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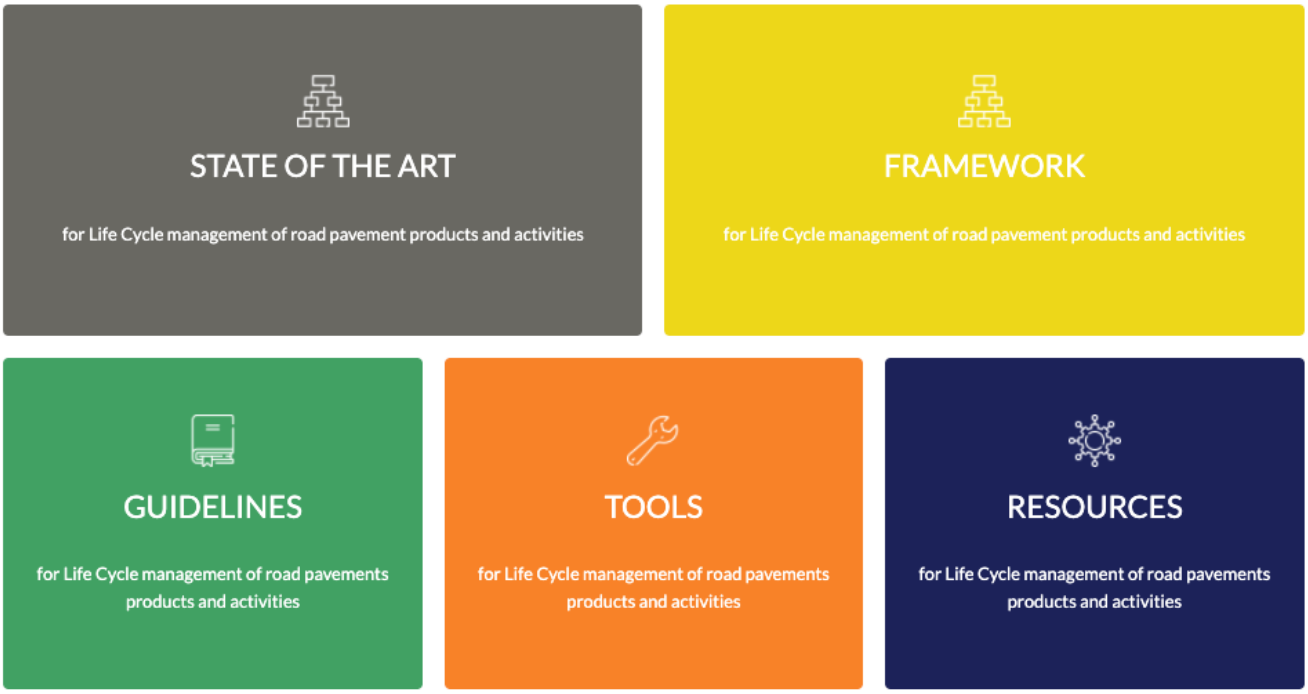
Call 2017 New Materials PavementLCM Final Report:

A package for implementing Life Cycle Management of road pavement



PavementLCM

December 2021

Call 2017 New Materials Pavement LCM Final Report

CEDR Contractor Report 2022-02

PavementLCM – A complete package for Life Cycle Management of more sustainable asphalt mixtures and road pavement

by

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The Project Executive Board for this programme consisted of:

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Executive summary

PavementLCM is a 2 year international project aiming at supporting European National Road Authorities to introduce sustainability at the core of their practices by providing training on Life Cycle Management techniques and a user-friendly package to support their widespread implementation.

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 strengthening 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 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 the results of Sustainability Assessment (SA) exercises as a support for decision making.

On this basis, the Pavement LCM provides NRAs with a package that has the ambition of being user-friendly enough for a wide-spread use across European NRAs and that could allow CEDR members to plan a harmonized implementation of these practices. This report provides NRAs with the main findings and further recommendations, together with the purpose, the scope and the methodology adopted to carry out the project. Furthermore, in order to facilitate the wide-spread distribution of the package, the main project products have been shaped in the form of 2-8 pages tech briefs, presented within this report although made to be used as a stand-alone information documents.

The PavementLCM package can be found here (https://www.pavementlcm.eu/pavementlcm-package/) and includes:

- “State of the Art” of the use of Sustainability Assessment for road pavements
- PavementLCM “Framework” to identify the Sustainability Assessment exercises for producers, contractros and road authorities
- PavementLCM “Guidelines” for carrying out the Sustainability Assessment of road pavements according to EN 15643-5-2017
- PavementLCM “Tools” as a support to carry out the Sustainability Assessment exercises
- PavementLCM “Resources” as a support for the implementation of project findings

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1. Definition of the Issue

1.1. Purpose

This report summarises the results of the research project " PAVEMENTLCM: life cycle management of green asphalt mixtures and road pavement", which was funded by CEDR within the call 2017 "New materials".

Sustainability is often defined as the balance between people, planet and profit. For national road authorities, these aspects are important to take into account when considering their asset management and project planning. However, there is no single way to assess the sustainability of assets. There are many different methods, tools and databases claiming to support sustainability assessment, but there is not one method defined as the most appropriate for National Road Authorities (NRAs). Amongst all available methods there is a core principle, namely that the impacts of a project or product should be analysed over its whole life cycle and that this impact can be quantified. This principle is generally referred to as Life Cycle Thinking and comprises amongst others environmental Life Cycle Assessment (LCA) and Life Cycle Costing analysis (LCC, sometimes referred to as LCCA). For these methodologies, not only general approaches exist but also specific standards for example the ISO 14040-14044 which describes the standard procedures for LCA, the ISO 15686-5 standard for LCCs of buildings and constructed assets, the EN 15804 standard for creating Environmental Product Declarations (EPDs) of building products, etc. Furthermore, a framework for sustainability assessment (SA) of civil engineering works has been recently defined in the European standard on Sustainability of Construction Works: Civil Engineering Works – Framework (EN 15643-5-2017) and Sustainability of Construction Works: Assessment of Environmental Performance of Buildings – Calculation method (EN 15978:2011). ***Using the results of these SA exercises in support of decision-making for road asset managers is what is here defined as Pavement Life Cycle Management.***

Despite these techniques are now widely used and despite the existence of ostensibly clear standards, their application within the road pavement industry is not unambiguous. There is a need of standardization of functional units, system boundary, improved data quality and reliability and broadening of study scopes. Another big issue is data uncertainty of both inputs and results. In fact, Road pavement LCM analyses are based on limited data, frequently of poor quality, and require assumptions (including durability) that are difficult to verify, and predictions of future evolutions of technology and processes. The subsequent problem is that over the past years many different approaches have been followed, datasets created, and tools developed for LCM of pavements. This increase in available tooling, and the lack of synergies and communication amongst NRAs, has however not led to clear and comparable information, but merely to an overload of slightly or hugely differing information sources.

Hence, the next steps towards simpler and better sustainability assessment for CEDR NRAs, are explicated in the three main objectives of the PAVEMENTLCM project as follows:

1) *Tailor guidelines towards the introduction of Life Cycle Management (LCM) in National Road Authorities with a focus on Sustainability Assessment.*
2) *Create as a platform for interactive transfer of knowledge on best practices on sustainability assessment and Life Cycle Management to generate reliable durability data for green asphalt.*
3) *Produce tools, guidelines, datasets, roadmaps and recommendations to introduce life cycle management practices in road authorities*

1.2. Scope

This final report aims to provide a summary of the several interconnected findings obtained during the project lifetime. In fact, the PavementLCM delivered a complete package to stimulate the conversation related to life cycle management of road pavements and allow NRAs, and other stakeholders, to introduce sustainability assessment exercises at the core of their practices. The project built-up over findings of a previous project, namely CEDR 2012 call - Allback2Pave, and it has been already applied to harmonise LCA results amongst the other two projects of the CEDR 2017 call CRABforOERE and FIBRA. The ambition is to be a reference for the implementation of life cycle management practices within NRAs and to be a milestone for the initiation of the "SA Knowledge Transfer Platform" allowing NRAs to share best practices, also with other stakeholders (e.g. EAPA) as well as learning from academics and experts from all over the world.

Details regarding the background of this final summary can be obtained from the deliverable reports from Work Package 2 to Work package 6 each of which discusses selected topics under research within the project, see Table 1.

Table 1 – main reports discussing details of project findings

No	**Deliverables / Reports in the PavementLCM Package** (https://www.pavementlcm.eu/pavementlcm-package/)	where in the Package
1	D1.5 Project final report	RESOURCES
2	D2.1a Pavement LCM State-of-the-Art	STATE OF THE ART
3	D2.1b Pavement LCM Sustainability Assessment Framework	FRAMEWORK
4	D3.1 Sustainability data analysis, including datasets and recommendations to perform LCA of road pavements	RESOURCES
5	D4.1 Durability data analysis, including datasets useful to estimate a value for a reference service life of wearing courses	RESOURCES
6	D5.1a: PavementLCM Sustainability Assessment Guidelines	GUIDELINES
7	D5.1b: PavementLCM Recommendations to use Multi-Criteria analysis for Decision Making (originally D5.4)	GUIDELINES
8	D5.2: Sustainability Assessment tools (originally only SA lookup tool): - Sustainability Assessment Compass - LCA data collection template - LCA result uncertainty analysis - Durability distribution from expert opinions	TOOLS
9	D5.3: Harmonization of environmental databases for road pavement in EU	RESOURCES
10	D6.1 State of the art and knowledge agenda of circular economy topics in pavement LCM D6.2: European NRAs and Circular economy D6.3 Circular models to favour the uptake of green asphalts	RESOURCES

1.3. Methodology

In order to achieve the stated goals, the strategy behind the workplan has been to follow a time-flow that would allow researchers to first gather information from partners and advisory board, carry out a review of practices and only then create the framework, case studies, guidelines, recommendations, datasets, roadmaps and tools within 6 work packages as follows:

- Coordinating and ensuring quality of project products through an advisory board (WP1)
- A platform to transfer knowledge on sustainability assessment to/from/amongst NRAs (WP2)
- Innovation in sustainability assessment (WP3,5)
- Introducing durability within sustainability Assessment (WP4)
- Progress in terms of implementation of Circular Economy in the pavement industry (WP6)

As can be seen in figure 1, the project was developed in three levels:

PLCM Level 1	PLCM Level2	PLCM Level 3
What is SA?	**How do I perform SA?**	**Pavement LCM Package**
• State of the Art • Interviews • Advisory workshops	• PavementLCM Framework *according to standardised procedure (EN CEN TC 350)*	• PavementLCM Guidelines • PavementLCM Tools • PavementLCM Resources

Figure 1- PavementLCM project development levels

LEVEL 1 – *State of the Art on Sustainability Assessment (SA) – WP2*

This level is dedicated to NRAs which has not yet implemented any SA in their practices and need to understand what SA is, why they should use it and how to start. The outcome of Level 1 is the **PavementLCM State-of-the-Art (more details in D2.1a)**, aimed to cover the content of Level 1 as follow:

- by helping the road authorities in their sustainability knowledge
- by performing a series of interviews with NRAs in order to better understand the variety of current practices around Europe, identify and share existing best practices as well as creating a state-of-the-art of international practices and standards.
- by creating and implementing a platform for knowledge transfer through a series of tailored advisory workshops/webinars aimed at involving NRAs in the project development as well as providing an opportunity to learn and share about the complex issue of engineering sustainability within the road industry

LEVEL 2 – *PavementLCM "Sustainability Assessment Framework" – WP2*

This level is dedicated to NRAs which already know about SA practices and would benefits from Pavement LCM Framework and Guidelines to perform SA exercises according to the most recent standards. The outcome of Level 2 is the **PavementLCM SA Framework (more details in D2.1b)**, aimed to cover the content of Level 2 by providing the general information for carrying out the assessment for NRAs but also for Manufacturers and Contractors.

The framework indicates to divide the SA in into main two groups: *Pavement Materials* and *Pavement Activities*, and identifies five different exercises as in the following 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.

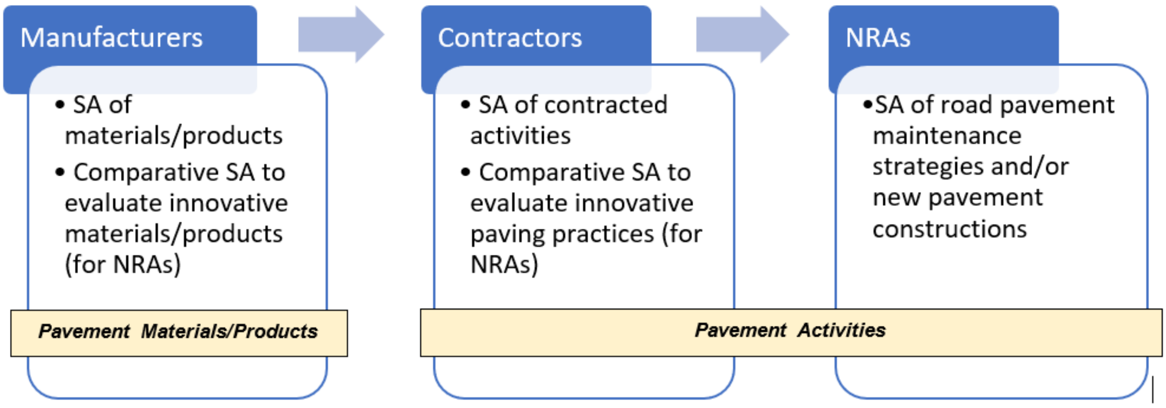

Figure 2 - SA exercises proposed by the Pavement LCM Framework

- 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).

The Framework also introduced a set of indicators, chosen according to the outcomes of the three advisory workshops as well as on the literature review. In fact, according to EN

15804:2012+A2:2019 and JRC Technical Report published in 2018, there are some core environmental indicators which have a main role in environmental assessment due to their potential burdens, furthermore the following list cover economic impacts and technical and functional requirements as suggested by the EN standard on SA for civil engineering works. The list of indicators still lacks for “social” indicators since the standard for Social LCA came out on mid-2021 and it is the opinion of the authors that the relative indicators still need to be investigated in order to be introduced within this framework.

The indicators have been grouped in macro-areas as follows in Table 2 and detailed in D2.1b

Table 2 – Indicators for the Sustainability Assessment of pavement materials and activities

Related to	SA Indicator	Object of assessment
Environment	**Global Warming Potential (GWP- total)**	Pavement materials and activities
Environment	**Acidification**	Pavement materials and activities
Environment	**Eutrophication**	Pavement materials and activities
Environment	**Natural resources consumption**	Pavement materials and activities
Environment	**Air pollution**	Pavement materials and activities
Environment	**Energy use**	Pavement materials and activities
Environment	**Secondary materials consumption**	Pavement materials and activities
Economy	**Cost** *This indicator differs for materials and activities:* - Cost - Net Present Value/ Whole life cycle cost	 Pavement materials Pavement activities
Technical and functional requirements	**Tyre-pavement noise**	Pavement activities
Technical and functional requirements	**Durability**	Pavement activities
Technical and functional requirements	**Optional indicators**	Pavement activities

LEVEL 3 – *PavementLCM “Sustainability Assessment Package*” - *WP3, WP4, WP5, WP6*
This level is focused on delivering a series of “products” that will support NRAs to carry out SA exercise. The Package, accessible through the PavementLCM website (https://www.pavementlcm.eu/pavementlcm-package/), is composed of four sections that have been tailored to carry our the SAexercises for pavement materials/products and activities:

1. SA State of The Art (level 1)

2. SA exercises Framework (level 2)

3. SA Guidelines (level 3)
   contains a step-by-step process to setup and perform the Sustainability Assessment of pavement materials/products, as well as pavement activities (pavement components and road pavement). The guidelines are aimed at tailoring the European standards for SA that at the moment specify the details of this process for buildings but not yet for road infrastructure. The guidelines are presented with two separate deliverables as follows:

- D5.1a report focuses on the PavementLCM Guidelines to carry out SA exercises according to EN 15643-5-2017
- D5.1b has been created as an addendum, due to the extent of information, to provide NRAs with recommendations to use Multi-Criteria analysis for Decision Making

4. SA Tools (level 3)

The PavementLCM "Tools" are part of the packaging process that aims at providing NRAs with tools that can facilitate the implementation of the SA exercises. These are:

- Sustainability Assessment compass, aimed at providing an overview and guidance on the best tools available for NRAs
- LCA Data collection template, to guide NRAs on data collection to perform both pavement materials and pavement components LCA
- A tool to account for advanced calculation of uncertainty of LCA results for asphalt mixtures
- A tool to calculate the distribution of the estimation of durability of a pavement component (e.g. wearing course) on the basis of the experts' opinion

5. SA Resources (level 3)

The PavementLCM "Resources" provides NRAs with documents that can facilitate the implementation of the project results, and more specifically the SA exercises. These are:

- D1.5 PavementLCM Final report
- D3.1 with Sustainability data analysis, including datasets and recommendations to perform LCA of road pavements
- D4.1 Durability data analysis, including datasets useful to estimate a value for a reference service life of wearing courses
- D5.3 Roadmap towards harmonised environmental database for road pavements
- D6.1_6.2_6.3 Recommendations to introduce Circular Economy concepts within NRAs
- Technical briefs of the main project products

2. Technical Briefs

In order to simplifying the transfer of knowledge within NRAs, the authors have produced a series of technical briefs that are here reported to illustrate the main products of the project as well being ready-to-be-used resources for a wide-spread distribution amongst NRAs.
Here is the list of technical briefs, detailed in the annex:

- TB1 - Sustainability assessment in pavement engineering
- TB2 - Life Cycle thinking and Life Cycle techniques
- TB3 - What are more sustainable asphalt mixtures and pavements?
- TB4 - Sustainability assessment Framework – *in a nutshell*
- TB5 - PavementLCM Guidelines – *in a nuthsell*
- TB6 - Recommendations in the use of sustainability datasets
- TB7 - Recommendations for durability assessment of wearing courses

- TB8 - Towards Circular asphalt pavement industry

3. Recommendations for the possible ways forward

The deliverables developed in this project aimed to serve the individual NRAs in implementing results within their organisation and at the core of their practices. Hence, implementation should start at the national context, however NRAs should continue with international cooperation towards a harmonized methodology for pavement life cycle management. The PavementLCM package contains framework, guidelines, resources and tools that can be used to start/evolve the utilisation of LCM practices. Furthermore, the project delivered products that are flexible enough to upgraded and updated and are ready-to-be-used by individual NRAs as well as from CEDR for future harmonization purposes. CEDR can also use the project results to develop European standards for LCM practices, for example together with bodies like CEN or ISO, or to support other association of stakeholders (i.e. EAPA) to define their Product Category Rules.

The results will not only be delivered for implementation in the NRA practices, but they will also be integrated into further research projects and communicated within the scientific community. Hence, this research will not stop after the project deadline, in fact it fits within the ongoing research portfolio of the consortium partners on engineering sustainability of road infrastructures.

Having said that, considering the complexity of the topic and in order to really make a change in the industry targeting sustainable development goals, it is of paramount importance that CEDR would keep the **"Transfer of Knowledge Platform"** initiated by this project. This would, first of all, allow a continuous exchange of good practices amongst NRAs. Also, the platform has already demonstrated the potential of being a valid channel to foster direct contamination with other industry stakeholders (i.e EAPA, ERF, etc..) and experts from academia and industry also from other countries (i.e FHWA). Furthermore, providing specific support to keep this effort ongoing will allow performing tailored research towards a continuous development of the PavementLCM package composed of State-of-the Art information, SA framework, as well as SA guidelines, tools and resources for their implementation (Figure 2)

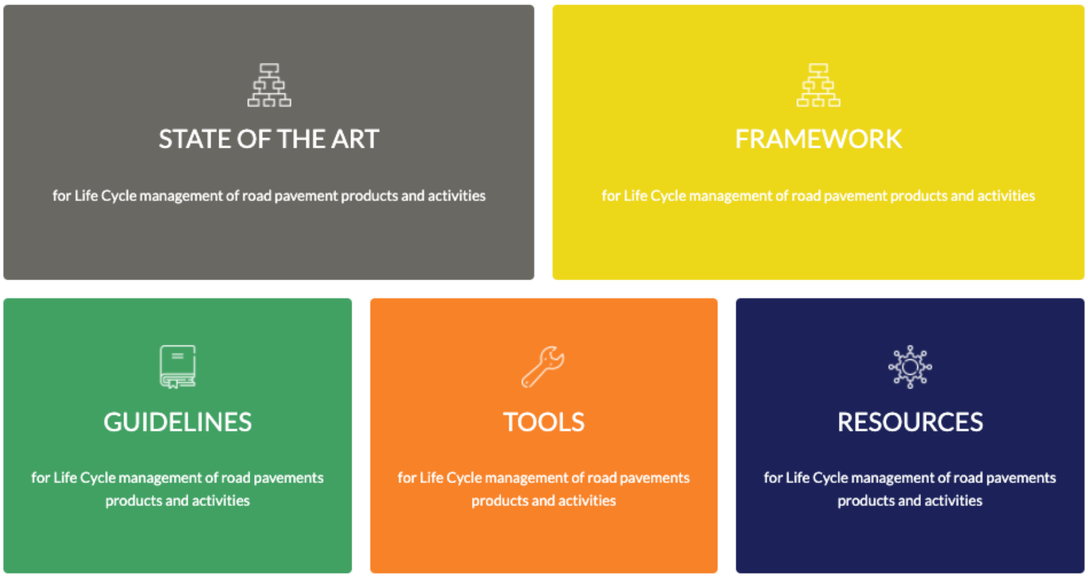

Figure 3- PavementLCM package (https://www.pavementlcm.eu/pavementlcm-package/)

4. Conclusions

PavementLCM Project had three main objectives:

1) Tailor guidelines towards the introduction of Life Cycle Management (LCM) in National Road Authorities with a focus on Sustainability Assessment.
2) Create a platform for interactive transfer of knowledge on best practices on sustainability assessment and Life Cycle Management to generate reliable durability data for green asphalt.
3) Produce tools, guidelines, datasets, roadmaps and recommendations to introduce life cycle management practices in road authorities

With regards to objective 1 and 3, the consortium was able to:

- deliver internationally recognized guidance on LCM for National Road Authorities through a package with State-of-the-art information on the topic;

- a framework to implement LCM practices amongst the road pavement industry stakeholders; Guidelines to carry out Sustainability Assessment exercises according to the most recent standards on the topic;

- together with several Tools and Resources created to facilitate the implementation at both European and national level.

- At last, with regards to objective 2, the project initiated a platform that for the first time in Europe allows NRAs to discuss and learn sustainability assessment best practices with other stakeholders as well as with academics and experts from several part of the world.

5. ANNEX. Technical Briefs

1. Sustainability assessment in pavement engineering
2. Life Cycle Thinking and Life Cycle Techniques
3. What are more sustainable asphalt mixtures and pavements?
4. Pavementlcm SA Framework
5. PavementLCM SA Guidelines
6. Recommendations in the use of Sustainability Datasets
7. Recommendations for durability assessment of wearing courses
8. Towards circular asphalt pavement industry

SUSTAINABILITY ASSESSMENT IN PAVEMENT ENGINEERING

What is Sustainability Assessment?

In 2017, Sustainability Assessment (SA) of civil engineering works was defined by the European Committee for Standardisation (CEN) as the "combination of the assessments of environmental performance, social performance and economic performance taking into account the technical requirements and functional requirements of a civil engineering work or an assembled system (part of works), expressed at the civil engineering works level" (**EN 15643-5** Framework on specific principles and requirements for civil engineering works). This standard provides a system for the sustainability assessment of civil engineering works using a life cycle approach and using quantifiable indicators measured without value judgements. As well as civil engineering works the SA of pavements and asphalt mixtures must comply with this EU standard.

Purpose of Sustainability Assessment

The SA can be performed for different purposes. According to EN 15643-5, these are:

- To **determine the sustainability aspects** and impacts of the pavement or asphalt mixture in its area of influence;
- To enable the client, users and designers to **make decisions and choices** that will help to address the need for sustainability of the pavement or asphalt mixture;
- To **demonstrate or communicate the sustainability performance** of the pavement or asphalt mixture.

The purpose of the assessment should be clearly identified at the beginning of the study, since it will influence the rest of the whole process.

Key features in EN 15643-5

- Environmental (ENV), social (SOC) and economic (ECON) performance must be assessed. However, in EN15643-5, no more details are provided about how to combine them or whether one pillar can have more importance than the others. The practitioner is free to define priorities in the assessment according to the purpose and goals of the study, project, legislation and company/institution values and strategy.
- Technical and functional requirements must be taken into account. Technical requirements are defined as "type and level of technical characteristics of a civil engineering work or an assembled system (part of works), which are required or are a consequence of the requirements made by the client, users and/or by regulations", and functional requirements are defined as "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". The technical and functional characteristics of the pavement and asphalt mixtures are fixed by the client's brief or project specification, and should always be included in the assessment.

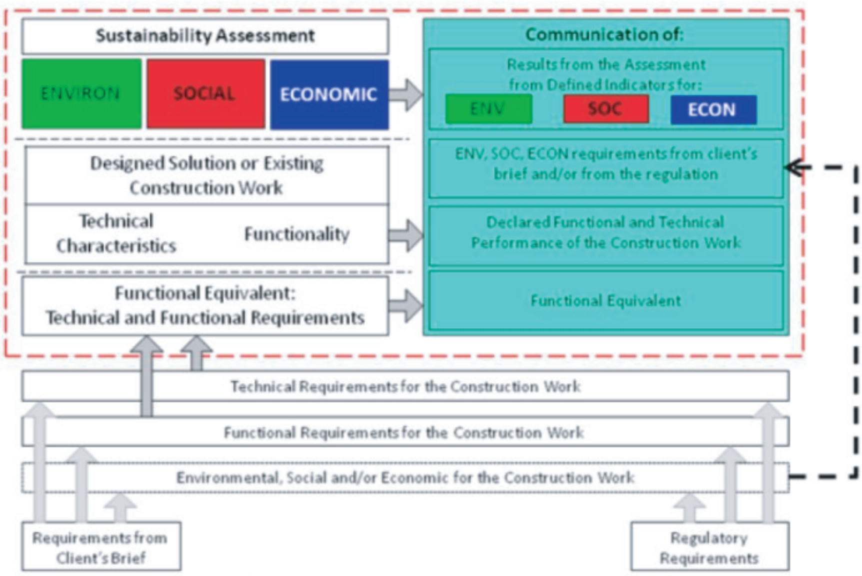

Figure 1. Concept of Sustainability Assessment of Civil Engineering Works (EN 15643-5)

- The SA should use a life cycle approach, therefore using Life Cycle Techniques to conduct the assessment.

- The SA should use quantifiable indicators measured without value judgements. The environmental, social and economic performance of the pavement and asphalt mixtures should be expressed in terms of quantifiable indicators. This requires the definition of indicators for the three pillars.

Tools, methodologies and techniques to perform Sustainability Assessment

Performance Assessment. This involves the assessment of the asset in relation to its intended function. Performance is most often addressed in relation to that of the current standard practice. For instance, if the current standard asphalt pavement surfacing lasts on average 15 years, the value of an alternative surfacing (e.g., open-graded friction course, stone matrix asphalt, or rubberized asphalt concrete) Is determined in relation to the current standard surface with a service life of 15 years. Performance may also be addressed in terms of specific physical attributes (e.g., pavement structural capacity, material attributes, and condition or distress measures) and the behaviour mechanisms that link these attributes to expected performance, such as longer service life, lower susceptibility to damages, lower rolling resistance or lower noise (Harvey et al. 2016).

Life Cycle Techniques. Life Cycle Techniques evaluate the impact of a product or system during its life cycle. A life cycle can begin with extracting raw materials from the ground and generating energy. Materials and energy are then part of the product's life cycle during manufacturing, transportation, use and eventual recycling, reuse, or disposal. Each part of the life cycle, (i.e., manufacturing, transportation, etc.) are referred to as life cycle stages. Using the life cycle approach means to recognize how choices influence what happens at each life cycle stage to allow balancing trade-offs and positively impact the economy, the environment, and society. Life cycle thinking means to consider the whole life cycle of a product while making a decision. Life Cycle Techniques are Life Cycle Cost Analysis (LCCA), Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA) and Life Cycle Sustainability Assessment (LCSA).ability Assessment (LCSA).

Sustainability Rating Systems. A sustainability rating system is essentially a list of practices or features that impact sustainability, coupled with a common unit of measurement (usually a point system) that quantifies the relative impacts. In this way, the diverse impacts of various practices and features (e.g., pollutant loading in storm water runoff, changes in pavement design life, tons of recycled materials used, energy consumed and saved, pedestrian accessibility, ecosystem connectivity, and even the value of art) can all be compared using a common unit (rating points). In its simplest form, a rating system may count the implementation of every best practice equally (e.g., all worth one point), in which case the rating system amounts to a tally of the number of best practices used. In more complex forms, rating systems weight best practices (usually in relation to their impact on a selected definition of sustainability or a selected set of priorities), which can assist in choosing the most impactful best practices to use given a limited scope or budget.

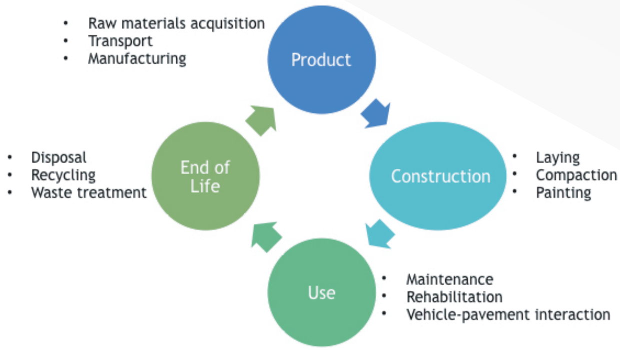

Figure 2. Example pavement structure life-cycle stages and activities associated

Levels of Sustainability Assessment

The SA can be performed at different levels, here some examples of use:

- **Product level.** SA can be used to report the sustainability performance of any material or technique and support their implementation, e.g. producing its Environmental Product Declaration.

- **Project level.** SA can be used to compare and select a pavement design alternative based on costs, environmental and social impacts, helping decision-making.

- **Network level.** SA can be used to prioritise network maintenance and preservation activities to minimise costs, environmental and social impacts.

Project Stages to perform Sustainability Assessment

The SA can be conducted at different stages in a pavement engineering project life, here some examples of use:

- **Planning**. SA can be used to be developed strategies to improve construction in terms of environmental, social or economic performance.

- Procurement. SA of some products, in particular innovative products, might be required during the procurement of a project to be provided as an evidence of their environmental, social or economic performance.

- Design. SA can be used to select a design alternative over other (i.e. decision-making) in terms of environmental, social or economic performance.

- Execution. SA can be performed during the execution of a pavement engineering project (i.e. construction and use) to evaluate the environmental, social or economic performance and evaluate whether impacts can be reduced.

- Closure. SA can be used at the end of a project to assess how it performed and what could have been better done to develop future strategies.

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LIFE CYCLE THINKING AND LIFE CYCLE TECHNIQUES

What is it Life Cycle Thinking?

EN 15643-5 introduces the concept of **Life Cycle Approach** to be used in the SA of civil engineering works. Life Cycle Approaches and Techniques are tools to apply (i.e. materialise) Life Cycle Thinking (LCT) **which "is about going beyond the traditional focus on production site and manufacturing processes to include environmental, social and economic impacts of a product over its entire life cycle** (Figure 1)" (Life Cycle Initiative). The main goals of LCT are to reduce a product's resource use and emissions to the environment as well as improve its socio-economic performance through its life cycle. This may facilitate links between the economic, social and environmental dimensions within an organization and through its entire value chain. A product life cycle can begin with the extraction of raw materials from natural resources in the ground and the energy generation. Materials and energy are then part of production, packaging, distribution, use, maintenance, and eventually recycling, reuse, recovery or final disposal. In each life cycle stage there is the potential to reduce resource consumption and improve the performance of products.

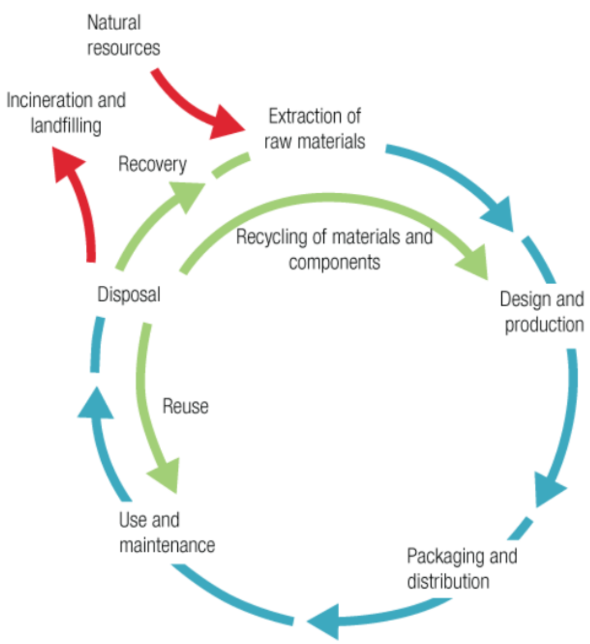

Figure 1. A typical product life cycle diagram (Life cycle initiative)

Life Cycle Thinking key steps

In every life cycle thinking process, there are three key steps:

- **Identifying the goal of the study.** The goal of the study will determine and guide the rest of the analysis (next two steps). Examples of goals are the comparison of the sustainability performance of several materials or the evaluation of scenarios for network-level decisions and strategies for preservation, maintenance and rehabilitation.
- **Defining the life cycle stages of the product or system being considered.** In pavement engineering, the products or systems to analyse can be asphalt mixtures, concrete, tack coats, pavement treatments, pavement structure, etc. Figure 2 shows an example of a pavement structure life cycle and activities associated to each stage. Depending on the goal of the study, the product or system and its life cycle stages to analyse will be different.
- **Conducting an analysis within the three pillars of sustainability using the appropriate techniques**. There are several methods of measurement that are used to quantify the three pillars of sustainability, known as Life Cycle Techniques, these include: Life Cycle Management (LCM), Life Cycle Costing (LCC), Life Cycle Assessment (LCA) and Social Life Cycle Assessment (S-LCA). Additional information about these techniques is provided in the next subsections.

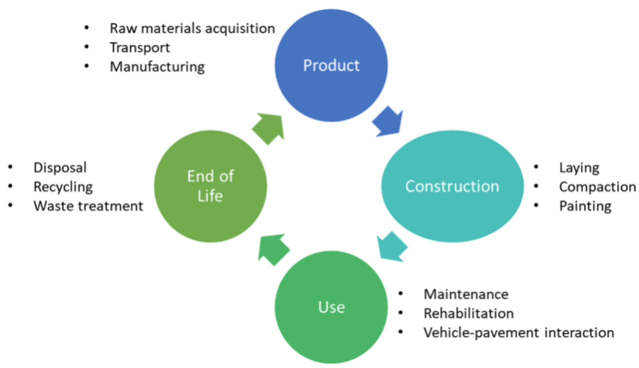

Figure 2. Example pavement structure life-cycle stages and activities associated

Benefits of Life Cycle Thinking and Approach

According to the Life Cycle Initiative, a life cycle approach **helps to make choices**. It implies that everyone in the whole chain of a product's life cycle has a responsibility and a role to play, considering all the relevant impacts on the economy, the environment and the society.

The impacts of all life cycle stages need to be considered comprehensively by all the stakeholders, when they make decisions on consumption and production patterns, policies and management strategies. A life cycle approach enables product designers, service providers, government agents and individuals **to make choices for the longer term and with consideration of the three pillars of sustainability**. It provides a **transparent methodology** that can be used to support the decision-making process for sustainability related issues at the product, project and network level (SPP Tech brief).

Life Cycle Thinking and Approach help to **identify the critical activities or points** in the whole life cycle of a product or system causing the highest environmental, social and economic impacts and therefore enable to develop strategies and policies for their mitigation and minimisation, involving the appropriate stakeholder to take actions towards Sustainable Development.

The **Sustainability Framework** in Figure 2 describes a scheme where sustainability is achieved through the use of life cycle approaches, programmes and activities, and is supported by relevant and reliable datasets, as well as an appropriate policy framework. Figure 2 highlights that the base to carry out any Sustainability Assessment is the availability of **data**.

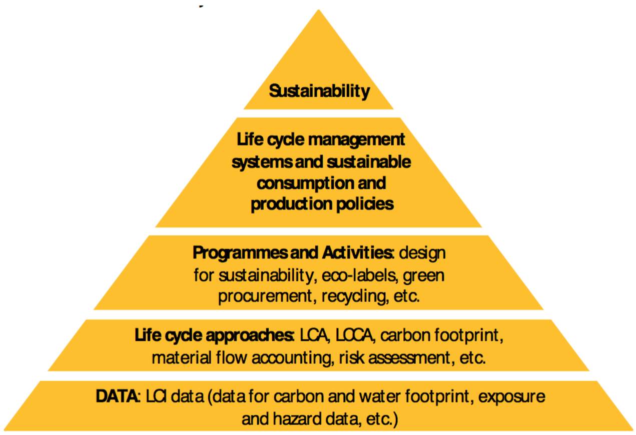

Figure 2. Sustainability Framework supported by Life Cycle Thinking and Approaches. Fava J. 2011. Adapted from Framework for Developing Greener Products, Iannuzzi Al. Greener Products: The Making and Marketing of Sustainable Brands. CRC Press. ch. 5, pp. 105-127

Life Cycle Costing (LCC) or Life Cycle Cost Analysis (LCCA)

Description

LCC or LCCA is a methodology for the systematic evaluation of the costs of an asset or its parts throughout its life cycle, while fulfilling the performance requirements and over a period of analysis (15686-5, 2017). This technique uses economic analysis to evaluate the total cost of an investment option in constant currency over the analysis period. It is therefore a measurement of the economic component of sustainability (Harvey et al. 2016). LCC will be further used to denominate this technique in this framework.

For pavements, LCC provides a way of measuring the economic consequences of changes in design, materials, construction techniques, maintenance schemes, and end-of-life treatments over a defined analysis period.

Methodology

LCC methodology has five steps:

1. Establish LCC Framework. Select analysis period for the LCC. Determine how inflation will be addressed and establish discount rate to be used. Establish economic analysis indicators to be used for presenting results (e.g. net present value (NPV), equivalent uniform annual costs (EUAC)).

2. Establish Design Alternatives. Identify a range of possible design alternatives. Consider a minimum of two options that offer the same level of performance for a selected analysis period.

3. Determine Activity Timing. Define the schedule of initial and future activities (e.g. construction, maintenance, end of life) and their performance period for each selected pavement design or treatment alternative.

4. Estimate Costs. Estimate agency and user costs associated with the activities of each pavement design or treatment alternative being investigated over the selected analysis period.

5. Compute Life Cycle Costs. Calculate the total life-cycle cost agency and user cost for each alternative considered. All cost are converted to present currency (e.g. Euros, Sterling Pounds) using an established engineering economics technique known as "discounting" to account for the time value of money. Next, all the initial and future costs are summed to provide a NPV for the entire analysis period. If different analysis periods are used, the costs may be expressed in terms of a EUAC.

Inputs and data needed

Analysis period
Alternatives to be considered
Timing, performance and cost of each activity to be performed during the analysis period for each alternative
Discount rate
Current and projected traffic volumes
If user costs are to be considered:
o Construction work zone inputs (such as number of work zone lanes, work zone duration, etc.)
o User cost inputs (value of time categories of vehicles using the pavement)

Output

LCC provides one indicator for the decision-making process. Agency costs and user costs can be included and may be expressed in terms of net present value (NPV) or equivalent uniform annual costs (EUAC).

Typical applications in pavement engineering

- Determine the pavement type or treatment strategy that results in the lowest overall life-cycle cost at the required level of performance
- Demonstrate the benefits of various maintenance strategies or construction processes on the users (e.g. vehicle operating cost, user delay costs, etc.)
- Estimate the initial costs and support future agency budget decisions for designing, constructing and maintaining a pavement at a specific performance level over a defined analysis period

Examples of practice within NRAs

- Trafikverket (Swedish Transport Administration) uses LCC at the core of their planning, procurement and design for any type of project. They have also used Green Procurement for years, providing discounts in the tender when a reduction in CO2 is given.
- The California Department of Transportation has developed a detailed LCC procedure manual and requires LCC to be performed on all project that include a pavement cost component (with some exceptions such as preservation projects).

NRAs resources needed to perform LCC

- Internal staff or hired experts in LCC
- Calculations can be performed using pencil and paper, calculator or simple spreadsheet-based tools
- Some NRAs have developed their own customised LCC policy and software tools

Available Information

- ISO 15686-5:2017 Building and constructed assets – Service life planning – Part 5: Life Cycle Costing (15686-5, 2017)
- EN 15643-4 Assessment of Buildings Part 4: Framework for the assessment of economic performance (EN 15643-4, 2012)
- Federal Highways Administration's LCC Primer (U.S. Department of Transportation, 2002)

Tools

- Real Cost LCCA (US, CA) - a tool to perform LCCA for pavement selection in accordance with FHWA best practice methods.
- SMART SPP - innovation through sustainable procurement" - Has been developed to help performing (LCC) and assessing emissions (CO2, CO2eq, NOx, SO2, NMHC and PM) of different products, work and services to assist in procurement decision-making.

Life Cycle Assessment (LCA)

Description

LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14040, 2006). LCA provides a comprehensive approach to evaluating the total environmental burden of a product or process by examining all of the inputs and outputs over the life cycle, from raw material production to end of life. This systematic approach identifies where the most relevant impacts occur and where the most significant improvements can be made while identifying potential trade-offs.

The processes and rules for conducting an LCA are generally defined by the International Organization for Standardization (ISO) in its 14040 family of standards (ISO 2006). These standards are quite broad; thus, more precise guidance is needed for their application to a specific material or process. Such guidance is usually developed by the relevant industries and other stakeholders. It is therefore a measurement of the environmental component of sustainability (Harvey et al. 2016).

Methodology

LCA methodology has four phases:

1. Goal and Scope definition. Goals for an LCA must first be set by the organization performing the LCA in order to determine the type of study, the scope and the approach for assessing impacts and making decisions. The scope of an LCA defines the system boundary (i.e., what is and is not to be included in the LCA). The scope should address the life cycle stages and processes to be included, identify the system boundaries of the analysis, define the functional unit of analysis, and define the required data quality, cut off rules and allocation procedures. These last elements are defined as:

a. System boundaries: set of criteria specifying which unit processes are part of a product system

b. Functional unit: quantified performance of a product system for use as a reference unit. When the LCA only includes the product stage as life cycle stage, the term used in declared unit

c. Data quality: characteristics of data that relate to their ability to satisfy stated requirements

d. Cut off rule: specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study

e. Allocation: 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

2. Life Cycle Inventory. The environmental flows (inputs of materials and energy, and outputs of waste, emissions and co-products) are estimated and quantified for each activity in the system being studied to produce the life cycle inventory (LCI).

3. Life Cycle Impact Assessment. The inputs and outputs flows from LCI are translated into selected impact category indicators, which varies depending on the Life Cycle Impact assessment methodology used. The most common impact category indicator in Global Warming Potential (GWP), and the most commonly used methodology in Europe is CML (Centre for Environmental Studies at the University of Leiden, the Netherlands).

4. Interpretation of Results. The overall results are summarised and discussed as a basis for conclusions, recommendations and decision-making in accordance to the defined goal and scope. Proper LCA practice, as defined by ISO 14044, includes an interpretation phase where the results are presented for the functional unit, the major environmental contributions are identified and explained in terms of where the environmental impacts are most pronounced (hotspots), the data uncertainty and variance are noted, and sensitivity analyses are conducted for the most important methodological assumptions.

Inputs and data needed

- Analysis period
- Timing, performance and material quantities for each activity to be performed during the analysis period
- Datasets for all materials used (LCI of aggregates, bitumen, reclaimed asphalt, cement, etc.) or Environmental Product Declarations (EPDs)
- Transportation modes and distances involved in all processes
- Plants operation data (energy consumption)
- Construction work zone inputs
- Construction site equipment (energy use, use duration, emissions)

Output

- A full-LCA generates a range of environmental indicators, such as global warming potential, ozone depletion, particulate formation, acidification and eutrophication. The importance of each indicator for decision-making depends on each case study

Product Category Rules (PCRs), LCA and Environmental Product Declarations (EPDs)

One of the purposes of performing the LCA of a product might be to develop and **Environmental Product Declaration** (EPD). An EPD is a transparent, verified report used to communicate the environmental impacts of a specific product, providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information (ISO 14025, 2010).

EPDs express the results of an LCA of a product performed according to the Product Category Rules (PCRs). EPDs are developed with industry stakeholders and LCA experts and subjected to a critical review process following the industry standards described in the PCR document. Figure 3 shows the connection between PCRs, LCA and EPDs.

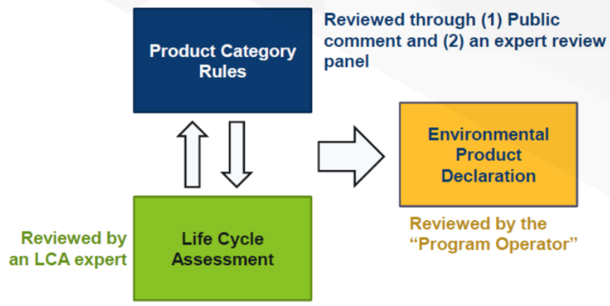

Figure 3. Relationship between PCRs, LCA and EPDs (Santero, 2014)

EPDs can then be used by industry for green procurement, communication and environmental performance progress evaluation.

Typical applications in pavement engineering

- Determine the pavement type or treatment strategy that results in the lowest overall life-cycle cost at the required level of performance
- Demonstrate the benefits of various maintenance strategies or construction processes on the users (e.g. vehicle operating cost, user delay costs, etc.)
- Estimate the initial costs and support future agency budget decisions for designing, constructing and maintaining a pavement at a specific performance level over a defined analysis period

Examples of practice within NRAs

- Rijkswaterstaat (Netherlands' Road Authority) uses LCCA and LCA for decision-making, performance measurement and green procurement as a requirement from the government. They applied these techniques at project level during the planning and realisation of projects. They have developed their own tool for LCA, Dubocalc.

- The California Department of Transportation and the Oregon Department of Environmental Quality are taking steps toward requiring Environmental Product Declarations (EPDs) for pavement and other transportation infrastructure materials for use in reporting, benchmarking, and LCA for design and asset management. California requires that EPDs for steel used by state agencies to be considered in procurement.

NRAs resources needed to perform LCA

- Dedicated internal staff or hired experts in LCA
- There are numerous LCA software tools that already include databases (LCIs) which can be used to develop LCA models
- Some NRAs have developed their own customised LCA policy and software tools, such as the Netherlands and Dubocalcassumptions.

Available Information

- ISO 14044:2006+A1:2018 Environmental management. Life cycle assessment. Requirements and guidelines ◊ ISO 14040:2006 Environmental management. Life cycle assessment. Principles and framework (ISO 14040, 2006)
- EN 15804 Environmental Product Declarations – Core rules for product category of construction products (EN 15804, 2012)
- EN 15643-2 Assessment of Buildings Part 2: Framework for the assessment of environmental performance (EN 15643-2, 2011)
- Federal Highways Administration Pavement LCA Framework (Harvey et al. 2016)

Tools

Common sustainability assessment tools:

- Simapro, GaBi and openLCA: generic LCA tools which are very flexible for modelling but not user friendly. The users usually have to be LCA experts to be able to handle them.

Common tools used by NRAs to compare products and verify sustainability claims in tendering processes are the following:

- asPECT (UK) - estimates CO2e emissions from asphalt paving processes in a cradle to gate scenario, meeting the specifications of the UK standard PAS 2050
- DuboCalc (NL) - calculates the environmental impacts over the entire life cycle. The environmental effects are converted into a single number via the "shadow price method".
- Ecorce M and SEVE (FR) - evaluate potential impacts on the environment in terms of several indicators using own database
- Klimatkalkyl (SE) - Calculates energy use and greenhouse gas emissions of transport infrastructure
- GreenDOT (USA) - Greenhouse Gas Calculator for State Departments of Transportation (GreenDOT), estimates CO2 emissions from construction, maintenance, and operations activities.
- EFFEKT (NO)

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WHAT ARE MORE SUSTAINABLE ASPHALT MIXTURES AND PAVEMENTS?

Considerations

Environmental concerns in pavement engineering are increasing and **NRA**s and all stakeholders are willing to reduce the environmental impact of this industry. **"Green" asphalt mixtures and pavements is the general term used for all types of asphalt mixtures and pavements in which specific materials or technologies are used with the aim of reducing the environmental impact**. However, when using the term "green" asphalt mixtures, two facts should be considered:

- There is not an absolute definition for "green", since any product, system, material or technology is considered to be beneficial for the environment in comparison to a reference product, system, material or technology. Therefore, the correct way to use the term "green" should have a comparative component, as "greenER" asphalt mixtures and pavements.
- In order to make decisions, NRAs have to balance environmental considerations against social and economic aspects, since roads should always correctly provide their function to society (safety and comfort) and financial resources are restricted. Therefore, not only the reduction of environmental impacts should be targeted, but also economic and social aspects.

Definition

Given these facts, **PavementLCM** suggests moving from the use of the term *"green"* to *"more sustainable"* asphalt mixtures and pavements, including in this way the comparative fact and the three dimensions of sustainability. The definition of "more sustainable" asphalt mixture and pavement is then:

"Asphalt mixture or pavement which provides a reduced impact on the environment, economy and society compared to a [reference asphalt mixture or pavement specified]"

The reference asphalt mixture and pavement must always be specified and should have the same functionality than the claimed more sustainable asphalt mixture or pavement.

Measurement

The reduced impact on the environment, economy and society should be documented and measured. In this regard, the sustainability performance of asphalt mixtures and pavements have to be assessed under the framework of **EN 15643-5** and therefore it must follow the principles of using a life cycle approach and be measured through indicators. The following requirements are further specified in EN15643-5 for the use of indicators:

- They should be quantitative or if not quantitative, shall be quantifiable
  - The indicators used at the product level also shall be applicable for the civil engineering works level assessment
- It shall be possible to aggregate the results of individual indicators from the product level to the civil engineering works level (while still keeping the modularity principle). It should be noted that aggregation is only possible for modules identified within the "product system"
- They shall avoid double counting

There have been several research and standardisation efforts aiming at defining indicators for the sustainability assessment of asphalt mixtures and pavements, identified as:

- **EN 15804 Sustainability of construction works** - Environmental product declarations - Core rules for the product category of construction products
- **CEN Workshop Agreement (CWA) 17089** - Indicators for the Sustainability Assessment of Roads 2016 (results of Life Cycle Engineering for Roads LCE4ROADS Project)
- **Evaluation and Decision Process for Greener Asphalt Roads** - EDGAR CEDR Project
- **Sustainable Pavement and Railways** - SUP&R ITN FP7 MSCA Actions Project

Considering these important research efforts and the recent requirements stablished by EN 15643-5, Table X presents the current available indicators that can be used to measure the sustainability performance of asphalt mixtures and pavements. Most of these indicators are obtained using life cycle techniques.

Figure 2. Example pavement structure life-cycle stages and activities associated

	Asphalt mixtures		Pavements	
	EN 15804 (Product Stage)	**EDGAR**	**CWA 17089**	**SUP&R ITN**
Environ mental impact	Global Warming Potential (GWP)	Global warming potential (GWP)	Global warming potential (GWP)	Global warming potential (GWP)
	Formation potential of tropospheric ozone (POCP)		Formation potential of tropospheric ozone (POCP)	
	Depletion Potential of the stratospheric ozone layer (ODP)		Depletion potential of the stratospheric ozone layer (ODP)	Depletion potential of the stratospheric ozone layer (ODP)
	Acidification Potential of soil and water (AP)	Leaching potential	Acidification potential of soil and water (AP)	Acidification potential of soil and water (AP)
	Eutrophication potential (EP)		Eutrophication potential (EP)	Eutrophication potential (EP)
	Abiotic depletion potential for non-fossil resources (ADP-elements)		Abiotic depletion potential for non-fossil resources (ADP-elements)	
	Abiotic depletion potential for fossil resources (ADP-fossil fuels)		Abiotic depletion potential for fossil resources (ADP-fossil fuels)	
		Air pollution	Human toxicity potential (HTP)	Particulate matter
			Ecotoxicity potential (ETP)	
Resource use	Use of renewable primary energy excluding renewable primary energy resources used as raw materials		Use of renewable primary energy excluding renewable primary energy resources used as raw materials	Energy demand
	Use of renewable primary energy resources used as raw materials		Use of renewable primary energy resources used as raw materials	
	Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)		Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	
	Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials		Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials	

Resource use	Use of non-renewable primary energy resources used as raw materials		Use of non-renewable primary energy resources used as raw materials	
	Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)		Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	
	Use of secondary material		Use of secondary material	Secondary materials used
	Use of renewable secondary fuels		Use of renewable secondary fuels	
	Use of non-renewable secondary fuels		Use of non-renewable secondary fuels	
	Net use of fresh water			Water consumption
		Depletion of resources & waste management	Primary materials consumption	
Waste	Hazardous waste disposed		Hazardous waste disposed	
	Non-hazardous waste disposed		Non-hazardous waste disposed	
	Radioactive waste disposed		Radioactive waste disposed	
Output flows	Components for re-use	Recyclability	Components for re-use	Materials or components to be reused or recycled
	Materials for recycling		Materials for recycling	
	Materials for energy recovery		Materials for energy recovery	
	Exported energy		Exported energy	
Economic impact		Financial cost	Whole life cost	Life cycle Agency Cost
				Life cycle User Cost
Social impact		Skid resistance	Comfort index	User comfort
			Safety audits and safety inspections	Safety audits and safety inspections
			Adaptation to climate change	
		Noise	Tyre-pavement noise	Noise reduction
		Responsible sourcing	Responsible sourcing	
		Traffic congestion	Traffic congestion due to maintenance activities	Traffic congestion
Performance		Performance related properties		

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PAVEMENTLCM SA FRAMEWORK

in a nutshell

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 strengthening 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 towards continuous improvement along the product life cycle (Remmen & Jensen, 2007).
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 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.

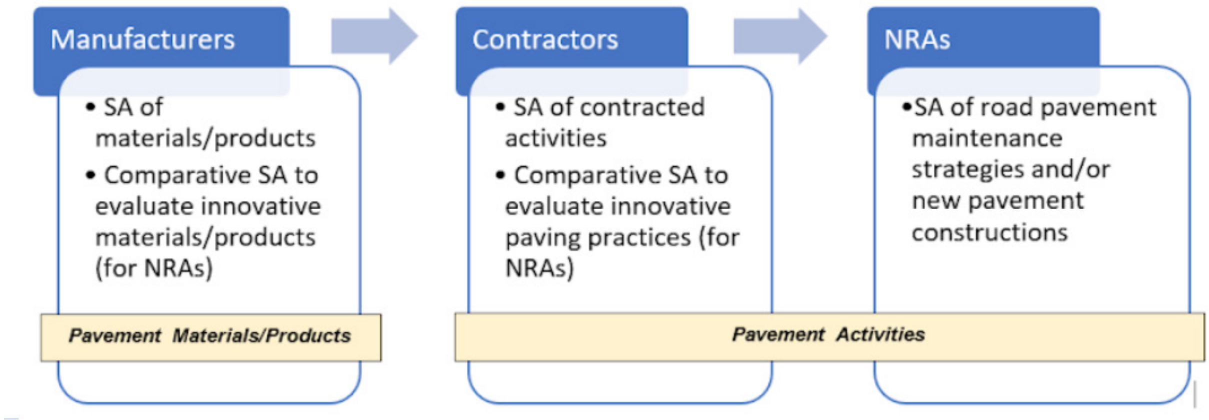


Figure SEQ Figure / ARABIC 1 - SA exercises proposed by the Pavement LCM Framework*

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

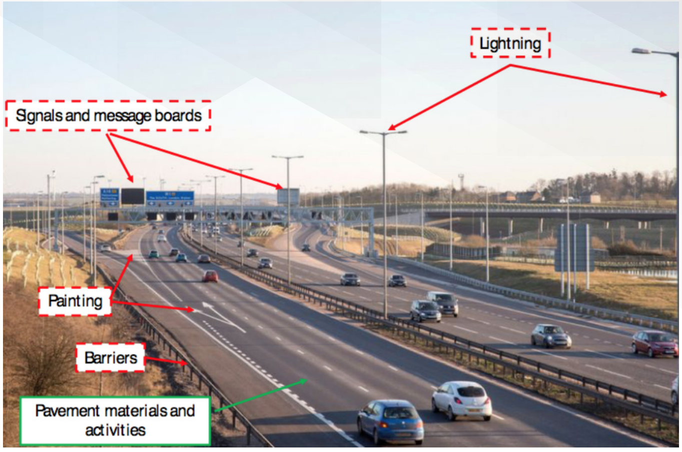
- Road owners (i.e., NRAs): must support their decision-making process by performing the SA of selected maintenance strategies and/or projects to be procured or awarded.

Scope of the framework

By definition, a pavement system is considered as the structure constructed (for motorized and non-motorized transport) above the native undisturbed subgrade soil, typically constructed in distinct layers and including compacted or stabi lized subgrade, bound or unbound subbase(s)/base(s), and the wearing surface. Broadly, this encompasses pavement structures in a number of different facility types, such as highways, streets, roads, shoulders and parking areas (Harvey et al., 2016). PavementLCM framework for Sustain- ability Assessment is focused on pavements for highways which are typically managed by National Road Authorities (NRAs) in Europe.

Furthermore, only those aspects strictly related to pavement materials and activities are included so a number of items of a pavement are not taken into account (Figure 1), such as:

- Unbound subbase or base layers
- Painting
- Signals and message boards
- Lightning
- Barriers
- Drainage structures



Objects of assessment: Pavement materials vs. pavement activities

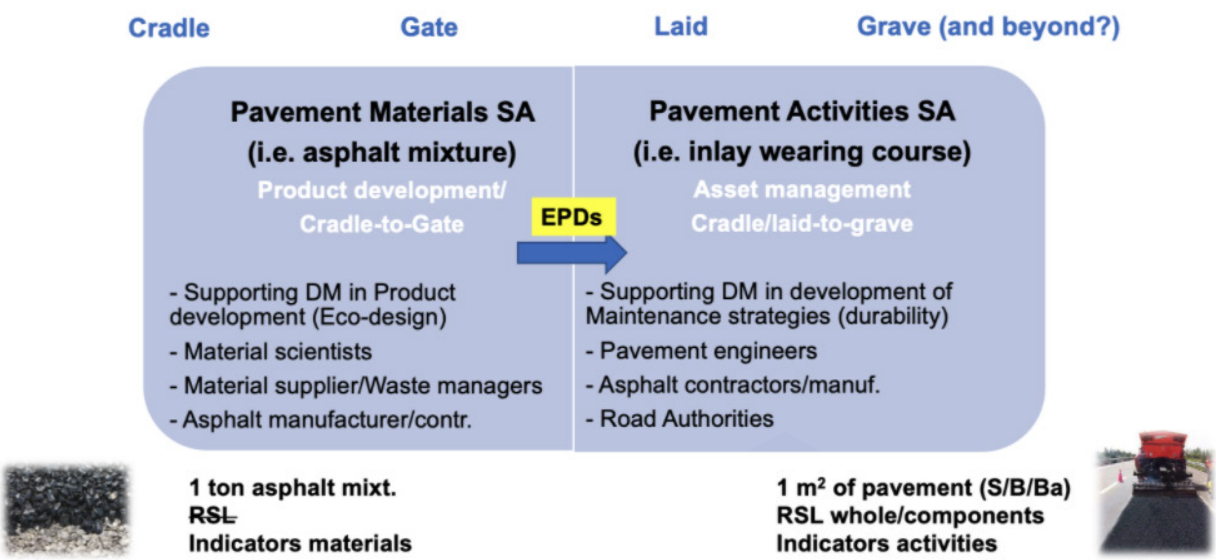
One of the main steps to perform a SA is to define the object of assessment. PavementLCM SA Frame- work includes two different systems which are considered crucial for NRAs: pavement materials and pavement activities.

It is important to highlight the importance of this differentiation since (Figure 2):

(1) The stakeholders involved in the SA of pavement materials and activities are different. While manufacturers and material designers are interested in the SA of materials to declare the sustainability performance of their products, the SA of activities is interesting for NRAs and contractors to help their decision-making process.

(2)The life cycle of each system is different.

(3) Different indicators are needed to perform the SA of each system.



Considering these two systems, the object of assessment in a SA using a life cycle approach (EN 15643-5) is defined by:

(a) A description of the object.
(b) System boundaries.
(c) Analysis period (if applicable).
(d) 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.
(e) 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.

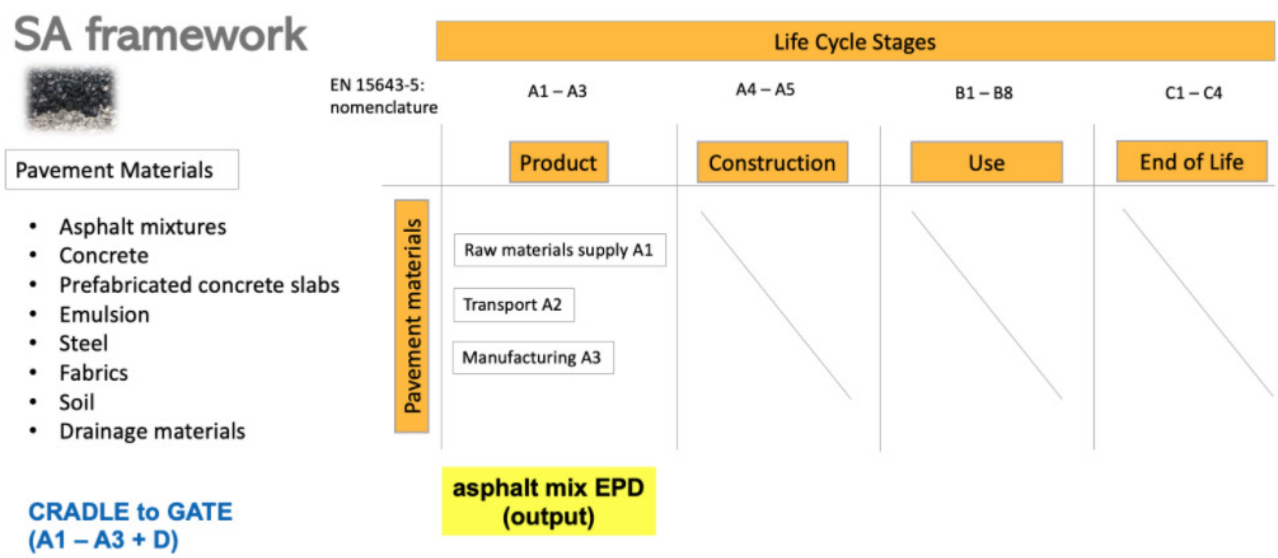
On this regard, in PavementLCM SA framework, the object of assessment for each of the two systems considered are defined as:

1) Pavement Materials

The following objects of assessment are included in this system:

- Asphalt mixtures Concrete
- Prefabricated concrete slabs Emulsion
- Steel Fabrics

(a) The description of the material under evaluation should be included in the definition of the object of assessment
(b) The system boundaries are as shown in Figure 3. These materials do not have a functionality assigned, and therefore their life cycle includes only the product stage, or in other words "cradle-to-gate" analysis. The system boundaries are as shown in Figure 3. These materials do not have a functionality assigned, and therefore their life cycle includes only the product stage, or in other words "cradle-to-gate" analysis.



(c) Analysis period: Not applicable (since only the product stage is included)
(d) Declared unit: 1 metric ton (tonne) of manufactured material (according to NAPA 2017, EATA 2017, The International EPD System 2017 The Norwegian EPD Foundation 2017)

2) Pavement Activities

This system includes all the activities linked to building, repairing, replacing and maintaining the functional and technical requirements of road pavement and its components and that's why it is referred to the responsibility of contractors and road owners.

Concerning the Contractors, the object of assessment can be:

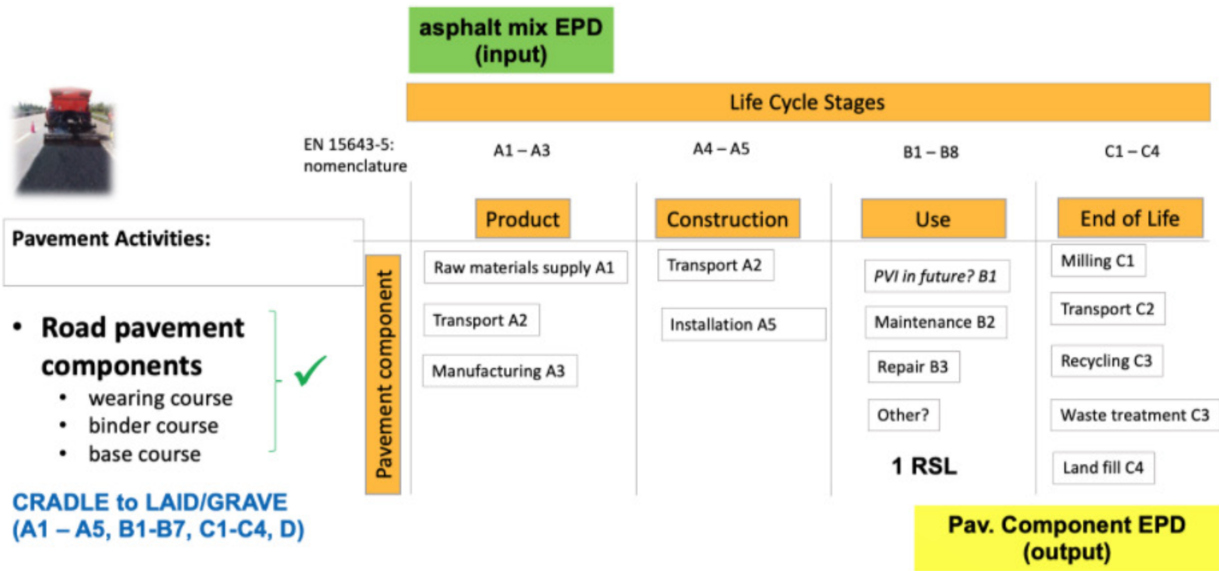
- Wearing course
- Binder course
- Base course

And the following elements should be provided:

(a) The description of the contracted activity under evaluation should be included in the definition of the object of assessment
(b) Estimated/Reference Service Life: durability of each road pavement component and/or contracted activities
(c) Analysis period: equal to the Reference Service Life of the object of the assessment (contracted activities/road pavement components)
(d) Functional Equivalent/ Functional unit: 1 m2 of surfaced pavement, as recommended by PCRs, together with a clear description of the physical boundaries in order to account for the exact volume (or weight) of the road pavement to be contracted and/or built as required at project-level. Furthermore, the functional equivalent should specify the Estimated Service Life of the component, specifying capacity (e.g. number of vehicles per hour [veic/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)
(e) Inputs: The asphalt contractor should receive information from material manufacturer (i.e. materials EPDs)
(f) Output: the SA exercise should be carried out to provide NRAs with vital information (i.e. EPDs for the contracted activitiy) to allow them to implement life cycle management practices
(g) The system boundaries are as shown below. This is a cradle-to-grave assessment that includes a use phase limited to a period equal to the estimated/reference service life of the road component(s) included in the contracted activities, as well as suggested end-of-life strategies.

The following lifecycle stages should be in the system:

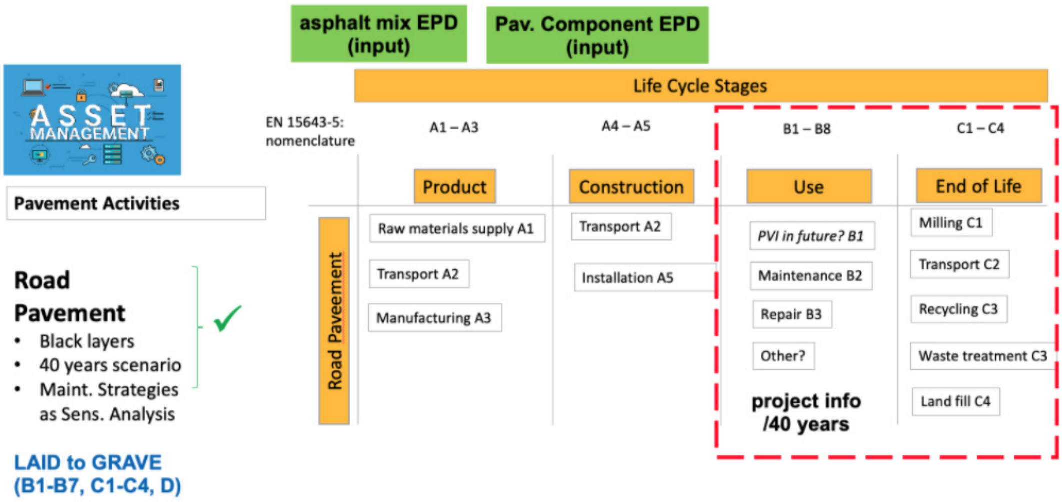
- Product (A1 – A3), derived from material manufactures' EPDs
- Transport to site (A4)
- Installation of pavement components (A5)
- Recycling strategies (D) for pavement components to be included.



Concerning the NRAs, the system can include:

- Project-level “New construction“
- Project-level “Asset Management“ divided in:

(a) Regular operations (also periodic or routine maintenance): involves all activities that are of a repetitive nature and are executed in short-term intervals (< 1 year). The activities are often small in terms of resource demand and aim at retaining the condition of road assets rather than bringing them to an increased performance level. Typical regular maintenance activities include cutting grass, cleaning drainages, and small pavement repairs. Winter maintenance and emergency repairs will be also classified as regular maintenance. Winter maintenance involves activities like snow ploughing and road salting and can form a larger part of a NRAs maintenance tasks depending on the climatological region. Emergency repairs can include pothole patching, lighting repair or flushing of blocked drainage systems (Hartmann, Aijo, & Roehrich, 2015). According to EN phases is the B2R Maintenance and B3R Repair.
(b) Rehabilitation operations (also variable maintenance): is carried out in longer, nonrepetitive intervals (>1year), involves a larger amount of work, and aims at enhancing the service life of a road asset or improving its performance. It is often based on a long-term planning taking the deterioration behavior of the assets into account. Typical rehabilitation activities include pavement resurfacing and bridge joint replacing (Hartmann et al., 2015), in other words the substitution of pavement components at the end of their service life. According to EN phases this is the B4R Replacement, however in the PavementLCM Framework for pavement component this represents the C1 – C4 phases for each pavement component.



The following objects of the assessment are included in this system and are valid for both new construction and/or repair, mainteinance and replacement:

(a) The description of the activity under evaluation should be included in the definition of the object of assessment
(b) Analysis period: the timeframe necessary for the specific project to include at least one major rehabilitation activity/replacement of the road surface (according to the model). This is usually 40 years
(c) Functional equivalent/ Functional unit: 1 m2 of surfaced pavement, as recommended by PCRs, together with a clear description of the physical boundaries in order to account for the exact volume (or weight) of the road pavement to be contracted and/or built as required at project-level. Furthermore, the functional equivalent should specify the Estimated Service Life of the component, specifying capacity (e.g. number of vehicles per hour [veic/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)
(d) Inputs: Together with primary data, road owners should request EPDs, with also information about economic, social, technical and functional indicators, to both materials manufacturer and contractors
(e) Outputs: Comparative analysis of project solutions to assess which is the most sustainable option
(f) The system boundaries are as shown in Figure 5. The life cycle includes product, construction, use and end of life stages + benefits and load beyond the system boundary. If all the stages are considered, the analysis is “cradle-to-grave + D”.
(g) Physical boundaries: It is recommended to perform the analysis by considering the road pavement as the surface layer: wearing course, the binder course and the base course

The following lifecycle stages should be in the system:

Product (A1 – A3), derived from material manufactures'EPDs + data on economic and social indicators

Construction (A4-A5):

- Transport to site (A4), derived from contractors'EPDs + data on economic, social and technical and functional indicators
- Installation of pavement components (A5) derived from contractors'EPDs + data on economic, social and technical and functional indicators

Use (B1-B7):

- Use of the installed pavement components over the analysis period (B1)
- Maintenance, Repair and Replacement (B2, B3, B4) of the road pavement components
- Refurbishment, Operational Energy Use and Operational Water use, (B5, B6, B7) of the road pavement components, might be considered for special pavement able to harvest energy and/or use operational water to guarantee a certain functional requirement

End-of-life (C1 – C4) activities:

- if road pavement physical boundaries are limited to surface, then the activities linked to the replacement of whole road pavement surface represents the end-of-life
- if physical boundaries are extended to subgrade end-of-life might not exist or it can be considered only if the pavement changes functionality (C1 – C4)

Benefits and Loads beyond the System Boundaries (D): Recycling strategies (D) for road pavement to be included. (see section 7.2 for advices on module D)

Indicators in PavementLCM SA framework

As a requirement in 15643-5, the sustainability of civil engineering works have to be measured through quantifiable indicators, taken from Standards and reports.

In PavementLCM SA Framework, the sets of indicators in those efforts were used as a basis for screen ing to reduce the number of indicators by recognizing which are the priorities of NRAs. This process was carried out by conducting interviews with NRAs and finalised in the 1st CEDR PavementLCM work- shop for Sustainability Assessment, where the set of indicators was approved. The philosophy behind the selection of indicators was as following:

- To reduce the number of indicators to help introducing SA in NRAs, based on the initial sets of indicators defined in EN15804 (only environmental), EDGAR, CWA17089 and SUP&R ITN which considered the most critical sustainability issues concerning pavement materials and activities.
- To use the most relevant indicators for NRAs to be able to assess their priorities for more sustainable pavement materials and activities.
- To consider indicators for the three pillars of sustainability and technical and functional requirements, as required in EN15643-5.
- To select indicators that can be calculated using available tools.

Furthermore, according to EN 15804:2012+A2:2019 and JRC Technical Report published in 2018, there some core environmental indicators which have a main role in environmental assessment due to their potential burdens.

In this regard, the indicators selected are shown in Table 1 including the object of assessment for which they can be calculated and their description. In total fourteen indicators are proposed for pavement materials, and seventeen are proposed for pavement activities.

The methodology proposed for the calculation of environmental indicators is EF Life Cycle Impact Assessment method, suggested by the ILCD-JRC., except for Energy Use and Secondary Materials Consumption, which do not need a specific LCA methodology.

Related to	Indicator	Object of assessment	Description
Environment	**Global Warming Potential**	Pavement materials and activities	Generally accepted equivalent of greenhouse gas (GHG) accumulation. It shall be expressed in kg CO2 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 is the sum 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 NH3, NO2 and SOX. 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)

Related to	Indicator	Object of assessment	Description
Environment	**Air pollution**	Pavement materials and activities	Assessing pollution potential on the basis of air pollution (non-CO2 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 is the sum 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** Net Present Value/ Whole life cycle cost	Pavement materials and activities	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, 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

Related to	Indicator	Object of assessment	Description
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..)

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PAVEMENTLCM GUIDELINES

in a nutshell

PavementLCM project proposes to introduce the Life Cycle Management (LCM) practices for NRAs by a systematic use of Sustainability Assessment (SA). LCM is a business management approach that can be used to target, organize, analyze and manage product-related information and activities in a sustainable way.

In order to facilitate the performance of a Sustainability Assessment for pavement materials/products and activities, a specific step-by-step procedure is provided, on the adaptation of standards available on Buildings (EN 15978:2011, EN 16627:2015, etc)

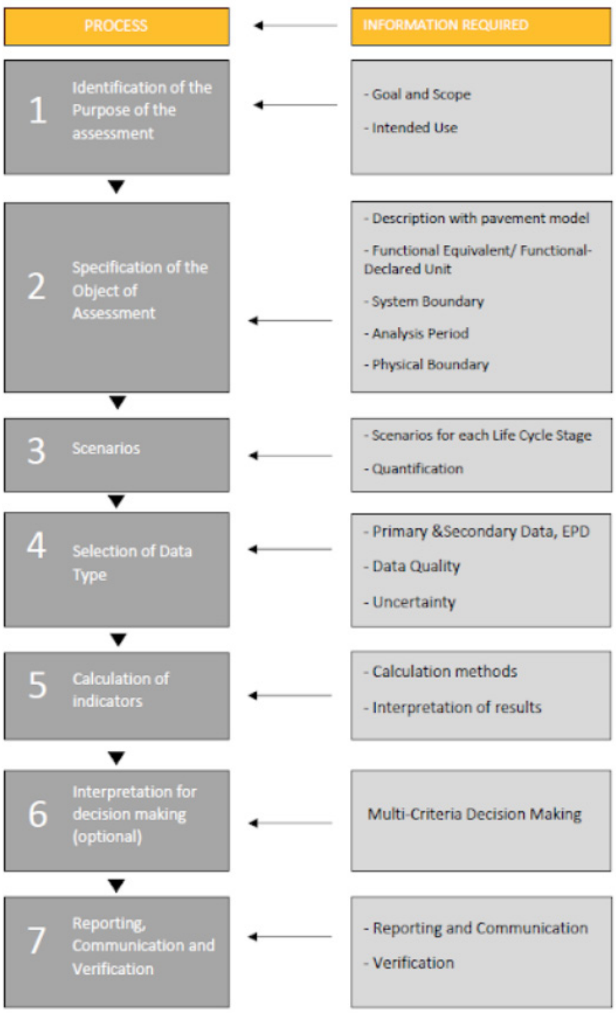

Figure 1 - Pavement LCM Guidelines to setup SA exercises

Each one of these steps is described and detailed below:

(1) Identify the purpose of the Sustainability Assessment

(1) Two elements must be defined in this phase: Goal and Scope, so the quantification of the environmental performance of the object of the assessment and the definition of what is included in the SA.
(2) Defining the Intended application of the study inside three different group: product improvement, product comparison and communication.

(2) Specification of the object of assessment

The object of the assessment should include:
(a) A description of the object, with the pavement model. (i.e. Pavement activity)
(b) System boundaries (usually A1-A3 for Pavement Products, A4-A5 + B1-B4 + C1-C4 + D for asset management, considered the Product EPD provided by producers.)
(c) Analysis period (if applicable) (usually between 40 and 50 years)
(d) Functional equivalent or Functional/declared unit. (1 ton of asphalt mixture for materials or the exact volume (or weight) of the road pavement to be contracted and/or built as required at project-level or 1 m2 of surfaced pavement together with a clear description of the physical boundaries for pavement activities)
(e) Physical boundary (such as surface, subgrade, etc)

(3) Scenarios

Scenarios, which 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.
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 have to be developed about how the pavement will be constructed, used, maintained, replaced, dismantled and reused during the specific analysis period.
This step includes the quantification of all materials and products needed.

Figure 2 - Pavement LCM road pavement SA model

(4) Selection of data type

Data is the core of any SA. The choice of data type and data forms can be different according to the scope of the assessment, the availability of information, the importance of the data in relation to the overall importance of the study.

The options of data collection are:
(1) Primary data, directly measured from source. They are usual the most expensive and reliable.
(2) Process activity data (primary or secondary), such as energy consumed, hours of operation, productivity, etc.
Secondary data, from literature and databases. It's
(3) important to check their representativeness and transparency.
(4) Use of EPD, provided by contractors.

According to ISO14044, data must satisfy some requirements and their quality have to be assessed through scoring criteria. The methodology proposed for Data Quality is that one developed by JRC in 2016: five quality indicators were chosen to which a score (1-5) must be attributed.

Data collection is always linked with uncertainty, so the spread of an observation and its distribution. This is due to several causes and factors, such as deficiencies in production or accuracy of equipment used.

The total uncertainty is the result of the combination of basic and additional uncertainty.

The basic uncertainty is used to describe the uncertainty due to for measurement inaccuracy and it can be defined through a Monte Carlo Simulation (MCS).

The additional uncertainty is linked to the quality of data and of sources and it's assessed thanks to scores attributed to data according to some parameters.

(5) Calculation of indicators

Within PavementLCM Framework, the Sustainability Performance Indicators (SPIs) proposed for pavement materials and pavement activities are referred the three pillar of sustainability (environment, economy and society) and to technical and functional requirements. According to questionnaires proposed to NRAs and to reports and Ens, 12 indicators have been selected plus some optional ones can be measured according to each NRAs priority.

(5.1) Environmental Indicators -> Life Cycle Assessment (LCA)

It's useful to calculate the potential environmental impacts related to the object of the assessment. The steps, also specified in, are:

(1) Goal & Scope Definition
(2) Life Cycle Inventory (LCI) analysis
(3) Life Cycle Impact Assessment
(4) Interpretation of results

Details on LCA are provided another Tech Brief.

(5.2) Economic Indicators – Life Cycle Costing

Materials/Product: Cost

These 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) are 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.

Pavement activities: Whole Life Cost

LCC methodology has five steps:

(1) Establish LCC Framework. (Analysis period for the LCC, inflation, discount rate, indicators (e.g. net present value (NPV), equivalent uniform annual costs (EUAC)).
(2) Establish Design Alternatives. -> already defined in previous steps
(3) Determine Activity Timing. Define the schedule of initial and future activities (e.g. construction, maintenance, end of life and their performance period) -> scenarios already defined above.
(4) Estimate Costs
(5) Compute Life Cycle Costs. Calculate the total life-cycle cost agency and user cost.

Details on LCC are provided another Tech Brief

(5.3) Social 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 of the S-LCA indicators and wait for the development of the method.

The only selected indicator with a "social" impact is the tyre/pavement noise, and its calculation is only applicable in the case of pavement activities and defined within technical and functional requirements.

(5.4) Technical and Functional Requirements

Two indicators were chosen to assess technical and functional requirements:

- Durability
- Tyre-pavement noise
- NRAs-specific indicators

Durability refers to a property of the pavement, 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."

Details for the determination of Durability performances (resistance to rutting and to fatigue, water sensitivity) are provided by WP4 in D4.1.

Tyre-pavement noise refers to the capability of reduction of tyre-pavement noise level.

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.)

(5.5) 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 already explained tools, such as:
- Uncertainty and sensitivity analysis. The consideration of uncertainty and sensitivity analysis have been explained for each particular indicator when applicable.
- Normalization of obtained results.

(6) Interpretation for decision making

Choosing the best sustainable alternative isn't easy, especially when several aspects are taken into account and regard different aspects of Sustainability (Enviornment, Society, Economy). For this reason, it's important to proceed with a a decision-making process, based on a Multi-Criteria decision method. In PavementLCM the chosen method is PROMETHEE, which provide a ranking for a set of alternatives based on a balance between the assigned outrankings.

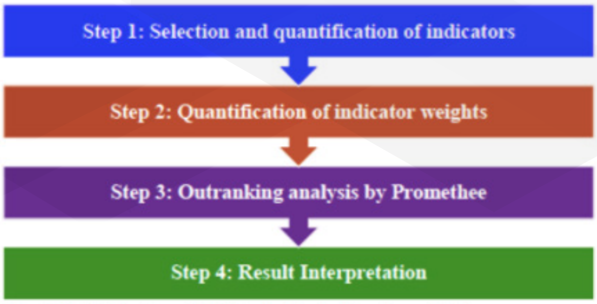

Figure 3. Application steps of MCDM analysis by the Ptomethee method

Table 7. MCDM Outranking results

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

Figure 3 – application of Multi-Criteria decision making with SA results

(7) Reporting, communication and verification

The reporting of the assessment should include the following information:

(1) Purpose of the assessment
(2) Object of assessment
(3) Statement of boundaries and scenarios
(4) Data sources
(5) List of indicators and expression of results
(6) Interpretation of results

The communication of results should be made according to the information groups, as defined by EN 15643-5 and they can be organized following the tables reported in ENs provided in D5.1, chapter 2.7.

The verification process (critical review) is essential if the results of the SA are to become public. ISO 14040 and 14044 provides some information to be included.

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Recommendations in the use of sustainability datasets

Why sustainability data assessment?

National Road Authorities (NRAs) in Europe have an increasing interest in implementing sustainability assessment of roads and road infrastructure to tackle the following main goals:

1) Be able to manage their assets in a more efficient way, thus reducing costs;
2) To help their countries comply with carbon emission reduction goals;
3) Reduce environmental impacts of road construction and maintenance, meaning also a reduction in resource usage through the re-use and the recycle of waste materials;
4) Reduce the social impact of roads through noise reducing pavement and minimizing hindrance for road users (travel delays due to maintenance).

What can I do with sustainability data in a road pavement context?

However, there are many sensitivities in sustainability assessment. The background report D3.1 of PavementLCM reveals important messages for those who want to deploy activities to enhance sustainability.

The first lesson is that the most sustainable pavement component is not just the mixture with the lowest temperature or the highest amount of RAP. Innovations lead only to real improvements in sustainability when they are considered on a systemic level, comparing road systems over longer time periods than when only focusing on production. System analysis will reveal trade-offs, for example between using RAP and needing additives, as well as provide insight in the results of specific circumstances like traffic, climate, etcetera. Only with this approach, it is possible to have a holistic overview of the impacts and performance of an asphalt mixture.

→ recommendation 1: always compare pavement solutions in a project context with a long term (at least 40 years) perspective, never on a mass-basis (1 ton of X vs 1 ton Y).

→recommendation 2: be aware of potential trade-offs in sustainability, especially when additives or modifications are applied to ensure success.

What should I know before I start using sustainability data?

Since "sustainability" is an umbrella concept, it is hard to find a single solution which ticks all boxes and scores best on all indicators.

For that reason, organizations who want to improve should define clearly what indicators they find most important and, in case they find many things important, how they will combine different indicators to a final decision. The Dutch system of shadow prices and MEAT procedures is an example of the integration of different indicators into a decision-making process.

→ recommendation 3: before you start to investigate sustainability and/or before you incorporate sustainability in a tender or a strategy document, define which indicators you find important.

→ recommendation 4: in case of multiple indicators, determine on beforehand how you will combine them. Options are: weighing (e.g. shadow prices) or equal weight (e.g. the solution with most "best scores" wins).

Where can I find the best sustainability data and tools for my organisation?

When implementing sustainability, users should be aware that sustainability calculations with different tools, databases and/or methodologies will definitely lead to different conclusions. There are dozens of tools available to perform Sustainability Assessments of roads. Each of them has its own specificities and is more appropriated to a certain region due to the impact assessment method employed in the calculations and the database in the background. Hence, the NRA should choose a tool that suits their needs in terms of indicators, impact assessment method and underlying database. The Sustainability Assessment Compass, delivered in WP5, will help NRAs to find the right tool for certain situations. The Sustainability compass can be found in the "*TOOLS*" *section of the PavementLCM Package* (*https://www.pavementlcm.eu/pavementlcm-package/*).

→recommendation 5: first decide what are your goals, then select the appropriate tool and only tolerate data or results which are generated by this tool.

→ recommendation 6: use the Sustainability Assessment Compass (WP5) to find the right tool for the right situation.

→recommendation 7: to make most efficient use of internationally available data, consider harmonisation of data on a European level; see "Roadmap to Harmonisation" (WP5).

[1] *MEAT stands for "Most Economically Advantageous Tender" and reflects a weighing system in which (environmental) impacts are taken into account in the decision-making process.*

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How can sustainability data assessment fit within my organization?

However, there are more aspects than only tool selection when implementing sustainability; it is crucial to design a complete system with clear boundaries and conditions. In the case of the Netherlands, Rijkswaterstaat, the Dutch Road Authority, noticed that using the same tool and method was still not enough to ensure comparability of different products, therefore, together with market parties, they developed Product Category Rules. This document provides very specific guidelines on how to perform LCAs for asphalt in a uniform way, so that they can be used in tendering procedures.

→recommendation 8: set clear boundary conditions when starting a green procurement system.

→recommendation 9: consider the development of European guidelines on LCAs of asphalt, in line with the Dutch Product Category Rules.

Can sustainability data from multiple sources be combined?

This system relies also on the quality of the data available. Datasets driving the LCA results of the asphalt mixtures, namely binder, aggregates and transport datasets, should be carefully modelled with high quality primary data to ensure that results of the sustainability analysis are reliable. The comparison of tools showed clearly that it is undesirable to mix datasets from different tools, even though the methodologies may seem similar, because the background databases can have huge and unexpected influence on the results. For an illustration, see

→recommendation 10: never mix results generated with different tools or databases.

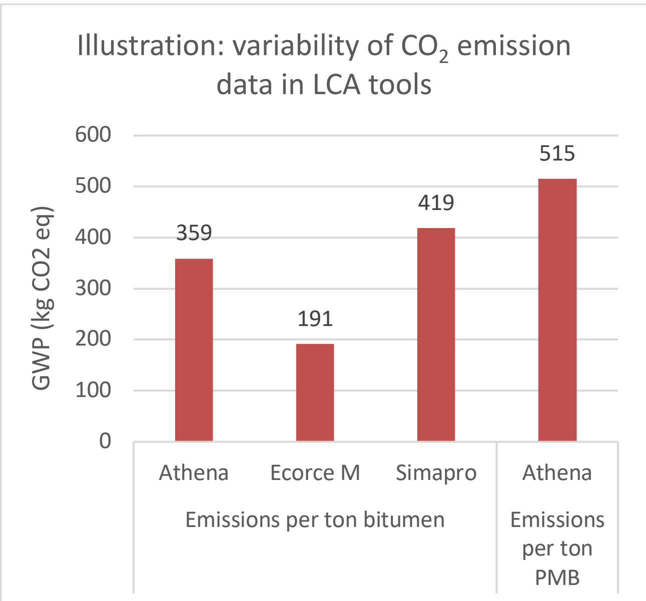

Figure 1 Illustration of variation in sustainability data in LCA tools.

What are the uncertainties in sustainability data?

Uncertainty estimation of LCA data demonstrated that there are high levels of uncertainty in the processes that contribute to the environmental impacts. *A specific tool to account for advanced calculation of uncertainty of LCA results for asphalt mixtures can be found in the "TOOLS" section of the PavementLCM Package (https://www.pavementlcm.eu/pavementlcm-package/).*

With a simpler approach, as a general rule of thumb, a process will have clear impact on the reliability of an LCA study results if it has a high impact and a large standard deviation. Sensitivity analyses can be used to identify the phases that contribute the most to the overall uncertainties. In the assessment of pavement activities, durability revealed to be a crucial factor. Uncertainties in durability have a direct effect on uncertainties of a whole project or study.

→recommendation 11: implement a basic form of uncertainty analysis in each project where sustainability is involved. The most basic form is to investigate the processes which are most impactful, and which have the largest standard deviations.

→recommendation 12: be extremely careful with uncertainties in durability. When durability is involved (for example in scenario analysis of pavement activities), make sure that uncertainties are addressed, for example by using ranges and by quantifying the impact on the results. When anyone will receive benefits from a long durability, make sure that this decision is based on the worst-case scenario of durability.

What is needed to implement sustainability successfully?

Overall, this study highlighted the crucial role of critical judgement in sustainability assessment for NRAs. This does not mean that the NRAs have to become experts in sustainability or statistics, but it challenges them to think critically of what they really want to achieve and how they organize their systems.

To achieve sustainability goals successfully, it is indispensable to take durability critically into account.

The biggest challenge, for NRAs, innovating companies, sustainability researchers and statisticians altogether, is to reduce the uncertainties in durability predictions and thereby to support sustainability statements.
Without reliable durability predictions, sustainability goals might easily be missed.

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Available Information

- ISO 14044:2006+A1:2018 Environmental management. Life cycle assessment. Requirements and guidelines ◊ ISO 14040:2006 Environmental management. Life cycle assessment. Principles and framework (ISO 14040, 2006)
- EN 15804 Environmental Product Declarations – Core rules for product category of construction products (EN 15804:2012+ A2:2019)
- EN 15643-2 Assessment of Buildings Part 2: Framework for the assessment of environmental performance (EN 15643-2, 2011)
- Federal Highways Administration Pavement LCA Framework (Harvey et al. 2016)
- Pavement Life Cycle Assessment Framework (FHWA, 2011)

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Recommendations for durability assessment of wearing courses

Durability of greener surface courses

What will be the service life of a particular pavement in a given location? The answer to this question is crucial for all road assets management regardless of whether the focus is limited to monetary aspects or if the scope is broader e.g. life cycle management or management from a circular economy perspective.

For surface courses that have been used for a long time in the region, the expected service life could be inferred from historical records. For new or tweaked products with a greener profile compared to the old products, the service life must be estimated.

The objective of the *Deliverable D4.1. "Report on durability data analysis"* is to provide an assessment of the lifetimes for established surface courses and assessment of the expected lifetimes for new and potentially greener types of mixes. D4.1 can be found in the "RESOURCES"section of the PavementLCM Package (https://www.pavementlcm.eu/pavementlcm-package/).

Assessment of the service lifetimes for existing surface courses

A literature review on the durability for two types of surface courses used in Europe, SMA and porous asphalt show that there are marked differences between the estimated service lives for the two types of surface courses between different countries but also between different literature sources.

In D4.1 we provide an example how service life distributions could be modelled using a Weibull distribution with increasing failure rate with time and historical survival data. These data have two types of events: Either the time for end of life is observed or the time at end of study is observed and the subject is still in use. The latter event is known as censoring. Censored observations contain partial information about the survival time even though end of live is not observed. Survival analysis methods properly take care of both the complete information in the cases and the partial information in the censored observations. With analytical expressions for the service lives makes it easier to implement the uncertainty in the lifetimes in the asset management.

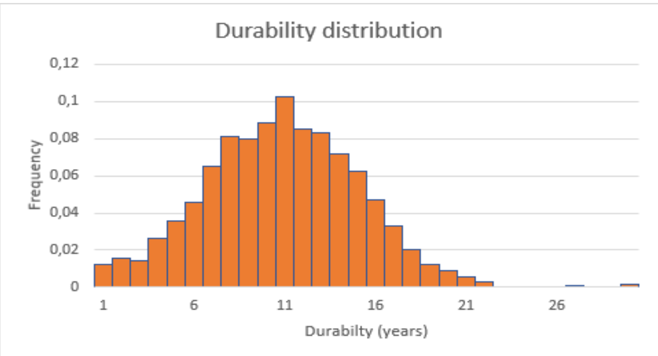

Figure 1 Predicted distribution of the durability of SMA16 using Bayesian inference theory

Durability assessment of the service lifetimes for new types of surface courses.

The durability assessments for new types of surface courses could be based on

- lab test results,
- accelerated load tests (ALT),
- lifetime expectancies of reference materials in different countries and the spectra of distress modes limiting the service life in different countries.

In the weighted assessment done in this work package, the latter parts, the lifetime expectancies, and typical distress modes for different countries were gathered through a questionnaire directed to local experts. In our lifetime assessment, the laboratory studies included tests for ageing of loose mix in an oven for one and two weeks; binder recovery and analysis of softening point and shear modulus; water sensitivity using a moisture induced stress test protocol; cyclic indirect stiffness modulus test; shear modulus test. The ALT used a circular road simulator and both unaged and aged mixes were tested in the ALT using both elevated temperatures and freeze-thaw cycles with water sprayed on the surface to cover different types of climate conditions.

The underlying assumption in using lab test results and accelerated load tests results to estimate the lifetime of a surface mix are that there are correlations between the lab tests and the field performance. Even if such correlations have been proven in the past, it is not certain that such a correspondence will be valid for new materials. Thus each part in the weighted assessment brings its own uncertainty into the total uncertainty in the estimate.

In the durability assessments for the new mixes done in WP4, the judgment from one local expert, or in some case the judgments of two local experts, have been used for each country considered. If several experts' opinions are available Bayesian inference theory can be used to account for the combined uncertainty. In the report we show an example of how Bayesian inference theory can be used to calculate uncertainty in the lifetime distributions when combining estimates from different sources and experts (Figure 1).
An Excel spreadsheet template for doing such an analysis can be found in the "RESOURCES" section of the PavementLCM Package (https://www.pavementlcm.eu/pavementlcm-package/).

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Towards Circular asphalt pavement industry

What is Circular Economy (CE)?

It is an economy that is restorative and regenerative by design, and which aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. Two different types of products can be identified; products that after their lifecycle can either return into the technical cycle (durables), or into the biological cycle (consumables). This definition is based on three principles:

- Design out waste and pollution
- Keep products, components, and materials at their highest value and in use
- Regenerate natural systems

Objectives

1. Explore and understand what Circular Economy means for the road engineering sector.
2. Identify through a rigorous literature review accompanied by questionnaires to various collaborating National Road authorities (NRAs) if there is a plan to understand, adopt, implement, communicate, and monitor the progress of said economy.
3. Guide NRAs towards implementing CE through a set of guidelines and recommendations based upon, circular business models, and green, sustainable, and circular public procurement.

WP development and outputs

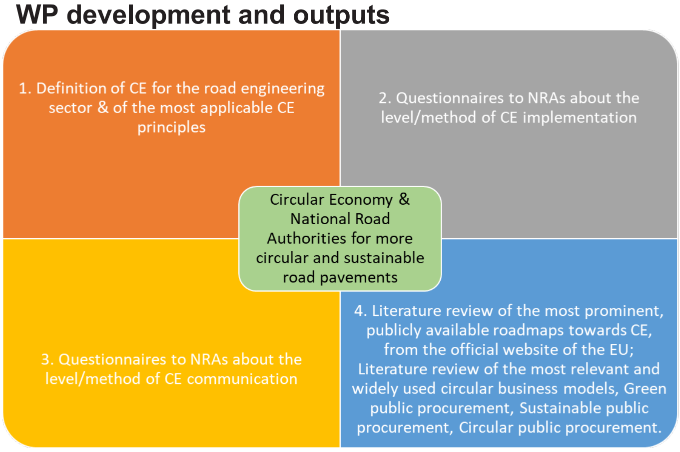

Figure 1- Work Package 6, plan deployment

As can be seen in Figure 1, WP6 was structured under 4 main methodological aspects, that are able to provide a transparent insight to the current situation and state-of-the-art when it comes to CE and its implementation in the road engineering sector. The topics covered were systematically analyzed and presented through three Sub-Work Packages:

1. ***"LCM and Circular Economy: New challenges and Approaches"***

The origins of CE are thoroughly analyzed by presenting the state-of-the-art on what CE is; and continuing by researching the meaning of CE in the context of transportation infrastructures. A review of all the different documents that have been published by regional/national authorities within the "European Circular Economy Stakeholder Platform" is also presented. The defined CE principles aligning with the scope of road engineering were:

- Design out waste and pollution
- Keep products, components, and materials at their highest value and in use
- Regenerate natural systems

It also became evident that only Highways England has published a tailored roadmap towards CE for the transportation infrastructure sector while the rest of the reviewed documents only mention possible strategies for the more general spectrum of the built environment.

2. ***European NRAs and Circular Economy***

The results of questionnaires sent to NRAs are presented. The questionnaires were focused on the levels of knowledge of CE by the NRAs, the level of implementation, and the methods, and channels of communications. The analysis concluded that all the NRAs are familiar with the concept of CE and most of them are also familiar with most of the principles it represents, but their majority is not implementing them thoroughly and/or holistically. Most of the NRAs replied that they are working towards:

- prioritizing the “designing out” of the waste of their products and that they
- attempting to prolong the life of their assets by conducting preventive maintenance.

Finally, when researching the methods via which NRAs communicate the implementation of CE, it was seen that 60% of the contacted NRAs do not put communicate anything about their (potential) implementation of CE. Thus, valuable recommendations and a specifically tailored knowledge development scheme along with a circular roadmap for the NRAs is delivered.

3. Circular models to favor the uptake of green asphalts

The definitions and functions of business models, sustainable business models, and circular business models are provided. Some insights are provided on how these aspects can be of use for the NRAs and their efforts towards more circular and sustainable overall operational patterns. The analysis of the questionnaires sent to the contacted NRAs proves that there is a conceptual misunderstanding of NRAs when it comes to the business/procurement aspect of circular economy. Most of the replies referred to life cycle assessment and EPDs or CO_2 foot printing. When it comes to circular economy and procurement schemes that can comply with it, the situation is much more complicated. Thus, NRAs should allocate higher budget percentages towards becoming more familiar with circular economy, circular business models and green procurement. Moreover, the collaboration with economists or economic analysts could be of great help for the NRAs for them to formulate a procuring and operating scheme that can fulfil their circular ambitions. To address this, business models with multiple layers (environment, society, economy) must be utilized. A combination of Top-down and bottom-up approaches must be implemented for the management and optimization of the supply chains and a strong collaboration and transparent communication must be established with all the involved stakeholders

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