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Towards the implementation of Life Cycle Management for road pavements in Europe

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Cycle XXXVI

Abstract

The evaluation of the Life Cycle of products, processes and projects has a significant potential for enhancing sustainability. This is also true for road pavements. However, the current usage of Life Cycle-based impact assessment techniques is limited and exhibits inconsistency across studies, primarily due to the absence of a specific methodology tailored for this sector.

This research addresses this gap by focusing on the harmonization of sustainability assessment practices through life-cycle assessment, in order to facilitate its application in road infrastructure projects and to achieve more consistent and comparable studies. The proposed methodology, once established, will serve as a valuable guide, providing practitioners in Europe with a step-by-step procedure for effective implementation and aiding stakeholders in incorporating Sustainability Assessment into their practices towards a Life Cycle-based Management of the asset.

The research included also an additional investigation to improve important aspects of the proposed guidelines. On one hand, this work was the first ever attempt aimed at exploring the possibility of introducing Social Life Cycle Assessment within a sustainability assessment framework for the road pavement sector. The work allowed identifying a possible list of social impact indicators for pavement materials in Germany and Italy. Moreover, with the aim of improving data availability and reliability, this research evaluated the potential of integrating Building Information Modelling (BIM) and SA in the context of Life Cycle Management of road pavements.

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List of abbreviation

AADT	Average Annual Daily Traffic
AC	Asphalt Concrete
ANAS	Azienda Nazionale Autonoma delle Strade
CEDR	Conference of European Directors of Roads
CRM	Cold Recycling Mixtures
d.u.	Declared unit
EAPA	European Asphalt Pavements Association
EPD	Environmental Product Declaration
ESL	Estimated Service Life
FHWA	Federal Highway Agency

f.u.	Functional unit
GER	Germany
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCM	Life Cycle Management
LCSA	Life Cycle Sustainability Assessment
LCT	Life Cycle Thinking
MCDM	Multi-Criteria Decision Making
NPV	Net Present Value
RA	Road Agencies
RAP	Reclaimed Asphalt Pavement
RSL	Reference Service Life
RSM	Republic of San Marino
PCR	Product Category Rules
SA	Sustainability Assessment
SB	System Boundaries
S-LCA	Social Life Cycle Assessment
SMA	Stone Mastic Asphalt
SPD	Sustainable Product Declaration
WC	Wearing Course

1. Chapter 1 INTRODUCTION

Sustainability is one of the biggest challenges in our century. Global warming, droughts, and adverse weather events are showing us how the uncontrolled use of resources and the constant emission of climate-changing gases is damaging our planet (Butera, 2021; UNEP, 2014). However, in addition to the environmental aspect, which is more often linked to sustainability, two other pillars are the basis of the sustainable development: economy and society. Addressing sustainability in its totality is more complex, but it will allow to come to more robust and consistent solutions for the future of our planet.

Sustainability, in the context of road pavements, is referred to "pavement's ability to achieve the engineering goals for which it was constructed, preserve and (ideally) restore surrounding ecosystems, use financial, human, and environmental resources economically, and meet basic human needs such as health, safety, equity, employment, comfort, and happiness" (Van Dam, 2015). The reader would probably think that this definition entails that assessing sustainability of a road pavement is not trivial. If this is the case the reader is absolutely right: understanding how much a road pavement is sustainable, it is not an easy task. However, in order to follow the path of sustainable development every sector is called upon to make a turnaround and if it is considered that the construction sector accounts for 37% of carbon emissions (WBCSD, 2018), it is obvious that this macro sector deserves special attention, and road pavements are a part of it. Civil engineers, scientists and stakeholders of the road pavement industry should be responsible of estimating how materials and related technologies can impact in terms of environmental, economic, and social impacts; in other words, pavement specialist should become acquainted with estimating sustainability performance of project, product, processes by means of Sustainability Assessment (SA). Performing a SA is not immediate and, according to the object of the assessment (project or product/process), it can be carried out through Sustainability Rating Systems (SRS) and Life Cycle analysis by means of impact evaluation techniques.

The SRS are based on assigning point values to actions that contribute to the overall sustainability of the project (Buttitta et al., 2022). They are composed of the current best practices for road design, construction, and maintenance (Mattinzioli et al., 2020), using a quantitative, qualitative, or semi-quantitative approach. They are context-based: methods and focuses change from varying geographical areas (Van Dam et al., 2015; Zietsman, Ramani, Potter, & Reeder, 2011). Several SRS have been defined specifically for road pavements.

The Life Cycle-based impact evaluation techniques, instead, allow performing a SA by analytically accounting for the impact on the planet of products and process within the entire life cycle of an asset and recognizing how our choices influence what happens at each of every step, to balance impacts in the economy, environment, and society (UNEP, n.d.-b). Nowadays, life-cycle based impact evaluation techniques are developed enough to cover the three pillars of sustainability: the environment with the Life Cycle Assessment (LCA), the economy with the Life Cycle Costing (LCC), and the society with the Social Life Cycle Assessment (S-LCA). When they are all taken into account and merged, a Life Cycle Sustainability Assessment (LCSA) is performed. Also, whenever the results of SA are used for decision-making to improve the sustainability performance of any business, organization and/or asset, this approach could be identified as Life Cycle Management (LCM). LCM can be used to target, analyse and manage product/process-related information towards continuous improvement along the product life cycle and overall ensuring more sustainable value chain management (Remmen et al., 2007).

1.1 Problem Statement and major Research Gaps

The use of SA through life cycle-based impact evaluation techniques is not country-related: at international and European levels, standards, methodological sheets, and guidelines have been provided to standardize the methodology (i.e. ISO 14040, S-LCA Guidelines, EN standards). Most of these documents are generic, not sector-specific, and leave the practitioners free to make their own choices. Another obstacle for the practitioners is data availability and quality; in fact, Life Cycle cycle-based impact evaluation techniques are data-intensive methodologies that needs inputs from several sources and fields (Santero et al., 2011b). This lack of consistency in the application of these techniques, as well as data quality and availability, occur also in road pavements. It leads to incompatibility and incomparability among studies (Santero et al., 2011a), difficulties and reluctance towards their implementation by the stakeholders involved in the sector, low trust in transferring the use of these exercises beyond the academic level, which in turns causes a lack of primary data. Furthermore, the inconsistencies found in literature, the difficulties in the comparability of results and in the application of life-cycle based techniques, and the lack of good data affect the SA of road pavements and the possible implementation of the results within LCM practices.

On this basis, it is evident that something must change quickly and that any possible effort towards harmonisation and pragmatic approach of SA should be pursued for road pavement specialist to include sustainability performance within their decision making. The sector needs boosting the research allowing a systematic and systemic use of Life Cycle-based impact evaluation techniques. The lack of specific procedures and standards leaves analysts with excessive freedom to choose, impacting the quality and reliability of the studies.

A support in this direction could come by tailoring the application of existing general standards on SA to the specifics of the road pavements sector, identifying with a univocal approach the main aspects (i.e. functional unit).

Collecting and storing data of each life-cycle stage of a road pavement should ensuring quality and availability of data, while the recently increased sensibility towards social impacts of our actions could be crucial towards the definition of integrated SA and LCM approaches for road pavements. However, several are the identified factors currently representing obstacles towards such harmonised approaches. After a literature review, the following are the gaps currently existing in this specific research area:

- Lack of specific methodology for the Life Cycle-based SA of road pavements. The existing standards are very generic (i.e. ISO 140040 (2006) for LCA) or specific for a similar sector (i.e. ENs series for civil engineering works), without any specification about the road pavements. This causes inconsistency in the studies and the difficulty in comparing the results;
- The most frequent inconsistencies are in the selection of the functional unit, the system boundaries, and the impact categories (Santero et al., 2011a);

▪ In an LCA, the characterization methodology chosen to assess the potential environmental burdens can change the results (Grael et al., 2021);

▪ The S-LCA is not yet well developed and social aspects are often not considered (Del Rosario & Traverso, 2023);

▪ The life-cycle based techniques are often considered too complicated to implement (Jiménez del Barco Carrión et al., 2021);

▪ The difficulty of finding large reliable data is a big obstacle to perform a quality study (Batouli et al., 2017);

▪ The experience in the use of SA results for assessing sustainability performance of road pavements is still limited. Most countries collect data, somehow perform SA of road pavements and then rarely consider them within LCM practices.

1.2 Aims of the Research

On the basis of the outlined problems and research gaps, this research does not want to investigate pure methodological aspects on the use of life cycle-based impact evaluation techniques, it neither wants to provide the much-needed benchmarks for the SA of road pavements. Instead, it wants to focus on filling existing gaps for two main reasons: proposing a harmonised approach to carry out Sustainability Assessment exercises of road pavements and providing guidelines for engineering the adoption of LCM as standard practice into the European road pavement industry.

The proposed methodology wants to comply with existing European standards for SA in the civil engineering works sector, covering the three pillars of sustainability through the identification of indicators related to environmental, economic, and social aspects, together with the technical and functional requirements.

Hence, the main aims of this research are:

1. harmonizing Life Cycle-based impact evaluation techniques into the road pavements sector by tailoring the existing European standards for SA of civil engineering works

2. facilitating the use of SA results in pavement construction and management decision making process, leading to a proposal of guidelines to implement LCM of road pavement,
3. exploring further developments of the proposed SA framework by investigating the possibility of improving the evaluation of the life social impacts into the SA framework and exploring possibilities for improving the quality and reliability of data.

1.3 Research Methodology

In order to achieve the overarching aims, this research involved the use of a literature review, the interactions with major National Road Authorities (NRAs), tailored data collection for the development of two case studies, the modelling with the software for the calculation of life-cycle impacts and the analysis of results.

In more details, the following approach has been considered:

▪ Carrying out a detailed review on the current standards for SA in the civil engineering works sector by means of life cycle-based techniques.

▪ Carrying out a review on the application of SA in road pavement sector, also considering the developed research projects at European level, and interviewing the major European road authorities to be aware of their current SA practices, related to LCA, LCC and any considered social impacts. These steps were fundamental to understand the context, the practices, standards, and the needs of the stakeholders involved.

▪ Developing a specific framework for conducting harmonized SA of road pavements in Europe and proposing guidelines for implementing road pavement LCM as standard practice, identifying two systems (pavement materials and pavement activities) and with the support of major European RAs.

▪ Applying the proposed SA framework and LCM guidelines in two case studies aiming at comparing the sustainability performance between the use of Hot Mix Asphalt (HMA) and a Cold Recycling Mixture (CRM) within base/binder courses. The two case studies differ in terms of geographical location (Republic of San Marino and Germany) and of used technology (plant vs in-situ). GaBi ts (*Thinkstep AG GaBi Ts 2019*, 2019)was used for the calculation of the environmental impacts.

- Investigating the possibility of tailoring current S-LCA methodologies within the road pavement sector;
- Investigating the potentialities of BIM as a reliable and high-quality data repository.

1.4 Related published Scientific Research products within the PhD studies

Scientific Reports

- Lo Presti, D., Mollenhauer, K., Vega, I. I., & Buttitta, G. (2022). Synthesised Results and Applicable Findings of CEDR Call 2017 New Materials (SyRAF) (No. CR2022-05) - ISBN: 979-10-93321-65-3 - https://www.cedr.eu/docs/view/6250155931c63-en

- Lo Presti, D., Carrion, A. J. D. B., Parry, T., Neves, L., Abed, A., Buttitta, G., Kalman, B. (2021). Call 2017 New Materials PavementLCM Final Report: A Package for Implementing Life Cycle Management of Road Pavement (No. CR2022-02). ISBN: 979-10-93321-62-2 - https://cedr.eu/docs/view/622f6c6ecc2db-en

- Lo Presti, D., Buttitta, G., Jiménez del Barco Carrión, A. (2021). PavementLCM Guidelines - https://www.cedr.eu/docs/view/61b9ebb7df179-en

- Lo Presti, D., Buttitta, G., Jiménez del Barco Carrión, A. (2021) Sustainability Assessment for Road Pavements: State-of-the- art + Framework- https://www.cedr.eu/docs/view/61b9e7e9803d9-en

- Lo Presti D., G. Buttitta, K. Mantalovas. (2021). LCA of CRAB Mixtures - https://www.cedr.eu/docs/view/61961be70119c-en

Scientific Papers in International Journals

- Abed A., Godoi Bizarro D.E., Neves L., Parry T., Keijzer E., Kalman B., Del Barco Carrion A.J., Mantalovas K., Buttitta G., Lo Presti D. & Airey G. (2023) Uncertainty analysis of life cycle assessment of asphalt surfacings, Road Materials and Pavement Design, DOI: 10.1080/14680629.2023.2199882

- Buttitta, G.; Giancontieri, G.; Parry, T.; Lo Presti, D. (2023). Modelling the Environmental and Economic Life Cycle Performance of Maximizing Asphalt Recycling on Road Pavement Surfaces in Europe (2023), Sustainability 2023, 15, 14546. https://doi.org/10.3390/su151914546

- Lo Presti, D., Jimenez Del Barco Carrion, A., Parry, T., Neves, L., Keijzer, E., Kalman, B., Buttitta, G., Mantalovas, K. (2023). A Framework for Life Cycle Management of Road Pavements in Europe, Transportation Research Procedia, Volume 72, 2023, Pages 1552-1559, ISSN 2352-1465, https://doi.org/10.1016/j.trpro.2023.11.623

Conference papers

- Buttitta, G.; Giancontieri, G.; Milazzo, S.; Mignini, C.; Hennig Osmari, P.; Ghani, U.; Lo Presti, D., Investigating Tools for Sustainability Assessment of Road Pavements in Europe., Eng. Proc. 2022, 17, 34. https://doi.org/10.3390/ engproc2022017034

- Buttitta G., Lo Presti, D., Life Cyle Management methodology for Road Pavements, in Abbondati, F. (2022). Sustainable Pavements and Road Materials: Proceedings of the 7th SIIV Arena, Naples, Italy 9th September 2022. FedOA-Federico II University Press.

- Buttitta, G., Milazzo, S., Mignini, C., Hennig Osmari, P., Ghani, U., Giancontieri, G., Lo Presti, D. (2022). Life Cyle Management delle pavimentazioni stradali, in Rete Italiana LCA, Atti del XVI Convegno dell'Associazione Rete Italiana LCA, 22-24 Giugno 2022

1.5 Thesis Organization

The thesis follows this scheme:

- Chapter 1 provides an overview of this work, with the introduction, identification of problem statement and research gaps, the research aims, the research methodology and the further research products already published by the author.

- Chapter 2 firstly provides a general overview on the policies about sustainability at European and non-European levels and on the ways in which sustainability performance can be assessed. It then provides a literature review on the Life Cycle Sustainability Assessment of Road Pavements, focusing on Life Cycle-based impact assessment techniques, hence Life Cycle Assessment, Social Life Cycle Assessment, Life Cycle Costing, and their previous research on the application in the sector of road pavements;
- Chapter 3 presents the first outcome of the research: it is the SA framework for European roads. It provides the definition of the scope of the assessment and the description of the object of the assessment and a set of indicators, covering environmental, economic and social aspects, plus the technical and functional requirements.
- Chapter 4 provides the description of step-by-step methodology for implementing LCM within the road pavement industry;
- Chapter 5 comprises the application of the methodology with the development of the case studies comparing the sustainability performance of using HMA or CRM for base/binder courses. The results of the assessment are discussed;
- Chapter 6 explores possible further development of the proposed SA framework by investigating the implementation of Social Life Cycle Assessment in the sector of road pavements, as well as showing the potential of using of the BIM as a data repository.
- Chapter 7 includes the conclusion of the proposed work and the future perspective.

Chapter 2 SUSTAINABILITY ASSESSMENT AND ROAD PAVEMENTS

2.1 Sustainability – an overview

Sustainability is one of the keywords for our society. In 1987, the United Nations Brundtland Commission defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." (Commission on Environment, 1987)

It is about finding a balance among environmental, economic and social components to tackle global problems such as global warming, resource use, loss of biodiversity, and social inequalities.

2.1.1 European and International policies towards a more sustainable planet

Climate change has become a focal point in numerous international agreements, established to confront this global challenge. These accords are designed to prompt countries to take proactive measures, establish targets, and collaborate in efforts to mitigate the impacts of climate change.

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) marked the inaugural treaty on this subject, then followed by the Kyoto Protocol, in 1997. The former defines a set of rules to make stable the GreenHouse Gas (GHG) concentrations in the atmosphere, while the latter established mandatory emission reduction targets for two different periods (2008-2012, 2012-2020). The protocol entered into force in 2005. Each participating country was assigned an individual target based on its historical emissions of certain pollutants (i.e. carbon dioxide (CO_2), methane (CH_4)), with a general average of 5.2% below their 1990 levels.

In 2015, a collaborative approach to facing climate change was adopted within the UNFCCC framework: it is the Paris Agreement. The goal is to restrict global warming under 2° C respect with to the pre-industrial levels, with trying to stay until 1.5° C. Each partner country is required to prepare its Nationally Determined Contributions (NDCs), showing its climate action plan.

Among the other noteworthy recent initiatives, it is crucial to highlight two of them, reported here below.

2.1.2 Agenda 2030 and Sustainable Development Goals (SDG)

The United Nations 2030 Agenda for Sustainable Development, well known as Agenda 2030, is the document issued by the United Nations and taken on by all its Member States in September 2015 (UNEP, n.d.-c).

The document is a plan of action which involves people, the planet and prosperity: it promotes peace and aims at eradicating poverty. It is made up of 17 Sustainable Development Goals (SDGs) and 169 targets encompassing a broad variety of sustainable development problems. Five main areas of critical importance were identified: 1. People, to fight poverty and hunger, and ensure equality and dignity; 2. Planet, to adopt policies for protection and sustainable management; 3. Prosperity, to ensure economic, social and technological progress; 4. Peace, for a society free from fear and violence; 5. Partnership, to strengthen collaboration and solidarity.

Figure 2-1 – SDGs (adapted from UN*)*

The SDGs address various global challenges, including hunger, health, gender equality, education, climate action, clean water, and more. The overarching aim is to reach sustainable development considering three dimensions (economic, social and environmental) in a harmonized way. Each country needs to work to consider its national realities and capacities, as well as in compliance with policies.

2.1.3 European Green Deal

The European Union is always very attentive to environmental policies, to the point of declaring that it accepts the challenge of fighting against climate change, promoting the SDGs and implementing the 2030 Agenda (European Council, 2019)

The 17 SDGs have been incorporated into various European policies and are also more or less openly articulated within the Green Deal, a policy framework outlined by the European Commission in December 2019. The Green Deal aims at reaching climate neutrality in the EU by 2050, fostering an inclusive and sustainable economic growth model. It includes a wide range of initiatives to tackle climate change, reduce GHG, and preserve the environment (European Commission, 2019; Koundouri et al., 2021).

The Green Deal aims at:

- Zeroing GHG by 2050;
- Separating economic growth from resource utilization, minimizing pollution, and protecting animals and plants;
- Neglect no place or person.
- Support green technologies;
- Promote the Green and Digital transition.

The goals cover nine areas and the related SDGs are (Koundouri et al., 2021):

• Biodiversity: Ecosystem regeneration is a main goal to achieve in a long-term plan but with some important steps by 2030. Restore forests, soils, wetlands and peatlands is a key aspect. (EU Commission,2020a). The connected SDGs are 14 and 15.

• From Farm to Fork: There is a necessity of a sustainable food system, capable of facing the climate change and make Europe competitive. This can be guaranteed by the

Farm to Fork Strategy (European Commission, 2020a). This is linked to SDG 2, 3, 6, 10, 14 and 15.

• Sustainable Agriculture: nutrition labelling, controlled use of pesticides, promotion of agri-food policy are some of the key aspects towards a sustainable agriculture system. The interconnected SDGs include the Goal 3, 6 and 15.

• Clean Energy: decarbonization and zero net emissions can be achieved through renewables, energy efficiency, and other solutions. Among the initiatives, REPowerEU foster to save energy, produce clean energy (39% of European electricity was produced through renewables in 2022 and solar and wind production increased) and diversify European energy suppliers (with new agreements with other countries). This is linked to goals 7, 8, 9 and 17.

• Sustainable Industry: an industrial plan aimed at expanding the EU's manufacturing capacity towards sustainable technologies and products necessary to achieve Europe's climate neutrality. This is linked to the "Third Industrial Revolution. It entails transitioning the industrial sector into an era of Green, Digital, and Circular. (EU Commission, 2020e). This is linked to SDG 6, 7, 9, 12 and 17.

• Building and Renovating: new and renovated buildings with updated energy efficiency can reduce emissions and decrease energy poverty. The plan is to raise the utilization of renewable energy in heating and cooling annually until 2030 (+1.1 point). This is linked to SDG 4, 7, 10 and 11.

• Sustainable Mobility: transport causes around 25% of the total European Union's GHG. Providing efficient, safe and environmentally friendly transport is a key aspect towards decarbonization (European Commission, 2020b). The measures include electrification, new incentives for low-emissions lorries, sustainable aviation fuels, as well as resilient networks. This is linked to SDG 3 and SDG 11.

• Eliminating Pollution: a toxic-free environment can be created through a zero-pollution plan for air, water, and soil. This is connected to the SDG 6, 13, 14 and 16.

• Climate Action: the EC defined two main dates: 2030 for reducing emissions of at least 55% and 2050 for Climate neutrality. Moreover, the idea is to boost global climate action through the development of policies and good practices that can inspire and benefit other countries. This is connected to the SDG 12, 13 and 16.

2.1.4 Other policies and initiatives

New Ecodesign for Sustainable Products Regulation (ESPR) is a proposal by the European Commission, built on the current Ecodesign Directive, which only covers energy-related products. The aim is to define a framework to set eco-design requirements for a set of product groups to improve their sustainability and circularity (European Commission, 2009).

It will set a range of requirements, such as durability, reusability, upgradability and reparability, recycled content, carbon and environmental footprints, and efficiency. The adoption is planned for the first quarter of 2024.

2.2 How to assess the sustainability of projects and products?

Assessing the sustainable performance of a project, product or process is a major challenge for our society. Performing a Sustainability Assessment (SA) means defining benchmarks, evaluating progress, and supporting the decision-making towards a more sustainable society. Several methodologies have been developed throughout the years, using qualitative and/or quantitative indicators. Among these, as explained in more details further, sustainability rating systems are mainly used for assessing projects, while life cycle analysis-based impact assessment techniques are more widely used for quantitative assessment of sustainability of products and processes.

2.2.1 Sustainability Rating Systems (projects)

A Sustainability Rating System (SRS) is mainly used as a framework or set of criteria employed to assess and quantify the sustainability of organizations, buildings, products, or projects. SRS can cover several aspects (i.e. environment, society) and can help in the decision-making process to lead to sustainable choices and practices.

At the organization level, for instance, Global Reporting Initiative Standards (GRI) can be used by companies for reporting their economic, environmental, and social performance

(GRI, 2023), while UN Global Compact promote the adoption of sustainable and socially responsible policies In business, concerning ten principles linked to human rights, labor, environment, and anti-corruption (United Nations, 2023).

In the construction sector, SRSs are mostly used for building projects (Del Rosario & Traverso, 2023), but their importance and use is increasing also in the road sector (Mattinzioli et al., 2020).

Nearly 600 SRS exist in the world (Del Rosario & Traverso, 2023), but there are some widely recognized and used. For instance, Leadership in Energy and Environmental Design (LEED), created by the U.S. Green Building Council, can evaluate building design, construction, and operation using criteria such as energy and water efficiency, indoor air quality, and materials choice (U.S. Green Building Council, 2019). Building Research Establishment Environmental Assessment Method (BREEAM) can be used for buildings and infrastructure projects. It considers environmental and social performance (BRE Group, 2023). Greenroads is widely used for transport infrastructure projects. The integration of life cycle assessment aspects for the calculation of environmental performance is a key aspect of this SRS (Transport Council, 2011).

2.2.2 Life Cycle Analysis – based techniques (products and processes)

The life cycle of a product starts from the extraction of materials and the production of energy, both necessary for its production, and continues with the transportation, the use and eventually the recycling, reuse or disposal. (Figure 2-2) (UNEP, n.d.-b). Conceiving this approach during a sustainability assessment means understanding how our choices impact what happens at each of these phases, to optimize trade-offs to foster a good impact on the economy, the environment, and society (UNEP, 2004).

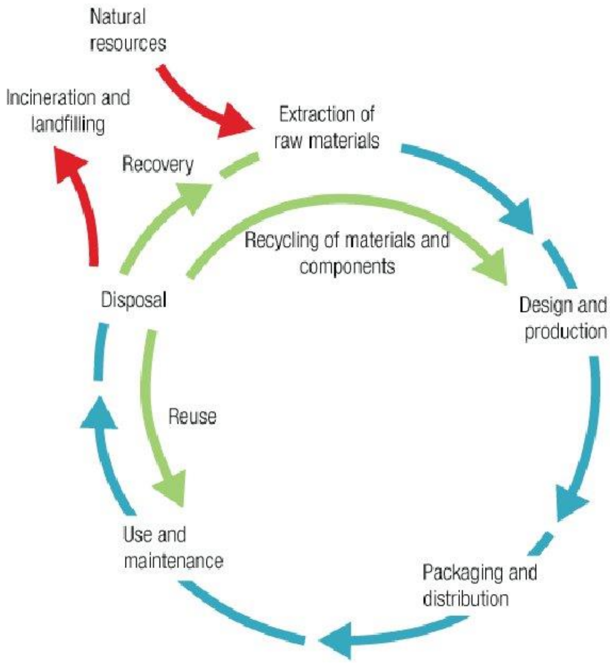

Figure 2-2 - A typical product lifecycle diagram (adapted from UNEP, 2023)

Using Life Cycle Thinking (LCT) leads to moving to a broader and more holistic view, including impacts throughout the life cycle, considering environmental, economic and social aspects.

Using a life cycle approach allows us to become aware that our choices are not separated, but affect a wider system, helping to make choices for a longer term and enhancing entire systems without triggering other environmental problems.

Each phase of the life cycle can be improved to lower consumption and increase performance. LCT therefore lays the foundation for calculating the impacts of products and/or processes by using Life Cycle-based impact assessment techniques to cover the three dimensions individually or in a comprehensive approach.

The LCT allows the calculation of three dimensions of sustainability: Life Cycle Assessment (LCA) addresses the environmental impacts, Life Cycle Costing (LCC) is employed for the economic dimension and Social Life Cycle Assessment (S-LCA) for the social component, while Life Cycle Sustainability Assessment (LCSA) integrates all three dimensions.

The life cycle-based approach becomes operational using Life Cycle Management (LCM), which allows to minimize the environmental and social impacts due to the product throughout the full life cycle. (UNEP, 2008)

2.2.2.1 Life Cycle Assessment (LCA)

The (Environmental) Life Cycle Assessment, more known as LCA, is the methodology to account for environmental impacts over the life cycle of a product/process. It is standardized by the ISO 14040:2006 + A1:2020 (Principles and a general description of the LCA method) (ISO, 2006a) and ISO 14044:2006 + A2:2020 (Concrete requirements and the methodological framework of LCA) (ISO, 2006b) and it can be used in every sector. LCA can support in several dimensions, from finding chances for enhancing the environmental performance at different steps in the life cycle to implementing ecolabelling and environmental product declarations (14040).

The ISO 14040 identifies four phases in an LCA study: 1. the goal and scope definition phase, 2. the inventory analysis phase, 3. the impact assessment phase, and 4. the interpretation phase, here below detailed.

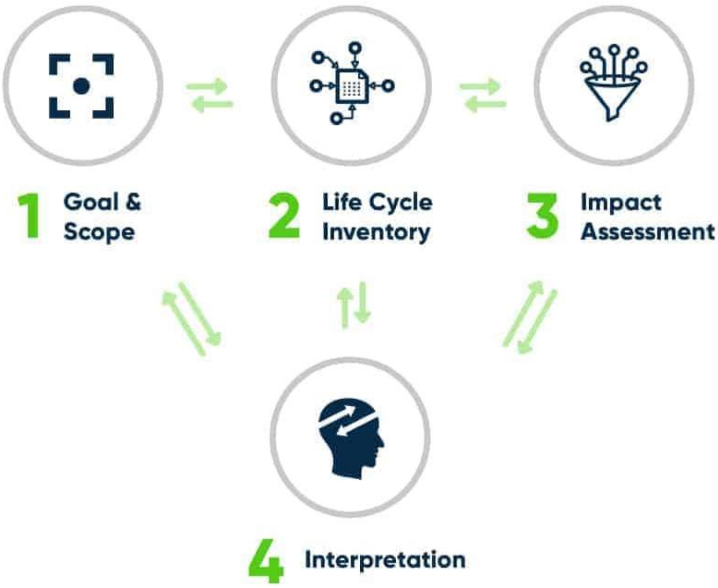

Figure 2-3 – Four phases for conducting an LCA (adapted from https://ecochain.com/blog/life-cycle-assessment-lca-guide/)

- <u>Goal and Scope Definition</u>

The first phase is necessary for identifying the main aspects of the study. It consists of defining the goal of the study, by stating the intended application, the reasons for carrying out the study, and the scope, through background information and methodological choices.

The scope definition includes the system boundaries (which life cycle stages are included or not) (Figure 2-4), the functional/declared unit (the unit of study, i.e. ton of asphalt mixtures), the cut-off rules (the threshold of materials and energy entering in the system excluded), the allocation (portioning the input/output between more than one product system), and the impact categories.

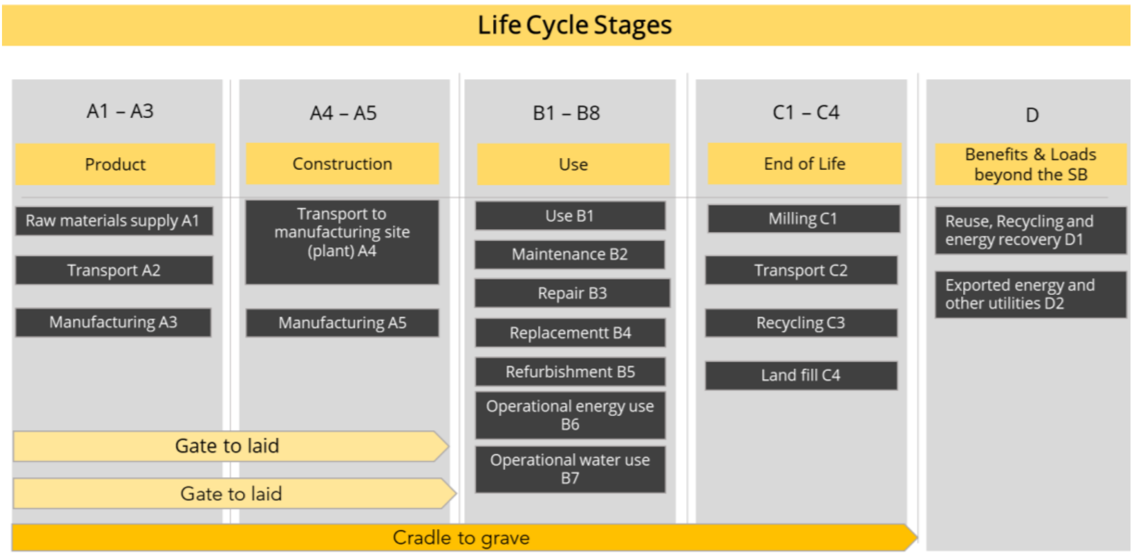

Figure 2-4 - Life Cycle stages of a product/process (adapted from EN 17472:2022)

- <u>Life Cycle Inventory</u>

It consists of the collection of all data inputs (energy, materials) and outputs (production, wastes) estimated for each activity in the system. This data is related to the processes included in the system boundaries, previously defined (i.e. raw materials extraction, energy consumption, transportation, manufacturing processes for a cradle-to-gate). The ISO suggests also to use of a pedigree matrix to evaluate the data quality, according to some parameters (i.e. technology representativeness).

- Life Cycle Impact Assessment (LCIA)

The goal is to evaluate the magnitude of these impacts on various environmental categories, which are "classes representing environmental issues of concern to which life cycle inventory analysis results may be assigned" (ISO, 2006a). Hence, the inputs and outputs of the previous phase are translated into potential impacts thanks to an "environmental mechanism", a system of physical, chemical, and biological processes for a specific impact category that establishes a connection among the life cycle inventory analysis results, the category indicators and the category endpoints to translate the emissions into impact categories.

The LCIA is composed of three mandatory and three optional phases.

The mandatory is the selection of impact categories, the category indicators and the characterization models, followed by the classification (hence the assignment of Life Cycle Inventory results) and the characterization (hence the calculation of category indicator results). The optional steps are the normalization of results, the grouping and the weighting.

Several methodologies have been defined to allow the translation of emitted compounds into indicators. Changing impact assessment methodology can lead to different results because the environmental mechanism behind the calculation of impacts is different. The most used methodologies are ReciPE, CML, and CF 3.0.

- Interpretation of results

This last phase is used for summarizing and commenting on all the results, providing conclusions and recommendations. According to the ISOs, three main steps are identified: the identification of significant issues (i.e. hotspot analysis), the evaluation of completeness, sensitivity, consistency and variability of the results (i.e. sensitivity analysis) and the conclusions, limitations and recommendations. A critical review is requested before disclosing the results to the public.

Following the ISO 14040-44, the European Commission proposed a specific methodologic framework to evaluate and communicate a product's environmental impact in a harmonized way within the EU (European Commission, n.d.): the Product

Environmental Footprint (PEF). PEF is structured similarly to a standardized LCA, providing several details to get more robust, consistent, and comparable results. It identifies and details five steps, clearly associable with the ones proposed by the ISO: 1. EF Goal and Scope Definition; 2. EF Inventory Analysis; 3. EF Impact Assessment; 4. Interpretation and Reporting; 5. Verification and validation.

Concerning the impact categories, while the LCA provides a wider range to calculate, the PEF predefines a default set of sixteen impact categories (i.e. climate change, photochemical ozone formation, etc). (European Commission, 2013)

PEF is often used to deliver an Environmental Product Declaration (EPD, a standardized document that provides information about a product's environmental performance) (ISO 14025:2006, 2006). It is a tool for transparent communication of environmental information to consumers and other stakeholders, also for commercial reasons. EPDs are often required in Green Public Procurement (GPP) and they can be a reliable source of data for further LCAs which use the product (Garbarino et al., 2016).

In the context of EPD, a fundamental role is played by the Product Category Rules (PCRs), which give a specific methodology for conducting an LCA on a specific product category. A PCR, usually developed through a stakeholder-driven process, contains all the information related to scope, system boundaries, functional unit, impact categories and data collection. It follows that all the LCAs related to the same category are carried out in a consistent approach, facilitating comparisons and decision-making (ISO 14025:2006, 2006).

2.2.2.2 Life Cycle Costing (LCC)

Life Cycle Costing assesses the costs of a product, an asset or its parts over its life cycle. It allows us to measure the economic component of sustainability (Harvey, 2016). Different typology of costs can be taken into account, and, about them, different approaches are defined (SETAC-Europe Working group): conventional, environmental and societal. The former evaluates all the internal costs from an operator’s perspective (industry, consumer), while the second one considers the costs and translates the environmental effects (the so-called “externalities”) into monetary terms. The latter one assesses the costs faced by all the stakeholders and actors involved.

No ISO standards refer to a general Life Cycle Costing, such as the ISO14040-44 for the LCA, but the ISO 15686-5 provides guidelines for the assessment in the context of service life planning of buildings and constructed assets (ISO, 2017). This standard emphasizes the need to assess the costs related to the entire life cycle, including acquisition, operation, maintenance, and disposal.

The ISO standards distinguish two different indicators (Figure 2-5):

1. Life Cycle Cost, that is the cost of an asset or its components over the life cycle while ensuring the technical and functional requirements;
2. Whole Life Cost, that encompasses all significant initial and future costs and benefits of an asset over its life, while meeting the technical and functional requirements.

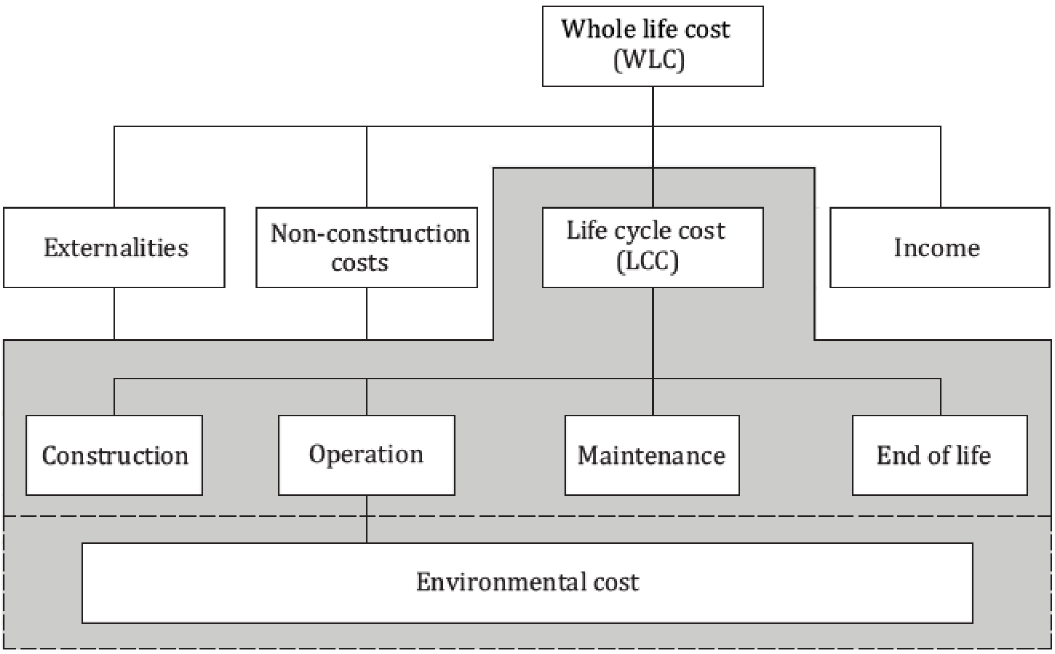

Figure 2-5 - Economic indicators for ISO 15686-5 (ISO 15686-5)

2.2.2.3 Social Life Cycle Assessment (S-LCA)

The third dimension of sustainability is society, whose introduction allows to adoption a holistic assessment, which includes the social impacts of a product throughout its entire life cycle (UNEP, 2020). The Social Life Cycle Assessment (S-LCA) is the methodology, still under development as explained later on, to increase knowledge, inform and promote the improvement of social conditions (Benoît et al., 2010). The core idea behind S-LCA is to recognize that every product has effects on various stakeholders along the life cycle of the considered product system, as identified by the UNEP Guidelines for Social Life Cycle Assessment of Products: workers, value chain actors, society, local community, consumers and children (UNEP, n.d.-a). For every stakeholder, a list of impact subcategories is suggested (Figure 2-6). In this regard, both negative and positive impacts can be considered in the context of employment generation and income, labour conditions, health and safety, and human rights, among others.

Stakeholder categories	Worker	Local community	Value chain actors (not including consumers)	Consumer	Society	Children
Subcategories	1. Freedom of association and collective barganing 2. Child lbor 3. Fair salary 4. Working hours 5. Forced labor 6. Equal opportunities / discrimination 7. Health and safety 8. Social benefits / social security 9. Employment relationship 10. Sexual harassment 11. Smallholders including farmers	1. Access to material resources 2. Access to immaterial resources 3. Delocalization and migration 4. Cultural heritage 5. Safe and healthy living conditions 6. Respect of indigenous rights 7. Community engagement 8. Local employment 9. Secure living conditions	1. Fair competition 2. Promoting social responsibility 3. Supplier relationships 4. Respect of intellectual property rights 5. Wealth distribution	1. Health and safety 2. Feedback mechanism 3. Consumer privacy 4. Transparency 5. End-of-life responsibility	1. Public commitments to sustainability issues 2. Contribution to economic development 3. Prevention and mitigation of armed conflicts 4. Technology development 5. Corruption 6. Ethical treatment of animals 7. Poverty alleviation	1. Education provided in the local community 2. Health issues for children as consumers 3. Children concerns regarding marketing practices

Figure 2-6 – Identification of stakeholders and related impact subcategories (adapted from UNEP, 2020)

S-LCA follows the approach of LCA as defined in the standards ISO 14040 and ISO 14044 by structuring the assessment in four main phases: Goal and Scope Definition, Life Cycle Inventory, Impact Assessment, and Interpretation (Kühnen & Hahn, 2017). Concerning the impact assessment, the Guidelines provide two different approaches: a reference scale (Type I), or an Impact Pathway approach (Type II). The former consists of the attribution of scores to the results and is quite subjective; the latter describes a causality between the inventory and the actual impact, being like the one followed in LCA (UNEP, 2020).

Besides the Guidelines, the United Nations Environment Program (UNEP) developed the Methodological Sheets to support the further development, application, and dissemination of the S-LCA method (Petti et al., 2018; UNEP, 2021). At the moment, no standard for S-LCA is still available: ISO 14075 is currently under development.

It follows that a deep methodological gap needs to be filled to harmonize procedures and results in the future.

2.2.2.4 Life Cycle Sustainability Assessment (LCSA)

The Life Cycle Sustainability Assessment (LCSA) is a complete and holistic approach which puts together all three dimensions of sustainability using a life cycle approach (UNEP-SETAC, 2011). In other words, LCSA looks at the results of environmental, economic and social assessments in a Triple Bottom Line (TBL) approach, emphasizing the necessity to harmonize environmental, social, and economic considerations to attain sustainability (Elkington, 1998).

2.2.2.5 Life Cycle Management (LCM)

Life Cycle Management (LCM) is a business strategy implemented across industrial and service sectors to enhance products and services, concurrently improving the overall sustainability performance of the business and its value chains (UNEP-SETAC & Initiative, 2009). LCM operationalizes life cycle thinking and product sustainability reducing businesses' environmental and socio-economic impacts while maximizing economic and social values. Rather than focusing solely on short-term business success, LCM directs businesses towards long-term achievements and sustainable value creation. Therefore, LCM necessitates a comprehensive perspective and a deep understanding of the interdependence of businesses to inform relevant decisions and actions. This approach aims to enhance sustainability performance by considering both environmental and social benefits while simultaneously providing numerous opportunities for value creation within the business.

2.3 General overview of LCT in civil engineering and road pavements

Road pavements play a crucial role in transportation infrastructure, providing the foundation for mobility and connectivity in our societies. A road performance embraces both technical requirements and sustainability aspects. It is important to go beyond and consider environmental, economic and social aspects.

Infrastructure is a crucial part of the SDGs promoted by the United Nations. Specifically, SDG 9 aims to 'Build resilient infrastructures, promote inclusive and sustainable industrialization and foster innovation'. Regarding infrastructures, it is recommended that they are built to meet the criteria of quality, reliability, sustainability, and resilience. Moreover, assessing the sustainability of road pavements entails complying with Goal 13 "Take urgent action to combat climate change and its impacts".

In this context, improving road pavement sustainability is becoming a duty and the lifecycle-based techniques represent valid support. By assessing the environmental, social, and economic impacts at each stage, researchers can develop a holistic understanding of how road pavements contribute to or detract from the broader objectives outlined in the SDGs.

Starting from the currently available standards in the sector and investigating the current applications of the life cycle-based techniques, this research delves into the complexities of integrating sustainability into road pavement practices, aiming to tracing the path towards more sustainable roads.

2.3.1 Current EN standards for civil engineering works

Specific regulations for the sustainability assessment of construction projects are required. The challenge of developing an EU standard on this matter has been accepted by the European Committee for Standardisation Technical Committee 350 (CEN/TC350) "Sustainability of construction works". Construction works are then divided into two groups: building and civil engineering works. The committee has then developed a series of European Standards addressing environmental, economic and social aspects in a life cycle perspective for both of the two groups, specifically for buildings. The idea is to ensure that construction practices are aligned with sustainability principles and to facilitate the calculation of impacts consistently.

The committee defines a holistic concept of sustainability, that encompasses environmental, social and economic along with technical and functional performance, as shown in Figure 2-7. While the evaluation of technical and functional performance is not included in this set of standards, recognizing their interdependence with environmental, social, and economic performance is essential for assessing the sustainability performance of civil engineering works and is thus considered.

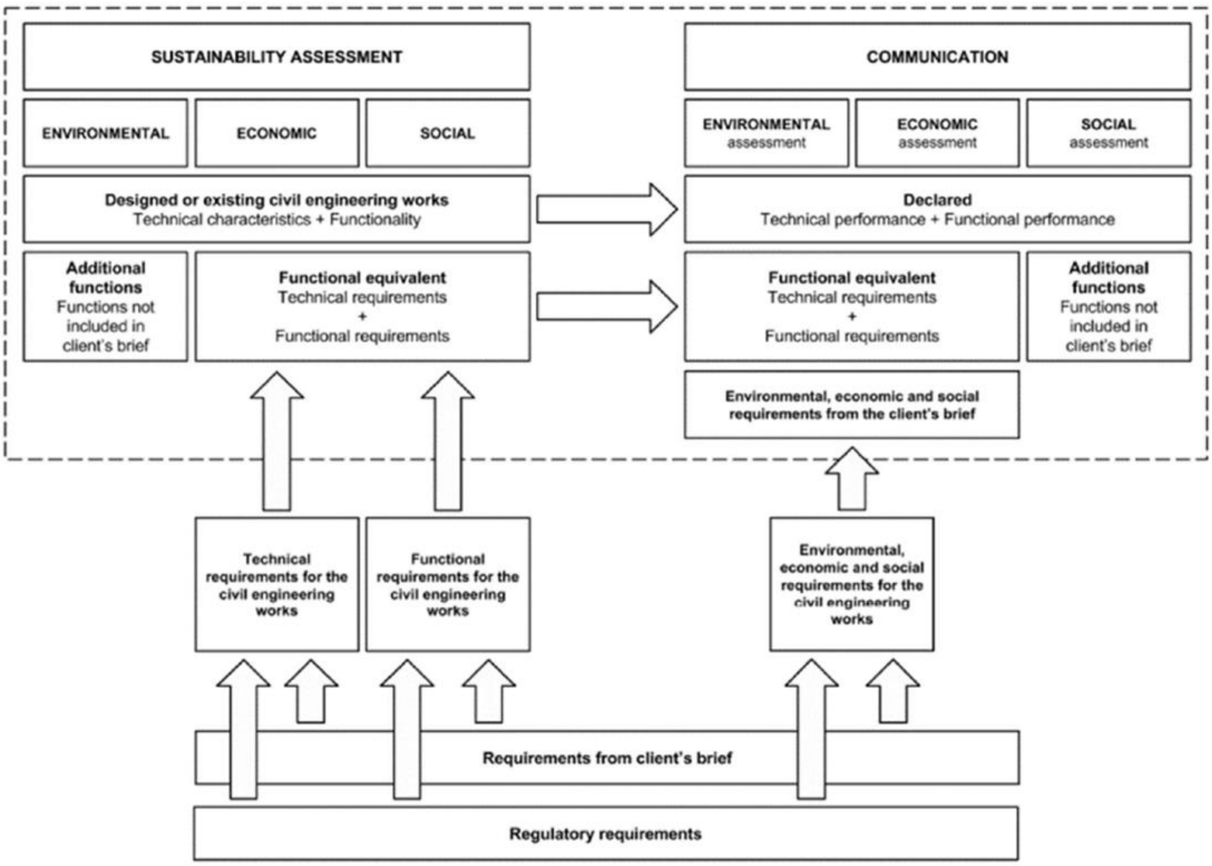

Figure 2-7 - Concept of sustainability assessment of civil engineering works according to prEN 17472.

The European Committee for Standardisation (CEN) Technical Committee 350 (CEN/TC350) is in charge of defining standardized methods for the assessment of construction works (buildings and civil engineering works). It is also responsible for the advancements of Product Category Rules (PCR) for construction products and for their Environmental Product Declarations (EPD).

In 2017, the CEN/TC350/WG6 focused on civil engineering works and produced the "EN 15643-5 Sustainability of construction works - Sustainability assessment of buildings and civil engineering works - Part 5: framework on specific principles and requirement for civil engineering works". This was the initial attempt to standardise the SA of civil engineering works and, after its release, being road pavements part of the civil engineering works, all the European studies should comply with it.

These standard forms part of the EN15643 series (Table 2-1) and follows a life cycle approach, as do other standards in the series. The structure of the series is composed of three levels of investigation.: 1) Framework level, to establish general principles and requirements for the SA of a system; 2) Work level, to provide a calculation methodology for the assessment of a system; 3) Product level, to define the Product Category Rules (PCR) for the construction products and define a structure for the Environmental Product Declarations (EPDs). Concerning the standard for civil engineering works, it is quite wide. It does not define the specifications for the different typologies, giving general guidance.

Table 2-1 - Levels for standardisation of construction works (adapted from EN 15643)

	Buildings	**Civil Engineering Works**
Framework level	EN 15643-1 Sustainability of Construction Works – Sustainability Assessment of Buildings Part 1: General Framework	EN 15643-5 Sustainability of Construction Works – Sustainability Assessment of Buildings and Civil Engineering Works Part 5: Framework on specific principles and requirement for civil engineering works
	EN 15643-2 Assessment of Buildings Part 2: Framework for the assessment of environmental performance	
	EN 15643-3 Assessment of Buildings Part 3: Framework for the assessment of social performance	
	EN 15643-4 Assessment of Buildings Part 4: Framework for the assessment of economic performance	
	EN 15978 Assessment of environmental performance of buildings – Calculation	

Works level – Calculation methods	method	EN 17472 Sustainability Assessment of civil engineering works -
	EN 16309 Assessment of social performance of buildings – Calculation method	
	EN 16627 Assessment of economic performance of buildings – Calculation method	
Product level	EN 15804:2021 + A2:2019 + AC:2021 Environmental Product Declarations – Core rules for product category of construction products	
	EN 15942 Environmental Product Declarations – Communication format - Business	
	CEN/TR 15941 Environmental Product Declarations – Methodology for selection and use of data	

It is important to note the attention paid to performing harmonised LCAs of the products, providing a specific standard (EN 15804:2012 + A2:2019) with the Product Categories Rules (PCR). It defines a common framework for the LCA of construction products and delivers the Environmental Product Declaration (EPD).

The EN settled different kinds of LCA, and consequently different kinds of EPDs, according to the selected system boundaries, such as:

- cradle-to-gate (A1-A3),
- cradle-to-gate with options (A1-A3 mandatory + other stages optional),
- cradle-to-gate with options and module C1-C4 and D (A1-A3 and C1-C4 + D mandatory, B optional)
- cradle-to-gate with module C1-C4 and module D (A1-A3 + C1-C4 + D)
- cradle-to-grave and module D (A1-C4 + D).

The standard also specifies the cut-off criteria, and the data quality, regulates the allocation and suggests the impact categories to calculate.

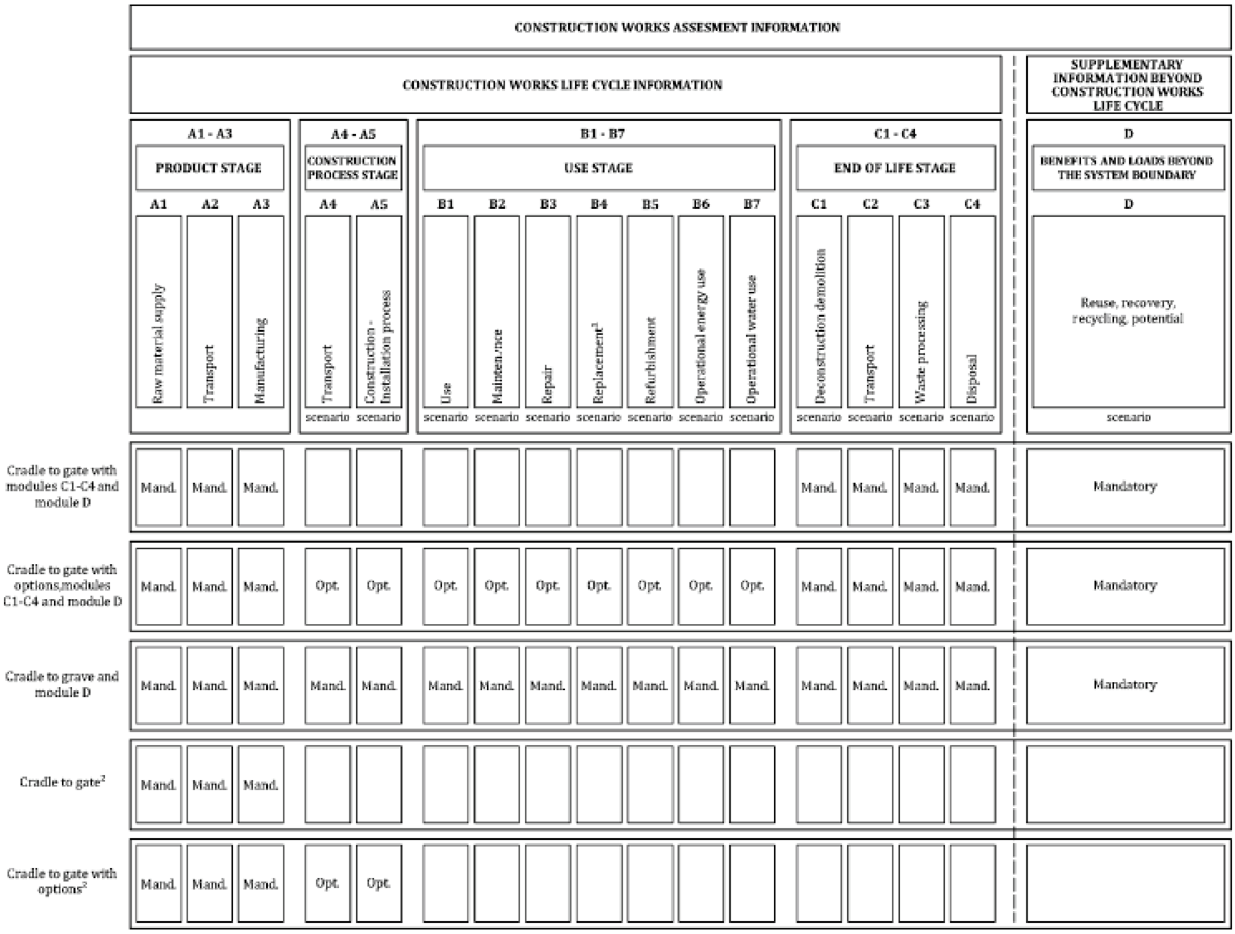

Figure 2-8 - Types of EPD concerning life cycle stages and modules covered for the assessment of construction works (adapted from EN 15804:2012 + A2:2019)

The EN 15978:2011 provides a "Building model" to guide the SA exercises for buildings (Figure 2-9). The model has the aim of facilitating the calculation, describing the physical characteristics of the object, and subdividing the building into parts and levels (element level, component level and product level). For instance, in the façade (part) the cavity wall and façade openings (element level) can be distinguished. The cavity wall can be made of plaster, calcium silicate blocks, insulation, wall tires and bricks (product level), while the façade openings can be made through a window or a door (component level). The window is composed of a frame, double glazing, rubber tightening and hinges locks (product level), while the door is composed of a door frame and insulated door (product level).

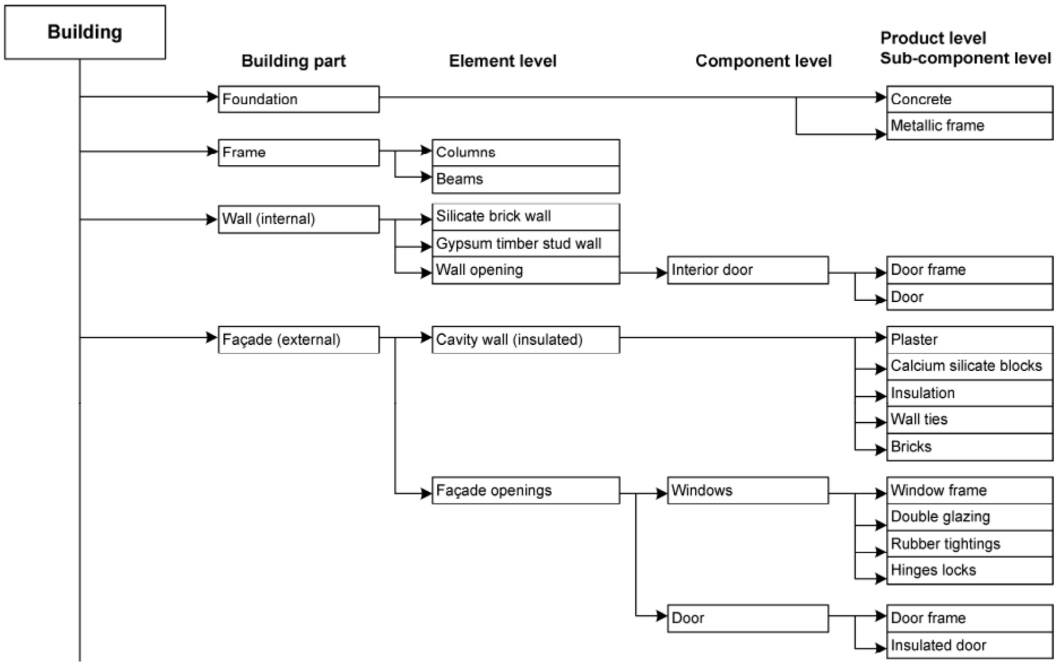

Figure 2-9 – Part of the building model as reported in the EN 15978:2011

2.3.1.1 Sustainability Assessment of civil engineering works – EN15643-5

The EN15643-5 is a crucial document aimed at fostering the harmonisation of SA practices in civil engineering works. It plays a fundamental role, in delineating principles and defining requirements for the assessment process. The objectives of the Sustainability performance assessment of civil engineering works are settled as: 1. Determinizing the sustainability aspects and impacts of the civil engineering works; 2. allowing the client, users and designers to make decisions and choices that meet sustainability requirements; 3. communicating the sustainability performance.

The key requirements include the ones for:

- object of the assessment: it encompasses the consideration of some key aspect of the assessment, such as the system boundaries, the declared/functional unit or functional equivalent, and the analysis period;
- data type and data quality: data types are established (i.e. primary, secondary) and the parameters to perform a data quality are provided. They include accuracy, precision, completeness, representativeness, ensuring a robust foundation for the assessment process;

- Reporting and communication: it elucidates how the results should be organized and provided. It is suggested to report and communicate according to the information modules. This facilitates the comprehension of the outcomes and the eventual dissemination;
- assessment method: they include the specification for the ISO standards for the assessment (i.e. 14040), the indicators categories for the environment (i.e. water use, energy use), society (i.e. accessibility, health and comfort) and economy (i.e. life cycle cost).

By delineating clear principles and stipulating essential requirements, the EN15643-5 provides a robust framework for conducting assessments in a harmonized way. Including environmental, societal, and economic dimensions assures a comprehensive approach.

2.3.2 LCA of road pavements

This sub-section wants to investigate the current practices of LCA in road pavements, focusing on case studies and available framework and PCRs.

2.3.2.1 FHWA Framework

The Framework for LCA of Pavements (FHWA, 2014) is an important document issued by the Federal Highway Administration (FHWA), to help the road agencies in the implementation of greener practices. The Framework defines some main features for the LCA, suggesting: 1. which life cycle stages to include in the assessment (full life cycle as default); 2) the functional unit, defined as a full pavement section; 3) the analysis period, typically 30-40 years; 4) the cut-off criteria as the 5% for all the flow; 5) the data quality (specifying the coverages required, i.e. technological) and the allocation. It also introduces the concept of physical boundaries, defined as the "portions of pavement structure to be considered part of the pavement system at the location(s) included in the study […] to define volumes, masses, surface areas and other quantities" for the LCA (FHWA, 2014).

2.3.2.2 PCRs and EPDs for the road pavements industry

Different institutions have already provided PCRs for road materials and pavements, to guide practitioners in in the calculations. Each institution defined the system boundaries, the declared unit, the cut-off criteria and the rules for allocation and data quality, as well as the calculation method to use.

For example, the National Asphalt Pavement Association (NAPA) issued a PCR valid for the USA, while the European Asphalt Pavement Association (EAPA) provided its own Guidance Document for PCR and EPD for asphalt mixtures in Europe. Some other countries (i.e. Italy and Norway) published their PCR for the road pavement sector. (Carrión et al., 2021; EAPA, 2017a)

Table 2-2 shows a summary of the main features of PCR for asphalt mixtures and pavements.

Table 2-2 - Summary of main features of PCRs for asphalt mixtures and pavements

	Object of assessment	System boundaries/LC stages	Functional / Declared Unit	Cut-off criteria	Data quality	Allocation	LCIA
NAPA 2017	Asphalt mixture	Cradle-to-gate (A1 to A3)	Declared unit 1 short tonne of asphalt mixture	1% of the total energy used in the foreground unit processes (i.e., fuels and electricity based on lower heating value) or 1% of the total mass inputs for the foreground unit processes (excluding fuels) whichever is lesser. Total sum < 5%	• Temporal Representativeness (Age) • Technological Representativeness • Geographical Representativeness (Geography) • Precision • Uncertainty • Completeness	According to ISO 14044 Recycled/reclaimed materials, such as RAP, RAS, GTR, and RFO, are treated as waste material without economic value.	TRACI 2.1: • Global warming potential • Depletion potential of the stratospheric ozone layer • Acidification potential of land and water • Eutrophication potential • Smog formation potential
EAPA 2017	Asphalt mixture	Cradle-to-gate (A1 to A3)	Declared unit 1 metric tonne of asphalt mixture	1% of the total energy used in the foreground unit processes (i.e., fuels and electricity based on lower heating value) or 1% of the total mass inputs for the foreground unit processes (excluding fuels) whichever is lesser. Total sum < 5%	• Age (<5years) • Representativeness • Geography • Use local data when available, and then regional or national • Alternative data sources modified with the local energy mix may be used • Precision (two significant figures) • Units (metric units) • Completeness • Uncertainty (sensitivity analysis)	According to ISO 14044 Bituminous binder according to LCI of bitumen from Eurobitume Recycled materials: a) The upstream impacts are excluded b) Impacts associated with the processes involved in preparing the recycled material are included	European Reference Life Cycle Database (ELCD): • global warming; • ozone depletion; • acidification of land and water; • eutrophication; • photochemical ozone creation; • depletion of abiotic resources (elements) (from CML); • depletion of abiotic resources (fossil) (from CML).

						Additives: mass-based allocation	
The International EPD System 2017	Asphalt mixture	Cradle-to-gate (A1 to A3)	Declared unit 1 metric tonne of manufactured asphalt mixture	Cut-off criteria to be met on the level of the modelled product system are the qualitative coverage of at least 99% of both the energy, the mass, and the overall relevance of the flows	• Age (<5years) • Representativeness (>5%) • Completeness	According to ISO 14044 Processes generating overall revenue of the order of 1% or less may be neglected. Other cases: table available If there is an inflow of recycled material to the production system, the recycling process and the transportation from the recycling process to where the material is used shall be included. If there is an outflow of material to recycling, the transportation of the material to the recycling process shall be included. Impacts associated with the processes involved in preparing the recycled materials for use in the asphalt mixture is	According to EN 15804: • Global Warming Potential: ○ Fossil ○ Biogenic ○ Land use/land transform ○ Total • Acidification potential • Eutrophication potential • Formation of tropospheric ozone • Abiotic depletion potential – elements • Abiotic depletion potential – fossil • Ozone layer depletion • Use of resources (all) • Waste (all)
	Asphalt mixture	Cradle-to-gate with options (A1 to A4)	Declared unit 1 metric tonne of manufactured asphalt mixture delivered to the construction site				
	Pavement activity	Cradle-to-gate with options (A1 to A5)	Functional Unit A paved surface of 1m², which fulfils the specified quality criteria during the Reference Service Life				
	Pavement activity	Cradle-to-gate with options (A1 to A5 + B1 and B4 minimum	Functional Unit A paved surface of 1m², which fulfils the specified quality criteria during the Reference Service Life of the construction				

			(default value of 40 years)			considered part of the system boundary. Landfilling has to be attributed to the studied process Incineration – see document	
The Norwegian EPD Foundation	Asphalt mixture	Cradle-to-gate with options (A1 to A3)	Declared Unit 1 tonne of manufactured asphalt mixture	As in EN15804	As in EN15804	As in EN15804 Allocation according to mass [kg] is used. Co-product allocation is relevant when several products are produced, transported or handled in the same process. For asphalt, this can occur for example when the asphalt raw materials (or their ingredients) are produced and transported or when asphalt is produced. In asphalt production and all transports, mass allocation shall be used Recycled asphalt used in new asphalt shall carry the burdens from the recycling process, and the transport from the place where it is removed to the recycling process shall be	The impact categories listed in EN 15804 shall be used, including the additional indicators listed in Clause 7.2.3
	Pavement activity	Cradle-to-gate with options (A1 to A5)	Functional Unit 1 m² surface covered with asphalt, which fulfils the specified quality criteria during the service life of asphalt surfacing.				
	Pavement activity	Cradle-to-gate with options (A1 to beyond A5)	Functional Unit 1 m² surface covered with asphalt, which fulfils the specified quality criteria during the Estimated Service Life of a construction work				

						included.	
The International EPD System 2018	Highways (except elevated highways), streets and roads	Cradle-to-gate (A1-A3 mandatory) Cradle-to-gate with options (A1-A3 mandatory + optional modules) Cradle-to-grave (A1-A3, A4-A5, B1-B7, C1-C4)	Declared unit 1 m² of road Functional unit 1 m² of road with a specific intended use	Life cycle inventory (LCI) data for a minimum of 99 % of total inflows to the core module shall be included. Inflows not included in the LCA shall be documented in the EPD. It is important to emphasize that – in most cases – all available data shall be used. Using cut-off rules should not give the perception of "hiding" information but rather, facilitate the data collection for practitioners	• Age (<5years) • Representativeness (>5%) • Completeness	As in 14040 If there is an inflow of recycled material to the production system, the recycling process and the transportation from the recycling process to where the material is used shall be included. If there is an outflow of material to recycling, the transportation of the material to the recycling process shall be included. The material going to recycling is then an outflow from the production system as an indicator Landfilling has to be attributed to the studied process Incineration – see document	• Global Warming Potential • Acidification potential • Eutrophication potential • Photochemical oxygen creation potential • Abiotic depletion potential – elements • Abiotic depletion potential – fossil • Ozone layer depletion • Use of resources • Waste
PCR EPDItaly022 – Use of Highways, streets, roads and airfields	Highway streets, roads and airfield	For Roads and Highways: cradle-to-gate with options" (A1-A3, A4-A5, B1 – B7, C1-C4 + D optional)	Declared unit the entire road for all the mandatory life cycle stages	It can be possible to exclude materials or energy flows whose impact is lower than 1%. The total amount of excluded processes shall	• Time-related representativeness • Geographical representativeness	Allocation shall be avoided; it is preferable to separate the unit process and create sub-processes. Therefore, the environmental data can be collected for each sub-process separately.	• Climate Change • Ozone Depletion • Human Toxicity – cancer effects (CE)* • Human Toxicity-non-cancer effect (NCE)

2.3.2.3 Application and inconsistencies of LCA for road pavements

The use of LCA in the road pavement sector has notably grown in recent years (Aryan et al., 2023). The databases have witnessed a proliferation of studies since the year 2006. However, despite the popularity of LCA, carrying out LCA without a specific standard or reference framework engenders a range of challenges and inconsistencies, linked to the choices made in the four phases of an LCA. The following paragraphs itemize the current practices and show problems, subdividing them into the above-mentioned four phases.

- *Goal & Scope definition*

This phase is a critical initial part of any LCA, aiming at outlining objectives and key aspects of studies. Firstly, it articulates the goal of the study: it is usually the environmental assessment of materials (A1-A3) (and their eventual comparisons) or project alternatives (and their eventual comparisons). Secondly, it is important to define the boundaries of the system, estimating the life cycle stages that will be examined. Various studies have presented different approaches. The cradle-to-gate approach is commonly used, followed by cradle-to-laid, whereas the B phase and end-of-life stages have received less attention, and the D module has not been considered by any researchers (Aryan et al., 2023; Del Rosario & Traverso, 2023; Santero et al., 2011a). However, limiting analysis to a cradle-to-gate/laid approach would be shortsighted, as the use phase, which is intricate due to various environmental impacts, actually has the greatest impact (Santero et al., 2011b; Santero & Horvath, 2009). The evaluation should include impacts related to usage, as well as maintenance operations. Some example of phenomena to consider in B1 are albedo, concrete carbonation, Pavement Vehicle Interaction (PVI), noise, urban heat island, and leachate (Aryan et al., 2023; Santero et al., 2011b). The increase in vehicle consumption caused by the construction of the area, which has an impact, is often ignored (Alaloul et al., 2021), despite being a crucial issue (Santero & Horvath, 2009).

C phase is challenging to evaluate due to the lack of a definitive end-of-life for pavements and the difficulty in assessing it. For instance, only 15% of the studies considered in the literature review performed by Aryan et al (2023) consider the end-of-life. It emerges that several studies, because recycling pavements are not a common practice in all countries, account for transportation but not for recycling practices (i.e. (R. Liu et al., 2015)

Thirdly, it identifies the declared/functional unit (DU/FU), defined as the quantified performance of a product system for use as a reference unit in a life cycle assessment study (ISO, 2006a; UNEP, n.d.-b). When materials are assessed, the DU is assumed to be one ton of asphalt mixtures (NAPA 2017, EATA 2017, The International EPD System 2017, and The Norwegian EPD Foundation 2017). When pavements are assessed, the FU should specify dimensions, indicators and criteria of performance (Aryan et al., 2023). Due to their complexity, pavements are not easily linkable to a single functional unit and for this reason, some inconsistencies are found. Many previous studies solely focused on dimensional aspects by selecting the m2 or the pavement area to be constructed, whereas functional aspects (such as ADT and RSL) were sparsely included (Buttitta et al., 2023, Athena, 2006). Due to the broad range of functional units, the results can't be amalgamated and juxtaposed.

Finally, in this phase, the practitioners should determine the impact categories and corresponding indicators to be assessed. It is important to note that some metrics, , such as energy consumption or CO2, may be favored over others, with the risk of disregarding some important environmental issues, such as land use, and water consumption (Carrión et al., 2021; Santero et al., 2011a).

There are several noteworthy indicators, including Abiotic Depletion fossil (ADP fossil), Acidification (AP), Eutrophication (EP), Global Warming (GWP), Human

Toxicity (HTP), Ozone layer Depletion (ODP), and Terrestrial Ecotoxicity (TEP) (Aryan et al., 2023; Santero et al., 2011a).

Some studies do not use impact categories, but report environmental burdens in terms of chemical compounds, like NOx, volatile organic compounds (VOC), etc. (Arthur Wai-Cheung Chan, 2007; Horvath & Hendrickson, 1998; Teri, 2017; Zhang et al., 2010). These studies should be better classified as LCI since they do not perform impact assessment, as defined by ISO 14040.

- *Life Cycle Inventory (LCI)*

Quantifying inputs and outputs require a huge amount of data, collected in this phase. It follows that the LCI is the most time-consuming step of any LCA, which is strictly dependent on the data quality.

As indicated, primary data, hence data highly specific for the case studies, collected from partners, is preferable to secondary data, obtained through databases and literature.

The researchers usually utilize both data types. It is not always easy to find primary information on impacts due to materials extraction and/or production. Some studies, such as (R. Liu et al., 2015), collected data directly from the work site. Others used databases, for instance, Ecoinvent, national averages (Batouli et al., 2017) or available reports, such as Eurobitume for bitumen impacts (Moretti et al., 2022; J. Santos et al., 2015).

Very few studies analyze data quality, as suggested by ISO and JRC (Zampori L. et al., 2016).

- *Life Cycle Impact Assessment (impact categories, methodology)*

This phase converts the inventory data into indicators using different methodologies available that group pollutants into impact categories based on the underlying environmental mechanisms. The selection of the methodology is highly significant because impacts can differ for similar impact categories when employing various methods (Grael et al., 2021). For example, Grael et al., (2021) evaluated the same system with different methods. It emerged that the difference in Global Warming Potential (GWP) between ReCiPe and IPCC methods was less than 2%, while ReCiPe underestimated Terrestrial Acidification by 6% compared to CML and overestimated Freshwater Eutrophication by 14% compared to EDIP.

Looking at the literature, the most used methods are Recipe and CML (Aryan et al., 2023), while recently the European Commission suggested to use of EF 3.0 for EPD and CF (to check). These databases are usually incorporated into LCA software and tools, such as Simapro (the most used one) or GaBi (Aryan et al., 2023). The use of this software is not mandatory, such that some studies use also an Excel spreadsheet, but it is suggested since it allows other many functionalities, such as uncertainty or sensitivity analyses.

- *Interpretation of the results*

This fourth phase is crucial to understand the implications of the assessment. Various tools can be used to enhance the robustness of the results (Wei et al., 2015) and reliability (Huijbregts et al., 2003), such as normalization, sensitivity and uncertainty analyses. Aryan et al. report that, out of 67 studies considered, only 27% carried out a sensitivity analysis, only 9% a uncertainty analysis and 6% both of them. The methodology commonly used in the propagation step of the uncertainty analysis is the Monte Carlo simulation. Concerning the sensitivity analysis, the parameters used were the variation of energy demand (Huang, 2009), technical parameters (i.e. lane width, IRI, albedo) (Loijos et al., 2013; Tang et al., 2020), service life (white et al.) and transport distances (Schlegel et al., 2016).

2.3.3 LCC of road pavements

In the last year, the application of LCC has playing an important role in pavement design and management (Lamptey et al., 2004). It is crucial to evaluate the economic effectiveness of different materials and pavement types over their entire lifecycle, facilitating decision-making for the most beneficial investments (Babashamsi et al., 2016). The LCC can be influenced by several aspects, such as the cost function, the time, the agency and user costs, and the maintenance costs. Some of these parameters depend on the selected system boundaries (i.e. if the B phase is included, maintenance and user costs should be assessed), but not always consistent approaches are used. While the cost function and agency costs are always assessed, most of the studies disregard the Road User Cost and the safety performance (Alaloul et al., 2021). The cost function expresses the production costs in terms of the amount produced and integrating the time variable allows for quantify the delays to pavement performance and serviceability (Jung et al., 2022), while the agency cost includes the initial construction costs plus the operations due to maintenance. The user costs are linked to pavement conditions and rehabilitation operations with consequent traffic delays (Maria et al., 2012) and maintenance management costs can affect the overall cost in a significant way, including all the expenses due to milling and overlaying.

Some inconsistencies are noticeable in the methodologies used to quantify the economic performance of road pavement (Alaloul et al., 2021).

2.3.3.1 Initiatives and Projects

Many efforts have been carried out to apply Life Cycle Costing in the evaluation of economic aspects linked to design, materials, maintenance strategies and end-of-life treatments (i.e. determining the benefits of a maintenance strategy, or estimating the initial and future costs to be afforded by an NRA.). Table 2-3 shows the most used tools worldwide for the assessment, as well as the current reference standards and current practices. Concerning the first one, two examples are reported: Real Cost, a specific tool for evaluating LCC of pavements and their maintenance, developed by FHWA, and SMART PP, used also for accounting environmental impacts. Three main references have been found: the EN 15643-4 Assessment of Buildings Part 4: Framework for the assessment of economic performance (EN 15643-4, 2012), the ISO 15686-5:2017 - Buildings and constructed assets - Service life planning - Part 5: Life-cycle costing and Federal Highways Administration's LCC Primer (U.S. Department of Transportation, 2002). Concerning the iniatives, the Trafikverket (Swedish Transport Administration) uses LCC for planning, procurement and design of each one of its projects, while the California Department of Transportation defined a LCC procedure manual and asked for LCC on all project that requires a pavement cost component (with some exceptions).

Table 2-3 – Tools, references and examples for LCC in road pavements

Tools	
Name	**Description**
Real Cost LCCA (US, CA)	Calculation of LCC for a pavement selection in accordance with FHWA best practice methods.
SMART SPP - innovation through sustainable procurement	Used to perform LCC and calculate also some emissions (CO2, CO2eq, NOx, SO2, NMHC and PM) of different products and services.
References	
EN 15643-4 Assessment of Buildings Part 4: Framework for the assessment of economic performance (EN 15643-4, 2012)	
ISO 15686-5:2017 - Buildings and constructed assets - Service life planning - Part 5: Life-cycle costing	
Federal Highways Administration's LCC Primer (U.S. Department of Transportation, 2002)	
Examples of applications within NRAs	
Trafikverket (Swedish Transport Administration) uses LCC for the planning, procurement and design of each one of its projects. The California Department of Transportation defined a LCC procedure manual and asked for LCC on all project that requires a pavement cost component (with some exceptions).	

2.3.3.2 FHWA Primer for Life Cycle Costing

In 2002, the Life-Cycle Cost Analysis Primer was introduced by the Federal Highway Administration's (FHWA) Office of Asset Management (FHWA, 2004). This tool was designed to explore the application of Life-Cycle Costing (LCC) in line with EU standards. The aim was to assess various infrastructure investment options, showcasing the valuable role of such analysis in making economically sound decisions.

The Primer outlined a structured approach with five key steps for conducting LCC:

1. Define design alternatives;
2. Determine activity timing,
3. Estimate costs (both agency and user);
4. Calculate life-cycle costs;
5. Analyze the results.

The approach is explained in Chapter 2, and it has already applied in several research in the world, demonstrating its easy applicability (Buttitta et al., 2023).

2.3.3.3 Applications

In literature, several researchers have tried to evaluate the economic performance of materials and pavements using LCC. Most of the research includes LCC and LCA, as reported by Aloul (2021), while few available papers concern only the economic assessment (i.e. (Jung et al., 2022)

Most are used to quantify the costs considering the maintenance scenarios and the various interventions required during the life cycle, while few of them stop at a cradle-to-gate analysis.

The costs for production were analysed to quantify the economic benefits of using high amount of RA content for European wearing courses. It emerged that with 60-90% RA content, the cost reduction goes from 25 to 60% (Buttitta et al., 2023).

A wider life cycle was considered for evaluating the costs alongside the life cycle of asphalt and concrete overlay methods (Jung et al., 2022), showing the importance of LCC in choosing the most beneficial option. It emerges that asphalt overlay at the initial construction is more expensive than concrete overlay, but in 20 years, the overlay with concrete is a more efficient choice because of its longer repair length. It emerged that traffic operations measures are fundamental to reducing cost and dissatisfaction of road users.

Rehabilitation and end-of-life scenarios, besides construction costs, were included in an LCC used to assess the economic benefits of using Asphalt Concrete Pavement rather than Plain Cement Concrete Pavement (Helder, 2017), showing a reduction of 30% in terms of cost. Other studies have already proved a cost reduction, variable on maintenance, materials and other conditions (Guo et al., 2019; E. B. Lee et al., 2018).

2.3.3.4 Integration of LCA and LCC

The integration of LCA and LCC has emerged as a pivotal approach in the domain of pavement projects, helping all the parties in identifying the most beneficial choice, in terms of economic and environmental burdens.

A contribution to the integration of these two dimensions is the framework proposed by Alaloul et al. (2021), which integrates LCA and LCC at various stages of pavement projects. The authors emphasize the importance of assessing user activities, such as travelling time and safety, thereby incorporating crucial aspects in the assessment.

Environmental and economic aspects were also integrated in the definition of a framework for the assessment of highways in China (Hou et al., 2022). it addresses nine aspects: air pollution, water pollution, solid waste pollution, noise pollution, energy consumption, pre-project cost, project construction cost, project operation cost, and post-project cost. The framework relies on an assessment index system, aligning with regulations and standards, with target, criterion, sub-criterion and index layers, and employs the Multi Criteria Decision Making (MCDM).

Furthermore, another study integrates LCA and LCC to assess the sustainability of porous pavements compared to traditional asphalt pavement across various traffic volumes and structures (J. Liu et al., 2020). Employing equivalent coefficients to translate environmental impacts into economic terms, the study reveals that while porous pavements exhibit higher environmental impacts, their overall cost, translated using the chosen coefficients, can be lower than the conventional pavement. Despite the higher initial costs, the equivalent calculation results suggest that, under the specified conditions, the economic value derived from the environmental profits can offset the initial cost difference.

In essence, the integration of LCA and LCC can offers a lens to holistically assess the intricate interplay between economic viability and environmental sustainability in pavement projects. Nevertheless, balancing economic considerations with environmental impacts, social factors, and other criteria may pose challenges, especially when different stakeholders have conflicting priorities.

2.3.4 S-LCA of road pavements

Within the context of road pavement evaluation, the social component has still a marginal importance, with limited attention given to it. There are only a few studies addressing this topic. Some of these studies consider social indicators that are not related to the S-LCA (Sustainable Life Cycle Assessment), while others apply the Guidelines (UNEP, n.d.-a) and Methodological Sheets (UNEP, 2021) to conduct their evaluation. As highlighted by Del Rosario et al (2023), out of the fifteen studies that consider social aspects, only four mention the UNEP documents, and both of them are included in this group. Both of them were provided by the United Nations Environment Programme (UNEP), in the context of a lack of specific standards. The Guidelines provide specific rules for the assessment, representing a skeleton to guide practitioners throughout the exercise and providing examples and references. The Methodological Sheets is a supplement for the first one and is developed as a public resource to guide the application of S-LCA.

These available guidance documents for S-LCA provide a lot of flexibility to the practitioners in terms of stakeholders to consider, indicators to choose or scales to use. This lack of specificity hinders the application of the method, due to the absence of specific instructions for the conduction of S-LCA studies in particular sectors. Furthermore, the lack of specific guidelines leads often to inconsistent and unreliable results. These issues are also evident in the road sector. Moreover, besides this methodological gap, the social aspects are often underrepresented in the SA of roads.

The research wants to provide an overview of the studies which looks at the social component, in a life-cycle-based approach and not, for two main reasons. The first one is to focus on the current state-of-the-art of international and European standards. This allowed us to identify previous initiatives in connection to the assessment of the social performance of roads. The second one is to evaluate which social indicators were assessed in scientific works and SRS. The review revealed a limited number of studies, both in road and in construction sectors.

The EN standards suggest assessing the social performance of civil engineering works, providing a set of different indicators which could affect society. These indicators are not assessed through an S-LCA methodology and they are referred to accessibility, health and wellbeing (i.e. workers' health and comfort), impacts on the neighbourhood (i.e. noise), safety and security.

Several studies address the social dimension considering pavement aspects linked to the human sphere (i.e. noise, safety), as reported in Table 2-4. These studies do not take into account the UNEP documents, providing indicators more linked to pavement engineering. The safety aspect is very often considered (Kadhim, 2020), as well as the noise (Inti et al., 2019). All the considered studies use their indicators for the assessment.

Table 2-4 - Social indicators (not S-LCA based) found in the analyzed papers

SAFETY	MOBILITY	HEALTHY COMMUNITY
Annual crashes/mile (Tatari et al., 2016)	Traffic delay costs (Inti et al., 2019)	Construction Noise (Bryce et al)
Safety audits and safety inspections (Santos)		Complete Streets (a street for all, pedestrians, cars, bicyclists, and buses) (Krishna R. Reddy)
increase in accidents due to increased roughness, dust, and reduction in friction (Ian Van Wijk)	Time lost due to queuing at construction or maintenance (Bryce et al)	Traffic noise (Sundeep Inti, Bryce et al)
Saving in the fatalities and serious injuries (Kadhim et al., 2020)		Air pollution (Ali J. Kadhim)

The other investigated studies take into account the UNEP Guidelines. All of them identified workers, the local community and society as the most relevant stakeholders (i.e.(da Rocha et al., 2022). Other studies also pointed to consumers (Balasbaneh & Sher, 2021; Zheng et al., 2019) and value chain actors (Balasbaneh & Sher, 2021) as further stakeholder groups that should be considered. It is interesting to note that studies that deviate from the UNEP recommendations introduce variations on the definition of stakeholders (Consumers are called Occupant by Tighnavard (2021) or introduce a new one (i.e. "local beneficiaries identified favouring black women, youth and disabled individuals" as Blaauw et al. (2021).

Even if the studies are declared guidelines-compliant, there is also a great variety in the choice of indicators belonging to the same subcategory (Table 2-5). As an example, concerning the indicators “workers” and the subcategory “working hours”, Zheng et al., (2019) assesses “Average working hours per month” and “Compensation strategies on overtime work”, while Dong (2015) assesses the weekly working hours. No other study investigates this aspect, which, although regulated by national contracts and laws, is probably a fundamental aspect of workers' quality of life.

Table 2-5 - Social indicators (S-LCA based) found in literature review

Stakeholder	Sub-category	Indicators
Local community	Local employment	Rate of local workforce hired
		Employment generation
		Use of technology to promote job creation
		Use of local labour
	Safe and healthy living conditions	Management behaviours to relieve local traffic congestion and accident incidences
		Management behaviours to reduce pollution emissions
		Complaints of the local community
		Pollution level
		Disease burden
	Access to material resources	Management measures for the sustainable use of local materials
		Soil occupation alteration
		Water use level
		Minerals resources extraction
	Cultural heritage	Inclusion of Local Heritage
		Protection of local cultural heritage
Workers	Working hours	Average working hours per month
		Compensation strategies for overtime work
	Equal opportunities/ discrimination	Rate of women employed
		Equal opportunities for different ethnic groups
		Equal opportunities for different genders
	Health and Safety	Management measures of daily work-related injuries
		Preventive measures on occupational diseases
		Occupational Accident
		Health Environment
	Child labor	Child labour control

Stakeholder	Sub-category	Indicators
		Use of child labour
	Freedom of association and collective bargaining	Rate of labor union organization
		Collective bargaining
		Union membership
		Management efforts to deal with labor dispute
Society	Public commitment to the sustainability issue	Obligation on public sustainability reporting
	Corruption	Execution of anti-corruption program
	Technology development	Strategies to promote the application of new materials construction technology
Consumers	Health and Safety	Solutions to keep satisfactory pavement PQI
		Noise due to tire and road surface interaction
	Feedback	Presence of consumer complaints
Value chain actors	Fair competition	Fair Competition
	Supplier	Supplier relationship

Furthermore, the same topic is often addressed using different indicators, but quite similar among them. For instance, for the local community - local employment, we found the "rate of the local workforce hired" (Zheng et al., 2019) "Employment generation" (da Rocha et al., 2022),"use of local labour" (Dong & Ng, 2015). It also happens that the studies do not specify what is considered behind these indicators (i.e. da Rocha et al., 2022).

The state-of-the-art shows that many identified sub-categories are often neglected, without a clear scientific justification. Moreover, studies that carry out a social assessment without following the guidelines provide an incomplete picture, focusing on technical/functional aspects of the pavements (i.e., safety and functional performance) and considering environmental aspects (i.e., climate change and pollution), while completely omitting workers-related indicators (Blaauw et al., 2021). These studies consider social performance as more related to the performance on traffic noise, traffic delay and vehicle operating costs (Inti et al., 2019; Inti & Tandon, 2021). All of the impacts measured with these indicators can be connected to consumers (road users) and the local community.

In regard to the impact assessment, the most used method to calculate the social impacts is the reference scales (Blaauw et al., 2021; Navarro et al., 2018; Gravina da Rocha et al, 2022; Zheng, 2021). Only one study uses PSILCA (Greendelta, 2023), a database specifically developed for S-LCA, expressing the results in med risk hour (Penadés-Plà et al., 2020), while some others base the assessment on laboratory models for the functional requirements (Inti et al., 2019; Inti & Tandon, 2021). Among the various inconsistencies already mentioned, the choice of reference scale is variable: the range spans from 0 to 1 (Navarro et al., 2018), from 1 to 5 (Blaauw et al., 2021; Zheng et al., 2021), from -2 to +2 (da Rocha et al., 2022).

What above report leads to a huge inconsistency among studies, with difficulty to harmonize results and comparing studies.

Besides the published research, the SRS were investigated. For this study, the screening of SRS focused on infrastructure to map the indicators used to assess social sustainability in the context of roads. In total, 30 SRS were found that focused on infrastructures. These rating systems were developed mostly in Europe (Germany, United Kingdom, Switzerland, Norway, Spain, and the Netherlands) and North America (USA and Canada), while two of the systems were created in Asia (Taiwan and Singapore) and one in Australia.

The review was prepared following the structure of S-LCA of stakeholders and sub-categories. Furthermore, considering the scope of this work, the collected indicators are those relevant to the manufacturing stage of asphalt mixtures (Modules A1-A3). The results of this review are presented in Table 2-6.

Table 2-6 Indicators for social sustainability collected from SRS

Stakeholder	**Sub-category**	**Indicator**	**Source**
Local community	Noise	Evaluation of noise reduction potential measured in dB using methods such as laboratory drum methods, Close-proximity (CPX) or Statistical pass-by (SPB)	EDGAR
	Resettlement	Amount of people or communities resettled	SuRe ®
	Affordability	Increase or decrease in wealth (income) in nearby communities	SuRe ®
	Direct employment and training	Percentage of hired staff that is locally measured in FTE (full-time equivalent/year), disaggregated by gender	SuRe ®
		Organization charts, job descriptions and/or payroll information showing the highest responsibility and/or highest-paid personnel, analyzed by gender and identifying whether they belong to the local community	SuRe ®
		Number of hours of training per year per employee (including managers and workers) disaggregated by gender and by local community staff OR the average amount of money spent per employee on training and development	SuRe ®
		Percentage of staff in formal and informal contracts, disaggregated by gender and by nationality	SuRe ®

Stakeholder	Sub-category	Indicator	Source
		Number of youth and adults in the community that participated in any form of training or education in the previous 12 months, offered by the Project (disaggregated by gender).	SuRe ®
	Economic development enabled by the project (direct / indirect)	Number of Small and Medium Enterprises (SME) or start-ups for which the Project has provided an enabling service or existing SMEs which have increased their business due to the services provided by the Project	SuRe ®
		Number of jobs created (direct and indirect)	SuRe ®
		Increase in tax revenues of local and/or national governments	SuRe ®
		Economic diversification in the community (e.g. number of different sectors or branches per capita)	SuRe ®
		Growth of the community (population growth)	SuRe ®
		Contribution to the local economy (e.g., percentage increase in Gross Domestic Product (GDP) or Gross National Product (GNP))	SuRe ®
Workers	Human rights	Number of incidents of human rights violations;	SuRe ®
		Absence of negative criminal or civil judgment within the previous 3 years for Direct Contractors, Sub-Contractors and Primary Suppliers.	SuRe ®
	Association and collective bargaining	Perception of workers regarding their right of freedom of association (if it is respected or not)	SuRe ®
	Non-discrimination	Report of gender indicators (number of women in different positions, number of women interviewed for vacancies, number of trainings given to women, number of lavatories for women, etc.)	SuRe ®
	Occupational health and safety	Annual rate of accident frequency with and without sick leaves	SuRe ®
		Annual rate of accident severity	SuRe ®
		Annual rate of workers trained on Health and Safety Issues	SuRe ®
	Working hours and leave	Record of working hours of the employees	SuRe ®
		Establishment of daily and weekly working hours limits	SuRe ®
		Weekly rest record of workers	SuRe ®
	Fair wages and access to employee documentation	Record of all wages paid (including time of payment, amount deducted, etc.)	SuRe ®

Stakeholder	Sub-category	Indicator	Source
Society	Bribery and corruption	Number of controversies, remediation actions, and evidence of enforceability on all parties involved in the Project.	SuRe ®
Other value chain actors	Human rights	Number of incidents of human rights violations;	SuRe ®
		Absence of negative criminal or civil judgment within the previous 3 years for Direct Contractors, Sub-Contractors and Primary Suppliers.	SuRe ®
Children	Forced and child labor	Record of ages of all workers (anonymized), whether directly employed or supplied under contract	SuRe ®
		Relevant monitoring plans for workers under 18 years, for example, monitoring health, working conditions, hours of work and training provided.	SuRe ®

As it is evident from the table, most indicators were extracted from SuRe ® (The Standard for Sustainable and Resilient Infrastructure), with only one exception (sub-category Noise) that was collected from EDGAR (Evaluation and Decision Process for Greener Asphalt Roads). SuRe ® is an SRS developed by the Global Infrastructure Basel Foundation (GIB) in Switzerland (GIB, 2021). The system assesses different types of infrastructure (water, energy, solid waste management, transport, communication, social, food system, and mining). The evaluation is based criteria on three evaluation categories: governance, society, and environment. (GIB, 2021) In turn, EDGAR was a project funded by the Conference of European Directors of Roads (CEDR) with which the focus was on the sustainability assessment of bituminous mixtures aiming to lessen the environmental impacts of roads (De Visscher et al., 2016). The indicators included EDGAR address the environmental, social, and economic dimensions along with technical aspects.

It is observed that almost all stakeholder categories of the UNEP Guidelines are represented except for consumers. Indeed, several indicators in the consulted SRS included indicators for this stakeholder. Furthermore, the screening highlights the life cycle approach of SuRe ® for the assessment of social impacts. Indeed, it was the only SRS (other than EDGAR) that addressed the social impacts beyond the use stage.

Finally, this literature review evidenced several challenges connected with the conduction of S-LCA for road pavements:

- Lack of Standardization: No universally accepted framework or set of indicators is defined. This is due also to the complexity of social aspects, in particular, the wide range of stakeholders and factors to account for (i.e., labor conditions, health and safety) and the specificity for each sector and country are a significant challenge. Moreover, there is no common way to calculate the social indicators. The current UNEP Guidelines propose two different approaches: the first one (the reference scales) has not been applied consistently in the analyzed studies, and the second (the impact pathway) is more complex and requires extensive research to define the cause-effect relationships between inventory and impacts. This gap in standardization can lead to inconsistency in the assessments.
- Data availability and quality: The availability and reliability of social data are an important challenge. They can be more complex to collect because they are related to the specific conditions in selected economic sectors of a particular country in a defined time frame. Consequently, the data may be subject to inaccuracies.
- Subjectivity and country dependency: S-LCA often involves subjective judgments and can be highly context-dependent. What is considered a positive or negative social impact may vary from one cultural or geographic context to another, making it difficult to standardize the assessment.
- Complexity: Assessing social aspects can be more complex than environmental or economic dimensions. The multitude of variables involved, the social backgrounds and policies, and the various laws in force in different countries make it challenging to develop standardized methodologies and metrics.

2.3.5 Towards LCSA of road pavements

LCSA is based on the calculation of a defined set of indicators representative of possible impacts on the environment, economy and society, following a specific procedure (Kloepffer, 2008; Finkbeiner et al., 2010; UNEP, 2011). In the road pavement sector, merging the three components has already been investigated, but it is not a widely spread practice (Del Rosario). It is the same for the construction sector, where an increasing trend is observable, but rarely applied (Backes & Traverso, 2021).

As indicated in the previous sections, LCA is the most well-established and utilised method, trailed by LCC and S-LCA, which is less frequently used. The varying degrees of development could be a contributing factor to the complexity of carrying out an LCSA, alongside issues regarding data availability, the complexity of managing the three dimensions and the consequent need for expertise. Furthermore, main policies focus on the environmental aspects (i.e. Green Deal), which means that the LCSA is not currently incentivized.

Nevertheless, certain European initiatives have introduced LCSA in road pavements, and there have been some research studies on the subject.

2.3.5.1 Projects at EU level

Several initiatives have been carried out throughout the years, to define a more precise methodology and assess more than one pillar in SA of road pavements.

In 2011, SUstainability – National Road Administrations (SUNRA) () tried to help NRAs in defining sustainability, adopting measures to improve sustainable practices and introducing sustainability rating systems. The project was articulated in three main parts: 1. Sustainability Definition, to allow the implementation of sustainability in NRAs practices; 2. Measures to improve Sustainability: it is a specific framework to monitor NRAs sustainable practices and priorities, to measure their sustainability knowledge; 3. Rating Systems for Roads: it provides a tool for assessing the projects according to an appropriate set of targets and selected indicators.

In 2012, the Conference of European Directors of Roads (CEDR) funded the AllBack2Pave project, aimed at using the highest amount possible of reclaimed asphalt in European surface courses (AB2P, 2011). Besides the laboratory tests to study the mechanical performance of these mixtures, the project investigated also the sustainability aspects. It defined the state-of-the-art related to methodologies for the SA of road pavements, with a focus on LCT and SRS, and provided an LCA (limited to the emissions of CO2) and an LCC of the investigated mixtures. The SA was carried out for three different European countries (Italy, Germany and the UK), comparing the current conventional asphalt mix used in the respective countries with the eight AB2P mixtures (AB2P, 2015). The analysis was performed both in terms of material production (cradle-to-gate) and laying activities (cradle-to-laid and cradle-to-grave, considering only the maintenance operations concerning B).

Evaluation and Decision Process for Greener Asphalt Roads (EDGAR), funded by CEDR in 2013, aimed at selecting sustainability criteria/rules, collecting data on sustainability aspects for new materials and technologies, selecting the best tools for evaluating sustainability and providing a methodology for the assessment. It provided a set of indicators, based on a review of available PCRs on the topic (*Table 2-2*), covering environmental, financial and technical aspects (Table 2-7). Two other projects were funded by the European Commission: LCE4ROADS and SUP&R ITN. They both proposed a list of indicators (called Sustainability Performance Indicators (SPI) the first one), covering the three pillars of sustainability (Table 2-7). Moreover, SUP&R ITN developed a specific tool to weight the results and to perform a Multi-Criteria Decision Analysis (MCDA) using PROMETHEE to rank different alternatives (J. Santos et al., 2019).

Table 2-7 - Set of indicators in CWA 17089 and SUP&R ITN

Pillar	EDGAR* (2013)	LCE4ROADS (2013/16) CWA 17089	SUP&R ITN (2013/17)
	Indicators	**Indicators**	**Indicators**
Environment	Global Warming Potential Depletion of resources and waste Air pollution Leaching potential Recyclability	Primary materials consumption Secondary materials used Materials or components to be reused, recycled, and exported energy Energy used Waste Global warming potential (GWP) Formation potential of tropospheric ozone (POCP) Depletion potential of the stratospheric ozone layer (ODP) Acidification potential of soil and water (AP) Eutrophication potential (EP) Abiotic depletion potential for non-fossil resources (ADP elements) Abiotic depletion potential for fossil resources (ADPRfossil fuels) Human toxicity potential (HTP) Ecotoxicity potential (ETP)	Global Warming Secondary materials consump. Energy demand Materials to be reused or recycled Water consumption Acidification of soil and water Eutrophication Ozone depletion Particulate matter
Economy	Financial Cost	Whole life cost	Life Cycle Highway Agency Costs (LCHAC) Life Cycle Road user costs (LCRUC)
Society	Traffic congestion Noise Responsible sourcing	Comfort index Safety audits and safety inspections Adaptation to climate change Tyre-pavement noise Responsible sourcing Traffic congestion due to maintenance activities	Safety audits & safety inspections User comfort Noise reduction Traffic congestion

* EDGAR also to calculate the skid resistance and durability with laboratory tests.

2.3.5.2 Developed practices

The research focused also on some studies addressing the three dimensions of sustainability, hence performing an LCSA. Looking at the literature, the methodological problems presented in the previous paragraphs were confirmed once again. Moreover, it emerged the absence of a standardized framework for LCSA, that leads to inconsistent results. It is evident also that different approaches were employed to analyze the results and assess an LCSA.

Diverse methodologies were employed by different studies, leading to varied approaches to performing and analyzing results. While the majority of studies embraced an integrated approach, synthesizing outcomes from all dimensions collectively, exceptions were observed in the works of Bryce et al. and Reddy et al. Bryce et al. left room for ambiguity by not explicitly stating whether the three pillars' results were to be collectively evaluated, while Reddy et al. opted for separate analyses for each dimension.

In studies pursuing a combined interpretation of results, a spectrum of distinct approaches emerged. Some studies defined a sustainability index, like the LCSA value function or Highway Sustainability Score. Other studies proposed the Multi-Criteria Decision Making to combine the three dimensions, such as Santos with PROMETHEE and Kuckvar with TOPSIS, and some others recurred to monetarization of the results or weighted rankings (Inti, 2021).

2.3.2.7 Decision Making in SA of road pavements

Several stakeholders are involved in the road pavement sector, hence various aspects and point of view need to be considered in selecting the best option that need to encompass technical, economic, environmental, and social consideration. In these occasions, decision-making in road pavements is a multifaceted process that allows one to evaluate the project and its eventual alternatives against chosen criteria. Each solution corresponds to the criteria to a certain degree, necessitating the identification of the best solution that aligns most closely with the considered criteria. The Multi-Criteria Decision-Making (MCDM) method can help in the process, offering tools and techniques for achieving a compromise solution. Within the different methods, choosing the best one is not easy. Each one has its limitations, assumptions and perspectives (Abed & Lo Presti, 2021).

In the road pavement sector, the MCDM can be very useful due to the wide aspects to consider, here reported. Firstly, the technical factors, compliant with local, national and international regulations, need to be considered and include:

- Materials choice: The selection of materials plays a crucial role in pavement construction. The different road authorities impose specifications in terms of granulometry, binder content, RAP percentage and mechanical performances (i.e. ANAS capitulate). (ASTM International, 2018).

- Pavements design: Pavements meet safety and performance criteria. Relevant standards are set by organizations such as the American Association of State Highway and Transportation Officials (AASHTO).

Secondly, in a context where the pollutant burdens need to be reduced, the environmental dimension has an important role. The results of an LCA (or an SA) should be included in the decision process and balanced with the other aspects. Moreover, it is possible that materials need to respect environmental regulations defining benchmarks or other parameters to follow.

Thirdly, the economic dimension plays another important role: Economic evaluations should consider the expenses of construction, maintenance, and end-of-life costs, while also taking into account the available budget and other relevant factors (World Road Association – PIARC, 2020).

In this more comprehensive approach, safety, noise, and impacts on the local community or workers' health should be evaluated.

MCDM can be implemented through various methodologies. Among them, the Analytical Hierarchy Process (AHP), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) or Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) are a notable example.

In literature, these methods are all applied to combine sustainability dimensions and other requirements. When discussing road infrastructure investment and maintenance interventions, Graziano et al. (2001) used the AHP with five selected criteria: Comfort, Environment, Safety, Road Agency Costs, and Road User Costs. The research demonstrated that MCDM can facilitate a more effective budget distribution, by considering a broader set of factors. The implementation of TOPSIS was proven beneficial in evaluating the efficiency of various pavement solutions (i.e. WMA or in-plant recycling mixing) in enhancing sustainability. The authors considered three criteria, namely highway agency costs, road user costs and environmental impacts (with eight sub-criteria) and assigned different weights to each sub-criterion (J. Santos et al., 2019) . The analysis enabled the selection of the solution that satisfies various stakeholders' interests. PROMETHEE is a well-utilized methodology for MCDM in the road pavement sector, also proposed in SUP&R DSS, a sustainability-based decision support system (DSS). It was developed for ranking the alternatives, using selected criteria encompassing the three pillars of sustainability. The authors suggest a set of weighting values selected through a survey or provides flexibility to choose.

Upon reviewing various studies, a consistent observation emerges: the MCDM approach, independent of the specific methodology employed, proves to be a valuable methodology in the decision-making process. However, to enhance its effectiveness and facilitate its integration into SA practices, it becomes imperative to offer more structured guidance on its application.

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2.4 Conclusions

The state-of-the-art provided a comprehensive background on sustainability policies and then on Life Cycle-based Sustainability of road pavements, considering the three pillars of sustainability, their merging and the utilization of multi-criteria decision-making.

Key conclusions and recommendations from this research include:

- For several years, both international and European policies have been directed toward enhancing sustainability practices and advancing a vision of a world free from burdens. The Sustainable Development Goals comprehensively address all facets of society, underlining a commitment to foster positive change and holistic development. A current imperative exists to align with Sustainable Development Goals across various domains. Pavement engineering significantly influences environmental, economic, and social sustainability pillars and is acting to minimize adverse impacts.

- The EN standards are a valid reference for the SA. Nevertheless, they give general guidance, not providing specific advice for road pavements.

- Several PCRs are available for LCA of asphalt mixtures and pavements and EU projects (i.e. EDGAR, LCE4ROADS) provide valid indicators to take into account.

- Life Cycle-based techniques have been already applied in the road pavement sector: the LCA has been extensively used, followed by the LCC. On the contrary, the S-LCA is more often disregarded.

- No specific framework exists for LCA and LCC in the road pavements sector at European Level. The current ISO and EN should guide during the assessment. Nevertheless, giving general guidance, the practitioners can take their own decisions. It follows that the considered studies present several inconsistencies in terms of system boundaries, functional unit, impact assessment and impact categories.

- S-LCA is the less developed methodology among the three. The lack of standardization, complexity in gathering reliable social data, subjectivity influenced by cultural contexts, and the intricate nature of assessing social aspects of Life Cycle Sustainability Assessment are big challenges for performing an S-LCA.

- LCSA is not a widely spread practice, due to the complexity, the high amount of required data, and the limits of the LCA, LCC and S-LCA methodologies. Inconsistencies and different approaches do not allow to compare results and to enhance their applicability. Addressing this gap is crucial for advancing its implementation.

- MCDM consistently demonstrates its value in the decision-making process, regardless of the specific methodology used. It is important to enhance its use in SA practices, guiding its application and suggesting a specific methodology.

In conclusion, the state-of-the-art demonstrated the commitment of international and European policies in promoting sustainability practices. However, the lack of specific guidance for road pavement sustainability leads to discrepancies in implementation. Therefore, establishing a framework and methodology would assist practitioners in achieving harmonised outcomes and facilitate the implementation of a life-cycle-based sustainability approach.

The next section, Chapter 3, will outline a framework to guide in the SA of road pavements, defining indicators, the object of the assessment and the scope of the assessment. Chapter 4 will offer a detailed step-by-step procedure to perform the assessment, with the option of implementing MCDM. Chapter 5 will validate the methodology with some case studies, while Chapter 6 will focus on enhancing the methodology through further development.

Chapter 3 TOWARDS HARMONIZED SUSTAINABILITY ASSESSMENT FRAMEWORK FOR ROAD PAVEMENTS IN EUROPE

3.1 Methodology

The current state of the art reveals consistent gaps and the absence of a practice for conducting a globally harmonized Sustainability Assessment (SA) related to road materials and/or pavements. Consequently, there is a pressing need to formulate a guide that can assist practitioners. It's important to note that this research does not aim to replace existing standards but rather serves as a valuable starting point towards harmonizing too much scattered practices.

Moreover, for the SA to be integrated into everyday practices, the active involvement of stakeholders such as Road Authorities (RAs), material manufacturers and road pavement contractors is crucial. These stakeholders should play a role in defining the framework to ensure a comprehensive understanding of the needs and concerns. This involvement is particularly important as they not only implement the exercise within their own administrations or delegate it to external consultancies but must also comprehend the basis, potentials, and limitations of an SA. Additionally, understanding what data needs to be collected or requested at various stages of the pavement life cycle is vital.

The definition of the proposed framework is built upon three fundamental steps: a comprehensive literature review, interactions with the RAs, and conducting Stakeholders workshops (Figure 3-1).

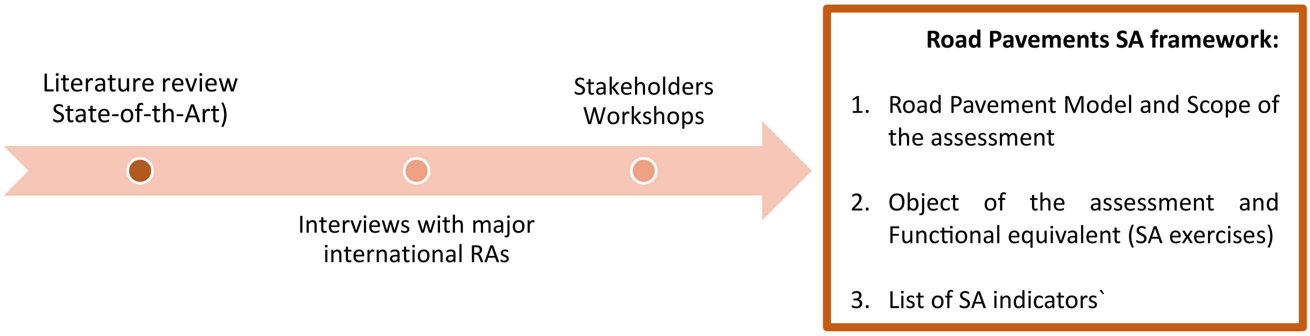


Figure 3-1 - Flow diagram towards harmonization of SA of road pavements in Europe

3.1.1 Literature review

The previous chapter showed the results of a comprehensive literature review for the life cycle-based SA of road pavements. Several methodological gaps were identified, however the research allowed finding out the following existing resources that proved being instrumental in this work:

FHWA Pavement LCA framework: In 2016, the Federal HighWay Administration (FHWA) published the Framework for LCA of Pavements , suggesting: 1. which life cycle stages to include in the assessment (full life cycle as default); 2) the functional unit, defined as a full pavement section; 3) the analysis period, typically 30-40 years; 4) the cut-off criteria as the 5% for all the flow; 5) the data quality (specifying the coverages required, i.e. technological) and the allocation. Furthermore, it introduced the concept of physical boundaries, which "define the portions of the pavement structure to be considered part of the pavement system at the location(s) included in the study. The dimensions permit the determination of volumes, masses, surface areas and other quantities needed to perform the LCA." (FHWA, 2014)

EN standards: The FHWA framework was the first building block in the road industry, however the game changer for implementing this approach in Europe are the European standardized practices for SA of buildings and civil engineering works.

In particular, the investigation delved into standards like the "Framework on specific principles and requirements for civil engineering works" (EN 15643-5), outlining principles and requirements for evaluating the impacts of civil engineering works. The "Calculation methods" (EN 15978:2011 and EN 17472:2022) for the environmental performance of buildings served as a basis for formulating and adjusting a seven-point procedure for Life Cycle Management (LCM) of pavements. Furthermore, the "Core rules for the product category of construction products" (EN15804:2011+A2:2019) played a pivotal role in delineating key indicators and proposing their calculation through the EF 3.0 methodology.

***Product Category Rules**:* Furthermore, several institutions provided Product Categories Rules (PCRs) to perform an LCA of road materials and pavements and delivering an Environmental Product Declaration (EPD). The European Asphalt Pavement Association (EAPA) published the Guidance Document for preparing PCR and EPD for asphalt mixtures to be used in Europe, while some other countries (i.e. Italy, Spain, Norway, Ireland) published their own PCR. All these efforts, clearly show that that there isn't a common way to perform a SA in road pavements globally and there is not harmonised procedure for implementing it in Europe

3.1.2 Interactions with major international RAs

International RAs are one of the main stakeholders involved in the path towards more sustainable roads. For this reason, they were privileged interlocutors within the PAVEMENTLCM project ("PavementLCM - Life Cycle Management of Green Asphalt Mixtures and Road Pavement," 2021). Eleven NRAs were interviewed with regards to the culture of sustainability within their current organisation and the implementation of best practices. In order to gather data and information a questionnaire was prepared with questions focused on green asphalt, circular economy, uncertainty and decision-making, sustainability data and assessment (PavementLCM, 2021).

As a result, there is a high awareness of sustainability assessment (score 8.7/10), particularly for economic and environmental aspects (7.9/10 and 7.8/10), while the social aspect is very low considered (5.9/10). Nevertheless, it emerged that only 64% of NRAs perform a sustainability assessment, at the planning phases of the project and/or at the project level, but that most of them are willing to implement it as a current practice. The interactions conducted also to a first attempt of a list of priority indicators within major international RAs practices, as follows:

1. Primary materials consumption;
2. Secondary materials used;
3. Energy use;
4. Waste;
5. Global Warming Potential;
6. Whole life costs;
7. Comfort index;
8. Safety audits and inspections;
9. Tyre - pavement noise;
10. Traffic congestion due to maintenance operations.

This list was very relevant for the further definition of the set of indicators below contained in the framework.

3.1.3 Stakeholders Workshops

Three workshops were organised with other stakeholders of the road pavement industry, to create a platform for learning and sharing knowledge about sustainability assessment of road materials and pavements. The workshops were carried out within the PAVEMENTLCM project and involved project partners, NRAs, Asphalt Pavement Associations, academics and industry representatives from manufacturers, contractors and consultants. Each one of the workshops was fundamental in the successive development of the framework and in a cross-contamination of the different actors of the industry. As a result, it clearly emerged that different approaches about SA of road pavements are adopted by the major international RAs and that harmonization could be beneficial to decrease scattering amongst practitioners. Also, the workshops' feedback conducted to the following main take-away messages:

1. It is paramount to distinguish SA exercises in two systems: pavement materials and pavement activities;
2. The set of SA indicators must be limited to a practical number and identical for the two systems, as reported in Table 3-1

Table 3-1 – Selection of the indicators for pavement materials and activities obtained through interaction with major RAs and other stakeholders

Indicators	Pavement materials	Pavement activities
Global Warming Potential	x	x
Energy use	x	x
Secondary materials consumption	x	x
Cost	x	x
Laboratory Performance indicators	x	
Tyre-pavement noise		x
Service Life of pavement components (Durability)		x
Air pollution		x

3. International best practices exist and should be considered towards harmonised efforts. Amongst these the following were considered:

- England: Use of LCC to allocate budget at strategic level based on the type of treatment for maintenance. Sustainability Strategy Developed (available online).
- Netherlands: Use of Green Procurement and development of their own tool "Dubocalc" for environmental assessment.

- Sweden: Use of Green Procurement. EKA tool is used as a declaration for giving bonus in evaluating tenders regarding asphalt materials. Climate tool is used to show climate impact and energy use for the construction, operation and maintenance of roads and railways, and for basic road contracts, from a life cycle perspective (available online).
- Norway: Development of own EPD for asphalt mixtures (product stage) plus optional scenarios for construction, use and EoL stages.
- Denmark: Use of socio-economic model to quantify the benefit to the society of new pavement types
- California: eLCAP tool is used for LCA with a specific database for California. RealCost is used for LCCA. A pilot scheme is requiring EPDs to all contractors from 2019

3.2 Sustainability assessment Framework for road pavements in EU

The current state-of-the-art and the interaction with the stakeholders, through workshops and interviews, led towards the definition of limitations and opportunities towards a harmonised European framework for the Sustainability Assessment of road pavements. Starting from the gap in the methodology for the life-cycle-based SA of road pavements, this research wants to provide a framework that comply with current standards and/or Product Category Rules (PCR), going towards harmonization of assessment practices and results for facilitating decision making of stakeholders and policy makers.

The Sustainability Assessment Framework (SA Framework) employs a combination of qualitative and quantitative assessment. The Life Cycle-based impact evaluation techniques are employed to calculate the indicators which cover the environmental and economic aspects while a rating system is used to assess a social indicator for pavement activities. To align with the EN standards, emphasizing the need of integrating environmental, social, and economic aspects, along with technical and functional performance, also a set of functional and technical requirements is defined (Figure 3-2).

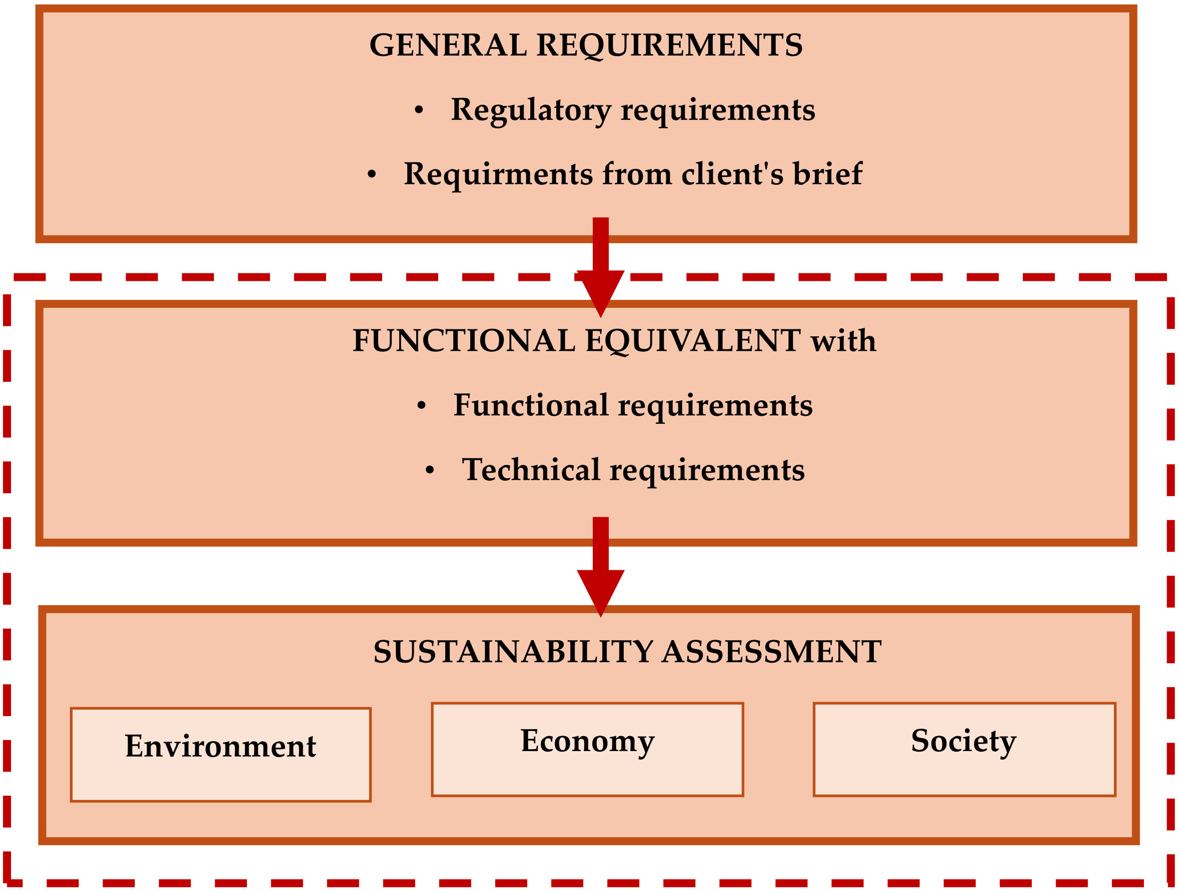


Figure 3-2 – Concept of Sustainability Assessment (adapted from EN 17472)

The main content of the framework can be distinguished into:

- Road Pavement Model and SA Scope
- Objects of assessment and Functional equivalent to include in the assessment
- Sustainability Assessment indicators.

3.2.1 Road Pavement Model and Scope of the Assessment

Based on the pavement model specified in the EN15978 and presented in the previous chapter, a "Road Pavement model" was created (

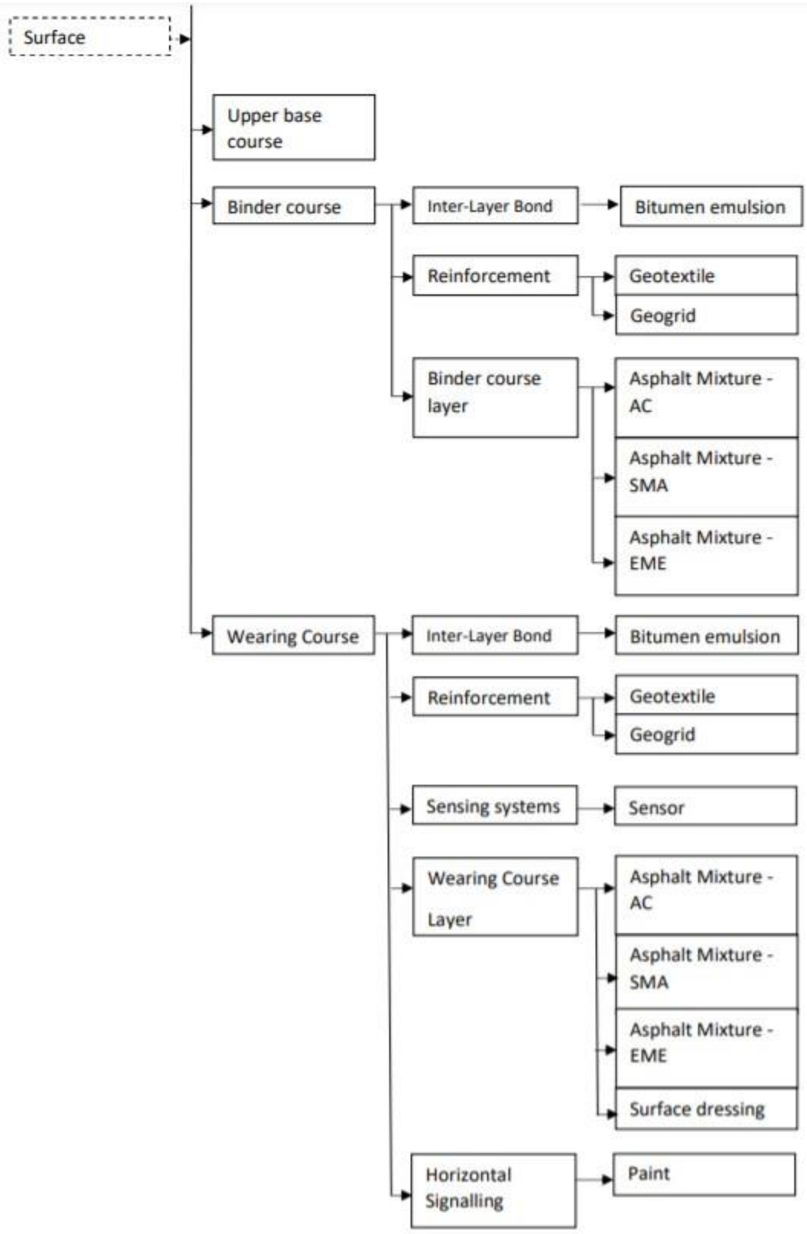
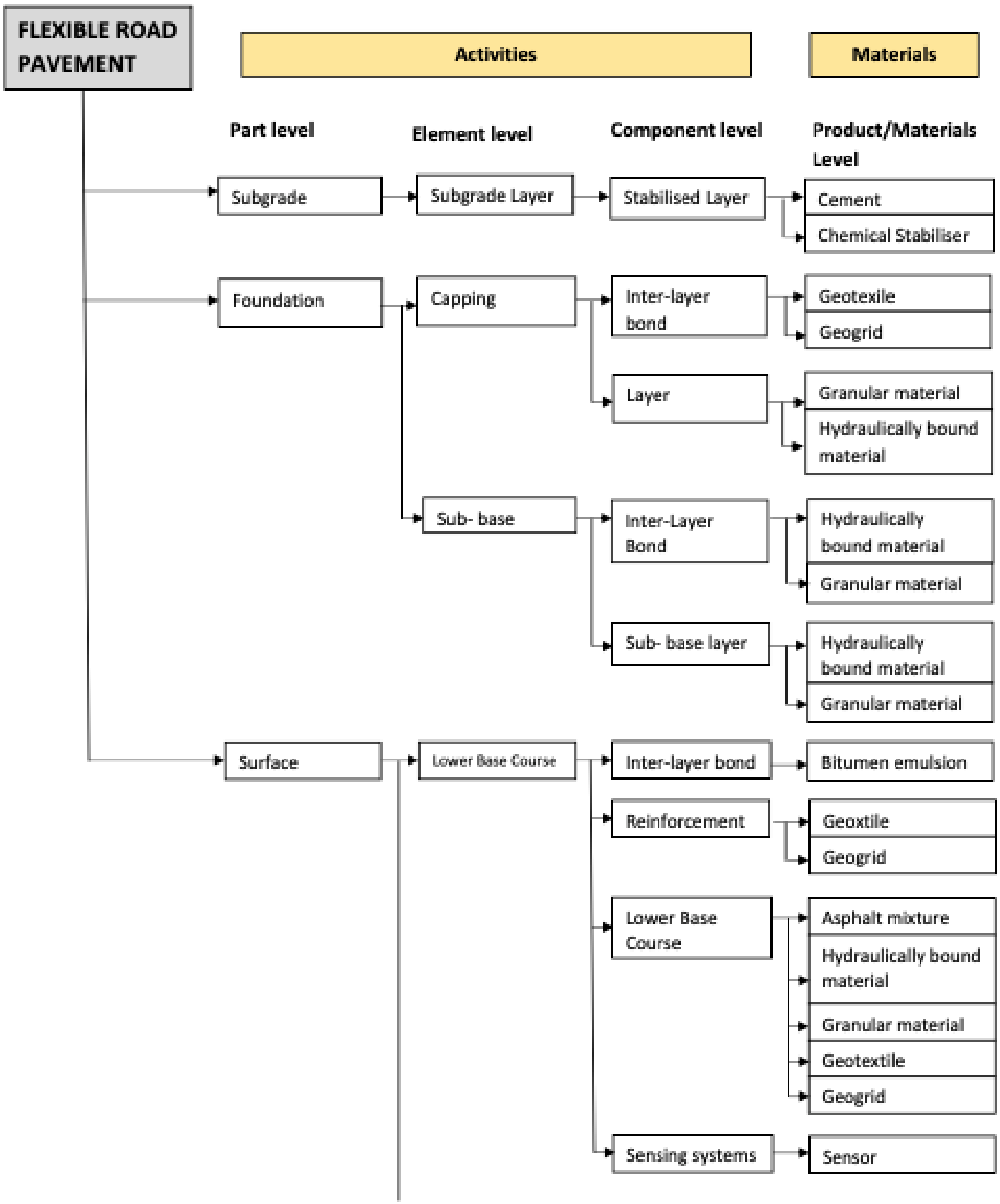


Figure 3-3). It has the aim of facilitating the calculation, subdividing the road pavement in levels. It is structured as follows:

- Part level: subgrade, foundation and surface.

- Element level: subgrade, sub-base, base course, binder course, wearing course, etc

- Component level: layer, sensors, etc
- Product/materials level: cement, asphalt mixture, bitumen emulsion, etc.



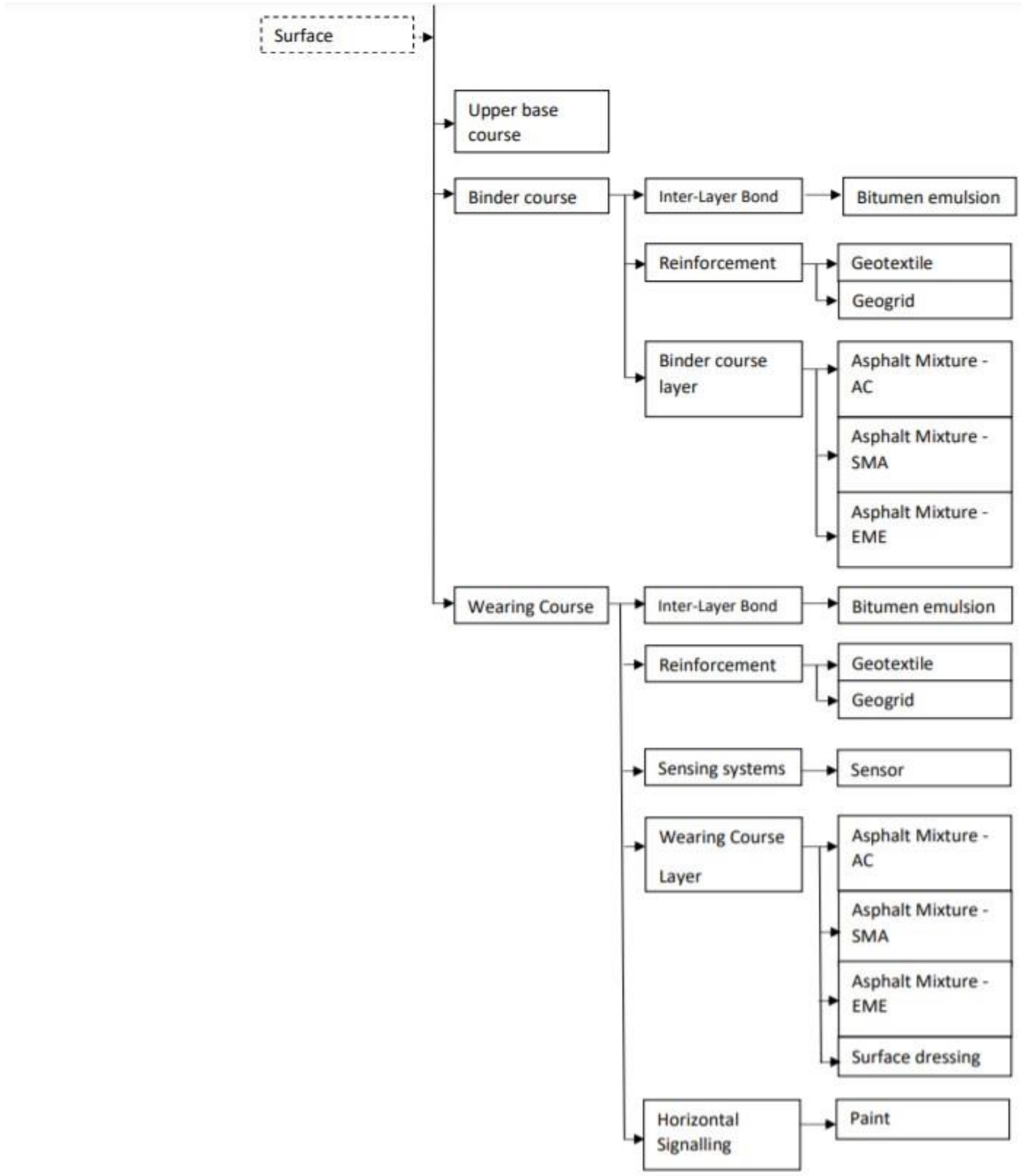


Figure 3-3 - Example of Flexible Road pavement model

The scope of the assessment is the road pavement, specifically pavement materials/products and pavement activities, as identified within the road pavement model.

Pavement materials/products are those entities that must be used to build, repair, replace and maintain road pavement and its components (Carrión et al., 2021; Lo Presti et al., 2021). In this case, the SA focuses on the product/materials level and the stakeholders involved are the manufacturers (materials producers). They must assess the burdens for each material and/or product supplied to RAs or contractors for the construction or maintenance of the pavements.

Pavement activities are those activities that must be carried out to build, repair, replace and maintain the functional and technical requirements of road pavement and its components (Carrión et al., 2021; Lo Presti et al., 2021). In this case, the exercise focuses on the part/element/component level of the road pavement model. The stakeholders involved, with their task, are: 1) the contractors, who have to show the sustainable performance of the contracted activity, such as the construction or replacement of the road pavement; 2) the road agencies, who have to assess the sustainability of projects and/or maintenance strategies. The SA can be used to evaluate innovative technologies and materials. The scope of the assessment excludes some items (Figure 3-4), such as the lightning, the signals and message boards, the painting, the unbound subbase layers, the barriers and the drainage structures.

Figure 3-4 - Scope of SA Framework. The elements in the green continuous line (pavementmaterials and activities) are inside the SA Framework, while the elements in the red dashedline are outside

3.2.2 Object of the assessment

The object of the assessment is usually the item (i.e. product) for which the assessment is carried out and the Life Cycle Thinking is applied. In this specific research, the object of the assessment can be a pavement material or a pavement activity. Nevertheless, according to the EN 15643-5:2019, it is defined by:

- **A Description of the object**: it consists in explaining the properties of the material/product/activity under evaluation. It can include the typology of asphalt mixture, its composition, the pavement design; in other words, all the useful information related to what is going to be studied.

- **An Analysis period** (if applicable), hence the chosen reference period of the study. If the analysis is related to materials, then analysis period can also not be defined. In fact, reference service life and durability are concept related to built components (i.e. wearing course). Instead, if the assessment is referred to a pavement component, the analysis period is defined equal to: 1) the estimated Reference Service Life (RSL) of the component (according to durability studies); 2) the timeframe necessary for the specific project to include at least one major rehabilitation (usually 40 years).

- **The functional equivalent or ~~functional/~~declared unit**, hence the unit of the assessment with the functions and performance characteristics, if identified. It can be equivalent to one ton of the material under study or to the exact volume (or weight) of the road pavement to be contracted and/or built as required at project-level, with all the information related to technical and functional requirements and RSL. At this purpose, the following functional and technical requirements were identified (*Table* **3-2**).

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Table 3-2 – Technical and functional requirements required for pavements

Technical and functional requirements	**Durability**	Pavement activities	Reference Service Life of pavement components. Increasing durability allows to reduce maintenance activities.
Technical and functional requirements	**Optional indicators**	Pavement activities	This indicator is left customisable by each road authority based on local priorities. (i.e. skid resistance, permeability, etc..)

- The **System boundaries**, hence, the life cycle phases taken into account for the assessment. They are: production, installation, use, end-of-life and benefits beyond the system life cycle (waste, reuse, recycle, etc); It has to be highlighted that if the aim of the SA is to provide an Environmental Product Declaration (EPD) for the pavement material, then EN 15804:2019 prescribes as mandatory to consider both End-of-Life phase (Module C) and Module D.

- Furthermore, according to FHWA Framework, the concept of **Physical boundaries**, was introduced. They define the portions of pavement structure to be considered as a part of the pavement system at the location(s) included in the study. With this adjustment, it is possible to determine volumes, masses, surface areas and other quantities needed to perform the SA. If the goal of the LCA does not include the complete pavement system, then the system boundaries can be adjusted. This very important addition was inspired by the FHWA Pavement Life Cycle Framework ((FHWA, 2014).

The author has distinguished two main systems. Each of them has its own peculiarities related to the object of the assessment and involves specific stakeholders. The possibility of distinguishing these two different systems is very helpful for the practitioners in carrying out the SA exercise. In fact, the authors identified generic rules and best practices to be applied to each of these systems, as presented below.

3.2.2.1 Pavement Materials/Products

This system includes the materials/products, such as: asphalt mixtures, concrete, prefabricated concrete slabs, emulsion, steel, etc. The analysis performed in this case is a cradle-to-gate, hence the production phase (A1 – Raw materials supply; A2 – Transport; A3 – Manufacturing). Module D is suggested by the framework and it's a mandatory phase for the EPDs (EN 15804:2012, 2012).

The analysis period is not applicable, since the analysis is a cradle-to-gate, and the declared unit is assumed to be 1 ton of manufactured materials (as suggested by NAPA 2017, EATA 2017, The International EPD System 2017, and The Norwegian EPD Foundation 2017).

The material producer can carry out the exercise to compare one or more products and/or to assess the sustainable performance of a product, providing a Sustainable Product Declaration (SPD).

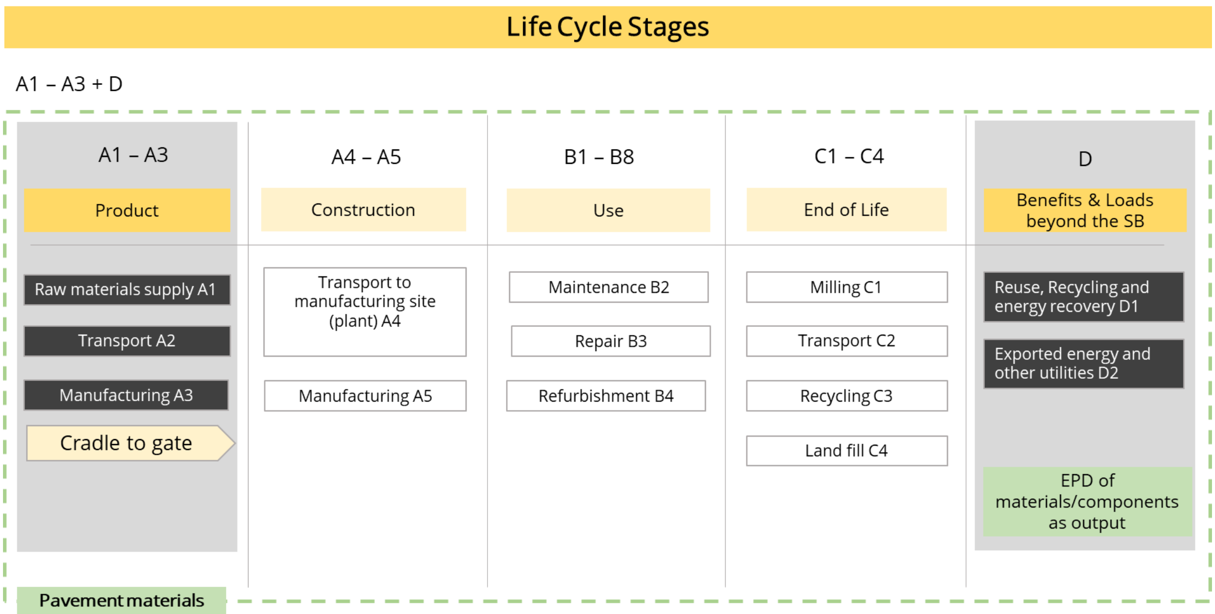


Figure 3-5 - System boundaries for pavement materials

- *Example*

Given a case study, the SA exercise consists in the calculation of sustainability performance of the selected mixes, with a specific mix design.

The system boundaries are A1-A3 + D, hence a cradle-to-gate + module D analysis (Figure 3-6).

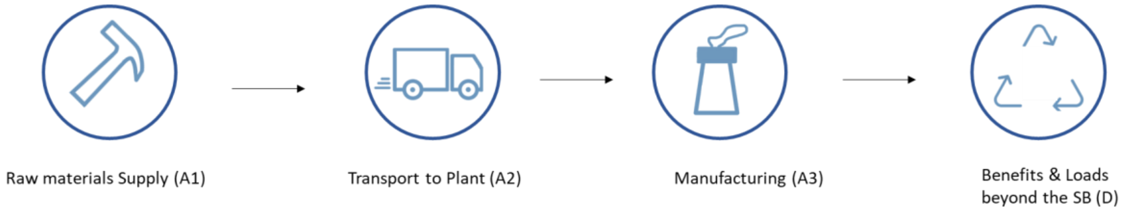


Figure 3-6 - Life Cycle Stages for SA exercise for Manufacturers

The declared unit is defined as 1 ton of the mixes object of the assessment. Any analysis period can be applied because of the only the production stage is considered.

The main output is the calculation of the environmental performance and the delivery of a Sustainable Product Declaration (SPD) to contractors and NRAs.

The selected indicators are the ones related to pavement materials of Table 3-4.

3.3.2.2 Pavement activities

The exercise related to pavement activities can involve both contractors and road owners, being related to contracted activities (i.e. construction or maintenance).

- ***SA Exercise for Contractors***

This exercise includes the SA of construction of a new road and/or of maintenance, repair or replacement of installed components (i.e. wearing course, binder course or base course).

In this specific case, the functional unit/equivalent is defined as the exact volume (or weight) of the pavement component to be contracted and/or built, as required at the project-level. It is requested to specify the technical and functional requirements and to define the Reference Service Life (RSL) of the component object of analysis.

Concerning the system boundaries, the assessment can be a cradle-to-laid (A1-A5) or a cradle-to-grave which includes a B phase (use) referred to as one RSL (Figure 3-7). As for the pavement materials, the calculation of module D is strongly recommended.

In case the material is produced by another stakeholder, the cradle-to-gate analysis can be covered by an SPD provided by the provider. In this case, the analysis is restricted to the missing stages. The contractor can perform the exercise to compare one or more pavement activities and/or to assess the sustainable performance of the installed component, providing a Sustainability Product Declaration (SPD).

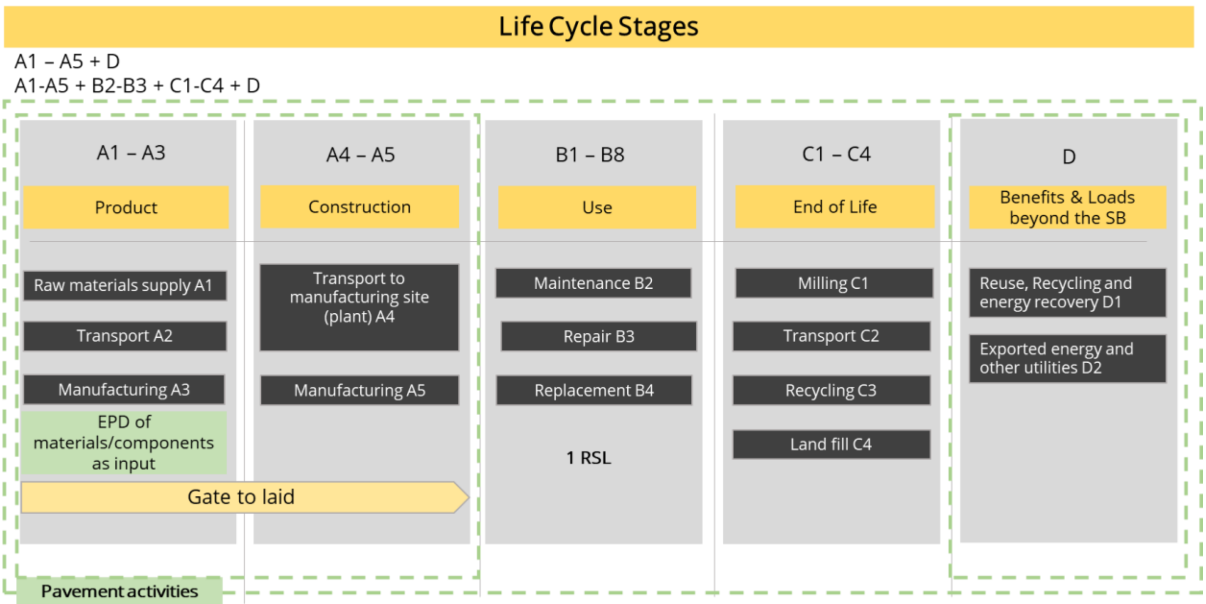


Figure 3-7 - System boundaries for pavement activities

- *Example*

Given a case study, the SA exercise consists in the comparison of the construction of two different pavement structures. In the first one, wearing and binder courses are both made with mixture 1, while in the second one mixture 1 is used for the wearing course, while mixture 2 for the binder course. The functional unit is the exact volume (or weight) of the road pavement to be contracted and/or built, hence it corresponds to the required tons of mixture 1 in the first pavement and of mixture 1 and 2 in the second. The physical boundaries are the surface and binder courses, while the system boundaries consist in A1-A5 + D (Figure 3-8 - Life Cycle Stages for SA exercise for Contractors (exercise a)Figure 5-5). If the contractor already has an SPD, the SA calculation are limited to A4-A5.

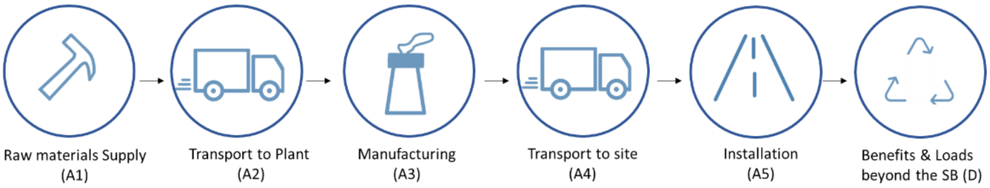


Figure 3-8 - Life Cycle Stages for SA exercise for Contractors (exercise a)

Moreover, the SA exercise can be related to assess the construction of one or more pavement components and the related Reference Service Life (RSL). The system boundaries correspond to an A1-A5, B1-B4, C1-C4 + D (Figure 5-6), while the physical boundaries of the selected case study are the surface and binder courses.

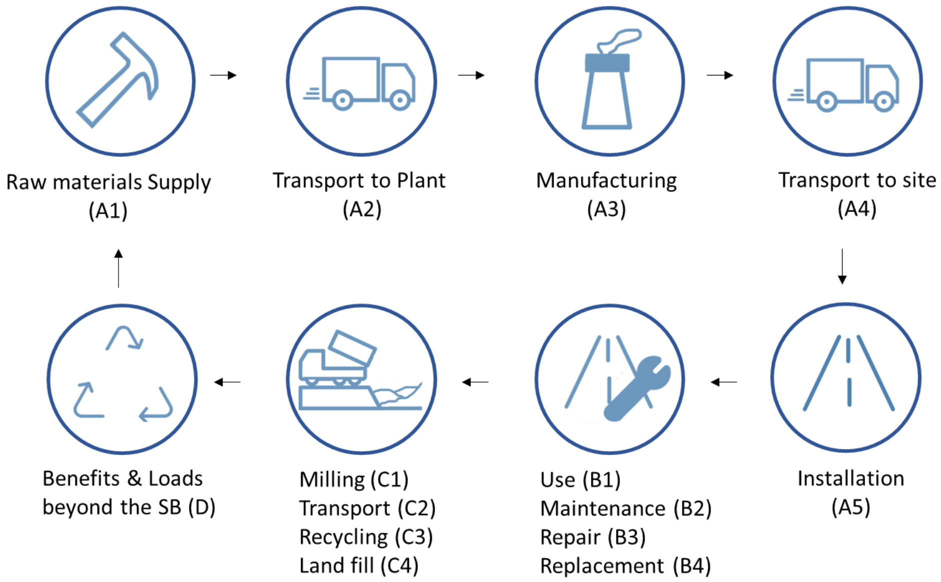


Figure 3-9 - Life Cycle Stages for SA exercise for Contractors (exercise b)

- *SA exercise for road owners/NRAs*

This exercise can be useful to help the stakeholders in the decision-making process of the construction of a new road or of maintenance strategies selection.

They have included all the activities referred to 1) Project-level "New construction" and 2) Project-level "Asset management", distinguished in:

- Regular operations: all the periodic activities realised in short-term periods (< 1 year), aimed at maintaining the initial construction conditions. These are, for example, cleaning drainages, pavement repairs or road salting. According to EN standards, these interventions correspond to the B2-Maintenance and B3-Repair phases.
- Rehabilitation operations: all the activities which improve pavement performance, enhancing their service life. They are made at longer intervals (>1 year) and they include substitution of components (i.e. replacement of wearing course). They correspond to B4- Replacement for EN standards.

In this case, the analysis period corresponds to the period that includes at least one rehabilitation, and it is usually assumed 40 years. The functional equivalent/unit is the same as for the previous exercise. By the intended application of the analysis, the system boundaries can be a "cradle-to-grave + D" for new construction (exercise a), as shown in Figure 3-7, or be limited to B2-B4, C1-C4 and D for maintenance activities (exercise b), as in Figure 3-10.

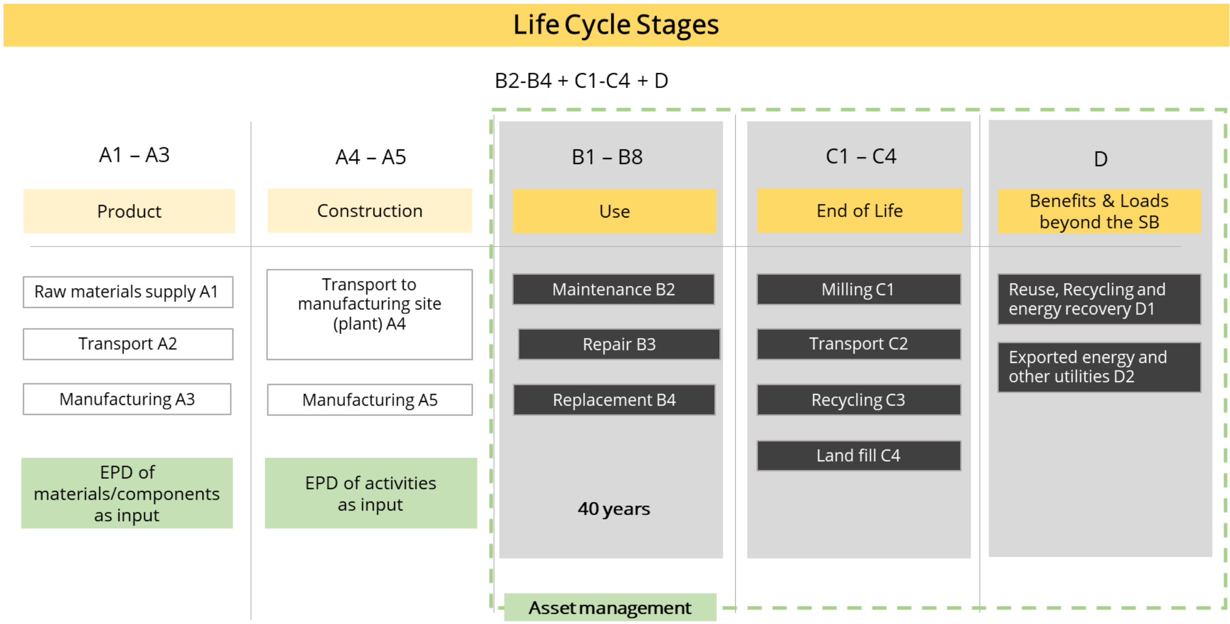


Figure 3-10 - System boundaries for pavement materials (Asset Management) (exercise b)

- *Example*

Given a case study, if its aim is helping in decision for asset management (regular operations executed in short term o rehabilitation operation executed in longer term), the SA consists in the evaluation of the impacts related to the use and maintenance of the pavement components, according to a maintenance plan, for a period of 20 years (*Table* **3-3**).

Table 3-3 – Typical maintenance information

Year	Procedure
y 10	milling surface course / paving surface / production new mixture
y 20	milling surface course + binder course / paving surface course + binder course / production new mixture

The functional unit and the physical boundaries are the same reported for the contractors' exercises, but in this case the system boundaries correspond to a use-to-grave + D (Figure 5-7).

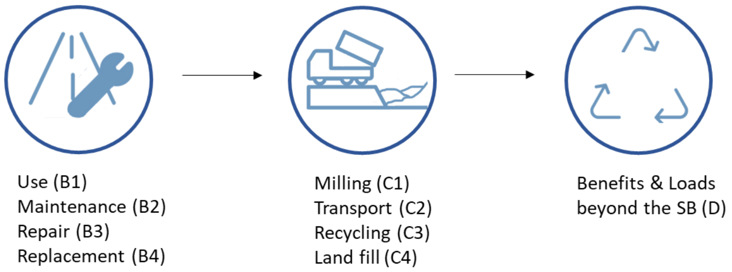


Figure 3-11- Life Cycle Stages for SA exercise for road owners/ NRAs (exercise b)

3.2.2.3 List of indicators

The ISO standard, as well as the EN 15643-5, require a quantitative measurement of sustainability using indicators. The list of indicators (Table 3-4) is the result of a review of the main documents and standards and the interactions with RAs. The philosophy behind these choices was: 1) the reduction of the number of indicators to facilitate the SA exercise within Ras, being always in compliance with current standards; 2) covering the pillars of sustainability, as well as the technical and functional requirements, as suggested by the EN 17472:2022; 3) taking into account the core environmental indicators according to JRC (Zampori L. et al., 2016), which have main potential burdens for the environment. Table 3-4 contains all the selected indicators, organised into main categories. In compliance with European Standards, and as reported by EN15804, the indicators are the ones assessed with the EF3.0 methodology, suggested to be used for EPDs and PEF (EAPA, 2017a).

Concerning the society, the selected indicator concerns tyre-pavement noise. It is a quantitative indicator and it can be expressed with a customizable rating system in advanced or basic approach.

Table 3-4 – Indicators for the Sustainability Assessment of pavement materials and activities (adapted from PavementLCM, 2021)

Related to	**SA Indicator**	**Object of assessment**	**Description**
Environment	**Global Warming Potential (GWP-total)**	Pavement materials and activities	Generally accepted equivalent of greenhouse gas (GHG) accumulation. It shall be expressed in kg CO_2 equivalent (see EN 15804). It refers to the midpoint impact category "Climate Change" of EF3.0 whose 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 cause a reduction in the system's acid neutralising capacity. Generally, it is caused by air emissions of NH_3, NO2 and SO_X. It refers to the midpoint impact categories of EF3.0 "Acidification" whose indicator is Accumulated Exceedance (AE)
Environment	**Eutrophication**	Pavement materials and activities	It measures the enrichment 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 aquatic freshwater", fraction of nutrients reaching freshwater end compartment (P) • "Eutrophication aquatic 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 scarcity”, deprivation potential, deprivation-weighted water consumption (WDP) • “Land use” Potential Soil Quality Index (SQP) • “Resources use, minerals and metals” - Abiotic depletion potential for non-fossil resources (ADP- minerals&metals) • “Resources use energy carriers” Abiotic depletion for fossil resources potential (ADP-fossil)
Environment	**Air pollution**	Pavement materials and activities	Assessing pollution potential based on air pollution (non-CO_2 emissions), evaluating particulate matter and photochemical oxidation potentials. It refers to two different midpoint impact categories of EF3.0: • “Particulate Matter“, a human health effect associated with the exposure to PM (PM) • “Photochemical ozone formation“, Tropospheric 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, obtained from the Life Cycle Inventory, making a distinction between renewable and non-renewable.
Environment	**Secondary materials consumption**	Pavement materials and activities	Includes a quantification of the material which substitutes primary materials and is recovered from previous use or from waste. It can be expressed by mass units or as a 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 Pavement 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 the life cycle, while fulfilling the performance requirements, see CWA 17089

Society	**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 qualitative and can be expressed with a customizable rating system in advanced or basic approach: • advanced: rating based on a quantitative assessment of the reduction of the tyre-pavement noise level in dB compared to the reference pavement (i.e. Level A: ≤9 dB, Level B: 3 dB<x< 6 dB, Level C; ≤ 3 dB) (Road GPP); • basic: rating based on the adopted mixtures used for wearing courses (Greenroads) (i.e. Level A: dense, Level B: gap graded, Level C: open grade)

3.3 Concluding remarks

Starting from the gap in the methodology for the SA of road pavements, this research was developed to provide a framework to be used by all the stakeholders involved in road construction and management: materials manufacturers, contractors and Road Authorities. Defined on the basis of constant interactions with stakeholders and of the state-of-the-Art, the framework does not replace current standards, but aims at complementing them, providing recommendations towards harmonised practices in Europe.

The framework was developed to harmonize some key aspects of the assessment, specifically:

- **Scope of the assessment:** introduces the concept of a road pavement model to identify the object of analysis and suggest exercises for the main stakeholders: material manufactures, road contractors and road authorities

- **Objects of assessment and functional unit:** provides two systems (pavement materials and activities), associating the operators involved, the system boundaries and the declared/functional unit.

- **SA indicators:** literature reviews and interactions with NRAs allowed identifying a limited set of practical indicators covering environmental, economic, social and technical/functional aspects, in compliance with the EN 15643-5

In conclusion, the proposed European SA framework for road pavements should provide analysts and policy makers with harmonized key aspects of life cycle analysis exercises. It is expected that these key aspects could be at the core of European Product/Process Category Rules for the road pavement industry.

The next section, chapter 4, would provide details of a step-by-step procedure to guide the practitioner through the implementation of life cycle management practices as a standard practice in Europe. Chapter 5 will instead provide insights towards further improvement of the proposed SA framework for road pavements in Europe.

Chapter 4 ROAD PAVEMENT LIFE CYCLE MANAGEMENT GUIDELINES - a step-by-step procedure towards using harmonized SA results within decision making into the road pavement industry in Europe

Once the SA framework is defined and some important aspects are harmonized, another important aspect considered in this thesis is the definition of a pragmatic procedure to take advantage of the SA results within decision-making linked to road pavements management. This is what is here called Life cycle Management (LCM). The suggested implementation of LCM is based on a step-by-step procedure with the aim of guiding practitioners, giving guidance on the various steps to be carried out. This procedure, referred to here as 'Road pavement LCM Guidelines', was deduced and adapted to the road pavements sector from the more general standard for SA of civil engineering works EN 15978:2011.

The EN 15978:2011 standard proposes an eight steps procedure which ensures that the SA is performed according to the current requirements. The steps disassembled the complexity of the exercise, showing what it is needed before and after the effective calculation (sixth step). The identified steps are the following:

1. Identify the purpose of the assessment, i.e. goal, scope and intended use
2. Specification of the Object of the assessment, i.e. functional unit, system boundaries, etc
3. Scenarios for building LC: all the future events are foreseen.
4. Quantification of the building and its life cycle: amounts of materials and energy required;
5. Selection of environmental data and other information: primary, secondary or through EPDs
6. Calculation of environmental indicators,
7. Reporting and communication, according to some specifications
8. Verification, if the SA will be published.

This research uses these eight points above-mentioned and defines its own structure for the road pavement field. The main structure is still the same, but some adjustments are proposed and the decision-making step is added. As reported in Figure 4-1, the first five points of the new procedure correspond to the first six ones of the EN, because of the merging of steps 3 and 4. In these steps, the main actions remain the same: defining the purpose and the object of the assessment, the scenarios, the collection of data and the calculation of the impacts are carried out. A particular attention was paid to the step 2, the "definition of the object of the assessment", which was developed with a high-level detail within the Sustainability Assessment framework. Instead, the sixth step introduces something new: the "decision-making" process. It allows to choose the best option according to some criteria previously defined and to make the results of the SA operational towards an asset's Life Cycle Management.

Finally, the seventh step merges steps 7 and 8 of the EN, thus proposing reporting, communication and validation.

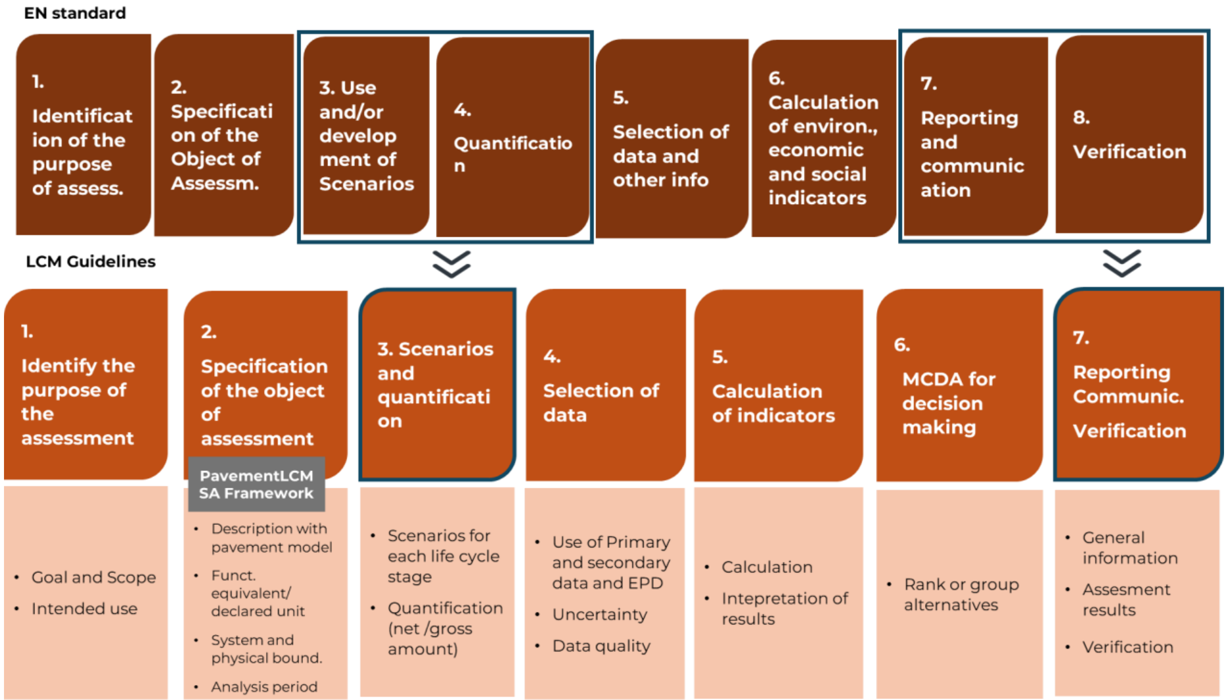


Figure 4-1 – Comparison between the step-by-step procedure for the calculation of the environmental impacts [EN 15978:2011] and for carrying out an LCM [PavementLCM]

4.1 STEP 1 – Identification of the purpose of the Sustainability Assessment

The initial phase of any SA study aims to define three essential aspects: the goal, the scope and the intended application. In other words, it is necessary to frame the problem and answer the question "Why am I doing this study?".

The goal of the study usually corresponds to the calculation of the sustainable performance of the product/process being assessed, through the quantification of all inputs and outputs towards the calculation of the selected indicators.

The scope of the assessment defines what is included in the assessment, with respect to the next steps. In few words, the scope is the pavement material or the pavement activities, with specifications here below explained.

The intended use is the purpose of the study and it may include: 1. Product improvement: detecting the hotspots or the issues of particular processes, pinpointing product categories with the highest environmental impact; 2. Support for policies and decision-making: addressing changes in product design (Green Procurement), developing new policies, comparing the sustainable behavior of different project alternatives or distinct maintenance strategies; 3. Communication: affirming the sustainability performance for Environmental Product Declaration (EPD) or for labeling or marketing.

4.2 STEP 2 - Specification of the object of assessment

This second step requires to specify all those information related to the identified system, following the suggestions presented in the previous chapter, related to pavement materials or activities: the functional equivalent/declared unit, the analysis period, the system boundaries, and the physical boundaries.

The framework harmonized some key aspects for the SA of European roads, such as:

- Scope of the assessment: introduces the concept of a road pavement model to identify the object of analysis, identifying two main systems: pavement materials and pavement activities. Pavement materials/products are those entities that must be used to build, repair, replace and maintain road pavement and its components (Lo Presti et al., 2021). In this case, the SA focuses on the product/materials level and the stakeholders involved are the manufacturers (materials producers). They must assess the burdens for each material and/or product supplied to RAs or contractors for the construction or maintenance of the pavements.

Pavement activities are those activities that must be carried out to build, repair, replace and maintain the functional and technical requirements of road pavement and its components (Lo Presti et al., 2021). In this case, the exercise focuses on the part/element/component level of the road pavement model. The stakeholders involved, with their task, are: 1) the contractors, who have to show the sustainable performance of the contracted activity, such as the construction or replacement of the road pavement; 2) the road agencies, who have to assess the sustainability of projects and/or maintenance strategies.

- Objects of assessment and functional equivalent: for each one of the two identified, the framework associates the operators involved, the system boundaries and the declared unit / functional equivalent. Concerning this last aspect, a set of technical and functional requirements was selected. Specifically, durability was selected as a technical and functional requirement. It is defined as the ability of a pavement to maintain a satisfactory level of performance over the structure's expected service life without significant maintenance, encompassing all the properties needed for the specific road situation (Nicholls, Mchale, & Griffiths, 2008). It is important to consider the 1. Resistance to rutting (EN 12697-22); 2. Resistance to fatigue (EN 12697-24); 3. Water sensitivity (EN 12697-12, EDGAR). Beside durability, other specific requirements, selected by the road authorities, can be calculated in compliance with sectoral standards and literature.

- SA indicators: literature reviews and interactions with NRAs allowed identifying a limited set of practical indicators covering environmental, economic, social aspects, in compliance with the EN 15643-5.

4.3 STEP 3 – Scenarios

According to EN 15978, a scenario is a collection of assumptions and information regarding a potential sequence of future events. In the case of pavement, this refers to the possible activities that occur throughout its life cycle, from construction to end-of-life (A4-C4). Scenarios are established based on the technical and functional requirements of the selected components.

The scenarios for A1-A3 should encompass all possible events that may occur during the production of pavement materials. This includes transportation within the site, potential loss of materials, and equipment used for moving materials.

The scenarios related to the A4-A5 phase (construction) should cover all processes from the plant to the construction site. The collection should encompass the impact of temporary and/or preliminary works, structures or facilities, such as storage, as well as the transportation of machinery, equipment, and workers to and within the construction site.

It is important to include all activities that have the potential to impact the B phase in the scenarios. The report should include information on the conditions of use, pavement management activities (such as maintenance strategies, client requirements for maintenance, service life, and manufacturers' information), and the use of energy and water (for possible future pavement typology).

In order to define scenarios related to the B phase, particularly those linked to maintenance and repair operations, it is important to establish the Reference Service Life (RSL). The RSL is the expected service life of a construction product under a set of reference in-use conditions and serves as a basis for estimating the service life under other in-use conditions (as defined by EN 15804). The Estimated Service Life (ESL) is the expected service life of a road or its components under specific in-use conditions, as determined from reference service life data, while accounting for any deviations from the reference in-use (EN15978, 2021).

The scenario for end-of-life stages should include information on milling, transport, and waste treatment of the pavement. The scenario for benefits and loads beyond the system boundaries should describe operations that potentially facilitate the replacement of primary resources. It should address the net environmental benefits and loads resulting from reuse, recycling, and energy recovery.

This step also requires quantifying all materials and products required throughout the life cycle, calculated based on the assessment object and scenarios. EN 15978 distinguishes between gross and net amounts of materials. The gross amount includes any material loss that may occur during transport or processing, while the net amount represents the exact quantity of materials and components that make up the pavement. The gross amount includes any material loss that may occur during transport or processing, while the net amount represents the exact quantity of materials and components that make up the pavement.

4.4 STEP 4 – Selection of Data

Data collection is one the most time-consuming step of a SA, but it is a key part in the process. In fact, the degree of confidence of the study strictly depends on the quality and on the level of precision of data. The information can be related to the unit process, hence to the smallest part of the inventory analysis (i.e. bitumen), or to the aggregate process, hence to a bigger element composed by more than one unit process (i.e. asphalt mixture). Three different ways can be used for data collection (Harvey at al., 2015):

1. Measured from source. It is the so-called primary data, directly obtained from plant/site;
2. Process-Activity Data and Modelling with Emission Factors. This is data is linked to energy consumed, hours of operation, productivity that can be directly measured (primary data) or can be obtained by an average of information related to a country or the EU (secondary data);
3. Data from literature. It is the so-called secondary data and used when the primary ones are not available.

Furthermore, the development and spread of SPD, provided by the manufacturers and contractors of the materials/components produced and installed, can be very powerful to use specific and robust data. Ideally, each practitioner should aim to possess an extensive set of primary data for their assessment.

Another distinction about data is presented in the EN 15978, which differentiate generic data, average data, collective data, specific data and measured data.

Beside the selection of data, this step suggests how to perform a data quality assessment. In line with the characteristics of data pertaining to their ability to meet specified requirements (ISO, 2006a), a score to each data is assigned in relationship to some criteria, such as the time-related, geographical and technological representativeness, the precision, the source of data, the completeness, the consistency, the reproducibility, and the uncertainty of information. As reported in Table 4-1, the score is between very good (1 point) to very poor (5 point): the lower the average, the higher the quality.

Table 4-1 – Data quality rating (adapted from JRC 2016)

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

The fourth step suggests also to estimate the data uncertainty, that can be caused by several aspects, such as quality of utilized equipment, defects in manufacturing and aspects linked to data quality, encompassing their completeness and reliability (Lo Presti et al., 2021). The uncertainty can be estimated using the following equation:

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

Where:

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

The Basic uncertainty (σ2bu) is employed to assess the inaccuracy in measurement, highlighting that any observation can never be deterministic. It can be calculated with the Monte Carlo Simulation (MCS), the additional uncertainty (σ2n=1:5) is linked to the data quality, calculable with Table 4-1.

The definition of uncertainty was developed within the project "PavementLCM" and furthermore information can be found in the deliverable D5.1b "Pavement LCM Resources - Recommendations for Multi--Criteria Sustainability Assessment" (Abed & Lo Presti, 2021).

4.5 STEP 5 – Calculation of indicators

As required by the standards, this fifth step consists of two parts: the calculation methods and the interpretation of the results.

4.5.1 Calculation method

This first part aims at quantifying the impacts related to the selected set of indicators, already presented in Chapter 3.

The proposed analysis is based on Life Cycle- based impact assessment techniques. It follows that the method of calculation is the one provided by the current LCA and LCC standards (ISO 14040 and 14044, ISO 15686-5:2017 for the economic dimension, EN 15978:2011 for the environmental aspects), while the social indicator is assessed by a quantitative approach. In fact, tyre-pavement noise can be expressed with a customizable rating system in advanced and basic approach:

- Advanced: rating based on a quantitive assessment of the reduction of the tyre-pavement noise level in dB compared to the reference pavement (i.e. Level A: ≤9 dB, Level B: 3 dB<x< 6 dB, Level C; ≤ 3 dB) (Garbarino et al., 2016);
- Basic: rating based on the adopted mixtures used for wearing courses(Transport Council, 2011) (i.e. Level A: dense, Level B: gap graded, Level C: open grade)

The procedure to perform an LCA or an LCC has already been described in chapter 2. The research does not focus on the definition of new impact assessment or procedures for calculating the results. The selected indicators can be assessed using software and impact assessment methods, such as EF 3.0, as suggested by the current standard EN 15804.

4.5.2 Interpretation of results

Once the calculations are completed, it is required to interpretate the results. They need to be analyzed under a common vision, to finally lead to conclusion and recommendations. The uncertainty analysis, the sensitivity analysis and the normalization of the results can be used to define more robust results.

The hotspot analysis allows the identification of key issues that can be related to specific flows or life cycle stage. The analysis can help in focusing on the priority issues, LC stages and actors to evaluate and implement solutions or allocating resources (i.e. time, money) to solve problems. A process, a flow or a LC stage is considered a hotspot if its contribution is >50% of the total contribution, while it is considered relevant if its contribution is >80% (European Commission, 2017).

The uncertainty analysis can support in enhancing comprehension of the results and in iteratively improving a SA study. The analysis can be carried out with the Monte Carlo analysis, that studies how a model responds to randomly generated inputs. It is generally based on the generation of "n" inputs and a number of "n" simulations and then analyzed. The calculation can be easily performed through different software which have this functionality incorporated, such as MATLAB or can be included in LCA softwares (i.e. GaBi).

The normalization allows to compare the results to a common scale, using normalization factors to translate the results to a common language. The EF 3.0 impact assessment method, suggested here to perform the environmental calculations, also includes normalization factors.

4.6 STEP 6 – Interpretation for decision making (optional)

This step is not included in the methodology proposed by the current standards. As optional, it is suggested to be applied when the intended application of the SA is the comparison of two or more options. In fact, in this case, choosing the best alternative is not so easy: different aspects of sustainability are taken into account and an option can be better under a certain aspect but worse under another.

Multi-Criteria Decision Making (MCDM) can help the practitioners in the decision process, helping in finding the optimal solution, evaluating the various options against chosen criteria. The solution will meet the criteria to a certain degree and the decision-maker must pinpoint the solution hat aligns most closely with the considered criteria.

In this research, the suggested methodology is PROMETHEE, developed by the professor Brans in 1982, which provides "an overall or net ranking for a set of alternatives established by weighting the positive outranking, showing how well an alternative is better than others, and the negative outranking, which reveals how bad an alternative compared to others."

The methodology was selected for the compliance to some criteria: transparency, applicability, flexibility, interpretation, compensation and amount of input data (Abed et al., 2023).

A MCDM can be performed following the steps presented in Figure 4-2.

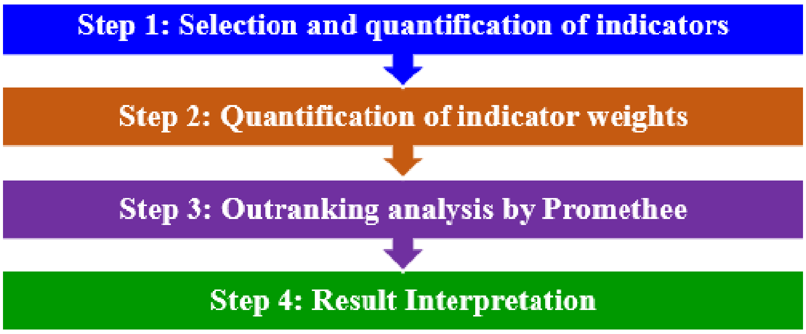


Figure 4-2 - MCDM analysis steps proposed by the PROMETHEE method

The use of MCDM makes more operational the results on a SA and leads to go towards a Life Cycle Management of the road pavement.

4.7 STEP 7 – Reporting, communication and verification

The final step of the Guidelines is aimed at reporting, communicating and verifying the results of the assessment.

The EN 15643-5 suggests using the information groups (modules) to report and communicate the results, hence the amount of emitted pollutant should be presented for each life cycle stage. For instance, in a cradle-to-laid analysis, the total amount of CO2eq emitted, should be split between the production phase (A1-A3) and the installation phase (A4-A5).

The communication of these results outside the company can be limited to few indicators and/or few modules, always specifying what was overlooked.

The verification process, or critical review, needs to be carried out if the results are made public outside the company, as required by ISO 14040 for environmental assessment (approach extended here for all other SA results). It consists in the analysis of the consistency throughout the study, the traceability and conformity of data, the completeness and the completeness and consistency of the quantification of materials and scenarios. Two different approaches can be used for the selection of experts called for the critical review: the first entails internal or external professionals, the second a panel of interested groups.

4.8 Concluding remarks

This chapter introduces the step-by-step procedure, known as the Guidelines, specifically tailored for road pavements based on the current European Norms (EN).

The main outcomes include:

- The guidelines facilitate the implementation of a harmonized Sustainability Assessment using the framework defined in chapter 3.
- The guidelines are user-friendly, aiding analysts in the stepwise application for organizations and specific content within the framework.
- The guidelines contribute to the implementation of Life Cycle Management (LCM) for European road pavements, utilizing SA results for asset management and promoting life cycle thinking among stakeholders.
- The guidelines foster interaction among different partners and stakeholders, primarily benefiting Road Authorities (RAs) but also aiding in information exchange and requests.
- Harmonizing procedures ensures consistency at the industrial level, ensuring that industries follow the same approach for assessing their products. This enables the definition of benchmarks and targets, promoting improved sustainability performance at the national and European levels.

- The establishment of benchmarks and targets can inform policy development at both national and European levels.
- Extending harmonization to other sectors of civil engineering works (e.g., aqueducts) and diverse products/processes in different fields ensures a consistent assessment across sectors.

Chapter 5 APPLICATION WITH CASE STUDIES: Are Cold Recycled Materials a more sustainable option than Hot Mix Asphalt?

5.1 Introduction

The research carried out so far has made it possible to define a methodology for the SA of road materials and pavements, including a reference SA framework and a step-by-step procedure to guide the practitioner through the implementation of LCM in road pavements. The objective of this chapter is to demonstrate the application of the LCM guidelines for the main SA exercises tipically related to the two different systems identified, pavement materials and pavement activities, and the three main stakeholders:

- pavement material MANUFACTURERS,
- pavement activities CONTRACTORS
- pavement activities ROAD AUTHORITIES.

In order to do that, a quite obvious research question "Are Cold Recycled Materials a more sustainable option for base courses than Hot Mix Asphalt?" was considered to demonstrate the application of the SA framework and LCM guidelines. In fact, in literature, several papers have already reported improved sustainability performances of replacing HMA with CRM (Bloom et al., n.d.; Oreto, Russo, Veropalumbo, Viscione, Biancardo, et al., 2021); this is due to a lower amount of virgin aggregates and production temperature (60° instead of 150-180°), implying a reduction up to 50% of the fuel consumption (D'Angelo et al., 2008; Del Carmen Rubio et al., 2013). This application wanted to provide further evidence of these results but through the use of the suggested SA framework; hence, a first exercise was carried out to compare two different mixtures (pavement materials), while a second one to compare two typologies of pavements (pavement activities). In both cases, the main goal was understanding the sustainability performance of using Cold Recycled Mixtures (CRM) in place to Hot Mix Asphalts (HMA), both in terms of mix production (pavement materials) and in terms of road construction (pavement activities).

The chapter at first presents the two considered case studies, one in Republic of San Marino (RSM) and one in Germany (GER). Each of them was considered to perform a sustainability assessment aiming at a comparative analysis of using cold-in-place and cold-in-plant Cold Recycled Materials (CRM) for base and/or binder courses, in place of Hot Mix asphalt (HMA). Then the chapter provides a general description of the adaptation of the SA framework to the selected application, followed by the details of the step-by-step procedure to identified in the Road pavement LCM Guidelines.

5.2 Case Studies

5.2.1 General Description

These case study were built thanks to the direct involvement of the author, and the huge support provided by the partners, within the CRABforOERE project (CRABforOERE, 2018), funded by the Conference of European Directors of Roads (CEDR), aiming at investigating the potentialities of using Cold Recycled Asphalt Base for Optimised Energy and Resource Efficiency (http://crabforoere.eu). Within this project, the partners have had the chance of gathering primary data from two case studies consisting in repaving operations:

- carried out in 2020 in the Republic of San Marino (RSM) including Cold Recycling Mixtures (CRM) mixtures produced through Cold Central Plant Recycling (CCPR) process;
- carried out on the E44 in Trier, in Germany (GER) including a CRM layer obtained through the Cold In-place Recycling (CIR).

Each case study included two pavement structures: one incorporating the CRM layer and the other one consisting of only Hot Mix Asphalt (HMA).

Case study 1 (RSM): The RSM case study was part of a maintenance intervention of four lanes with a double carriageway road, which is the main connector between the historic centre of the Republic of San Marino and Rimini (Italy) on the Adriatic coast. The road is characterised by an annual average daily traffic of about 4000 vehicles per day and 10% heavy vehicles (Graziani et al., 2022). The maintenance operations included the binder and wearing courses. *Figure* ***5-1*** depicts the two pavement structures placed after the milling of the old asphalt layers. The binder and wearing layers of the reference pavement structure (RSM_REF) were both in HMA. The second pavement structure (RSM_CCPR) included a CRM as binder course produced using the CCPR technology. The RA, produced by milling the existing pavement, has been collected over time in the stockpiling facility located in the production plant. The plant, where both HMA and CRM were produced and where the paving equipment is stored, is located in San Leo (Italy), which is 15 km far from the pavement construction site. The CRM was produced in a mixing plant for cement treated mixtures specifically modified by adding an inlet and storage system for the bituminous emulsion (Ferrotti et al., 2020). The heat source of both HMA and CRM plants is electricity. The produced mixtures were then transferred to the construction site, laid using a paver and compacted.

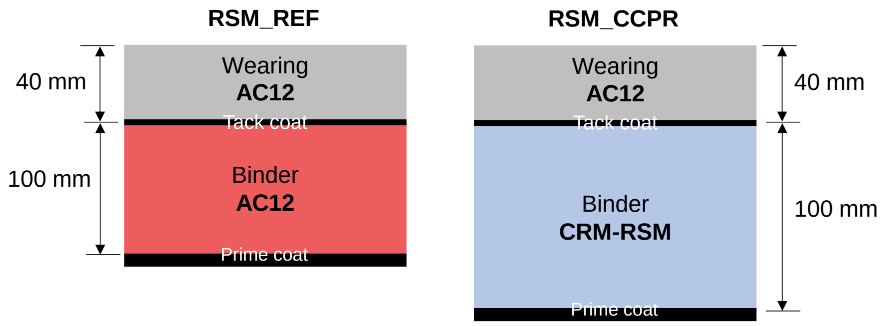


Figure 5-1. Pavement structures considered for the Republic of San Marino case study: reference pavement (on the left) and pavement with CRM (on the right)

<u>Case study 2 (GER):</u> *Figure* 5-2 shows the two pavement structures considered in the German case study. According to the German design, the rehabilitation of this section would have had a pavement structure made of asphalt concrete SMA8 S, over a binder course AC16 BS and base course AC32 TS (GER_REF). The design method suggests using, as an alternative, a solution in which the HMA base course is thinner, and a CRM base layer is added below it (GER_CIR). In this case study, the HMA mixtures were produced in a plant located in Trier, 2.9 km distant from the pavement construction site and where the paving equipment is stored. A hot oil heater is the heat source of the HMA plant. The CRM was instead produced using the CIR technology by means of a recycling train.

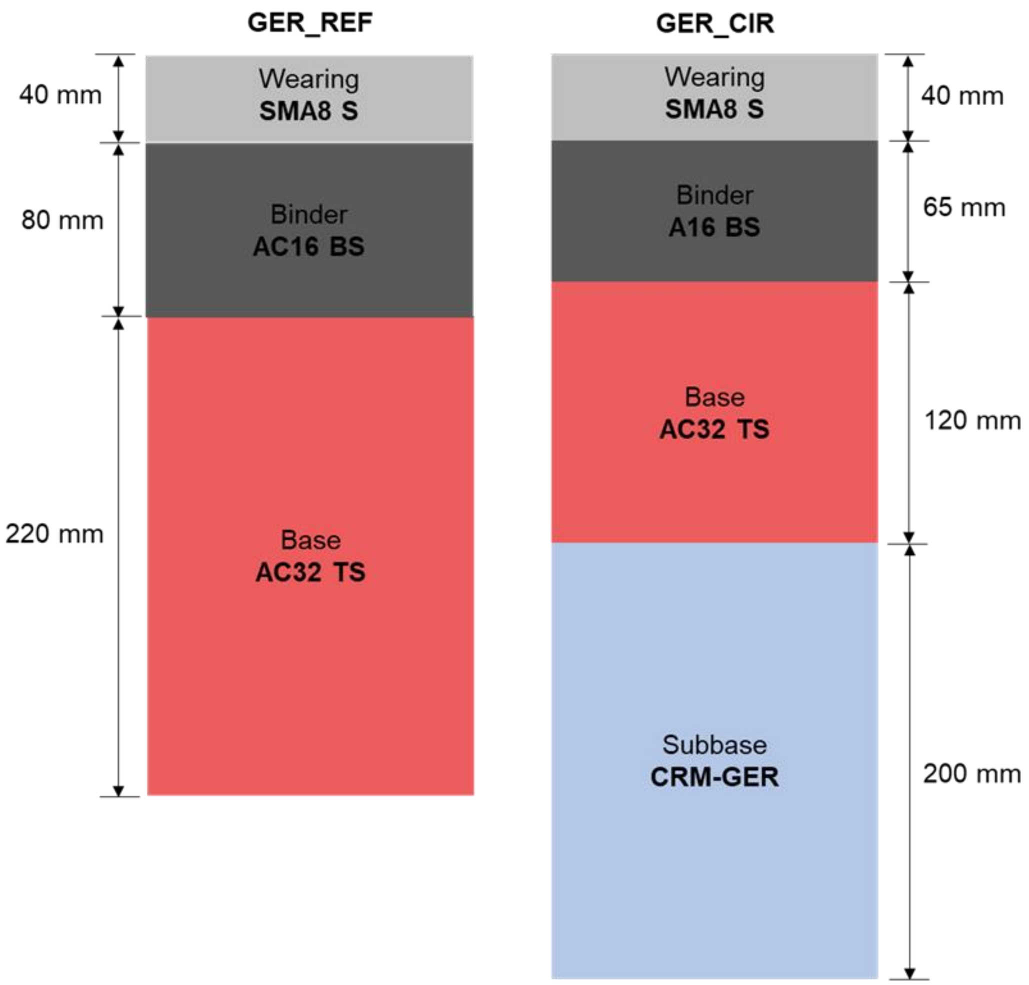


Figure 5-2. Pavement structures considered for the German case study: reference pavement and pavement with CRM

5.2.1.1 Mixtures composition

The LCA considered a wide range of CRM with high RA contents (>70%) and HMA. The materials composition was established by the road agencies and contractors, based on the National guidelines. This composition was then considered in the maintenance activities carried out in the two case studies considered in the Republic of San Marino (RSM) and in Germany (GER).

In particular, for the RSM case study, a CRM for binder courses was adopted (herein coded “CRM-RSM”). The mixture included RA, natural aggregates, SBR latex modified bitumen emulsion C60BP10 (according to EN 13808), Portland-limestone CEM II/B-LL 32.5R (EN 197-1), and water. The HMA (HMA-RSM) was an AC12 mixture employed for both binder and surface courses, and produced using natural aggregates and PMB bitumen Table 5-1 and Table 5-2 report the composition of CRM-RSM and HMA-RSM, respectively, which were identified according to the specification of the San Marino road agency (Azienda Autonoma per i Lavori di Stato, 2020; Graziani et al., 2022)

The cold mixture considered in the German case (CRM-GER) study was produced using RA, bitumen emulsion C60B10 (according to EN 13808), cement and water. As far as HMA concerns, the AC32 TS (coded HMA-GER), according to the National standard, is used for base courses. Table 5-1 and Table 5-2 report the compositions by weight of the German cold and hot mixtures, respectively.

To deepen the analysis of the impact of CRM composition in terms of binders dosages, i.e. bitumen emulsion and cement, an additional set of four CRM was considered. The mixtures, coded CRM-01, CRM-02, CRM-03 and CRM-04, included RA, natural aggregates, bitumen emulsion C60B10 (EN 13808), Portland cement CEM I 42.5 R (EN 197-1) and water. They are characterised by the same aggregate composition and total water content (4.5% by dry aggregate weight). The only difference is the bitumen emulsion and cement dosages selected:

- bitumen emulsion dosage (by dry aggregate weight) equal to 6% for CRM-01 and CRM-03, and 3.3% for CRM-02 and CRM-04;
- cement dosage (by dry aggregate weight) equal to 0% for CRM-01, 1.5% for CRM-02 and CRM-03, and 3% for CRM-04.

Table 5-1 summarises their compositions, selected according to the specification ranges identified within the National mix design study applied in several European Countries (Mollenhauer et al., 2021)

Table 5-1. Composition by mixture weight of the CRM considered in the LCA

	CRM-RSM	CRM-GER	CRM-01	CRM-02	CRM-03	CRM-04
Max dimension (mm)	10	*na*	16	16	16	16
Reclaimed asphalt (%)	83.9	89.4	72.5	73.3	71.6	72.4
Natural aggregate (%)	3.6		12.6	12.7	12.4	12.6
Filler (%)	3.6		5.4	5.5	5.3	5.4
Bitumen emulsion (%)	4.1*	3.8	5.4	3.0	5.3	3.0
Cement (%)	1.8	3.8	0.0	1.4	1.3	2.7
Water (%)	2.9	3.0	4.1	4.1	4.0	4.0

* SBR modified bitumen emulsion

Table 5-2. Composition by mixture weight of the HMA considered in the LCA

	HMA-RSM	HMA-GER		
Denomination	*AC12*	*AC32 TS*	*SMA8 S*	*AC 16 BS*
Max dimension (mm)	12	32	32	16
Coarse natural aggreg. (%)	40	29.5	29.5	90.5
Fine natural aggregate (%)	50.5	60	60	-
Filler (%)	4	7	7	5
Bitumen (%)	5.5	3.5	3.5	4.5

5.2.1.1 Selected maintenance strategies and general assumptions

Several studies report that new materials should have a similar or quite similar durability as the conventional mixtures to be really sustainable (reference). In this study, in order to account the benefits of using cold technologies, a similar maintenance strategy has been defined for cold and conventional pavements. In both case studies, the maintenance consists of milling and paving surface course, complemented with interventions on binder course and on base course (only in Germany) (Table 5-3).

It is assumed that the road pavement foundation and sublayers will not deteriorate and the asphalt will only last for its full estimated lifetime with no under/over performance.

1414 *Table 5-3 - Maintenance information*

	Maintenance information			
Maintenance Treatment	- Surface treatments with periodic inlay of wearing course and occasional inlay of binder and base course. - Maintenance is undertaken in one carriageway (two lane), or one lane at a time, with the traffic diverted onto the other carriage/lane.			
Materials for maintenance strategies	Republic of San Marino		Germany:	
	Current asphalt mixture used for binder course will be compared with a C4O mix technology (90% RA, 10% sand).		Current asphalt mixture used for base will be compared with the C4O mix composed of RA, Cement (4%), Bitumen Emulsion (4%) and water (3.1%).	
Analysis period	20 years		50 years	
Country dependent maintenance strategy	*year*	*procedure*	*year*	*procedure*
	y 7,5	Crack repair with bitumen emulsion	Y 12.5	milling surface course / paving surface course / production new HMA
	y 10	milling surface course / paving surface / production new HMA	Y 25	milling surface+ binder course paving surface+ binder course production new HMA
	y 20 -	milling surface course + binder course / paving surface course + binder course / production new HMA and CRAB -	Y 37.5	milling surface course / paving surface course / production new HMA
			Y 50	full rehabilitation of all bounded layers _ new HMA + CRAB in- situ recycling
Equipments	• Asphalt and CRAB Paving: Vogele Super 1803-3i paver,4 h paving, fuel consumption (l/h): 11,25 • Asphalt Compaction: Steel-wheeled roller CAT, 4m to 1 h compaction, fuel consumption (l/h): 3,75		• Asphalt Milling: Recycler 0,0788 l/m^2 • CRM mixing: Bitumen emulsion tanker, water tanker, cement tanker • CRM Compaction: Padfoot Compactor: 0,0077 l/m^2	

	• CRM Compaction: Pneumatic-tired HAMM GRW180i 50l/8h • Asphalt reclaiming: Cold milling machine Wirtgen W200i, fuel consumption (l/h) : 25	• Asphalt Compaction: Vibratory Compactor: 0,0077 l/m² Tandem roller: 0,0077 l/m² • CRM paving: Static roller 0,007 l/m²

5.3 Adapting the SA framework to selected application

The framework suggests differentiating the typical scheme for conducting SA for:

- Sustainability Assessment of pavement materials
- Sustainability Assessment of pavement activities

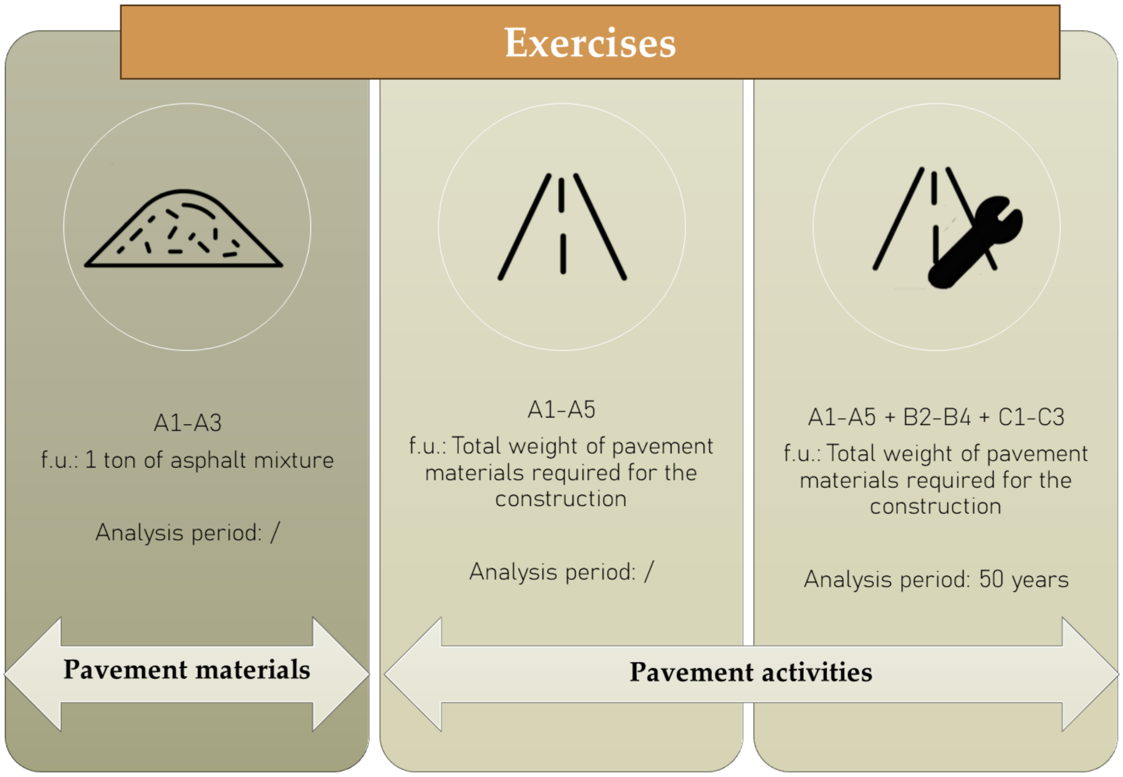


Figure 5-3 – Description of the exercises

These exercises are related to two three different stakeholders (one for pavement materials, two for pavement activities) involved in the sector. Each one carries out an exercise for a specific purpose, defines a specific object of the assessment and delivers its own results. Chapter 3 provided details of the differentiations among the systems and exercises. Figure 5-3 summarizes the main aspects of the three different exercises used in this chapter.

5.3.1 SA of pavement materials (manufacturers)

According to the SA framework, the exercise involves the materials/products manufacturers of asphalt mixtures, concrete, bitumen, etc. The system boundaries are tipically A1-A3 + D, hence a cradle-to-gate + module D analysis, which considers the extraction of raw materials, transport to asphalt plant and production of the mixtures (*Figure 5-4*).

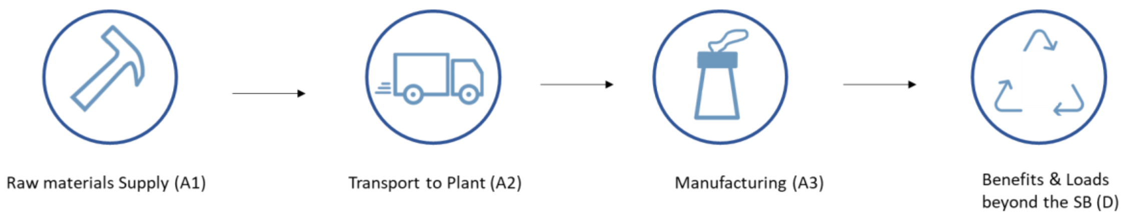


Figure 5-4 - Typical life cycle stages for SA of pavement materials (Manufacturers)

- The declared unit is defined as 1 ton of CRM and 1 ton of HMA, composed as above-described. Any analysis period can be applied because of the only the product stage is considered.
- The main output is the calculation of the environmental performance and the delivery of an Environmental Product Declaration (EPD) to contractors and NRAs.
- The selected indicators are the ones related to pavement materials of Table 3-4.

In this case study, the SA exercise consists in the calculation of sustainable performance of HMA and CRM, with a specific mix design. Also, the exercise aims at quantifying the sustainability implications of using different cold Recycling techniques, i.e. CCPR and CIR, in the production stages of mixtures for road pavements in Europe.

5.3.2 SA of Pavement Activities (Contractors, Road Owners)

Contractors are called to construct, repair, maintain or replace the pavement component (i.e. base course built with HMA or CRM). Their work can consists in:

- constructing, at year x, one or more layers. In this case, the system boundaries consist in A1-A5 + D (Figure 5-5). If the contractor already has an EPD, the SA calculation are limited to A4-A5.

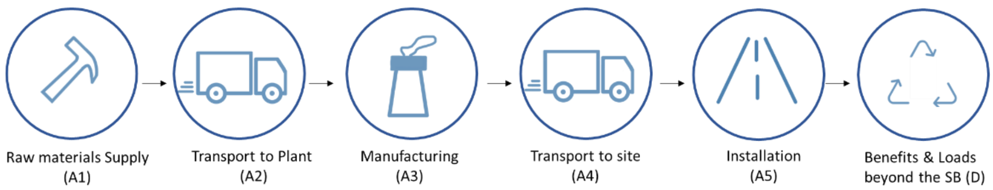


Figure 5-5 - Life Cycle Stages for SA exercise for Contractors (exercise a)

In this study, the first SA exercise (RSM) consists in the comparison of the performance of 1) a road section with wearing course in HMA and base course in CRM; 2) a road section composed of two layers of HMA. The second exercise (GER) consists in in the comparison of the performance of 1) a road section with wearing, binder and base courses in HMA; 2) a road section composed of wearing, binder and base courses in HMA and base course in CRM.

In RSM, the functional equivalent is the exact volume (or weight) of the road pavement material, with the specific technical and functional requirements, to be contracted and/or built, hence if the wearing course is made of HMA and the binder course of CRM, the f.u. is 30 tons of HMA and 60 tons of CRM, while if the two layers are made of HMA, the f.u. corresponds to

105 tons of HMA (30 for wearing course and 75 for binder course). In GER, xxxx The physical boundaries are the above-mentioned layers to be built.

5.3.3 SA exercise for road owners/ NRAs:

Road owners/NRAs can carry out a SA exercise to support their decision both for activities of new construction (Figure 5-6) and for asset management (regular operations executed in short term or rehabilitations executed in longer term) (Figure 5-7). In both cases, it is important to estimate the Reference Service Life (RSL) of the installed components (durability), to understand the number of interventions.

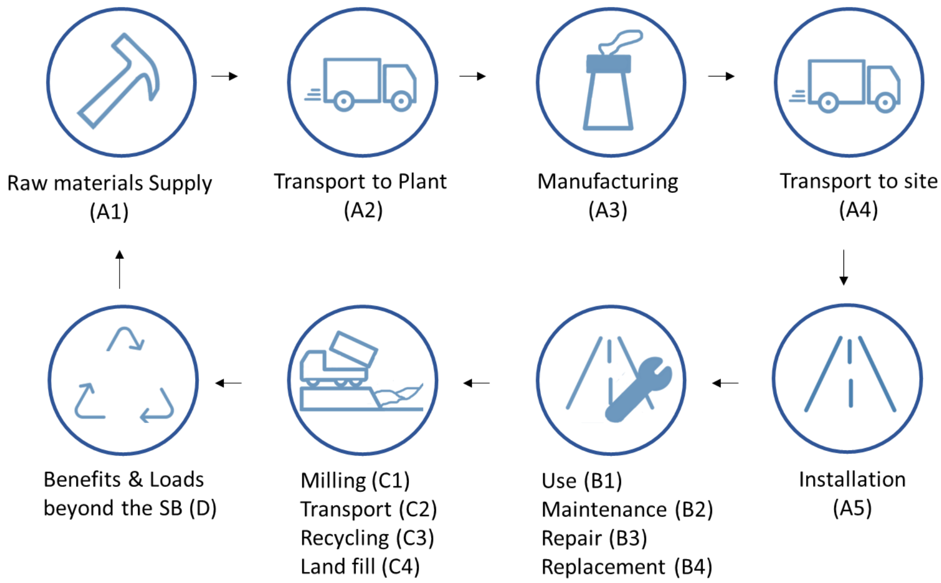


Figure 5-6 - Life Cycle Stages for SA exercise for Contractors (exercise b)

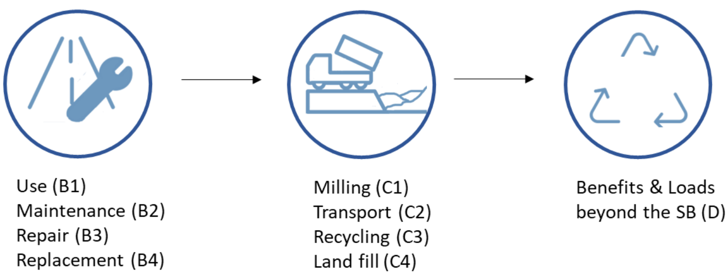


Figure 5-7 - Life Cycle Stages for SA exercise for road owners/ NRAs

In the RSM case study, the SA exercise consists in the comparison of the performance, for an analysis period of 20 years, of a: 1) a road section with wearing in HMA and binder courses in CRM; 2) a road section with the two layers of HMA..

In GER case study, the SA exercise consists in the comparison of the performance, for an analysis period of 50 years, of a: 1) a road section with wearing, binder and base courses in HMA; 2) a road section with wearing, binder courses in HMA and base course in CRM.

For both case studies, the pavement design is the same as above, while the maintenance strategy is reported Table 5-3.

5.4 EXERCISE 1 - SA of pavement materials (MANUFACTURERS)

As the research focuses on the evaluation of the impact of CRM during the production stages (A1-A3, no module D for this example), the analysis has been carried out on the cold mixtures, i.e. CRM-RSM and CRM-GER, and the conventional mixtures used in the corresponding layers in the reference pavement structures, i.e. AC12 for RSM and AC32 TS for GER. Their composition is presented in Section 2.1.1. To fully answer the questions about the sustainability of asphalt mixtures, sensitivity and hotspot analyses were carried out as reported in *Figure 5-8*.

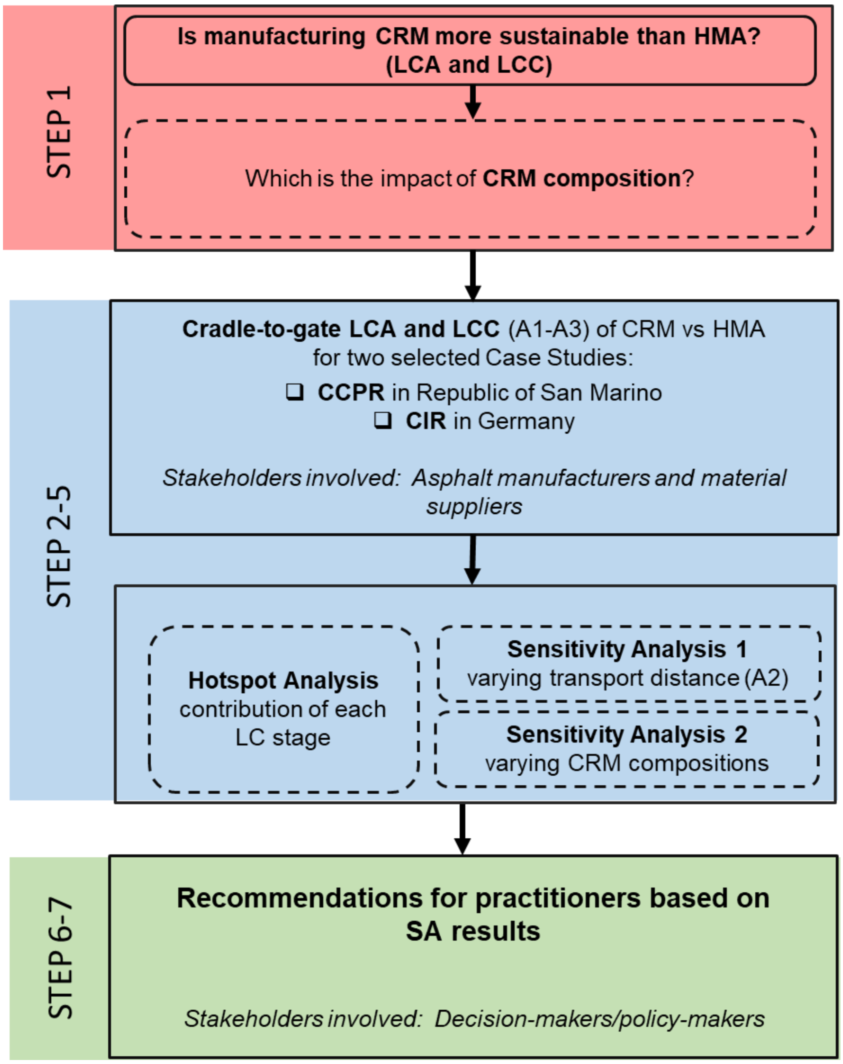


Figure 5-8 - Structure of the SA investigation and involved stakeholders

5.4.1 STEP 1 - Identify the purpose of the SA

This study aims to assess and compare the environmental and economic performance of two distinct technologies: hot production and cold production. The comparison involves different mixtures, specifically contrasting a conventional mixture (HMA_GER) with a cold mixture (CRM_GER) produced in Germany, and another conventional mixture (HMA_RSM) with a cold mixture (CRM_GER) in the Republic of San Marino. The cold mixtures are produced through varying methods, including in-situ (CIR) and in-plant (CCPR) processes, which are also examined. The intended application encompasses material production, spanning from raw material extraction to mix manufacturing. Ultimately, the objective is to offer Road Agencies and manufacturers valuable recommendations for optimizing their overall sustainability practices.

5.4.2 STEP 2 – Specification of the object of the assessment

The object of the assessment is represented by the four asphalt mixtures, two for RSM (CRM-RSM and HMA-RSM) and two for GER (CRM-GER and HMA-GER).

The declared unit is one ton of each asphalt mixture, composed as in Table 5-1. The system boundaries include only a cradle-to-gate (manufacturers level), omitting the construction, use and end-of-life (Contractors/NRAs level).

In accordance with the framework, the identified declared unit (d.u.) was one ton of asphalt mixtures whose composition was derived in accordance with Table 5-1 and Table 5-2. In addition, it has been assumed that:

- RA brings zero emission into the considered system boundaries (EAPA, 2017b);
- RA is stockpiled at the asphalt plant (zero transport);
- waste and/or over consumption of energy and materials during the A3 at the asphalt plant are not considered.

5.4.3 STEP 3 – Scenarios

The assumption and information to collect are related to the extraction of raw materials, mix design (Table 5-1, Table 5-2), transport distances to plant.

Site	**HMA**		**CRM**	
	Location	*Distance (km)*	*Location*	*Distance (km)*

Refinery[a]	Bologna, Italy	125	Bologna, Italy	125
Fine aggregate quarry	Forlì, Italy	65	Ravenna, Italy	65
Coarse aggregate quarry	Castel Viscardo, Italy	235		
Filler quarry	Serra San Quirico, Italy	150	Gubbio, Italy	145
RA processing and stockpiling			San Leo, Italy[b]	0
Cement storage			Monselice, Italy	210
Water	San Leo, Italy[b]	0	San Leo, Italy[b]	0

[a] bitumen and bitumen emulsion, [b] asphalt plant

Table 5-4, Table 5-5) and energy used at the plant (typology and quantity) (Table 5-6). It has been assumed that only the net amount of material is taken into account in this study. Once the analysis is a cradle-to-gate, any RSL was considered.

5.4.4 STEP 4 – Selection of data

5.4.4.1 Environmental data

In this research both primary and secondary data were used: when primary data (directly provided by partners) missed, GaBi database was used. Specifically, the A1 stage involves the materials supply. Table 5-1 Table 5-2 report the composition of all the mixtures taken into account, while the information for their extraction and preparation was provided by the database. The transport stage (A2), concerning the distances from the quarry/refinery to the plant/site of production, were entirely provided by partners (

Site	**HMA**		**CRM**	
	Location	*Distance (km)*	*Location*	*Distance (km)*
Refinery[a]	Bologna, Italy	125	Bologna, Italy	125
Fine aggregate quarry	Forlì, Italy	65	Ravenna, Italy	65
Coarse aggregate quarry	Castel Viscardo, Italy	235		

Filler quarry	Serra San Quirico, Italy	150	Gubbio, Italy	145
RA processing and stockpiling			San Leo, Italyb	0
Cement storage			Monselice, Italy	210
Water	San Leo, Italyb	0	San Leo, Italyb	0

[a] bitumen and bitumen emulsion, [b] asphalt plant

Table 5-4 and Table 5-5). The manufacturing stage (A3) includes all the energy consumption needed to produce the mixtures, hence for heating and mixing and were provided by partners (*Table* **5-7).**

Table 5-4. RSM case study: locations and transport distances of the different sites from the asphalt plant (A2)

Site	HMA		CRM	
	Location	*Distance (km)*	*Location*	*Distance (km)*
Refinery[a]	Bologna, Italy	125	Bologna, Italy	125
Fine aggregate quarry	Forlì, Italy	65	Ravenna, Italy	65
Coarse aggregate quarry	Castel Viscardo, Italy	235		
Filler quarry	Serra San Quirico, Italy	150	Gubbio, Italy	145
RA processing and stockpiling			San Leo, Italy[b]	0
Cement storage			Monselice, Italy	210
Water	San Leo, Italy[b]	0	San Leo, Italy[b]	0

[a] bitumen and bitumen emulsion, [b] asphalt plant

Table 5-5. GER case study: locations and transport distances of the different sites from the asphalt plant (for HMA) and the pavement installation site (for CRM)

Site	**HMA**		**CRM**	
	Location	*Distance* (km)*	*Location*	*Distance+ (km)*
Pavement installation site	Trier, Germany[c]	2.9	Trier, Germany[c]	0
Refinery[a]	Bonn, Germany	163	Bonn, Germany	163
Fine aggregate quarry	Neumagen-Dhron, Germany	28		
Coarse aggregate quarry	Neumagen-Dhron, Germany	28		
Filler quarry	Neumagen-Dhron, Germany	28		
RA processing			Trier, Germany[c]	0
Cement storage			Allmendingen, Germany	392
Water	Trier, Germany[b]	0	Trier, Germany[b]	2.9

* from asphalt plant, + from pavement installation site
[a] bitumen and bitumen emulsion, [b] asphalt plant, [c] pavement installation site

Table 5-6. Energy consumption for production (A3)

	RSM		**GER**	
	HMA_RSM	**CRM-RSM**	**HMA-GER**	**CRM-GER**
Electricity (kWh/t)	0.65	0.65	3.33	-
Water (kg/t)			2	
Diesel (kg/t)	10	40	-	0.16
Natural gas (m^3/t)	10			
Heating oil (kg/t)	-	-	10	

A data quality assessment has been performed giving a score to the used data from 1 (very good) to 5 (very poor) as suggested by JRC (Zampori et al., 2016). The results in *Table* **5-7** indicates that average rating is satisfactory, being comprised between good and very good (2 and 1, respectively).

Despite suggested from the Road pavement LCM guidelines, this exercise will not include the economic indicators and uncertainty analysis of the results (Lo Presti et al., 2021). The reader will find more details on the uncertainty analysis of SA results within two related research products: "D5.1b Recommendations for Multi-¬Criteria

Sustainability Analysis" (Abed & Lo Presti, 2021) and "Uncertainty analysis of life cycle assessment of asphalt surfacings" (Abed et al., 2023)

Table 5-7. Data quality

Data	Type*	Source	Technological Representativ.	Geographical Representativ.	Temporal correl.	Completeness	Methodological Appropriateness and Consistency	Average
EU-28: Crushed rock 16-32 mm	Secondary	GaBi	1	2	1	2	2	1.6
EU-28: Crushed sand grain 0-2 mm	Secondary	GaBi	1	2	1	2	2	1.6
EU-28: Bitumen at refinery	Secondary	GaBi	2	2	1	2	2	1.8
EU-28: Limestone	Secondary	GaBi	2	2	1	2	2	1.8
EU-28: Bitumen emulsion	Secondary	GaBi	3	2	1	2	2	2
EU-28: Cement (CEM II)	Secondary	GaBi	2	2	1	2	2	1.8
Reclaimed Asphalt (RA)	Secondary	GaBi	2	2	2	2	1	1.8
EU-28: Water	Secondary	GaBi	2	2	1	2	2	1.8
EU-28: Diesel mix at filling station	Secondary	GaBi	2	2	1	2	2	1.8
Other resources : EU-28: Oil	Secondary	GaBi	2	2	2	1	2	1.8
EU-28: Electricity Grid mix	Secondary	GaBi	2	2	2	1	2	1.8
Electricity consumption	Primary	Material Producer	1	1	1	1	1	1
Gas Consumption in Asphalt Plant	Primary	Material Producer	1	1	1	1	1	1
Oil Consumption	Primary	Material Producer	1	1	1	1	1	1
Transport Distances	Primary	Real Distances related to the specific case study	1	1	1	1	2	1.2
Transport Mean	Secondary	GaBi Database	1	2	1	2	1	1.4
Total Average								1.54

*P=Primary, S=Seccondary

5.4.4.2 Economic data

Also concerning the economic indicators, both primary and secondary data were used: when primary data (directly provided by RSM and GER contractors in December 2023, bur referred to 2020) missed, literature and European datasets (i.e. Eurostat) were used. Specifically, the A1 stage involves the costs for materials supply, reported in

Table 5-8. All this data is directly provided by the partners. Concerning the

Site	RSM	GER
Fine aggregates (€/kg)	0.020	0.0125
Coarse aggregates (€/kg)	0.018	0.0175
Filler (€/kg)	0.06	0.16
Reclaimed Asphalt (€/kg)	0.01	0.01
Cement (€/kg)	0.10	0.14
Bitumen (€/kg)	0.58	0.7
Bitumen emulsion (€/kg)	0.53	0.8
Water	0.001	0.005

transport stage (A2), the amount of diesel was obtained from GaBi database using the environmental models where transport distances and type of trucks were added, while the costs of diesel, while the cost of diesel was deduced by Eurostat. The information on manufacturing stage (A3) includes all the unitary costs consumption needed to produce the mixtures. The exact amounts of energy required were provided by partners, as mentioned for the economical assessment, while the costs were sourced from Eurostat (*Table* ***5-11****Table* ***5-12).***

The data is related to the costs of materials and fuels, hence any other agency costs (i.e. projects, workers, occupational safety) were not considered.

Site	RSM	GER
Fine aggregates (€/kg)	0.020	0.0125

Coarse aggregates (€/kg)	0.018	0.0175
Filler (€/kg)	0.06	0.16
Reclaimed Asphalt (€/kg)	0.01	0.01
Cement (€/kg)	0.10	0.14
Bitumen (€/kg)	0.58	0.7
Bitumen emulsion (€/kg)	0.53	0.8
Water	0.001	0.005

Table 5-8. RSM and GER case studies: unitary costs for materials supply (A1)

Table 5-9. RSM and GER case studies: unitary costs for energy (A3)

Site	**RSM**	**GER**
Electricity (€/kWh)	0.09	0.2181
Diesel (€/l)	1.29	1.095
Gas (€/kWh)	0.03	0.0349
Heating oil (€/l)	-	0.44

5.4.5 STEP 5 – Calculation of indicators

The calculation of indicators for pavement activities covers the environmental and economic dimensions. This section will provide the tables/graphics with impact calculated for each indicator, as well as the interpretation of results with Hot spots and Sensitivity analyses

5.4.5.1 Environmental impact indicators

The environmental impacts are calculated using the EF 2.0 methodology and they are related to a set of selected indicators defined in accordance with the framework. Table ***5-10*** provides the complete list of the indicators examined in the research and their abbreviations, while *Table* ***5-11*** shows the numeric results of the LCA in terms of impacts for the mixtures referred of each case study.

Table 5-10. Impact indicators considered in the analysis

Macro category	Indicators	UoM	Abbreviation
Climate Change	EF 2.0 Climate Change	kg CO2 eq.	CC
	EF 2.0 Climate Change (biogenic)	kg CO2 eq.	CC - biogenic
	EF 2.0 Climate Change (fossil)	kg CO2 eq.	CC - fossil
	EF 2.0 Climate Change (land use change)	kg CO2 eq.	CC - land use ch.
Acidification	EF 2.0 Acidification terrestrial and freshwater	Mole of H+ eq.	Acid.
Eutrophication	EF 2.0 Eutrophication freshwater	kg P eq.	Eutr. freshwater
	EF 2.0 Eutrophication marine	kg N eq.	Eutr. marine
	EF 2.0 Eutrophication terrestrial	Mole of N eq.	Eutr. Terrestrial
Air Pollution	EF 2.0 Photochemical ozone formation - human health	kg NMVOC eq.	Phot. ozone form.
Natural Resources	EF 2.0 Land Use	Pt	Land use
	EF 2.0 Resource use, energy carriers	MJ	Res. use, energy carriers
	EF 2.0 Resource use, mineral and metals	kg Sb eq.	Res. use, min. and met.
	EF 2.0 Water scarcity	m^3 world equiv.	Water scarc.
Energy	Energy use	kg	Energy res.
	Non renewable energy resources	kg	Non renew. energy res.
	Renewable energy resources	kg	Renew. energy res.
Secondary materials consumption	Secondary materials consumption	kg	Second. mat. cons.

Table 5-11 Impacts related to mixtures production

Indicators	HMA-RSM	CRM-RSM	HMA-GER	CRM-GER
CC (kg CO_2 eq.)	57.50	34.80	69.70	47.50
CC – biogenic (kg CO_2 eq.)	0.11	0.10	0.11	0.08
CC – fossil (kg CO_2 eq.)	56.70	34.10	69.50	47.40
CC - land use ch. (kg CO_2 eq.)	0.66	0.61	0.11	0.06
Acid. (Mole of H+ eq.)	0.199	0.113	0.209	0.0695
Eutr. Freshwater (kg P eq.)	0.000244	0.000220	0.000107	0.0000625
Eutr. Marine (kg N eq.)	0.0497	0.0267	0.0434	0.0203
Eutr. Terrestrial (Mole of N eq.)	0.555	0.301	0.479	0.221
Phot. ozone form. (kg NMVOC eq.)	0.16	0.09	0.142	0.0637
Land use (Pt)	590	546	346	163
Res. use, energy carriers (MJ)	3530	1460	2350	880
Res. use, min. and met. (kg Sb eq.)	1.1E-05	6.6E-06	9.5E-04	5.6E-06
Water scarc. (m^3 world equiv.)	3.54	4.91	6.79	1.98
Energy res. (kg)	83.92	35.45	57.78	24.14
Non renew. energy res. (kg)	83.92	35.45	57.78	24.14
Renew. energy res. (kg)	1.6E-22	2.3E-22	1.2E-10	4.5E-22
Second. mat. Cons. (kg)	0	936	0	845

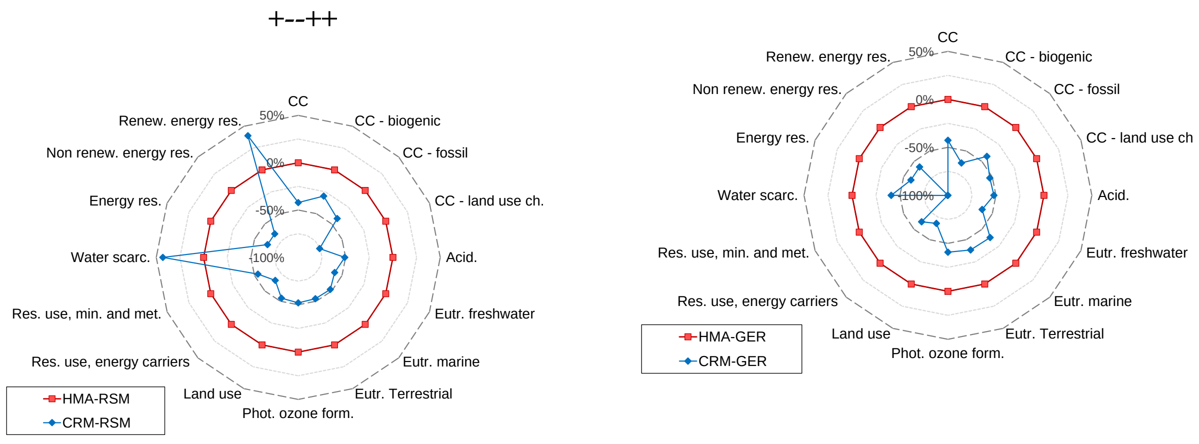
Interpretation of the results

Table **5-11** shows the results of the LCA in terms of impacts for the four mixtures referred to the case studies. The results indicate that the production of CRM-RSM has generally lower impacts than the production of HMA for all the indicators, except for water scarcity and renewable energy resources. In the GER case study, a reduction of the impacts was observed for all the indicators by manufacturing CRM.

Those outcomes are better showed in Figure 5-9, which represents the variation in the impacts due to the mixtures' manufacturing between the HMA and the respective CRM, computed respect to the HMA itself, i.e. AC12 for the RSM case study and AC32 TS for the GER one. In general, compared to the HMA, the production of CRM implies a reduction of the impacts for all the indicators (-27% for RSM, -57% for GER on average).

In particular, in the RSM case study, the manufacturing of CRM through CCPR technology rather than HMA is particularly beneficial in terms of resource use, energy carriers (-59%), energy resources (-58%) and non-renewable energy resources (-58%) (Figure 5-9a). In the GER case study, the benefits obtained by adopting CRM manufacturing by CIR instead of the traditional HMA production are in general even higher. In particular, the greater impacts reductions are calculated for: resource use, mineral and metals (-99%), water scarcity (-71%), acidification terrestrial and freshwater (-67%) and resource use, energy carriers (-63%) (Figure 5-9b). The production of cold mixtures in both case studies showed satisfactory results in terms of climate change, which is one of the best-known indicator in terms of sustainability. The reduction of climate change impact obtained passing from HMA to CRM is 39% and 32% for RSM and GER case studies, respectively.

Although CRM can be considered in general more environmentally friendly than HMA, the only exceptions, as stated above, are water scarcity (+39%) and renewable resources (+39%) for the RSM case study. Regarding the water scarcity, it should be noticed that this indicator is mostly affected by the type of operating energy of the plant and the materials adopted. In particular, bitumen emulsion and fuel oil are the two most impactful materials between the one considered in the study indeed. In the RSM case study, on one side the impact in terms of water scarcity is high due to the use of the bitumen emulsion for the CRM, whereas on the other side the impact for the HMA il low because the asphalt plant is heated using natural gas instead of fuel oil (*Table* ***5-11***). Therefore, CRM results more impactful. On the contrary, the German plant heating is obtained using the fuel oil which is much more impactful than the bitumen emulsion used for the cold mixtures, then the variation of impact obtained adopting the CRM instead of HMA is negative.



(a) (b)

Figure 5-9. Comparison of the variation of the impact during the production: a) HMA-RSM in plant and CRM-RSM CCPR (calculated respect to HMA-RSM), b) HMA-GER in plant and CRM-GER CCPR (calculated respect to HMA-RSM)

Hotspot Analysis

Figure 5-10 and

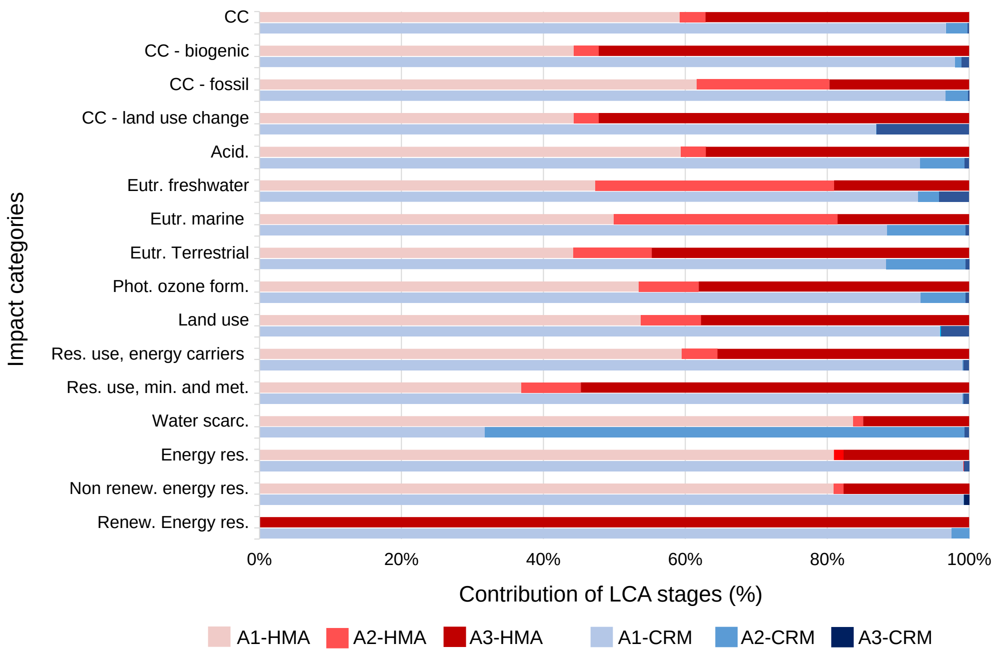


Figure *5-11* show the results of the hotspot analysis carried out to assess the contribution of each production stage (A1, A2 and A3) on the overall impact, for the RSM (CRM-RSM and AC12) and GER (CRM-GER and AC32 TS) case studies. A hotspot can be defined as a stage or process contributing more than 50% to the overall impact, whereas the impact is considered relevant when its contribution is higher than 80% (James & Galatola, 2015). The results indicate that the acquisition of raw materials (A1) impacts more than 50% for the majority of the indicators for both mixtures types, i.e. HMA and CRM and case studies, i.e. RSM and GER.

In particular, in RSM case study (Figure 5-10), the general trend of the hotspot analysis is similar for the two mixture types (HMA or CRM) even though some differences can be observed. A2 is always the less impacting stage. A1 is even relevant in terms of Water scarcity (for CRM), Non renew. energy res. (for CRM as well) and Renew. Energy res.. Besides A1 contributes more than 50% to the total impact in almost all the other categories. The only exception are CC – biogenic, Eutrophication Freshwater, Land use, and Eutrophication Terrestrial (for CRM), for which A3 is the hotspot or the relevant stage.

In the GER case study (

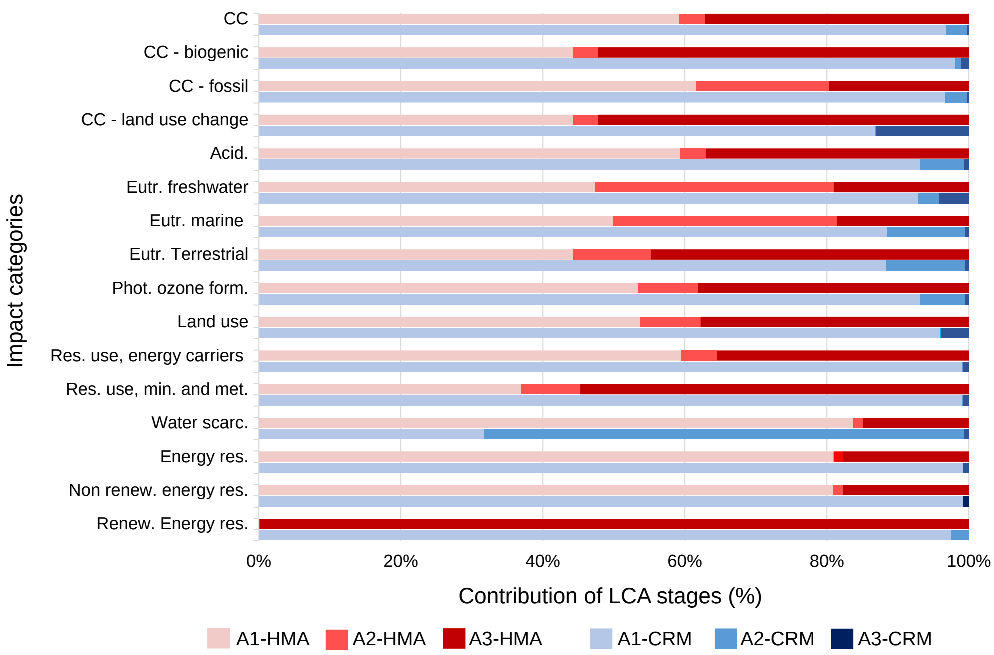


Figure *5-11*), the differences among the hotspot analysis of HMA and CRM is more evident. For the HMA, the hotspot analysis trend resembles what observed for RSM, with A1 being a hotspot stage for the major part of the indicators. A2 affect less the impacts, whereas A3 is the relevant stage in terms of energy resources, and an hotspot for CC – biogenic, CC - land use change and Resource use, mineral and metals. For the CRM, A1 is almost always the most impactful stage, commonly the relevant one, with the only exception of Water scarcity, for which the A2 stage impact for the 67% of the total.

Looking at HMA, it can be seen a balance of the contributions of A1 and A3. This can be explained because of the high amount of energy required to heat the plant, especially in the German case study.

It is interesting to note that some impact categories, such as Climate Change-land use change, Eutrophication marine and Land Use are strongly influenced by the consumed diesel, hence they are higher for CRM_RSM.

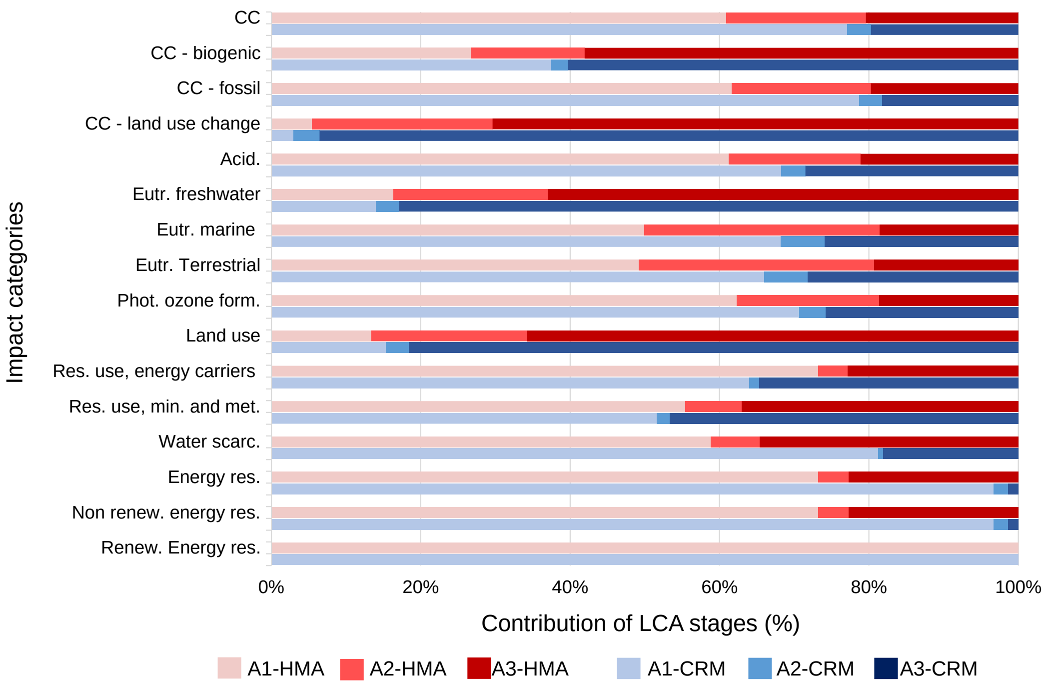


Figure 5-10. Hotspot analysis for the production of HMA and CRM produced in RSM

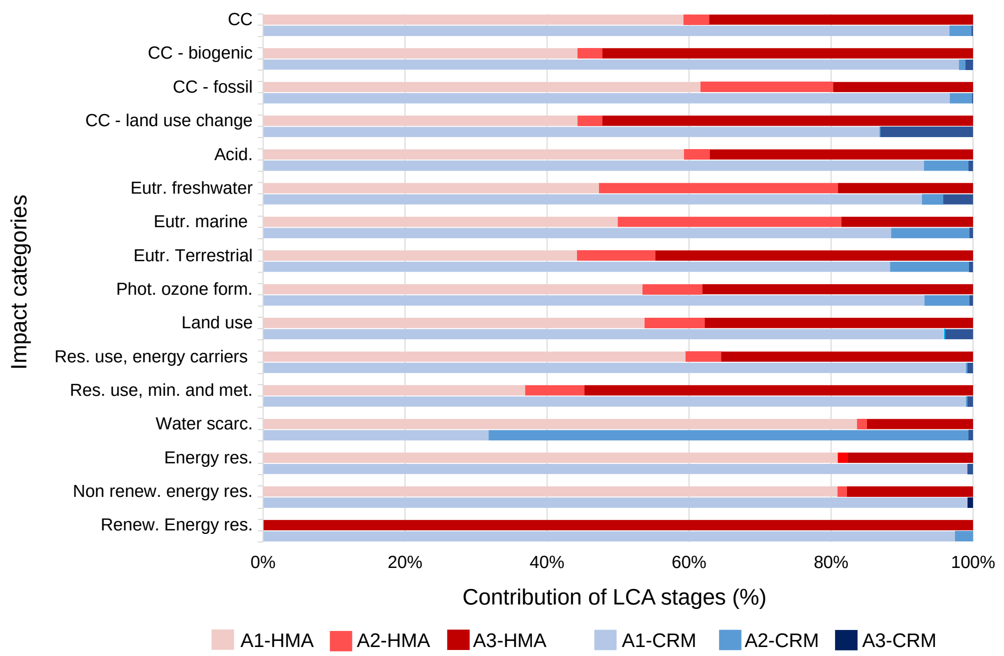


Figure 5-11. Hotspot analysis for the production of HMA and CRM produced in GER

Sensitivity Analysis 1: varying transport distances (A2)

The sensitivity analysis about the influence of the A2 distances was carried out assuming that each distance from the material supply location to the asphalt plant (or the construction site for the CIR material) was constant and equal to 50 km, 100 km and 200 km. These results have been compared to the impacts of the mixture with the HMA with current distance. Figure 5-12 shows the variation of the impacts of CRM with the different transport distances compared to respective HMA. For both case studies, as distances increase, also impacts become bigger. In general, if the transport distance is lower than 200 km, the CRM production always led to a reduction of the impacts if compared to the actual HMA. Besides, the decrease of the A2 distance generally leads to an impact reduction: on average, if distances are equal to 50 km or 200 km respectively, the impacts decrease from 44% to 40% for CRM-RSM and from 58% to 55% for CRM-GER. However, for some impact categories, such as water scarcity, Resource use-mineral and metals, this effect can be considered negligible.

Some impact categories are most affected by the increase of the transport distance from 50 to 200 km, such as Climate Change - land use change (from -82% to -

69% in RSM case study and from -70% to -53% in GER case study), land use (from -57% to -49% in RSM case study from -73% to -68% in GER case study). The sensitivity analysis confirms two extreme results: the increase of impacts in terms of water scarcity when CRM is used in RSM case study (Figure 5-12a) and the reduction of 100% of resource use- mineral and metals in GER case study (Figure 5-12b).

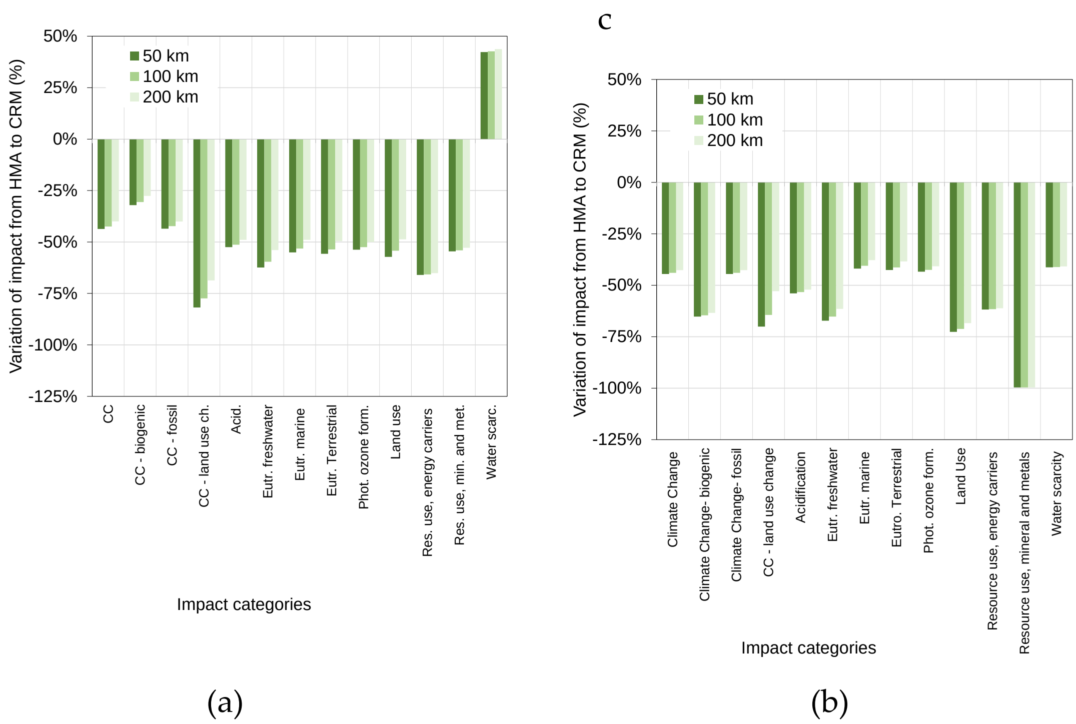


Figure 5-12. Variation of impact of CRM determined at changing transport distances respect to HMA (real case study impact) for a) RSM case study and b) GER case study

Sensitivity Analysis 2: varying mixture compositions

The LCA results are strictly linked to the boundary conditions assumed in the analysis, including the type of processes and energy sources, as well as the geographic conditions, like the transportation distances (Oreto, Russo, Veropalumbo, Viscione, Acqua, et al., 2021). For this reason, the life cycle impacts related to the production of the six types of CRM and the two types HMA were calculated for both case studies to compare the impacts under the same boundary conditions and geographic areas.

Table 5-12 and Table 5-13 show the sensitivity analysis carried out on the six mixtures using the primary and secondary data used for the four main mixtures. The values presented in the tables are the percentage variation of impacts obtained for the six cold mixtures (CRM-01, CRM-02, CRM-03, CRM-04, CRM-GER and CRM-RSM)

- produced through CCPR, and compared to those obtained for AC12 (Table 5-12) Both mixtures production were considered happening in asphalt plant of the RSM case study;
- produced through CIR in the Germany site and compared to AC32 TS produced in the asphalt plant of the GER case study (Table 5-13).

The investigation demonstrated that CRM, independently on their specific mix design, are generally more environmentally friendly than HMA, thanks to the lower temperatures of mixing, and the consequent lower energy demand, and the use of RA which implies a reduction of virgin materials. Besides, a visible trend can be distinguished for both case studies: when the cement decreases, the CO_2eq emitted is reduced.

Looking at RSM case study, the majority of impact indicators are lower for CRM than AC12, with water scarcity and renewable energy as exception. It can be observed that some indicators vary more depending on the composition. In particular, the variation of the impact passing from CRM to HMA, fluctuate of about 77% for Renewable energy resources (from +33% to +110%), 43% for water scarcity (from +38 to + 81%), 32% for Climate Change and Climate Change fossil (from -52% to -20%). For the other indicators the differences are always lower than 20%.

As regards GER case study (Table 5-13) the impacts due to CRM production in site are always lower than those due to the AC32 TS one. The indicators that are mainly influenced by the variation of the mixtures' composition are Water scarcity (52% of fluctuation in the impact variation), Climate Change- biogenic (41%), Climate Change and Climate Change- fossil (38%), CC – land use change (37%), Eutrophication freshwater (26%), and Resource use, energy carriers, Energy resources and Renewable energy resources (22%).

Table 5-12 Variation of impacts due to the composition of CRM (CCPR) compared to HMA-RSM

Impact indicator	CRM-RSM	CRM-01	CRM-02	CRM-03	CRM-04	CRM-GER
CC	-39%	-52%	-50%	-35%	-31%	-20%
CC- biogenic	-7%	2%	-13%	4%	-10%	-8%
CC - fossil	-40%	-52%	-50%	-36%	-32%	-20%
CC - land use ch.	-7%	-3%	-6%	-4%	-5%	-8%
Acid.	-43%	-44%	-51%	-36%	-41%	-35%
Eutr. freshwater	-10%	-4%	-11%	-4%	-9%	-11%
Eutr. marine	-46%	-50%	-52%	-39%	-39%	-34%
Eutr. Terrestrial	-46%	-50%	-52%	-39%	-39%	-34%
Phot. ozone form.	-46%	-50%	-54%	-39%	-42%	-35%
Land use	-7%	-2%	-9%	-1%	-7%	-8%
Res. use, energy carriers	-59%	-51%	-65%	-50%	-64%	-60%
Res. use, min. and met.	-41%	-33%	-47%	-31%	-45%	-42%
Water scarc.	39%	75%	42%	81%	49%	38%
Energy res.	-58%	-50%	-64%	-49%	-63%	-59%
Non renew. energy res.	-58%	-50%	-64%	-49%	-63%	-59%
Renew. energy res.	39%	106%	75%	110%	79%	33%

Table 5-13. Variation of impacts due to the composition of CRM (CIR) compared to HMA-GER

Impact indicator	CRM-GER	CRM-01	CRM-02	CRM-03	CRM-RSM	CRM-04
CC	-32%	-70%	-67%	-56%	-61%	-52%
CC- biogenic	-28%	-55%	-69%	-52%	-65%	-65%
CC - fossil	-32%	-70%	-67%	-56%	-61%	-52%
CC - land use ch.	-43%	-30%	-46%	-36%	-68%	-38%
Acid.	-67%	-62%	-68%	-54%	-63%	-58%
Eutr. freshwater	-42%	-49%	-63%	-49%	-68%	-59%
Eutr. marine	-53%	-58%	-59%	-46%	-57%	-44%
Eutr. Terrestrial	-54%	-58%	-60%	-47%	-57%	-44%
Phot. ozone form.	-55%	-58%	-62%	-47%	-56%	-48%
Land use	-53%	-59%	-71%	-58%	-72%	-67%
Res. use, energy carriers	-63%	-48%	-69%	-46%	-60%	-67%
Res. use, min. and met.	-99%	-100%	-100%	-100%	-100%	-100%
Water scarc.	-71%	-22%	-39%	-19%	-59%	-35%
Energy res.	-58%	-49%	-69%	-47%	-59%	-67%
Non renew. energy res.	-58%	-49%	-69%	-47%	-59%	-67%
Renew. energy res.	-100%	-100%	-100%	-100%	-100%	-100%

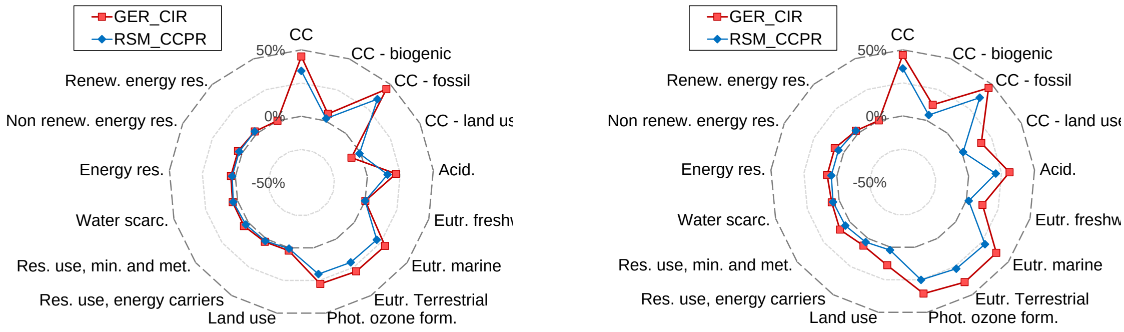
Figure 5-13 and Figure 5-14 more clearly display how the binders dosages (i.e. bitumen emulsion and cement) influence the LCA outcomes, by focusing on mixtures CRM-01, CRM-02, CRM-03 and CRM-04 which are characterised by the same aggregates composition and water dosage (Section 2.1.1). In particular, Figure 5-13 shows the effect of the increase in the dosage of cement, being the bitumen emulsion dosage the same (6% 3.3% by dry aggregate weight respectively). It emerges that, for both the production technologies (CCPR and CIR),:

- when CRM-03 is compared to CRM-01, effect of the increase of cement content from 0% to 1.5% by dry aggregate weight (Figure 5-13a);
- when CRM-04 is compared to CRM-02, effect of the increase of cement content from 1.5% to 3% by dry aggregate weight (Figure 5-13b).

The increase in the cement content lesser influence the impacts in terms of Natural Resources and Energy (variation of the impacts always lower than 4% passing from 0% to 1.5% of cement and than 14% from 1.5% to 3%), whereas it is in general more impactful for the other macro-categories considered (Climate Change, Acidification, Eutrophication and Air Pollution). For example, the increase of 1.5% of cement (from 0% to 1.5% and from 1.5% to 3%) worsen the impacts on average of 35% and 45% for CCPR and CIR, respectively. Some differences can be observed between the variation of the impacts due to increase in the cement content for the GER (CIR) and RSM (CCPR) case studies. In particular, the GER-CIR case study more negatively affected, especially passing from 1.5% to 3% of cement.

Figure 5-14 displays the variation of the impacts of CRM-03 respect to those of CRM-02, evaluating the influence of the increase of the emulsion dosage (from 3% to 6% by dry aggregate weight) being equal the cement one. In this case, almost all indicators are significantly affected by the increase in the bitumen emulsion dosage. Again, the GER-CIR case study results more impacted by this change in the composition.

Therefore, one can conclude that CRM mixtures should be produced using the lower amounts of binders (i.e. cement and bitumen emulsion) while maximising the RA dosage, in order to enhance their sustainability performance. However, it must be noticed that this may be beneficial during the production phase, but may lead to worst mechanical performances and durability, as well as may lead to the need of a higher thickness of the layer. Therefore, the optimal mixture composition should be selected as the one characterised by the better performances in terms of mechanical properties and durability (validated also through the LCA technique) obtained with the lower possible dosages of binders. Also a cradle-to-gate analysis can be helpful, showing in a life cycle approach the possible benefits and limits of the use of different mixtures.



(a) (b)

Figure 5-13. Variation of impacts (due to the increase of cement content) of a) CRM-03 respect to CRM-01 and b) CRM-04 respect to CRM-02

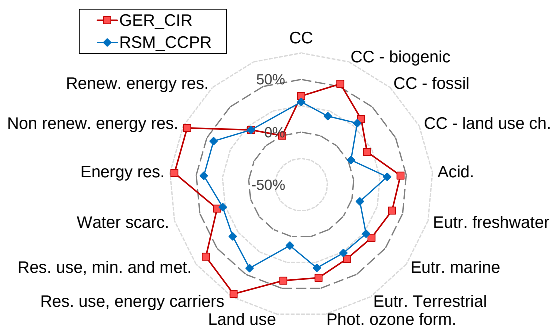


Figure 5-14. Variation of impacts of CRM-03 respect to CRM-02 (due to the increase of the emulsion content)

5.1.1 STEP 6 – Multi-Criteria Decision Making

As being optional, no MCDCM was calculated for this exercise. Hence decision making could be done considering values of each indicator separately and with equal weights.

5.4.5.2 Economic impact indicator

Concerning the economic indicator, the cost related to the production of one ton of asphalt mixture was assessed. The calculation was performed both for conventional and cold mixtures, showing a better performance for CRM in both case studies (Figure 5-14, Figure 5-15). Nevertheless, it is important to notice that the economic benefits in using CRM in RSM is much higher than in GER, as showed in *Table 5-18*.

Table 5-14 – Life Cycle costing contribution for each layer for production (A1-A3) for RSM and GER case studies

Description	HMA_RSM (€)	CRM_RSM (€)	HMA_GER (€)	CRM_GER (€)
A1	€ 51.39	€ 30.64	49.89	47.12
A2	€ 3.74	€ 0.51	0.74	0.51
A3	€ 16.32	€ 13.01	4.30	0.18
Total	€ 71.45	€ 44.16	54.93	47.80

In fact, in the RSM a decrease of 38% is registered, while in GER the decrease is of 13%. Looking at the figures, it is possible to state that the supply of materials for one ton of conventional asphalt in RSM and in GER, with its respective mix design, has more or less the same cost (€51.39 vs €49.89). A2 is more impactful in RSM because of longer transport distances, as well as A3 because of the use of natural gas, that costs more compared to heating oil.

This difference is mainly due to the cost for A1. In fact, the difference between CRM and HMA in Germany is negligible, while it is more significant for RSM. This can be explained as follows:

- In Germany, coarse aggregates and RAP have a similar price (0.0125 €/kg vs 0.010 €/kg), while fine aggregates, filler and cement are more expensive (0.0175 €/kg, 0.16 €/kg and 0.14 €/kg). It follows that Germany the supply of aggregates is higher for HMA than for CRM. Nevertheless, bitumen emulsion is more expensive than bitumen (0.7 €/kg vs 0.8 €/kg), that is the reason why CRM and HMA have at the end a similar price for A1.
- In Republic of San Marino, both coarse and virgin aggregates cost more than RAP (0.018 €/kg and 0.020 €/kg vs 0.01 €/kg), hence the supply of aggregates is less impactful for CRM in terms of costs. Moreover, bitumen emulsion, even if not in an important way, costs less than bitumen and bitumen emulsion is low (0.53 €/kg vs 0.58 €/kg). This contributes to the overall cost for CRM.
- The difference between CRM in GER and RSM can be explained not only for the different prices in the two countries, but also for the different mix

design. CRM_GER contains more bitumen emulsions and cement, that are the most expensive materials in the mix.

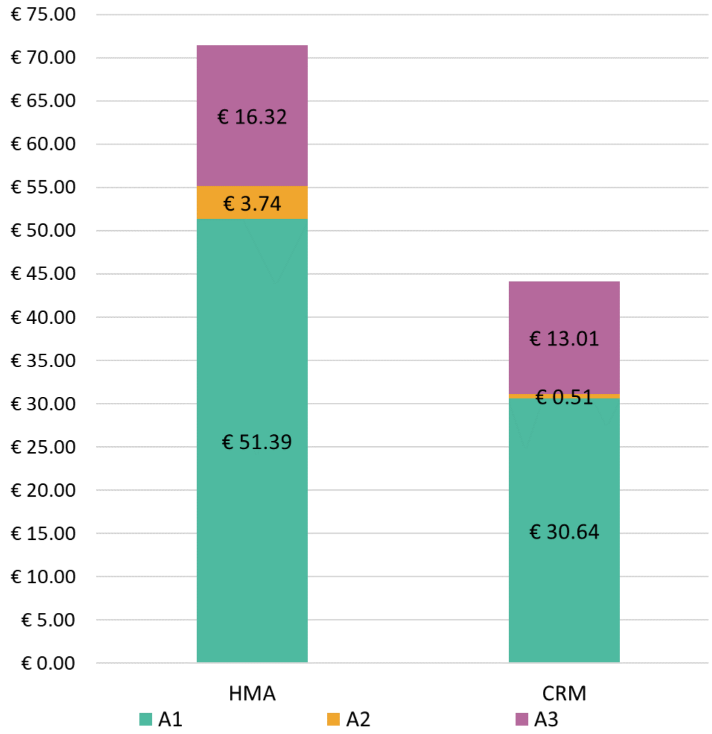


Figure 5-15. Comparison of cost production of HMA and CRM in RSM

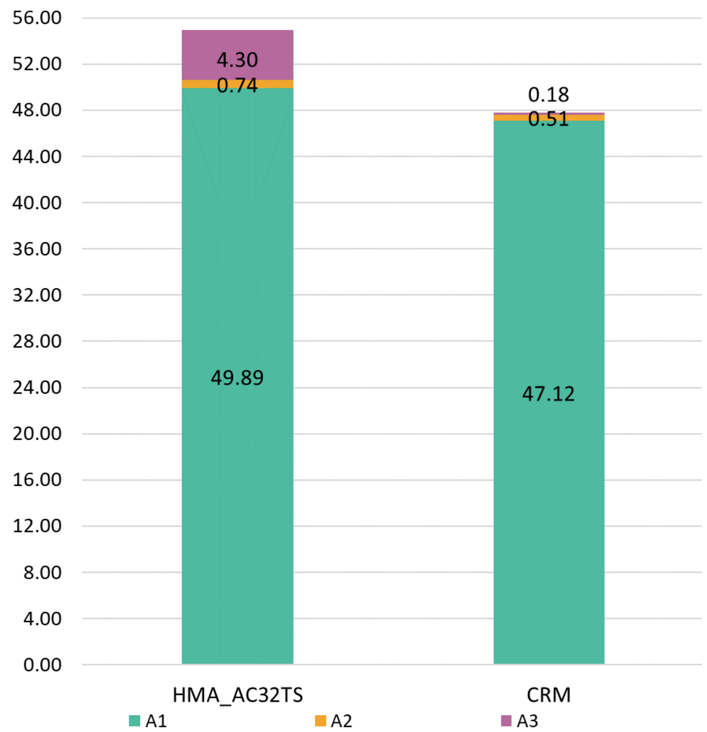


Figure 5-16. Comparison of cost production of HMA and CRM in GER

Sensitivity Analysis 1: varying bituminous materials costs

Looking at the unitary costs, it emerges that the bituminous materials (bitumen for HMA and bituminous emulsion for CRM) has a major contribution in the overall cost. For this reason, a first sensitivity analysis was carried out considering a percentage change of this initial cost, assuming an increase of +20% and +10% and a decrease of -10% and -20%.

In both case studies, as showed in Figure 5-17, it emerged that the price for the production (A1-A3) linearly varies at the percent change in the input value for bitumen. The HMA registers a variation of ±9% in both case studies, while the CRM of ±10% in RSM and of ±13% in GER. In general, the higher influence in bituminous emulsion costs in CRM can be explained because it contributes for around 70% of the total cost of raw materials (A1). In GER, where the contributions due to transport (A2) and production (A3) have a marginal influence, the contribution of bituminous emulsion to the total cost is around 67%, while in RSM, where there is a higher energy consumption, it is 49%. For this reason, CRM_GER registers this bigger variation.

In general, a ±20% variation in the cost of bitumen corresponds to a ±9% variation in the cost of a tonne of conventional mixture.

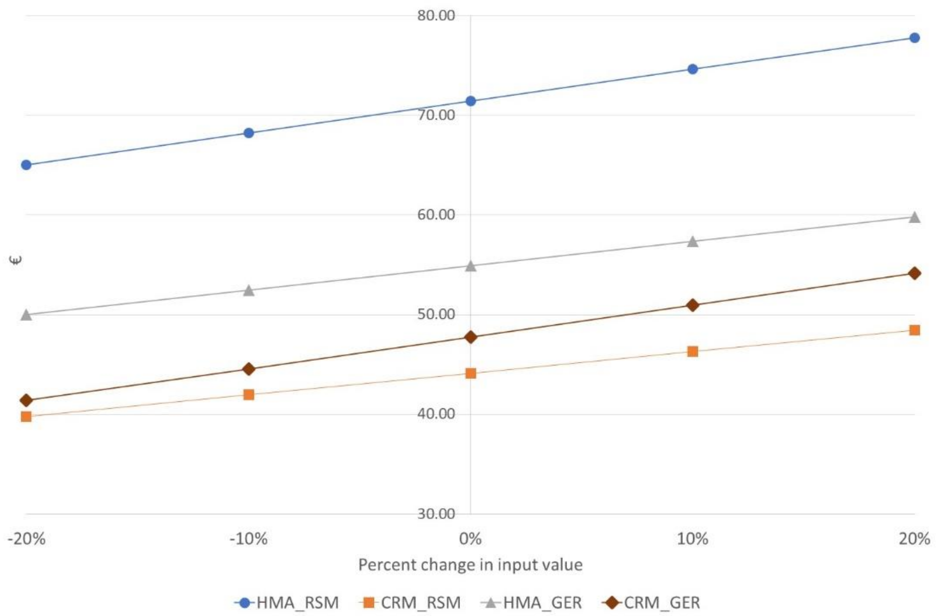


Figure 5-17. Sensitivity analysis of production costs at changing of bituminous materials cost in RSM and GER

Sensitivity Analysis 2: varying energy costs

A second sensitivity analysis was carried out to show how the changes in terms of energy inputs (i.e. diesel, electricity) can affect the total cost. In fact, as explained in the previous paragraphs, the costs used for this analysis refer to 2020/2021, during the Covid-19 pandemic, where the energy costs were particularly low. Hence, this sensitivity analysis examines the behaviour of these costs from 2020 to 2023. For this purpose, the costs were assumed to be those recorded for the second half of 2023 , as reported in *Table 5-15*.

Table 5-15. RSM and GER case studies: unitary costs for energy in 2023 (A3)

Site	**RSM**	**GER**
Electricity (€/kWh)	0.18	0.2671
Diesel (€/l)	1.66	1.73
Gas (€/kWh)	0.07	-
Heating oil (€/l)	-	1.05

These costs affected the total cost of one tonne of asphalt mixture in different percentages, depending on the mixture and on the country. In fact, producing one tonne of HMA in RSM cost 13% in 2023 than in 2020, while in Germany the difference is 10%, as showed in Figure 5-18. This difference is mainly due to the fact that the contribution of A2 and A3 in RSM is around 36%, while in Germany around 18%. It follows that HMA_RSM is more affected by the variations in fuels and other energy sources costs.

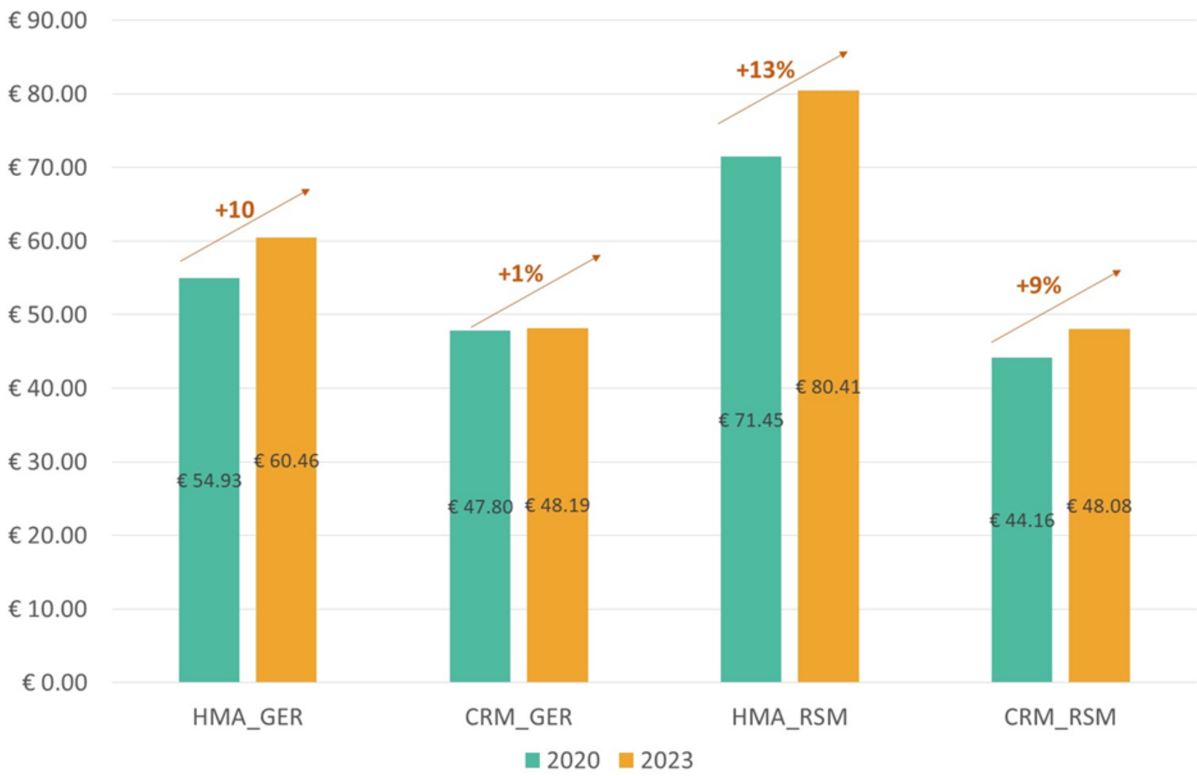


Figure 5-18. Sensitivity analysis of production costs at changing of energy costs in RSM and GER (2020 vs 2023)

For the production of CRM, the difference in Germany is minimal (1%) because the amount of diesel used is very small and therefore the variation in its cost does not have a significant impact (3% of the total costs). On the contrary, producing the CRM in RSM costs 9% more in 2023 than in 2020, because the higher contribution of A2 and A3 in RSM (around 35% of the total impact).

5.1.2 STEP 7 - Reporting, communication and verification

This research has the purpose of investigating the possible environmental benefits of the production and installation of CRM is more environmentally friendly than HMA, considering in-place recycling and in-plant recycling. The exercise, related to material production (A1-A3), has been developed within two case studies, one in Republic of San Marino, where CRM have been produced in-plant and one in Germany, where CRM have been produced in-place.

The study showed that:

- CRM have a better environmental performance when compared with HMA, reducing the impacts on average of 40%, even if in RSM water scarcity and renewable energy increase. This increase is due to the type of operating energy of the plant and the materials chosen. Bitumen emulsion and fuel oil emerge as the most impactful materials in the study. In the RSM, the use of bitumen emulsion for CRM contributes to a high water scarcity impact, while the Hot Mix Asphalt HMA has a lower impact due to the use of natural gas for heating. Conversely, in the German case study, where the plant is heated using fuel oil, the impact of CRM becomes more significant compared to HMA, which results in a negative variation of impact;
- Independently on the mix design (binder content) and transport distances (A2), CRM are always less impactful than HMA;
- CRM production always leads to a reduction of the impacts if compared to the actual HMA if the transport distance is lower than 200 km. Some impact categories are most affected by the increase of the transport distance from 50 to 200 km, such as Climate Change - land use change and land use.
- The hotspot analysis of production stages revealed that, across various indicators, the acquisition of raw materials (A1) consistently contributes more than 50% to the overall impact for both Hot Mix Asphalt (HMA) and Cold Recycled Mixtures (CRM) in both case studies. It is interesting to note that some impact categories, such as Climate Change- land use change, Eutrophication marine and Land Use are strongly influenced by the consumed diesel, hence they are higher for CRM_RSM.
- It can be suggested that, concerning the mixture production, CRM are always a better option that HMA, independently on the mix design and transport distances. Moreover, CIR is more environmentally friendly than CCPR, in particular concerning Climate Change- land use change, Eutrophication Freshwater and Land Use.

- Concerning the economic indicator, in RSM producing one ton of CRM implies a cost reduction of 38%. This is mainly due to the costs of aggregates and to the specific mix design for CRM. In Germany, the prices of the two mixes are almost the same. This can be explained for the high percentage of cement and bitumen emulsion and for the same price of RA and coarse aggregates. It follows that in RSM pushing towards CRM can lead towards more financially efficient choices, while in GER the road authorities afford the same expense.
- The sensitivity analyses produced interesting results. A first analysis involved the variation in the cost of bituminous materials. It was found that the cost of CRM and HMA varied with a linear trend: HMAs vary of ±10% when the bitumen increases of ±20%, while the CRM_RSM of ±9%, while CRM_GER of ±13%. It follows that CRM_RSM is always a better solution than HMA, even in cases of cost increases. However, in Germany, although CRM is less expensive than HMA, its benefits may diminish. A second analysis involved the variation of energy costs (i.e. diesel, electricity) of ±20%. A variation of ±10% of costs for HMA, while a variation of ±6% for CRM_HMA and ±1 for CRM_GER are registered. Considering that the price of energy could increase due to geopolitical balances or shortages, CRM represents a better option to spend less money.

5.5 EXERCISE 2 - SA for pavement activities (CONTRACTORS)

This second exercise involves the contractors; hence the aim is extended also in quantifying and comparing the sustainability performances of manufacturing and laying components made of Cold Recycling techniques and of HMA. Also in this case, the life cycle techniques (LCA and LCC) were used to investigate the impact of the materials composition and layers construction in the production and installations stages of Germany and Republic of San Marino. The different steps are shown in Figure 5-19, considering the so-called “cradle-to-laid”. It also includes a sensitivity analysis to deepen the influence of the impacts due to transport distances (A4). The final goal was to provide recommendations to optimize their overall sustainability approach, also showing which is the most environmentally friendly techniques (CIR vs CCPR).

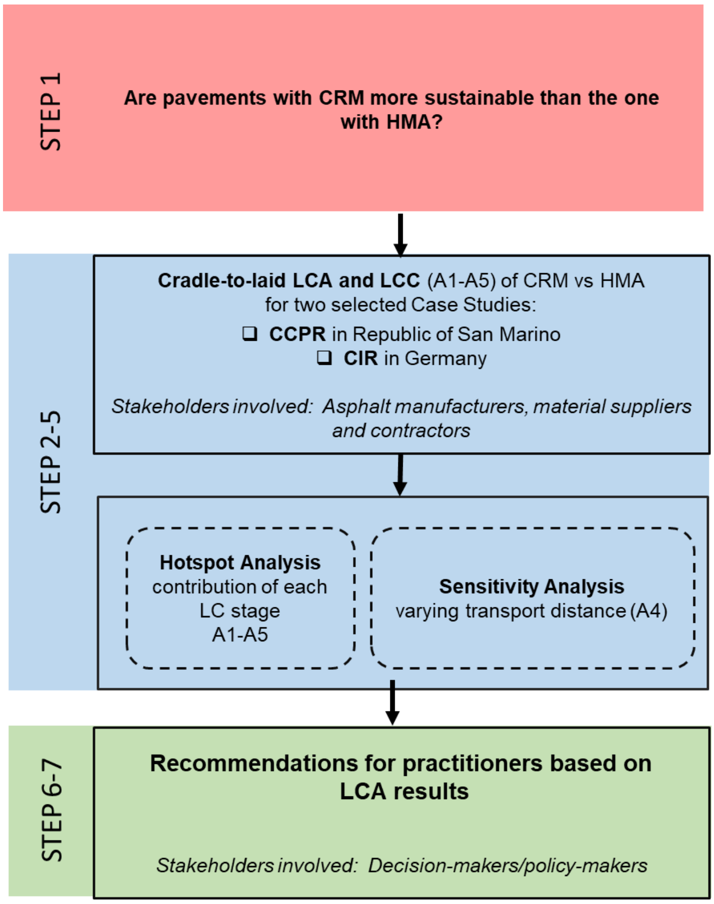


Figure 5-19. Structure of the investigation and involved stakeholders at contractor level

As the research focuses on the evaluation of the performance of CRM during the production and installation stages (A1-A5), the LCA and the LCC have been carried out on the pavement components made with cold mixtures, i.e. CRM-RSM and CRM-GER, and the conventional mixtures (i.e. AC12 for RSM and AC32 TS for GER) used in the corresponding reference pavement structures.

5.5.1 STEP 1 - Identify the purpose of the SA

The goal of this study is to compare the environmental and economic performance of pavements built using two different technologies: hot production and cold production. To answer this question, the production and laying of four different mixtures were compared. The scope of this study is the construction of pavement layers, considering the production of the mixtures and the successive laying and compaction. The intended application is to offer Road Agencies and manufacturers valuable recommendations for optimizing their overall sustainability practices.

5.5.2 STEP 2 – Specification of the object of the assessment

According to the pavement model, this exercise concerns a pavement activity, involving the building of a pavement component.

The functional equivalent is defined as the exact weight/volume of road pavement component to be built at project level, as reported here below (Table 5-16, Table *5-17*), capable of meeting the technical requirements needed by the RA, in terms of traffic volume, durability, as described in the section 5.2.1

Table 5-16. Functional unit considered in the RSM case study (contractor level)

Pavement layer	**Mixture type**	**RSM_REF**		**RSM_CCPR**	
		by volume (m3)	f.u. by weight (tons)	by volume (m3)	f.u. by weight (tons)
Wearing	HMA-RSM	13	30	13	30
Binder	HMA-RSM	25.6	60	-	-
Binder	CRM-RSM	-	-	32	75

Table 5-17. Functional unit considered in the GER case study (contractor level)

Pavement layer	Mixture type	GER_REF		GER_CIR	
		by volume (m3)	f.u. by weight (tons)	by volume (m3)	f.u. by weight (tons)
Wearing	HMA-GER_1	75	184	66	160
Binder	HMA-GER_2	150	375	122	305
Base	HMA-GER_3	413	1047	150	381
Base	CRM_GER	-	-	375	863

The physical boundaries correspond to the layers to be built, hence wearing and binder courses in Republic of San Marino and wearing, binder and base courses in Germany.

The system boundaries correspond to a cradle-to-laid, hence A1-A5.

Any analysis period has been selected, being the only the construction of the road the phases to be assessed.

The durability of the pavement components needs to cover the RSL required in the maintenance scenario (*Table* **5-3**).

5.5.3 STEP 3 – Scenarios

The assumption and information to collect are related to the extraction of raw materials, mix design, energy used at the plant and to build the road (typology and quantity) and transport distances to plant and site, as reported in the data collection section (6.4.4). It has been assumed that only the net amount of material is considered in this study.

5.5.4 STEP 4 – Selection of data

5.5.4.1 Environmental data

In this research both primary and secondary data were used: when primary data (directly provided by partners) missed, GaBi database was used. Specifically, the A1 stage involves the materials supply. The information related to A1-A3 are the same contained in the section 5.3, while the data related to A4 and A5, provided by the partners, are shown here below, while *Table 5-24* show the data quality.

Table 5-18. Locations and transport distances of the different sites from the asphalt plant (A2 and A4)

Site	HMA		CRM	
	Location	*Distance (km)*	*Location*	*Distance (km)*
Pavement installation site	Republic of San Marino	15	Republic of San Marino	15
Refinery[a]	Bologna, Italy	125	Bologna, Italy	125
Fine aggregate quarry	Forlì, Italy	65	Ravenna, Italy	65
Coarse aggregate quarry	Castel Viscardo, Italy	235		
Filler quarry	Serra San Quirico, Italy	150	Gubbio, Italy	145
RA processing and stockpiling			San Leo, Italy[b]	0
Cement storage			Monselice, Italy	210
Water	San Leo, Italy[b]	0	San Leo, Italy[b]	0

[a] bitumen and bitumen emulsion, [b] asphalt plant

Table 5-19. Equipment (fuel type) used in the pavement construction operations (A4-A5)

Construction operation	HMA courses	CRM course
Removal of the old pavement	Milling machine *(diesel)*	
Mixture transportation and laying	5 axel dumper truck *(diesel)*, paver *(diesel)*	5 axel dumper truck *(diesel)*, paver *(diesel)*
Mixture compaction	Steel-wheeled roller *(diesel)*	Steel-wheeled roller *(diesel)*, Pneumatic-tired compactor (binder course) *(diesel)*
Prime/Tack coat spraying	Emulsion tank lorry *(diesel)*	

Table 5-20. Energy consumption for production (A3) and installation (A5) stages

	Production (A3)		Installation (A5)	
	CRM_RSM	**HMA-RSM**	**CRM-RSM**	**HMA-RSM**
Electricity (kWh/t)	0.65	6.75	-	-
Natural gas (m^3/t)		10	-	-
Water (kg)	29		-	-
Diesel (kg/t)	8.35	8.35	1.87	1.01

Table 5-21. Locations and transport distances of the different sites from the asphalt plant (for HMA) and the pavement installation site (for CRM)

Site	HMA		CRM	
	Location	*Distance* (km)*	*Location*	*Distance+ (km)*
Pavement installation site	Trier, Germany[c]	2.9	Trier, Germany[c]	0
Refinery[a]	Bonn, Germany	163	Bonn, Germany	163
Fine aggregate quarry	Neumagen-Dhron, Germany	28		
Coarse aggregate quarry	Neumagen-Dhron, Germany	28		
Filler quarry	Neumagen-Dhron, Germany	28		
RA processing			Trier, Germany[c]	0
Cement storage			Allmendingen, Germany	392
Water	Trier, Germany[b]	0	Trier, Germany[b]	2.9

* from asphalt plant, + from pavement installation site
[a] bitumen and bitumen emulsion, [b] asphalt plant, [c] pavement installation site

Table 5-22. Equipment (fuel type) used in the pavement construction operations

Construction operation	HMA courses	CRM course
Mixture transportation and laying	Dumper truck *(diesel)*, paver *(diesel)*	Recycler*(diesel)*, bitumen emulsion tanker *(diesel)*, water tanker*(diesel)*, cement spreader *(diesel)*
Mixture compaction	Vibratory compactor *(diesel)*	Padfoot compactor *(diesel)*, tandem roller *(diesel)*, static roller *(diesel)*
Removal of the old pavement	Recycler *(diesel)*	

Table 5-23. Energy consumption for production (A3) and installation (A5) stages

	Production (A3)		Installation (A5)	
	CRM_RSM	HMA-RSM	CRM-RSM	HMA-RSM
Electricity (kWh/t)	0.65	0.65		
Water (kg/t)				
Diesel (kg/t)	40	10	0.052	0.072
Natural gas (m^3/t)		10		

Despite suggested from the Road pavement LCM guidelines, this exercise will not include the uncertainty analysis of the results (Lo Presti et al., 2021). The reader will find more details on the uncertainty analysis of SA results within two related research products: "D5.1b Recommendations for Multi-Criteria Sustainability Analysis" (Abed & Lo Presti, 2021) and "Uncertainty analysis of life cycle assessment of asphalt surfacings" (Abed et al., 2023)

Table 5-24. Data quality

Data	Type *	Source	Technological Representativ.	Geographical Representativ.	Temporal correl.	Completeness	Methodological Appropriateness and Consistency	Average
EU-28: Crushed rock 16-32 mm	S	GaBi	1	2	1	2	2	1.6
EU-28: Crushed sand grain 0-2 mm	S	GaBi	1	2	1	2	2	1.6
EU-28: Bitumen at refinery	S	GaBi	2	2	1	2	2	1.8
EU-28: Limestone	S	GaBi	2	2	1	2	2	1.8
EU-28: Bitumen emulsion	S	GaBi	3	2	1	2	2	2
EU-28: Cement (CEM II)	S	GaBi	2	2	1	2	2	1.8
Reclaimed Asphalt (RA)	S	GaBi	2	2	2	2	1	1.8
EU-28: Water	S	GaBi	2	2	1	2	2	1.8
EU-28: Diesel mix at filling station	S	GaBi	2	2	1	2	2	1.8
Other resources : EU-28: Oil	S	GaBi	2	2	2	1	2	1.8
EU-28: Electricity Grid mix	S	GaBi	2	2	2	1	2	1.8
Electricity consumption	P	Material Producer	1	1	1	1	1	1
Gas Consumption in Asphalt Plant	P	Material Producer	1	1	1	1	1	1
Oil Consumption	P	Material Producer	1	1	1	1	1	1
Diesel consumption (A5)	P	Contractors	1	1	1	1	1	1
Transport Distances (A2)	P	Real Distances related to the specific case study	1	1	1	1	2	1.2
Transport Distances (A4)	P	Real Distances related to the specific case study	1	1	1	1	2	1.2
Transport Mean	S	GaBi Database	1	2	1	2	1	1.4
Mix design	P	Material Producer	1	1	1	1	1	1
Total Avarage								*1.48*

***P=Primary, S=Secondary**

5.5.4.2 Economic data

In this research both primary and secondary data was used. The data concerning the cradle-to-gate analysis are the same reported in

Table 5-8 and *Table* ***5-11*** for the manufacturers. To model the A4, the amount of

Site	RSM	GER
Fine aggregates (€/kg)	0.020	0.0125
Coarse aggregates (€/kg)	0.018	0.0175
Filler (€/kg)	0.06	0.16
Reclaimed Asphalt (€/kg)	0.01	0.01
Cement (€/kg)	0.10	0.14
Bitumen (€/kg)	0.58	0.7
Bitumen emulsion (€/kg)	0.53	0.8
Water	0.001	0.005

diesel required for the transport was deduced from GaBi, where the model for the environmental burdens was built. In fact, the software calculates the amount of diesel required for the transport from the plant to the installation site, knowing the type of truck and the distances. The consumptions for the laying process are reported in the table above (*Table 5-23*) and the price for diesel is the same as reported in *Table* ***5-11***.

As for the previous exercise, only the costs of the required materials and fuels were considering, excluding any type of agency costs.

5.5.5 STEP 5 – Calculation of indicators

The calculation of indicators for pavement activities covers the environmental, economic and social dimensions. This section will provide:

- The tables with impact calculated for each indicator
- Interpretation of results with Hot spots and Sensitivity analyses

5.5.5.1 Environmental indicators

The indicators selected for the calculation of environmental impacts are the same reported in Table ***5-10***, to be calculated by means of an LCA. The social indicator is the tyre-pavement noise, assessed with a basic approach.

Regarding the assumptions for the LCA, it was decided that:

- RA brings zero emission into the considered system boundaries (EAPA, 2017b);
- RA is stockpiled at the asphalt plant (zero transport);
- waste and/or over consumption of energy and materials during the A3 at the asphalt plant are not considered.

Table 5-25 shows the results of the cradle-to-laid LCA for the four pavements considered.

Table 5-25. Impacts related to mixtures production and laying

Indicators	**HMA-RSM**	**CRM-RSM**	**HMA-GER**	**CRM-GER**
CC (kg CO_2 eq.)	5294.36	4454.36	117000.00	98100.00
CC – biogenic (kg CO_2 eq.)	9.94	10.96	195.00	143.00
CC – fossil (kg CO_2 eq.)	5220.05	4375.55	117000.00	97800.00
CC - land use ch. (kg CO_2 eq.)	61.70	68.03	223.00	176.00
Acid. (Mole of H+ eq.)	18.30	14.84	353.00	278.00
Eutr. Freshwater (kg P eq.)	0.02	0.02	0.20	0.15
Eutr. Marine (kg N eq.)	4.64	3.67	76.30	65.50
Eutr. Terrestrial (Mole of N eq.)	51.87	41.14	842.00	720.00
Phot. ozone form (kg NMVOC eq.)	14.83	11.67	248.00	210.00
Land use (Pt)	53391.12	58941.12	596000.00	412000.00
Res. use, energy carriers (MJ)	332355.86	230055.86	4310000.00	3240000.00
Res. use, min. and met. (kg Sb eq.)	0.00	0.00	1.37	0.68
Water scarc. (m^3 world equiv.)	323.22	479.07	10200.00	8580.00
Energy res. (kg)	7601.84	5225.27	106000.00	79800.00
Non renew. energy res. (kg)	7597.59	5221.02	106000.00	79800.00
Renew. energy res. (kg)	205.05	205.05	596000.00	412000.00
Second. mat. Cons. (kg)	0	845	0	

Interpretation of results - LCA

The study shows clear environmental benefits of cold materials, but it is interest of the authors understanding the differences between the two ways of producing and installing, considered that:

- if the mixture is made in situ (CIR) the step A4 is null;
- producing mixtures in situ may result in lower quality due to reduced control over temperature, humidity, aggregates, and machinery calibration (Gu et al., 2019).

As for materials production, in GER case study the pavement with CRM looks more environmentally friendly for all the indicators, particularly for Renewable energy resource (-51%), Resource use, mineral and metals (-50%), Land use (-31%), CC-biogenic (-27%) (Figure 5-20).

In RSM, something different happens. Once again, as for the production of one ton of materials, the water scarcity increase, but pavements with CRM are more impactful than the conventional for other indicators, such as: CC-biogenic (+10%), CC-land use (+10%), eutrophication freshwater (+8%) and land use (+10%) (Figure 5-20). The increases, with the exception of water scarcity (+48%), are all within 10%. Water scarcity is mainly influenced by the type of operating energy of the plant and the materials adopted, in particular bitumen emulsion and fuel oil. In the RSM case study, on one side the impact in terms of water scarcity is high due to the use of the bitumen emulsion for the CRM, whereas on the other side the impact for the HMA is low because the asphalt plant is heated using natural gas instead of fuel oil (Figure 5-20)

Therefore, CRM results more impactful. On the contrary, the German plant is heated with fuel oil which has a higher impact than the bitumen emulsion used for the cold mixtures, then the variation of impact obtained by using the CRM instead of HMA is negative. Concerning the other indicators, the difference due to the production of one ton of material is very low. A pavement in CRM requires more materials (105 tons vs 60 tons), hence, even if the emissions are lower for one ton, the impact increases by up to 10% when the whole pavement is considered.

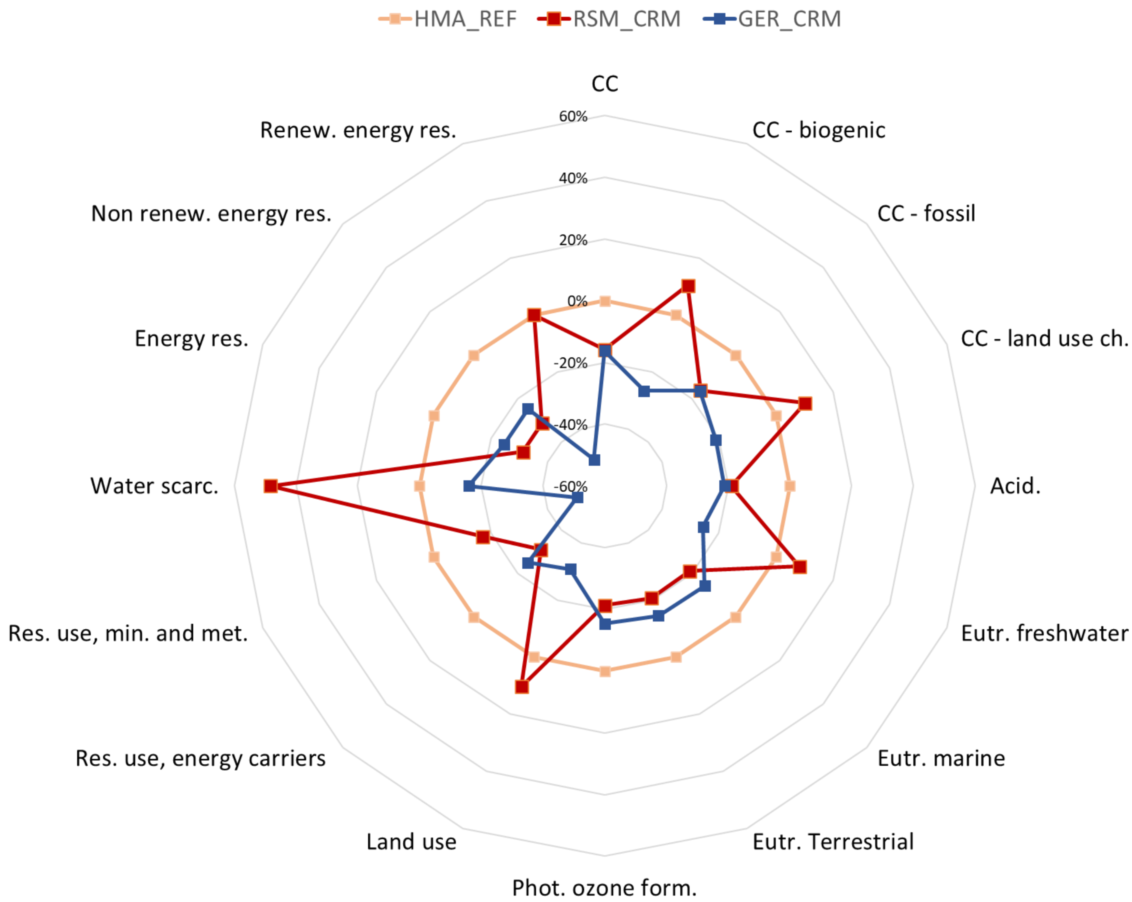


Figure 5-20 – Comparison between pavement with CRM and its respective pavement with HMA (here HMA_REF) in both case studies

Hotspot Analysis

Table 5-26 and Table 5-27 show the results of the hotspot analysis carried out for the RSM and GER case studies, respectively. The analysis aims at investigating how each stage, and in particular A4 and A5, contributes to the overall impact.

Confirming the results presented above, the highest impacts can be attributed to A1- A3, in both case studies. In RSM, being the mixtures production less impactful for CRM than for HMA, it emerges that the weights are differently distributed, hence the transport distances seem to impact more, but they are exactly the same. Concerning the A5, laying a CRM component is lightly more impactful because of the higher amount of diesel required.

In GER, the fact that CRM is produced in situ lightly reduces the impacts due to A4: the other layers are in HMA, hence the materials need to be transported to the site.

Table 5-26 Hotspot RSM– cradle-to-laid analysis

	RSM_REF			RSM_CCPR		
Impact Indicator	**A1-A3**	**A4**	**A5**	**A1-A3**	**A4**	**A5**
CC	98.08%	1.84%	0.07%	96.90%	2.94%	0.16%
CC - biogenic	98.07%	1.55%	0.37%	96.48%	2.67%	0.84%
CC - fossil	98.10%	1.82%	0.06%	96.94%	2.99%	0.14%
CC - land use ch.	90.46%	7.70%	1.83%	80.36%	14.90%	4.72%
Acid.	98.40%	1.50%	0.088%	97.00%	2.78%	0.22%
Eutr. freshwater	94.92%	4.10%	0.97%	90.28%	7.37%	2.33%
Eutr. marine	97.97%	1.97%	0.05%	95.67%	4.16%	0.15%
Eutr. Terrestrial	97.940%	1.99%	0.06%	95.60%	4.22%	0.17%
Phot. ozone form.	98.40%	1.52%	0.07%	96.88%	2.92%	0.18%
Land use	99.10%	0.83%	0.06%	98.19%	1.64%	0.16%
Res. use, energy carriers	94.98%	4.04%	0.95%	90.76%	7.01%	2.22%
Res. use, min. and met.	99.37%	0.50%	0.12%	98.77%	0.93%	0.29%
Water scarc.	98.97%	0.83%	0.19%	98.02%	1.50%	0.47%
Energy res.	99.31%	0.55%	0.13%	99.23%	0.58%	0.18%
Non renew. energy res.	99.37%	0.50%	0.12%	98.78%	0.92%	0.29%
Renew. energy res.	99.37%	0.50%	0.12%	98.78%	0.92%	0.29

Table 5-27 Hotspot GER – cradle-to-laid analysis

	GER_REF			GER_CIR		
Impact Indicator	**A1-A3**	**A4**	**A5**	**A1-A3**	**A4**	**A5**
CC	99.59%	0.36%	0.05%	99.69%	0.26%	0.05%
CC - biogenic	98.84%	0.59%	0.52%	98.88%	0.48%	0.64%
CC - fossil	99.59%	0.36%	0.05%	99.69%	0.26%	0.05%
CC - land use ch.	98.53%	0.74%	0.72%	98.68%	0.57%	0.75%
Acid.	99.56%	0.37%	0.07%	99.64%	0.29%	0.07%
Eutr. freshwater	98.67%	0.67%	0.65%	98.74%	0.54%	0.72%
Eutr. marine	99.16%	0.78%	0.06%	99.39%	0.50%	0.06%
Eutr. Terrestrial	99.12%	0.80%	0.08%	99.36%	0.56%	0.07%
Phot. ozone form.	99.47%	0.47%	0.07%	99.62%	0.33%	0.07%
Land use	99.66%	0.23%	0.11%	99.68%	0.19%	0.12%
Res. use, energy carriers	98.57%	0.73%	0.71%	98.55%	0.62%	0.82%
Res. use, min. and met.	99.59%	0.13%	0.12%	99.73%	0.10%	0.13%
Water scarc.	99.99%	0.00%	0.00%	99.99%	0.00%	0.00%
Energy res.	99.94%	0.03%	0.03%	99.95%	0.02%	0.03%
Non renew. energy res.	99.76%	0.12%	0.12%	99.77%	0.1%	0.13%
Renew. energy res.	99.76%	0.12%	0.12%	99.77%	0.1%	0.13%

Sensitivity Analysis varying transport distances (A4)

One of the aims of this study was understanding how much A4 can influence the overall impact. For this purpose, three scenarios have been defined, assuming and fixing this distance at 50 km, 100 km and 200 km. The results of these assessment have been compared with the results of reference pavements.

Figure 5-21 and Figure 5-22 show the results of this analysis and it emerges that:

- In RSM case study, it can be seen a variation from 4% to 22% for CRM pavements and from to 8% to 41% for HMA pavement with some impact category particularly affected, such as Climate Change- land use change (86% in CRM Pavement and 172% in HMA Pavement), Land use (45% for CRM

Pavement and 80% for HMA Pavement) and Eutrophication freshwater (45% in CRM Pavement and 21% in HMA Pavement).

- In GER case study, it can be seen a variation from 4% to 16% for CRM pavements and from to 5% to 22% for HMA pavements and the most affected impact categories are Eutrophication terrestrial (45% in CRM Pavement and 28% in HMA Pavement), Resource Use- Energy Carriers (33% in CRM Pavement and 7% in HMA Pavement).

From what stated above, it can be stated that A4 can't affect very importantly the impact, never representing a hotspot, except for Pavement with CRM in Republic of San Marino, where Eutrophication freshwater, Land Use and Climate Change- land use change become hotspot or relevant when the distance increase at 100 km or 200 km. Moreover, in both case studies, as distance increase the impacts are higher, but it can be seen that:

- for pavement with CRM in Germany this rise is the lowest calculated and this is due to the reduced quantities of materials to be transported (smaller layers thickness and recycling in situ);
- for pavement with CRM in for Republic of San Marino this rise is bigger, and this is the result of a higher quantity of material to be transported for the layers of this pavement, which corresponds to a higher number of trips.

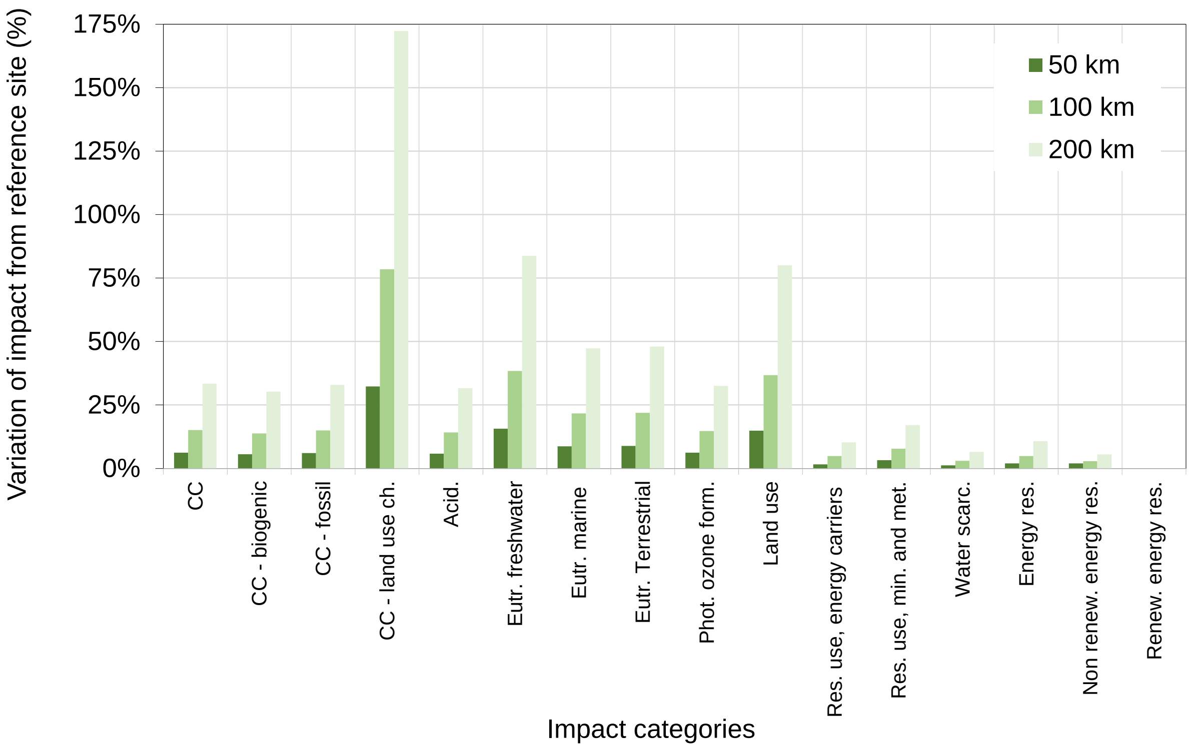


Figure 5-21. Sensitivity analysis varying transport distances (A4) in RSM case study

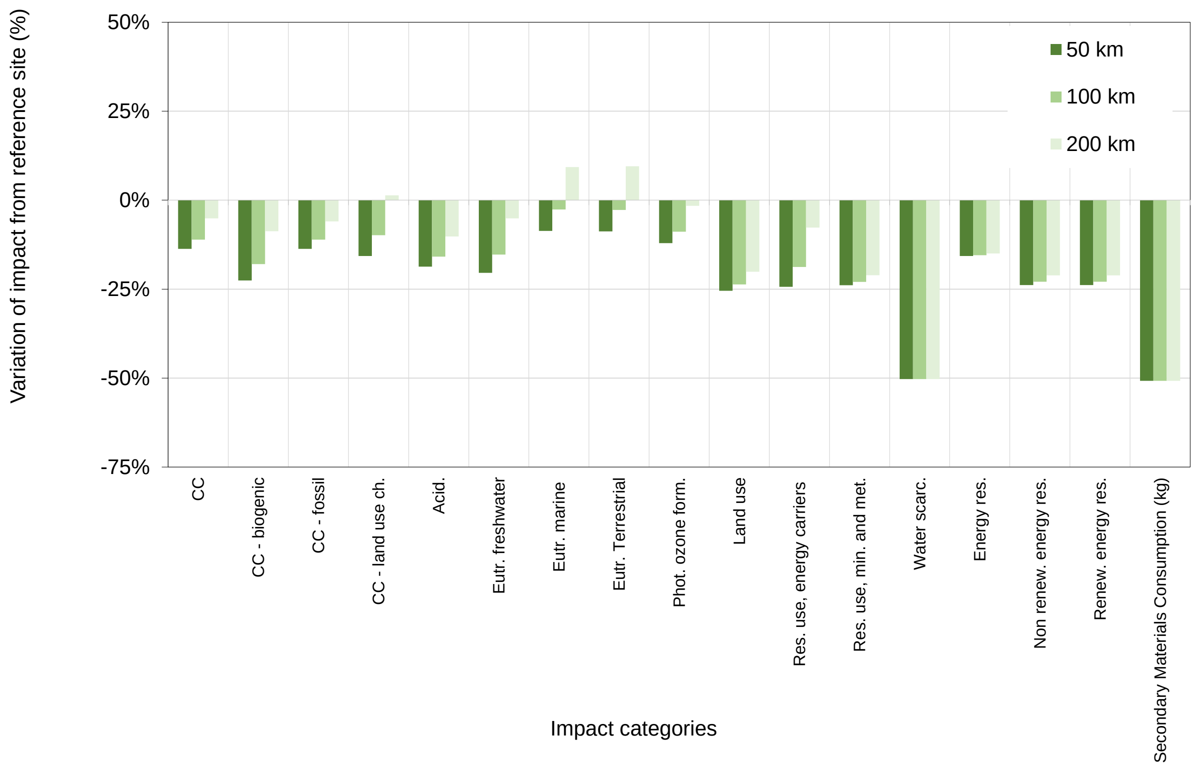


Figure 5-22 - Sensitivity analysis varying transport distances (A4) in GER case study

5.5.5.2 Economic indicator

The life cycle cost is assessed considering the cost due to the production and installation of the selected pavement components for both case studies.

The contribution due to each layer is provided in the table below (*Table 5-28).*

Table 5-28 – Life Cycle costing contribution for each layer for production and installation (A1-A5) for RSM and GER case studies

Description	HMA_RSM (€)	CRM_RSM (€)	HMA_GER (€)	CRM_GER (€)
Wearing course	€ 2,208.48	€ 2,208.48	€ 15,394.37	€ 13,390.64
Binder course	€ 4,352.05	€ 3,386.34	€ 22,199.82	€ 18,055.83
Base course	-	-	€ 57,629.61	€ 20,971.04
Milling	€ 257.80	€ 257.80	€ 1355.96	€ 1355.96
Totale	€ 6,818.33	€ 5,852.62	€ 96,579.75	€ 95,049.47

In RSM, the difference between the conventional pavement and the cold pavement is exclusively given by the binder layer, since the amount of milled pavement and the thickness of wearing course are the same in both cases. As shown in Figure 5-23, producing the cold mixture and laying the respective pavement component costs € 3386.34, while the same operations in HMA costs €4352.05, hence 30% more. It is interesting to note that the layer in CRM is less expensive, even if the amount of required material is bigger than the one in HMA.

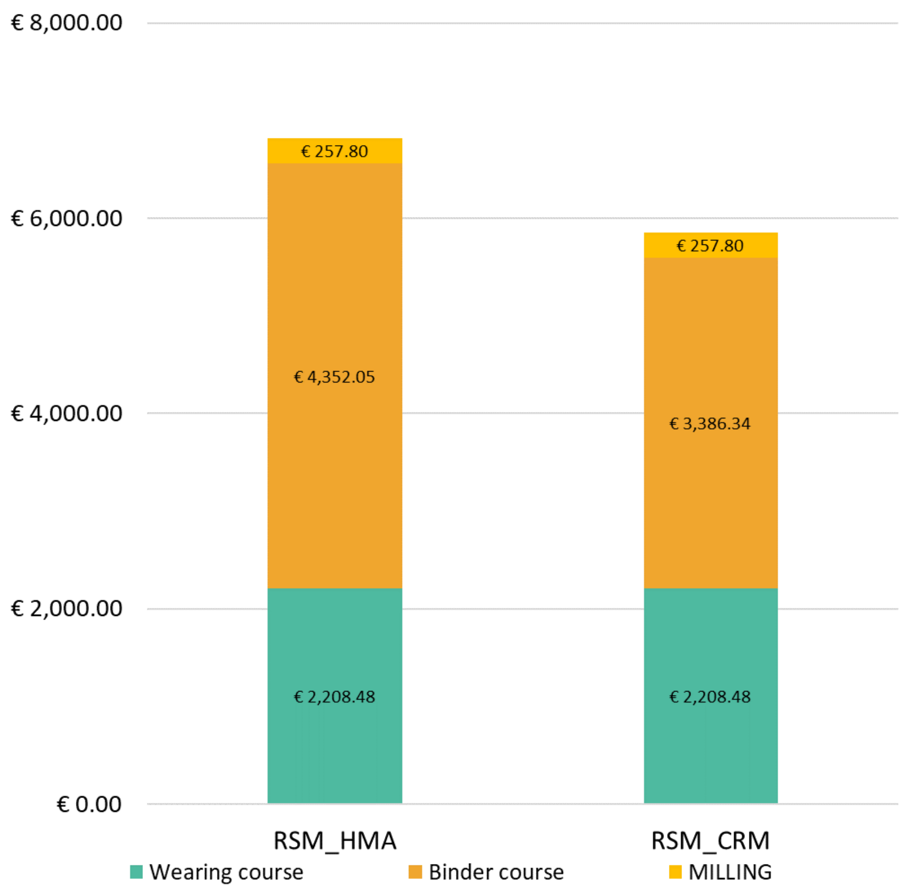


Figure 5-23 – Life Cycle Cost of pavement activities (A1-A5) in RSM

In Germany, choosing HMA or CRM for this pavement design is less determining in terms of costs. In fact, as shown in Figure 5-24, the pavement in HMA costs €167.202,05, while the one in CRM costs €155.509,96, with a reduction of 7%. This is mainly due to base layer, whose cost is almost comparable in the two options. In fact, in CRM pavement, the base is composed of both HMA and CRM layers, whose total cost is € 62.247.05, hence higher than the base fully in HMA. Nevertheless, pavement in CRM looks less expensive because the higher cost of the base is offset by the lower cost of wearing (€ 15.394.37 vs € 13.390.64) and binder course (€ 22.199,82 vs € 18055,83), due to a reduced thickness. The milling operation has the same cost because the initial pavement to be milled is the same for both alternatives, hence the consumption of diesel used by the equipment, as well as the amount of material to be transported do not change.

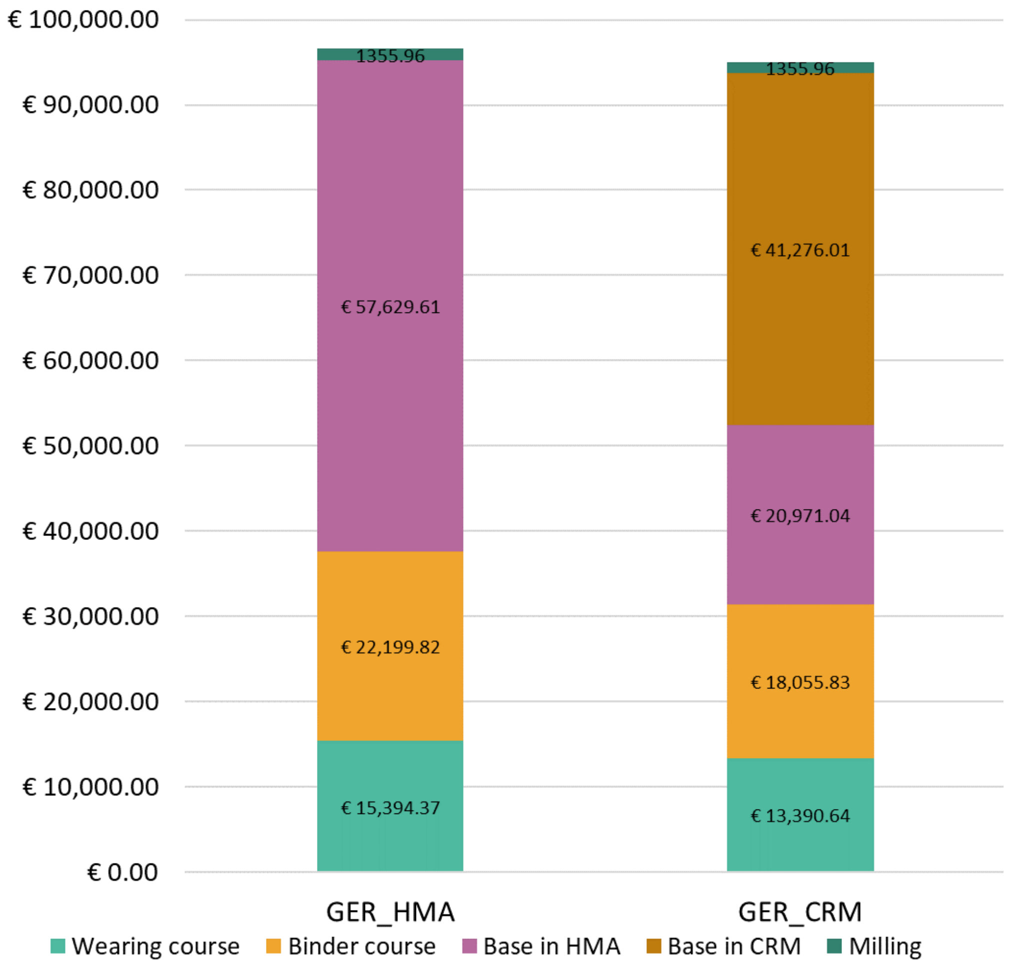


Figure 5-24 – Life Cycle Cost of pavement activities (A1-A5) in GER

Sensitivity Analysis: varying energy costs

This sensitivity analysis was carried out to show how variations in the cost of energy (diesel, electricity, etc.) can affect the total cost of producing and laying the pavement. The selected costs are the one registered for the second half of 2023 (*Table* ***5-15***) and compared to the initial ones, referred to 2020 (*Table* **5-9**).

In RSM the increase registered for HMA and CRM is almost the same (13% and 12%), while for the production of one ton there was a bigger difference (13% and 9%). This can be explained because the quantity of mixture to be produced for pavement in CRM is bigger than the one for the conventional pavement, leading to an increase of the total cost.

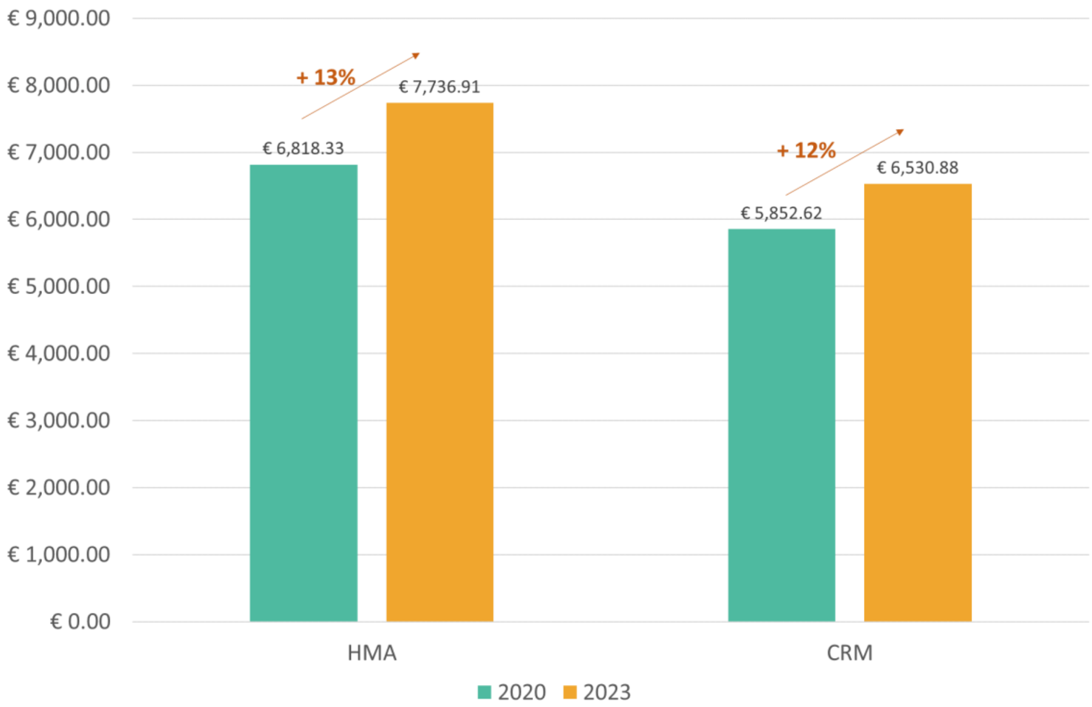


Figure 5-25 – Sensitivity analysis varying energy costs in RSM

In the GER, the increase is 10% for HMA and 6% for CRM, for the following reasons. In fact, the total cost of pavement with CRM is influenced by nearly 50% due to the cost of the CRM base layer. As energy costs fluctuate, the CRM layer experiences a less significant variation compared to other layers (1% versus 7-10% for the others), as it requires less energy for production. In 2023, the cost of HMA layers increases by about 10% across the board. Consequently, using CRM for the base layer helps reduce the total intervention cost, resulting in a 6% increase compared to the 10% increase for HMA.

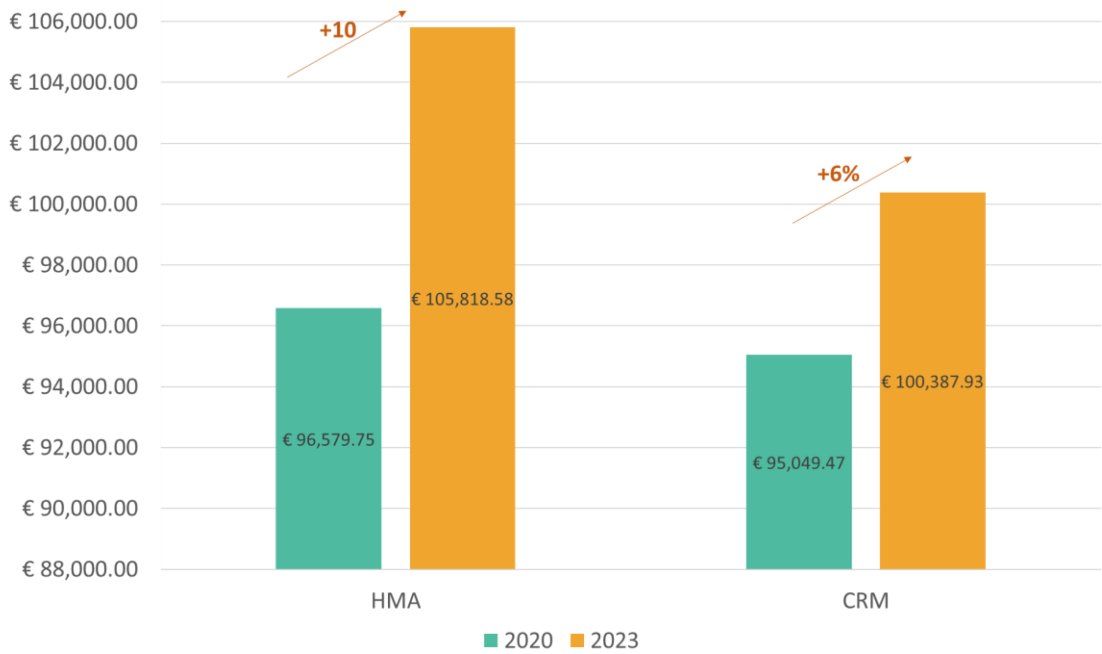


Figure 5-26 – Sensitivity analysis varying energy costs in GER

5.5.5.3 *Social indicator*

The tyre-pavement noise is assessed with the basic approach. In both case studies the material used for the wearing course is the same, independently on the use of CRM for the other lower course. In RMS, an AC is used, while in GER an SMA. Considered the rating levels, RMS is level C, while GER is level A.

5.5.6 STEP 6 – Multi-Criteria Decision Making

As being optional, no MCDCM was calculated for this exercise. Hence decision making could be done considering values of each indicator separately and with equal weights.

5.5.7 STEP 7 - Reporting, communication and verification

The LCA analyses have demonstrated the environmental benefits of manufacturing and installing CRM, in both case studies, but with some exceptions for RSM.

In fact, even if when only on ton of material is produced, the benefits are registered for all the indicators, excluded water scarcity and renewable resources, when the total amount of mixtures is produced and layed, something changes. In fact, together with the other mentioned indicators, CC-biogenic (+10%), CC-land use (+10%), eutrophication freshwater (+8%) and land use (+10%) increase. This is due to the different quantities of materials that a pavement in CRM requires (105 tons vs 90 tons), hence, even if the emissions are lower for one ton, the impact increases by up to 10% for the above-mentioned indicators when the whole pavement is considered. The higher impacts due to water scarcity and material resources are due, as for materials, to the use of bitumen emulsion and heating oil.
In the RSM, the use of bitumen emulsion for CRM contributes to a high water scarcity impact, while the HMA has a lower impact due to the use of natural gas for heating. Conversely, in the German case study, where the plant is heated using fuel oil, the impact of CRM becomes more significant compared to HMA, which results in a negative variation of impact.

The hotspot analyses showed that, both for material production and pavement activities, the acquisition of raw materials is the most impactful stage. In fact, HMA need a high amount of virgin materials and the relative contribution of A1 is particularly high for some indicators, while some other else are influenced by the energy consumption at the plant (i.e. in Germany for crude oil). On the other side, CRM is produced at lower temperature, hence the demand of energy is lower and, even if the quantity of RA is high, the relative contribution of A1 is very important (sometimes > 80%). The stage of transport to site (A4) and installing (A5) are very low impactful.

Concerning the economic indicator, it emerged that building the pavement in CRM implies a reduction in both case studies. Nevertheless, this benefit is higher in RMS, where the reduction by 14% and mainly due to the layer in CRM, since milling operations and binder course have the same price in both case studies. In GER, the reduction is by 7% rather than a pavement in HMA. This low difference is due to the high costs for the base in CRM pavement, composed of both HMA and CRM layers, which is more expensive than the respective base in the other option. It follows that to increase the economic benefits of cold mixtures, a reduction of layer thickness is requested.

5.6 EXERCISE 3 - SA of pavement activities (ROAD AUTHORITIES)

This third exercise involves the RAs, evaluating the sustainable performance of construction and maintenance of a pavement whose components are fully built in HMA or partially built in CRM. Also in this case, the assessment was performed using the life cycle techniques (LCA and LCC). The different steps are shown in Figure 5-27, considering the so-called "cradle-to-grave". The final goal was to provide recommendations to optimize their overall sustainability approach.

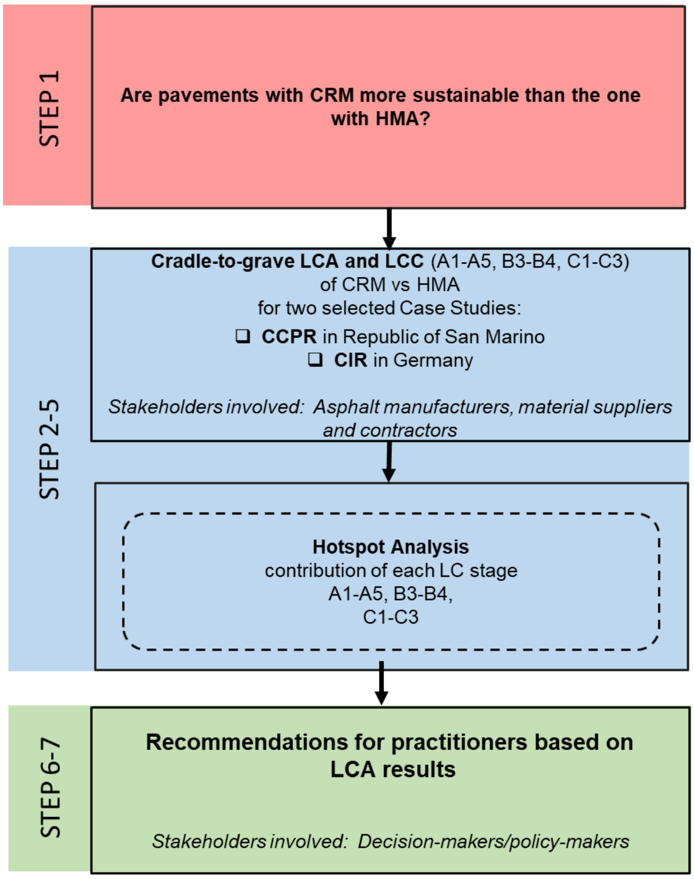


Figure 5-27. Structure of the investigation and involved stakeholders – RAs level

5.6.1 STEP 1 - Identify the purpose of the SA

The goal of this study is to compare the environmental and economic performance of pavements and their maintenance scenarios, considering two different technologies for the mixture production: hot production and cold production. To answer this question, the production and laying of four different mixtures were compared. The scope of this study is the construction of pavement layers, considering the production of the mixtures and the successive laying and compaction, as well as all the other operations required for maintenance. The intended application is to offer Road Agencies and manufacturers valuable recommendations for optimizing their overall sustainability practices.

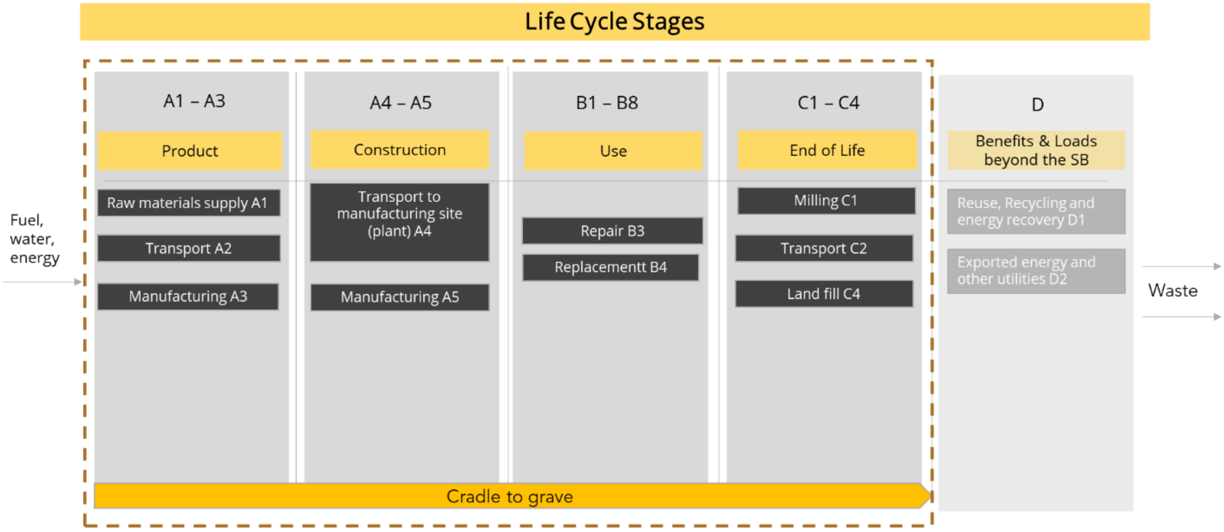
5.6.2 STEP 2 – Specification of the object of the assessment

According to the pavement model, this exercise concerns a pavement activity, involving the building, the maintenance and the end-of-life of a road pavement.

The functional equivalent is defined as the exact weight/volume of road pavement component to be built, maintained and dismissed at project level (Table 5-16,

Table *5-17*), capable of meeting the technical requirements needed by the RA, in terms of traffic volume, durability, etc.

The system boundaries are a cradle-to-grave, as reported in the Figure 5-28.



"B3- Repair" is considered only for Republic of San Marino Case Study

Figure 5-28 - System boundaries of the selected case studies – RAs level

Concerning the physical boundaries, they include the layers to be built and substituted: wearing and binder course in RSM, wearing, binder course and base course in GER.

The analysis period for both case studies was assumed to be long enough to include at least one CRM layer replacement. This is 20 years for RSM (binder replacement) and 50 years for GER (base replacement).

5.6.3 STEP 3 – Scenarios

The assumption and information to collect are related to the scenarios due to the maintenance strategy (*Table 5-3*). The needed information covers several aspects, such as the data required to model A1-A5 phases (already reported in the section above), the amount of material required at each intervention, the distances from site to the plant to process the milled asphalt and the energy to process.

It has been assumed that only the net amount of material is taken into account in this study, as reported in

Table 5-29, Table 5-30, Table 5-31 and Table 5-32.

Table 5-29. Mass (ton) of HMA involved in each activity in GER

	Process	SMA8S Surface	AC16 Binder	AC32TS Base
Initial construction	Production & construction	184	375	1047
Maintenance (year 12,5 + 37,5)	Milling	368	0	0
	Production & construction	368	0	0
Maintenance (year 25)	Milling	184	375	0
	Production & construction	184	375	0
End-of-life (year 50)	Milling	184	375	1047

Table 5-30. Mass (ton) of HMA and CRAB involved in each activity in GER

	Process	SMA8S Surface	AC16 Binder	AC32TS Base	CRAB
Initial construction	Production & construction	160	305	381	863
Maintenance (year 12,5 + 37,5)	Milling	320	0	0	0
	Production & construction	320	0	0	0
Maintenance (year 25)	Milling	160	305	0	0
	Production & construction	160	305	0	0
End-of-life (year 50)	Milling	160	305	381	863

Table 5-31. Mass (ton) of HMA involved in each activity in RSM

	Process	AC12 Surface	AC12 Binder
Initial construction	Production & construction	30	60

Maintenance (year 12,5 + 37,5)	Milling	30	0
	Production & construction	30	0
Maintenance (year 25)	Milling	30	60
	Production & construction	30	60
End-of-life (year 50)	Milling	30	60

Table 5-32. Mass (ton) of HMA and CRAB involved in each activity in RSM

	Process	**AC12 Surface**	**CRAB Binder**
Initial construction	Production & construction	30	75
Maintenance (year 12,5 + 37,5)	Milling	30	0
	Production & construction	30	0
Maintenance (year 25)	Milling	30	75
	Production & construction	30	75
End-of-life (year 50)	Milling	30	75

5.6.4 STEP 4 – Selection of data

5.6.4.1 Environmental data

The data used in this research ere directly provided by partners, when possible, or taken from GaBi database when missing. The information related to A1-A5 are the same contained in the section 6.3 and 6.4, while the data related to B and C phase, provided by the partners, are shown here below.

In B phase, only B3 (in RSM) and B4 (both in RSM and GER) were considered within the selected system boundaries. The related impacts cover the crack repair (B3) in RSM and the milling and overlay (M&O) of the layers in RSM and GER, according to the respective maintenance strategy. In details, the processes included in the M&O operation are milling of the deteriorated asphalt layer, the transportation to the recovery centre, the production of the new materials (A1, A2 and A3), their transportation to the roadwork (A4) and the construction of the new layer (A5). It follows that the equipment, the consumptions and the distances for the new materials production are the same of the cradle-to-laid, while the info for milling process and truck transportation are provided by the partners (Table 5-33, Table 5-34)

Table 5-33 - LCI Sources for the use stage

B3	Crack Repair	Gabi Database: EU:28- Propane mix at refinery
B4	Milling process	Primary data obtained from partners
	Diesel combustion for milling	GaBi Database: EU:28- Diesel mix at refinery
	Truck transportation (RAP)	GaBi Database: Transport, freight, lorry, 16–32-ton, EURO 5
	Overlay process	Same as in A1 to A5

Table 5-34. Locations and transport distances of the different sites from the asphalt plant

Site	*Location*	*Distance (km)*
Plant for producing RAP	Republic of San Marino	15
Raw materials and mixtures	The same as A2 and A4	

In C phase, the processes belonging to the selected system boundaries are the milling of the three asphalt layers (C1) and the transportation of the milled pavement to the recovery centre (C2) and the landifill (C4). The data is the same as the ones for B4 (Table 5-33, Table 5-34).

A data quality assessment was performed giving a score to the used data from 1 (very good) to 5 (very poor) as suggested by JRC (Zampori et al., 2016). The results in Table 5-35 indicates that average rating is satisfactory, being comprised between good and very good (2 and 1, respectively).

Despite suggested from the Road pavement LCM guidelines, this exercise will not include the uncertainty analysis of the results (Lo Presti et al., 2021). The reader will find more details on the uncertainty analysis of SA results within two related research products: "D5.1b Recommendations for Multi-Criteria Sustainability Analysis" (Abed & Lo Presti, 2021) and "Uncertainty analysis of life cycle assessment of asphalt surfacings" (Abed et al., 2023)

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Table 5-35. Data quality

Data	Type *	Source	Technological Representativ.	Geographical Representativ.	Temporal correl.	Completeness	Methodological Appropriateness and Consistency	Average
EU-28: Crushed rock 16-32 mm	S	GaBi	1	2	1	2	2	1.6
EU-28: Crushed sand grain 0-2 mm	S	GaBi	1	2	1	2	2	1.6
EU-28: Bitumen at refinery	S	GaBi	2	2	1	2	2	1.8
EU-28: Limestone	S	GaBi	2	2	1	2	2	1.8
EU-28: Bitumen emulsion	S	GaBi	3	2	1	2	2	2
EU-28: Cement (CEM II)	S	GaBi	2	2	1	2	2	1.8
Reclaimed Asphalt (RA)	S	GaBi	2	2	2	2	1	1.8
EU-28: Water	S	GaBi	2	2	1	2	2	1.8
EU-28: Diesel mix at filling station	S	GaBi	2	2	1	2	2	1.8
Other resources : EU-28: Oil	S	GaBi	2	2	2	1	2	1.8
EU-28: Electricity Grid mix	S	GaBi	2	2	2	1	2	1.8
Electricity consumption	P	Material Producer	1	1	1	1	1	1
Gas Consumption in Asphalt Plant	P	Material Producer	1	1	1	1	1	1

Oil Consumption	P	Material Producer	1	1	1	1	1	1
Diesel Consumption (A5)	P	Material Producer	1	1	1	1	1	1
Transport Distances (A2)	P	Real Distances related to the specific case study	1	1	1	1	2	1.2
Transport Mean	S	GaBi Database	1	2	1	2	1	1.4
Mix design	P	Material Producer	1	1	1	1	1	1
Transport Distances (A4)	P	Real Distances related to the specific case study	1	1	1	1	2	1.2
Transport Distances (C2)	P	Real Distances related to the specific case study	1	1	1	1	2	1.2
Total Avarage								1.48

***P=Primary, S=Secondary**

5.6.4.2 Economic data

In this research both primary and secondary data was used. The data concerning the cradle-to-laid analysis are the same reported in

Table 5-8 and *Table 5-11* for manufacturers, and the assumptions done for A4-A5 are the

Site	RSM	GER
Fine aggregates (€/kg)	0.020	0.0125
Coarse aggregates (€/kg)	0.018	0.0175
Filler (€/kg)	0.06	0.16
Reclaimed Asphalt (€/kg)	0.01	0.01
Cement (€/kg)	0.10	0.14
Bitumen (€/kg)	0.58	0.7
Bitumen emulsion (€/kg)	0.53	0.8
Water	0.001	0.005

same reported in section 5.5.4.2. The maintenance scenario is the same reported in

Table *5-29*, Table 5-30, Table 5-31 and Table 5-32.

As for the previous exercise, only the costs of the required materials and fuels were considered, excluding any type of agency costs.

5.6.5 STEP 5 – Calculation of indicators

The calculation of indicators for pavement activities covers the environmental and social dimensions. This section will provide:

- The tables with impact calculated for each indicator

- Interpretation of results with Hotspots

In addition, it has been assumed that:

- RA brings zero emission into the considered system boundaries (EAPA, 2017b);
- RA is stockpiled at the asphalt plant (zero transport);
- waste and/or over consumption of energy and materials during the A3 at the asphalt plant are not considered.

5.6.5.1 Environmental indicators

The environmental impacts are calculated using the EF 2.0 methodology and they are related to a set of selected indicators defined in accordance with the SA framework.

reports the numeric results of the environmental LCA for the mixtures of each case study.

Table 5-36 – Impacts related to mixtures cradle-to-grave

Indicators	HMA-RSM	CRM-RSM	HMA-GER	CRM-GER
CC (kg CO_2 eq.)	12424.72	10782.51	306508.00	264370.00
CC – biogenic (kg CO_2 eq.)	23.34	25.47	536.44	437.83
CC – fossil (kg CO_2 eq.)	12249.11	10597.43	305499.00	263065.00
CC - land use ch. (kg CO_2 eq.)	145.50	158.97	698.01	541.66
Acid. (Mole of H+ eq.)	42.94	36.15	909.72	719.91
Eutr. Freshwater (kg P eq.)	0.05	0.06	0.56	0.44
Eutr. Marine (kg N eq.)	10.94	9.03	206.93	175.83
Eutr. Terrestrial (Mole of N eq.)	122.12	101.27	2289.41	1933.93
Phot. ozone form (kg NMVOC eq.)	34.50	28.22	659.39	550.74
Land use (Pt)	124482.55	135680.20	0.01	0.01
Res. use, energy carriers (MJ)	772341.72	570456.91	1629000.00	1229910.00
Res. use, min. and met. (kg Sb eq.)	1960.00	2290.00	11486500.00	8928740.00
Water scarc. (m^3 world equiv.)	752.64	1069.48	3.11	1.80
Energy res. (kg)	17724.52	12957.30	23909.10	19184.83
Non renew. energy res. (kg)	17759.34	13023.84	283345.37	222195.70
Renew. energy res. (kg)	456.60	521.38	283345.37	222195.70
Second. mat. Cons. (kg)				

Interpretation of results

The cradle-to-grave assessment (Table 5-36) demonstrates once again a better performance of CRM pavements when compared to HMA pavement in GER, while some increases for a group of categories in RSM. Once again, as for the production of one ton of materials, the water scarcity increase, but pavements with CRM are more impactful than the conventional for other indicators, such as: CC-biogenic (+10%), CC-land use (+10%), eutrophication freshwater (+8%) and land use (+10%) (Figure 5-20). The increases, with the exception of water scarcity (+48%), are all within 10%. Water scarcity is mainly influenced by the type of operating energy of the plant and the materials adopted, in particular bitumen emulsion and fuel oil. In the RSM case study, on one side the impact in terms of water scarcity is high due to the use of the bitumen emulsion for the CRM, whereas on the other side the impact for the HMA il low because the asphalt plant is heated using natural gas instead of fuel oil. Therefore, CRM results more impactful. On the contrary, the German plant is heated with fuel oil which has a higher impact than the bitumen emulsion used for the cold mixtures, then the variation of impact obtained by using the CRM instead of HMA is negative. Concerning the other indicators, the difference due to the production of one ton of material is very low. A pavement in CRM requires more materials (105 tons vs 60 tons), hence, even if the emissions are lower for one ton, the impact increases by up to 10% when the whole pavement is considered.

Concerning the other indicators in RSM, the best improvements can be found for Resource use, energy carriers (-26%), Eutrophication marine and terrestrial (-17%), Photochemical ozone depletion (-18%), Acidification (-16%), while the Climate Change is reduced of 13% Figure 5-29). In GER, the best improvement is for water scarcity (-42%), Land use (-25%), resource use, minerals and metals and renewable energy resources (-24%), while Climate Change is reduced of 14 (*Figure* **5-29**).

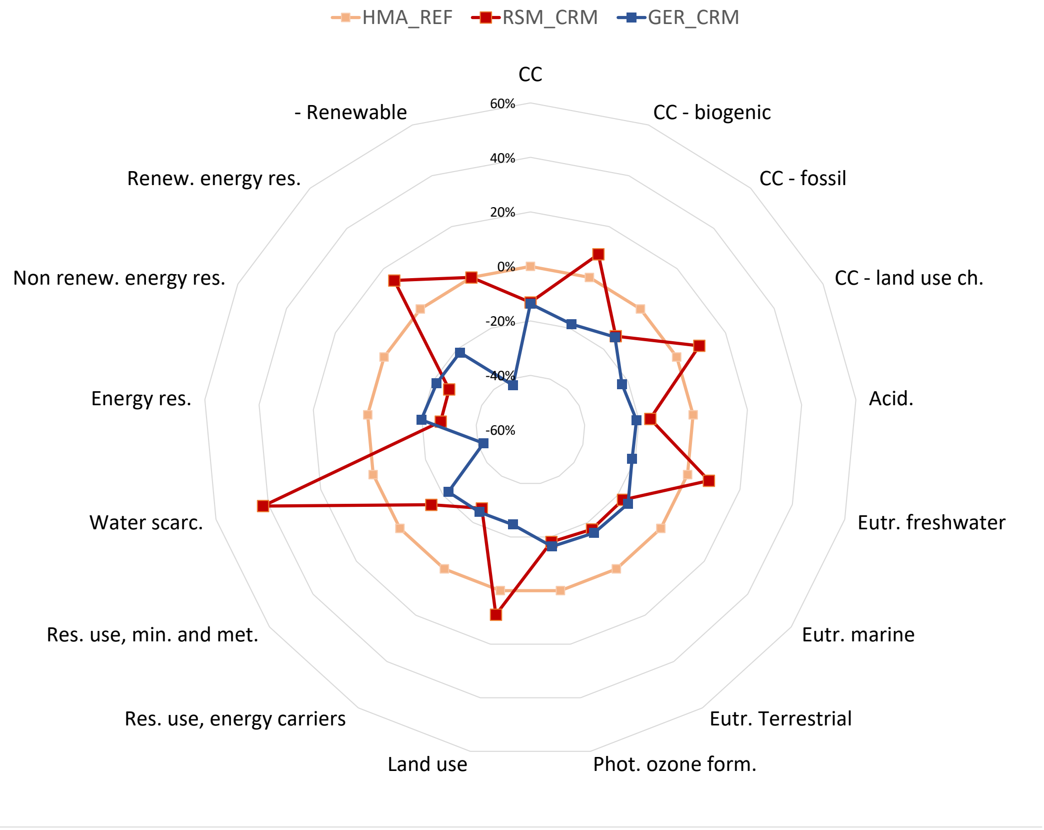

Figure 5-29- Comparison between PAVEMENT with CRM and its respective pavement with HMA (here HMA_REF) in both case studies

Hotspot Analysis

Figure 5-30 and Figure 5-31 show the results of the hotspot analysis carried out for the RSM and GER case studies, respectively. As in the previous exercises, the analysis aims at investigating how each stage contributes to the overall impact. In all the analyses, it's evident that the most impactful stages are the Production (A1-A3) and the Use (B), being B always a hotspot.

It can be stated that:

- On average, for RSM Case Study, the production of Pavement with CRM is less impactful than that one with HMA (33% vs 39%), as supposed. In fact, CRM mixtures are manufactured at law temperatures during the mixing process, that's why the impacts linked to the production are reduced. Furthermore, the specific case study implies the production of one layer with conventional way and another in cold, while in Germany three layers are made of HMA, while just one is in CRM. In fact, analyzing the average of impacts linked to A1-A3 of both German case study, the difference between the two pavements is almost trifling (38% HMA, 36% CRAB).

- In San Marino, B always represents a hotspot (>56%), except for water scarcity in Pavement with CRAB and for Respiratory Inorganics for both pavements.
- Furthermore, A4-A5 is particularly linked with Climate Change- land use change, due to the use of diesel and fossil fuels.
- In Germany, A4-A5 and C1-C3 give a null contribution to the overall impact: they are influent compared with the burdens due to production and maintenance. Furthermore, the distance from plant/stockpile and site is almost irrelevant (2,9 km) and CRABs is produced in-situ, so a huge quantity of milled asphalt is not transported to stockpile, hence also these burdens are avoided.

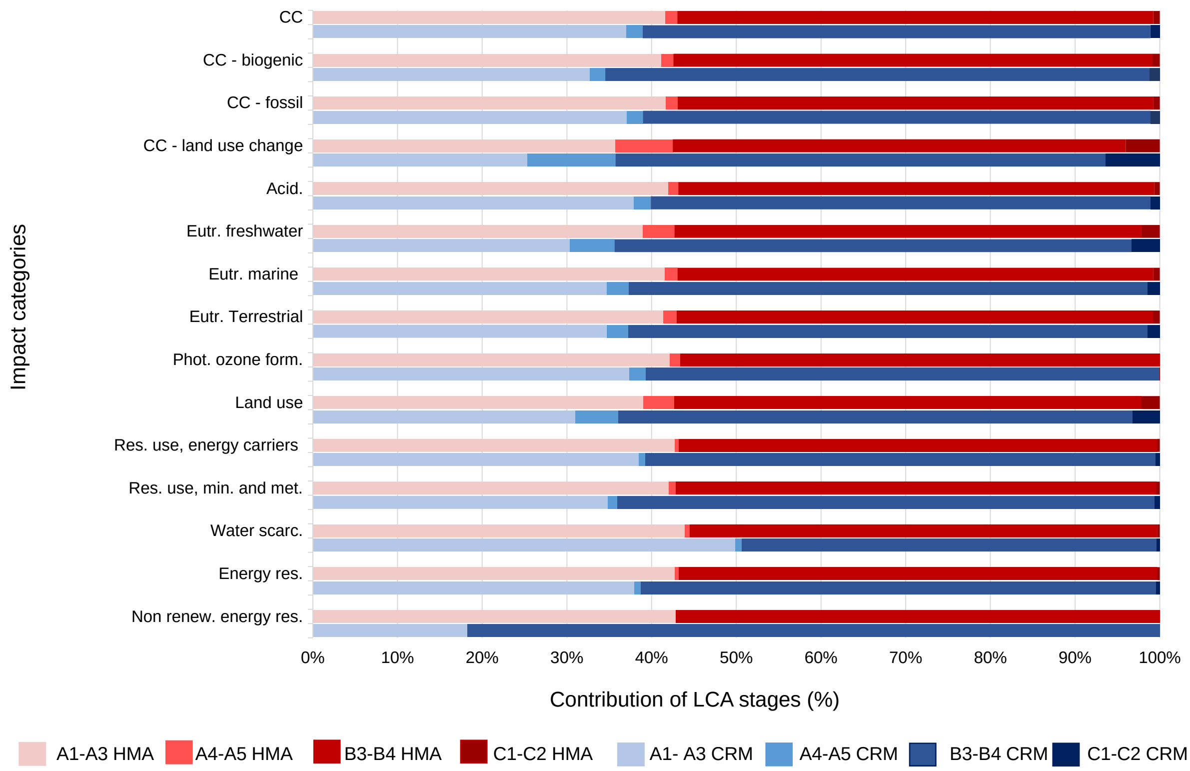

Figure 5-30 -Hotspot analysis in GER case study

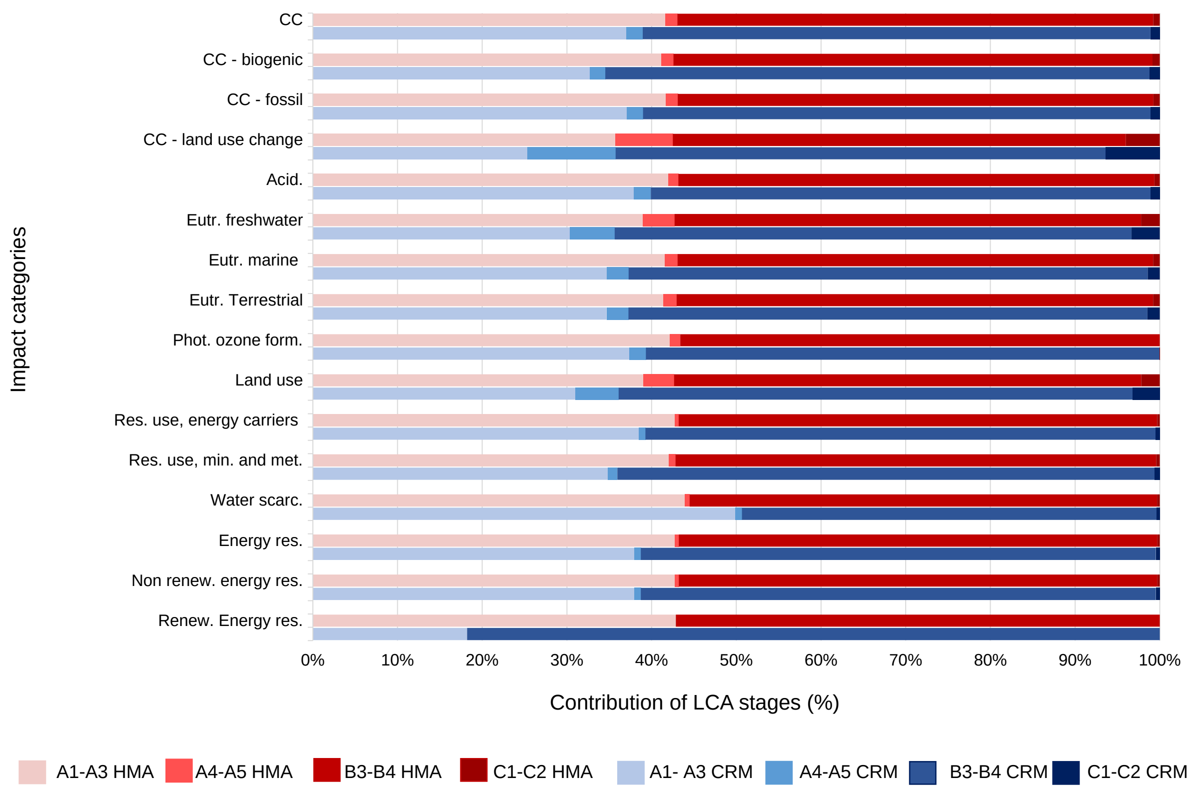

Figure 5-31 - Hotspot analysis in RSM case study

5.6.5.2 Economic indicators

The calculation was performed considering the discount rate valid for 2020, when the pavements were constructed. This value is equal to 0%, as reported by the European Central Bank (European Central Bank, 2024a, 2024b).It means that no time preference is expressed, the costs of today are equally weighted to the benefits of tomorrow.

The calculations were carried out using Real Cost and providing the results showed in . The results of the undiscounted sum (equivalent in this case to the NPV) is obtained by RealCost assuming that at the end of the twenty years the new pavement has a remaining service life whose value is subtracted from the total agency cost, given by the sum of each intervention. The Equivalent Uniform Annual Cost (EUAC) is given by the breakdown of total cost by number of years of analysed service life.

Table 5-37 – Life Cycle Costing results for RSM and GER (discount rate= 0%)

Description	HMA_RSM (€)	CRM_RSM (€)	HMA_GER (€)	CRM_GER (€)
Undiscounted Sum	€ 21,468.80	€ 17,596.80	€ 174,174.66	€ 162,361.69
NPV	€ 21,468.80	€ 17,596.80	€ 174,174.66	€ 162,361.69
EUAC	€ 1,022.32	€ 837.94	€ 3,415.19	€ 3,183.56

The results can be summarised as follows:

- In RSM, the NPV is € 21,468.80 for conventional pavement, while it is € 17,596.80 for pavement with CRM. It means that the actual value is 18.04% lower than the undiscounted rate, with an Equivalent Uniform Annual Cost (EUAC) equal to € 1,022.32 for HMA_RSM and € 837.94 for CRM_RSM.
- In GER, the NPV is € 174,174.66 for conventional pavement, while it is € 162,361.69 for pavement with CRM. It means that the actual value is 10 % lower than the undiscounted rate, with an Equivalent Uniform Annual Cost (EUAC) equal to € 3,415.19 for HMA_RSM and € 3,183.56 for CRM_RSM.

More in details, the contribution of each life cycle phase in both case studies contributes as shown below (

Table 5-38):

Table 5-38 – Life Cycle costing contribution for each life cycle stage for RSM and GER (discount rate= 0%)

Description	**HMA_RSM (€)**	**CRM_RSM (€)**	**HMA_GER (€)**	**CRM_GER (€)**
A	€ 6,818.33	€ 5,852.62	*€ 96,579.75*	*€ 95,049.47*
B	€ 8,854.73	€ 8,232.54	€ 165,849.09	€ 154,154.00
C	€ 257.80	€ 300.34	1355.96	€ 879.46
Total	€ 15,930.86	€ 14,041.97	€ 263,784.80	€ 250,082.93

More in details, the analysis of the entire life cycle in terms of economic impacts shows a reduction by 12% for pavement with CRM (Figure 5-32). This in mainly due to:

- The reduction in A phase (production of materials and installation of pavement components), explainable through the reduced costs for CRM mixture, even if the required amount is higher than the respective layer in HMA.
- The reduction in B phase, explainable with the same reasons expressed above for A phase.

- C phase, even if for CRM_RSM is a bit more impactful because the amount of diesel to be milled and transported is bigger than for HMA_RSM, is little and negligible.

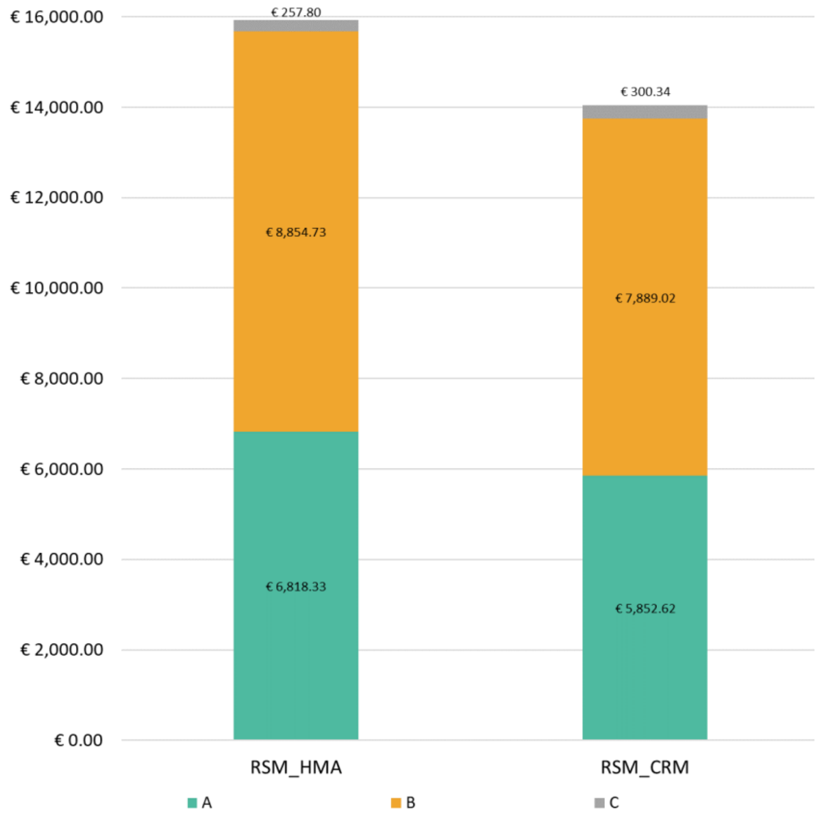

Figure 5-32 – Life Cycle Cost in RSM case study

Figure 5-33 shows the singular contribution during B phase. It emerges that the main difference is given by the second intervention that is the one affecting the binder course, whose thickness differs between the two alternatives.

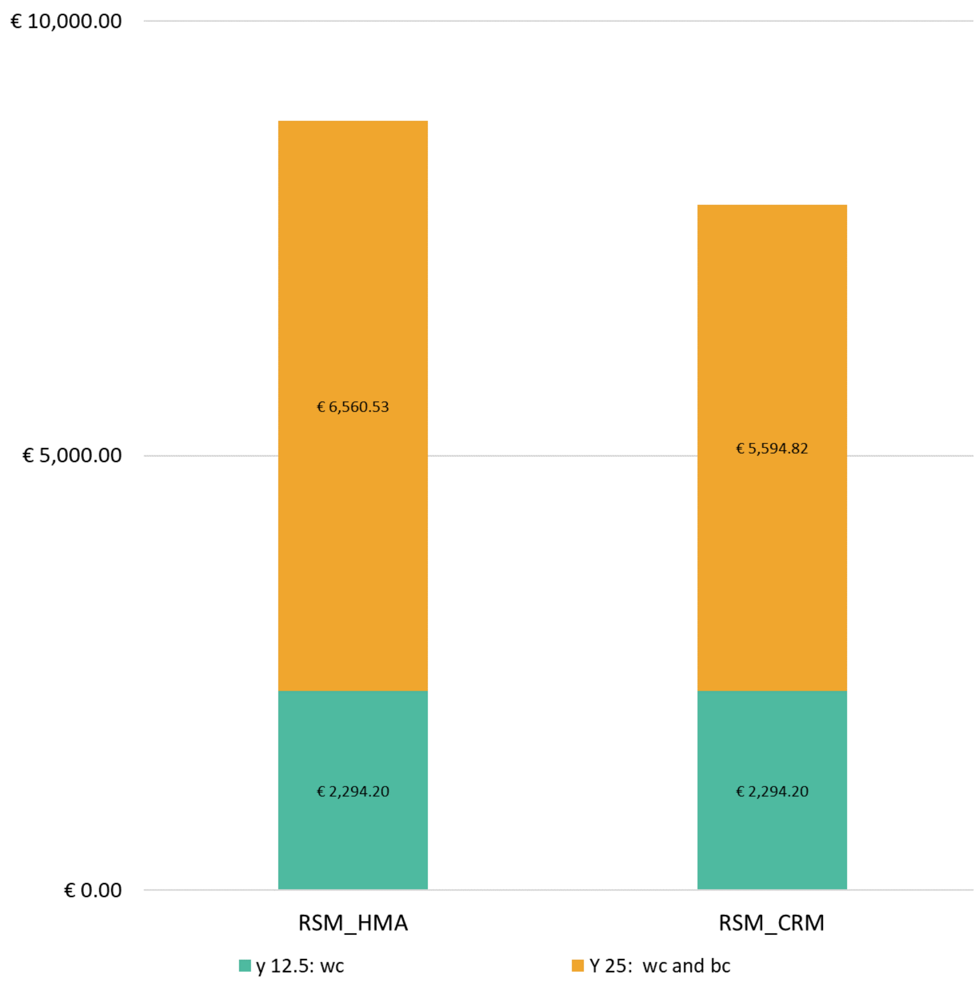

Figure 5-33 – Economic contribution for each intervention during B phase in RSM case study

In GER case study, comparing the entire life cycle of the two selected alternatives shows a reduction by 5% when CRM is used (Figure 5-34). This low percentage, that is similar to the one reported for the cradle-to-laid analysis, is explained as follows:

- As showed in the cradle-to-laid analysis, the difference between the production and installation phase (identified as "A") between the two alternatives is minimal. This is due to the high contribution of the base layer in pavement with CRM, that costs more than the one in the other alternative (€ 96,579.75 vs € 95,049.47).
- The most frequent maintenance activities affect wearing and binder courses, made of HMA, but thinner in pavement with CRM. As a consequence, this

allows a reduction of costs throughout the entire life cycle (€ 167,205.05 vs € 155,509.96) by 7%.

- C phase affects in a very low percentage the total life cycle. Moreover, it impacts less the alternative with CRM because the total amount of materials to be transported to the landfill (C2) is lower than in the other alternative (-35%).

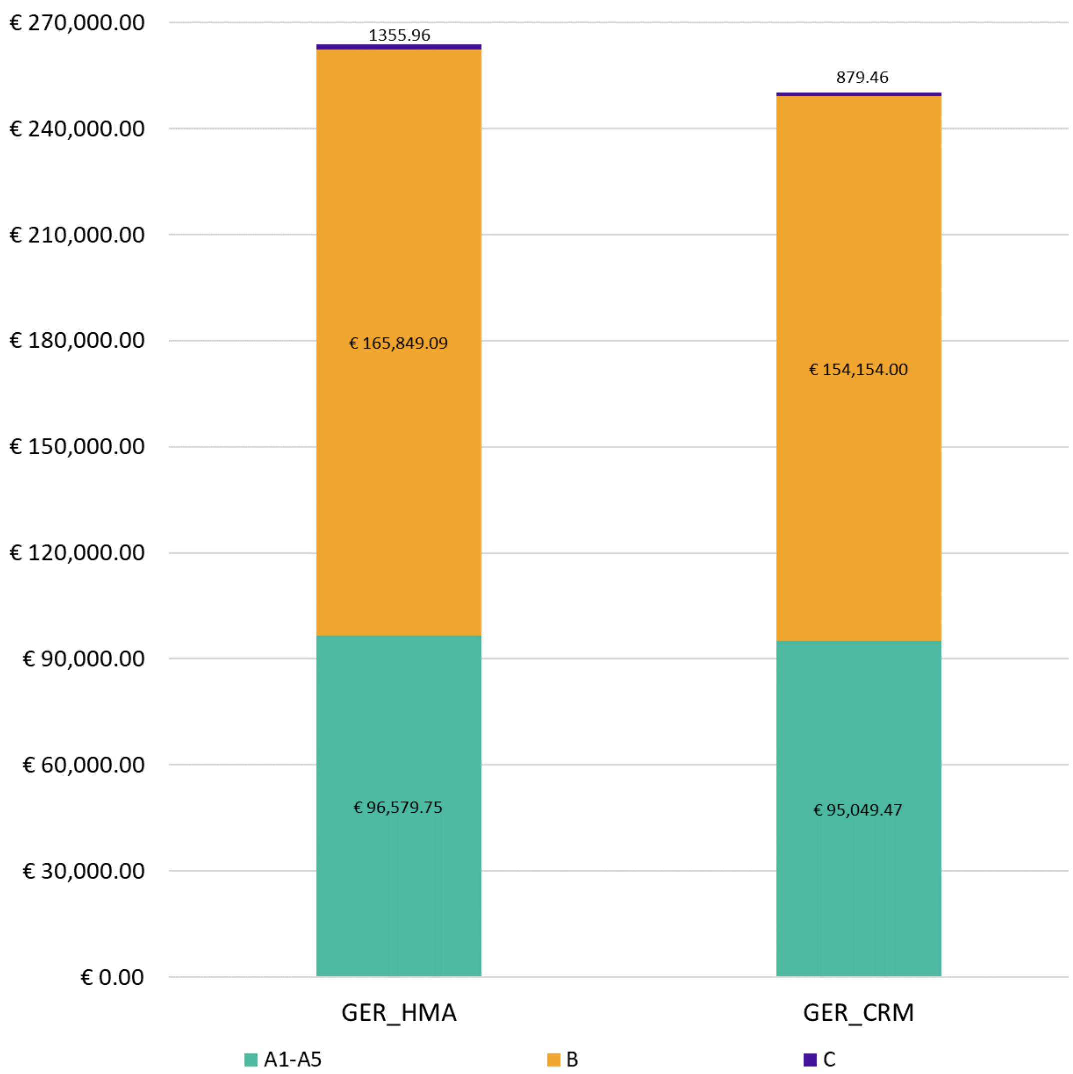

Figure 5-34 – Life Cycle Cost in GER case study

Figure 5-35 shows the single contribution of each maintenance activity held during B phase. It emerged that a thinner wearing course implies a cost reduction by 13%, while a thinner binder course allows a decrease of 16%. The benefits are then reduced at year 50, when the cost reduction, for the reasons already explained, is only 2%.

Figure 5-35 – Economic Contribution for each intervention during B phase in GER case study

From what stated above, it can be concluded that the main goal should be reduce the thickness of the base layer, and as a consequence the amount of material required, in pavement with CRM, so as to reduce the contribution at year 50 and improve the overall economic performance.

Sensitivity Analysis 1: varying energy costs

This first sensitivity analysis showed how variations in the cost of energy (diesel, electricity, etc.) can affect the total life cycle of the pavement. The selected costs are the one registered for the second half of 2023 (Table 5 15) and compared to the initial ones, referred to 2020 (Table 5 9).

In RSM, the increase is nearly the same for HMA and CRM (13% and 12%, respectively) (*Figure 5-36*), as observed in the cradle-to-laid analysis. However, it differs when compared to the production of one ton (13% vs. 9%). This discrepancy can be attributed to the larger quantity of mixture needed for CRM pavement compared to conventional pavement, resulting in a higher total cost.

Figure 5-36 – Variation of total costs at changing energy costs for cradle-to-grave analysis

In GER, the variation in energy costs from 2020 to 2023 results in a 9% increase for pavement with HMA and a 6% increase for pavement with CRM (*Figure 5-37*). The most significant contribution is provided B phase, which account for all required interventions necessary in the life cycle. The layers in pavement with HMA are thicker than the ones in

CRM, with consequent higher costs for material production and installation. It follows that pavement with CRM looks less influenced by variations in energy costs.

Figure 5-37 – Variation of total costs at changing energy costs for cradle-to-grave analysis in GER

The analysis shows that, particularly in GER, using CRM can be a better solution to reduce economic impacts, considering that the price of energy could increase due to geopolitical balances or shortages.

Sensitivity Analysis 2: varying discount rate

A sensitivity analysis was conducted assuming that the discount rate is equal to 4.5%, that is the value for both countries since September 2023, according to European Central Bank (European Central Bank, 2024a, 2024b).

In this case, the results are the following one:

- In RSM, the NPV assuming a discount rate equal to 4.5% is € 19.177,10 for conventional pavement, while it is € 15,454.58 for pavement with CRM. It means that the actual value is 19.41% lower than the undiscounted rate, with an Equivalent Uniform Annual Cost (EUAC) equal to € 1,430.62 for HMA_RSM and € 1,152.92 for CRM_RSM.
- In GER, the NPV assuming a discount rate equal to 4.5% is € 122,886.63 for conventional pavement, while it is € 117,715.36 for pavement with CRM. It means that the actual value is 10 % lower than the undiscounted rate, with an EUAC equal to € 6,185.17 for HMA_RSM and € 5,924.89 for CRM_RSM.

Table 5-39 – Life Cycle Costing results for RSM and GER (discount rate= 4.5%)

Description	HMA_RSM (€)	CRM_RSM (€)	HMA_GER (€)	CRM_GER (€)
Undiscounted Sum	€ 21,468.80	€ 17,596.80	€ 174,174.66	€ 162,361.69
NPV	€ 19,177.10	€ 15,454.58	€ 122,886.63	€ 117,715.36
EUAC	€ 1,430.62	€ 1,152.92	€ 6,185.17	€ 5,924.89

5.6.5.3 Social indicator

The tyre-pavement noise is assessed with the basic approach. In both case studies the material used for the wearing course is the same, independently on the use of CRM for the other lower course. In RMS, an AC is used, while in GER an SMA. Considered the rating levels, RMS is level C, while GER is level A.

6.6.6 STEP 6 – Multi-Criteria Decision Making

As being optional, no MCDCM was calculated for this exercise. Hence decision making could be done considering values of each indicator separately and with equal weights.

6.6.7 STEP 7 - Reporting, communication and verification

The study compared the construction and maintenance of different pavement designs, whose mixtures were produced with hot technology and/or with cold technology, in two different countries (RSM and GER).

The assessment, in terms of environmental assessment, consists in the evaluation of all the processes and materials required for the construction at year 0 and for all the maintenance activities (i.e. milling and overlaying of the wearing course).

The GER case study considers a wider temporal range (50 y) and the physical boundaries include the wearing, binder and base courses, while the RSM case study is based on a 20 years scenarios and considers only wearing and binder course. It follows that, looking at the impact, in GER case study they look much higher.

As reported in the other exercises, in GER the use of CRM always leads to environmental benefits, for all the selected indicators. These benefits, on average, are lower than the ones linked to the production of the mixtures: in the considered scenario, the CRM is used only for the base, while all the other layers (hence, all the other interventions) are made with HMA. Consequently, the benefits are reduced by the other interventions.

In RSM, the benefits are linked to all the indicators, excluded the ones already mentioned in the contractors' assessment. The reasons are always the same.

The hotspot analysis showed that the highest contribution is always linked to the maintenance activities (B4), because a wide set of operations is required: the milling, the transport to asphalt plant and the production and laying of new components. This implies that, for effectively reduce impacts, it is important to work on the durability of pavement components, as to reduce the interventions.

Considering the economic indicator, building and managing a pavement in CRM costs less than one in HMA, in both case studies. This is particularly true in GER, where the economic benefits are more noticeable, due in general to the less amount of total material required. This was also trusted by the sensitivity analysis which involved the energy cost variation.

5.7 Conclusions

This chapter demonstrates the implementation of the proposed methodology in two distinct case studies involving the identified stakeholders. The process proves effective in conducting Sustainability Assessment (SA) and applying the results for Life Cycle Management (LCM).

Key findings include:

- The guidelines streamline the implementation of a harmonized Sustainability Assessment (SA), providing a step-by-step guide for analysts. The methodology guarantees consistency in the results obtained from the analysis of different stakeholders.
- Consistent results can help in comparison of practices within the same country or at international level. This can facilitate the enhancement of sustainability.
- The application in the three exercises proved that this distinction is helpful for the analyst and the stakeholders involved.
- The results of the assessment, after interpretation, can be used for recommendations to the stakeholders involved to enhance their sustainability practices. The decision-making can be carried out also without MCDM, giving the same weight to all the indicators. Nevertheless, it is important to advocating for collaborative decision-making through workshops and discussions among stakeholders.
- The specific case study emphasized the importance of considering the entire life cycle (beyond A1-A3) to avoid distorted results and being aware of the impacts until the end-of-life.

To enhance the presented case studies and methodology, further exploration of B1 (use) implications, selecting calculation models, is recommended. Additionally, the application of Multi-Criteria Decision Making (MCDM) is already suggested, but it is not applied. In the future, the results can be analyzed with MCDCM, which can provide valuable insights.

The upcoming chapter will delve into the potential integration of S-LCA, with the explanation of the first steps moved towards the definition of a framework for S-LCA of road pavement materials. Moreover, the chapter will investigate the use of Building Information Modeling (BIM) as a data repository.

Chapter 6 FURTHER DEVELOPMENTS : exploring the potential of S-LCA and BIM for improving the proposed SA framework for road pavement

This chapter examines two main topics for improving the methodology. In fact, the proposed framework includes only one social indicator, related to pavement activities, that is not calculated by a S-LCA methodology. In addition, it was found that data collection is the most time-consuming step and that the quality and reliability of a study is strictly dependent on data. For these reasons, the following two sections focus on two main issues. On the one hand, the introduction of S-LCA in road pavements, with the definition of a specific methodology (not completed yet) for pavement materials and applying it to Germany and Italy (assumed as Republic of San Marino for geographical proximity). On the other hand, the possibility of using Building Information Modelling (BIM) as a data repository for a life-cycle based SA.

6.1 Towards the definition of social indicators using S-LCA

As mentioned in the second chapter, an integrated approaches such as LCSA is founded upon assessing a predetermined set of indicators that represent potential on the environment, economy and society, following a specific procedure (Finkbeiner et al., 2010; Kloepffer, 2008, UNEP, 2011). The social dimension, as emerged by the literature review, is often disregarded. Implementing a Social Life Cycle Assessment (S-LCA) can lead to a holistic assessment, which includes the social impacts of a product throughout its entire life cycle (UNEP, 2020).

The framework proposed an indicator covering the social dimension: the tyre-pavement noise. Assessing only this aspect does not give a complete outlook on social sustainability: other indicators need to be implemented with a S-LCA approach. The first steps have been already moved towards this direction. The research started focusing on pavement materials and already led to some results.

6.1.1 Methodology

The study identified two distinct systems: paving materials and paving activities. To establish a framework of indicators for conducting an S-LCA, initial efforts were focused on the former. The ensuing paragraphs present the first steps taken to identify a collection of metrics evaluating the social impact of paving materials. The literature review showed that no study had focused exclusively on the social impacts of road pavements and social impacts have never been systematically assessed in a life cycle perspective.

Moreover, S-LCA is very complex and requires a large amount of data, which hinders its application (Backes et al., 2023). To enhance its practicality, it's crucial to pinpoint the key social issues that should be the focus of evaluation and data collection efforts. Consequently, this study employs the social hotspot assessment method. A social hotspot is a location or activity in the life cycle of a product where a social issue or risk is likely to take place (UNEP, 2020). With the social hotspot assessment, it is possible to identify the most relevant social issues or risks connected to a specific economic sector (new earth b, 2022; Green Delta, 2022; UNEP, 2020). This assessment is carried out using dedicated databases such as Social Hotspot Database (SHDB) or PSILCA (new earth b, 2022; Green Delta, 2022). At the basis of these two databases, there is an S-LCA approach, in which the social hotspots are identified for different stakeholders using a wide set of sub-categories and indicators. Nevertheless, the definition of sub-categories and indicators, as well as the sources utilized for conducting the hotspot assessment, can vary significantly across databases. This variation can occasionally result in conflicting outcomes.

In this research, the social hotspot assessment was carried out for two asphalt mixtures to be produced in Italy and Germany. The evaluation was made employing the SHDB risk mapping tool and the PSILCA database.

The social hotspot assessment is modelled based on the economic sectors related to the processes of the particular product or activity being assessed, which is cradle-to-gate in this study. Both the mixtures are HMA, hence the processes associated are the extraction and production of raw materials (bitumen, aggregates – coarse (gravel) and fine (sand, filler)), the transport, and the asphalt mixing.

The economic sectors employed in modelling the asphalt mixture within the SHDB and PSILCA databases exhibit differences in the level of aggregation compared to the mentioned processes. Additionally, these sectors differ between the two databases. SHDB relies on the GTAP database for defining economic sectors (Aguiar et al., 2016), whereas PSILCA utilizes the Eora database for the same purpose (Lenzen et al., 2012).

Therefore, all the processes for mixture production must be matched to the economic sectors available in the assessment tools, as reported in Table 6-1.

Table 6-1 Processes and economic sectors associated with the production of an asphalt mixture

Process	Designation	Economic sector SHDB	Economic sector PSILCA
Production of bitumen	Bitumen	Petroleum, coal production	Coal, coke and petroleum products, nuclear fuels (GER) Coke, refined petroleum products and nuclear fuel (IT)
Extraction and processing of coarse aggregates	Gravel	Mineral products	Quarrying of stone and soil (GER) Manufacture of other non-metallic mineral products (IT)
Extraction and processing of fine aggregates	Sand	Mineral products	Manufacture of Non-metallic mineral products (GER) Other mining and quarrying products (IT)
Transport of raw materials to asphalt mixing plant	Transport	Transport nec	Road and pipeline transport (GER) Land transport, transport via pipelines (IT)
Asphalt mixing process	Electricity	Electricity, Gas	Electricity and district heat (GER) Electrical energy, gas, steam, and hot water (IT)

The different levels of aggregation (processes vs economic sectors) obliged to employ various proxies in the models. For instance, neither SHDB nor PSILCA have specific economic sectors for the extraction and processing of aggregates. Therefore, the sectors "manufacture of other non-metallic mineral products" and "other mining and quarrying products" in PSILCA, and "mineral products" in SHDB were used as proxies. The bitumen production was depicted with "Petroleum, coal production" in SHDB and to "Coke, refined petroleum products and nuclear fuel" in PSILCA.

Concerning the transport of the raw materials to the asphalt mixing plant, it was associated with the sector "Transport nec" in SHDB since no specific sector for road transport was found, while in PSILCA a more specific one was found. Moreover, the asphalt mixing process was associated with the processes "Electrical energy, gas, steam, and hot water" in PSILCA and "Electricity" in SHDB.

Once the economic sectors were selected, the social hotspots were determined. These tools assign different judgements to the social hotspots: no evidence, (very) low risk, medium risk, (very) high risk, and no data. In this work, only those risks defined as "high" and "very high" were considered relevant and the associated indicators were then to be calculated.

The hotspot analyses showed some contradictory results, as imaginable. The data sources and definitions of common indicators used for the hotspot assessment are not necessarily the same in the two tools, leading to inconsistent results. To deal with those incongruities, a deep analysis of the background information leading to the results in both tools was performed. In particular, for those indicators with contradictory results, their definition and the data used for the assessment were investigated to decide which tool used more reliable information and was going to be used as a reference for the particular social issue. Indicators defined quantitatively and calculated with the most recent data were preferred for the social hotspot assessment.

Based on this procedure, the social issues for the stakeholder categories local community, value chain actors, and workers were identified. Finally, the indicator framework was complemented with suitable indicators found in the literature review.

6.1.2 Social Hotspot Assessment Results

Based on the procedure described in Chapter 4, the social hotspot analysis of an asphalt mixture in the context of Germany and Italy was conducted using both SHDB and PSILCA. Table 6-2 and Table 6-3 show the results obtained in both databases for the economic sectors for those cases in which a "very high risk" or "high risk" outcome was obtained in at least one of the consulted databases.

Following the hotspot analysis and the identification of the most relevant topics/indicators in the two databases, the outcomes were compared following the methodology described above.

Table 6-2 Selection of social issues based on the results of the social hotspot analysis with SHDB and PSILCA for Germany

No.	B	G	S	E	T	Stakeholder	Category	Indicator	Source
1	X		X		X	Local community	Access to material resources	# of CEMS (Certified Environmental Management Systems) (ISO 14001) per 10,000 employees in the time frame (5 years)	PSILCA
2	X	X	X	X	X	Local community	Access to material resources	Biomass consumption measured	PSILCA
3	X	X	X	X	X	Local community	Access to material resources	Industrial water depletion	PSILCA
4				X	X	Local community	Access to material resources	Embodied biodiversity footprints	PSILCA
5				X	X	Local community	Access to material resources	Embodied CO2 footprint / Global Warming Potential	PSILCA
6		X	X	X	X	Workers	Migrant labour	Immigrants employed in the project	PSILCA

7		X			X	Society	Corruption	Active involvement of enterprises in corruption and bribery	PSILCA
8	X		X			Value chain actors	Fair competition	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	PSILCA
9	X		X	X	X	Value chain actors	Promoting social responsibility	Membership in an initiative that promotes social responsibility along the supply chain	PSILCA
10	X	X	X	X	X	Workers	Equal opportunities / discrimination	Gender wage gap	PSILCA
11	X	X	X	X	X	Workers	Fair salary	Living wage, per month	PSILCA
12	X	X	X	X	X	Workers	Freedom of association and collective bargaining	Trade union density	PSILCA
13	X	X	X	X	X	Workers	Health and safety	Overall risk occupational toxics and hazards	SHDB
14	X	X	X	X	X	Workers	Health and safety	Overall risk occupational toxics and hazards	SHDB
15	X	X	X	X	X	Workers	Health and safety	Occupational cancer-related risk	SHDB
16	X	X	X	X	X	Workers	Health and safety	Occupational COPD-related risk	SHDB
17	X					Workers	Health and safety	Occupational noise-related risk	SHDB
18	X	X	X	X	X	Workers	Health and safety	Occupational-related fall injuries and fatalities	SHDB

B = Bitumen, G = Gravel, S = Sand, E = Electricity, T = Transport

* only if a stand-alone S-LCA is carried out

Table 6-3 - Selection of social issues based on the results of the social hotspot analysis with SHDB and PSILCA for Italy

No.	B	G	S	E	T	Stakeholder	Category	Indicator	Source
1	X	x	X	x	X	Local community	Access to material resources	# of CEMS (Certified Environmental Management Systems) (ISO 14001) per 10,000 employees in the time frame (5 years)	PSILCA
2	X	X	X	X	X	Local community	Access to material resources	Industrial water depletion	PSILCA
3	X	X	X	X	X	Society	Contribution to economic development	Embodied value-added total	PSILCA
4	x	X	X	X	X	Workers	Migrant labour	Immigrants employed in the project	PSILCA
5	x	X	x	x	X	Society	Corruption	Active involvement of enterprises in corruption and bribery	PSILCA
6	X	x	X	x	x	Value chain actors	Fair competition	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	PSILCA
7	X	x	X	X	X	Value chain actors	Promoting social responsibility	Membership in an initiative that promotes social responsibility along the supply chain	PSILCA
8	X	X	X	X	X	Workers	Fair salary	Living wage, per month (AV)	PSILCA
9	X	X	X	X	X	Workers	Working time	Weekly hours of work per employee	PSILCA
10	X	X	X	X	X	Workers	Health and safety	Overall risk occupational toxics and hazards	SHDB
11	X	X	X	X	X	Workers	Health and safety	Overall risk occupational toxics and hazards	SHDB
12	X	X	X	X	X	Workers	Health and safety	Occupational cancer-related risk	SHDB
13	X	X	X	X	X	Workers	Health and safety	Occupational cancer-related risk	SHDB
14	X	X	X	X	X	Workers	Health and safety	Occupational COPD-related risk	SHDB
15	X					Workers	Health and safety	Occupational noise-related risk	SHDB
16	X	X	X	X	X	Workers	Health and safety	Occupational-related fall injuries and fatalities	SHDB

B = Bitumen, G = Gravel, S = Sand, E = Electricity, T = Transpor

Next, the indicators of the studies analyzed in Chapter 2 were reviewed to determine which social issues particular to roads and related to the identified social hotspots should be addressed. These issues relate to the stakeholder "Workers" and the category "health and safety" and the stakeholder "Society" and the category "corruption" and are shown in Table 6-4.

Table 6-4 Selected indicators from the literature

Social Hotspot Indicator	Indicator from literature	Source
Overall risk occupational toxics and hazards	Number of preventive measures on occupational diseases (at project level)	Hosseinjou et al. Navarro et al.
Occupational-related fall injuries and fatalities	Number of occupational accidents disaggregated in fatal and non-fatal	Hosseinjou et al. Navarro et al.
Active involvement of enterprises in corruption and bribery	Execution of anti-corruption program	Zheng et al., 2018

From these tables, it can be deduced that eighteen hotspots have been identified for the S-LCA of road pavement materials in Germany, while sixteen for the S-LCA of road pavement materials in Italy. In the future, the assessment will be carried out through the definition of reference scales related to specific indicators, defined and provided by the authors.

6.1.3 Potential technology gaps

Once the indicators are defined, the use of IT tools is indispensable to proceed with the calculation of results. However, important technological gaps emerged. These gaps are linked to different aspects of the data collection and quality and the calculation process, such as:

- Data Collection Tools: Collecting social data can be time-consuming, given the complexity and context-dependent nature of social impacts. There is a discrepancy in the establishment of standardized tools and methodologies for collecting and analyzing data related to the social dimension. Introducing questionnaires for primary data collection can be beneficial in filling this gap.

-Databases: Handling social data, from acquisition to processing, is complex. Therefore, databases offering secondary data might be an alternative to promote the application of S-LCA and serve as a screening step in preparation for the actual assessment. At the moment, only two databases providing secondary data for social assessment – SHDB and PSILCA - are available. However, these databases do not cover all economic sectors and countries, often providing very generic and aggregated data. Moreover, in several instances and depending on the geographical context being assessed, the data provided is not reliable. As a consequence, the consistency, accuracy and reliability of social data are re-compromised, requiring attention in the ongoing development of S-LCA.

- Calculation methods: Significant discrepancies persist in modelling techniques. The UNEP Guidelines report two distinct methods for impact assessment: the reference scales and the impact pathway. The former is susceptible to subjectivity and practitioner-dependent, while the latter focuses on identifying and tracking the consequences of activities possibly to longer-term implications. However, it is quite complicated to develop.

- Software for calculation: all the above-mentioned gaps are also reflected in the development of software for the calculation of an S-LCA, which should also be integrated alongside a comprehensive sustainability assessment. The development of user-friendly software capable of integrating the three dimensions would be of great support for easier implementation of sustainability practices. This sort of software is only feasible with the development of reliable databases and consistent impact assessment methods.

6.1.4 Conclusions and further development

This research is the first step of a wider effort for the development of a S-LCA framework for the road pavement sector. The pavement materials were selected as the first system to start the investigation. The defined approach has proved valid for selecting suitable and specific hotspots to assess social performance.

The main social issues were selected based on literature review and social hotspot analysis using the two available databases for social data: PSILCA and SHDB. Sixteen social issues were identified for Italy and eighteen for Germany, embracing four stakeholders: workers, value chain actors, society and local community.

The next efforts aspire to convert these social issues into specific measurable indicators, meant to be assessed through reference scales. The methodology will be validated with a case study based on primary data collected using data collection tools. In a second moment, the approach will be extended to the pavement activities too.

6.2 BIM as a POTENTIAL repository OF RELIABLE PRIMARY data

Building Information Modeling (BIM) is a technology and process that facilitates the generation and management of the digital representations of constructive and functional attributes of a facility.

Most definitions of BIM emphasize its role in digital and intelligent visualization, facilitating decision-making (Miller & Garcia, 2021), providing quick and iterative access to shareable data sources, and fostering interoperability among working groups (Williams, 2017). By providing a digital twin, BIM enables real-time visualization and analysis of various parameters, such as material composition, energy consumption, and environmental impacts (Johnson et al., 2019).

Furthermore, it allows to manage the project throughout the full life cycle, improving its efficiency during all the phases. Hence, BIM can also facilitate the integration of sustainability performance for its capability of managing the project in different phases and containing a high quantity of data.

For all these reasons, as for the building, the integration of BIM in the life cycle sustainability assessment of road pavements can greatly contribute to the effective evaluation of their impacts and the identification of sustainable solutions.

As the demand for sustainable road pavements continues to rise, understanding the role of BIM in life cycle sustainability assessment holds paramount importance in ensuring sustainable road construction practices.

6.2.1 How can BIM support SA in road pavements?

BIM has emerged as a valuable tool, offering benefits such as early error detection, enhanced productivity, and structural simulation also in the infrastructure sector, even though some obstacles (Oreto et al., 2023). Recently, BIM tools have gained importance among infrastructure engineers for road pavement monitoring (Davila Delgado et al., 2018), structural control and design ((Tang et al., 2020), quality control checks (S. Lee et al., 2015) and easier management of projects (19). Moreover, due to the increasing importance of sustainable policies, also environmental indicators are starting to be introduced (Abbondati et al., 2020). The use of BIM for life-cycle-based sustainability of road pavements is still in progress and requires further research is needed for a full integration of BIM and LCA (Oreto et al., 2023). Among the several potentialities linked to this integration, there are the easier incorporation of sustainability assessment practices in the sector (Biancardo et al., n.d.) and the possibility of managing and storing big quantities of data. In fact, for its nature, BIM offers an integrated approach to the management of digital representations and data of physical infrastructure (Jones & Brown, 2018). It can help in efficient archival, storage, management, and analysis of vast data provided by diverse stakeholders and analytical tools in road asphalt pavement design and management (Biancardo et al., n.d.). Hence, it could be a robust data repository for Life Cycle Sustainability Assessment (LCSA) in the sector of road pavements (Smith, 2020).

Using a BIM-based LCA for data repository is helpful for two reasons. Firstly, it allows obtaining an LCI (Soust-Verdaguer et al., 2017), extracting the exact amount of material from the model to then assess the sustainability performance. Designers and stakeholders can access and analyze data related to the complete life cycle of a building, from its initial design stages to its construction, operation, and eventual demolition or renovation.

This includes information on materials, energy consumption, and waste generation (Soust-Verdaguer et al., 2022). Secondly, it is possible to incorporate the SA results into BIM. By doing so, the information is always available, enabling to make informed decisions and identify opportunities for improving sustainability (Soust-Verdaguer et al., 2022)

The integration and automation of LCA with BIM are rising **(Safari & AzariJafari, 2021)**. The phenomenon is more detachable for the building sector, but also the other civil engineering works are quite affected. The integration process of BIM-LCA can follow one of three main approaches: conventional, dynamic and static **(Safari & AzariJafari, 2021)**. They differ in terms of data collection procedure and exchange, and type of calculation. In a conventional approach, the information from BIM is transferred into an Excel spreadsheet, used to fill the information into the LCA tool. ((Feng et al., 2020)). In the static approach, BIM data are extracted into the IFC format (specifically for data exchange in the construction sector) or using Application Programming Interfaces or other software for database integration and inserted into the LCA software. In the dynamic approach, the connection between the wo systems is automatic, using parametric capabilities and visual programming (Lobaccaro et al., 2018; R. Santos et al., 2019, 2020). Oreto et al. (2023) demonstrated that, if a dynamic model is used, the integration can automate the LCA calculation process and minimize the need for manual input data. This reduces the complexity and time required to perform LCA, making it more feasible to incorporate environmental considerations into the early stages of pavement design.

6.2.2 Limitations and Future Development

Despite the promising opportunities presented by BIM, several limitations and challenges must be addressed to fully unlock its potential in SA for road pavements.

A key challenge involves establishing standardized data formats and protocols to facilitate interoperability across diverse BIM platforms and software applications **(Safari & AzariJafari, 2021)**.

The interoperability between BIM and other data extensions (i.e. another information model) (Miettinen & Paavola, 2014) is one of the main issues in this field. As a consequence, the collaborative potential among stakeholders offered by BIM is limited (Jones, 2019). Overcoming this challenge necessitates industry-wide efforts to establish common ground and promote interoperability.

Another critical consideration is the accuracy and reliability of data input into BIM models, as these factors significantly influence the outcomes of SA (Miller, 2018). The accuracy of the data directly impacts the reliability of sustainability predictions, underscoring the need for rigorous standards and quality control mechanisms throughout the life cycle phases. It is important that all the stakeholders involved provide reliable data to enrich the model and that some data can directly be taken during construction works, such as equipment's fuel consumption or emissions into the atmosphere, or integrated in real-time, such as traffic patterns or climate variations. Of course, this requires sophisticated algorithms and computing resources (Brown, 2021). The use of sensors for monitoring road pavement conditions, as well as big data, should be integrated into the digital twin. All this information can enhance the accuracy and reliability of sustainability assessments. This involves not only advancing computational capabilities but also ensuring that the models adequately represent the dynamic and interconnected nature of road infrastructure.

6.2.3 Conclusions

The integration of Building Information Modeling (BIM) and Sustainability Assessment (SA) in road infrastructure leads to numerous advantages. Promoting collaboration among stakeholders, fostering transparency and integration in sustainability considerations, enabling the integration of real-time information, and handling and storing big amounts of data, BIM and Digitalization in general can be used as a repository for data throughout the life cycle of road pavements, allowing for a comprehensive understanding of sustainability parameters.

Moreover, depending on the integration model used, the SA calculations can be automated, reducing the need for manual input data and making it more feasible the incorporate environmental considerations.

In the context of integrating BIM and SA, a significant challenge due to the absence of standardized data formats and protocols needs to be faced to enhance interoperability across various BIM platforms and software applications. It is important to use reliable data, provided by all the stakeholders involved and directly obtained from a construction site or in real-time. This requires, besides the above-mentioned standardized data formats, advancements in algorithms and computer sciences. Consequently, managing the BIM model becomes a task fraught with complexity, given the intricate nature of road infrastructure dynamics.

To face all these challenges, further steps towards the use of BIM as data repository for SA practices are:

- standardize procedures and formats for data collection, to facilitate the cooperation of all the stakeholders involved (the materials producers, the contractors and the road authorities);

- Promote advancements in computational efficiency to integrate data from sensors and vehicles, as well as data directly during constructions (i.e. emissions, equipment used).

6.3 CONCLUSIONS

This chapter focused on two main topics exploring further development of the road pavements SA framework: S-LCA and BIM. On one hand, this research marks the initial phase of a broader initiative aiming to establish a Social Life Cycle Assessment (S-LCA) framework for the road pavement sector, with a focus on pavement materials.

The approach consisted in identifying the main social issues in two selected countries (Germany and Italy) using literature and two available databases (PSILCA and SHDB). Eighteen hotspots for Germany and sixteen for Italy were identified.

They are related to workers, value chain actors, society, and the local community. The next steps involve converting these issues into indicators, measurable with reference scales, validated through case studies and extended to pavement activities.

On the other hand, the integration of BIM and SA in road infrastructure offers numerous advantages, including collaboration promotion, transparency, and managing and storing a big amount of data. Hence, BIM holds great promise for being used as a data repository. This integration should make the studies more robust and the assessment faster. However, challenges such as standardized data formats, interoperability and collaboration among different stakeholders need to be addressed. In the future, the implementation of BIM as data repository can be improved by:

- Standardizing procedures for data collection, so as to facilitate the collaboration among stakeholders;
- Pushing towards the digitalization of construction works to acquire primary data directly during construction and a spreader installation of sensors to receive data from pavements and cars.

Chapter 7 CONCLUSIONS AND FUTURE WORK

This work focused on filling existing gaps towards a harmonized Sustainability Assessment (SA) of road pavements and proposes Guidelines for implementing Life Cycle Management (LCM) within the sector in Europe.

The research wants to comply with existing European standards for SA in the civil engineering works sector, covering the three pillars of sustainability through the identification of indicators related to environmental, economic, and social aspects, together with the technical and functional requirements. The calculation of environmental and social impacts is carried out using life cycle-based impact assessment techniques, hence Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), already used for assessing road pavements' performance with several inconsistencies among the studies.

By evaluating the life cycle performance of road pavements, the aim is to pave the way for more informed decision making, promoting infrastructure development that not only meets immediate needs but also contributes positively to sustainable development.

The research wanted to achieve the following aims:

1. harmonizing Life Cycle-based impact evaluation techniques into the road pavements sector by tailoring the existing European standards for SA of civil engineering works
2. engineering the implementation of SA's results as aid for decision making into the road industry, leading to a proposal of guidelines to implement LCM of road pavement,
3. exploring further developments of the proposed SA framework by investigating the possibility of improving the evaluation of the life social impacts into the SA framework and exploring possibilities for improving the quality and reliability of data.

The main outcomes for each aim are summarized here below.

AIM 1 – Harmonization of SA practices

The research started with a thorough review of the state of the art of sustainability policies and sustainability in road pavements and ended with the definition of a SA framework.

- The review of the state of the art of sustainability policies showed the importance of introducing sustainability in the light of international and European policies (i.e. SDGs, Green Deal) and the potential of using a life cycle thinking (LCT). LCT allows accounting for the impact of products and process within the entire life cycle of an asset and recognizing how our choices influence what happens at each of every step, to balance impacts in the economy, environment, and society. To do so, the life cycle-based impact evaluation techniques, with different levels of development, can cover the three pillars of sustainability, namely Life Cycle Assessment (LCA) for the environment, Life Cycle Costing (LCC) for costs and Social Life Cycle Assessment (S-LCA) for society.
- The review of current practices in the SA of road pavement sector showed that no specific framework or standard for road pavements exist at European level. Current EN Standards for civil engineering works are not sector specific. The lack of specific guidance leads to difficulties and inconsistencies between different studies. The most common inconsistencies are the choice of system boundaries, declared/functional units and indicators. Furthermore, often only one dimension is considered at a time and the results obtained are not used and implemented. It follows that harmonizing procedures is fundamental.
- The path towards the harmonization entailed the stakeholders involved in road construction and operation, including material manufacturers, contractors, and road authorities, to catch their opinions and needs for an easier implementation of SA in their practice.

The output of this phase, including the state of the art and the workshops/interviews with stakeholders, was the definition of a Framework for the SA. This framework, which does not replace current standards, provides recommendations for harmonised practices in Europe and complements existing standards (i.e. EN15978). It defines:

- Scope of the assessment: introduces the concept of a road pavement model to identify the object of analysis and suggest exercises for the main stakeholders: material manufactures, road contractors and road authorities.
- Objects of assessment and functional equivalent: provides two systems (pavement materials and activities), associating the operators involved, the system boundaries and the declared/functional unit.
- SA indicators: literature reviews and interactions with NRAs allowed identifying a limited set of practical indicators covering environmental, economic, social and technical/functional aspects, in compliance with the EN 15643-5.

AIM 2 – Towards LCM of road pavements in Europe

To achieve the second goal, hence engineering the implementation of SA's results as aid for decision making into the road industry, the author proposed a step-by-step procedure (called Guidelines) to implement LCM of road pavement. The procedure was then applied to two case studies, both comparing the use of conventional and cold recycled mixtures in different countries: Republic of San Marino (RSM) and Germany (GER). In both cases, pavement materials and pavement activities were assessed: firstly, the production of one tonne of mixture (cradle-to-gate, manufacturers level), secondly the construction of the pavement (cradle-to-laid, contractors level) and thirdly the construction and management of the asset, considered an analysis period of 20 years (RSM) and 50 years (GER) (cradle-to-grave, RAs level).

- The Guidelines are based on seven steps, tailored following the EN standard. They aim at guiding the analyst during the implementation of a SA and using these results for managing the asset. The procedure suggests to use the Multi-Criteria Decision Making to manage the results and select the best option.
- The procedure was found to be valid and useful to facilitate the implementation, calculating the SA results and provide recommendations to the stakeholders.
- The guidelines facilitate the implementation of a harmonized approach for the SA through the proposed framework.
- The guidelines are user-friendly, aiding analysts in the stepwise application for organizations and specific content within the framework.
- The guidelines contribute to the incorporation of Life Cycle Management (LCM) in European practices, utilizing SA results for asset management and promoting life cycle thinking among stakeholders.
- The guidelines foster interaction among different partners and stakeholders, primarily benefiting Ras but also aiding in information exchange and requests.
- Harmonizing procedures ensures consistency at the industrial level, ensuring that industries follow the same approach for assessing their products. This enables the definition of benchmarks and targets, promoting improved sustainability performance at the national and European levels.
- The consistent use of harmonised SA framework facilitates the identification of industry’s benchmarks and targets that can inform policy development at both national and European levels.
- Extending harmonization to other sectors of civil engineering works (e.g., aqueducts) and diverse products/processes in different fields ensures a consistent assessment across sectors.

AIM 3 – Further development to improve the SA Framework

Concerning the third goal, the investigation for improving the SA framework touched two main aspects: S-LCA for introducing life-cycle based social impacts and Building Information Modelling (BIM) as a data repository.

- Regarding the S-LCA, the first steps were moved towards the definition of a specific methodology for pavement materials. The main social issues were selected based on literature review and social hotspot analysis using the two available databases for social data: PSILCA and SHDB. Sixteen social issues were identified for Italy and eighteen for Germany, embracing four stakeholders: workers, value chain actors, society and local community. The next efforts aspire to convert these social issues into specific measurable indicators, meant to be assessed through reference scales, and extend the approach also to pavement activities.
- Regarding the BIM, it was found that it can support the road pavement sector for designing, interconnecting operators and handling and storing large amounts of data. Consequently, BIM can be used as a repository for data throughout the life cycle of road pavements and can help in automating sustainability calculations. Nevertheless, some efforts are required for facilitating its use and implementation, such as standardizing procedures for data collection and a higher level of digitalization in construction works to acquire primary data directly during construction and a spreader installation of sensors to receive data from pavements and cars.

The results of this work could potentially help policy development at national and European levels. By fostering collaboration among stakeholders and encouraging a harmonised assessment, this work contributes to advancing the implementation of sustainable practices in the road pavement industry. The research also lays the groundwork for a more sustainable future in civil engineering works.

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