044):

- ✓ Normalization: calculating the magnitude of category indicator results relative to reference information;
- ✓ Grouping: sorting and possibly ranking of the impact categories;
- ✓ Weighting: converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices; data prior to weighting should remain available;

Further information can be found in ISO 14044. These optional elements are not further discussed in PavementLCM Framework because of the reduced number (3+1) of environmental indicators proposed in the framework, which for a full LCA can be up to 21 and it is in that case in which these elements might be of further interest.

There are many different impact categories in LCA (e.g. global warming potential, human toxicity, eutrophication, photochemical oxidant formation), and different LCIA methodologies (e.g. ILCD, EF 3.0, CML, ReCiPe, TRACI) available to calculate the impact indicators. Each of these methodologies has its own .impact categories and characterisation factors and sometimes it can provide normalization and weighting factors too (i.e. EF 3.0).

In PavementLCM Framework, the following set of indicators for the environmental impact is selected. According to the studies proposed by the JRC and the EN15804:2012+A2:2019, the selected methodology is the EF Life Cycle Impact Assessment method, which provide its own list of indicators and characterization factors (CF). To have more details on CF, the JRC Technical Notes “Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods” published in 2018 could be useful.

- ✓ ***Global Warming Potential – EF3.0***

This is the Indicator linked with Climate Change Impact Category which identifies a “change in the state of the climate tha can be identified by changes in the mean and/or the variability of itd properties“.

This indicators is the generally accepted equivalent of greenhouse gases (GHG) accumulation which describes the relevance of emissions for the global warming effect and it’s the characterisation factor describing the radiative forcing impact of one mass-based unit of a given GHG relative to that carbon dioxide over a given period.

The geographic scope of this indicator is a global scale. It shall be expressed in kg CO_2 equivalent and calculated according to EN 15804 using CML – IA version 4.1 dated October 2012 as LCIA methodology for the selection of characterisation factors.

It’s the sum of: - Global Warming Potential-Fossil fuels (GWP- Fossil fuels)

- Global Warming Potential-Biogenic (GWP-biogenic)

- Global Warming Potential- Land use and land use change (GWP-luluc)

✓ ***Acidification – EF3.0***

This indicator represents the decreasing capacity of a system to neutralize acid, so the reduction of substances able to neutralise hydrogen ions. It is caused by emission of gases which realese hydrogen. In particular it is caused by Sulphur oxides (SO_2, SO_3 and H_2SO_3), Nitrogen Oxides (NO and NO_2), Ammonia and Strong Acid.

It quantifies the hydrogen ions present in the environment and for this reason it is measured in mol H+ eq.

✓ ***Eutrophication – EF3.0***

This indicator expresses the increase of nutrients, caused by the abundance of nitrates and phosphates. In particular, this condition can cause an increased biomass production in the acquatic environment and can affect soil quality too.

It has been proposed to measure three different kinds of Eutrophcation potential:

- Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-freshwater) is measured in kg P eq. and expresses the level of Phosphate, phosphoric acid, phosphorus total in freshwater. These chemicals cause an increased biomass production of algae, plankton and other acquatic plants which reduces water quality and cause a decrease of oxygen level.
- Eutrophication potential, fraction of nutrients reaching marine end compartment (EP-marine) is measured in kg N eq. and expresses the quantities of Ammonia, ammonium ion, nitrate, nitrite**, nitrogen dioxide, nitrogen monoxide**, nitrogen total present in marine water. They cause an increased biomass production of algae, plankton and other acquatic plants which reduces water quality and cause a decrease of oxygen level.
- Eutrophication potential, Accumulated Exceedance (EP-terrestrial) is measured in mol N eq. and quantifies the level of NH3, NO2, NO3-.

✓ ***Natural Resources – EF3.0***

This is the name given to a set of impact indicators linked with the use of natural resources such as water, land, fuels, minerals and metals.
In details it takes into consideration:

- Water use
- Land use
- Depletion of abiotic resources (minerals and metals)
- Depletion of abiotic resources use (Fossil fuels)

- ***Water use***

Water is a renewable resource which doesn't disappear, directly linked to

geography and season.
It can be calculated using several indicators, depending on the kind of deprivation caused. In this case the indicator used is Water (user) deprivation potential, deprivation-weighted water consumption (WDP), measured in KG world eq. deprived.
In the chosen methodology consumption is defined as the difference between withdrawal and release of blue water. Green water, rainwater, seawater and fossil water, are not characterized.

- ***Land use***

Land Use is caused by the antrophogenic activities in a given soil area and is linked to climate regulation, erosion, change in food production, etc.

The CF used by the chosen methodology takes into consideration all the impacts due tot he use of soil, such as erosion resistance, mechanical filtration, physicochemical filtration, groundwater regeneration and biotic production.

The indicator linked is the Potential soil quality index , dimensionless and it's an aggregated index which takes into account kg biotic production and kg soil..

- ***Depletion of abiotic resources***

The abiotic resources are those natural non-living resources, such as minerals, metals and fossils exacracted and used in production processes.

The depletion of minerals and metals is linked to Abiotic depletion potential for non fossil resources and measured in kg of Antimony (Sb) equivalents, while the depletion of fossil has as indicator the Abiotic depletion for fossil resources potential (ADP-fossil) measured in MJ.

✓ ***Air pollution – EF3.0***

Air pollution impact category is characterised by two indicators: formation potential of tropospheric ozone (POCP) and particulate matter (PM).

- Particulate matter	- Human health effect associated with exposure to PM
-Photochemical ozone formation	- trophospheric ozone concetration increase

- ***Human health effects associated with exposure to Particulate Matter***

It's the indicator linked to Particulate matter impact category.

Ambient concentrations of particulate matter (PM) are elevated by emissions of primary and secondary particulates. The mechanism for the creation of secondary emissions involves emissions of SO_2 and NO_x that create sulphate and nitrate aerosols. This indicators accounts for the adverse health effects on human health caused by emissions of PM and its precursors (NOx, SOx, NH3).

According to EF Methodology, it can be measured in Disease incidence.

- ***Tropospheric ozone concentration increase***

It's the indicator linked to Photochemical ozone formation impact category.

This indicator POCP (for Photochemical Ozone Creation Potential) is the most widely used value in Europe for describing this phenomenon. This indicator is related to the formation of reactive substances (mainly ozone) by the action of sunlight which are injurious to human health and ecosystems and which also may change crops.

It is measured in kg NMVOC eq. and takes into consideration non-methane Volatile Organic Compunds and CH_4. The characterisation factors can be found in EN15804 and are those of LCIA model in:

✓ Jenkin, M.E. & G.D. Hayman, 1999: Photochemical ozone creation potentials for oxygenated volatile organic compounds: sensitivity to variations in kinetic and mechanistic parameters. Atmospheric Environment 33: 1775-1293.
✓ Derwent, R.G., M.E. Jenkin, S.M. Saunders & M.J. Pilling, 1998. Photochemical ozone creation potentials for organic compounds in Northwest Europe calculated with a master chemical mechanism. Atmospheric Environment, 32. p 2429-2441.

✓ ***Energy used - CWA 17089***

Includes a quantification of the energy required during the life cycle of the object of assessment. It should be divided in renewable and non-renewable, and can be split as defined in EN 15804:

- Use of renewable primary energy excluding renewable primary energy resources used as raw materials in MJ, net calorific value
- Use of renewable primar.y energy resources used as raw materials in MJ, net calorific value
- Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials) in MJ, net calorific value
- Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials in MJ, net calorific value
- Use of non-renewable primary energy resources used as raw materials in MJ, net calorific value
- Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials) in MJ, net calorific value

The energy use is inventoried per energy source and if relevant, per energy carrier. The aggregation for each information module is declared in MJ. This indicator is a direct result of the LCI, meaning that no LCIA methodology is applied.

✓ ***Secondary materials used - CWA 17089***

This indicator includes a quantification of the material recovered from previous use or from waste which substitutes primary materials. It can be expressed by mass units or as percentage of recycled materials used related to the total consumption.

This indicator is a direct result of the LCI, meaning that no LCIA methodology is applied. The total Recycled Material Consumption per type of component ($RMC_{T,i}$) is the sum of the individual quantities (rm) per component (i):

$$RMC_{T,i} = \sum rm_i$$

4C. Interpretation of results

Interpretation is the phase of LCA in which the findings are considered together. The interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations.

Interpretation of the results of a LCA study is a mandatory phase of LCA and it is a key aspect in order to derive robust conclusions and recommendations. One of the key aims of LCA is to provide the decision makers with comprehensive and understandable information: this task is achieved by a proper interpretation of the results of an LCA study (Zampori et al., 2016).

The recommendations provided in PavementLCM SA Framework are based on the “Guide for interpreting life cycle assessment result” produced by the Joint Research Centre of the European Commission in 2016 (Zampori et al., 2016). This report provides the flowchart shown in **Errore. L'origine riferimento non è stata trovata.** to develop this task.

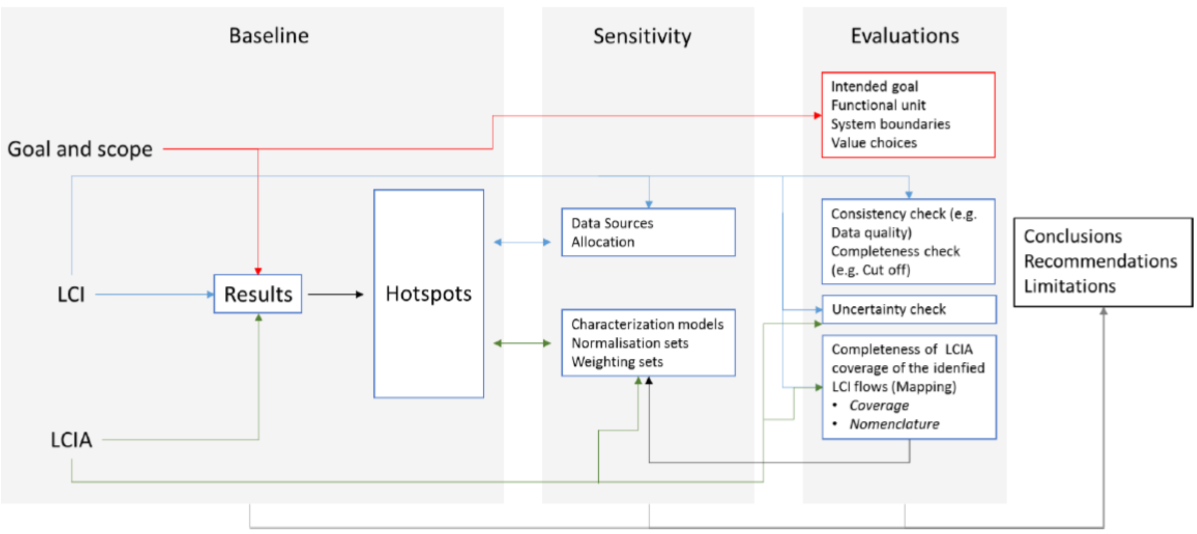

Figure C1 - Interpretation of results flowchart (Zampori et al. 2016)

4.1 Steps in Interpretation of results

According to Zampori et al. (2016), which takes into account ISO 14040 and ILCD Handbook (European Commission - Joint Research Centre, 2010), the elements of interpretation of results can be grouped in three steps, as represented in this scheme provided by FHWA

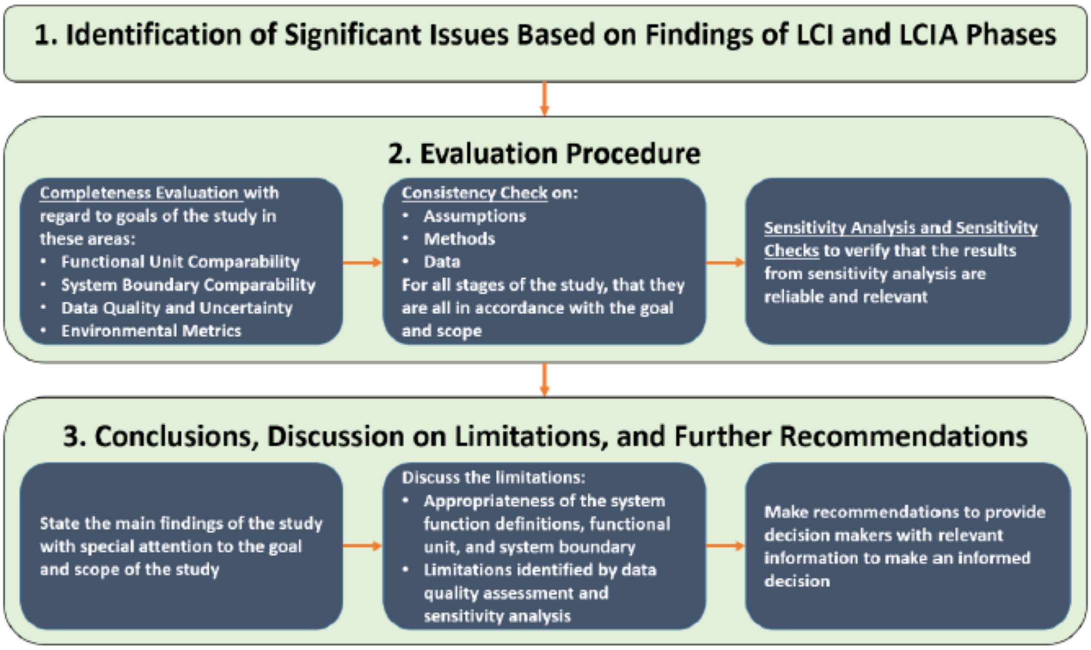

Figure C2 – Interpretation of results steps (FHWA, 2011)

1. <u>Identification of significant issues</u> (based on the results of the LCI and LCIA phases)

The purpose of this first element of interpretation is to analyse and structure the results of earlier phases of the LCI/LCA study in order to identify the significant issues. There are two interrelated aspects of significant issues: i) firstly there are the main contributors to the LCIA results, i.e. most relevant life cycle stages, processes and elementary flows, and most relevant impact categories, termed as hotspot analysis; ii) secondly, there are the main choices that have the potential to influence the precision of the final results of the LCA. These can be methodological choices, assumptions, foreground and background data used for deriving the process inventories, LCIA methods used for the impact assessment, as well as the optionally used normalisation and weighting factors.

2. <u>Evaluation that considers completeness, sensitivity and consistency checks</u>

Completeness checks on the inventory are performed in order to determine the degree to which it is complete and whether the cut-off criteria have been met.

Some processes and flows can be judged „negligeable“ if that such processes/flows make up together less than 10 % of the part of the share that is cut off.

Sensitivity checks have the purpose to assess the reliability of the final results and of the conclusions and recommendations of the LCA study, determining how they are affected by uncertainties in the data, allocation methods or calculation of category indicator results. ILCD recommends to conduct a sensitivity check along all the LCA phases.

The consistency check is performed to investigate whether the assumptions, methods and data have been applied consistently throughout the LCI/LCA study (i.e. consistency beteween the study and: - the standards, - the goal and scope or consistency in definition of: -functional unit, system boundaries, impact categories, ..)

3. Conclusions, limitations and recommendations

Integrating the outcome of the other elements of the interpretation phase, and drawing on the main findings from the earlier phases of the LCA, the final element of the interpretation is to draw conclusions and identify limitations of the LCA, and to develop recommendations for the intended audience in accordance with the goal definition and the intended applications of the results.

4.2 Focus on useful analyses in Interpretation Phase

1. Hotspot Analysis

In order to get started with interpretation of results, it is necessary to identify what the key issues are. Once the key issues are identified it is possible to further evaluate the overall robustness of the LCA study by using for example completeness, consistency and sensitivity checks. The benefits of hotspots analysis include ensuring:

- ✓ Focus on priority issues (e.g., waste, water, materials of concern)
- ✓ Focus on the right life cycle stage (e.g., material acquisition, manufacturing, use, end of life)
- ✓ Focus on the right actors (e.g. producers, manufactures, suppliers, retailers, customers) to evaluate, influence and implement solutions
- ✓ Implications of trade-offs are understood
- ✓ Resources (e.g. time, money) can be effectively allocated to actions

Here a default list with the possibile most impactful stages:

- Raw material acquisition and pre-processing
- Production of the main product
- Product distribution and storage
- Use stage
- end-of-life

LC stages, processes and flows can be

- Hotspots (>50% contribution)
- Relevant (>80% contribution)

Table 12 summarises the different items of a LCA that can be subjected to hotspot analysis, at what level it should be done and the thresholds stablished for their definition.

Table 12- - Summary of requirements to define most relevant contributions and hotspots (European Commission, 2017)

Item	**At what level does relevance need to be identified?**	**Threshold**
Most relevant impact categories	In the final results, starting from normalized and weighted results but deviations possible if justified	No threshold. Decision left to practitioner but subject to stakeholder consultation
Most relevant life cycle stages	For each impact category, before normalization and weighting. Not relevant for data needs identification	All life cycle stages contributing cumulatively more than 80% to any impact category
Hotspots	For each impact category, before normalization and weighting	Either (i) life cycle stages, processes, and elementary flows cumulatively contributing at least 50% to any impact category, or (ii) at least the two most relevant impact categories, life cycle stages, processes and at least two elementary flows (minimum 6). Additional hotspots may be identified by the practitioner
Most relevant processes	For each impact category, before normalization and weighting. Essential for data needs identification	All processes contributing cumulatively more than 80% to any impact category
Most relevant elementary flows	For each impact category, before normalization and weighting. Essential for data needs identification	All elementary flows contributing cumulatively more than 80% to any impact category and in any case all those contributing more than 5% individually

2. Uncertainty Analysis

ISO 14044 defines uncertainty analysis as systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability. The estimation of uncertainty serves three main purposes:

- It supports a better understanding of the results obtained
- It supports the iterative improvement of an LCA study
- It also helps the target audience to assess the robustness and applicability of the study results

The SA exercises performed in PavementLCM will include the estimation of uncertainty in LCA. Where inputs to an indicator are characterised by a probability distribution, uncertainty analysis can be undertaken using techniques such as Monte Carlo analysis. Ranges of values for selected inputs are combined in a series of combinations to identify the range of possible values for an indicator SA and the probability of each occurring. Where this is a computational intractable problem due to the number of inputs, it can be simplified by prioritising hot spot inputs and by assuming the values for certain inputs are the same for comparative assessments (paired Monte Carlo analysis).

The complete methodology used to estimate uncertainty will be delivered together with the SA exercise results and in WP5 PavementLCM Guidelines.

3. Normalization

Usually, the calculation of potential impacts is represented by several indicators measured on different units. The aim of this normalization step is to compare the object of the assessment's results to a chosen common scale (same unit, same quantity of product, same dimensions, etc).
In practice, to carry out this step, normalization factors are needed. They can be calculated wih a formula or, easily, they are provided by the LCA methodology chosen. For instance, EF 3.0 realised by JRC provides characterisation, normalization and weighting factors.

Impact category	Model	Unit	global NF for EF	global NF for EF per person *	Inventory coverage completeness	Inventory robustness	Recommendation level of EF impact assessment
Climate change	IPCC (2013)	kg CO_2 eq	5.79E+13	8.40E+03	II	I	I
Ozone depletion	WMO (1999)	kg CFC-11 eq	1.61E+08	2.34E-02	III	II	I
Human toxicity, cancer	USEtox (Rosenbaum et al., 2008)	CTU_h	2.66E+05	3.85E-05	III	III	II/III
Human toxicity, non-cancer	USEtox (Rosenbaum et al., 2008)	CTU_h	3.27E+06	4.75E-04	III	III	II/III
Particulate matter	Fantke et al., 2016	disease incidences	4.95E+06 (a)	7.18E-04	I/II	I/II	I
Ionising radiation	Frischknecht et al., 2000	kBq U-235 eq.	2.91E+13	4.22E+03	II	III	II
Photochemical ozone formation	Van Zelm et al., 2008 as applied in ReCiPe (2008)	kg NMVOC eq.	2.80E+11	4.06E+01	III	I/II	II
Acidification	Posch et al., 2008	mol H^+ eq	3.83E+11	5.55E+01	II	I/II	II
Eutrophication, terrestrial	Posch et al., 2008	mol N eq	1.22E+12	1.77E+02	II	I/II	II
Eutrophication, freshwater	Struijs et al., 2009	kg P eq	5.06E+09	7.34E-01	II	III	II
Eutrophication, marine	Struijs et al., 2009	kg N eq	1.95E+11	2.83E+01	II	II/III	II
Land use	Bos et al., 2016 (based on)	pt	9.64E+15 (b)	1.40E+06	II	II	III
Ecotoxicity freshwater	USEtox (Rosenbaum et al., 2008)	CTUe	8.15E+13	1.18E+04	III	III	II/III
Water use	AWARE 100 (based on; UNEP, 2016)	m^3 water eq of deprived water	7.91E+13 (b)	1.15E+04	I	II	III
Resource use, fossils	ADP fossils (van Oers et al., 2002)	MJ	4.50E+14	6.53E+04	I	II	III
Resource use, minerals and metals	ADP ultimate reserve (van Oers et al., 2002)	kg Sb eq	4.39E+08	6.36E-02	I	II	III

Figure C3 – Global Normalization factors for emizzionis and resource exraction in 2010, based on EF 2017 method (Sala et al 2017)

Annex D- Life Cycle Costing (LCC)

D1 – Materials: Cost

This indicators should account for the costs related to the acquisition of materials, transport and production of the asphalt mixture under study and shall be expressed in € (or any other currency) per tonne of manufactured asphalt mixture.

Examples of costs included in these phases (A1-A5)

- Professional fees (Project and engineering)
- Products supplied at factory gate ready for construction
- Taxes on construction of goods and services
- Construction costs, including security costs

D2 - Pavement activities: Whole Life Cost

The five-step procedure to perform a LCC analysis for pavement activities that FHWA suggests in their report "Life-Cycle Cost Analysis Primer" from 2002 is adapted here as calculation method merged with the requirements/guidelines of ISO 15686-5, the EN 16627 and CWA 17089.

1. Establish possible design and alternatives

The first step to perform a LCC analysis is to define a possible design and, if the purpose of the assessment is decision-making or comparison, a range of design alternatives for the pavement activity under study. The option of defining alternatives will be taken for the rest of the description, considering that otherwise, only one design would be evaluated for the case of just determining the sustainability performance of a single pavement activity.

In this first step, the component activities for each alternative have to be described detailing the NRA activities that create and maintain it, and the analysis period has to be decided. The initial construction, regular maintenance and rehabilitation operations required to keep the specified level of performance of the pavement have to be defined for the selected analysis period. In this regard, different alternatives will likely require different maintenance and rehabilitation operations.

Considering that only the asphalt components of the pavements are included in PavementLCM framework of this deliverable, an analysis period of 40 years was suggested to follow the recommendation of including at least one major rehabilitation activity.

2. Determine activity timing

Once the component activities of each alternative have been identified, the plan/schedule of when the future maintenance and rehabilitation activities will occur and when NRA funds will be expended should be developed. Each NRA decides when to perform maintenance and rehabilitation activities based on the desired level of performance and previous experience.

The prediction of when such activities will occur needs to be as accurate as possible, since they can represent a high portion of the total LCC of each alternative.

3. Estimate costs

CWA 17089 follows the guidance of ISO 15686-5 to calculate the LCC as indicator, and the main difference with the recommendations of the FHWA is the costs that they include. While ISO 15686-5 only consider the cost of the agency (NRA), FHWA introduces also user costs.

Agency costs have to be considered

According to CWA 17089, the costs to be considered (depending on the component activities included) in the LCC are:

a) Initial cost, divided into:
   - Design costs: sum of the individual costs related to preliminary design activities
   - Construction costs: raw materials and labour cost
   - Start-up cost: sum of the individual cost related to the start-up of the pavement derived from commissioning, evaluation and handover activities
   - They are the cost linked with the A1-A5 phases.

b) Asset management: total of the necessarily incurred labour, material and other related costs incurred to retain the pavement in a state in which it can perform its required functions during the analysis period. It can include all costs related to use, maintenance, management, inspections, repair, refurbishment of the pavement throughout its life cycle.

   → Examples of costs in these phases (B1- B8):
   - Regular and routine activities
   - Energy costs
   - Professionale fees
   - Repairs, replacement (materials, security, salary)
   - Inspections
   - Some indirect costs (disruption of business activity, related costs to non-availability of the road, loss of function for a certain period)

   In particular, the EN16627 makes a focus on the calculation of the cost for replacement (B4), which include the cost of dismantling and disposal of the old component to be upgraded and the cost of production, delivery and installation oft he new component to be installed.

   It's important to define, as suggested in Scenario phase (2.3) the ESL for all materials and components used, in order to know the number of replacements, calculated with thespecific formula provided in the EN.

   Two possibilities to calculate this cost:

   1. The actual number of replacements that occur within the reference study period will be taken into account for the calculation oft he costs;
   2. For all components the costs of replacements are calculated and divided by the duration of their service life.

c) End of life cost: total of the necessarily incurred labour, material and other related costs incurred to deconstruction, transport associated, end of life fee and taxes, waste processing for re-use, recovery and recycling.

→ Examples of costs in these phases (C1- C4):
- Dismantling
- site clean up
- costs from reuse, recycling, energy recovery

d) Terminal value. There are two options for this:
- Salvage value: usually the net value from the recycling of materials at the end of a project's life. This value exists only if the alternative will not continue in operation after the end of the analysis period.
- Residual asset value (Remaining service life value in FHWA's terminology): value assigned to the asset at the end of the period of analysis. This value exists only if the alternative will continue in operation after the end of the analysis period.

EN 16627 adds a third potential income: the potential income for the pavement owner resulting from the sale of products and materials for reuse, recycling and recovery.

The final agency costs are the initial costs, maintenance costs and end of life costs minus terminal value.

User costs to be considered (optional)

If user costs are to be considered, they include: vehicle operation costs, travel time costs and crash costs. While user costs may be similar between alternative during normal operation (and therefore can be omitted for comparison), they are very dependent on the timing, duration, scope and number of construction, maintenance and rehabilitation work zones, characterising therefore each alternative.

Although incorporating user costs in LCC analysis improves its accuracy, it is still a challenging task.

4. <u>Compute Life Cycle costs</u> (converting future costs to current costs – present value and discount rate)

In previous steps, the alternatives were defined with respect to agency costs, optional user costs, and the time when these events will occur. At this point, the objective is to calculate the total LCCs for each alternative so that they may be directly compared. However, because € (or other currency) spent at different times have different present values, the projected activity costs for an alternative cannot simply be added together to calculate total LCC for that alternative. Economic methods are available to convert anticipated future costs to present € values so that the total lifetime costs of each alternative can be summed up and the different alternatives can be directly compared. According to EN1667 for buildings, the costs and incomes shall be calculated without applying any discount or escalation rate. This gives the nominal value.

In order to do this, both FHWA and ISO 15686-5 recommends to use the Net Present Value (NPV) approach to undertake this step. FHWA presents a deterministic and a probabilistic approach, while ISO 15686-5 presents a deterministic approach with the consideration of uncertainty and sensitivity analysis. The recommendation in PavementLCM Framework to calculate this indicator follows ISO 15868-5.

In order to understand the NPV approach, three concepts need to be described:

- Real cost: cost expressed as a value at the base date (e.g. date of the analysis), including estimated changes in price due to forecast changes in efficiency and technology, but excluding general price inflation or deflation.
- Nominal cost: expected price that will be paid when a cost is due to be paid, including estimated changes in price due to, for example, forecast change in efficiency, inflation or deflation and technology.

The nominal costs should be calculated by multiplying the real cost by the inflation/deflation factor $q_{i.d}$ which should be determined using the following formula:

$$q_{i,d} = (1 + a)^n$$

Where,

a is the expected percentage increase in prices per annum

n is the number of years between the base and the occurrence of the cost

- Discounted cost: resulting costs when the real cost is discounted by the real discount rate or when the nominal cost is discounted by the nominal discount rate.

Discounted costs should be calculated by taking costs that occur in future years and reducing them by a factor derived from the discount rate. Different discount rates may apply depending on whether nominal costs or real costs are being discounted. If nominal costs are used, the nominal discount rate includes an inflation/deflation factor. If real costs are used, the real discount rate does not include an inflation/deflation factor.

- A **discount factor**, q_d, should be calculated from the discount rate, d, using the following formula:

$$q_d = \frac{1}{(1 + d)^n}$$

Where

d is the expected real discount rate per annum

n is the number of years between the base and the occurrence of the cost

A real cost should be converted to a discounted cost using the factor q_d.

A nominal cost should be converted to a discounted cost using the factor $q_{d,nc}$ calculated using the formula:

$$q_{d,nc} = \frac{1}{(1 + d)^n (1 + a)^n}$$

Where

d is the expected real discount rate per annum a is the expected percentage increase in prices per annum

n is the number of years between the base and the occurrence of the cost

Real discount rates used in LCC analysis typically range from 3 to 5 percent, representing the prevailing rate of interest on borrowed funds, less inflation. Because there is always an opportunity value of time, real discount rates will always exceed zero.

- Calculation of Net Present Value (NPV)

The NPV should be calculated by discounting future cash flows (costs and benefits/revenues) to the base date and should be used for comparing alternatives over the same period of analysis. NPV calculations should be used to calculate the present monetary sum that should be allocated for future expenditure on an asset, and to determine and compare the cost effectiveness of proposed options.

Therefore, the NPV may be described as the sum of the discounted benefit of an alternative less the sum of the discounted costs.

If only the costs are included this may termed Net Present Cost (NPC).

The EN16627 suggests to calculate Annual Cost or Annual Equivalent (AC or AEV)

5. Analysis of results

The most basic analysis of a deterministic LCC is to compare the agency and optional user cost NPVs among alternatives. However as mentioned above, considering uncertainty and performing a sensitivity analysis is highly recommended in ISO 15686-5. This standard identifies the causes of uncertainty in detail which are not presented here for brevity.

In order to consider uncertainty, it suggests that where a range of possible costs is calculated, it can be beneficial to model the uncertainty attached to the cost or time variables using statistical techniques, such as the Monte Carlo analysis. This should allow the identification of a distribution of possible costs and a range of more and less probable figures for use in calculations.

Finally, sensitivity analysis can be undertaken on the key assumptions that can have the biggest effects on uncertainties including: discount rates, period of analysis and incomplete or unreliable service life or maintenance, repair and replacement cycles or cost data based on assumptions.

According to ISO 15686:2017 the results of a LCC analysis shall be documented in a report so that users can clearly understand both the outcomes and the implications, including clearly defining the purpose, scope, key assumptions, limitations, constraints, uncertainties, risks and effects of any sensitivity analysis.