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CERCOM
Circular Economy in Road COnstruction and Maintenance

Case studies I & II - Protocol and results

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List of Abbreviations

ABB	Asphalt Concrete Binding Base Layer
ADR	Advanced Dry Recovery
AHP	Analytic Hierarchy Process
BSM	Bituminous Stabilized Materials
C2CA	Concrete to Cement and Aggregates
CE	Circular Economy
CEI	Circular Economy Index
CERCOM	Circular Economy in Road COnstruction and Maintenance
C&DW	Construction and Demolition Waste
DC	Cost of Additional Delays
DE	Country Code for Germany
DK	Denmark
ELCA	Environmental Lifecycle Assessment
EOL	End-of-Life
EPD	Environmental Product Declaration
EU-28	European Union – 28 Member Countries
FHWA	Federal Highway Administration
G_e	Geography
GLO	Global
HAS	Heating Air Classification System
IRI	International Roughness Index
KPI	Key Performance Indicator
LCA	Lifecycle Assessment
LCCA	Lifecycle Cost Assessment
LFI	Linear Flow Index
MCI	Material Circularity Indicator
NL	Netherlands
NPV	Net Present Value
NRA	National Road Administrations
NRRG	Net Risk Reduction Gain
PEB	Program Executive Board
PSV	Polished Stone Value
RBAF	Risk Based Analysis Framework
RCA	Recycled Concrete Aggregates
RE	Resource Efficiency
RER	Geographical Resolution Code for Europe
RRI	Risk Reduction Index
SI	Skid Resistance Index
SLCA	Social Lifecycle Assessment
SMA	Stone Matrix Asphalt
SR	Skid Resistance
SWP	Stationary Wet Processing

T_e	Technological
T_i	Time
VOC	Vehicle Operating Cost
WP3	Work Package 3
WP4	Work Package 4
ZOAB	Porous Asphalt Concrete Pavement

Glossary

Agency costs	The agency costs refer to the expenditures incurred by the road agency during a pavement construction / maintenance / rehabilitation activity
Analysis periods	It refers to the period of time considered for a lifecycle assessment study.
Average daily traffic	It is defined as the ratio of total traffic volume during a given analysis period and the number of days in that analysis period. It is expressed in vehicles per day (vpd)
Characterization	As per the FHWA's pavement lifecycle assessment framework, characterization is the identification and quantification of the relationships between the lifecycle inventory results and the impacts under consideration
Circular economy index	It is defined as the ratio of material value added to the material value for reproducing end-of-life product
Circularity	In the context of CEI, circularity is the percent value of stressed resources added to an asset or a product that is returned after its end-of-life
Delay costs	The delay costs are the additional costs incurred by the road users either due to an increase in the travel distance or lower traffic speeds caused by an ongoing pavement maintenance / construction activity
Depreciation expense	It refers to the cost of an asset that has been depreciated over time, and is indicative of the asset's value that has been lost
Design life	It is defined as the time period for which the pavement serves its function satisfactorily without the need for major maintenance or rehabilitation
Detour length	It refers to the additional distance travelled by a through-bound vehicle due to the closure of a pavement lane
Discount rate	It is the interest rate that is used to discount all future cash flows of a maintenance activity to derive the asset's net present value
Functional unit	It refers to the product or system whose impacts are calculated over a given analysis period using lifecycle assessment approach such that it meets the desired specifications
Hotspots	Hotspots are defined as activities in the product supply chain that highlight potential risk of violation and social concerns that need to be considered in a specific country and sector
Impact indicator	These are the metrics that are used to assess the effectiveness of a strategy by measuring them along a suitable scale
Key performance indicator	Key performance indicators are metrics that are used to compare the performance of a maintenance strategy over time across a set of assessment categories
Lifecycle cost assessment	It is defined as the process that is used to quantify and compare the economic value of different materials, systems, and designs over their service life
Linear flow index	It refers to the quantity of material sourced from virgin feedstock and ending up as unrecoverable waste
Material circularity indicator	It is a tool or metric that is used to assess the flow of materials (restorative or linear) at product / company levels
Net present value	It is the difference between the present value of cash inflows and outflows over a defined time period

Rejuvenation	It is defined as a pavement preservation technique where a compound is sprayed over an existing road surface to restore the physical and chemical characteristics of oxidized asphalt binders
Relative percentage	It is metric that is used in social lifecycle assessment studies to quantify the scores for direct social impact indicators. Mathematically, it is the ratio between site specific social lifecycle inventory data and statistical data obtained from National databases
Resource efficiency	It is the ratio of incorporated product value to the value of stressed resources
Road user costs	Road user costs are defined as the incremental daily costs borne by the road users due to pavement maintenance or construction activities
Salvage value	It refers to the remaining value of the pavement alternative at the end of an analysis period
Scrap value	It is defined as the difference between the residual cost of materials in the year under consideration and the depreciation expense. It is also referred to as the residual value of the pavement
Serviceable value	It represents the differences in remaining service life between various pavement alternatives at the end of analysis period
Social impacts of pavements	Social impacts are defined as the consequences of an activity on the different groups of stakeholders and society along the lifecycle of an asset
System boundary	The system boundary is defined in ISO 14044 as the “set of criteria specifying which unit processes are part of a product system"
Vehicle operating costs	They are the costs associated with operating and maintaining a vehicle including fuel consumption, tire wear, maintenance, depreciation, etc.
Weighting	As per the FHWA's pavement lifecycle assessment framework, weighting is the process of converting indicator results of different impact categories by using numerical factors typically based on expert judgment

Executive Summary

This report forms deliverables D4.1 & D4.2 of the Circular Economy in Road COnstruction and Maintenance (CERCOM) project, funded under the CEDR 2020 Transnational Research Programme on Resource Efficiency and Circular Economy. The CERCOM project aims to deliver tools and supporting resources to assist National Road Administrations (NRAs) to adopt a more resource efficient (RE) approach to highway maintenance. This is consistent with the principles of a circular economy (CE) where greater emphasis is placed on reusing, repairing, repurposing and recycling materials, preserving their value through multiple lifecycles. This change forms the basis of the European Commission's plan for addressing climate change challenges and building a "greener, more digital and more resilient Europe".

The major objective of this report is to demonstrate the validity of the Risk-Based Analysis Framework (RBAF) developed as part of the CERCOM project (in Deliverables D3.1 and D3.2) through technical case studies covering a range of pavement maintenance options. The steps associated with the quantification of risks in adopting a particular maintenance strategy such as life extension (R4), refurbishing (R5 or R6), and use of recycled materials (R8) were detailed. In addition, the different assessment categories that must be utilized to understand the circularity and sustainability potential of various strategies were elucidated along with the development of specific technical, environmental, economic, circularity, and social Key Performance Indicators (KPIs) relevant to the case studies examined as part of deliverables D4.1 & D4.2.

To accomplish the proposed objective, the case studies were selected to include a selection of pavement maintenance options and recycling technologies to identify the data requirements for quantifying KPIs, assessing the progress of different NRAs in achieving circularity, and build stakeholder confidence in the proposed set of tools and methods. The pavement maintenance options comprise in-situ rejuvenation as a preventive pavement preservation technology (The Netherlands) and use of bituminous stabilized materials (BSM) pavement base layers (Denmark). In addition, a case study on concrete processing technologies was also undertaken to examine the suitability of using recycled concrete aggregates in pavement systems. A key contribution was the development and use of a simple yet robust circularity and resource efficiency assessment methodology, which was well-aligned with the European circularity policies and considered both quality and quantity of materials, unlike mass-based indicators that ignore the market value of resources.

Once the system boundaries, analysis period (involving multiple lifecycle phases), and comparative scenarios were developed, lifecycle inventories were prepared and discussions were organized with relevant stakeholder to collect the data for each KPI. The procedure associated with quantification of KPIs are detailed in this document. Secondary data from published literature, online platforms, and technical documents was also collected in case primary data was unavailable. The tool also provides the capability to incorporate expert judgement via the 'pre-set scales' option, which can be used in the absence of reliable dataset or where the level of accuracy required does not warrant the extent of time required to gather detailed information. While resorting to the pre-set scales option, the user must take into account the accuracy of the data when interpreting the results. Further, the risks associated with each scenario were quantified in terms of probability of a failure event and associated cost of consequences. Lastly, the inputs were fed into the RBAF tool and weightings were provided to different assessment categories to compute the Net Risk Reduction Gain (*NRRG*) to identify the optimum solution. *NRRG* is an index that is used to optimize the different assessment categories and obtain a single score (detailed in Deliverable D3.1). Furthermore, it is advised to gather weights based on expert opinion and judgement of decision-makers and experts. However, objective-based weighting methods may also be used in the absence of such information.

Based on the results of RBAF, the in-situ rejuvenation maintenance (being followed in the Netherlands) was found better than the traditional resurfacing option. The *NRRG* for the rejuvenation was 60% higher than resurfacing. Further, in-situ rejuvenation maintenance was found to be almost twice as circular as resurfacing with virgin materials, while satisfying the technical performance requirements in terms of skid resistance and ravelling. For the Danish case study, Bituminous Stabilized Materials (BSM) maintenance option was better than conventional patch repair and resurfacing. The *NRRG* for BSM was 2.5 times higher than patch repair and resurfacing, and the technical performance of the two maintenance schemes was similar. Further, the lifecycle costs were 2 times higher for patch repair and resurfacing, and the corresponding material circularity indicator was 0, which indicates completely linear flow of materials. Hence, it may be suggested that NRAs must transition towards the maintenance options that allow utilization of high recycled materials in pavements and extend the service life of in-place assets. An adoption of such maintenance and construction options will reduce the raw material consumption, keep the materials in the existing loop for prolonged duration, and reduce the overall lifecycle impacts associated with pavement infrastructure.

The results of case study on concrete processing technologies (in the Netherlands) indicated that Concrete to Cement and Aggregates (C2CA) technology contributed to reduced environmental burdens, higher social benefits, better circularity, and greater material value addition than stationary wet processing (SWP). Further, the *NRRG* indicated that the technical performance risk associated with the use of aggregates from C2CA in pavements were lower than SWP.

The RBAF outlined in this document is flexible as it can be tailored to suit the requirements of NRAs with different circularity maturity levels. However, it must be noted that the tool requires vast amount of reliable datasets to quantify the KPIs for different assessment categories. Hence, there is an urgent need to collate spatially and temporally harmonized data, and develop prediction models between pavement performance characteristics and material properties. The use of RBAF will allow NRAs to investigate the impact of certain criteria on the optimisation of maintenance management and to evaluate risks associated with various options and prioritize based on case specific requirements. This will facilitate prioritising the development and integration of specific technical performance and circularity metrics in the existing standards and procurement practices. This will eventually lay the foundation for procurement of circular solutions and use of alternative materials and methods in roadway construction and maintenance.

1 Introduction

The Circular Economy in Road COnstruction and Maintenance (CERCOM) project has developed an innovative risk-based framework and management tool to facilitate a step change in the adoption of Resource Efficiency (RE) and Circular Economy (CE) principles in procurement and multi-life cycle management by National Road Administrations (NRAs) across Europe. This report comprises Deliverables 4.1 and 4.2 of the project, which describes three case studies that:

- Validate and demonstrate the risk-based methodology developed in Work Package (WP) 3,
- Evaluate various pavement maintenance technologies in terms of technical performance, circularity, cost, and social as well as environmental impacts, and
- Explore the interactions between specification standards and procurement methods and opportunities to enhance their compatibility through consultations with relevant stakeholders (technical and procurement professionals).

In general, this report demonstrates the implementation of Risk-Based Analysis Framework (RBAF) to investigate schemes that cover a range of technical areas carried out by NRAs at different circularity maturity levels. One of the key strengths of this work is the use of simple value-based key performance indicators (KPIs) to assess the circularity levels of different maintenance options and material processing technologies.

2 Scope

This report is an output of WP4 that encompasses the work performed as part of CERCOM tasks 4.1 and 4.2. The KPIs for the different assessment categories, namely, technical, economic, environmental, social, and circularity were identified. Further, the system boundaries were defined and inventories were formulated to collect the data with respect to the proposed case study per assessment category. Importantly, the data for technical KPIs was compared with threshold performance characteristics to determine whether the proposed solution complied with standard specifications.

Section 3 presents the approach behind the selection of case studies involving typical asphalt pavement maintenance options and concrete processing technologies that selected NRAs adopt in Europe. Further, the methodology adopted to develop and quantify the KPIs (along with threshold values) for different assessment categories, namely, technical, economic, environmental, social, and circularity are presented in Section 4. The case studies covering asphalt pavement maintenance options in the Netherlands (NL), Denmark (DK), and United Kingdom (UK) are elaborated in Sections 5, 6, and 7, respectively, while the case study on concrete processing technologies is discussed in Section 8. Lastly, the lessons learned from the case studies and multiple pathways to implement the RBAF within NRA procurement processes are outlined and the flexibly of the developed framework to account for varying levels of RE/CE maturity is discussed.

3 Approach for case studies selection

In general, the selection of the case studies was performed in three stages. First, the projects selected by the CERCOM team along with the list of potential case studies was sent to the Program Executive Board (PEB) panel. Following their feedback in July 2022, the case studies were finalized in an online meeting with the PEB in September 2022.

3.1 Selection criteria

The case studies were chosen based on various selection criteria, namely the type of pavement (asphalt concrete), material (demolished concrete) being processed, CE maturity level, location of the project, and the expected availability of data. The motivation behind the selection of case studies covering different pavement maintenance options and concrete processing methods was to identify data requirements, assess the maturity levels of different NRAs in terms of circularity potential, and build stakeholder confidence in the proposed set of tools and methods.

During the preliminary phases of the project, five case studies were selected for asphalt concrete pavements and two case studies were chosen for cement concrete as shown in Table 1. Following this, a series of discussions were organized with the respective case study holders, contractors, industrialists, material suppliers, and representatives from the NRAs. It was understood that a substantial amount of information was required for the case studies. The overlap within the conceptual scope of different case studies helped in shortlisting case studies for further development. For instance, the scope of case study on ‘in-situ rejuvenation of ZOAB’ (here ZOAB refers to Porous Asphalt Concrete Pavement) in the NL was similar to the case of ‘Rhinophalt resin’ application in the UK. However, as the information available for the case study in the NL was more robust and complete for the different assessment categories, the Rhinophalt application in the UK was excluded from the final set of studies.

The case study on the use of ‘waste plastic as warm mix modifier’ was not selected as this is a relatively new technology and limited data relevant to long term performance is available. Furthermore, it is important to mention that the construction/maintenance technologies considered in this work are relatively new with limited information on the long term performance. Due to limitations in empirical data, the preset scales option was also not utilized. The demolition of rail and road bridges in DK was not accomplished within the timeline of this deliverable. Therefore, the case of ‘recycled concrete from old and degraded civil structures’ in DK was not included in the final list. However, the CERCOM team in the NL was successful in obtaining the necessary data for investigating ‘processing technologies for aggregate recycling’. The inclusion of waste concrete processing methods as one of the case studies was anticipated to demonstrate the robustness of RBAF beyond conventional pavement maintenance methods.

Table 1. Initial Proposed Case Studies

Case study	Type of application	Project	Country	Circularity level
Maintenance options for asphalt pavements	Asphalt	In-situ rejuvenation of ZOAB	Netherlands (NL)	Extend lifespan of pavements (R4)
		Refurbishing milled asphalt into new bound layers - BSM technology	Denmark (DK)	Reuse existing pavement to create new pavement with addition of limited materials (R5 or R6)
		High recycled content in surface course	United Kingdom (UK)	Recycle (R8)
		Waste plastic as warm mix modifier	United Kingdom (UK)	Reduce (R2)
		Rhinophalt resin	United Kingdom (UK)	Extend lifespan of pavements (R4)
Recycling concrete technologies	Concrete	Processing technologies for aggregate recycling	Netherlands (NL)	Recycle (R8)
		Recycled concrete from old and degraded civil structures	Denmark (DK)	Recycle (R8)

One basis for circularity models is the 9R framework, where 9R stands for refuse (R0), reduce (R1), rethink (R2), reuse (R3), repair (R4), refurbish (R5), remanufacture (R6), repurpose (R7), recycle (R8), and recover (R9) (Cramer 2017; Lamb et al. 2022). The tighter the material loop, lesser the external inputs required for closing the loops, and the more circular the strategy (Kirchherr et al. 2017). Note that the in-situ rejuvenation is a preservation technique, which is being successfully utilized in the NL to prevent the need for major rehabilitation or repair during the life of pavements. Since this maintenance method falls within the upper medium loop (R3-R4) of the circularity model, it shows that the NRAs in the NL are transitioning towards the use of options with higher circularity levels. Though the cases of UK and DK emphasize on recycling the material within the same pavement system, they lie among the long loops (R8-R9) as external equipment and energy inputs are required to generate the new value of the material. Similarly, the concrete recycling technologies (R8) follow a closed loop of circularity models. As understood from the discussion above, the selected case studies are representative of medium and long loops of circularity levels.

3.2 *Final case study selection*

The final case studies that were selected for the demonstration of RBAF (based on data availability and maturity levels of NRAs) are presented in Table 2. Though it was initially planned to study the case of using ‘high recycled content in surface course’, it was neither included in the final list nor presented in the report due to the absence of relevant data needed for its completion.

Table 2. Selected Case Studies

Case study	Type of application	Project	Country	Circularity level
Maintenance options for asphalt pavements	Asphalt	In-situ rejuvenation of ZOAB	Netherlands	Extend lifespan of pavements (R4)
		Refurbishing milled asphalt into new bound layers - BSM technology	Denmark	Reuse existing pavement to create new pavement with addition of limited materials (R5 or R6)
		High recycled content in surface course	United Kingdom	Recycle (R8)
Recycling concrete technologies	Concrete	Processing technologies for aggregate recycling	Netherlands	Recycle (R8)

4 Methodology

This Section provides information on the RBAF and methodology associated with the quantification of the different KPIs that were used for the case studies.

4.1 *Risk-based analysis framework*

The steps involved in the RBAF are outlined in CERCOM Deliverable 3.1. For each potential construction or maintenance option, the associated risk was calculated (Risk = probability of failure (P_f) x consequences of failure event). Within the RBAF, consequences are represented as the costs associated with a failure event (e.g., the direct and/or indirect costs). For each potential action, the risk associated with each option was calculated and used to generate the Risk Reduction Index (*RRI*), outlined in Equation (1).

$$RRI_i = \frac{R - R_i}{R} \quad (1)$$

R = risk associated with the “do minimum” option,
R_i = risk associated with i^{th} maintenance/construction option,

The *RRI* was then used within the optimization step. Further, the KPIs for other assessment categories were calculated using a ranked interpolation approach as described in Deliverables D3.1 and 3.2 of the CERCOM project. The “do minimum” option was used to establish a baseline scenario for the evaluation of risk, and it may be defined as a case that does not involve any maintenance activities during the design life of pavement. Although it seems a hypothetical scenario as pavements are always maintained to perform satisfactorily during the design life, it helps evaluate the budgets and compare available maintenance methods. For this study, the purpose of the baseline scenario was to evaluate the risks of carrying out minimal or no maintenance over the reference period, and provide a means to quantify the reduction in risk associated with carrying out different maintenance options.

As discussed in Deliverable 3.1, the CERCOM consortium have proposed quantifying all other KPIs using a ranked interpolation approach. In order to accomplish this task, KPIs for different assessment categories including circularity, environment, economy, and social aspects were developed as shown in subsequent sections. Figure 1 illustrates the categories under which criteria and KPIs for optimization are assigned for the case studies outlined as part of Deliverables 4.1 and 4.2. Other performance criteria can be selected depending on the purpose and scope of the scenario under consideration.

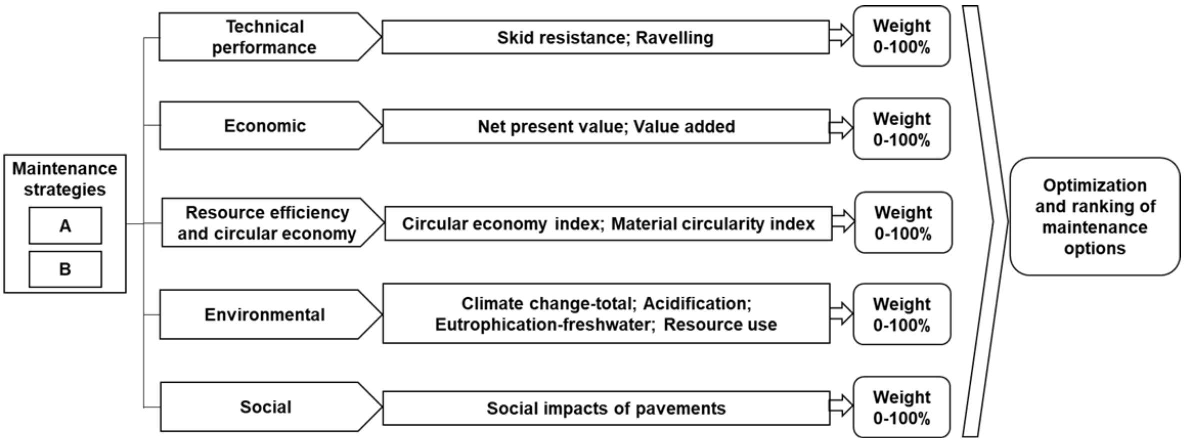


Figure 1. Assessment Categories and Key Performance Indicators for Optimization

The procedure for quantifying the KPIs by ranked interpolation is as follows:

1. Determine the number of ranks required to quantify the KPI;
2. Set the minimum rank to a value of 0.0, and the maximum rank to a value of 1.0;
3. Determine the mathematical relationship between each KPI rank;
4. Score the KPI for the scenario being evaluated and interpolate according to the ranked relationship.

The first rank should always be assigned a value of 0.0, and the final rank should be assigned 1.0, to keep the KPIs commensurate with each other. In the simplest case, a linear relationship can be assumed between the first and final rank. In this case, only two ranks are necessary. Where a more subtle response is required, a multi-linear or quadratic relationship may be determined between different KPI ranks. In the present study, due to limited availability of data, a linear relationship has been adopted for interpolation between each rank.

4.1.1 Net risk reduction gain

To rank various construction or maintenance solutions, Net Risk Reduction Gain (NRRG) was selected as the metric to integrate the KPIs into a single score (see Equation (2)).

$$NRRG_i = w_1 \times RRI_i + w_2 \times KPI_{1,i} + w_3 \times KPI_{2,i} + w_4 \times KPI_{3,i} + \cdots. \tag{2}$$

Where,

RRI = risk reduction index
$KPI_{3,4,5\ldots,i}$ = value of each KPI associated with maintenance/construction option, and
$w_{1,2,3\ldots}$ = value of weights for each KPI. Note that the sum of weights must be 1.0.

The construction/maintenance option with the highest *NRRG* is selected as the optimal solution. Additional information on the factors involved in the calculation of *NRRG* are provided in Deliverable 3.1. The guide to using the software tool is detailed in Section 6 of the Deliverable 3.2, the methodology for assessment is detailed in Sections 4.2 – 4.5 of this report and the KPIs selected to represent the different assessment categories are presented in Section 4.6.

4.2 Methodology for environmental lifecycle assessment

Environmental Lifecycle Assessment (ELCA) is a recognized methodology to assess the environmental impacts of a defined system (E.g.: a system involved with the production of a product or a service, such as road maintenance). The ELCA methodology is framed by the International Standards Organization (ISO) standards 14040 and 14044 (ISO 2006a, 2006b). The methodology has the specificity to evaluate the environmental impacts of a system by including the upstream and downstream impacts within the defined boundaries of the assessment. The ISO standards define four steps to conduct an LCA: 1) definition of the goal and scope, 2) inventory analysis, 3) impact assessment, and 4) interpretation. These steps are defined in the following sections.

4.2.1 Goal and scope definition

During the definition of the goal and scope, the system under study and the objective of the analysis are described. Elements of the process description are the geographical location of the system, the timeframe for which the results are valid, the function of the system under study, the system boundaries and key methodological choices. The function of the system is defined by the functional unit, which provides the reference to which all assessment data are normalized. The functional unit should reflect as much as possible the function delivered by the system under study, especially when the ELCA is conducted to compare different systems.

The system boundaries also need to be defined. They define all the processes included in the assessment. Some processes can be disregarded because of their insignificance in contributing to environmental impacts already identified. The system boundaries include two sub-systems: the foreground system and the background system. The foreground system includes all the processes which are of direct interest to the product and technology developers. The background process includes all the processes which support the foreground process. They include for example the production of electricity and chemicals consumed in the foreground process, from the extraction of raw materials to their final production before entering the foreground process.

4.2.2 Inventory analysis

In the inventory analysis, all data necessary for impact assessment are gathered for the system under study and for the background system. All the materials, chemicals, water and energy going in and all the products, waste streams and emissions going out of the foreground system should be represented by the data gathered in the Inventory.

The data inventory for the background processes is based on databases such as Ecoinvent™ (Wernet et al. 2016) or Gabi™ (GaBi Manual 2022). The production of each input of the foreground system (E.g. electricity, material, etc.) is modelled by a background process simulated in these databases. For example, if it has been inventoried that electricity is consumed in the foreground process, the relevant background process for production of electricity should be identified in the databases.

4.2.3 Life-cycle impact assessment

The inventory results in a list of emissions and natural resources consumed along the process chain, from the extraction of raw materials to the final stage of the life cycle. These flows of natural resources and emissions to air, water and soil, called elementary flows, are multiplied by characterization factors, which converts them into environmental impacts. Characterization factors are defined by impact assessment methods, developed mostly by research institutes and academia. For example, when the impact category Climate Change is analysed, each emission contributing to global warming occurring along the supply chain is multiplied by a specific characterization factor which reflects the emissions contribution to Climate Change, by kg of CO_2 equivalence.

4.2.4 Interpretation

The Interpretation aims to check the validity of the data and methodological choices made to conduct the study and draw the conclusions regarding the sustainability of the system. The validity can be assessed through analysing the uncertainty of specific data and assumptions. This will identify parameters to be tested in a sensitivity analysis, whereby parameters with high degrees of uncertainty are incrementally changed, and the resulting effect on the ELCA impacts is analysed. The knowledge gained from this analysis should be used to revise and guide subsequent ELCA iterations.

4.3 Methodology for economic lifecycle assessment

Lifecycle Cost Assessment (LCCA) is defined as the process that is used to quantify and compare the economic value of different materials, systems, and designs over their service life (Diependaele 2018; Walls III and Smith 1998). LCCA takes into consideration the present and future economic trends, and is aligned towards the quantification of direct and indirect costs. Although there are multiple ways to represent the costs associated with any activity, Net Present Value (NPV) is the most commonly utilized parameter, which takes into account the future and / or preservation cash flows (discounted to base year) and results in a single economic output that allows comparison between distinct alternatives (Braham 2016; Chen et al. 2019; Diependaele 2018).

In general, a minimum of two mutually exclusive scenarios were considered for the analysis, and the LCCA framework adopted for the case studies is presented below (Braham 2016; Chen et al. 2019; Diependaele 2018; Federal Highway Administration (FHWA) 2002; Walls III and Smith 1998).

4.3.1 Pavement maintenance

As a first step of the LCCA process, possible alternative pavement maintenance / rehabilitation / reconstruction strategies were identified. For instance, the case study in the NL included the following: (a) rejuvenation of ZOAB (LVOv treatment) to extend the lifespan, and (b) ZOAB resurfacing. Although the Federal Highway Administration (FHWA) recommend a minimum analysis period of 35 years (to account for at least one rehabilitation activity and reflect long-term variations), the analysis period for the CERCOM case studies was selected based on project specific requirements and guidelines provided elsewhere (Harvey et al. 2016). All the strategies were evaluated for equivalent functional units and system boundaries as specified in the Section 4.2 to allow for rational comparisons. The traditional practice has been to use a discount rate ranging between 3 and 5% (Braham 2016; Chen et al. 2019; Federal Highway Administration (FHWA) 2002; Rodríguez-Fernández et al. 2020). In the absence of information relevant to the actual discount rates for pavement activities in the NL and DK, the discount rates for the case studies in the NL and DK were 5% and 4%, respectively. Additionally, sensitivity tests were performed to account for the effect of varying discount rates on the LCCA results.

Once the pavement scenarios, analysis period, and discount rates were identified, the agency and road user costs were computed. The agency costs refer to the expenditures incurred by the road agency. Since the scope of this project is restricted to the assessment of different maintenance technologies, the road agency costs included the expenditure associated with maintenance interventions only and the initial construction cost of the assets was excluded from the analysis. The costs that were common for the various considered pavement alternatives (such as initial construction for the case in the NL) were excluded from the analysis. Further, the routine maintenance costs were ignored as their contribution to the NPV is negligible (Diependaele 2018; Federal Highway Administration (FHWA) 2002; Walls III and Smith 1998). Another parameter that affects the total agency expenditures is salvage value, which refers to the remaining value of the pavement alternative at the end of an analysis period. This has been incorporated as a negative cost in the LCCA. The salvage value expressed in terms of serviceable value represents the differences in remaining service life between various pavement alternatives at the end of analysis period, and was computed using Equation (3).

$$Salvage\ value = cost\ of\ last\ treatment\ \times \frac{remaining\ life\ of\ last\ treatment}{service\ life\ of\ last\ treatment} \tag{3}$$

User costs refer to the costs incurred by road users over the design life of a pavement. Typically, user costs depend on the duration (days / weeks / months), time (working hours), and number and type of maintenance/rehabilitation/reconstruction activities associated with different pavement alternatives. For this study, user costs comprised Vehicle Operating Costs (VOC) and costs of additional delays (DC). User costs are expressed as the sum of the quantity of the user cost components (VOC, DC) and the unit Euro value was assigned to the respective components. The DC (price/person-hour) are based on value of time made up of factors such as average wage, type of vehicle, goal of the trip, travel type, and vehicle occupancy. In addition, the work zone user costs are dependent on factors such as the work zone features (preventive maintenance/rehabilitation/reconstruction), traffic characteristics (directional frequency, vehicular distribution, and annual average daily traffic), road type (motorways, dual and single carriageway roads) and traffic management type (carriageway closure, lane closure, speed restriction). Data for the evaluation were mainly identified from the national and European databases. The VOC and DC were determined using Equations (4) and (5) (Decò and Frangopol 2011; Khakzad and Gelder 2016).

$$VOC = \left[C_{Run,car}\left(1-\frac{T}{100}\right) + C_{Run,truck}\left(\frac{T}{100}\right)\right] * D_1 * A(t) * d * \frac{1}{(1+i)^{n_k}} \tag{4}$$

$$DC = \left[C_{AW}O_{Car}\left(1-\frac{T}{100}\right) + (C_{ATC}O_{Truck} + C_{goods})\frac{T}{100}\right] * \frac{D_1 A(t) d}{S} * \frac{1}{(1+i)^{n_k}} \tag{5}$$

Where,

T	= average daily truck traffic (%)
$C_{Run,truck}$	= average running cost for trucks per km (Euro/km)
D_1	= detour length (km)
A(t)	= average daily traffic on year t
d	= duration of the detour (days)
i	= annual discount rate (%)
n_k	= year into the future of cash flow of activity k
C_{AW}	= average wage of car driver per hour (Euro/h)
O_{Car}	= average vehicle occupancy for cars
C_{ATC}	= average wage of truck driver per hour (Euro/h)
O_{Truck}	= average vehicle occupancy for trucks
C_{goods}	= time value of the goods transported in cargo (Euro/h)
S	= average detour speed (km/h)
$\frac{1}{(1+i)^{n_k}}$	= discount factor

Once all the scenarios, associated timings of the activities, and the costs were established, future costs were discounted to the base year. The sum of initial costs and discounted future costs represent the NPV as given in Equation (6). Though initial construction costs were not used for analysis in this research, it has been added in Equation (6) to allow for its inclusion in other case studies.

$$NPV = IC + \sum_{k=1}^{n} MC_k \left[\frac{1}{(1+i)^{n_k}}\right] - \left[\frac{SC}{(1+i)^{k}}\right] \qquad (6)$$

Where,

IC = initial cost,

MC_k = maintenance cost of activity k in the year under consideration and it includes both agency as well as road user (VOC and DC) costs,

SC = salvage cost.

4.4 Methodology for circularity assessment

Circular economic models are aimed at maximising the use of existing resources and minimizing waste generation by keeping resources within the economic loop and maintaining the value of products for prolonged periods (Ellen MacArthur Foundation 2019; Maio and Rem 2015). In the domain of pavements, attempts are being made to incorporate circular practices by utilizing waste and recycled materials as substitutes (in partial or full) to virgin constituents (Riekstins et al. 2022; Zou et al. 2020). Further, the recovery and utilization of materials such as reclaimed asphalt pavement after the pavements' End-of-Life (EOL) is gaining attention (Bressi et al. 2022; Elnaml et al. 2022). Additionally, there is an increased focus on designing perpetual pavements, which have lower environmental and economic impacts than traditional pavements over their lifecycle (Walubita et al. 2022; Yang et al. 2021).

Past studies have shown that though mass based circularity indicators are useful in quantifying the circularity potential of different maintenance strategies, they have inherent limitations (Di Maio et al. 2017; Ellen MacArthur Foundation 2019; Mantalovas and Di Mino 2020). Therefore, other researchers have suggested the use of value based KPIs, which consider both quality and quantity of materials (Di Maio et al. 2017; Maio and Rem 2015). Hence, this section details the calculation methodology for two distinct KPIs (mass as well as value based) that can be used to assess and quantify the CE potential of EOL strategies for pavements. Note that the measurement of circular approaches in road maintenance is at an early stage and requires implementation to assist the NRAs in identifying sustainable and circular solutions.

4.4.1 Material circularity indicator

Material Circularity Indicator (MCI) is defined as a tool or metric that is used to assess the flow of materials (restorative or linear) at product/company levels (Ellen MacArthur Foundation 2019). MCI is assigned a score between 0 and 1, where score 1 indicates 100% restorative flow, and score 0 indicates 100% linear flow. MCI is based on six principles:

- Collect biological materials from renewable resources that can replenish at similar (or faster) rate than consumption
- Utilize raw materials extracted from reused/recycled sources
- Keep products in use longer (e.g.: reuse/redistribute, high durability)
- Reuse/recycle materials and/or components after EOL
- Intensify product use (e.g. via service, sharing/performance models), and
- Ensure biological materials remain uncontaminated and biologically accessible

Essentially, MCI is composed of the following product characteristics:

- Mass (V) of virgin feedstock required in manufacturing,
- Mass (W) of non-recoverable waste attributed to a product, and
- Utility factor (X), which is a measure of the length and intensity of the product's use.

4.4.1.1 Calculation of feedstock

The first step involved in assessing the MCI for pavement infrastructure and processing technologies include the computation of mass of virgin feedstock (V). Therefore, if,

F_R = fraction of feedstock from recycled sources,
F_U = fraction of feedstock from reused sources,
F_S = fraction of biological feedstock originating from sustained production, and
M = mass of the finished product.

So, the proportion of feedstock obtained from virgin resources may be represented as ($1 - F_R - F_U - F_S$), and 'V' can be computed by Equation (7). Note that the biological materials must be differentiated based on their origin to prevent outcomes such as habitat loss, soil degradation, and deforestation, which disrupts material circularity flows.

$$V = M \times (1 - F_R - F_U - F_S) \qquad (7)$$

4.4.1.2 Calculation of unrecoverable waste

The next step involves assessment of the mass of unrecoverable waste (W) during a material production or recycling activity. Therefore, if,

C_R = fraction of mass of product collected for recycling at the EOL,
C_U = fraction of mass of product collected for component reuse,
C_C = fraction of mass of product containing uncontaminated biological materials which is being composted, and
C_E = fraction of mass of product containing biological materials originating from sustained production and being used for energy recovery.

Therefore, mass of waste going to landfill (W_o) may be given by Equation (8).

$$W_o = M \times (1 - C_R - C_U - C_C - C_E) \qquad (8)$$

The inclusion of composting as part of circularity is applicable only for the biological materials under the following conditions:

- Material must be derived from biological source,
- Material must be biocompatible and non-toxic, and
- The by-products of composting must be biological and should not harm the ecosystem.

Only if all the above conditions are met, the composting of biological material may be regarded as completely (100%) efficient. The inclusion of energy recovery is applicable for the biological materials only if the following conditions are met:

- Material must be derived from biological source,
- Material must be biocompatible and non-toxic,
- The by-products should not harm the ecosystem,
- Other EOL options besides the landfill must be exhausted, and
- Energy recovery must be employed to displace non-renewable alternatives.

Bitumen being a non-biological source cannot be burned for energy recovery owing to the potential environmental impacts from the resulting emissions. Further, landfilling is not the recommended option. Therefore, it is advised to either extract or recycle the bitumen for use as a raw material in construction activities. Hence, energy recovery is generally not associated with pavement maintenance activities and aggregate recycling processes. As a result, the assessment of C_E is generally not applicable to pavement infrastructure. If E_C represents the process efficiency to recycle a pavement after its EOL, then the proportion of waste produced during recycling (W_C) may be given by Equation (9). Similarly, if E_F represents the process efficiency to produce a recycled feedstock (reclaimed materials), the waste generated in producing a recycled content being used as a feedstock (W_F) may be represented by Equation (10). Note that in closed loop system, $E_F = E_C$, because the feedstock produced after EOL forms an input to the next lifecycle. However, this may not necessarily be the case for pavements as the recycled feedstock may also be derived from sources that are different to those of the original product.

$$W_C = M \times C_R \times (1 - E_C) \tag{9}$$

$$W_F = M \times F_R \times \frac{1-E_F}{E_F} \tag{10}$$

If a pavement is initially designed with recycled materials but none of that pavement material is collected for reuse after its EOL, a certain amount of waste fraction would be generated that would require disposal. However, it must be noted that as no recycling activity is taking place, so the waste generated during recycling would be zero ($W_F > 0$ assuming that $E_F < 1$). Similarly, if a product is designed with 100% virgin materials but is collected for recycling after its use, no waste would be generated in producing the recycling feedstock ($W_F = 0$ and $W_C > 0$). However, if W_C and W_F are simply added together, it will lead to double count of some or all the waste fractions generated during the two recycling processes. To overcome this problem, a 50:50 approach is adopted, where 50% each of W_F and W_C are assigned to the product that the recycled feedstock came from and the product that will utilize the collected and recycled material. Therefore, total unrecoverable waste (W) may be computed using Equation (11).

$$W = W_o + \frac{W_F + W_C}{2} \tag{11}$$

Where:

W_o = mass of waste going to landfill (see Equation (8)),

W_C = mass of waste produced during recycling (see Equation (9)), and
W_F = mass of waste generated in producing a recycled content being used as a feedstock (see Equation (10)).

4.4.1.3 Calculation of the linear flow index

The Linear Flow Index (LFI) is indicative of the quantity of material sourced from virgin feedstock and ending up as unrecoverable waste. LFI (Equation (12)) lies between 0 and 1, where 1 represents completely linear flow and 0 is indicative of the restorative flow.

$$LFI = \frac{V+W}{2M+\frac{W_F-W_C}{2}} \tag{12}$$

Where:
V = mass of virgin material,
W = mass of total unrecoverable waste, and
M = mass of finished product.

4.4.1.4 Calculation of product utility

The utility of a pavement (Equation (13)) is given as a function of the lifetime (duration of use phase) and functional units (intensity of use). In the context of material circularity indicator, the number of functional units achieved during the use of a product refers to the number of times a product can be used to fulfil its intended purpose before it reaches the end of its life cycle. The lifetime/length component is given as $\frac{L}{L_{avg}}$ which represents an increase (or reduction) in the waste fraction in a given time interval for pavements that have shorter (or larger) lifespan (L) compared to average industrial lifespan (L_{avg}). Similarly, the intensity of use component ($\frac{U}{U_{avg}}$) indicates the extent to which a pavement is utilized to its full capacity.

$$X = \frac{L}{L_{avg}} \times \frac{U}{U_{avg}} \tag{13}$$

Where:
X = utility,
L = actual lifespan of the pavement under consideration,
L_{avg} = typical average lifespan of the pavement under consideration
U = number of functional units achieved during the use of a product, and
U_{avg} = number of functional units during the use of an industry average.

An increase in the lifespan or a pavement's use intensity will result in more efficient utilization of the resources and augment the material circularity. In general, either lifetime or the intensity are used to compute utility instead of both parameters. If both components are utilized, it is essential to ensure that a given effect is only considered once either as an impact on lifetimes or on intensity of use.

4.4.1.5 Quantification of the material circularity indicator

The MCI of a product is given by Equation (14).

$$MCI^*_p = 1 - LFI \times F(X) \tag{14}$$

Factor F(X) is a function (F) of the utility (X), which evaluates the influence of a product's utility on its MCI. However, looking at F, the value of MCI may be negative for products with nearly linear flows (LFI ~ 1) and the utility lower than an average industrial product (X < 1). To avoid the negative resultant, MCI is capped off at zero and is represented by Equation (15). As can be seen from Equation (15), it may not be appropriate to compare two products with nearly linear flows as this would result in an MCI value of either zero or very close to zero.

$$MCI_p = (0, MCI^*{}_p) \tag{15}$$

4.4.2 Circular economy index

As an alternative to the MCI, the resource efficiency and material circularity can be expressed as the amount of physical units (mass) in monetary terms (price × physical value), thereby reflecting both quality and quantity. Therefore, in this section, the authors propose the utilization of Circular Economy Index (CEI), which is a conceptually simplified value-based indicator and accounts for the economic, social, and environmental externalities of materials after EOL (Maio and Rem 2015). It is important to note that although economic, social and environmental factors are considered as part of the CEI, they are independent of aspects considered within corresponding KPIs. The CEI is computed using Equation (16).

$$CEI = \frac{Material\ value\ recycled\ from\ end-of-life\ product}{Material\ value\ needed\ for\ reproducing\ end-of-life\ product} \tag{16}$$

Although measurement units such as mass, volume, embodied energy, and carbon-dioxide equivalent are available, Maio and Rem adopted an economic value to integrate the material quantity as well as social and environmental features (Maio and Rem 2015). Note that the market value must be measured immediately after the collection of EOL products and just before the material enters the production stream. Unlike LCA and mass recycling rate approaches, computations associated with the CEI are relatively simple. In addition, the CEI being governed by the market value of products (which are further driven by the economic, environmental, and social taxes) adjusts itself if a material becomes cheaper or more expensive due to the adoption of an efficient recycling technology or strategic issues. Therefore, the CEI being a simple indicator driven by the market price can be easily adopted by the industry stakeholders and policy-makers to assess the RE and CE associated with a product or system. Further, the value of materials contained in each functional component (pavement) may be computed using Equation (17).

$$Gross\ value\ added = recycling\ firm\ revenues - non\ factor\ costs \tag{17}$$

Recycling firm revenues account for the revenues generated by selling the secondary materials, while the non-factor costs refer to the expenditure associated with energy and input materials to produce the secondary materials. In such a scenario, the CEI may also be defined as the ratio of gross value added to the material input value.

4.4.3 Assumptions and limitations of the circularity indicators

Based on the two indicators discussed above, it was understood that both value based and material circularity indicators have inherent limitations. The major assumptions and limitations of the MCI are as follows:

- The quantification of the indicator requires a comprehensive dataset,
- The indicator does not explicitly favour closed loops because a recycled material derived from a pavement does not necessarily have to be returned to the original manufacturer of the product,
- The material losses during the collection of components for reuse are negligible,
- There is an assumption that the recovered material after the EOL of a product can be processed to a similar quality to that of virgin material, and

- MCI assumes that the mass of a product remains constant from the manufacture to EOL.

The assumptions and limitations of the value-based indicator (CEI) are as follows:

- The indicator is based on the value of recycled materials after their EOL, thereby more suited for recycling activities,
- The indicators do not consider the utility in the assessment, i.e., the value added by the increased lifespan of a pavement after a certain maintenance activity was not covered, and
- There is an assumption that the mass of recycled materials produced after extraction and processing from an EOL pavement remains similar to the quantity of materials used during manufacture.

4.4.4 Proposed circularity indicator

As understood, the value-based indicator seems to be a promising alternative to the conventional MCI method as it considers the quality of the recycled materials along with the quantity, while also taking into account the environmental, economic, and social aspects. Further, the CEI, being a simplified index that is driven by market values would assist in easy assessment of the achieved circularity. However, it is essential to modify the CEI in its current form to cover a broad range of pavement maintenance alternatives such as rejuvenation, surface treatment, etc. Therefore, a revised CEI is presented in Equation (18).

$$CEI_i = \sum_i \left[\frac{Material\ value\ added}{Material\ value\ for\ reproducing\ end-of-life\ product}\right] \tag{18}$$

Here, the material value added is the difference between the scrap value of the materials in the given year and the non-factor costs. Further, the scrap value for pavements is defined as the difference between the initial cost of materials in the year under consideration and the cumulative depreciation expense. In addition, attempts were made to identify the various depreciation methods that could assist in the computation of construction materials' value lost over the design life of pavements. Although straight line method is commonly used to assess the depreciation rates for financial estimates, this study utilized declining balance method, which was found more appropriate for pavement assets. A recent investigation suggested that the annual depreciation rate for highway infrastructure with a service life of 45 years was 2.02% (Kornfeld and Fraumeni 2022). Further, the annual depreciation was defined as the ratio of declining balance rate (0.91 for non-residential infrastructure) and design life of asset. In this study, the depreciation rate was expressed as the ratio of design life of an asset. The methodology to compute the scrap value with declining balance method is presented in Appendix A.

Importantly, this method is only applicable when the assets have a certain value (non-zero) at their EOL, which is reasonable for the pavement/construction materials highlighting the suitability of this method. Further, the use of resource-based dataset in a product's value chain is well-aligned with the time and location as explained next. Consider the construction of surface pavement layers (similar configurations and mix proportions) with virgin binder in the DK and in the UK. The value-based indicator will result in different values for both countries considering that the binder was imported to the DK from a neighbouring nation, while they were domestically produced and consumed in the UK. Hence, value-based indicator has the potential to deal with the specific conditions and stressed resources at local level.

4.5 Methodology for social lifecycle assessment

Social impacts may be defined as the consequences of an activity on different groups of stakeholders and society during the lifecycle (Zheng et al. 2019). Though significant improvements have been made in refining and updating the environmental (ISO: 14040 2006; ISO: 14044 2006) and economic (Diependaele 2018; Federal Highway Administration (FHWA) 2002; Walls III and Smith 1998) Lifecycle Assessment (LCA) methods, Social LCA (SLCA) is an emerging tool, which is gaining attention in the context of pavement technologies (Martínez-Blanco et al. 2014; Zheng et al. 2019). SLCA involves various stakeholders, namely, workers, local community, society, and consumers. Note that the SLCA does not necessarily furnish information if a certain activity must be performed or not but is used for decision making in conjunction with environmental, economic, and circularity models. Social impacts are the consequences of the following aspects:

- Behaviours: relates to specific decisions. E.g.: allowing illegal child labour during a construction activity,
- Socio-economic processes: relates to decisions made at micro and macro levels. E.g.: investments for technological advancement, and
- Capitals: relates to the characteristics of an individual, society, or group. E.g.: EOL responsibility for disposal of waste products.

The SLCA framework is similar to the methodology proposed in ISO: 14040 (ISO: 14040 2006):

- Goal and scope definition,
- Social lifecycle inventory,
- Social lifecycle impact assessment, and
- Interpretation

4.5.1 Goal and scope definition

The possible alternative pavement maintenance / rehabilitation / reconstruction strategies were identified and compared with respect to their social dimensions. In general, a minimum of two mutually exclusive scenarios were considered for the analysis. The scope included construction / maintenance stages of the pavement project. Though a functional unit similar to that for LCCA and ELCA may be adopted, studies have recommended that the social impacts are mainly related to human well-being and are difficult to connect with a specified physical unit (UNEP / SETAC 2009; Zheng et al. 2019, 2020). Further, SLCA utilizes the characteristics of various activities and their associated companies, which makes it inappropriate to summarize outputs per functional unit. Thus, a functional unit similar to ELCA and LCCA was not defined, and semi-quantitative or qualitative data was used in the analysis. The social impacts were categorized into five main stakeholder categories:

- Workers / employees,
- Local community,
- Society (global or national),
- Consumers, and
- Value chain actors

In the context of pavement maintenance, the stakeholder categories that are potentially affected by maintenance/rehabilitation/reconstruction activities were identified for every case study along with information on the sub-categories and development of the SLCA indicators. Four stakeholders, namely, worker, local community, consumers, and society were used, and a detailed list of various sub-categories as well as impact indicators that form part of maintenance activities are presented in Table 3. Further, the social impacts relevant to the stakeholder for value chain actors were excluded as the laws and regulations pertinent to fair competition and intellectual property rights are well-established in the pavement sector (Zheng et al. 2020). The social indicators proposed in Table 3 were identified based on International guidelines (UNEP / SETAC 2009, 2013), literature (Zheng et al. 2019, 2020), and processing technologies (Gebremariam et al. 2020; Moreno-Juez et al. 2020). Note that the contents of Table 3 may be refined based on the data available and maturity levels of the different NRAs, and the final list of impact indicators may differ from the ones presented in Table 3.

Table 3. Classification of Stakeholders, Subcategories and Social Indicators for Pavement Scenarios

Stakeholders	**Sub-categories**	**Impact indicators**
Worker	Working hours	Average working hours per month
		Compensation of overtime hours
	Child labour	Child labour control
		Use of child labour
	Fair salary	Minimum wage
		Standard of living
		Gender pay gap
	Equal opportunities / discrimination	Equal opportunities for different genders
		Equal opportunities for different ethnic groups
		Equal opportunities for specially abled
	Health and safety	Management measures of daily work-related injuries
		Use of appropriate protective gear
	Freedom of association and collective bargaining	Freedom to join unions of their choice
Local community	Respect of indigenous rights	Land claims
	Local employment	Local labour
		Generation of employment
	Access to material resources	Local materials (water, land, mineral, and biological)
		Use of non-renewable resources
		Use of renewable resources
		Use of scarce resources
		Use of non-scarce resources
	Access to immaterial resources	Community education initiatives
	Safe and healthy living conditions	Minimizing pollution level (soil, water, air, and noise)
		Minimize local traffic congestion
		Minimize accident rates
	Secure living conditions	Public safety
		Legal complaints against the working organization with regards to security concerns
Society	Public commitment to sustainability issues	Legal obligation on public sustainability reporting
	Technological developments	New technology
		Technology transfer
		Research and development costs
		Partnership in research and development
		Cleaner production (high quality raw materials, assets with lower emissions)
	Contribution to economic development	Contribution of activity to reduce unemployment
		Contribution of activity to GDP
Consumer	Safe operation conditions	Maintain adequate performance (strength and durability)
		Diversion / re-routing signs
		Incidents of non-compliance with regulations complying to safety impacts of pavement
	Feedback mechanism	Surveys to assess consumer satisfaction
	Transparency	Publishing a sustainability report
		Organization rating in sustainability indices
	End-of-life responsibility	Product disposal (landfill, recycling, incineration, reuse)
		Environmental health impacts
		Public health impacts

As can be seen from Table 3, four stakeholders, nineteen subcategories, and forty-two impact indicators are proposed in this report. The worker category is expected to be involved in most of the pavement lifecycle phases. For instance, the workers may be employed on site beyond the scheduled hours to successfully complete the maintenance / rehabilitation / reconstruction activity for certain pavement systems (jointing in concrete layers). In such scenarios, the workers, must be adequately compensated. Further, it is essential to understand if the conditions of operation are suitable for the well-being and personal growth of children employed (if any) on different pavement projects. Fair salary is one of the most essential criteria for social development as workers without fair wages may not be able to meet basic necessities (such as food, clothing, shelter, and medical expenses) for themselves and their family. In addition, the sub-categories for equal opportunities/discrimination and freedom of association are proposed. Importantly, workers are susceptible to work-related injuries and diseases and this has led to the development of a health and safety sub-category.

The local community will be involved during all the pavement lifecycle phases for the different scenarios. As shown in Table 3, five impact indicators have been proposed for the access to material resources sub-category. Material resources are an integral component of societal development, and this sub-category will indicate the extent to which road agencies make efforts to sustainably utilize the local materials and existing resources. Similarly, safe and healthy living conditions will be indicative of the efforts made by the road agencies to minimize pollution levels (air and noise from to vehicle operations and materials transportation), traffic congestion, and accident rates (different agencies may employ different levels of measures for specific activities). Further, management efforts to use local labour and generate employment opportunities for different groups will be considered under the local employment sub-category. In addition, the efforts of the organizations to encourage secure living conditions within neighbouring communities during various activities will encourage sustainability.

Society will be involved during pavement maintenance, rehabilitation, reconstruction, and disposal activities. It is anticipated that the use of new / innovative materials that are less resource intensive and technologies that minimize on-site activities or increase the lifespan of an asset will have positive societal impacts. Further, the efforts undertaken by organizations to exploit low tier suppliers/employees or investments made to create more competent suppliers/employees will contribute to sustained economic development. In addition, the dissemination of information by the road organizations to the communities pertaining to the reduction of impacts by use of sustainable technologies will be discussed under the ‘public commitment to sustainability issues’ sub-category.

Consumers refers to the users (e.g. drivers and passengers, pedestrians, etc.) using the pavement system. Under the sub-category health and safety, consumers will expect the asset to perform satisfactorily (while meeting the relevant standards) over its design life. In addition, the efforts of management to put necessary sign boards during an activity will be used to award scores. The feedback mechanism sub-category will indicate consumer satisfaction levels pertaining to the maintenance activities conducted and use of the asset. Organizational transparency refers to the information supplied by the organizations to the consumers about the impacts of the activity or the product, which would assist in informed decision making. Furthermore, the measures taken by road organizations to dispose the assets after their EOL (e.g.: sustainable consumption in new product designs) will certainly minimize the environmental / public impacts and augment the quality-of-life.

4.5.2 Social lifecycle inventory

Once the system boundaries were established, the hotspots were evaluated at national levels. As per Benoit-Norris *et al.*, hotspots may be defined as activities in the product supply chain that highlight potential risk of violation and social concerns that need to be considered in a specific country and sector (Benoit-Norris et al. 2012). Note that the level of details varied for different processes in a specific agency. In order to prioritize the processes for data collection, a common activity variable (to reflect the share of a given activity with unit processes) was identified for the different processes. For instance, the emission of fumes was used as an activity variable to assess the social impacts of working conditions. Site-specific data was collected to model the system by conducting interviews with road agencies, research experts, and project managers.

4.5.3 Social impact assessment

Once the impact categories, sub-categories, and related impact indicators were defined, the impact assessment phase included:

- Selection of characterization methods and models,
- Classification – relating inventory to specific sub-categories, impact indicators and stakeholders, and
- Characterization – calculation of results for the sub-category indicators.

The characterization step involved translation of lifecycle inventory to common units and aggregation of results within the same impact categories. In SLCA, the characterization step comprised scoring, weighting, and aggregation of the inventory data into a single unit for various social indicators. The scores were assigned based on the reference points, and helped assess the meaning of the inventory data. This study attempted to compute the social impacts based on the methodology proposed in previous literature (Wang et al. 2016; Zheng et al. 2020).

a. Scoring

The direct indicators (directly relating to the stakeholder and lifecycle phase under consideration) were evaluated using a score ranging between 1 and 5 having nine distinct relative percentage (between generic and site-specific data) levels as shown in Table 4. Relative percentage is defined as the ratio between site specific inventory data and the statistical data obtained from national database. Lower positive scores were assigned for indicators that have fewer social benefits/high negative impacts and vice-versa.

Table 4. Scores for Direct Social Indicators

Score	**Relative percentage**								
	< 25	**25-50**	**50-75**	**75-100**	**100**	**100-125**	**125-150**	**150-175**	**> 175**
Positive indicator	1	1.5	2	2.5	3	3.5	4	4.5	5
Negative indicator	5	4.5	4	3.5	3	2.5	2	1.5	1

For indirect social indicators (indirectly relating to the stakeholder and lifecycle phase under consideration), the scores were based on five different components as follows: policy, measure, communication, response, and record (Wang et al. 2016). The accomplishment levels of these components were used for assigning the scores as below:

- ✓ Fully implemented: 1
- ✓ Partially implemented: 0.5
- ✓ Not implemented: 0

Further, the general interpretation of the five different components is as follows:

- ✓ Policy: establishing the policies to support the measure into daily work,
- ✓ Measure: systematic solutions from technical and management level into daily work,
- ✓ Communication: for integrating the measure into daily work,

- ✓ Record: recording all measures, communications, and responses, and
- ✓ Response: create the response system for handling complaints and suggestions

The aggregation of scores assigned for the five components resulted in a single score. For example, the scores for maintenance of ZOAB for the indirect social indicator “compensation of overtime hours” may be computed as follows:
If there was a strict ‘policy’ within the firm to hire local labour, then the score of ‘1’ was provided, so fully implemented. Similarly, if necessary ‘measures’ were taken to implement the desired policy, then the score is ‘1’ (fully implemented). However, if the ‘measures’ were not ‘communicated’ to the local community (not implemented), a score of ‘0’ was assigned. If there was no ‘response’ system to handle the complaints of local community, a score of ‘0’ was provided. Similarly, if there was no ‘record’ of historical data but present information relevant to the locally employed workforce was stored, a score of ‘0.5’ was provided. Therefore, the final scores for indirect social indicators were as below:

- ✓ Policy (fully implemented): 1
- ✓ Measure (fully implemented): 1
- ✓ Communication (not implemented): 0
- ✓ Response (not implemented): 0
- ✓ Record (partially implemented): 0.5

b. Weighting

Past studies have indicated that the relative importance of stakeholders, sub-categories, and impact indicators are different (Manik et al. 2013; Traverso et al. 2012; Wang et al. 2016; Zheng et al. 2019). Therefore, analytical hierarchy process (Saaty 1987), which is a subjective weighting system is generally adopted to compute the weights based on the responses from multiple stakeholders and experts. This approach is prone to bias, e.g.: industry stakeholders may force the results to meet market competitiveness. Therefore, in the present study, an objective based weighting method known as entropy was used to ascertain the weights of impact indicators. The detailed steps for computation of weights by Entropy method can be found elsewhere (Singh et al. 2022). Entropy approach is scientific and minimizes the bias as the weights are based on the relative scores of different indicators, and not the judgement of various groups.

c. Aggregation

Based on the scores and weights (indicator and lifecycle phase), the final score of the pavement was computed using Equation (19) (Zheng et al. 2019).

$$SIP = \sum_{i=1}^{n} S_i \times W_i \qquad (19)$$

Where;

SIP = social impacts of pavements,
S_i = score of indicator i, and
W_i = weight of indicator i.

4.5.4 Interpretation

The findings of SLCA were reported and meaningful conclusions were drawn. In general, the following tasks were undertaken during this phase:

- Identification of the hotspots,
- Assessment of the consistency/completeness of the study,

- Conclusions, recommendations, and systematic reporting.

Completeness aimed at verifying if the necessary data was gathered and crucial issues were addressed. Consistency aimed at assessing if the modelling and methodological choices were in accordance with the goal and scope of the research.

4.6 Selection of Key Performance Indicators

Based on the various impact assessment categories discussed in Sections 4.2 to 4.5, a set of KPIs were defined for the selected case studies, which could be adopted for different maturity levels of NRAs and utilized as per the data availability (discussed further within each case study). A mass based KPI may be selected instead of a value-based KPI for NRAs with lower maturity levels or low loop circularity models. Further, mass-based KPI can also be used in conjunction with the value-based indicator. Once the KPIs were ascertained, they were embedded into the risk-based framework (see Equation (2)) to quantify the risks associated with different maintenance options and rank the alternatives to select the optimum solution.

5 Case Study Ia: Asphalt – LVOv (the Netherlands)

In this case study, two pavement alternatives, namely, in-situ rejuvenation and resurfacing were investigated under various assessment categories. Basically, rejuvenation is a preventive maintenance technique that involves spraying a compound over the existing pavement surface wearing course layer to extend its service life. Extending the lifetime increases the overall sustainability of the road network by keeping the materials in use for longer periods, minimizing the energy consumed and decreasing traffic disruption due to maintenance operations. In this case study, resurfacing involved milling the existing surface layer and inlaying the layer with virgin raw materials. Although not the case in this example, an inlay may also comprise 100% recycled material or a mix of recycled as well as virgin materials.

5.1 Goal and scope definition

The goal of this case study was to compare two pavement maintenance alternatives, i.e., in-situ rejuvenation and resurfacing by integrating the environmental, economic, social, and circularity factors along with assessing the risk associated with their technical performance to select the best solution from a decision-making perspective. To ensure consistency in evaluation, the functional unit for the analysis was a single lane road, 1000 m long, 3.5 m wide, and 0.05 m thick. The analysis period for the study was 42 years, which was estimated in accordance with the guidelines provided in FHWA document (Harvey et al. 2016). The timeline of different maintenance activities that were considered for the two scenarios are presented in Figure 2. Note that the maintenance activities for the resurfacing scenario were considered until year 42 (analysis period), as shown by the downward arrow in Figure 2. In the Netherlands, the typical design life of pavement is 15 years (assuming preventative maintenance is carried out). As per the Dutch experience, the lifespan of a pavement increases by a minimum of three years for every rejuvenation activity. Therefore, rejuvenation in years 5 and 10 will facilitate in achieving a design life of 15 years and lead to an increase in service life by 6 years (3+3). Hence, the service life of pavement subjected to in-situ rejuvenation treatment was 21 years (initial life of 15 years + 6 years extension). On another hand, the service life of a pavement that does not undergo preventive maintenance is typically 12 years, which was selected for the resurfacing scenario. Further, it was understood from discussions with the representatives of Rijkwaterstraat road agency and material suppliers that the underlying layers of pavements remain structurally sound and full depth reclamation is usually undertaken only at the end of 50 years. Therefore, the maintenance of only the surface layer for an analysis period of 42 years was considered pragmatic and rational.

Note that the initial construction phase was excluded from the assessment as it would result in equal impacts for both the alternatives. Further, the EOL phase was not considered in the absence of information pertinent to recycling and disposal of the pavement materials. Though the system boundaries for technical performance evaluation, ELCA, LCCA, and circularity assessment were similar, it was slightly different for SLCA, which is consistent with past literature (Martínez-Blanco et al. 2014; UNEP / SETAC 2009). It can be explained as follows: (a) the unit processes for the SLCA were different from other assessment categories and they were assessed based on the industry's management behavior towards the respective stakeholders (Dreyer et al. 2010), and (b) the goal of this study is to determine the most sustainable and circular pavement alternative, which can be accomplished even with slightly different system boundaries as also suggested by other researchers in the context of pavement sustainability assessment (Zheng et al. 2019).

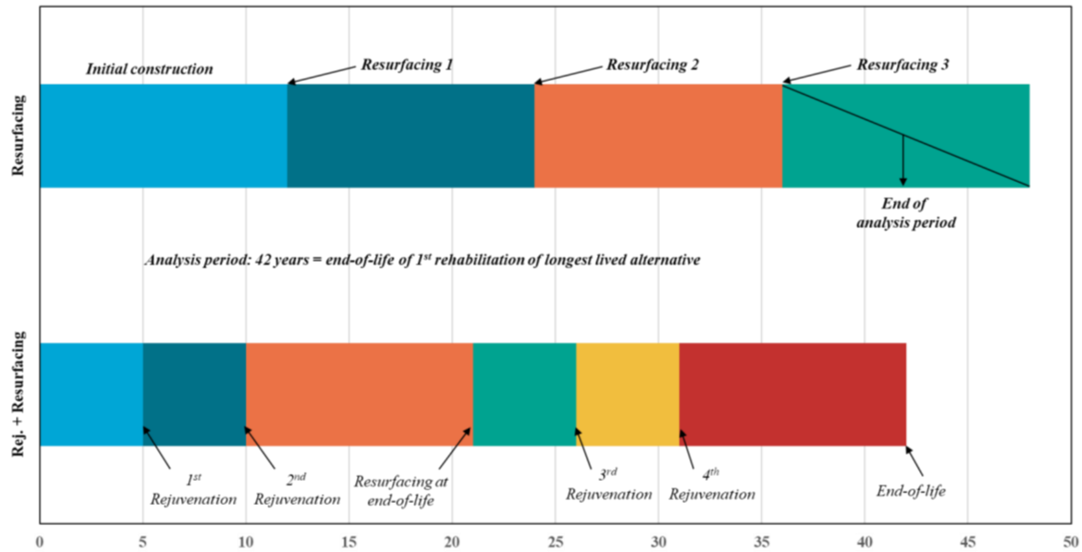


Figure 2. Analysis Period and Timeline of Various Maintenance Activities

Figure 3 below depicts the system boundaries of the ELCA and LCCA categories. As can be seen, both cover all the material resources and utilities that are required for the different maintenance options. With regards to the SLCA, only the on-site activities (maintenance / rehabilitation / reconstruction) were considered as the inventory data for SLCA was dependent on the scores assigned by different industry (management) and research stakeholders, and did not consider the volume of material flowing in and out of the process.

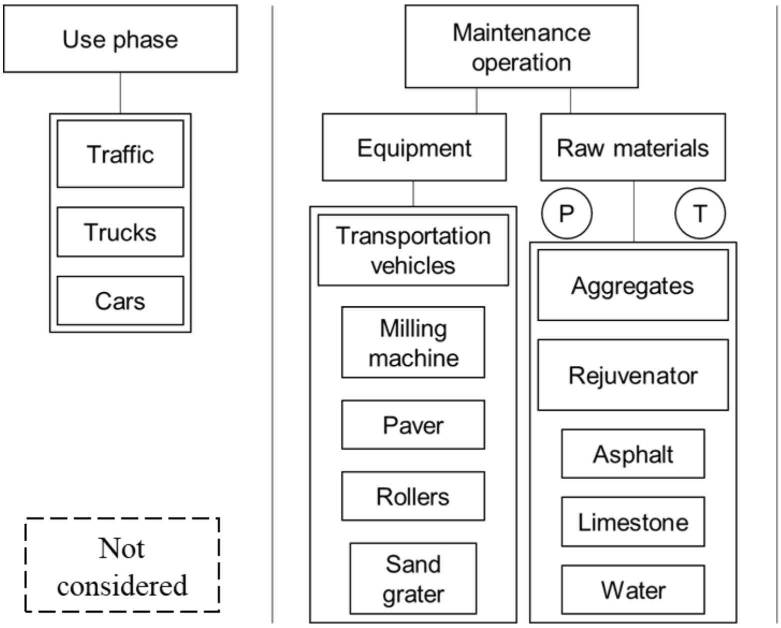


Figure 3. System Boundary for Environmental and Economic Lifecycle Assessment

5.2 Lifecycle inventory

Once the goal and scope were defined, the lifecycle inventory was generated by collecting the data from primary and secondary sources. To collect the primary data, a series of meetings, interviews, and questionnaire surveys were organized with representatives from different road agencies, material suppliers, and research experts. The sequence of activities performed in the field and associated unit processes were understood. The secondary data was collected from existing literature specific to the case study, Eurostat's database, OECD's database, and national statistics board. Further, the data quality was verified by cross-checking with multiple data sources specific to the case studies. Additional information relevant to the lifecycle inventory and input values are presented in subsequent sections.

5.2.1 Environment

The background reference data utilized in modelling the life cycle impacts of the elementary flows incurred by the rejuvenation and resurfacing are presented in Table B 1 of Appendix B. The data source includes information from industry partners, certified environmental product declarations (EPDs), and background modelling data provided in the Gabi™ and Ecoinvent™ databases. This information was used to model the elementary flows associated with each scenario as well characterizing the environmental impacts resulting from each flow. The data quality was evaluated in accordance with the EPD standard, EN15804+A2, which recommends consideration of geography (G_e), time (T_i), and technological (T_e) relevance. Each of these three metrics were assessed on a scale from very good (VG), good (G), fair (F), poor (P), to very poor (VP). The data quality in this study generally ranged between VG and G. The few 'F' quality data points occurred when either global processes or generic data points were used in the absence of site specific data (E.g.: using generic data for soap production instead of specific production data for the pre-rejuvenator).

5.2.2 Lifecycle cost and circular economy

The quality of data collected for LCCA case study in the Netherlands is indicated in Table B 2 of Appendix B and the corresponding source is mentioned in Table B 3. Note that the primary data refers to the specific raw data that was collected directly from the material suppliers and contractors and is specific to the set of activities associated with a process. Secondary data refers to the information that was not directly collected from a contractor or material supplier but sourced from a third party such as existing literature and scientific databases.

The inputs such as raw material costs, material transportation charges, duration of maintenance, and other agency as well as road user costs that were used to conduct the LCCA study are supplied in Table B 4 and Table B 5 of Appendix B. Further, the circularity assessment was conducted by utilizing the costs for different raw materials and maintenance options as well as the timeline for various maintenance regimes as discussed previously in the goal and scope section.

5.2.3 Social

The data collected for the direct and indirect indicators of SLCA corresponding to rejuvenation and resurfacing scenarios is presented in Table B 6 of Appendix B. The data for direct indicators was gathered by conducting interviews with the technical representatives of the industry as well as national averages from online databases (Eurostat 2020a; Eurostat2020b; World Bank 2021). Indirect indicator scores were obtained from interviews with two material suppliers, two construction agencies, four researchers, and one academic expert. Note that only a selected number of direct indicators were adopted from Table 3 due to unavailability of precise data for others. However, a broader set of direct indicators may be included in future when more reliable data is available. Further, indicators with similar scores for both rejuvenation and resurfacing activities (E.g.: average working hours of labour were 8 for both maintenance methods) were not considered in the analysis.

5.2.4 Lifecycle impact assessment and interpretation

5.2.4.1 Environmental

The ELCA assessment was carried out in accordance with the EPD standard, EN15804 +A2, which is based on the environmental footprint methodology (EF3.0) for assessing lifecycle impacts. This methodology was selected to ensure compatibility with the impact data from the EPD used in modelling the impacts of producing the rejuvenator. Table 5 presents the performance of both scenarios for 15 core environmental impact indicators for the given functional unit (1000 × 3.5 × 0.05 m) and analysis period of 42 years. Negative values reflect a beneficial impact, while positive values reflect a detrimental impact.

The results of the ELCA suggest that the maintenance of motorways in the NL using rejuvenation yielded significant benefits to climate change compared to resurfacing. The rejuvenation scenario resulted in emission of 39% lower kg CO_2 eq. than resurfacing. This difference came primarily from the avoided need for calcium hydroxide and bitumen, which are essential for the production of fresh ZOAB for resurfacing activities. For resurfacing, the respective contribution of calcium hydroxide and bitumen to the kg CO_2 eq. emissions was 35% and 32%. In the rejuvenation scenario, the combustion of kerosene accounted for 12% of the kg CO_2 eq. emissions. Further, 60% of the total kg CO_2 eq. emissions were associated with the production of rejuvenator during rejuvenation maintenance.

The rejuvenation process resulted in a net biogenic carbon benefit as well as land use associated carbon emissions. This result was consequential of the use of proxy dataset (soap production) for prerejuvenator from Ecoinvent™ dataset, which utilizes palm oil and coconut oil as raw materials in the production. Furthermore, the production of rejuvenator was responsible for the largest share of environmental impacts, not just for the climate change category but also for detrimental impacts to ozone, acidification, eutrophication, photochemical ozone formation, and resource use. The contributions to these impacts from rejuvenation production was the cause for rejuvenation underperforming against the resurfacing scenario. The resource use of minerals and metals was the most impacted category, where rejuvenation carried an impact of 74 orders of magnitude larger than resurfacing.

Table 5. Environmental Impact Scores for Rejuvenation and Resurfacing Scenarios

Environmental Impact indicators	Rejuvenation	Resurfacing
Climate Change - total [kg CO_2 eq.]	30938	50320
Climate Change, fossil [kg CO_2 eq.]	32652	50075
Climate Change, biogenic [kg CO_2 eq.]	-4992	198
Climate Change, land use and land use change [kg CO_2 eq.]	3278	47,0
Ozone depletion [kg CFC-11 eq.]	1.25E-03	6.93E-04
Acidification [Mole of H+ eq.]	179	170
Eutrophication, freshwater [kg P eq.]	4.74	0.16
Eutrophication, marine [kg N eq.]	111	47.8
Eutrophication, terrestrial [Mole of N eq.]	809	528
Photochemical ozone formation, human health [kg NMVOC eq.]	145	156
Resource use, mineral and metals [kg Sb eq.]	0.74	0.01
Resource use, fossils [MJ]	9.65E+05	2.03E+06
Water scarcity (no hydropower) [m^3 world equiv.]	2705	4284
Water scarcity (only hydropower) [m^3 world equiv.]	113	282
Water use [m^3 world equiv.]	15484	4675

The respective impacts of rejuvenation and resurfacing scenarios during the roads use phase were separately assessed to compare the direct impacts of these maintenance techniques to their indirect effect through pavement vehicle interactions on fuel efficiency. A study was carried out by the Concrete Sustainability Hub (Greene et al 2013) to assess in part, the impact of road roughness on fuel efficiency. They found that for every m/km increase in International Roughness Index (IRI) above 1 m/km, cars travelling on the pavement would experience a roughly 1% increase in fuel consumption.

As primary data on the evolution of IRI on a road's surface over time was unavailable for ZOAB, values reflecting IRI before and after maintenance were used with values plotted linearly in between 3.5 m/km. Note that an IRI of 3.5 m/km is the maximum allowable threshold on roads by the Dutch NRA. A value of 0.6 was used as the data point for IRI after the road was treated, which is equivalent to the value of IRI immediately after construction. A value of 1 m/km was assumed to be IRI value prior to rejuvenation taking place. The justification for this assumption is that rejuvenation strengthens the road surface, improving its resistance to stone loss, and ravelling, as well as the fact that rejuvenation takes place more frequently, after only five years in comparison with resurfacing taking place after 12 years. These IRI values, and their resulting impacts on increasing fuel consumption are presented in Figure 4.

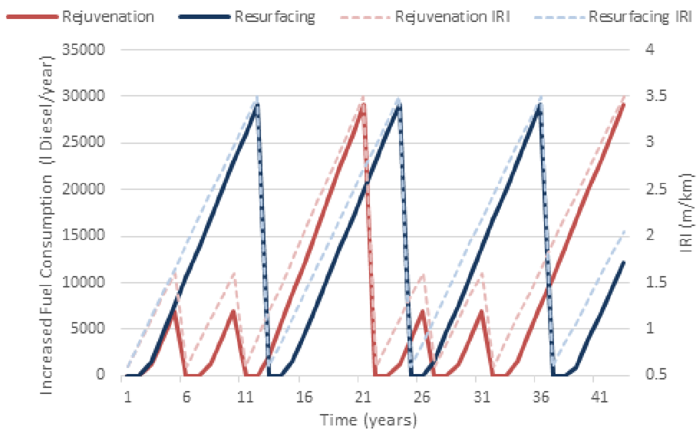


Figure 4. Increased Fuel Consumption Over Time for Rejuvenation and Resurfacing Scenarios

5.2.4.2 Economic

A deterministic LCCA was undertaken in this study and a discount rate of 5% was used. Table 6 shows the breakdown of the costs associated with rejuvenation and resurfacing treatments at the base year. It is noteworthy to mention that the cost of rejuvenation was almost 7 times lower than the milling operation. Additionally, each rejuvenation activity extends the service life of pavement by about three years, thereby delaying the need for resurfacing and saving costs. Further, the costs associated with transportation and disposal of milled material were excluded as these processes were beyond the system boundary considered in this study. The element with the highest contribution to the ZOAB construction was the asphalt mixture whose production cost (including raw material production and transportation charges) was almost 205 times greater than the mix transportation and 26 times higher than the resurfacing activity.

Table 6. Breakdown of Costs for Rejuvenation and Resurfacing

Rejuvenation (€)		**Resurfacing (€)**	
Material and application	Sand gritting	Milling	ZOAB construction
8085	581.25	56000	94251.70

For the given functional unit, the maintenance cost for the rejuvenation alternative was reported as 0.08 Million Euros, and the corresponding cost for the resurfacing activity was about 0.18 Million Euros. The breakdown of different maintenance costs for the two pavement maintenance alternatives are presented in Table 7. The corresponding share of VOC (running costs) and DC over the analysis period was about 14 and 19% for the rejuvenation and resurfacing scenarios. Their smaller share may be attributed to the fact that road closures are not permitted during a maintenance or rehabilitation activity in the NL. As such, drivers are not forced to take alternative routes to reach the destination and traffic speed during maintenance or rehabilitation activities is restricted to around 50 km/h. Road agencies are required to ensure that the IRI on highways in the NL is maintained at 3.5 m/km throughout their service life (Silva 2013). Other researchers have also suggested that vehicle maintenance and repair costs were lowest for IRI up to 3 m/km (Chatti and Zaabar 2012). In addition, the IRI of pavements never goes below the threshold over a 50 year period (Santos et al. 2017). As a result, the cost of vehicle maintenance and fuel consumption remain similar to the scenario before maintenance.

Table 7. Breakdown of Maintenance Costs

Maintenance alternative	**Agency costs (Euros)**	**Vehicle operating costs (Euros)**	**Delay costs (Euros)**	**Salvage value (Euros)**	**Total (Euros)**
Rejuvenation	72265.28	7040.55	5581.29	0	84887.12
Resurfacing	156196.07	18926.58	14982.06	12923.09	177133.67

The total user costs for the rejuvenation alternative are about 63% lower than the resurfacing scenario, mainly due to the lower time required for carrying out the treatment. Other researchers have also suggested that corrective maintenance methods exhibit poor economic performance and imply financial overburden on road users attributed to an increase in the number of associated maintenance activities and consequentially more time than other maintenance methods (Santos et al. 2017). From the two ZOAB maintenance cases discussed above, it may be stated that the rejuvenation maintenance is expected to result in cost savings of almost 0.09 Million Euros.

Next, sensitivity analysis was undertaken to understand how the variations across a given set of inputs and assumptions influenced the outcomes. The potential effects of discount rate and detour length on the lifecycle costs and road user costs were assessed, and the results are presented in Figure 5. Each parameter was uniformly varied with respect to the baseline values. The effect of lower (2, 3, and 4%) and higher (6, 7, and 8%) discount rates on the NPV were assessed. Since the detour length can never be equal to zero (being one of the essential inputs in Equations (5) and (6)), it was varied in increments of 0.5 km (1, 1.5, 2, 2.5, 3, 3.5, and 4 km) from the baseline value of 0.001 km. Rejuvenation was the optimal economical maintenance solution at lower and higher discount rates. Further, the road agency costs were more sensitive to variations in the discount rate than road user costs as indicated by their relatively steeper curve. On another account, when a certain detour due to maintenance activities was considered, the road user costs depicted a sharp linear increase with increasing detour distance. Further, the increase in user costs for resurfacing activity was more pronounced than rejuvenation, highlighting the benefits of using rejuvenation (preservation technique) over corrective maintenance method of resurfacing.

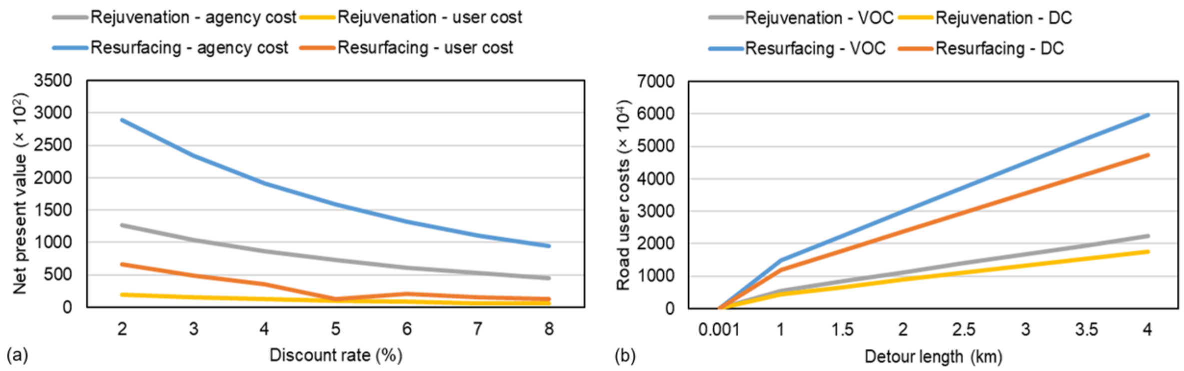


Figure 5. Sensitivity Test Results for: (a) Discount Rate, and (b) Detour Length

5.2.4.3 Circular economy and resource efficiency

As explained in the methodology section, though resource efficiency can be measured in the units of mass, the present study adopts value-based indicator as it is strongly aligned with the current European policies that aim at improving the quality of life by minimizing environmental and social impacts. Based on the functional unit, mix proportions, material densities, and transportation charges (see Section 5.2.2), the raw material quantities and associated costs were estimated as shown in Table 8. The costs relevant to the future year were estimated using the Equation (20) (Decò and Frangopol 2011):

$$Future\ value = present\ value\ \times (1 + r)^n \tag{20}$$

Where,

r = discount rate, and

n = future year of consideration

Table 8. Raw Material Quantities and Estimated Costs

Material	Quantity (tonnes)	Base year price (Euros)	Rejuvenation maintenance	Resurfacing maintenance			
			Price after 21 years (Euros)	Price after 12 years (Euros)	Price after 24 years (Euros)	Price after 36 years (Euros)	Price after 42 years (Euros)
Coarse aggregates	279.99	4611.48	12847.42	8281.56	14872.50	26708.87	35792.44
Fine aggregates	158.15	2604.75	7256.73	4677.75	8400.57	15086.22	20216.97
Limestone	9.10	397.49	1107.39	713.83	1281.94	2302.18	3085.14
Bitumen	7.77	4741.49	13209.60	8515.03	15291.77	27461.82	36801.47

Typically, ZOAB has a design life of 15 years, which was used to compute the depreciation rate (reciprocal of design life) of 6.67%. A recent study reported that annual depreciation rate for highway infrastructure is 2.02% (Kornfeld and Fraumeni 2022). However, this depreciation rate was computed when the pavement system had a service life of 45 years. Further, the annual depreciation was defined as the ratio of declining balance rate (0.91 for non-residential infrastructure) and design life of asset. Therefore, for a design life of 15 years, the asset will have a depreciation rate of 6.07%, which is close to the original depreciation rate proposed in this study. Therefore, annual depreciation of 6.67% was used and sensitivity tests were conducted to check its effect on the circularity potential of two maintenance methods. Further, the study recommended that declining balance method was more suitable than double declining method as the latter leads to much higher depreciation rates, which are not always practical in the context of roadway systems.

When a rejuvenating agent is applied on a pavement, the properties of aged asphalt binder are recovered due to alteration in its chemical and rheological parameters (Chen et al. 2018). In simple terms, the performance characteristics of the pavement are restored to a certain extent. Based on experience in the Netherlands (NL), it is well understood that each application of rejuvenation restores the asset value (or increases the service life) by at least three years. Therefore, if a pavement is rejuvenated 5 years after construction, it would be logical to consider that the value of raw materials in ZOAB will be equivalent to that in year 2. The depreciating value of raw materials with time is regarded as the scrap value as shown in Figure 6. Further, for a pavement design life of 15 years, one lifecycle will correspond to 21 years of service life (total six years lifetime extension for 2 rejuvenation activities). Therefore, for an analysis period of 42 years, ZOAB subjected to rejuvenation treatment underwent one resurfacing treatment compared to an extreme scenario of maintenance by resurfacing, which included three lifecycles.

As can be seen in Figure 6, when rejuvenation was conducted in years 5 and 10 during the first 21 years lifecycle, the corresponding raw material scrap values were represented by those at years 2 and 7. Similarly, the respective scrap values at years 25 and 30 were equivalent to those at years 22 and 27. In other words, higher scrap values were reported after a maintenance intervention, as also presented for the case of resurfacing. Though higher scrap values are indicative of greater material value added, it must not be misunderstood with higher RE and CE. For instance, despite the higher scrap values in Figure 6, the amount of virgin raw materials consumed during the analysis period was two times higher for resurfacing as compared to rejuvenation, which is consequential of higher resource depletion, waste generation, economic burdens, and social implications. Further, the non-factor costs associated with resurfacing was much higher than the rejuvenation activities.

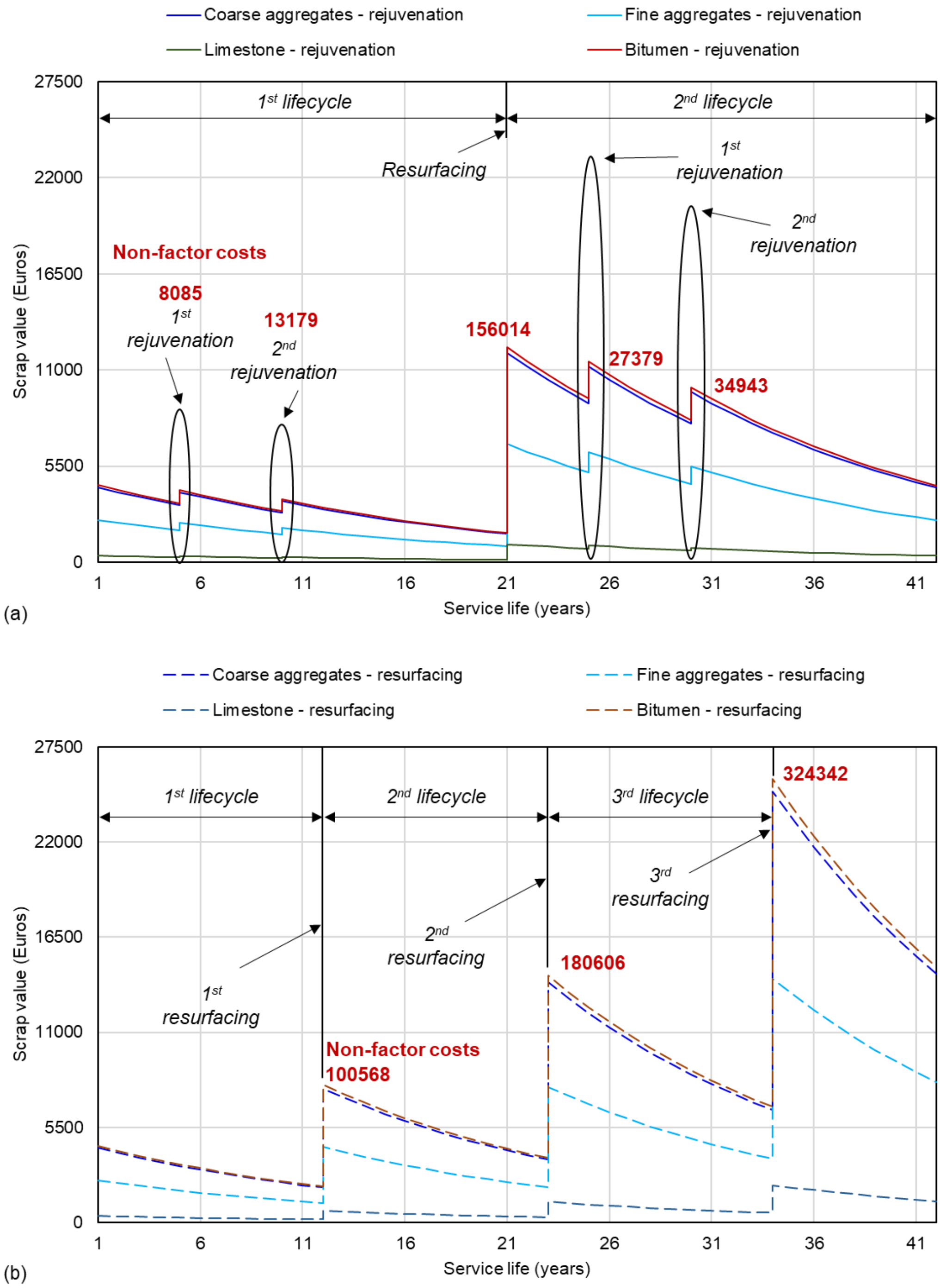


Figure 6. Variation in Scrap value of Raw Materials with Different Maintenance Activities

Once the scrap value was ascertained, the next step involved computation of the material value added, which is the difference between scrap value and non-factor costs. As per Maio and Rem, non-factor costs are the expenditure relevant to waste material processing to produce new material value (Maio and Rem 2015). Since there was no recycling activity associated with the case of rejuvenation (EOL processing beyond the system boundary), the non-factor costs were represented by the expenditure incurred during maintenance comprising inputs such as materials, energy, and transportation of equipment. The results for scrap value and non-factor costs are presented in Table 9. Further, the material value needed for reproducing EOL product was computed using Equation (20), and the results are tabulated in Table 9. Finally, the CEI for the two maintenance methods (a dimensionless number) was determined by Equation (18), and the results are shown in Table 9.

Table 9. Circular Economy Index for Proposed Maintenance Scenarios

<table>
<tr><th colspan="7">Rejuvenation</th></tr>
<tr><td>Maintenance year</td><td>5</td><td>10</td><td>21</td><td>25</td><td>30</td><td>42</td></tr>
<tr><td>Scrap value</td><td>10762.76</td><td>9375.56</td><td>32126.40</td><td>29984.64</td><td>26119.95</td><td>11413.37</td></tr>
<tr><td>Non-factor cost</td><td>8085</td><td>13169,6</td><td>156014</td><td>27378,7</td><td>34942,9</td><td>434649</td></tr>
<tr><td>Material value added</td><td>2677.76</td><td>-3794.04</td><td>-123887.60</td><td>2605.94</td><td>-8822.95</td><td>-423235.63</td></tr>
<tr><td>Material value to reproduce EOL ZOAB</td><td>15768.72</td><td>20125.33</td><td>34421.14</td><td>41839.11</td><td>53398.49</td><td>95896.02</td></tr>
<tr><td>CEI</td><td>0.170</td><td>-0.189</td><td>-3.599</td><td>0.062</td><td>-0.165</td><td>-4.413</td></tr>
<tr><td colspan="5">Resurfacing</td><td colspan="2" rowspan="7">CEI (rejuvenation): -8.134

CEI (resurfacing): -14.991</td></tr>
<tr><td>Maintenance year</td><td>12</td><td>24</td><td>36</td><td>42</td></tr>
<tr><td>Scrap value</td><td>20708,96</td><td>34710,97</td><td>66788,48</td><td>38458,80</td></tr>
<tr><td>Non-factor cost</td><td>100567.95</td><td>180605.6</td><td>324341.7</td><td>434648.9</td></tr>
<tr><td>Material value added</td><td>-79858.99</td><td>-145894.63</td><td>-257553.22</td><td>-396190.1</td></tr>
<tr><td>Material value to reproduce EOL ZOAB</td><td>22188.18</td><td>39846.78</td><td>71559.08</td><td>95896.02</td></tr>
<tr><td>CEI</td><td>-3.599</td><td>-3.661</td><td>-3.599</td><td>-4.131</td></tr>
</table>

As observed from Table 9, a higher negative CEI was obtained for the resurfacing option attributed to the higher virgin material consumption during its lifecycle compared to maintenance by rejuvenation. Although the percent contribution of aggregates and bitumen to the scrap value (a measure of material value added) was similar (Figure 7), the mass of bitumen was very small compared to aggregates.

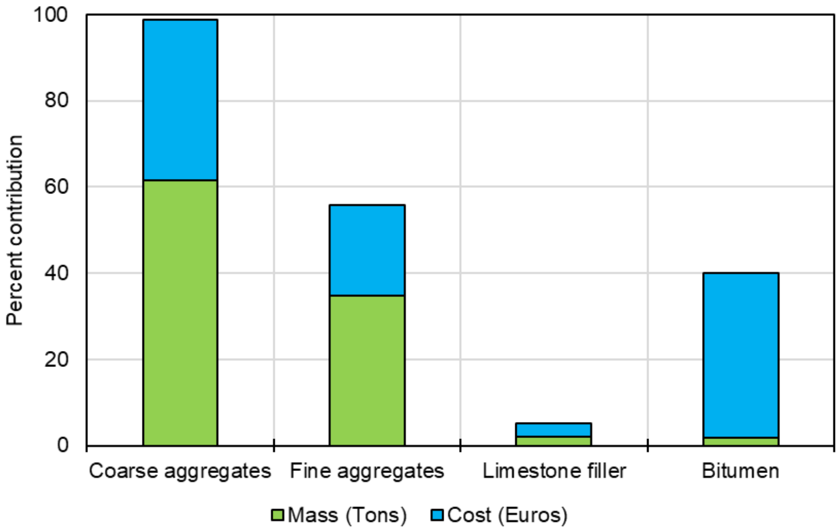


Figure 7. Percent Contribution of Mass (quantity) and Cost (quality) to Scrap Value

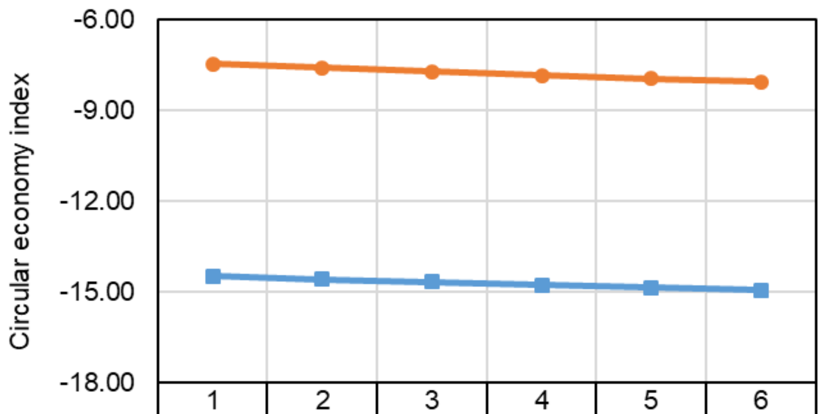
This demonstrates the strength of CEI to capture the resource efficiency based on material quantity and its quality, which is driven by the market forces such as scarcity versus competition and damage to the environment and society. Note that a larger CEI value is indicative of higher value addition. The negative sign was ascribed to the maintenance costs being higher than the raw material costs during the later phases and EOL of pavement. However, it does not have any implication on the physical meaning of results because the scrap value would always be higher in the first few years since construction and decrease subsequently with time. Further, a corrective maintenance (higher non-factor costs) will result in lower value addition due to the inflow of large proportions of virgin materials, which would result in higher negative numerator (a negative CEI that is closer to zero results in higher value addition). Therefore, the CEI for rejuvenation (most favorable alternative) and resurfacing (least favorable option) were reported as -*8.134* and -*14.991*, respectively.

From the perspective of mass-based circularity, the largest material contributing to RE and CE would be aggregates as significant proportions of low grade reclaimed asphalt aggregates can be recycled from ZOAB at EOL. However, even when bitumen was used in extremely small proportions compared to aggregates, it has a much higher market price. The major implications of the binders on quality of life and circularity practices can be explained by the following:

- The global warming impacts associated with the production of 1 tonne of asphalt binder (173.03 kg CO_2 equivalent) are about 99% higher than aggregate (1.43 kg CO_2 equivalent) production (Mazumder et al. 2016).
- In general, bitumen is about 70 to 80 times more expensive compared to aggregates.
- Improper disposal of bitumen has high social impacts attributed to the presence of toxic and sulfur compounds, and its potential to cause fire hazards compared to aggregates.

As evident from above, mass-based approach provides a lower incentive to valorize asphalt binder at the EOL. However, CEI encourages the extraction of reclaimed binder from the mix as 7.77 tonnes of binder has higher market value than 279.99 tonnes of coarse aggregates. Researchers have shown that the use of 40% reclaimed binder as partial replacement of virgin binder could help reduce the environmental impacts and costs of asphalt concrete mix over its lifecycle by 19 and 18%, respectively (Moins et al. 2022). Therefore, rejuvenation is a promising preventive maintenance alternative as it extends the service life of pavements and minimizes excessive virgin material consumption, thereby promoting RE. CEI can also drive the use of methods that extract higher reclaimed binder contents and produce high-grade aggregates for reuse in pavement surface applications.

Following this, sensitivity analysis was undertaken to understand the effects of variation in the depreciation rate on the CEI, and the results are shown in Figure 8. Further, the CEI for the rejuvenation scenario was more than half as that for resurfacing, which clearly dictates that the input virgin material flows and associated costs were significantly lower when preventive maintenance was undertaken. Therefore, it can be advocated that the preventive maintenance options such as rejuvenation could assist in closing the material circularity loops when compared to conventional milling and resurfacing options, and promote RE.



	1	2	3	4	5	6
Resurfacing	-14.49	-14.59	-14.68	-14.77	-14.86	-14.94
Rejuvenation	-7.46	-7.60	-7.73	-7.85	-7.96	-8.07

Depreciation rate (%)

Figure 8. Variation in the Circular Economy Index with Change in Depreciation Rate

5.2.4.4 Social impact of pavement maintenance methods

The scores for direct indicators were assigned based on the relative percent matrix (refer Table 4) that was discussed earlier in the methodology section. Basically, relative percent is the ratio of site specific and generic (statistical data from International database) quantities. Since the use of non-renewable resources is detrimental to society and the environment, the indicator “proportion of non-renewable resources” was recognized as a negative impact indicator, while other three indicators were categorized as positive. The direct indicator scores are presented in Table 10. Further, the average scores for the indirect indicators that were based on the predictions of experts are shown in Table 10. The weights that were computed using the Entropy method along with the aggregated scores (multiplication of weights and indicator scores) for rejuvenation and resurfacing are tabulated in Table 11.

As can be seen in the Table 11, the SIP is higher for rejuvenation compared to resurfacing, which confirms that the in-situ maintenance schemes oriented at lifetime extension of a pavement are more beneficial compared to traditional milling and filling activities. For the case of rejuvenation, the proportion of renewable resources impact indicator contributed most to social impacts. On the other hand, exposure to fumes impact indicator was one of the highest contributors to the social impacts associated with resurfacing. This indicated that adequate measures are being taken during resurfacing activities for health and safety of workers.

Table 10. Impact Indicator Scores

Direct Indicators	Rejuvenation		Resurfacing	
	Relative percentage	**Impact scores**	**Relative percentage**	**Impact scores**
Local workforce (%)	89.55	2.5	104.48	3.5
Proportion of non-renewable resources (%)	58.13	4	104.64	2.5
Proportion of renewable resources (%)	357.40	5	71.48	1
Research and development costs (% of revenue)	436.68	5	218.34	5
Indirect indicators			**Average scores**	
			Rejuvenation	**Resurfacing**
Exposure to fumes			3.50	3.63
Generation of employment			2.50	2.88
Community education initiatives			2.00	1.38
Legal complaints against the working organization with regards to security concerns			2.88	3.50
Legal obligation on public sustainability reporting			2.25	2.38
New technology			3.75	3.25
Partnership in research and development			3.75	2.88
Cleaner production (high quality raw materials, assets with lower emissions)			3.00	2.63
Contribution of activity to reduce unemployment			0.75	1.63
Incidents of non-compliance with regulations complying to safety impacts of pavement			3.63	2.63
Surveys to assess consumer satisfaction			3.13	2.88
Product disposal (landfill, recycling, incineration, reuse)			3.50	3.00

Table 11. Impact Indicator Weights and Aggregated Scores for Maintenance Methods

Impact Indicators	Weights	Rejuvenation	Resurfacing
Local workforce (%)	0.062	0.155	0.218
Proportion of non-renewable resources (%)	0.063	0.250	0.156
Proportion of renewable resources (%)	0.069	0.345	0.069
Research and development costs (% of revenue)	0.062	0.309	0.309
Exposure to fumes	0.062	0.216	0.224
Generation of employment	0.062	0.155	0.178
Community education initiatives	0.062	0.125	0.086
Legal complaints against the working organization with regards to security concerns	0.062	0.178	0.217
Legal obligation on public sustainability reporting	0.062	0.139	0.147
New technology	0.062	0.232	0.201
Partnership in research and development	0.062	0.233	0.178
Cleaner production (high quality raw materials, assets with lower emissions)	0.062	0.185	0.162
Contribution of activity to reduce unemployment	0.064	0.048	0.104
Incidents of non-compliance with regulations complying to safety impacts of pavement	0.062	0.225	0.163
Surveys to assess consumer satisfaction	0.062	0.193	0.178
Product disposal (landfill, recycling, incineration, reuse)	0.062	0.216	0.185
Final score (SIP)		**3.20**	**2.77**

The scores for the different stakeholder categories are presented in Figure 9. The local community was identified as the key stakeholder category in the maintenance schemes owing to its highest (%) contribution to the SIP. Though past studies have reported higher social impact scores for worker category, its contribution was lowest in this study. This is ascribed to the fact that experts generally assign higher weights to worker category considering the tough working conditions. However, based on the scientific scores, the results are different, and this could be described by the recent technological improvement that have improved working conditions and minimized labor requirement.

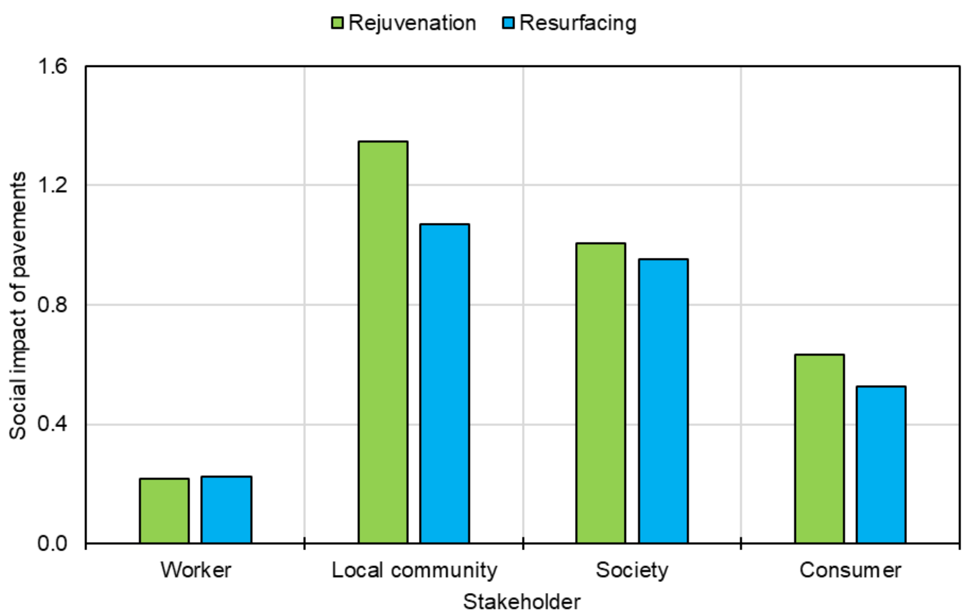


Figure 9. Social Impact of Pavements for Different Stakeholders

5.3 Technical performance and cost of consequences

Skid Resistance (SR) and ravelling were used as technical KPIs to evaluate the performance risks associated with different maintenance schemes. Since the tool requires assessment of the risk associated with different maintenance activities in the form of probability of exceedance of a certain limit state and associated consequences in terms of costs, attempts were made to relate SR and ravelling with the crash rate, which was further categorized as fatal (loss of life), serious, and minor. The average annual single crash costs corresponding to fatal, severe, and minor crashes are 6.3, 0.7, and 0.04 million Euros, respectively (SWOV 2020). In addition, the average proportion of annual cost associated with road fatalities, severe injuries, and minor injuries in the Netherlands has been reported as 15, 55, and 17%, respectively. The costs associated with other damages (property – 13%) were not considered in the absence of reliable information.

5.3.1 Skid resistance

SR is one of the most important functional characteristics of ZOAB, which is represented by the friction between the tyre and pavement surface (Silva 2013; Vos et al. 2017). Research has shown that the deterioration of road surface characteristics with time plays a major role in governing the loss of SR among others such as environmental, loading conditions, and vehicle type. A pavement must possess an adequate level of SR throughout its design life to offer safe riding conditions. In the Netherlands, Rijkswaterstraat and other road authorities determine the SR of ZOAB under wet conditions at a speed of 70 km/h (Vos et al. 2017) and the threshold value is reported as 0.42. For a newly constructed surface layer, the Skid Resistance Index (SI) per hectometre must be at least 0.02 higher than the threshold. A pavement is considered to have undergone serious damage when the SI is 0.01 to 0.06 lower than the threshold. An urgent damage will correspond to SI being 0.07 to 0.10 lower than the threshold.

Past studies have attempted to establish relationships between the pavement SR and crash rate, and one such model is shown in Equation (21) (Silva 2013). Further, the reduction in the SI with passage of time was determined using the Equation (22). It is important to mention that the Equation (21) is based on the SR measurements on a ZOAB motorway that was designed with Greywacke mineral aggregates. Though the use of “Greywacke” was common in the Netherlands during 1990’s, its physical properties such as hardness and specific gravity are similar to the aggregates being used more recently. However, it would be ideal to collect real-time field data for the ZOAB sections constructed after 2010, and develop models specific to the SI and crash rates. A “do-minimum” scenario was considered as a baseline case (though unrealistic) to highlight the difference in the level of risk with the proposed maintenance activities and the benefits associated with each of those.

$$CR = 27.239 \times 10^{3} \times e^{-7.55 \times SI} \tag{21}$$

$$SI = -0.0143 \times t + ISI \tag{22}$$

Where,
CR = crash rate per 100 million vehicle km,
SI = skid resistance index,
t = time in years, and
ISI = initial skid resistance index.

The difference in the level of risk associated with both maintenance strategies was quantified in terms probability of collision and associated cost of consequences. A yearly collision probability was determined based on the rate at which the SR of pavement was deteriorating. The average proportion of collisions resulting in fatality, serious injury, and minor injury was collected from the literature (SWOV 2020). The total risk (crash costs) associated with the "do-minimum", rejuvenation, and resurfacing maintenance scenarios for a 1000 m long roadway section having an annual average daily traffic 2589 vehicles over the analysis period of 42 years are presented in Table 12. Further, the year wise crash rates and annual risk (crash costs) corresponding to the do-minimum, rejuvenation, and resurfacing maintenance scenarios are detailed in Appendix B in Table B 7, Table B 8, and Table B 9, respectively. All the crash costs are expressed in million Euros.

Table 12. Total Risk (costs) Associated with Maintenance Methods – Skid Resistance

Maintenance scenario	Fatality cost (million Euros)	Serious injury cost (million Euros)	Minor injury cost (million Euros)
Do-minimum	1651	6053	1871
Rejuvenation	135	494	153
Resurfacing	161	589	182

The crash rates and the associated risk (costs) increased with a decrease in SI. The lowest risk was observed for rejuvenation treatment, which indicated that rejuvenation once every 5 years is an effective and cost-friendly maintenance technique to ensure the desired level of functionality for the ZOAB pavement. Though concerns have been raised about the low SR immediately after the rejuvenation treatment, studies have shown that a pavement regains 90% of the initial SR within one-day after being opened to traffic and gets close to the initial value within few weeks (Su et al. 2012). Further, researchers have indicated that ZOAB offers similar level of functionality once it undergoes a maintenance intervention. Therefore, this study used a simplified approach where the SI of the pavement after each maintenance activity was assumed similar to the initial SI. However, additional data must be supplied by NRAs in the future to pursue research that will lead to the development of precise prediction models to estimate the reduction in the SR of ZOAB sections undergoing different maintenance treatments.

5.3.2 Ravelling

In the Netherlands, ravelling has been classified in four distinct groups based on the percent stone loss per square meter as follows: (a) no ravelling (0-6%), (b) light (6-10%), (c) moderate (11-20%), and (d) severe (> 20%) (Miradi 2009; Silva 2013). Ravelling occurs due to a combination of factors including ageing of bitumen and environmental as well as loading conditions. A stronger bond between the aggregates and binder is characteristic of lower ravelling and higher durability. Therefore, ravelling may also be characterized by road surface characteristics such as texture depth. Although it is known that the texture depth of ZOAB is higher compared to conventional asphalt pavements, there does not exist a direct relation between texture depth and ravelling. A research study has indicated that the annual decrease in the mean texture depth of ZOAB in the Netherlands was 0.041 mm (Silva 2013), which was used for the assessment of the texture depth for the given analysis period. The next step involved establishing a power function relationship (Equation (23)) between the crash rate and texture depth based on data supplied in the Rijkswaterstaat manual on skid resistance (Vos et al. 2017). Since the function has been derived using a very limited dataset, it may not generate accurate results. However, the objective of this step was not to develop a predictive model but rather showcase the trend of increasing crash rates with decreasing texture depth. The crash rates and risk (expressed in million Euros) associated with the three maintenance scenarios are presented in Table 13. Further, the annual crash rates and associated risk for the do-minimum, rejuvenation, and resurfacing scenarios are detailed in Appendix B in Table B 10, Table B 11, and Table B 12, respectively.

$$CR = 3.7891 \times TD^{-0.701} \quad (23)$$

Where,
TD = texture depth (mm)

Table 13. Total Risk (costs) Associated with Maintenance Methods - Ravelling

Maintenance scenario	Fatality cost (million Euros)	Serious injury cost (million Euros)	Minor injury cost (million Euros)
Do-minimum	1.60	5.86	1.81
Rejuvenation	0.78	2.88	0.89
Resurfacing	0.81	2.96	0.92

Similar to the skid resistance, the crash rates and the associated costs increased with a decrease in texture depth. Based on the results, it may be suggested that the reduction in risk (crash rates and associated costs) were comparable for both rejuvenation and resurfacing.

5.4 Key performance indicators

This section presents the output values for each criteria that were computed based on the impacts quantified under different assessment categories, which are presented in Table 14.

Table 14. Key Performance Indicators

Assessment categories	Key performance indicators	Units	Rejuvenation	Resurfacing
Environmental	Climate change – total	kg CO_2 eq.	30938	50320
	Acidification	Mole of H^+ eq.	188.74	194.88
	Eutrophication, freshwater	kg P eq.	4.74	0.17
	Resource use, mineral and metals	kg Sb eq.	0.74	0.009
Cost	Net present value	Million Euros	0.08	0.18
Circular economy and resource efficiency	Circular economy index	-	-8.13	-14.99
Social	Social impact of pavements	-	3.20	2.77

5.5 Integration of key performance indicators in software tool

This step involved integration of the performance metrics computed for various assessment categories into the Excel® based software toolkit. The foremost requirement of the software was to input the generic information such as analysis period, road length, and proposed maintenance schemes. Next, the input format was defined along with the considered assessment categories. Since the key performance indicators (KPIs) under all assessment categories were numerically computed, 'numerical input' format was chosen. There exists an option to define the 'preset scale', which uses typical benchmarks to assign values when precise data is not available. Third, the risk associated with different maintenance options and technical KPIs was entered in the tool in terms of cost of consequences. Note that the probability of occurrence of one or more collisions for the maintenance schemes and do-minimum scenario was 1.0. As such, the differentiation in terms of risk for the alternative maintenance options was dictated by costs associated with failure consequences over the lifetime considered.

Fourth, a ranked interpolation system was adopted to compute KPI for each assessment category. A linear relationship was assumed between the maximum and minimum rank. The first rank for each KPI (also referred as least favorable output) was assigned a KPI value of zero, and the final rank (or most favorable output) was assigned a KPI value of one. The corresponding lower and upper benchmarks were defined for each KPI based on past roadway construction and maintenance experience. In the present study, only two ranks are considered, and a linear interpolation was done to determine the KPIs associated with each strategy. For instance, the LCCA KPI, i.e., the NPV for rejuvenation and resurfacing scenarios were 0.08 and 0.18 Million Euros, respectively. Based on expert judgement, the least and most favorable ranks were assigned data scores of 0.20 and 0.05 Million Euros, respectively. This scoring system may be explained by the fact that a maintenance strategy with lower expenditure and higher distress improvement (most favorable) is preferred over an expensive technique. The respective KPIs for rejuvenation and resurfacing were reported as 0.80 and 0.20. A higher KPI value is representative of more economic strategy. For CEI, the corresponding scores for least and most favorable ranks were given as -20 and 0. It is because a CEI value closer to zero (number of higher order) would indicate lower virgin material consumption and better circularity potential garnered through life extension, as already explained in the results Section on CEI. Similarly, the KPIs for other categories were determined and the results are presented in Table 15. Next, weights (see Table 15) were assigned to each KPI as per their relative importance. In general, all KPIs had a similar weight except SR, NPV, and CEI. SR is an important functional performance characteristic in the Netherlands, while costs associated with the maintenance activities have a direct implication on national budgets for roadway maintenance. Further, the objective of this study was to integrate circular procurement solutions in current pavement management practices. Therefore, higher weights were given to SR, NPV, and CEI.

Table 15. Key Performance Indicators for Pavement Maintenance Methods and Weights Per Assessment Criteria

Key performance indicators	KPI value		Weight	
	Rejuvenation	Resurfacing	Rejuvenation	Resurfacing
Skid resistance	0.92	0.90	0.15	0.15
Ravelling	0.51	0.49	0.05	0.05
Climate change-total	0.66	0.44	0.05	0.05
Acidification	0.56	0.53	0.05	0.05
Eutrophication-freshwater	0.26	0.49	0.05	0.05
Resource use, minerals and metals	0.38	0.50	0.05	0.05
Net present value	0.80	0.20	0.25	0.25
Circular economy index	0.59	0.25	0.3	0.3
Social impact of pavements	0.64	0.55	0.05	0.05

The NRRG for rejuvenation was higher than the resurfacing maintenance option. As can be seen in Figure 10, the technical risks associated with the two maintenance options was similar indicative of both technologies being equally efficient in augmenting the skid resistance and alleviating ravelling. Further, the economic and circularity benefits were more pronounced in rejuvenation. Especially, the contribution of NPV to NRRG in rejuvenation maintenance was significant as it assisted in minimizing the high expenditure associated with typical maintenance option of resurfacing. Though the contribution of CEI to NRRG was high in both the maintenance methods, it was substantial for rejuvenation highlighting the benefit of keeping the asset in place for prolonged periods. Other assessment categories had a relatively lower impact on the two maintenance schemes. Overall, based on the data available, results indicate that preventative maintenance is optimal over the corrective maintenance option of resurfacing.

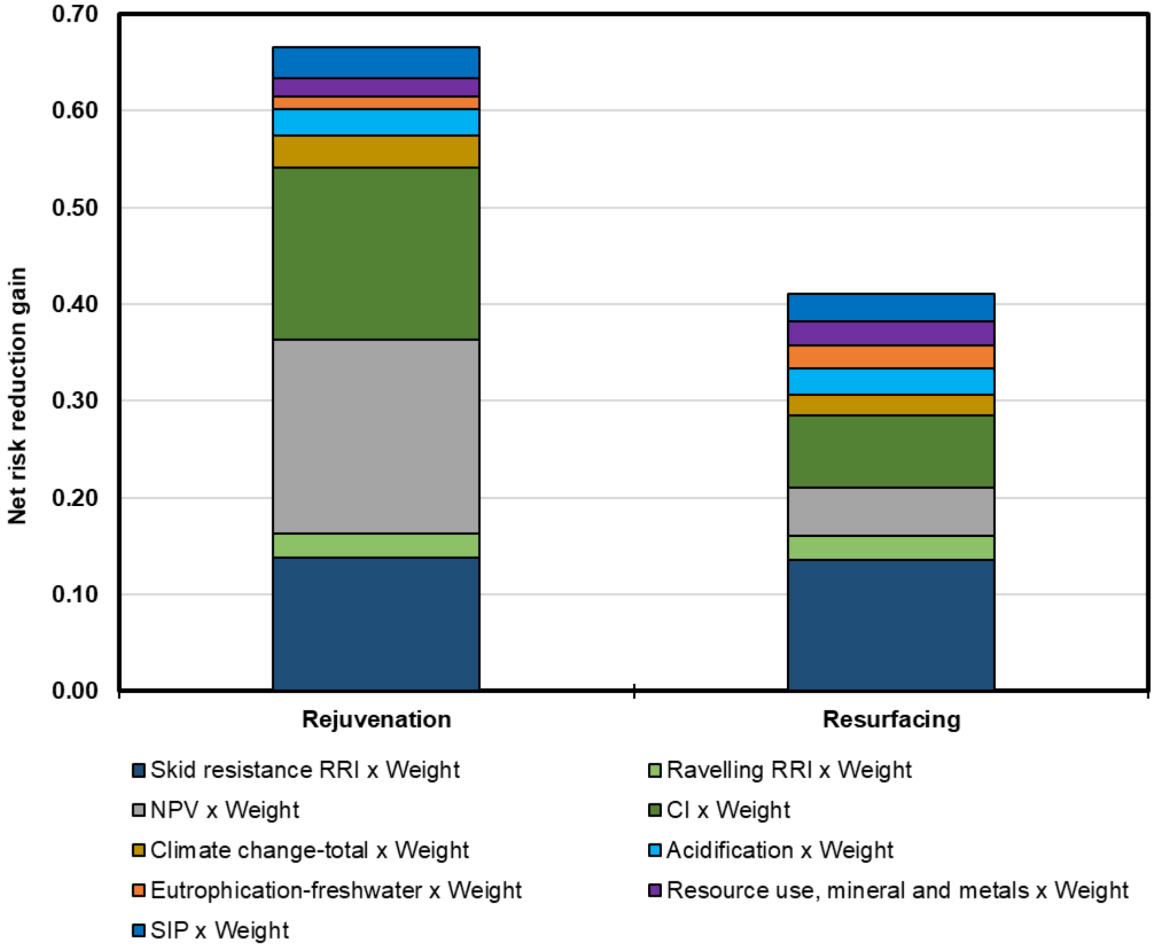


Figure 10. Net Risk Reduction Gain for Porous Asphalt Maintenance Options

6 Case Study Ib: Asphalt – BSM (Denmark)

In this case study, two pavement maintenance alternatives were investigated. The first scenario is based on the concept of using bituminous stabilized materials (BSM) involving reconstruction of base layer with 100% reclaimed materials extracted from the old pavement and small quantity of foamed bitumen (2.2%). The concept of BSM is being used in the DK for construction of rural roads by municipalities and private actors. The second maintenance alternative involves patch repair of binder layer followed by resurfacing.

6.1 Goal and scope definition

The goal of this case study was to compare two maintenance alternatives, i.e., reconstruction of pavement with a bound base layer versus routine resurfacing by integrating the environmental, economic, and circularity dimensions along with assessing the risk associated with their technical performance to select the best solution from a decision-making perspective. To ensure consistency in evaluation, the functional unit for the analysis was a single lane road 1000 m long and 3.5 m wide. For both scenarios, the thicknesses of surface wearing course constructed with Stone Matrix Asphalt (SMA) and Asphalt Concrete Binding Base (hereafter referred to as ABB) layer were 0.034 m and 0.08 m, respectively. Further, the thickness of BSM base layer was 0.20 m. The analysis period for the study was 50 years, and the timeline of different maintenance activities that were considered for the two scenarios are presented in Table 16.

Table 16. Timeline of Various Maintenance Activities

Year	BSM scenario	Routine maintenance
0	Reconstruct with BSM	New wearing course + patch repair
5		New wearing course + patch repair
10		New wearing course + patch repair
15	New wearing course + patch repair	New wearing course + patch repair
20		New wearing course + patch repair
25		New wearing course + patch repair
30	New wearing course + patch repair	New wearing course + patch repair
35		New wearing course + patch repair
40	New wearing course + patch repair	New wearing course + patch repair
45		New wearing course + patch repair
50	(new cycle)	(new cycle)

Note that the initial construction phase (ABB and overlying layers) was excluded from the assessment as it would result in equal impacts for both the alternatives. Further, the EOL phase was not considered in the absence of information pertinent to recycling and disposal of the pavement materials. The system boundaries (Figure 11) for technical performance evaluation, ELCA, LCCA, and circularity assessment were similar. SLCA was not considered in this study due to unavailability of inventory scores for the pavement designed with ABB layer.

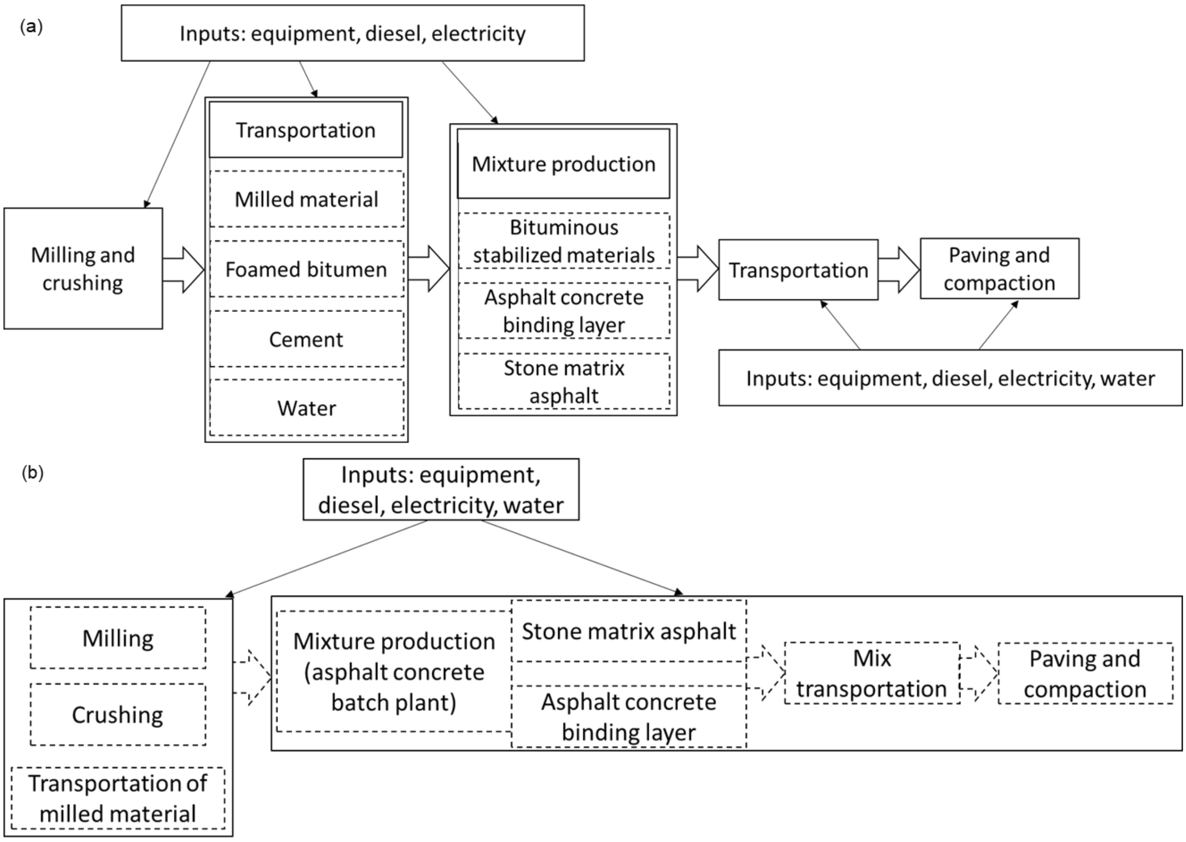


Figure 11. System Boundary for Lifecycle Assessment: (a) Bituminous Stabilized Materials, and (b) Patch Repair and Resurfacing

6.2 Lifecycle inventory

Once the goal and scope were defined, the lifecycle inventory was generated by collecting the data from primary and secondary sources. To collect the primary data, a series of meetings, interviews, and questionnaire surveys were organized with the representatives from different road agencies, material suppliers, and research experts. The sequence of activities performed in the field and associated unit processes were understood. The secondary data was collected from the existing literature specific to the case study, Eurostat's database, and national statistics board. Further, the data quality was verified by cross-checking with multiple data sources specific to the case studies. Additional information relevant to the lifecycle inventory and input values are presented in subsequent sections.

6.2.1 Environment

The inventory of all background data sets used in the modelling of the DK BSM and patch repair and resurfacing cases is presented in Table C 1 of Appendix C. The quality of data gathered for these cases was assessed to be between VG and F for all three metrics.

6.2.2 Lifecycle cost

The quality and source of data collected for the LCCA case study in the DK are indicated in Table C 2 and Table C 3 of Appendix C. Further, the input values for construction of BSM, ABB, and SMA layers are presented in Table C 4. Note that the costs associated with ABB and SMA construction include operations from milling the existing surface until road marking. The input values for estimation of road user costs are presented in Table C 5 of Appendix C.

6.3 Lifecycle impact assessment and interpretation

6.3.1 Environment

The results of ELCA are shown in Table 17. The maintenance of asphalt pavements by replacing the wearing course and performing patch fixing on binding layer resulted in higher impacts for all 15 environmental indicators. Further, the construction of BSM was more detrimental than patch repair and resurfacing. However, for the given analysis period of 50 years, BSM resulted in lower environmental impacts than patch repair and resurfacing attributed to the reduced frequency of maintenance activities. A single BSM treatment on 1 lane-km resulted in emission of 106.92 kg CO_2 eq. compared to 21.05 kg CO_2 eq. for one treatment of patch repair and resurfacing. However, the BSM case requires only 3 patch repair and resurfacing treatments, whereas the traditional patch repair and resurfacing scenario required 10 cycles of maintenance over the same period.

In BSM case, the highest emissions were attributed to the production of binder layer and bitumen (for BSM base production) whose magnitude were 38.29 kg CO_2 eq. and 24.64 kg CO_2 eq., respectively. The hotspot in patch repair and resurfacing scenarios was the construction of wearing course, which accounted for 85.60% of the total emissions, where bitumen and cement filler were the major contributors to emissions.

Table 17. Environmental Impact Scores for BSM and Patch Repair and Resurfacing Scenarios for Maintaining 1 lane-km of Asphalt Pavement

Environmental Impact indicators	BSM	Patch repair and resurfacing
Climate Change - total [kg CO_2 eq.]	170927	212419
Climate Change, fossil [kg CO_2 eq.]	170054	211353
Climate Change, biogenic [kg CO_2 eq.]	693	851
Climate Change, land use and land use change [kg CO_2 eq.]	180	214
Ozone depletion [kg CFC-11 eq.]	5.18E-04	1.05E-03
Acidification [Mole of H+ eq.]	670	719
Eutrophication, freshwater [kg P eq.]	0.276	0.397
Eutrophication, marine [kg N eq.]	181	197
Eutrophication, terrestrial [Mole of N eq.]	1994	2171
Photochemical ozone formation, human health [kg NMVOC eq.]	598	655
Resource use, mineral and metals [kg Sb eq.]	0.029	0.036
Resource use, fossils [MJ]	8.50E+06	1.01E+07
Water scarcity (no hydropower) [m^3 world equiv.]	5724	6814
Water scarcity (only hydropower) [m^3 world equiv.]	1384	1913
Water use [m^3 world equiv.]	7190	8892

IRI was modelled over the same period for both BSM and patch repair and resurfacing scenarios. The same threshold values from the IRI assessment of rejuvenation scenario (0.6 and 3.5 m/km) were used along with the same vehicle volume (i.e. 2589 vehicles/hour) and baseline fuel consumption (0.05 L/km). Figure 12 presents the annual change in IRI and fuel consumption. Since the patch repair and resurfacing scenario does not consider the removal of base material as in the BSM scenario, the condition of the road deteriorates at a much faster rate. Hence, the number of maintenance cycles of patch repair and resurfacing were much higher to ensure desirable stiffness. This resulted in total increased fuel consumption to be of similar magnitude between the two scenarios, with BSM resulting in a 685.48 L increase in diesel consumption, while patch repair and resurfacing resulting in slightly smaller increase (669.36 L) in diesel consumption.

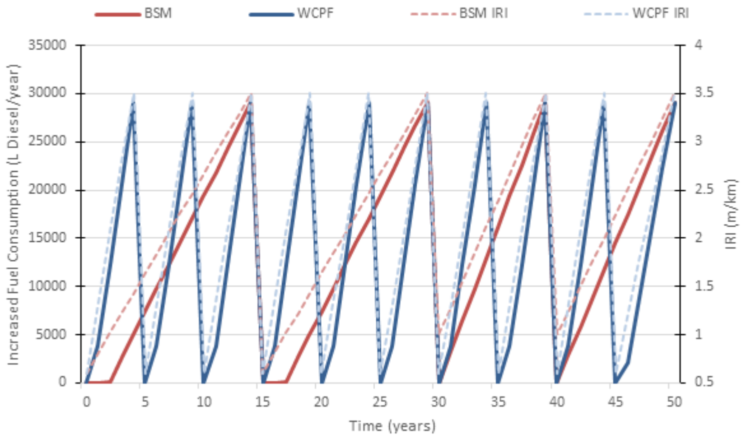


Figure 12. Increased Fuel Use, and Road Roughness plotted Over Time for Both BSM and Patch Repair and Resurfacing Scenarios

The environmental impacts upon consideration of increased fuel consumption are presented Table 18. The differences between the two scenarios with respect to the increased fuel consumption did not differ significantly. However, it must be noted that these values, with respect to climate change, were roughly 10 times higher than the kg CO_2 eq. emissions associated directly with the maintenance processes, consumption of materials, and resources.

Table 18. Environmental Impacts Due to Increased Fuel Consumption With Change in International Roughness Index

Environmental Impact indicators	BSM	Resurfacing
Climate change - total [kg CO_2 eq.]	2132663	2082519
Climate change, fossil [kg CO_2 eq.]	2108815	2059232
Climate change, biogenic [kg CO_2 eq.]	9832	9601
Climate change, land use and land use change [kg CO_2 eq.]	14016	13687
Ozone depletion [kg CFC-11 eq.]	0	0
Acidification [Mole of H+ eq.]	6115	5971
Eutrophication, freshwater [kg P eq.]	11	11
Eutrophication, marine [kg N eq.]	2532	2472
Eutrophication, terrestrial [Mole of N eq.]	29403	28712
Photochemical ozone formation, human health [kg NMVOC eq.]	5550	5420
Resource use, mineral and metals [kg Sb eq.]	0	0
Resource use, fossils [MJ]	27061986	26425696
Water scarcity (no hydropower) [m^3 world equiv.]	127740	124736
Water scarcity (only hydropower) [m^3 world equiv.]	3888	3796
Water use [m^3 world equiv.]	131627	128533

6.3.2 Economic

A deterministic LCCA was undertaken in this study and a discount rate of 4% was used. The initial construction cost of the pavement constructed using BSM technology was 0.37 Million Euros and that for patch repair of ABB and resurfacing with SMA was 0.18 Million Euros. The high initial cost associated with the BSM technology was attributed to the reconstruction of base and ABB layers. Further, the total agency cost associated with the construction of pavement using BSM technology was about 107% higher than patch repair and resurfacing over the analysis period of 50 years. However, the overall maintenance cost (agency and road user) associated with patch repair and resurfacing was about 2 times greater than BSM technology. In particular, both VOC and DC for BSM were about 59% lower than patch repair and resurfacing option. Though road closures are not permitted in the DK, the frequent patching and resurfacing activities (every five years) compared to BSM option lead to an increase in the traffic on adjacent lanes for relatively long durations, thereby causing a reduction in operating speed of vehicles and resulting in higher road user costs. The breakdown of different maintenance costs for the two pavement maintenance alternatives are presented in Table 19. Accident costs were not considered in this study due to the high uncertainty associated with their computation (Santos et al. 2017).

Table 19. Breakdown of Maintenance Costs

Maintenance alternative	Agency costs (Euros)	Vehicle operating costs (Euros)	Delay costs (Euros)	Total (Euros)
BSM concept	367859.60	523989.29	307237.36	1199085.98
Patch repair + resurfacing	177703.87	1271088.07	745037.89	2193829.83

Next, sensitivity analysis was undertaken to understand the potential effects of discount rate on the agency and road user costs, and the results are presented in Figure 13. Each parameter was uniformly varied with respect to the baseline values. The effect of lower (2 and 3%) and higher (5 and 6%) discount rates on the NPV were assessed. The agency costs for BSM were higher than conventional patch repair and resurfacing maintenance scenario at lower and higher discount rates. Further, the road user costs were more sensitive to variations in the discount rate than road agency costs as indicated by their relatively steeper curve. The increase in user costs for patch repair and resurfacing activity was more pronounced than BSM option, highlighting the benefits of minimizing the frequency of maintenance activities during the service life of a pavement.

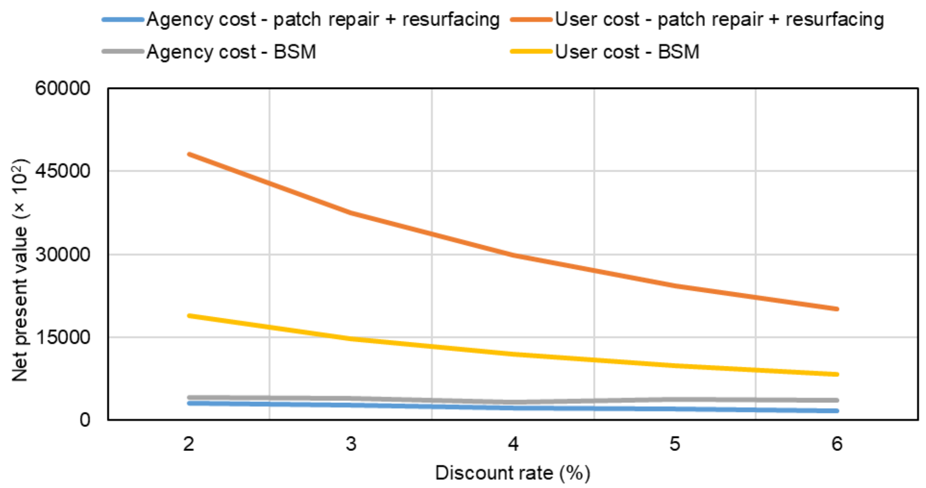


Figure 13. Sensitivity Test Results for Discount Rate

6.4 Circular economy and resource efficiency

In the absence of information relevant to the raw material production, transportation, and recycling costs for the SMA and ABB, the circularity potential of the two alternative pavement maintenance scenarios was determined using MCI, whose methodology is already detailed in section 4.4.1. The inputs and outputs for computation of the MCI for BSM are given in Table 20. In the absence of information on efficiency of recycling process, the data was collected from literature that discussed about sustainability assessment of reclaimed asphalt mixtures (Mantalovas and Di Mino 2020). Further, the MCI results for patch repair and resurfacing scenario are presented in Table 21. The industry average lifespan for the BSM, ABB, and SMA layers was 15 years.

Table 20. Value of Material Circularity Indicator for Bituminous Stabilized Materials Scenario

Mass of recycled material (BSM)	1358	tonne
Mass of recycled material (ABB)	165	tonne
Mass of recycled material (ABB – patch repair)	4.94	tonne
Mass of recycled material – SMA	55.93	tonne
Efficiency of recycling process at the end of use phase	98	%
Efficiency of the recycling process to produce recycled feedstock	100	%

Component \ Material	BSM	ABB				SMA			
		0	15	30	40	0	15	30	40
Mass of virgin feedstock (tonne)	77.49	493.5	14.81	14.81	14.81	223.72	223.72	223.72	223.72
Mass of finished product (tonne)	1435	658	19.74	19.74	19.74	279.65	279.65	279.65	279.65
Amount of waste going to landfill or energy recovery (tonne)	0	0	0	0	0	0	0	0	0
Waste generated at the end of recycling process (tonne)	28.70	13.16	0.39	0.39	0.39	5.59	5.59	5.59	5.59
Waste generated to produce recycled feedstock (tonne)	0	0	0	0	0	0	0	0	0
Amount of unrecoverable waste (tonne)	14.35	6.58	0.20	0.20	0.20	2.80	2.80	2.80	2.80
Product lifespan (years)	50	15	15	10	10	15	15	10	10
Industry average lifespan (years)	50	15	15	15	15	15	15	15	15
Utility	1	1	1	0.67	0.67	1	1	0.67	0.67
Linear flow index	0.52	0.38	0.38	0.38	0.38	0.41	0.41	0.41	0.41
MCI	0.97	0.66	0.66	0.48	0.48	0.63	0.63	0.45	0.45
Average MCI						**0.60**			

Table 21. Value of Material Circularity Indicator for Patch Repair and Resurfacing Scenario

Mass of recycled material (ABB – patch repair)	4.94	tonne
Mass of recycled material – SMA	55.93	tonne
Efficiency of recycling process at the end of use phase	98	%
Efficiency of the recycling process to produce recycled feedstock	100	%

Component \ Material	ABB	SMA
Mass of virgin feedstock (tonne)	14.81	223.72
Mass of finished product (tonne)	19.74	279.65
Amount of waste going to landfill or energy recovery (tonne)	0	0
Waste generated at the end of recycling process (tonne)	0.39	5.59
Waste generated to produce recycled feedstock (tonne)	0	0
Amount of unrecoverable waste (tonne)	0.20	2.80
Product lifespan (years)	5	5
Industry average lifespan (years)	15	15
Utility	0.33	0.33
Linear flow index	0.38	0.41
MCI	0	0
Average MCI	**0**	

A higher MCI was obtained for the BSM scenario attributed to the lower frequency of maintenance activities during its design life, which was consequential of lesser virgin material consumption. Further, an MCI of ‘0’ for the patch repair and resurfacing scenario is indicative of completely linear flow majorly ascribed by the short service life of surface and intermediate layers, which call for frequent maintenance (every 5 years). As a result, higher proportions of virgin raw materials are consumed during the design life of pavement. Therefore, it may be suggested that the NRAs must favour strategies that promote the use of high recycled material and allow the asset to be in place for longer durations, minimizing the overall maintenance activities and contributing to circular pathways.

6.5 Key performance Indicators

This section presents the output values for each criteria that were computed based on the impacts quantified under different assessment categories, which are presented in Table 22.

Table 22. Key Performance Indicators

Assessment categories	**Key performance indicators**	**Units**	**BSM**	**Patch repair and resurfacing**
Environment	Climate change – total	kg CO_2 eq.	170927	212419
	Acidification	Mole of H^+ eq.	670	719
	Eutrophication, freshwater	kg P eq.	0.276	0.397
	Resource use, mineral and metals	kg Sb eq.	0.029	0.036
Cost	Net present value	Million Euros	1.19	2.19
Circular economy and resource efficiency	Material circularity indicator	-	0.60	0

6.6 Integration of key performance indicators in software tool

This step involved integration of the performance metrics computed for various assessment categories into the Excel® based software toolkit. The foremost requirement of the software was to input the generic information such as analysis period, road length, and proposed maintenance schemes. Next, the input format was defined along with the considered assessment categories. Note that little information relevant to the technical KPI for the DK case study was available. However, from discussions with relevant case study owners, it was understood that the technical risks associated with the two maintenance options was equal. In essence, the BSM option was equally efficient in maintaining the structural and functional performance of pavement as that of frequent patch repair and resurfacing. Therefore, the computations associated with the technical performance KPI were not included for quantifying the NRRG.

The KPIs for each assessment category were computed using the same methodology explained in section 5.5 for the NL case studies. A higher KPI value is representative of more beneficial strategy. For MCI, the corresponding scores for least and most favorable ranks were given as 0 and 1. An MCI value closer to zero would indicate nearly linear flow. The KPI values and their corresponding weights are presented in Table 23. Since economy and circularity metrics are anticipated to play a vital role for the recycling activities, the corresponding weights for NPV and MCI were higher than other KPIs.

Table 23. Key Performance Indicators for Pavement Maintenance Methods and Weights Per Assessment Criteria

Key performance indicators	KPI value		Weight	
	BSM	Patch repair and resurfacing	BSM	Patch repair and resurfacing
Climate change-total	0.53	0.25	0.15	0.15
Acidification	0.38	0.30	0.10	0.10
Eutrophication-freshwater	0.45	0.21	0.15	0.15
Resource use, minerals and metals	0.42	0.28	0.10	0.10
Net present value	0.61	0.27	0.30	0.30
Material circularity indicator	0.60	0	0.20	0.20

The NRRG for BSM option was 2.5 times higher than the patch repair and resurfacing maintenance option. As can be seen in Figure 14, the contribution of NPV to NRRG was more pronounced in BSM option as it assisted in minimizing the high expenditure associated with typical maintenance option of patch repair and resurfacing. Another major contributor to the NRRG in BSM option was MCI. However, the contribution of MCI to patch repair and resurfacing was nil attributed to its zero MCI. Though the contribution of environmental KPIs to NRRG was high in both the maintenance methods, it was substantial for BSM option highlighting the benefit of minimizing the frequency of maintenance methods. Overall, it may be suggested that the risks associated with BSM maintenance was much lower than the typical patch repair and resurfacing.

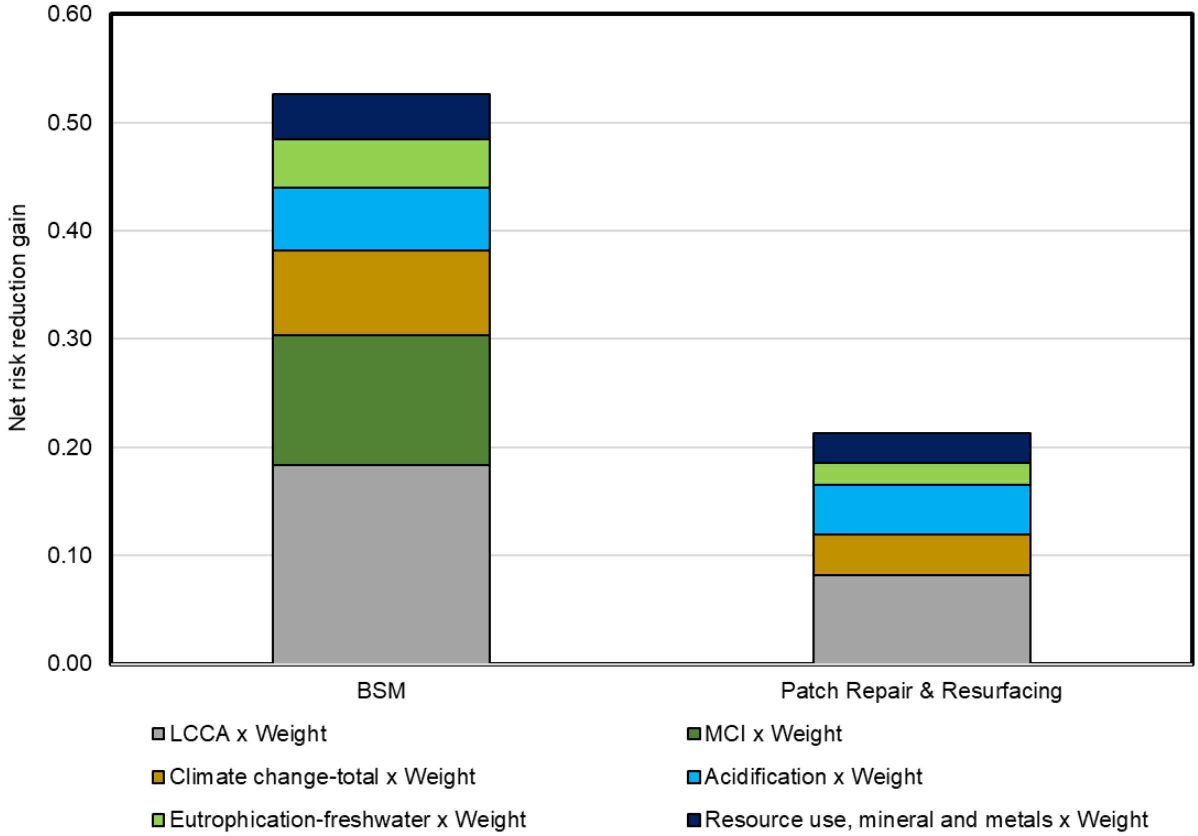


Figure 14. Net Risk Reduction Gain for Bitumen Stabilized Materials and Patch Repair and Resurfacing Pavement Maintenance Options

7 Case Study Ic: Asphalt – High Recycled Content in Surface Course (UK)

In the absence of detailed information relevant to the different assessment categories, the case study of UK was not conducted in this report.

8 Case Study II: Concrete Processing Technologies (the Netherlands)

The generation of Construction and Demolition Waste (C&DW) due to civil engineering works such as maintenance and demolition is one of the major sources of solid waste streams (Gebremariam et al. 2020). C&DW is a source of recycled aggregate and in the NL, recycled aggregate production constitutes about 25% of the total aggregate production. However, a majority of the material is downcycled in the base layers of pavements, attributed to the presence of hydrated mortar over their surface, which restricts its application in pavement surface layers and building works. Recent advancements in the processing technologies have allowed production of high grade Recycled Concrete Aggregates (RCA) and the technical risk associated with such technologies by integrating the circularity with economic, environmental, and social performance.

Therefore, the major aim of this case study was to analyse and compare two EOL concrete recycling technologies, namely, concrete to cement and aggregates (C2CA) and Stationary Wet Processing (SWP). Essentially, C2CA is a mobile recycled concrete processing plant that comprises the following operating units (or equipment): (a) advance dry recovery (ADR) system, which is a sieve that uses kinetic energy to separate fine fractions from coarse aggregates (4-16 mm), and (b) heating air classification system (HAS), which results in clean fine recycled aggregates (0.25-4 mm) and ultrafine cementitious material (< 0.25 mm). In addition, a crushing equipment is employed on-site for reducing the size of EOL concrete between 16 and 32 mm before feeding into the C2CA processing units. SWP is another EOL concrete recycling technology that operates in two phases: (a) dry route, where about 50 mm chunks of crushed concrete are broken into 40-22 mm size, and (b) wet route, where smaller fractions (22-4 mm) are processed in the presence of water to produce clean aggregate fractions, namely, sieve sand (0-4 mm) and clean sand.

8.1 Goal and scope definition

The goal of this study was to compare C2CA and SWP concrete recycling technologies. The different assessment categories included environmental, economic, circularity, and social aspects. In addition, the risks associated with the technical performance of the recycled aggregates produced from two technologies were discussed. The declared unit was defined as the processing of 1 tonne source separated clean EOL concrete fraction from C&DW having size lower than 50 mm. The system boundary considered for the two scenarios is presented in Figure 15. Further, the different inputs (such as water and energy) associated with the transportation and processing of C&DW as well as the various output materials (e.g., aggregates, sand, steel scrap, etc.) generated through recycling are shown in Figure 15. With regards to the SLCA, only the material processing activity (excluding transportation of crushed concrete or the recycling facility to C&DW site) within the recycling plants was considered as the inventory data was dependent on the judgement of experts (research and technological) and did not consider the volume of material flowing in and out of the process.

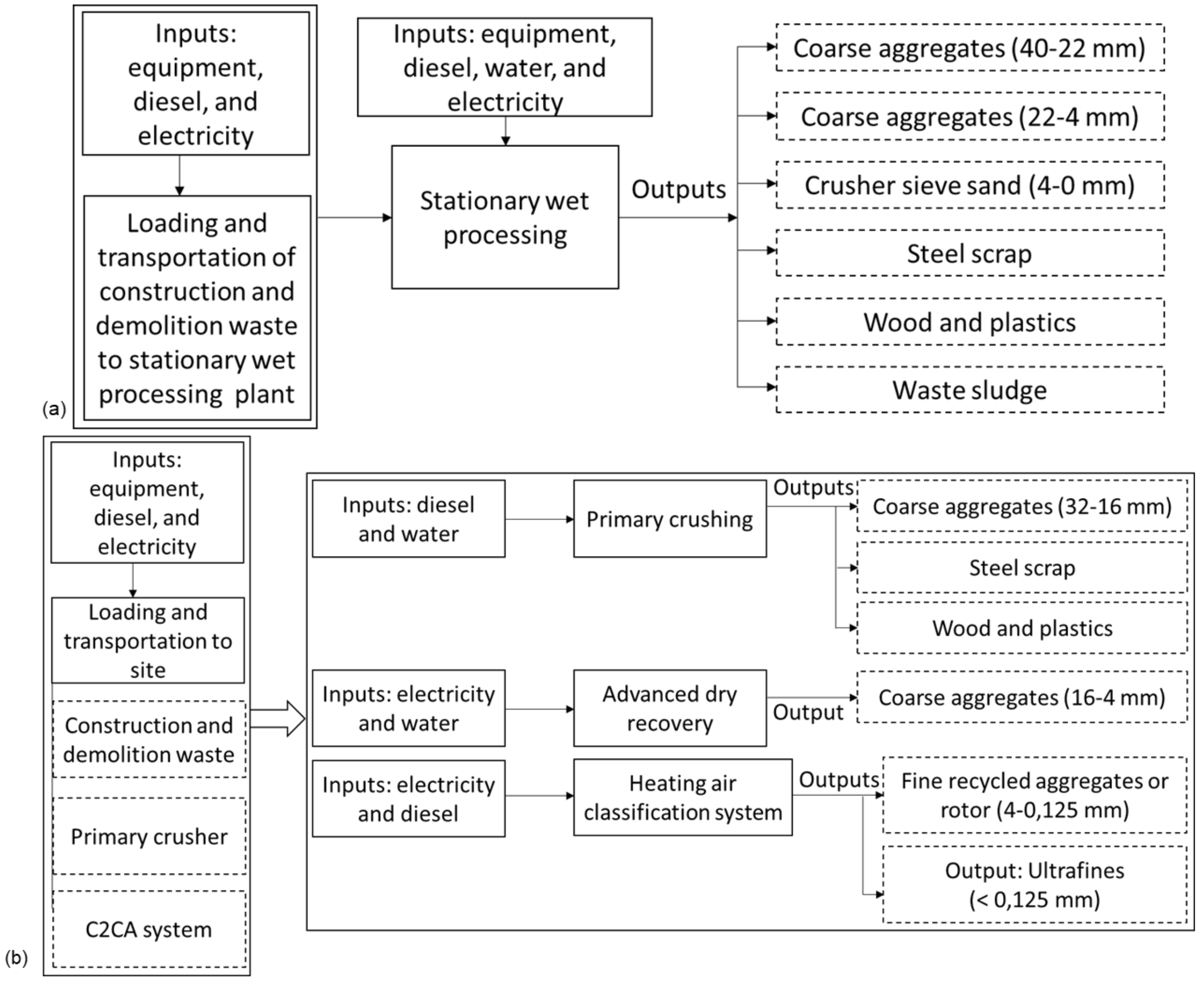


Figure 15. System Boundary for: (a) Stationary Wet Processing, and (b) Concrete to Cement and Aggregates

8.2 Lifecycle Inventory

The inventory data was collected from series of reports and publications available on SWP and C2CA technologies (Gebremariam et al. 2020; Hu and Kleijn 2013; Koullapis 2022; Moreno-Juez et al. 2020; Zhang et al. 2019). The economic data collection in these reports was performed with the support of relevant industry stakeholders.

8.2.1 Environment

Table D 1 (Appendix D) presents the ELCA inventory for processing C&DW using C2CA and SWP processing technologies. The data quality was evaluated by using the procedure as explained before in section 5.2.1. The quality of data gathered in this inventory was assessed to be between VG and F by its geographic, time, and technological relevance. No data was available for the flocculent, which is used for sedimentation during treatment of wastewater from SWP. Therefore, a proxy thickening agent was used because of its similarity to flocculants. Hence, the data was of lower quality as it had a higher degree of uncertainty. The information relevant to the energy, fuel, and water consumption in the stationary wet processing plant and C2CA unit is provided in Table D 2.

8.2.2 Economic

The LCCA was conducted in accordance with the steps detailed in the SETAC guide 'Environmental Life Cycle Costing: A Code of Practice' (Swarr et al. 2011). Although, the SETAC guide is based on the same principle as that for ELCA (ISO: 14040 2006) it does not consider the impact assessment phase as the inventory data is expressed in a single measuring unit, namely, currency. However, in concrete processing technologies, the costs include processing as well as the revenue generation. Therefore, an impact assessment phase was included in this research, which involves breakdown of cost into different components to evaluate the economic impacts of processing technologies (Zhang et al. 2019). The LCCA shared a similar system boundary as that for ELCA. The concrete recycling costs comprise three lifecycle phases, namely, transportation, recycling, and secondary material production. Further, the costs can be categorized into five different components as transportation charges (TC), equipment cost (EC), personnel cost (PC), utility charges (UC), and waste treatment charges (WTC). Therefore, the lifecycle cost can be estimated using Equation (24), which would assist in understanding the costs associated with each category during concrete recycling. Further, it is considered that the costs incurred during processing and benefits gained from selling the recycled products occur within a short period of time. Hence, a static-type LCCA model was used and discount rate was not applied over the costs and benefits.

$$Lifecycle\ cost\ for\ concrete\ processing = TC + EC + PC + UC + WTC \tag{24}$$

The different inputs that were used to compute the processing and output material costs are presented in Table D 3 in Appendix D. Since the data relevant to various economic aspects was distributed over different years, all the prices were converted to the present year market prices using the inflation rate between those periods. Although this may not reflect the actual prices of different products and units, it ensures a rational comparison between the processes provided there are no technological breakthroughs that led to substantial differences in cost of one material over another. It was assumed that both SWP plant and C2CA unit operated for 8 h per day, 250 working days in a year for 10 years. Based on productivity rate, the annual capacity of SWP, ADR, and HAS units were 300000, 100000, and 6000 T/year, respectively.

8.2.3 Social

In the absence of relevant information, a qualitative assessment was undertaken and the data for SLCA indicators corresponding to SWP and C2CA technologies is presented in Table D 4 in Appendix D. The indirect indicator scores were obtained from two researchers and one academic expert. Note that only a selected number of indicators were adopted in this study, which may be expanded in future depending on data availability.

8.3 Lifecycle impact assessment and interpretation

8.3.1 Environment

The environmental lifecycle impacts for C2CA and SWP technologies were calculated using the same methodology as described earlier in section 5.2.4.1 and the results are presented in Table 24. The results indicated that SWP performed better than C2CA in most of the impact categories. In both cases, the most significant environmental benefit was derived from the 44 kg of steel scrap recovered from C&DW, which avoids 76 kg CO_2 eq. for every tonne of C&DW processing. In addition, the C2CA technology allowed for recovering 83 kg of ultrafine aggregates from 1 tonne of C&DW, which can replace cement, thereby avoiding 70 kg of CO_2eq. In SWP, the largest contributor to climate change comes from the incineration of recovered wood, which resulted in 16.8 kg of CO_2 eq. In comparison, the same incineration process in C2CA emitted only 8.40 kg of CO_2 eq. as it recovered only half the amount of wood.

The emissions due to transportation (50 km) of C&DW from the site to the SWP plant were 4.7 kg CO_2 eq. per tonne. In C2CA, the most significant contributor to climate change was the transportation of HAS and ADR mobile systems on site (about 151 kg CO_2 eq.) followed by thermal energy (6.9 kg CO_2 eq.) that was used for operating the HAS. The climate change benefits provided by C2CA's novel ability to recover cement were outweighed by the large upfront impact of transporting the C2CA system on site.

Table 24: Environmental Impact Scores for C2CA and SWP

Environmental Impact indicators	C2CA	SWP
Climate change - total [kg CO_2 eq.]	20.73	-63.4
Climate change, fossil [kg CO_2 eq.]	14.5	-71.7
Climate change, biogenic [kg CO_2 eq.]	5.35	8.37
Climate change, land use and land use change [kg CO_2 eq.]	0.90	0.02
Ozone depletion [kg CFC-11 eq.]	1.32E-07	1.15E-07
Acidification [Mole of H+ eq.]	0.99	-0.13
Eutrophication, freshwater [kg P eq.]	4.70E-04	1.25E-05
Eutrophication, marine [kg N eq.]	0.29	-0.02
Eutrophication, terrestrial [Mole of N eq.]	3.32	-0.15
Photochemical ozone formation, human health [kg NMVOC eq.]	0.79	-0.09
Resource use, mineral and metals [kg Sb eq.]	-1.76E-04	-1.88E-04
Resource use, fossils [MJ]	1167	-657
Water scarcity (no hydropower) [m^3 world equiv.]	-107	-107
Water scarcity (only hydropower) [m^3 world equiv.]	93.3	93.6
Water use [m^3 world equiv.]	-13.6	-13.1

The climate change benefits provided by C2CA's novel ability to recover cement were outweighed by the large upfront impact of transporting the C2CA system on site. This was attributed to the small functional unit considered herein. Therefore, a sensitivity test (Figure 16) was performed on the functional unit, which suggested that C2CA outperforms SWP once the quantity of C&DW processed was larger than 2.25 tonnes.

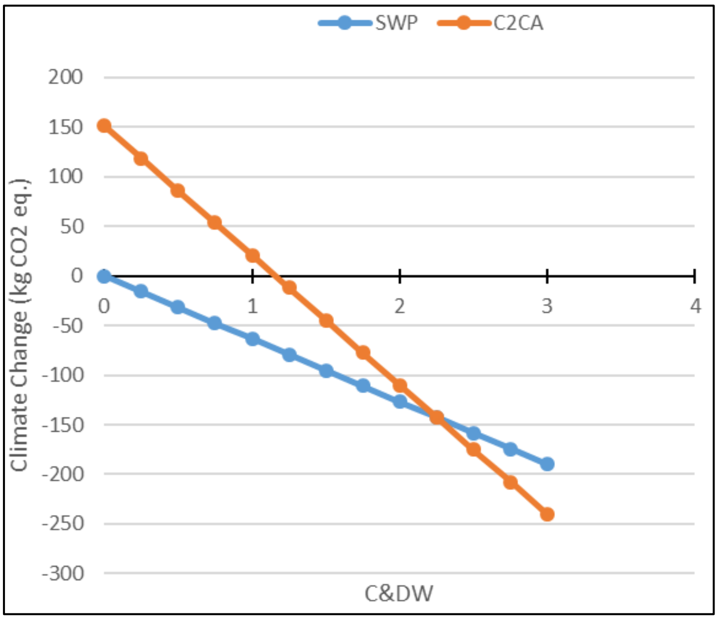


Figure 16: Sensitivity of Climate Change Indicator to Change in Functional Unit, Mass of Construction and Demolition Waste

8.3.2 Economic

Since C2CA and SWP technologies result in the production of materials with similar sizes, it was essential to understand the costs incurred during the different lifecycle phases of these processing methods. Table 25 and Table 26 show the breakdown of different costs associated with the C2CA and SWP concrete processing technologies. The EOL concrete crushing cost for C2CA technology was 12% higher than SWP. The higher costs of C2CA were majorly attributed to the use of diesel to run the HAS, which accounted for almost 66% of the total expenditure. Other researchers have also suggested that there is a need to utilize cleaner energy sources such as biofuels to improve the operational efficiency of the HAS and minimize the overall costs (Koullapis 2022). In SWP technology, the transportation of raw materials (EOL concrete) to the plant was the major contributor to costs (38%) followed by capital investments (29.21%). On the other hand, transportation cost of C2CA system was about 31 times lower than SWP technology attributed to the absence of transportation phase from C&DW site to the plant.

Table 25. Cost Associated with Cement to Concrete and Aggregates Technology for Processing 1 tonne End-of-life Concrete

<table>
<tr><td colspan="7">Transportation cost of ADR and HAS for processing EOL concrete (Euros)</td><td>0.16</td></tr>
<tr><td rowspan="3">Capital investment</td><td>Unit</td><td colspan="2">Depreciation (Euros/h)</td><td>Working hours</td><td>Working days</td><td>Years</td><td>Total (Euros)</td></tr>
<tr><td>ADR</td><td colspan="2">100.48</td><td rowspan="2">8</td><td rowspan="2">250</td><td rowspan="2">10</td><td>2009600</td></tr>
<tr><td>HAS</td><td colspan="2">17.68</td><td>353600</td></tr>
<tr><td colspan="7">Capital investment of ADR and HAS system (Euros)</td><td>2.36</td></tr>
<tr><td colspan="7">Maintenance cost of ADR system (Euros)</td><td>1.26</td></tr>
<tr><td colspan="7">Maintenance cost of HAS system (Euros)</td><td>0.18</td></tr>
<tr><td colspan="7">Certification and insurance cost of ADR and HAS system (Euros)</td><td>0.09</td></tr>
<tr><td rowspan="3">Utility</td><td colspan="2">Primary crusher</td><td colspan="2">ADR</td><td colspan="2">HAS</td><td rowspan="2">Total (Euros)</td></tr>
<tr><td>Diesel charges (Euros)</td><td>Water charges (Euros)</td><td>Electricity charges (Euros)</td><td>Water charges (Euros)</td><td>Electricity charges (Euros)</td><td>Diesel charges (Euros)</td></tr>
<tr><td>0.22</td><td>0.14</td><td>0.058</td><td>0.14</td><td>0.001</td><td>9.31</td><td>9.82</td></tr>
<tr><td rowspan="2">Personnel</td><td>Weighting of in and outgoing truck</td><td>Crane operator</td><td>Loader operator</td><td>Crusher operator</td><td>Plant operator</td><td>Labor charges (Euros/man h)</td><td>Total (Euros)</td></tr>
<tr><td>0.7</td><td>1</td><td>0.4</td><td>1</td><td>1</td><td>35.9</td><td>1.09</td></tr>
<tr><td colspan="7">Total processing cost (euros/T)</td><td>14.96</td></tr>
</table>

Table 26. Cost Associated with Stationary Wet Processing Technology to Recycle 1 tonne End-of-life Concrete

<table>
<tr><td colspan="7">Capital investment of SWP (Euros)</td><td>4.04</td></tr>
<tr><td colspan="7">Maintenance cost of SWP (Euros)</td><td>1.26</td></tr>
<tr><td colspan="7">Insurance and certification cost (Euros)</td><td>0.40</td></tr>
<tr><td colspan="7">Site rental (Euros)</td><td>0.40</td></tr>
<tr><td colspan="7">Auxiliary material (Euros)</td><td>0.02</td></tr>
<tr><td rowspan="2">Transporting EOL concrete</td><td colspan="2">Charges (Euros)</td><td colspan="2">Distance (km)</td><td colspan="2">Quantity (T)</td><td>Cost (Euros)</td></tr>
<tr><td colspan="2">0.1</td><td colspan="2">50</td><td colspan="2">1</td><td>5</td></tr>
<tr><td rowspan="2">Utility</td><td>Power (kWh/T)</td><td>Diesel (L/T)</td><td colspan="2">Electricity charges (Euros)</td><td colspan="2">Diesel charges (Euros)</td><td>Total (Euros)</td></tr>
<tr><td>4</td><td>0.27</td><td colspan="2">0.504</td><td colspan="2">0.448</td><td>0.95</td></tr>
<tr><td rowspan="2">Personnel</td><td>Weighting of in and outgoing truck</td><td>Crane operator</td><td>Loader operator</td><td>Ground operator</td><td>Plant operator</td><td>Labor charges (Euros/man h)</td><td>Total (Euros)</td></tr>
<tr><td>0.8</td><td>1</td><td>0.4</td><td>0.9</td><td>1</td><td>35.9</td><td>0.96</td></tr>
<tr><td rowspan="2">Sludge disposal</td><td colspan="2">Kemira A120 charges (Euros)</td><td colspan="2">Citex 493 charges (Euros)</td><td>Water (Euros)</td><td>Disposal charges (Euros)</td><td>Total (Euros)</td></tr>
<tr><td colspan="2">0.023</td><td colspan="2">0.003</td><td>0</td><td>0.17</td><td>0.20</td></tr>
<tr><td colspan="7" align="right">Total processing cost (Euros/T)</td><td>13.23</td></tr>
</table>

Since new products were generated through the two recycling technologies, the next step involved assessment of the revenue that was produced from C2CA and SWP recycling, and the results are presented in Table 27. Though different EOL products are generated from the two processes, this step will assist in understanding the economic benefits associated with the use of EOL products in civil engineering works. The assessment was based on the amount of virgin raw materials that could be replaced in the market supply chain with products of SWP and C2CA. The proportion of each recycled fraction is also presented in Table 27. The revenue generated by the products obtained from C2CA technology were 1.31 times higher compared to SWP. This was attributed to the production of cleaner fine fractions in the C2CA unit, whose net selling price was 4.92 times higher compared to fine products of SWP technology.

Further, the value added by each concrete recycling technology was computed as the difference between the associated processing costs and corresponding revenues. Therefore, use of C2CA technology resulted in value addition of 10.56 Euros for processing 1 tonne recycled material, while the value addition from SWP unit was 6.31 Euros/T. This indicates that though the initial processing costs with C2CA process were higher than SWP, it is more cost-effective as the selling price of recycled materials was superior to those from SWP.

Table 27. Revenue Generated from Stationary Wet Processing Technology and Concrete to Cement and Aggregates to Recycle 1 tonne End-of-life Concrete

Product	**Proportion (%)**	**Cost (Euros)**	**Application**
Cement to concrete and aggregates			
Coarse aggregates (32-16 mm)	25.73	3.57	Concrete aggregates
Coarse aggregates (16-4 mm)	28.17	3.90	
Rotor* (1-0.125 mm)	33.14	1.04	Fine concrete aggregates
Ultrafines (less than 0.125 mm)	8.28	6	Cement replacement
Steel	4.37	11.01	-
Revenue generated		**25.52**	
Stationary wet processing			
Coarse aggregates (40-22 mm)	51.34	7.12	Concrete aggregates
Coarse aggregates (22-4 mm)			
Crusher sieve sand (4-0 mm)	38.04	1.20	Road base aggregates
Clean sand (4-0.63 mm)	5.14	0.23	Asphalt mix production or road base aggregates
Steel	4.36	10.99	-
Revenue generated		**19.54**	

**Rotor – clean fine recycled concrete aggregate fractions with particle size between 1 and 0.125 mm*

8.3.3 Social

The scores for different impact indicators and stakeholders are presented in Figure 17. For C2CA, the society had highest contribution to the social impacts followed by consumer and local community. The higher social impacts for society stakeholder were attributed to the use of advanced technological systems that result in production of high quality raw materials that could be used in varied civil engineering works. Further, the recycling industry (C2CA) is constantly looking for partnership with research and innovation groups, thereby contributing to higher social impacts. In addition, sludge is not produced during the C2CA process, thereby minimizing the landfilling or waste disposal requirements and resulting in higher social impacts than SWP. For the worker stakeholder, the exposure to dust was slightly lower in SWP technology than C2CA mainly due to the use of water during processing. Further, recycling through C2CA is performed at the C&DW site, which might generate higher dust than working at SWP plant.

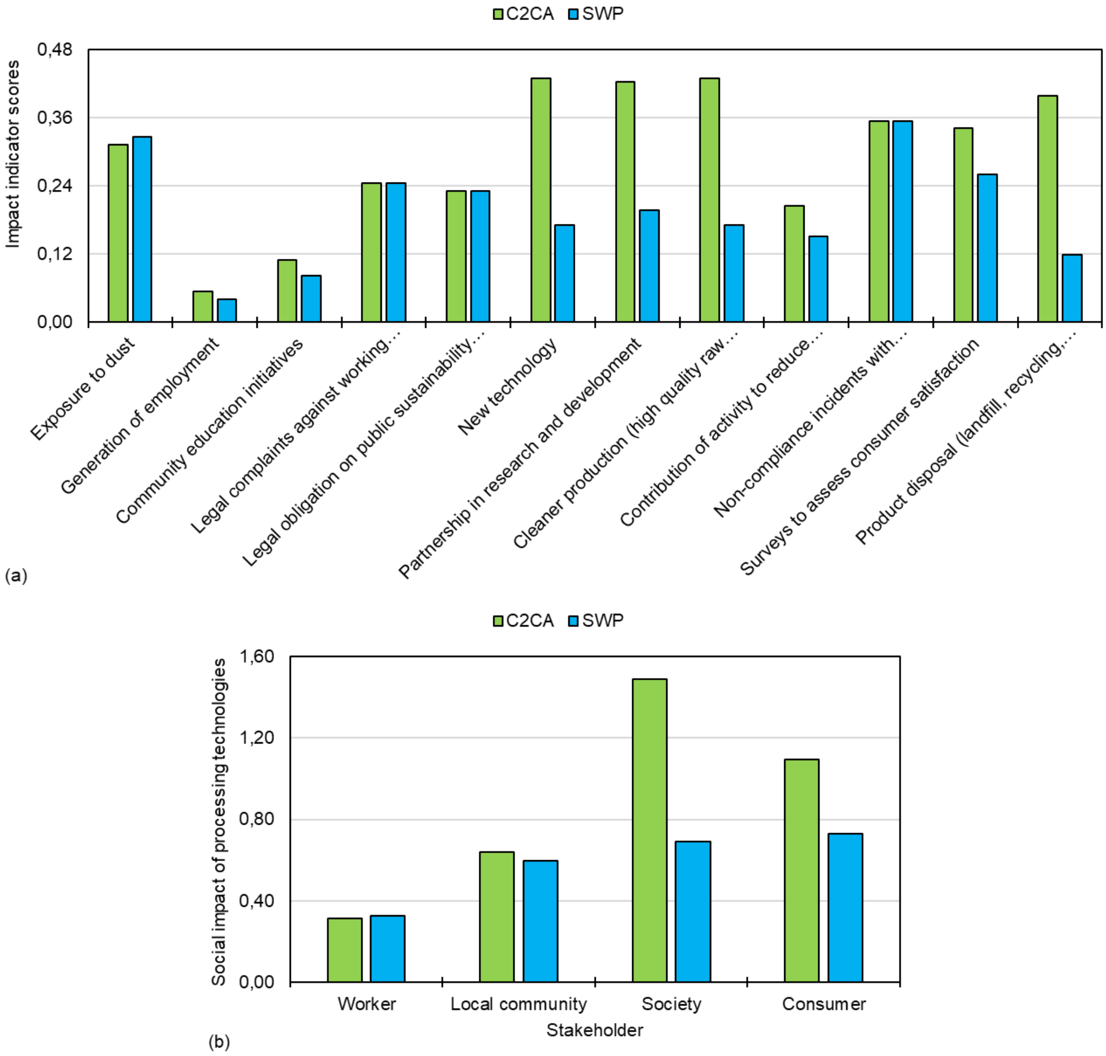


Figure 17. Social Impact of Concrete Processing Technologies: (a) Impact Indicator Scores, and (b) Stakeholder Scores

8.4 *Circular economy and resource efficiency*

The circularity potential of the two processing technologies was determined using two indicators, i.e., CEI and MCI as already discussed in the methodology section (refer to Section 4.4).

8.4.1 Circular economy index

For CEI, the material as well as processing costs that were presented in Sections 8.2.2 and 8.3.2 were used. Since the CEI is better suited to recycling activities, it was not essential to compute the depreciating expense of the materials. Instead, the material value added was given as difference between the recycling firm revenues and processing costs. The material costs needed to reproduce the EOL product are presented in Table 28. In the absence of relevant information, a transportation distance of 20 km was assumed for all material procurement. Further, the cost of transportation per product was assumed as 0.1 Euros/T-km. Note that the EOL product comprised 95.31% crushed concrete (Hu and Kleijn 2013) whose mix proportions were gathered from the literature (Moreno-Juez et al. 2020). The results for C2CA and SWP are presented in Table 29.

Table 28. Material Cost to Reproduce 1 tonne End-of-life Product

Material	Proportion (%)	Quantity (tonnes)	Cost (Euros/T)	Cost (Euros)	Transport (Euros)	Total cost (Euros)
Coarse aggregates	37.58	0.3758	13.86	5.21	0.75	5.96
Fine aggregates	31.13	0.3113	13.86	4.31	0.62	4.94
Limestone	6.04	0.0604	309.4	18.59	0.12	18.81
Cement	13.88	0.1388	85	11.80	0.28	12.08
Water	6.68	0.0668	2	0.13	0.13	0.27
Wood	0.29	0.003	30	0.09	0.01	0.09
Plastics	0.02	0.0002	500	0.10	0.00	0.10
Steel	4.37	0.044	500	21.85	0.09	21.94
Non-ferrous	0	0	1000	0.00	0.00	0.00
Total	100	1.000	2454.12	62.18	2	64.18

Table 29. Results of Circular Economy Index for Concrete Processing Technologies

Technology	Processing costs (Euros)	Revenue (Euros)	Value added (Euros)	Material value for reproducing EOL product (Euros)	CEI
C2CA	14.96	25.52	10.56	64.18	0.16
SWP	13.23	19.53	6.30		0.09

As observed from Table 29, when EOL concrete was recycled using C2CA technology, a higher CEI was obtained than SWP. For the case of pavement maintenance (LVOv case study), a higher negative CEI (which in essence indicates a number of lower order), was consequential of greater virgin material consumption and low RE and CE. However, for a typical material recycling scenario, where the revenue generated is anticipated to be higher than the processing costs, a higher positive CEI would reflect greater RE and CE. In simple words, a greater CEI is indicative of better RE and CE. A lower CEI was obtained for SWP technology, which reflects the lower quality of secondary materials (as reflected by their market value and point of application) produced during recycling. Further, five different recycled products were obtained from C2CA while the SWP resulted in four secondary materials. As can be seen from Figure 18, both technologies produced coarse recycled aggregates that could be used in similar applications (e.g.: mixtures with similar grade of concrete) with C2CA being 4.98% more productive than SWP. Further, the quality and quantity of sand (4-0.125 mm for C2CA) and cementitious particles (ultrafines) obtained through C2CA were higher allowing for their valorization in concrete mixtures and surface wearing course layers of pavement, unlike SWP, which resulted in production of sand suitable for application only in road base layers. Although the mass of ultrafines and recovered steel from C2CA was very small compared to other secondary products, their contribution to the value addition was the highest. This demonstrates the strength of CEI to capture the RE based on material quantity and its quality, which is driven by the market forces such as scarcity versus competition and damage to the environment and society during their production.

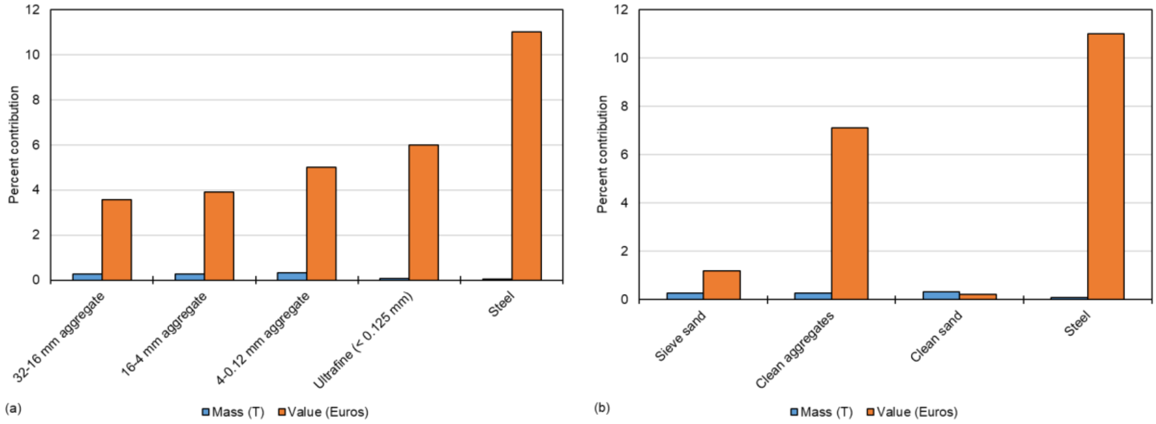


Figure 18. Percent Contribution of Mass and Value: (a) Concrete to Clean Aggregates and Cement, and (b) Stationary Wet Processing

8.4.2 Material circularity indicator

An Excel® based MCI tool developed by 'thinkstep-anz' (thinkstep-anz 2006) that is based on the Ellen McArthur's methodology detailed in Section 4.4.1 was used for mass-based circularity assessment. The material proportions stated in Table 28 were used as inputs. Further, the source of each input material (virgin, recycled, or remanufactured) was defined and the collection rate of each component material at the EOL of the product was identified. It was assumed that the materials (except wood and plastics) are being recycled in a pavement having design life of 15 years. In addition, the industry average lifespan of the pavement was also assumed as 15 years (typical for flexible pavements), thereby resulting in a utility factor of 1. The MCI scores for the two recycling processes are presented in Table 30.

Table 30. Material Circularity Indicator Scores for Concrete Processing Technologies

Material	**EOL treatment**	**MCI score for each component**			
		Collection rate (%)	**C2CA**	**Collection rate (%)**	**SWP**
Coarse aggregates	Recycle	53.90	0.31	51.34	0.30
Fine aggregates		33.14	0.23	43.18	0.27
Limestone		0	0.10	0	0.10
Cement		8.28	0.13	0	0.10
Wood		0.29	0.10	0.29	0.10
Steel		4.37	0.12	4.37	0.12
Plastics	Landfill	0.03	0.10	0.03	0.10
Water	Landfill (sludge)	-	-	0.57	0.10
MCI		***0.18***		***0.23***	

In general, a higher MCI score was assigned to the aggregates compared to other materials that were also a part of the recycling process. This was attributed to the presence of higher proportion of aggregates in concrete mixtures compared to other elements. Further, the quantity of recycled aggregates produced through C2CA were higher than SWP, resulting in a high MCI score. In addition, the quantity of steel recycled in both process was similar resulting in equal MCI.

The limitation of MCI lies in the fact that despite steel and cement being two major contributors for high environmental, economic, and social impacts compared to aggregates in concrete, their circularity scores were lower. In other words, mass-based approach provides a lower incentive to valorize cement and steel at the EOL. Further, MCI assumes that the quality of products remains constant over time, i.e., the scrap value of secondary material is same as that of the virgin material, which is not true. Note that the clean aggregates produced from C2CA technology can be used to replace 100% aggregates in a concrete mix, and ultrafines could replace up to 5% of cement. However, only the coarse fraction obtained from SWP can be used to replace a certain proportion of aggregates, and the fine aggregates are suitable for downcycling in road base layers, which require inferior quality of products. Hence, the value added by the production of secondary materials from C2CA was higher than SWP attributed to their ability to replace large proportions of virgin raw materials in mixtures with first grade applications, minimizing extraction of natural resources, thereby promoting RE and CE.

8.5 Technical performance and cost of consequences

As the major goal of this deliverable was to quantify the risks associated with pavement construction and maintenance, a hypothetical scenario was designed such that the recycled aggregates from two processing technologies were used to prepare asphalt concrete pavement mixtures. The proportion of coarse and fine aggregates in the mix were considered as 59.7 and 34%, respectively (Zhang et al. 2021).

Polished Stone Value (PSV) of the aggregates was used as the technical KPI to evaluate the risks associated with different recycling technologies. Since the tool requires assessment of the risk associated with different maintenance activities in the form of probability of exceedance of a certain limit state and associated consequences in terms of costs,, attempts were made to relate PSV with crash rate as already discussed in Section 5.3. The quality of raw materials produced in the recycling facilities is generally ascertained by quantifying their physical characteristics such as specific gravity, water absorption, abrasion value, and impact resistance. No major attempts are made to assess their polishing value, which is an important criterion for pavement safety. Therefore, literature survey was conducted to identify the relationships between aggregate properties and PSV. Note that the technical data for aggregates produced only through the C2CA technology was available with no information on aggregate characteristics produced from SWP.

Next, the model that predicts PSV based on the aggregate water absorption (Equation (25)) was used (Đokić et al. 2015). Although models that correlate mechanical properties (impact and abrasion) of coarse aggregates with PSV were available, such tests are performed only on coarse fractions. Researchers have suggested that the water absorption of coarse and fine aggregates produced from C2CA was 6.2 and 7.6%, respectively. Although the water absorption of recycled aggregates is high, they satisfy the permissible limits for impact and abrasion tests (< 30%), and have performed satisfactorily in the concrete mixtures without signs of premature deterioration (Gebremariam et al. 2021; Moreno-Juez et al. 2020). Hence, it is claimed by the researchers that the aggregates can be suitably used in pavement surface layers. However, additional tests such as resistance against chemical agents must be performed in future to build higher confidence on their application.

The coarse aggregates derived from both C2CA and SWP technologies are suitable for similar applications in concrete and possess same economic value. Therefore, it was reasonable to assume that the secondary coarse aggregates from C2CA and SWP possess similar characteristics (specific gravity, water absorption, abrasion value). Hence, the water absorption of coarse aggregates generated from SWP was considered to be the same as that for C2CA (6.2%), and the water absorption of virgin fine aggregates was taken as 0.3% (Gebremariam et al. 2021). The average water absorption of the aggregate blends for mixtures comprising recycled aggregates from C2CA and SWP was determined in accordance with AASHTO T85 (AASHTO T 85 2022), which was inputted into Equation (25) to get the PSV.

$$PSV = 54.076 + (1.731 \times WA) \quad (25)$$

Where,
PSV = polished stone value, and
WA = water absorption (%).

The PSV of recycled aggregates from C2CA and SWP technologies were reported as 65 and 61, which was higher than the minimum requirement of 58 for Dutch highways (Vos et al. 2017). Further, a do-minimum scenario was created (an arbitrary scenario with no maintenance after the EOL) to compare the risks associated with designing pavements with recycling materials. An analysis period of 12 years (typical ZOAB inlay design life) was chosen such that the surface layers of two pavement systems were replaced with recycled materials from two processing technologies. Next, the SI in base year was determined using Equation (26) (Szatkowski and Hoskings 1972; Vaiana et al. 2012), which was later used to predict the crash rates and associated risks as per the framework already detailed in Section 5.3.1. The initial SI for the do-minimum scenario was considered as 0.44, which was equivalent to the SI of ZOAB overlay after the EOL of 12 years (see Table B 7). The crash rates and risk (expressed in million Euros) associated with the three scenarios are presented in Table 31. Further, the annual crash rates and associated risk for the do-minimum case and use of recycled aggregates from C2CA and SWP technologies are presented in Appendix D in Table D 5, Table D 6, and Table D 7, respectively.

$$MSSC = 0.024 - (0.0000663 \times CVD) + (0.010 \times PSV) \quad (26)$$

Where,
MSSC = mean summer SCRIM coefficient,
CVD = commercial vehicles per lane per day (assumed as 2000), and
PSV = polished stone value

Table 31. Total Risk (costs) Associated with the Do-minimum Case and Use of Recycled Aggregates from C2CA and SWP Technologies

Maintenance scenario	Fatality cost (million Euros)	Serious injury cost (million Euros)	Minor injury cost (million Euros)
Do-minimum	5.7	21.0	6.5
SWP	3.6	13.3	4.1
C2CA	2.7	9.9	3.0

As observed from Table D 5 to Table D 7 (Appendix D), the crash rates or the associated cost of consequences (risk) increased with a decrease in SI. Further, the SI was dependent on the PSV, which was highest for the virgin aggregates followed by recycled aggregates from C2CA and SWP technologies. This further confirms that the secondary aggregates derived from C2CA technology offer higher technical advantages over a prolonged period attributed to the 100% recyclability and better resistance to surface wear. However, predictive models must be created in future to establish relationship between pavement surface texture, skid resistance, and crash rates specific to the conditions of the Netherlands.

8.6 Key performance indicators

This section presents the output values for each criteria that were computed based on the impacts quantified under different assessment categories, which are presented in Table 32.

Table 32. Input Values for Key Performance Indicators

Assessment categories	Key performance indicators	Units	C2CA	SWP
Environment	Climate change - total	kg CO_2 eq.	20.73	-63.35
	Acidification	Mole of H^+ eq.	0.99	-0.13
	Eutrophication, freshwater	kg P eq.	0.00047	0.00001
	Resource use, mineral and metals	kg Sb eq.	-0.00018	-0.00019
Cost	Material value added	Euros/T	14.47	6.30
Circular economy and resource efficiency	Circular economy index	-	0.23	0.10
	Material circularity indicator	-	0.18	0.23
Social	Social impact of pavements	-	3.54	2.44

8.7 Integration of key performance indicators in software tool

The performance metrics computed for various assessment categories were integrated into the Excel® based software toolkit, which was developed as part of the CERCOM project. The fundamental approach adopted to input the data was same as that explained before in Section 5.5 for the ZOAB case study. Once the generic information along with the input format was defined, the risk associated with different maintenance options was entered in the tool in terms of probability of collision and associated cost of consequences. Next, the ranked interpolation system was used to compute KPI for each assessment category by assuming a linear relationship (two ranks – zero and one) between the minimum (most favorable output) and maximum (least favorable output) rank.

For instance, the LCCA results, i.e., the value added for C2CA and SWP scenarios were 14.47 and 6.3 Euros/T, respectively. Based on expert judgement, the least and most favorable ranks were assigned data scores of 0 and 20 Euros/T, respectively. This scoring system may be explained by the fact that generation of higher revenue is preferred by any industry for an activity. The respective KPIs for C2CA and SWP were reported as 0.72 and 0.32. In this case, a higher KPI value is representative of more revenue generation. However, it is important to mention that the data scores for least and most favorable options can be adapted to suit the NRA's requirements. For instance, if an NRA favors an expensive technology that results in either zero or negative value addition and simultaneously zero waste generation, then the scoring system would be opposite to the current scheme.

For MCI, the corresponding scores for least and most favorable ranks were given as 0 and 1. A MCI value closer to zero would indicate fully linear flow or poor circularity potential and vice-versa. On another account, a negative result for ELCA was indicative of positive impacts on the environment, while a higher positive result corresponds to larger negative impacts. Therefore, the least and most favorable ranks for 'climate change-total' category were 150 and -150, respectively, and the corresponding climate change KPIs for C2CA and SWP were 0.43 and 0.71. Similarly, the KPIs for other categories were determined, which are presented in Table 33.

Next, the weights (see Table 33) were assigned to each KPI as per their relative importance. In general, all KPIs had a similar weight, except polished stone value and CEI. This may be explained by the fact that irrespective of the maintenance or construction strategy, a pavement must meet the structural and functional requirements throughout their design life. In addition, the objective of this deliverable is to inculcate circular procurement in road construction and maintenance. Therefore, CEI, which considers both quality and quantity of materials flowing into the system was assigned a weight 0.15.

Table 33. Key Performance Indicators for Pavement Maintenance Methods and Weights Per Assessment Criteria

Key performance indicators	KPI value		Weight	
	C2CA	SWP	C2CA	SWP
Polished stone value	0.53	0.36	0.15	0.15
Climate change-total	0.43	0.71	0.1	0.1
Acidification	0.34	0.52	0.1	0.1
Eutrophication-freshwater	0.50	0.50	0.1	0.1
Resource use, minerals and metals	0.50	0.50	0.1	0.1
Value added	0.72	0.32	0.1	0.1
Circular economy index	0.23	0.10	0.15	0.15
Material circularity indicator	0.18	0.23	0.1	0.1
Social impact of pavements	0.71	0.49	0.1	0.1

The NRRG for each maintenance option was identified, which is the weighted sum of KPIs. As can be seen in Figure 19, C2CA recycling technology showed a higher NRRG compared to SWP. Based on the performance models extracted from the literature, the technical performance of the pavements designed with recycled materials from C2CA and SWP technologies had a major contribution to the NRRG. The pavement designed with recycled aggregates derived from C2CA resulted in lower number of crashes over the design life than SWP attributed to the higher PSV of aggregates, resulting in better SR of the pavement. Additional discussion on the efficacy of models is presented in Appendix D under the section 'influence of variation in polished stone value on net risk reduction gain'. Further, the value addition from C2CA was higher than SWP ascribed to the greater revenue generation due to the production of high quality secondary materials. On another account, the contribution of other assessment categories towards the selection of recycled materials was similar. Overall, taking account of available data, it can be suggested that the performance associated with designing a pavement with new generation concrete processing technology (C2CA) was lower than the more conventional method (SWP).

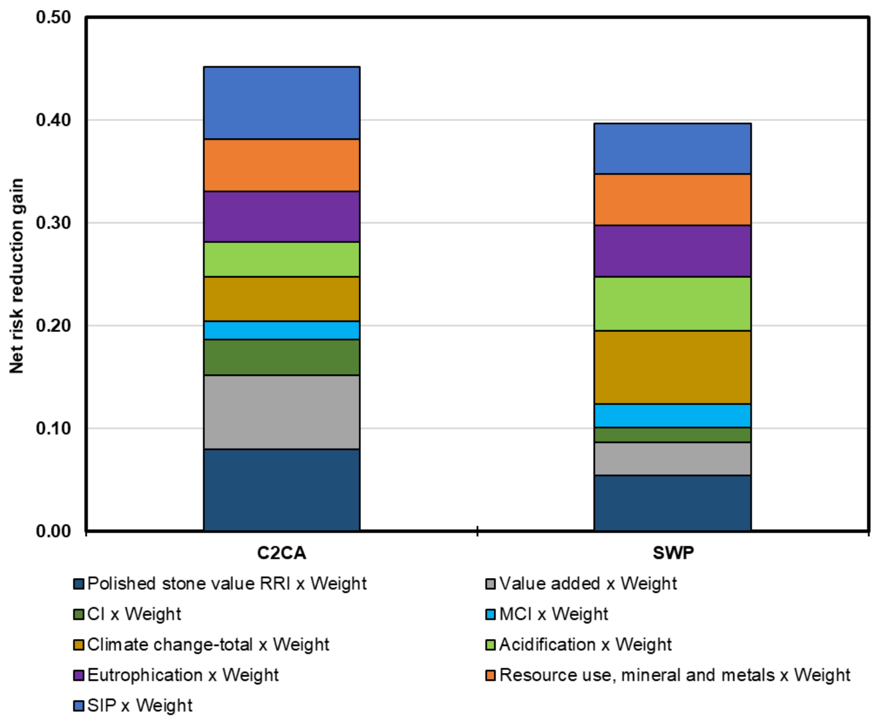


Figure 19. Net Risk Reduction Gain for Concrete Processing Technologies

9 Key Takeaways and Future Recommendations

Based on the case studies presented in this deliverable, the key takeaways and research way forward are presented below.

9.1 Case study I: Asphalt – LVOv (The Netherlands)

9.1.1 Environmental lifecycle assessment

The preventative maintenance approach utilizing rejuvenating maintenance resulted in significant environmental benefits to climate change through a 39% reduction in the kgCO_2eq, when benchmarked against traditional resurfacing. This is equivalent to avoiding roughly 20 tonnes of CO_2eq emissions when maintaining 1 lane-km of roadway over a period of 42 years. The impacts related to IRI and the fuel consumption of vehicles on the road suggest that maintaining a low IRI value is of much greater significance, than reducing impacts incurred from carrying out maintenance activities.

9.1.2 Lifecycle cost assessment

Rejuvenation maintenance leads to considerable lifecycle savings compared to resurfacing. For an analysis period of 42 years, rejuvenation maintenance was about 53% economical than resurfacing. Regardless of the maintenance activity type, the major share of lifecycle costs belonged to the material production phase. However, the cost associated with rejuvenation was 7 times lower than that of milling, and this can drive the economic benefits of using pavement preservation technique like rejuvenation.

9.1.3 Resource efficiency and circular economy

In this research, a simple value-based indicator was proposed to assess the circularity potential of pavement assets and recycling technologies, which is more aligned with the market value of resources, and considers the quality as well as the quantity of materials. The value-based circularity assessment approach was presented using declining balance method, which eliminates the limitation of CEI being applicable only for recycling activities and makes it more robust to encompass a broad range of infrastructure maintenance schemes. Though the mass of bitumen used in an asphalt mix was very low compared to aggregates, it is the most resource intensive material in asphalt concrete, and steps must be taken to advance technologies for its efficient extraction and reuse. The maintenance strategy with higher CEI was more resource intensive attributed to the flow of large quantities of virgin raw materials and other inputs such as energy, which are consequential of higher resource depletion and lower material circularity.

9.1.4 Social lifecycle assessment

A systematic approach that followed international standards was presented to quantify the social impacts of pavement technologies. Rejuvenation maintenance involves less use of non-renewable resources compared to resurfacing, resulting in its higher social impact. Although it is a convention to use the Analytic Hierarchy Process (AHP) for weighting in SLCA, it is subject to bias. Therefore, a new objective weighting methodology based on inventory scores supplied by different experts was used to determine the social impacts of alternative pavement maintenance options.

9.1.5 Technical performance

In the absence of direct relationships between pavement performance characteristics and material properties, a generic framework was proposed that could be utilized to quantify the risks associated with reducing levels of SR and texture depth with passage of time. The proposed approach could be utilized to ascertain the generic increase in the level of risks (collision rates and associated costs) associated with the reduction in SR and texture depth of pavements during their design life. Further, the SR and ravelling were above the general requirements indicating that the two maintenance schemes assisted in maintaining appropriate safety performance levels throughout the design life of ZOAB.

9.1.6 Risk-based analysis framework

The use of RBAF tool provided a quantification of the risks associated with the rejuvenation and resurfacing maintenance schemes. It highlighted that the NRRG for rejuvenation was 60% higher than resurfacing. The technical performance risks with preventive maintenance method (rejuvenation) was similar to resurfacing, which is a corrective maintenance scheme. In addition, the importance of NPV and circularity potential was highlighted in selecting pavement maintenance options, as they were the major contributors to NRRG.

9.2 Case study I: Asphalt – Denmark

9.2.1 Environmental lifecycle assessment

The ELCA found that the BSM scenario performs better than patch repair and resurfacing for all environmental indicators when assessing the direct impacts related to the material and resource consumption of the maintenance processes undertaken. These benefits are however negated when taking into account the impact of road condition on fuel economy, where patch repair and resurfacing slightly outperforms BSM. This would suggest that the impact on IRI be a priority when designing maintenance strategies for improved environmental performance.

9.2.2 Lifecycle cost assessment

Although BSM option was consequential of higher agency costs (by about 107%) throughout the analysis period compared to patch repair and resurfacing scenario, the lifecycle costs were much lower. This was attributed to the 59% lower VOC and DC for BSM compared to patch repair and resurfacing. The frequent patching and resurfacing activities (every five years) lead to increased traffic movement on adjacent lanes for relatively long durations, thereby causing a reduction in operating speed of vehicles and resulting in higher road user costs.

9.2.3 Resource efficiency and circular economy

In the absence of costs pertaining to the unit processes, MCI was adopted to quantify the RE and CE. The MCI scores for the BSM and patch repair and resurfacing scenarios were 0.55 and 0, respectively. A ‘0’ score for the patch repair and resurfacing maintenance is indicative of poor material circularity and completely linear flow. This dictates that NRAs must transition towards the use of maintenance options similar to BSM technology, which comprise high recycled material proportions and also minimize the frequency of maintenance activities during the design life, thereby contributing to development of circular habitats.

9.2.4 Social lifecycle assessment

SLCA study was not undertaken for the DK case study due to the absence of inventory scores for the patch repair and resurfacing maintenance option. However, the framework proposed in this deliverable may be utilized in future to assess the social impacts.

9.2.5 Technical performance

Although data relevant to the technical KPIs was unavailable, discussions with the case study owners indicated that the technical performance of BSM solution was similar to the case of patch repair and resurfacing.

9.2.6 Risk-based analysis framework

The NRRG for the BSM option was 2.2 times higher than patch repair and resurfacing. Note that the technical performance KPI was not included in the final computations as it was considered that both maintenance schemes resulted in equal performance. The NPV and circularity potential were two major assessment categories that assist in selection of appropriate pavement maintenance options, as they were the major contributors to NRRG.

9.3 Case Study II: Concrete processing technologies

9.3.1 Environmental lifecycle assessment

C2CA exhibited significantly larger environmental benefits than SWP. However these benefits were negated by the initial impact of transporting the C2CA mobile equipment onsite. C2CA was found to only outperform SWP from a climate standpoint, once more than 2.25 tonnes of C&DW was processed. From processing 100 tonnes of C&DW, roughly 13 tonnes of CO_2eq are saved when using C2CA compared to the 6.3 tonnes saved from using SWP.

9.3.2 Lifecycle cost assessment

Although the cost to recycle one tonne of C&DW using C2CA technology was higher than SWP, the revenue generated through the secondary materials was almost 51% higher. This assessment uses market rates for the value of the materials produced. This is an indicator of the high-quality secondary products that could be used to replace virgin raw materials for broader applications other than conventional downcycling in road base layers, thereby improving the material flows and promoting upcycling activities.

9.3.3 Resource efficiency and circular economy

The computations involved with MCI are complex as compared to CEI. Further, CEI being a value-based metric can be easily used by roadway agencies to compute circularity of products provided their market prices and mass are known. The MCI score is dominated by materials with greater mass after recycling, whereas the value-based indicator was critical of the quality of material along with their mass.

9.3.4 Social lifecycle assessment

The SLCA approach presented in this study was flexible as it could be utilized to quantify the social impacts associated with concrete recycling technologies with very minute modifications in the data checklist. Further, the impacts of recycling technologies on society were the highest attributed to the use of advanced technological systems that result in production of high quality raw materials that could be used in varied civil engineering works.

9.3.5 Technical performance

A generic approach was presented to use the aggregate properties such as water absorption to predict the PSV of recycled aggregates, which was later used to compute the ISI of the pavement. Next, the models utilized in ZOAB case study were adopted to quantify the reduction in SI with time and associated cost of consequences. The aggregates produced from C2CA technology resulted in lower risk than SWP. A reduction in PSV was consequential of increase in risk. However, the magnitude of increase in risk for both processing technologies was similar. Further, the models for ISI assessment were robust for lower traffic, and resulted in significantly lower ISI at increased traffic (> 3500 commercial vehicles per day).

9.3.6 Risk-based analysis framework

A hypothetical pavement scenario was created to quantify the risks associated with the use of recycled materials in the Excel® based toolkit. The NRRG indicated that the overall risk associated with designing a pavement with C2CA was lower than the more conventional SWP method.

9.4 Limitations and research way forward

This research has inherent limitations, which are discussed below along with research way forward:

- There is an urgent need to collate spatially and temporally harmonized data for the different assessment categories presented in this deliverable.
- Relevant industry stakeholders must develop repositories to record variation in pavement performance characteristics with time and engage in knowledge sharing activities with research partners. Further, premature pavement failures owing to material and other factors such as environment, traffic, etc. must be noted along with the possible causes.
- The approach adopted to quantify the risks was generic and indirect as models from different sources were extracted to investigate the variations in pavement features such as SR and PSV over time. This is one of the major limitations of this work, which also highlights the need to collect real time field data and development of predictive models for assessing the deterioration of pavement characteristics with time based on multi-parameters such as traffic loads, vehicular flow, and environmental conditions.
- Only one form of technical consequence, i.e., crashes was discussed in this study. Further, three technical KPIs were assessed, namely, SR, ravelling, and PSV. Additional work will be needed in future to include additional technical KPIs and quantification of consequence with respect to more other categories such as vehicle fuel consumption.
- The models used to quantify the loss in SR or increase in crash rates over time did not consider the dynamic effect of changing traffic characteristics. Further, very low volume of commercial vehicles per day was used to ascertain the crash rates in concrete processing case study. Therefore, new predictive models that include vehicular, environmental, material, and pavement performance characteristics must be developed.
- Although the methodology proposed for SLCA was rational, scores were collected from a limited group of stakeholders and experts, which must be expanded in future to have higher confidence on the results. Further, there is a need to integrate objective and subjective weighting methods to assign weights based on available data as well as predilections of experts. In addition, the present study considered only the maintenance/processing phase of lifecycle, and future studies must focus on conducting cradle-to-grave SLCA studies.
- The tool requires definition of the threshold values per assessment category. Therefore, attempts must be made in the future to quantify the thresholds (upper and lower limits) associated with different available maintenance options for each assessment category considered in this study.

10 Conclusions

The objective of this deliverable was to assess the suitability of risk-based Excel® tool that has the potential to evaluate the risks associated with adoption of different roadway construction and maintenance practices. Different case studies on asphalt pavement maintenance options and concrete processing technologies were undertaken to cover a range of technical areas and maturity levels of NRAs. The methodology involved investigation of the environmental, economic, circularity, and social aspects along with assessment of the technical risks associated with each case study to select the optimum solution.

An important contribution of this deliverable to CERCOM and the overarching goal to achieve circularity was the development of a simple value-based KPI and associated methodology to quantify the RE and CE potential of NRAs. Further, the KPIs were chosen based on their relevance for different projects, available data, ease of computation, and experience. The integration of these KPIs in RBAF will allow rewarding the contractors for producing a scheme that is environment-friendly, cost effective, used minimal raw materials, and allowed keeping the asset and materials in use for prolonged periods. In addition, the frameworks proposed for quantification of different KPIs have the potential to encompass case studies that were beyond the scope of this deliverable. Moreover, the data collection methods provided a harmonized approach that can be suitably adopted by all NRAs in the Europe. However, the generic methods of quantifying technical performance over time that were proposed to quantify the risks demonstrate that it is important to collect and record historical pavement performance data (surface properties, environment, and traffic), which must be further utilized to develop prediction models relevant to distress progression, road user safety, and vehicle-fuel consumption.

The RBAF tool provided flexibility to include multiple KPIs for the same assessment category such as CEI and MCI to assess the circularity levels. Further, the NRAs have choice to assign different weights (either based on expert opinion or using mathematical procedures) to various KPIs based on their level of importance in a particular project. Therefore, the RBAF has potential to be integrated into current procurement procedures and provides sufficient scope for enhanced capability over time as the maturity of NRAs evolve over the coming years. On this basis, the RBAF could play a vital role in transition to resource efficient and circular approaches in the procurement of construction and maintenance solutions for road infrastructure in the future.

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Appendix - A

Declining balance method

This method is also known as diminishing or reducing balance method. A fixed percentage of depreciation rate is used in this method. Assume that one tonne of virgin coarse aggregates are required to produce a unit pavement geometry whose design life is 15 years. If the initial cost of material used for construction is 111 Euros (without any depreciation), then the calculations involved in the assessment of scrap value are presented in Table A 1. In the absence of information on the depreciation rate, it may be expressed using Equation (A.1). Therefore, for the current example, the depreciation rate was 6.67%, and Table A 1 presents the scrap value of coarse aggregates.

$$Depreciation\ rate = \frac{1}{Design\ life\ of\ asset} \tag{A.1}$$

Table A 1. Scrap Value of Coarse Virgin Aggregates using Declining Balance Method

Year	Cost of aggregates (€)	Depreciation value @6.67%	Scrap value (€)
1	111.00	7.40	103.60
2	103.60	6.91	96.69
3	96.69	6.45	90.25
4	90.25	6.02	84.23
5	84.23	5.62	78.62
6	78.62	5.24	73.37
7	73.37	4.89	68.48
8	68.48	4.57	63.92
9	63.92	4.26	59.66
10	59.66	3.98	55.68
11	55.68	3.71	51.97
12	51.97	3.46	48.50
13	48.50	3.23	45.27
14	45.27	3.02	42.25
15	42.25	2.82	39.43

Appendix - B

Lifecycle inventory: Asphalt – LVOv (the Netherlands)

Environment: Table B 1 presents the background data and quality that was used to assess the environmental impacts of rejuvenation and resurfacing methods.

Table B 1. Environmental Lifecycle Inventory Used to Model Rejuvenation and Resurfacing Scenarios

Foreground Data	Background Data	Reference Year	Geo	Source	Data Quality		
					G_e	T_i	T_e
Rejuvenator	Rejuvenator	2021	NL	EPD – Ecochain	VG	VG	VG
Pre-rejuvenator	Soap production	2021	RER	Ecoinvent ™ v3.8®	G	VG	F
Water	Tap water from groundwater	2021	EU-28	Gabi™	G	VG	VG
Sand	Limestone, crushed stone fines (Grain size 0/2) (EN15804 A1-A3)	2021	EU-28	Gabi™	G	VG	VG
Coarse Aggregate	Limestone, crushed gravel (grain size 2/15) (EN15804 A1-A3)	2021	DE	Gabi™	F	VG	G
Fine Aggregate	Limestone, crushed stone fines (Grain size 0/2)	2021	EU-28	Gabi™	G	VG	G
Hydrated Lime (filler)	Calcium Hydroxide (Ca(OH)2; dry; slaked lime)	2021	DE	Gabi™	F	VG	VG
Road Base Aggregate	Gravel 2/32	2021	EU-28	Gabi™	G	VG	G
Bitumen	Bitumen at refinery	2021	EU-28	Gabi™	G	VG	VG
Electricity	Residual grid mix	2021	NL	Gabi™	VG	VG	VG
Diesel	Diesel mix at filling station / at refinery	2021	EU-28	Gabi™	G	VG	VG
Kerosene	Kerosene / Jet A1 at refinery	2021	EU-28	Gabi™	G	VG	VG
Heavy Fuel Oil	Heavy fuel oil at refinery (1.0wt. % S)	2021	EU-28	Gabi™	G	VG	VG
Running Diesel Equipment	Machine operation, diesel, steady state	2021	GLO	Ecoinvent ™ v3.8®	F	VG	G
Turbojet	Cargo plane, 65t payload	2021	GLO	Gabi™	F	VG	F
Excavator	Excavator, 100kW, construction	2021	GLO	Gabi™	F	VG	VG
Truck Transport	Truck, Euro 6, 28-31t gross weight / 22t payload capacity	2021	GLO	Gabi™	G	VG	VG
Ship Transport	Container ship 5,000 to 200,000 dwt payload capacity, ocean going	2021	GLO	Gabi™	G	VG	VG

Lifecycle cost: The quality of data collected for LCCA case study is indicated in Table B 2, while the corresponding source is provided in Table B 3.

Table B 2. Source and Data Quality for Lifecycle Cost Analysis – Agency Costs

Maintenance type	Component	Data quality	Data source
Rejuvenation	Type of rejuvenator	Primary	Material supplier and contractor
	Execution time; dosage; application charges		
Sand gritting	Material (sand)	Primary	Material supplier
	Sand transportation charges	Secondary	(Yang et al. 2015)
	Dosage; spraying rate; application charges	Primary	Material supplier and contractor
Resurfacing	Aggregates	Primary	Material supplier
	Limestone filler		
	Bitumen		
	Material densities and mix proportions	Secondary	(Zhang et al. 2021) and (RF Cafe 2022)
	Payload capacity of vehicles	Secondary	(Qiao et al. 2022)
	Transportation cost of materials		(Yang et al. 2015)
	Production cost of ZOAB		(HomeGuide 2020a)
	Traffic growth rate		Assumed
	Speed of laying fresh mix		(Koster 2013)
	Paver charges		(HomeGuide 2020a)
	Compaction speed		Assumed

Table B 3. Source and Data Type for Lifecycle Cost Analysis – User costs

Category	Component	Data quality	Data source
Vehicle operating cost	Running cost of cars and trucks	Secondary	(Decò and Frangopol 2011)
	Average daily traffic; proportion of trucks and cars		(CBS - Statistics Netherlands 2018)
	Detour length and duration	Primary	Contractor and roadway agency
Delay costs	Average wage of truck driver	Secondary	(U.S. Bureau of Labor Statistics 2021)
	Average wage of car driver		(Economic Research Institute 2021)
	Vehicle occupancy for cars		(Eurostat 2022a)
	Vehicle occupancy for trucks		(Decò and Frangopol 2011)
	Time value of goods transported		

Further, the different inputs including raw material charges, transportation costs, maintenance duration, and other agency as well as road user costs are given in Table B 4 and Table B 5.

Table B 4. Input Values for Lifecycle Cost Analysis – Agency Costs

Maintenance type	Component	Data inputs
Rejuvenation	Duration of application (min/sq.m)	30
	Dosage (kg/sq.m)	0.8
	Application cost (€/sq.m)	2.31
Sand gritting	Material (sand) (€/T)	7.67
	Sand transportation charges (€/T-km)	0.44
	Spraying speed (m/h)	5000
	Spraying charges (€/sq.m)	0.16
Resurfacing	Aggregates (€/T)	7.67
	Limestone filler (€/T)	34
	Bitumen (€/T)	600
	Density of coarse aggregates (kg/m^3)	2680
	Density of fine aggregates (kg/m^3)	2658
	Density of limestone filler (kg/m^3)	2600
	Density of bitumen (kg/m^3)	1032
	Density of asphalt concrete (kg/m^3)	2100
	Transportation cost of materials (€/T-km)	0.44
	Production cost of ZOAB (€/T)	72.5
	Asphalt concrete mixture transported per trip (cu.m)	8
	Traffic growth rate (%)	3
	Speed of laying fresh mix (m/h)	277
	Paver charges (€/h)	269.25
	Compaction speed (m/h)	277
	Milling cost (€/sq.m)	16

Table B 5. Input Values for Lifecycle Cost Analysis – User Costs

Category	Component	Data inputs
Vehicle operating cost	Running cost of cars (€/h)	0.08
	Running cost of trucks (€/h)	0.375
	Average daily traffic (vehicles/h)	2589
	Proportion of trucks (%)	11
	Proportion of cars (%)	82
	Detour duration (days)	0.33
Delay costs	Average wage of truck driver (€/h)	23
	Average wage of car driver (€/h)	12
	Vehicle occupancy for cars (persons/vehicle)	1.38
	Vehicle occupancy for trucks (persons/vehicle)	1.05
	Time value of goods transported (€/h)	4

Social: The SLCA data for the direct and indirect indicators of SLCA for the two maintenance scenarios is presented in Table B 6.

Table B 6. Indicator Scores for Social Lifecycle Assessment - Rejuvenation

Direct Indicators	**Generic quantity (statistical data)**	**Site specific quantity**	
		Rejuvenation	**Resurfacing**
Local workforce (%)	67	60	70
Proportion of non-renewable resources (%)	86.01	50	90
Proportion of renewable resources (%)	13.99	50	10
Research and development costs (% of revenue)	2.29	10	5
Indirect indicators		**Sum of scores by experts**	
Exposure to fumes		14	14.5
Generation of employment		10	11.5
Community education initiatives		8	5.5
Legal complaints against the working organization with regards to security concerns		11.5	14
Legal obligation on public sustainability reporting		9	9.5
New technology		15	13
Partnership in research and development		12	11.5
Cleaner production (high quality raw materials, assets with lower emissions)		12	10.5
Contribution of activity to reduce unemployment		3	6.5
Incidents of non-compliance with regulations complying to safety impacts of pavement		14.5	10.5
Surveys to assess consumer satisfaction		12.5	11.5
Product disposal (landfill, recycling, incineration, reuse)		14	12

Cost of consequences: Asphalt – LVOv (The Netherlands)

Skid resistance: The crash rates and the annual risk (crash costs) associated with the "do-minimum", rejuvenation, and resurfacing maintenance scenarios for a 1000 m long roadway section having an annual average daily traffic 2589 vehicles over the analysis period of 42 years are presented in Table B 7, Table B 8, and Table B 9, respectively. All the crash costs are expressed in million Euros.

Table B 7. Crash Rates and Associated Risk (costs) for Do-minimum Scenario – Skid Resistance

Do-minimum								
Year	**SI**	**CR**	**Fatality**	**Serious injury**	**Minor damage**	**Fatality cost (million Euros)**	**Serious injury cost (million Euros)**	**Minor damage cost (million Euros)**
0	0.61	61.76	0.3	9.6	51.9	1.83	6.71	2.08
1	0.60	68.80	0.3	10.7	57.8	2.04	7.48	2.31
2	0.58	76.64	0.4	11.9	64.4	2.27	8.33	2.58
3	0.57	85.38	0.4	13.3	71.7	2.53	9.28	2.87
4	0.55	95.11	0.4	14.8	79.9	2.82	10.34	3.20
5	0.54	105.96	0.5	16.5	89.0	3.14	11.52	3.56
6	0.52	118.04	0.6	18.3	99.2	3.50	12.83	3.97
7	0.51	131.49	0.6	20.4	110.5	3.90	14.29	4.42
8	0.50	146.48	0.7	22.7	123.0	4.34	15.92	4.92
9	0.48	163.19	0.8	25.3	137.1	4.84	17.74	5.48
10	0.47	181.79	0.9	28.2	152.7	5.39	19.76	6.11
11	0.45	202.52	1.0	31.4	170.1	6.00	22.01	6.80
12	0.44	225.60	1.1	35.0	189.5	6.69	24.52	7.58
13	0.42	251.33	1.2	39.0	211.1	7.45	27.32	8.44
14	0.41	279.98	1.3	43.5	235.2	8.30	30.44	9.41
15	0.40	311.90	1.5	48.4	262.0	9.25	33.91	10.48
16	0.38	347.46	1.6	54.0	291.9	10.30	37.77	11.67
17	0.37	387.07	1.8	60.1	325.1	11.48	42.08	13.01
18	0.35	431.20	2.0	67.0	362.2	12.78	46.87	14.49
19	0.34	480.36	2.3	74.6	403.5	14.24	52.22	16.14
20	0.32	535.13	2.5	83.1	449.5	15.86	58.17	17.98
21	0.31	596.14	2.8	92.6	500.8	17.67	64.80	20.03
22	0.30	664.10	3.1	103.1	557.8	19.69	72.19	22.31
23	0.28	739.81	3.5	114.9	621.4	21.93	80.42	24.86
24	0.27	824.16	3.9	128.0	692.3	24.43	89.59	27.69
25	0.25	918.12	4.3	142.6	771.2	27.22	99.80	30.85
26	0.24	1022.79	4.8	158.8	859.1	30.32	111.18	34.37
27	0.22	1139.40	5.4	176.9	957.1	33.78	123.86	38.28
28	0.21	1269.30	6.0	197.1	1066.2	37.63	137.98	42.65
29	0.20	1414.01	6.7	219.6	1187.8	41.92	153.71	47.51
30	0.18	1575.22	7.4	244.6	1323.2	46.70	171.24	52.93
31	0.17	1754.81	8.3	272.5	1474.0	52.03	190.76	58.96
32	0.15	1954.88	9.2	303.6	1642.1	57.96	212.51	65.68
33	0.14	2177.75	10.2	338.2	1829.3	64.56	236.73	73.17
34	0.12	2426.03	11.4	376.7	2037.9	71.92	263.72	81.51
35	0.11	2702.62	12.7	419.7	2270.2	80.12	293.79	90.81
36	0.10	3010.74	14.2	467.6	2529.0	89.26	327.29	101.16
37	0.08	3354.00	15.8	520.9	2817.4	99.44	364.60	112.69
38	0.07	3736.38	17.6	580.2	3138.6	110.77	406.17	125.54
39	0.05	4162.36	19.6	646.4	3496.4	123.40	452.47	139.86
40	0.04	4636.91	21.8	720.1	3895.0	137.47	504.06	155.80
41	0.02	5165.55	24.3	802.2	4339.1	153.14	561.53	173.56
42	0.01	5754.47	27.1	893.6	4833.8	170.60	625.54	193.35
Total costs (million Euros)						***1650.95***	***6053.48***	***1871.07***
							9575.50	

Table B 8. Crash Rates and Associated Risk (costs) for Rejuvenation Scenario – Skid Resistance

Rejuvenation								
Year	**SI**	**CR**	**Fatality**	**Serious injury**	**Minor damage**	**Fatality cost (million Euros)**	**Serious injury cost (million Euros)**	**Minor damage cost (million Euros)**
0	0.61	61.76	0.3	9.6	51.9	1.83	6.71	2.08
1	0.60	68.80	0.3	10.7	57.8	2.04	7.48	2.31
2	0.58	76.64	0.4	11.9	64.4	2.27	8.33	2.58
3	0.57	85.38	0.4	13.3	71.7	2.53	9.28	2.87
4	0.55	95.11	0.4	14.8	79.9	2.82	10.34	3.20
5	0.54	105.96	0.5	16.5	89.0	3.14	11.52	3.56
1	0.60	68.80	0.3	10.7	57.8	2.04	7.48	2.31
2	0.58	76.64	0.4	11.9	64.4	2.27	8.33	2.58
3	0.57	85.38	0.4	13.3	71.7	2.53	9.28	2.87
4	0.55	95.11	0.4	14.8	79.9	2.82	10.34	3.20
5	0.54	105.96	0.5	16.5	89.0	3.14	11.52	3.56
1	0.60	68.80	0.3	10.7	57.8	2.04	7.48	2.31
2	0.58	76.64	0.4	11.9	64.4	2.27	8.33	2.58
3	0.57	85.38	0.4	13.3	71.7	2.53	9.28	2.87
4	0.55	95.11	0.4	14.8	79.9	2.82	10.34	3.20
5	0.54	105.96	0.5	16.5	89.0	3.14	11.52	3.56
6	0.52	118.04	0.6	18.3	99.2	3.50	12.83	3.97
7	0.51	131.49	0.6	20.4	110.5	3.90	14.29	4.42
8	0.50	146.48	0.7	22.7	123.0	4.34	15.92	4.92
9	0.48	163.19	0.8	25.3	137.1	4.84	17.74	5.48
10	0.47	181.79	0.9	28.2	152.7	5.39	19.76	6.11
11	0.45	202.52	1.0	31.4	170.1	6.00	22.01	6.80
1	0.60	68.80	0.3	10.7	57.8	2.04	7.48	2.31
2	0.58	76.64	0.4	11.9	64.4	2.27	8.33	2.58
3	0.57	85.38	0.4	13.3	71.7	2.53	9.28	2.87
4	0.55	95.11	0.4	14.8	79.9	2.82	10.34	3.20
5	0.54	105.96	0.5	16.5	89.0	3.14	11.52	3.56
1	0.60	68.80	0.3	10.7	57.8	2.04	7.48	2.31
2	0.58	76.64	0.4	11.9	64.4	2.27	8.33	2.58
3	0.57	85.38	0.4	13.3	71.7	2.53	9.28	2.87
4	0.55	95.11	0.4	14.8	79.9	2.82	10.34	3.20
5	0.54	105.96	0.5	16.5	89.0	3.14	11.52	3.56
1	0.60	68.80	0.3	10.7	57.8	2.04	7.48	2.31
2	0.58	76.64	0.4	11.9	64.4	2.27	8.33	2.58
3	0.57	85.38	0.4	13.3	71.7	2.53	9.28	2.87
4	0.55	95.11	0.4	14.8	79.9	2.82	10.34	3.20
5	0.54	105.96	0.5	16.5	89.0	3.14	11.52	3.56
6	0.52	118.04	0.6	18.3	99.2	3.50	12.83	3.97
7	0.51	131.49	0.6	20.4	110.5	3.90	14.29	4.42
8	0.50	146.48	0.7	22.7	123.0	4.34	15.92	4.92
9	0.48	163.19	0.8	25.3	137.1	4.84	17.74	5.48
10	0.47	181.79	0.9	28.2	152.7	5.39	19.76	6.11
11	0.45	202.52	1.0	31.4	170.1	6.00	22.01	6.80
Total costs (million Euros)						***134.60***	***493.53***	***152.55***
						780.68		

Table B 9. Crash Rates and Associated Risk (costs) for Resurfacing Scenario – Skid Resistance

Resurfacing								
Year	**SI**	**CR**	**Fatality**	**Serious injury**	**Minor damage**	**Fatality cost (million Euros)**	**Serious injury cost (million Euros)**	**Minor damage cost (million Euros)**
0	0.61	61.76	0.3	9.6	51.9	1.83	6.71	2.08
1	0.60	68.80	0.3	10.7	57.8	2.04	7.48	2.31
2	0.58	76.64	0.4	11.9	64.4	2.27	8.33	2.58
3	0.57	85.38	0.4	13.3	71.7	2.53	9.28	2.87
4	0.55	95.11	0.4	14.8	79.9	2.82	10.34	3.20
5	0.54	105.96	0.5	16.5	89.0	3.14	11.52	3.56
6	0.52	118.04	0.6	18.3	99.2	3.50	12.83	3.97
7	0.51	131.49	0.6	20.4	110.5	3.90	14.29	4.42
8	0.50	146.48	0.7	22.7	123.0	4.34	15.92	4.92
9	0.48	163.19	0.8	25.3	137.1	4.84	17.74	5.48
10	0.47	181.79	0.9	28.2	152.7	5.39	19.76	6.11
11	0.45	202.52	1.0	31.4	170.1	6.00	22.01	6.80
12	0.44	225.60	1.1	35.0	189.5	6.69	24.52	7.58
1	0.60	68.80	0.3	10.7	57.8	2.04	7.48	2.31
2	0.58	76.64	0.4	11.9	64.4	2.27	8.33	2.58
3	0.57	85.38	0.4	13.3	71.7	2.53	9.28	2.87
4	0.55	95.11	0.4	14.8	79.9	2.82	10.34	3.20
5	0.54	105.96	0.5	16.5	89.0	3.14	11.52	3.56
6	0.52	118.04	0.6	18.3	99.2	3.50	12.83	3.97
7	0.51	131.49	0.6	20.4	110.5	3.90	14.29	4.42
8	0.50	146.48	0.7	22.7	123.0	4.34	15.92	4.92
9	0.48	163.19	0.8	25.3	137.1	4.84	17.74	5.48
10	0.47	181.79	0.9	28.2	152.7	5.39	19.76	6.11
11	0.45	202.52	1.0	31.4	170.1	6.00	22.01	6.80
12	0.44	225.60	1.1	35.0	189.5	6.69	24.52	7.58
1	0.60	68.80	0.3	10.7	57.8	2.04	7.48	2.31
2	0.58	76.64	0.4	11.9	64.4	2.27	8.33	2.58
3	0.57	85.38	0.4	13.3	71.7	2.53	9.28	2.87
4	0.55	95.11	0.4	14.8	79.9	2.82	10.34	3.20
5	0.54	105.96	0.5	16.5	89.0	3.14	11.52	3.56
6	0.52	118.04	0.6	18.3	99.2	3.50	12.83	3.97
7	0.51	131.49	0.6	20.4	110.5	3.90	14.29	4.42
8	0.50	146.48	0.7	22.7	123.0	4.34	15.92	4.92
9	0.48	163.19	0.8	25.3	137.1	4.84	17.74	5.48
10	0.47	181.79	0.9	28.2	152.7	5.39	19.76	6.11
11	0.45	202.52	1.0	31.4	170.1	6.00	22.01	6.80
12	0.44	225.60	1.1	35.0	189.5	6.69	24.52	7.58
1	0.60	68.80	0.3	10.7	57.8	2.04	7.48	2.31
2	0.58	76.64	0.4	11.9	64.4	2.27	8.33	2.58
3	0.57	85.38	0.4	13.3	71.7	2.53	9.28	2.87
4	0.55	95.11	0.4	14.8	79.9	2.82	10.34	3.20
5	0.54	105.96	0.5	16.5	89.0	3.14	11.52	3.56
6	0.52	118.04	0.6	18.3	99.2	3.50	12.83	3.97
Total cost (million Euros)						***160.53***	***588.61***	***181.93***
							931.07	

Ravelling: The annual crash rates and risk associated with do-minimum, rejuvenation, and resurfacing scenarios are given in Table B 10, Table B 11, and Table B 12, respectively.

Table B 10. Crash Rates and Associated Risk (costs) for Do-minimum Scenario – Ravelling

Do-minimum								
Year	**TD (mm)**	**CR**	**Fatality**	**Serious injury**	**Minor damage**	**Fatality cost (million Euros)**	**Serious injury cost (million Euros)**	**Minor damage cost (million Euros)**
0	1.80	0.57	0.0	0.1	0.5	0.02	0.06	0.02
1	1.76	0.58	0.0	0.1	0.5	0.02	0.06	0.02
2	1.72	0.59	0.0	0.1	0.5	0.02	0.06	0.02
3	1.68	0.60	0.0	0.1	0.5	0.02	0.07	0.02
4	1.64	0.61	0.0	0.1	0.5	0.02	0.07	0.02
5	1.60	0.62	0.0	0.1	0.5	0.02	0.07	0.02
6	1.55	0.63	0.0	0.1	0.5	0.02	0.07	0.02
7	1.51	0.64	0.0	0.1	0.5	0.02	0.07	0.02
8	1.47	0.66	0.0	0.1	0.6	0.02	0.07	0.02
9	1.43	0.67	0.0	0.1	0.6	0.02	0.07	0.02
10	1.39	0.68	0.0	0.1	0.6	0.02	0.07	0.02
11	1.35	0.70	0.0	0.1	0.6	0.02	0.08	0.02
12	1.31	0.71	0.0	0.1	0.6	0.02	0.08	0.02
13	1.27	0.73	0.0	0.1	0.6	0.02	0.08	0.02
14	1.23	0.74	0.0	0.1	0.6	0.02	0.08	0.03
15	1.19	0.76	0.0	0.1	0.6	0.02	0.08	0.03
16	1.14	0.78	0.0	0.1	0.7	0.02	0.09	0.03
17	1.10	0.80	0.0	0.1	0.7	0.02	0.09	0.03
18	1.06	0.82	0.0	0.1	0.7	0.02	0.09	0.03
19	1.02	0.85	0.0	0.1	0.7	0.03	0.09	0.03
20	0.98	0.87	0.0	0.1	0.7	0.03	0.09	0.03
21	0.94	0.90	0.0	0.1	0.8	0.03	0.10	0.03
22	0.90	0.93	0.0	0.1	0.8	0.03	0.10	0.03
23	0.86	0.96	0.0	0.1	0.8	0.03	0.10	0.03
24	0.82	0.99	0.0	0.2	0.8	0.03	0.11	0.03
25	0.78	1.03	0.0	0.2	0.9	0.03	0.11	0.03
26	0.73	1.07	0.0	0.2	0.9	0.03	0.12	0.04
27	0.69	1.11	0.0	0.2	0.9	0.03	0.12	0.04
28	0.65	1.16	0.0	0.2	1.0	0.03	0.13	0.04
29	0.61	1.21	0.0	0.2	1.0	0.04	0.13	0.04
30	0.57	1.27	0.0	0.2	1.1	0.04	0.14	0.04
31	0.53	1.34	0.0	0.2	1.1	0.04	0.15	0.05
32	0.49	1.42	0.0	0.2	1.2	0.04	0.15	0.05
33	0.45	1.51	0.0	0.2	1.3	0.04	0.16	0.05
34	0.41	1.62	0.0	0.3	1.4	0.05	0.18	0.05
35	0.37	1.74	0.0	0.3	1.5	0.05	0.19	0.06
36	0.32	1.89	0.0	0.3	1.6	0.06	0.21	0.06
37	0.28	2.08	0.0	0.3	1.7	0.06	0.23	0.07
38	0.24	2.32	0.0	0.4	2.0	0.07	0.25	0.08
39	0.20	2.65	0.0	0.4	2.2	0.08	0.29	0.09
40	0.16	3.11	0.0	0.5	2.6	0.09	0.34	0.10
41	0.12	3.82	0.0	0.6	3.2	0.11	0.42	0.13
42	0.08	5.14	0.0	0.8	4.3	0.15	0.56	0.17
Total costs (million Euros)						***1.60***	***5.86***	***1.81***
						9.27		

Table B 11. Crash Rates and Associated Risk (costs) for Rejuvenation Scenario – Ravelling

Rejuvenation								
Year	**TD (mm)**	**CR**	**Fatality**	**Serious injury**	**Minor damage**	**Fatality cost (million Euros)**	**Serious injury cost (million Euros)**	**Minor damage cost (million Euros)**
0	1.80	0.57	0.0	0.1	0.5	0.02	0.06	0.02
1	1.76	0.58	0.0	0.1	0.5	0.02	0.06	0.02
2	1.72	0.59	0.0	0.1	0.5	0.02	0.06	0.02
3	1.68	0.60	0.0	0.1	0.5	0.02	0.07	0.02
4	1.64	0.61	0.0	0.1	0.5	0.02	0.07	0.02
5	1.60	0.62	0.0	0.1	0.5	0.02	0.07	0.02
1	1.76	0.58	0.0	0.1	0.5	0.02	0.06	0.02
2	1.72	0.59	0.0	0.1	0.5	0.02	0.06	0.02
3	1.68	0.60	0.0	0.1	0.5	0.02	0.07	0.02
4	1.64	0.61	0.0	0.1	0.5	0.02	0.07	0.02
5	1.60	0.62	0.0	0.1	0.5	0.02	0.07	0.02
1	1.76	0.58	0.0	0.1	0.5	0.02	0.06	0.02
2	1.72	0.59	0.0	0.1	0.5	0.02	0.06	0.02
3	1.68	0.60	0.0	0.1	0.5	0.02	0.07	0.02
4	1.64	0.61	0.0	0.1	0.5	0.02	0.07	0.02
5	1.60	0.62	0.0	0.1	0.5	0.02	0.07	0.02
6	1.55	0.63	0.0	0.1	0.5	0.02	0.07	0.02
7	1.51	0.64	0.0	0.1	0.5	0.02	0.07	0.02
8	1.47	0.66	0.0	0.1	0.6	0.02	0.07	0.02
9	1.43	0.67	0.0	0.1	0.6	0.02	0.07	0.02
10	1.39	0.68	0.0	0.1	0.6	0.02	0.07	0.02
11	1.35	0.70	0.0	0.1	0.6	0.02	0.08	0.02
1	1.76	0.58	0.0	0.1	0.5	0.02	0.06	0.02
2	1.72	0.59	0.0	0.1	0.5	0.02	0.06	0.02
3	1.68	0.60	0.0	0.1	0.5	0.02	0.07	0.02
4	1.64	0.61	0.0	0.1	0.5	0.02	0.07	0.02
5	1.60	0.62	0.0	0.1	0.5	0.02	0.07	0.02
1	1.76	0.58	0.0	0.1	0.5	0.02	0.06	0.02
2	1.72	0.59	0.0	0.1	0.5	0.02	0.06	0.02
3	1.68	0.60	0.0	0.1	0.5	0.02	0.07	0.02
4	1.64	0.61	0.0	0.1	0.5	0.02	0.07	0.02
5	1.60	0.62	0.0	0.1	0.5	0.02	0.07	0.02
1	1.76	0.58	0.0	0.1	0.5	0.02	0.06	0.02
2	1.72	0.59	0.0	0.1	0.5	0.02	0.06	0.02
3	1.68	0.60	0.0	0.1	0.5	0.02	0.07	0.02
4	1.64	0.61	0.0	0.1	0.5	0.02	0.07	0.02
5	1.60	0.62	0.0	0.1	0.5	0.02	0.07	0.02
6	1.55	0.63	0.0	0.1	0.5	0.02	0.07	0.02
7	1.72	0.64	0.0	0.1	0.5	0.02	0.07	0.02
8	1.68	0.66	0.0	0.1	0.6	0.02	0.07	0.02
9	1.64	0.67	0.0	0.1	0.6	0.02	0.07	0.02
10	1.60	0.68	0.0	0.1	0.6	0.02	0.07	0.02
11	1.55	0.70	0.0	0.1	0.6	0.02	0.08	0.02
Total costs (million Euros)						***0.78***	***2.88***	***0.89***
						4.55		

Table B 12. Crash Rates and Associated Risk (costs) for Resurfacing Scenario – Ravelling

Resurfacing								
Year	**SI**	**CR**	**Fatality**	**Serious injury**	**Minor damage**	**Fatality cost (million Euros)**	**Serious injury cost (million Euros)**	**Minor damage cost (million Euros)**
0	1.80	0.57	0.0	0.1	0.5	0.02	0.06	0.02
1	1.76	0.58	0.0	0.1	0.5	0.02	0.06	0.02
2	1.72	0.59	0.0	0.1	0.5	0.02	0.06	0.02
3	1.68	0.60	0.0	0.1	0.5	0.02	0.07	0.02
4	1.64	0.61	0.0	0.1	0.5	0.02	0.07	0.02
5	1.60	0.62	0.0	0.1	0.5	0.02	0.07	0.02
6	1.55	0.63	0.0	0.1	0.5	0.02	0.07	0.02
7	1.51	0.64	0.0	0.1	0.5	0.02	0.07	0.02
8	1.47	0.66	0.0	0.1	0.6	0.02	0.07	0.02
9	1.43	0.67	0.0	0.1	0.6	0.02	0.07	0.02
10	1.39	0.68	0.0	0.1	0.6	0.02	0.07	0.02
11	1.35	0.70	0.0	0.1	0.6	0.02	0.08	0.02
12	1.31	0.71	0.0	0.1	0.6	0.02	0.08	0.02
1	1.76	0.58	0.0	0.1	0.5	0.02	0.06	0.02
2	1.72	0.59	0.0	0.1	0.5	0.02	0.06	0.02
3	1.68	0.60	0.0	0.1	0.5	0.02	0.07	0.02
4	1.64	0.61	0.0	0.1	0.5	0.02	0.07	0.02
5	1.60	0.62	0.0	0.1	0.5	0.02	0.07	0.02
6	1.55	0.63	0.0	0.1	0.5	0.02	0.07	0.02
7	1.51	0.64	0.0	0.1	0.5	0.02	0.07	0.02
8	1.47	0.66	0.0	0.1	0.6	0.02	0.07	0.02
9	1.43	0.67	0.0	0.1	0.6	0.02	0.07	0.02
10	1.39	0.68	0.0	0.1	0.6	0.02	0.07	0.02
11	1.35	0.70	0.0	0.1	0.6	0.02	0.08	0.02
12	1.31	0.71	0.0	0.1	0.6	0.02	0.08	0.02
1	1.76	0.58	0.0	0.1	0.5	0.02	0.06	0.02
2	1.72	0.59	0.0	0.1	0.5	0.02	0.06	0.02
3	1.68	0.60	0.0	0.1	0.5	0.02	0.07	0.02
4	1.64	0.61	0.0	0.1	0.5	0.02	0.07	0.02
5	1.60	0.62	0.0	0.1	0.5	0.02	0.07	0.02
6	1.55	0.63	0.0	0.1	0.5	0.02	0.07	0.02
7	1.51	0.64	0.0	0.1	0.5	0.02	0.07	0.02
8	1.47	0.66	0.0	0.1	0.6	0.02	0.07	0.02
9	1.43	0.67	0.0	0.1	0.6	0.02	0.07	0.02
10	1.39	0.68	0.0	0.1	0.6	0.02	0.07	0.02
11	1.35	0.70	0.0	0.1	0.6	0.02	0.08	0.02
12	1.31	0.71	0.0	0.1	0.6	0.02	0.08	0.02
1	1.76	0.58	0.0	0.1	0.5	0.02	0.06	0.02
2	1.72	0.59	0.0	0.1	0.5	0.02	0.06	0.02
3	1.68	0.60	0.0	0.1	0.5	0.02	0.07	0.02
4	1.64	0.61	0.0	0.1	0.5	0.02	0.07	0.02
5	1.60	0.62	0.0	0.1	0.5	0.02	0.07	0.02
6	1.55	0.63	0.0	0.1	0.5	0.02	0.07	0.02
Total cost (million Euros)						***0.81***	***2.96***	***0.92***
						4.68		

Appendix - C

Lifecycle inventory: Asphalt – BSM (Denmark)

Environment: Table C 1 presents the background data (and quality) that was used to assess the environmental impacts of BSM technology as well as patch repair and resurfacing pavement maintenance scenarios.

Table C 1. Environmental Lifecycle Inventory Used to Model Danish Studies

Foreground Data	**Background Data**	**Ref. Year**	**Geo**	**Source**	**Data Quality**		
					G_e	**T_i**	**T_e**
Cement filler	Cement (CEM I 42.5) Portland cement	2021	EU-28	Gabi™	G	VG	VG
Binding coarse	Asphalt supporting layer (EN15804 A1-A3)	2021	EU-28	Gabi™	G	VG	VG
Wearing coarse	Stone mastic asphalt (EN15804 A1-A3)	2021	EU-28	Gabi™	G	VG	VG
Water	Tap water from groundwater	2021	EU-28	Gabi™	G	VG	VG
Hydrated lime (filler)	Calcium hydroxide ($Ca(OH)_2$); dry; slaked lime)	2021	DE	Gabi™	F	VG	VG
Road base aggregate	Gravel 2/32	2021	EU-28	Gabi™	G	VG	G
Bitumen	Bitumen at refinery	2021	EU-28	Gabi™	G	VG	VG
Diesel	Diesel mix at filling station / at refinery	2021	EU-28	Gabi™	G	VG	VG
Heavy fuel oil	Heavy fuel oil at refinery (1.0wt. % S)	2021	EU-28	Gabi™	G	VG	VG
Running diesel equipment	Machine operation, diesel, steady state	2021	GLO	Ecoinvent™ v3.8®	F	VG	G
Excavator	Excavator, 100kW, construction	2021	GLO	Gabi™	F	VG	VG
Truck transport	Truck, Euro 6, 28-31t gross weight / 22t payload capacity	2021	GLO	Gabi™	G	VG	VG
Ship transport	Container ship 5,000 to 200,000 dwt payload capacity, ocean going	2021	GLO	Gabi™	G	VG	VG
Passenger car	Passenger car average, Euro 3-5, engine size from 1,4 l to 2 l.	2021	GLO	Gabi™	F	VG	G

Lifecycle cost: The source and quality of data used for the LCCA is presented in Table C 2 and Table C 3. Further, the input values for construction of BSM, ABB, and SMA layers are presented in Table C 4. In addition, the input values for estimation of road user costs are presented in Table C 5 of Appendix C.

Table C 2. Source and Data Quality for BSM Construction – Agency Costs

<table>
<tr><th>Activity</th><th>Component</th><th>Data quality</th><th>Data source</th></tr>
<tr><td rowspan="2">Milling and crushing operation</td><td>Execution time; charges</td><td rowspan="6">Primary</td><td rowspan="6">Contractor</td></tr>
<tr><td>Water consumption and charges</td></tr>
<tr><td rowspan="3">Transportation distance and vehicle payload capacity</td><td>Milled material</td></tr>
<tr><td>Foamed bitumen</td></tr>
<tr><td>Density of recycled material</td></tr>
<tr><td rowspan="10">Mix proportions – BSM</td><td>Proportion of recycled material and cement filler</td></tr>
<tr><td>Cost of recycled materials</td><td rowspan="3">Secondary</td><td rowspan="3">(Eurostat 2022b; HomeGuide 2020b; Praneeth et al. 2021)</td></tr>
<tr><td>Cost of cement</td></tr>
<tr><td>Density of cement</td></tr>
<tr><td>Density of foamed binder</td><td rowspan="3">Primary</td><td rowspan="3">Contractor</td></tr>
<tr><td>Foamed binder content</td></tr>
<tr><td>Density of BSM</td></tr>
<tr><td>Production cost per tonne asphalt concrete</td><td>Secondary</td><td>(HomeGuide 2020a)</td></tr>
<tr><td>Transportation distance between batch plant and site</td><td rowspan="2">Primary</td><td rowspan="4">Contractor</td></tr>
<tr><td>Vehicle payload capacity</td></tr>
<tr><td rowspan="6">Construction of BSM</td><td>Layer thickness</td><td rowspan="2">Primary</td></tr>
<tr><td>Speed of paving</td></tr>
<tr><td>Paver charges</td><td>Secondary</td><td>(HomeGuide 2020a)</td></tr>
<tr><td>Speed of compaction</td><td rowspan="2">Primary</td><td rowspan="2">Contractor</td></tr>
<tr><td>Width of rollers</td></tr>
<tr><td>Charges for compaction</td><td>Secondary</td><td>(HomeGuide 2020a)</td></tr>
<tr><td>Asphalt concrete binding base layer</td><td rowspan="2">Raw material cost, mix production cost, transportation charges (raw materials and mixtures), paving and compaction charges</td><td rowspan="2">Primary</td><td rowspan="2">Contractor</td></tr>
<tr><td>Stone matrix asphalt</td></tr>
</table>

Table C 3. Source and Data Type for Lifecycle Costs Analysis – Road User Costs

<table>
<tr><th>Category</th><th>Component</th><th>Data quality</th><th>Data source</th></tr>
<tr><td rowspan="3">Vehicle operating cost</td><td>Running cost of cars and trucks</td><td rowspan="2">Secondary</td><td>(Decò and Frangopol 2011)</td></tr>
<tr><td>Average daily traffic; proportion of trucks and cars</td><td>(CBS - Statistics Netherlands 2018)</td></tr>
<tr><td>Detour length and duration</td><td>Primary</td><td>Contractor and roadway agency</td></tr>
<tr><td rowspan="5">Delay costs</td><td>Average wage of truck driver</td><td rowspan="5">Secondary</td><td>(U.S. Bureau of Labor Statistics 2021)</td></tr>
<tr><td>Average wage of car driver</td><td>(Economic Research Institute 2021)</td></tr>
<tr><td>Vehicle occupancy for cars</td><td>(Eurostat 2022a)</td></tr>
<tr><td>Vehicle occupancy for trucks</td><td rowspan="2">(Decò and Frangopol 2011)</td></tr>
<tr><td>Time value of goods transported</td></tr>
</table>

Table C 4. Input Values for Construction of BSM Layer – Agency Costs

Activity	Component	Data inputs
Milling operation	Milling charges per lane km (1000 m length, 3.5 m width, and 0.284 m thickness)	13440 Euros
Crushing operation	Crushing charges	3000 Euros per 10 h
	Crushing duration	5.83 h
	Number of labour	2
Transportation of milled material to asphalt mix plant	Milled pavement to asphalt plant	15 km
	Transportation charges	127.7 Euros per trip
	Vehicle payload capacity	38 t
	Density of recycled material	2350 kg/cu.m
Transportation of foamed bitumen to asphalt mix plant	Bitumen supplier and asphalt mix plant	300 km
	Vehicle payload capacity	33 t
	Density of foamed bitumen	1000 kg/cu.m
Mix proportions - BSM	Binder content	2.20%
	Cement filler	0.8% by volume of mix
	Recycled material	94.6%
	Water	2.5%
	Density of cement	1440 kg/cu.m
Production and transportation – BSM mix	Density of BSM mix	2050 kg/cu.m
	Production cost of asphalt concrete	106.24 Euros/t
	Distance between site and asphalt plant	15 km
	Vehicle payload capacity	38 t
BSM construction	Layer thickness	0.20 m
	Speed of laying mix	1200 m/h
	Number of labour during paving	4
	Width of pneumatic tired roller	1.98 m
	Charges for pneumatic tired roller	270 Euros/h
	Width of static steel wheel roller	1.2 m
	Charges for static steel wheel roller	16.94 Euros/h
	Number of labour during compaction	2
	Water consumption	1500 L/10h
Construction of ABB layer	Construction charges for ABB including milling	125 Euros/t
	Length × width × thickness	1000 × 3.5 × 0.08 m
	Mixture density	2350 kg/cu.m
	Binder content	5%
	Recycled material	25%
Construction of SMA layer	Construction charges for SMA including milling	161 Euros/t
	Length × width × thickness	1000 × 3.5 × 0.034 m
	Mixture density	2350 kg/cu.m
	Binder content	7.2%
	Recycled material	20%
Patch and repair - ABB	Patch area per lane km	4%
	Total (length × width × thickness)	58.34 × 2.40 × 0.06 m

Table C 5. Input Values for Lifecycle Cost Analysis – Road User Costs

Category	Component	Data inputs
Vehicle operating cost	Running cost of cars (€/h)	0.08
	Running cost of trucks (€/h)	0.375
	Average daily traffic in base year (vehicles/h)	16235
	Proportion of trucks (%)	6
	Proportion of cars (%)	93
	Detour duration (days)	7
Delay costs	Average wage of truck driver (€/h)	28.23
	Average wage of car driver (€/h)	14.92
	Vehicle occupancy for cars (persons/vehicle)	1.68
	Vehicle occupancy for trucks (persons/vehicle)	1.05
	Time value of goods transported (€/h)	4

Appendix - D

Lifecycle inventory: concrete processing technologies (the Netherlands)

Environment: Table D 1 and Table D 2 present the background data (and quality) that was used to assess the environmental impacts of C2CA and SWP technologies.

Table D 1. Environmental Lifecycle Inventory Used to Model Scenarios of Concrete Processing Technologies

Foreground Data	Background Data Reference	Year	Geo	Source	Data Quality		
					G_e	T_i	T_e
C2CA							
Running diesel fuelled equipment	Machine operation, Diesel, steady state	2021	GLO	Ecoinvent ™ v3.8®	F	VG	G
Sieve sand, clean sand	Sand 0/2	2021	EU-28	Gabi™	G	VG	F
Coarse aggregate	Limestone, crushed gravel (grain size 2/15) (EN15804 A1-A3)	2021	DE	Gabi™	F	VG	G
Fine aggregate	Limestone, crushed stone fines (grain size 0/2)	2021	EU-28	Gabi™	G	VG	G
Cement	Cement (CEM I 42.5) Portland cement	2021	EU-28	Gabi™	G	VG	VG
Road base, ultra-/coarse aggregate	Gravel 2/32	2021	EU-28	Gabi™	G	VG	G
Electricity	Residual grid mix	2021	NL	Gabi™	VG	VG	VG
Diesel	Diesel mix at filling station / at refinery	2021	EU-28	Gabi™	G	VG	VG
Thermal energy	Thermal energy from natural gas	2021	NL	Gabi™	VG	VG	G
Heavy fuel oil	Heavy fuel oil at refinery (1.0wt. % S)	2021	EU-28	Gabi™	G	VG	VG
Steel scrap	Value of scrap	2021	GLO	Worldst-eel	F	VG	G
Incineration of plastic	Plastics (unspecified) in waste incineration plant	2021	NL	Gabi™	VG	VG	G
Incineration of wood	Untreated wood in waste incineration plant	2021	NL	Gabi™	VG	VG	G
Excavator	Excavator, 100kW, construction	2021	GLO	Gabi™	F	VG	VG
Truck transport	Truck, Euro 6, 28-31t gross weight / 22t payload capacity	2021	GLO	Gabi™	G	VG	VG
Ship transport	Container ship 5,000 to 200,000 dwt payload capacity, ocean going	2021	GLO	Gabi™	G	VG	VG
SWP							
Flocculent	Thickening agent	2021	GLO	Gabi™	F	VG	F
Water	Rain water	2021	EU-28	Gabi™	G	VG	VG
Landfilling of sludge	Inert matter (unspecified construction waste) on landfill	2021	EU-28	Gabi™	G	VG	G

Table D 2. Primary Data for the Crushing Plants (Hu and Kleijn 2013; Moreno-Juez et al. 2020)

Component	**Productivity (T/h)**	**Power (kWh/T)**	**Diesel (L/T)**	**Water (L/T)**
Stationary wet processing	150	4	0.27	Compensated by rain water
C2CA				
Crusher	300		0.13	0.7
ADR	50	0.46		0.7
HAS	3	0.01	5.68	-

Lifecycle cost: The different economic inputs are presented in Table D 3.

Table D 3. Cost of Inputs in Different Lifecycle Phases (Hu and Kleijn 2013; Koullapis 2022)

Inputs	**Cost**
Transportation (Euros/T-km)	0.1
Transportation distance from site to SWP plant (km)	50
Transportation distance from C2CA storage to site (km)	50
Electricity (Euros/T)	0.504
Diesel (Euros/T)	0.448
Kemira A120 (Euros/T)	1.3
Citex 493 (Euros/T)	0.17
Sludge disposal (Euros/T)	25
Transportation cost of C2CA to process 100 tonne EOL concrete (Euros)	15.99
Water (Euros/T)	0.14
Depreciation cost of ADR (Euros/h)	100.48
Depreciation cost of HAS (Euros/h)	17.68
Coarse aggregates (Euros/T)	13.86
Sieve sand (Euros/T)	3.15
Clean sand (Euros/T)	4.41
Rotor (Euros/T)	3.15
Ultrafines (Euros/T)	72.42

Social: The average impact scores are presented in Table D 4.

Table D 4. Indicator Scores for Social Lifecycle Assessment

Impact indicators	**Average impact scores**	
	SWP	**C2CA**
Exposure to dust	4.00	3.83
Generation of employment	0.50	0.67
Community education initiatives	1.00	1.33
Legal complaints against the working organization with regards to security concerns	3.00	3.00
Legal obligation on public sustainability reporting	2.83	2.83
New technology	2.00	5.00
Partnership in research and development	2.33	5.00
Cleaner production (high quality raw materials, assets with lower emissions)	2.00	5.00
Contribution of activity to reduce unemployment	1.83	2.50
Incidents of non-compliance with regulations complying to safety impacts of pavement	4.33	4.33
Surveys to assess consumer satisfaction	3.17	4.17
Product disposal (landfill, recycling, incineration, reuse)	1.33	4.50

Cost of consequences: concrete processing technologies (the Netherlands)

Polished stone value: The crash rates and the annual risk (crash costs) associated with the do-minimum and use of recycled aggregates from C2CA and SWP technologies are presented in Table D 5, Table D 6, and Table D 7, respectively. All the crash costs are expressed in million Euros.

Table D 5. Crash Rates and Associated Risk (costs) for Do-minimum Scenario

Do-minimum								
Year	**SI**	**CR**	**Fatality**	**Serious injury**	**Minor damage**	**Fatality cost (million Euros)**	**Serious injury cost (million Euros)**	**Minor damage cost (million Euros)**
0	0.44	7.17	0.0	1.1	6.0	0.21	0.78	0.24
1	0.43	7.99	0.0	1.2	6.7	0.24	0.87	0.27
2	0.41	8.90	0.0	1.4	7.5	0.26	0.97	0.30
3	0.40	9.92	0.0	1.5	8.3	0.29	1.08	0.33
4	0.38	11.05	0.1	1.7	9.3	0.33	1.20	0.37
5	0.37	12.31	0.1	1.9	10.3	0.36	1.34	0.41
6	0.35	13.71	0.1	2.1	11.5	0.41	1.49	0.46
7	0.34	15.28	0.1	2.4	12.8	0.45	1.66	0.51
8	0.33	17.02	0.1	2.6	14.3	0.50	1.85	0.57
9	0.31	18.96	0.1	2.9	15.9	0.56	2.06	0.64
10	0.30	21.12	0.1	3.3	17.7	0.63	2.30	0.71
11	0.28	23.53	0.1	3.7	19.8	0.70	2.56	0.79
12	0.27	26.21	0.1	4.1	22.0	0.78	2.85	0.88
Total costs (million Euros)						5.7	21.0	6.5
						33.22		

Table D 6. Crash Rates and Associated Risk (costs) of using Recycled Aggregates of Stationary Wet Processing Technology

Stationary wet processing								
Year	**SI**	**CR**	**Fatality**	**Serious injury**	**Minor damage**	**Fatality cost (million Euros)**	**Serious injury cost (million Euros)**	**Minor damage cost (million Euros)**
0	0.50	4.56	0.0	0.7	3.8	0.14	0.50	0.15
1	0.49	5.08	0.0	0.8	4.3	0.15	0.55	0.17
2	0.47	5.66	0.0	0.9	4.8	0.17	0.62	0.19
3	0.46	6.31	0.0	1.0	5.3	0.19	0.69	0.21
4	0.44	7.02	0.0	1.1	5.9	0.21	0.76	0.24
5	0.43	7.83	0.0	1.2	6.6	0.23	0.85	0.26
6	0.41	8.72	0.0	1.4	7.3	0.26	0.95	0.29
7	0.40	9.71	0.0	1.5	8.2	0.29	1.06	0.33
8	0.39	10.82	0.1	1.7	9.1	0.32	1.18	0.36
9	0.37	12.05	0.1	1.9	10.1	0.36	1.31	0.40
10	0.36	13.43	0.1	2.1	11.3	0.40	1.46	0.45
11	0.34	14.96	0.1	2.3	12.6	0.44	1.63	0.50
12	0.33	16.66	0.1	2.6	14.0	0.49	1.81	0.56
Total costs (million Euros)						3.6	13.3	4.1
						21.12		

Table D 7. Crash Rates and Associated Risk (costs) of using Recycled Aggregates from Concrete to Cement and Aggregates Technology

Concrete to cement and aggregates								
Year	**SI**	**CR**	**Fatality**	**Serious injury**	**Minor damage**	**Fatality cost (million Euros)**	**Serious injury cost (million Euros)**	**Minor damage cost (million Euros)**
0	0.54	3.37	0.0	0.5	2.8	0.10	0.37	0.11
1	0.53	3.76	0.0	0.6	3.2	0.11	0.41	0.13
2	0.51	4.18	0.0	0.6	3.5	0.12	0.45	0.14
3	0.50	4.66	0.0	0.7	3.9	0.14	0.51	0.16
4	0.48	5.19	0.0	0.8	4.4	0.15	0.56	0.17
5	0.47	5.79	0.0	0.9	4.9	0.17	0.63	0.19
6	0.45	6.45	0.0	1.0	5.4	0.19	0.70	0.22
7	0.44	7.18	0.0	1.1	6.0	0.21	0.78	0.24
8	0.43	8.00	0.0	1.2	6.7	0.24	0.87	0.27
9	0.41	8.91	0.0	1.4	7.5	0.26	0.97	0.30
10	0.40	9.93	0.0	1.5	8.3	0.29	1.08	0.33
11	0.38	11.06	0.1	1.7	9.3	0.33	1.20	0.37
12	0.37	12.32	0.1	1.9	10.3	0.37	1.34	0.41
Total costs (million Euros)						2.69	9.87	3.05
							15.61	

Influence of variation in polished stone value on net risk reduction gain

In order to assess the influence of varying PSV on the technical performance KPI and NRRG, the PSV values were reduced in intervals of 5% until a maximum reduction of 25%. A further reduction in the PSV was not considered as it resulted in ISI below the permissible threshold of 0.42. The average number of commercial vehicles per day were 2000. The PSV for the C2CA, SWP, and 'do-minimum' scenarios at reduced levels are presented in Table D 8. Further, the corresponding change in NRRG is shown in Table D 9. As can be seen in Table D 9, the technical performance of the pavements had a major contribution to the NRRG. A reduction in the PSV was consequential of increasing technical risks. However, the magnitude of increase in risk for C2CA and SWP methods was similar.

On another account, an increase in the average daily traffic for the selected PSV resulted in very low ISI. For the given PSV and average daily traffic beyond 3500 vehicles, the respective ISI for aggregates derived from C2CA and SWP technologies was 0.43 and 0.39, which is marginally above and below the threshold ISI. Therefore, there are certain limitations associated with the models used in this study, which reduce the reliability of the current findings, and call for the need to collect data and develop prediction models for precise assessment of technical failure risks of pavements.

Table D 8. Polished Stone Value of Aggregates from Different Processing Technologies

Polished stone value	Concrete to cement and aggregates	Stationary wet processing	Do-minimum
Initial	64.96	60.66	72.00
-5%	61.71	57.63	68.40
-10%	58.46	54.59	64.80
-15%	55.21	51.56	61.20
-20%	51.96	48.53	57.60
-25%	48.72	45.49	54.00

Table D 9. Variation in Net Risk Reduction Index at Varying Polished Stone Values

Assessment category	**5%**		**10%**		**15%**		**20%**		**25%**	
	C2CA	**SWP**	**C2CA**	**SWP**	**C2CA**	**SWP**	**C2CA**	**SWP**	**C2CA**	**SWP**
Performance	*0.08*	*0.05*	*0.08*	*0.06*	*0.09*	*0.07*	*0.09*	*0.07*	*0.09*	*0.07*
Cost	0.07	0.03	0.07	0.03	0.07	0.03	0.07	0.03	0.07	0.03
CE	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.02
	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Environment	0.04	0.07	0.04	0.07	0.04	0.07	0.04	0.07	0.04	0.07
	0.03	0.05	0.03	0.05	0.03	0.05	0.03	0.05	0.03	0.05
	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Social	0.07	0.05	0.07	0.05	0.07	0.05	0.07	0.05	0.07	0.05
Net risk reduction gain	***0.45***	***0.40***	***0.45***	***0.40***	***0.46***	***0.41***	***0.46***	***0.41***	***0.46***	***0.41***