MAPPING THE ROAD TO SUSTAINABILITY: A CRITICAL ASSESSMENT OF CIRCULARITY INDICATORS IN PAVEMENT INFRASTRUCTURE

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By

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CERTIFICATE

As a statement for this paper, I declare that this thesis proposal complies with the TU Delft Integrity Regulation, especially the B and D of the TU Delft Integrity Statement about responsible research and innovation, and academic integrity, respectively.

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ABSTRACT

The rapid development of infrastructure has led to various environmental, economic, and societal challenges. The pavement industry, in particular, is known for its high energy consumption, resource utilization, and pollution generation. Despite recent efforts to augment the sustainability and circularity of pavement infrastructure, there remains a lack of comprehensive assessment methods to evaluate the existing practices and technological advancements, which makes the implementation of innovations challenging.

This study reviewed twelve existing circular economy indicators and frameworks to understand the challenges associated with their use in evaluating pavement infrastructure. The indicators included Material Circularity Indicator (MCI), Circular Economy Index (CEI), CB'23 framework, Environmental Sustainability and Circularity Indicator (ESCi), Circular Economy Indicator Prototype (CEIP), Material Reutilization Score (MRS), Value-based Resource Efficiency (VRE), Circular Economy Performance Indicator (CPI), Recyclability Benefit Rate (RBR), Reuse Potential Indicator (RPI), Product-level Circularity Metric (PLCM), and Building Circularity Indicator (BCI). These indicators cover different aspects of circularity and sustainability, such as resource efficiency, material circularity, product's lifetime, preservation of product's functions, and environmental and economic impacts. However, none of the indicators provide a comprehensive assessment tailored for pavements, encompassing circularity and all three aspects of sustainability.

Considering factors such as data availability, overlap of conceptual and methodological approach, and the scope covered, six of the twelve circularity indicators were evaluated in this study, namely, MCI, CEI, CB'23, ESCi, CEIP, and MRS. Since these indicators were not originally developed to assess pavements, appropriate methodological modifications were proposed and validated using three different pavement construction and maintenance methods that are commonly adopted in the Netherlands. In order to map the road to sustainability, the analysis was complemented with the Environmental Cost Indicator (ECI, or in Dutch, MKI) and Net Present Value (NPV).

The three case studies adopted in this study included: (a) resurfacing the pavement once in every 12 years with 25% Reclaimed Asphalt Pavement (RAP), hereafter referred as Business As Usual (BAU) scenario, (b) life-extension maintenance by rejuvenating the pavement in years 5 and 10 since construction followed by resurfacing, and (c) use of low-emission technology, i.e., Warm-Mix Asphalt (WMA) with higher RAP

percentage (50% by mass) in the mix. An analysis period of 36 years was chosen as per the Federal Highway Administration guidelines and the foreground data was collected from roadway stakeholders. Additional missing information was also gathered from Dutch asphalt product category rule, international databases, and existing literature.

The results revealed the strengths and limitations of each indicator. MCI being a mass-based indicator captured the material circularity and product's service life but failed to represent the environmental and economic impacts. Although CEI indirectly captures the environmental impacts as it is governed by market prices, which takes into consideration the societal and environmental taxes, it is volatile as it is can also be influenced by the supply and demand of raw materials and material quality, potentially overlooking the benefits of using higher percentages of recycled materials. CB'23 provides detailed information by classifying pavement components across different circular economy principles, which aids in targeted improvements but complicates the comparison of alternatives as a whole. ESCi combines MCI and MKI to incorporate circularity and environmental sustainability but requires extensive modelling and lacks economic and social considerations. CEIP, as a questionnaire-based indicator, covers a wide range of circularity principles, but the weighting and scoring of questions is subjective as it is based on the expert opinion leading to concerns of bias in decision-making. MRS involves simplified mathematical computations, thereby serving as an attractive choice for quick decision-making. However, it is fundamentally biased to cover only the recycling strategy, and ignores the aspect of lifecycle use, thereby not accounting for durability of the asset.

With regards to the case studies, MKI, MCI, ESCi, and MRS indicate that the WMA alternative was the most circular strategy. LCCA, CEI, and CEIP favour the rejuvenation alternative, while CB'23 may favour one alternative when the result of one sub-indicator is designated to be the criterion for decision making. However, since all the indicators cover different aspects of circularity, it is important to complement the results with environmental, economic, and social sustainability indicators for comprehensive and robust assessments. In practice, choosing different alternatives based on the selected indicators can lead to varying end result. Therefore, it is essential to handle these implications carefully and the scope, boundaries, methods, assumptions and any limitations must be clearly stated for transparent decision-making. Future research should focus on improving data quality and developing methods to integrate social sustainability, wherever feasible.

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ACRONYMS

ART	Asphalt Recycling Train
BCI	Building Circularity Indicator
CE	Circular Economy
CEI	Circular Economy Indicator
CEIP	Circular Economy Indicator Prototype
CIR	Cold In-situ Recycling
CPI	Circular Economy Performance Indicator
DC	Delay Costs
ECI	Environmental Cost Indicator
EMF	Ellen MacArthur Foundation
EOL	End-of-Life
ESC_i	Environmental Sustainability and Circularity Indicator
FHWA	Federal Highway Administration
HIR	Hot In-situ Recycling
HMA	Hot Mix Asphalt
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LEAB	Laag Energie Asfalt Beton
LFI	Linear Flow Index
MCI	Material Circularity Indicator
MKI	Milieu Kosten Indicator

MRS	Material Reutilization Score
NPV	Net Present Value
PCR	Product Category Rules
PLCM	Product Level Circularity Metric
RA	Reclaimed Asphalt
RAP	Reclaimed Asphalt Pavement
RBR	Recyclability Benefit Rate
RPI	Reuse Potential Indicator
SDG	Sustainable Development Goal
UN	United Nations
VOC	Vehicle Operation Costs
VRE	Value-based Resource Efficiency
WMA	Warm Mix Asphalt
ZOAB	Zeer Open Asfaltbeton

1. INTRODUCTION

1.1 Background

Though the recent technological advancements have served as a boon for infrastructure development, concerns relevant to the environmental, societal, and economic factors have increased at an alarming rate. Environmental problems such as air, water, and soil pollution, biodiversity loss, soil degradation, global warming, and deforestation are damaging the living environment of the current and future generations. Societal problems such as poverty, hunger, poor health services, and inequality are affecting people's living quality. Economic challenges such as weakening growth of global trade, high level of external debts, and inflation bring uncertainties to the prosperity of nations across the globe. In short, the current way of development is not sustainable. Such an emergency has raised the importance of a Circular Economy (CE) to the policymakers in many countries. In 2008, China became the first nation to introduce a legislation on CE (Beaulieu et al., 2016). The European Union published its first CE action plan in 2015 and updated it to a new version in 2020. The plan is intended to guide the transition to a regenerative growth model, the reform of consumption, and ultimately the achievement of a cleaner and more competitive Europe (European Commission, 2020). In addition to countries, institutions and organizations have also made efforts in establishing a CE. For instance, the Ellen MacArthur Foundation (EMF) have published through their report "Towards the Circular Economy" their understanding of the demand for a circular economy, and also an indicator for measuring circularity through report "Circularity Indicators" (Ellen MacArthur Foundation, 2013, 2019).

Sustainability and circular economy are two different concepts. Compared with the CE, sustainability provides a broader framing (Geissdoerfer et al., 2017). According to the definition of the World Commission on Environment and Development, sustainability is the "ability to meet the needs of the present without compromising the ability of the future generations to meet their own needs" (World Commission on Environment and Development, 1987). Sustainable development can be characterized by three complementary and mutual supportive aspects, or the 'three pillars': environment, economy, and society (UN, 2005). It is possible that the achievement of one aspect requires compromise from the others, and sometimes there are even conflicts within the same pillar (Hansmann et al., 2012). To address this issue, methods of integration have been researched to balance the three dimensions to reach an unbiased sustainable development. As a guideline to achieve sustainability, the UN has chartered out the seventeen Sustainable Development Goals (SDGs), which lists the practical challenges in terms of the three aspects (environment, economy, and society) of sustainable development that countries around the world can focus upon.

Although the exact year and author of origin are not traceable, it is believed that the practice of the CE started back in the 1970s (Ellen MacArthur Foundation, 2013). Through decades of theoretical development and practical application, researchers from different institutions have formed various versions of the definition of the CE, among which a representative one was made by the EMF, who characterizes the CE as "an economic and industrial model that is restorative and regenerative by design" (Ellen MacArthur Foundation, 2019). To be more specific, being an opposite of the current linear economy where resources follow a 'take-make-dispose' model that results in a large amount of waste generation and use of virgin materials, the CE minimizes resource input and waste output by keeping them inside the loop as much as possible (Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017). The incentive and hence the aim of the CE model, as being stated in the previous section, is the decoupling of economic growth from using finite virgin materials. Such an aim can possibly be achieved by various approaches. The EMF proposes three principles: elimination of waste and pollution, maximizing the utility of materials and products, and regeneration of natural resources (Ellen MacArthur Foundation, 2019). The EU, however, adopts a waste hierarchy (or the 4R framework), which proposes 'reduce', 're-use', 'recycle', and 'reduce' in a priority order (The European Union, 2008).

1.2 Pavement infrastructure

The main assessment target of this study is pavement, which is an essential part of road infrastructures. Generally, there are two major types of pavements based on its composition: asphalt pavement and concrete pavement. Since most of the pavement in the Netherlands are made from asphalt, asphalt pavement is selected specifically for this study. There are four major components of an asphalt pavement: coarse aggregate, fine aggregate, bitumen, and filler. The varying percentages of these components result in different types of pavements that have different performances.

1.3 Developments in the pavement sector

According to the definition by the Ellen MacArthur Foundation, one of the principles of the circular economy is to eliminate waste and pollution (Ellen MacArthur Foundation, 2019). The construction industry, however, is known for generating a considerable amount of waste, which also causes negative environmental impact. It is believed that about 30% of the total waste generated globally is construction and demolition waste (Purchase et al., 2021). As one sector in the construction industry, the pavement construction is no exception to that. Road pavement, together with its maintenance, is investment and energy intensive and cause considerable pollution through multiple stages in its life cycle (Salehi et al., 2021). To address these issues, technological innovations and legislative improvements have taken place.

1.3.1 Asphalt recycling

Asphalt is a 100% recyclable material (European Asphalt Pavement Association, 2014). Depending on the place where the recycling activity takes place, asphalt recycling can generally be classified into two types: ex-situ and in-situ.

1.3.1.1 Ex-situ recycling

In ex-situ recycling, the end-of-life (EOL) pavement is first excavated from the road and then transported to a processing plant. The asphalt collected from the site is called the reclaimed asphalt pavement (RAP). In the asphalt plant, the RAP is mixed with virgin raw materials at high temperature to produce new asphalt that can be paved on the road. The proportion of the RAP may vary according to the performance requirement of the final product.

1.3.1.2 In-situ recycling

As an opposite to ex-situ recycling, the recycling activities of in-situ recycling are carried out on-site. Depending on the temperature at which the recycling is carried out, in-situ recycling can be further classified into hot in-situ recycling (HIR) and cold in-situ recycling (CIR). In both methods, the asphalt is milled and collected from the road and then mixed with virgin materials. The difference is that for HIR, the asphalt is heated before milling, and for CIR, asphalt emulsion is added to the RAP before mixing with virgin aggregates (Dam et al., 2015). In the domain of in-situ recycling, new technologies like the Asphalt Recycling Train (ART) are being examined on their feasibility in the Netherland and are believed to be beneficial to sustainable development (Rijkswaterstaat, 2024).

In this study, asphalt recycling is assumed to be ex-situ recycling due to its relatively wider application in the Netherlands.

1.3.2 Rejuvenation

Rejuvenation is a life-extension maintenance activity carried out during the use phase of asphalt pavement. This technology involves spraying a rejuvenator compound on the road using a sprayer, which reacts with the oxidized bitumen to restore its binding capability. As the application of rejuvenator leads to smoothening of the pavement surface and reduction in friction, a thin sand layer is spread over the pavement to allow safe movement of traffic. By rejuvenation, the service life of the pavement.

1.3.3 Warm Mix Asphalt

Warm mix asphalt is an asphalt production technology that can reduce energy consumption. Conventionally, in a production plant, the asphalt is produced at a temperature higher than 140°C, which is called Hot Mix Asphalt (HMA). In response to the desire of lower emission and energy consumption, asphalt that can be produced at a lower temperature, Warm Mix Asphalt (WMA), is developed. There are three major methods that can be used to produce WMA: organic additives, chemical additives, and foaming process. Among these three methods, organic additives and foaming process achieve lower temperature by reducing the viscosity of the bitumen, while chemical additives improve the coating capability of the bitumen directly (Caputo et al., 2020; Diab et al., 2016). Some representative organic additives are Sasobit®, Asphaltan B, and Licomont BS. Examples for chemical additives are Evotherm®, Rediset, and Iterlow, and for foaming process, there are LEAB® (in Dutch: Laag Energie Asfalt Beton), LT-Asphalt, and WAM-Foam (Caputo et al., 2020; D'Angelo et al., 2008).

While the effect of WMA technology on the service life of pavement is unknown, it is expected that energy consumption at production is reduced due to a lower temperature requirement. Though the extent of reduction varies from different sources, studies generally show that WMA production consumes approximately 10 to 30% less energy compared with HMA (Hettiarachchi et al., 2019; Milad et al., 2022; Mohammad et al., 2015; Oner & Sengoz, 2015). Another benefit of WMA is that it allows for a higher percentage of RAP used in asphalt production. By experience, in HMA, there is 25% of RAP and 75% of virgin materials. However, in a LEAB® process, it is typical that 50% of RAP is used, which improves the circularity of the asphalt (D'Angelo et al., 2008).

Three types of effort in making pavements more sustainable and circular are introduced above. However, although there are various technologies for improving the circularity and sustainability of pavement infrastructures, there still lacks key performance indicators (KPIs) to assess different practices, making the implementation of these technologies difficult. Therefore, investigating the suitability of various indicators in assessing the circularity and sustainability of pavement becomes necessary.

1.4 Thesis organization

The first Chapter of this thesis provides a general background to the concept of circular economy and challenges faced by the pavement sector. Chapter 2 elaborates on the fundamental differences between circular economy and sustainability as well as reviews the existing circular economy indicators in the context of pavement sector. Chapter 3 provides the problem statement and lists the main research questions and objectives. Chapter 4 introduces the methodology used to conduct this study. Chapter 5 presents the results obtained with the methodology. Chapter 6 discusses the results. Chapter 7 draws conclusions and limitations of the study and provides recommendations.

2. LITERATURE REVIEW

2.1 General

In the previous section, a general background to the topic was provided. It was understood that the concepts of circular economy and sustainability are essential pillars of this research. This chapter discusses the confusion between the concepts of sustainability and circularity as well as reviews circular economy indicators used to assess pavements or products of other sectors. Specifically, Section 2.2 discusses the relations between sustainability and circular economy. Section 2.3 introduces the circularity assessment of pavements. And Section 2.4 reviews all the indicators being chosen.

2.2 Sustainability and circular economy

While sustainability and circular economy has become increasingly important in policy making, it is rather common that these two concepts cause confusion to people, who often find troubles in identifying the relationship between them. Geissdoerfer et al. (2017) reviewed extensive literatures regarding these two concepts and summarized their relationships into three categories: conditional, beneficial, and trade-off, and each category can further be divided into more specific sub-categories.

In the context of a conditional relationship, there are conditional relation, strong conditional relation, and necessary but not sufficient relation. In the conditional relation, the establishment of a circular economy is a condition of transforming to a sustainable system. In the strong conditional relation, the circular economy becomes a major solution of sustainability. And for the necessary but not sufficient relation, the establishment of circular economy must be accompanied with other conditions to achieve sustainability.

There are two types of beneficial relationships: beneficial relationship and subset relation. For the first type, improving circularity contributes to improving sustainability. For the second type, the improvement of circularity is one of the several options to improve sustainability.

For the trade-off relationship, there are three sub-categories: degree relation, cost-benefit relation, and selective relation. In the degree relation theory, it is believed that circular economy results in a certain degree of sustainability, which could be larger or smaller than that of other solutions. In the cost-benefit relation, the achievement of circular economy may harm sustainability. Similarly, in the selective relation, the improvement of circularity may benefit some aspects of sustainability while harming other aspects.

It can be observed that there are contradictions but also overlaps in these relationships. Geissdoerfer et al. (2017) considered the subset relation the reasonable one due to its adaptability and compatibility to other sustainability strategies. This study also adopts this relation because sustainability is a broad concept that covers environmental, economic, and societal aspects, and all the efforts devoted in improving pavement circularity can be considered to contribute to one of these three aspects, though more on the environmental aspect. By considering circular economy as a subset of sustainability, it contributes to its integrated use with other environmental, economic, and social strategies as no hierarchy is defined between them. In this way, the transition to a sustainable society is more likely to be achieved.

2.3 Circularity assessment in pavements

Although an indicator specifically designed for assessing the circularity of pavement cannot be found at current stage, there have been some practices trying to use indicators originally designed for other use in the context of pavement. Mantalovas and Di Mino (2019) used Material Circularity Indicator (MCI) to investigate the circularity of the wearing course, binder course, and base course and compared the results with the MCI results of the regulation limits and technical limits. This indicator was developed by the Ellen MacArthur Foundation (2019), and considers the linear material flow and the utility (lifetime or intensity of use). They concluded that the base course has the highest circularity, and there is room for the circularity performance of the current pavement to improve. Though this indicator assess circularity of pavements, it is a mass-based indicator, which does not include sustainability assessment. To improve this, Mantalovas and Di Mino (2020) also tried to combine environmental sustainability and circularity assessment of pavements by developing a new indicator, Environmental Sustainability and Circularity indicator (ESC_i). This indicator combines the environmental aspect of sustainability and circularity by incorporating the result of life cycle assessment (LCA) and MCI in one equation. The researchers used this indicator to assess pavements with different percentage of Reclaimed Asphalt (RA). It was found that the ESC_i results increase with the percentage of RA, therefore making the pavement with the highest percentage of RA the one with the best performance. The LCA component of ESC_i enables the integration of environmental sustainability with circularity. However, the LCA parts requires additional data collection, modelling, and calculation works. In addition, only one of the three aspects of sustainability is covered.

Therefore, it might be undesirable if a quick decision or a more comprehensive sustainability assessment is required.

2.4 Other indicators in building infrastructure

There are limited practices that can be found to have used circular economy indicators to assess pavements. Nevertheless, many of these indicators have the potential of being used for the purpose of this study. To identify the existing indicators, several literatures compiling circular economy indicators were reviewed (De Pascale et al., 2021; Moraga et al., 2019; Saidani et al., 2019).

Circular Economy Index (CEI) is a value-based indicator developed by Di Maio and Rem (2015). Instead of assessing circularity by mass, CEI captures the environmental benefits of recycling activities with the value of the materials. Di Maio et al. (2017) also developed a similar indicator, value-based resource efficiency (VRE). VRE also adopts a value-based methodology and can be used to assess resource efficiency along the supply chain.

As mentioned in Section 1.1, the main goal of a circular economy is to reduce resource input and waste output, and one of the main approaches is recycling (Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017; The European Union, 2008). Therefore, it is natural that numerous circular economy indicators assess the level of circularity by targeting at recycling activities and recycled materials related to the product. Apart from the CEI mentioned above, there are the circular economy performance indicator (CPI), the recyclability benefit rate (RBR), the Material Reutilization Score (MRS), the Product-level Circularity Metric (PLCM), and the reuse potential indicator (RPI). The CPI compares the ideal environmental benefit with the actual environmental benefit brought by different recycling options. The environmental benefit is calculated through life cycle assessment (LCA) (Huysman et al., 2017). Similarly, the RBR developed by the same author compares the environmental benefit of recycling the product against the burden of using virgin materials for production followed by disposal after use. The environmental benefit and burden involved in RBR are also calculated with LCA (Huysman et al., 2015). Also targeting at the recycling activities, the RPI measures circularity by calculating the mass portion of a product that is economically profitable to recycle (Park & Chertow, 2014). The MRS, focusing more on the product itself, assess circularity with the mass percentage of the recycled and recyclable materials in a product (Cradle to Cradle Products Innovation Institute, 2016). The PLCM, however, uses a similar approach by investigating the portion of the value instead of mass of the recirculated parts in a product (Linder et al., 2017).

The abovementioned indicators mainly consider the ‘recycle’ strategy of the 4R framework. As an indicator that requires a multi-step calculation, the Building Circularity Indicator (BCI) considers more aspects that could affect circularity. It incorporates the MCI along with other considerations like disassembly possibilities, weighting of the product, and level of importance (Verberne, 2016). A questionnaire-based indicator, the circular economy indicator prototype (CEIP), carries out a circularity score of a product by asking questions regarding circular economy principles and strategies (Cayzer et al., 2017).

There is also one indicator, CB’23, that, instead of carrying out a single number as its result, delivers detailed information about the components of a product. The product is divided with different ways, including input or output materials, primary or secondary materials, and abundant or scarce materials etc. Each category is quantified and the final deliverable is a list of figures (Platform CB'23, 2022).

Table 2-1 provides the characterization of the indicators reviewed. Not all of these indicators are used in the assessment part of this study, and the detailed explanation of the indicators being selected is provided in Chapter 4.

Table 2-1 Characterization of the indicators reviewed.

Indicators	**CE Strategies**	**Measurement Scope**	**Scale**	**Models**	**Measurement Type**	**LCA Phase Coverage**	**Source**
MCI	Strategy 2, 4, 5, and 6	Scope 1	Micro	Table 2-2	Direct circularity	Cradle-to-cradle	(Ellen MacArthur Foundation, 2019)
CEI	Strategy 4	Scope 2	Micro		Direct circularity	Reuse-recycling-recovery	(Di Maio & Rem, 2015)
CB'23	Strategy 1, 3, 4, 5, and 6	Scope 1 and 2	Micro		Direct circularity	Cradle-to-cradle	(Platform CB'23, 2022)
ESC$_i$	Strategy 2, 4, 5, and 6	Scope 1 and 2	Micro		Direct circularity	Cradle-to-cradle	(Mantalovas & Di Mino, 2020)
CEIP	Strategy 1, 2, and 4	Scope 1	Micro		Direct circularity	Cradle-to-cradle	(Cayzer et al., 2017)
MRS	Strategy 4	Scope 0	Micro		Direct circularity	Reuse-recycling-recovery	(Cradle to Cradle Products Innovation Institute, 2016)
VRE	Strategy 4	Scope 2	Macro, Meso, Micro		Direct circularity	Cradle-to-cradle	(Di Maio et al., 2017)
CPI	Strategy 4 and 5	Scope 2	Micro		Direct circularity	Reuse-recycling-recovery	(Huysman et al., 2017)
RBR	Strategy 4	Scope 2	Micro		Direct circularity	Reuse-recycling-recovery	(Huysman et al., 2015)
RPI	Strategy 4	Scope 1	Micro		Direct circularity	Reuse-recycling-recovery	(Park & Chertow, 2014)
PLCM	Strategy 2, 3, and 4	Scope 2	Micro		Direct circularity	Reuse-recycling-recovery	(Linder et al., 2017)
BCI	Strategy 1, 2, 3, 4, 5, and 6	Scope 1	Micro		Direct circularity	Cradle-to-cradle	(Verberne, 2016)

Table 2-2 Mathematical descriptions of the indicators.

Indicators	**Equations**
MCI	$MCI_P^* = 1 - LFI \cdot F(X)$ $MCI_P = (0, MCI_P^*)$
CEI	$CEI = \frac{Material\ value\ added}{Material\ value\ for\ reproducing\ the\ EOL\ product}$
CB'23	Table 4-4
ESCi	$ESC_i = \frac{1}{LCA_T^{(1-MCI)}} \times 100$
CEIP	Table 4-9 and Table 4-10
MRS	$MRS = \frac{\left[\begin{matrix}\%recycled\ or\ rapidly\ renewable\\ product\ content\end{matrix}\right] + 2\left[\begin{matrix}\%\ of\ product\ recyclable\\ or\ biodegradable/compostable\end{matrix}\right]}{3} \times 100$
VRE	$VRE = \frac{GO - E - M - S}{E + M}$
CPI	$CPI = \frac{actual\ benefit\ of\ treatment}{ideal\ benefit\ of\ treatment\ according\ to\ quality}$
RBR	$RBR = \frac{environmental\ savings\ from\ recycling}{environmental\ burdens\ from\ production}$
RPI	$RPI = \frac{economically\ reusable\ portion}{current\ level\ of\ generation}$
PLCM	$c_{1\&2} = c_1 \times \frac{v_1}{v_1 + v_2} + c_2 \times \frac{v_2}{v_1 + v_2}$
BCI	$PCI_p = \frac{1}{F_d}\sum_{i=1}^{n} MCI_p * F_i$ $SCI_s = \frac{1}{W_s}\sum_{j=1}^{n} PCI_j * W_j$ $BCI = \frac{1}{LK_i}\sum_{k=1}^{n} SCI_k * LK_k$

Table 2-1 describes the indicators reviewed with a few categories, and some categories refer to the classification framework of CE indicators proposed by Moraga et al. (2019). The first category is CE strategies, which aims to describe the circular economy strategies the indicator assess. In total there are six strategies recommended and are listed in Table 2-3. Each indicator may correspond to one or more strategies.

Table 2-3 Circular economy strategies and the corresponding definitions (Moraga et al., 2019).

Strategies	**Definition**
Strategy 1	Preserve the function of products.
Strategy 2	Preserve the product itself.
Strategy 3	Preserve the components of the product.
Strategy 4	Preserve the materials.
Strategy 5	Preserve the embodied energy.
Strategy 6	Measure the linearity or lack of preservation strategies.

The next category is the measurement scope. When assessing the product, an indicator may adopt a Life Cycle Thinking (LCT) approach, which considers the indicator from the prospective of its whole lifecycle from design to disposal, and is believed to be beneficial in preventing problem shifting, by which solving one problem may cause other environmental, economic, or social problems unintentionally (Mazzi, 2020). The measurement can be classified into three scopes, which are shown in Table 2-4.

Table 2-4 Measurement scopes and the corresponding definitions (Moraga et al., 2019).

Scopes	**Definition**
Scope 0	The indicator only measures the physical properties within the technological cycles without adopting LCT.
Scope 1	The indicator incorporates partial or full LCT with physical properties within the technological cycles.
Scope 2	The indicator measures the environmental, economic, and social effects caused by technological cycles with a cause-and-effect modelling approach.

Scale of measurement is the next category. There are three scales: micro, meso, and macro, and scales are shown in Table 2-5. It is possible for an indicator to be capable of measuring several scales.

Table 2-5 Scales of measurement and the corresponding coverage (Kristensen & Mosgaard, 2020; Moraga et al., 2019).

Scales	**Coverage**
Micro	Product, service, or organization.
Meso	Eco-industrial parks, industrial symbiosis.
Macro	City, province, region, nation, globe.

Additionally, an indicator can also be described mathematically by the model, which can be derived with tools, used to calculate it (Moraga et al., 2019; Sala et al., 2012). Although the types of models are not defined by Moraga et al. (2019), this study still identifies the models to be equations for most indicators. One exception is CEIP, which is calculated by adding up the scores of several questions. The mathematical descriptions of the indicators are shown in Table 2-2.

By the type of measurement, the indicators can be classified into direct CE or indirect CE. The types and the definitions are listed in Table 2-6. Since all the indicators reviewed in this study target at one or more CE strategies, the measurement types are all direct CE.

Table 2-6 Measurement types and the corresponding definition (Moraga et al., 2019).

Measurement types	Definition
Direct CE with specific strategies	The indicator assesses one or more identifiable CE strategies.
Direct CE without specific strategies	The indicator assesses more than one CE strategies, though unidentifiable.
Indirect CE	The indicator evaluates CE not by directing at CE strategies.

The last category is the lifecycle stage coverage. In the lifecycle of a product, there are various stages: product stage, construction stage, use stage, EOL, and the reuse-recycling-recovery. Each stage may have several steps. Among these stages and steps, three milestones have been identified as the key points: the raw material extraction as the cradle, the end of manufacturing as the gate, and the disposal as the grave. By using these milestones, the coverage of lifecycle stages can be clearly described.

2.5 Summary

This Chapter discussed the confusion between sustainability and circularity. In addition, twelve circular economy indicators are reviewed. The next Chapter presents the problem statement and research objective as well as the tasks of this study.

3. PROBLEM STATEMENT AND RESEARCH OBJECTIVE

Based on the literature presented in the previous Chapter, it has been understood that continuous attempts are being made to transition to circular practices. However, limited attention has been paid in the pavement sector and the existing circularity indicators have their own strengths and limitations including but not limited to inadequate coverage of sustainability aspects and incompatibility with pavement scenarios. Importantly, the challenge in implementing eco-friendly pavement construction and maintenance technologies lies in the lack of suitable indicators to effectively measure the circularity and sustainability credentials. Therefore, this study aims at addressing the following research questions:

1. What is potential of existing indicators to assess the circularity and sustainability of the pavement construction and maintenance technologies such as life-extension (preservation), recycling, and resurfacing (business as usual)?
2. What are the different methodological challenges (quantification) associated with the current circularity indicators?
3. Which indicators allow transparent assessment of the circularity and sustainability of different pavement technologies?

The first sub-question aims to provide an overview of the existing circularity and sustainability indicators and potential feasibility for use in the pavement sector. As it was not practical to assess all the existing indicators, a thorough review was undertaken to identify the strengths and limitations of various indicators and representative ones were selected for demonstration using case studies.

The second sub-question intends to understand the mathematical and practical scope for applicability of indicators to quantify the circularity potential of different pavement strategies, while also highlighting the gap in linking the findings to sustainability.

The third sub-question focuses on proposing methods for quantifying the circularity and sustainability performance of pavements using the selected indicators. The results were examined, and recommendations were made.

The different tasks that were undertaken in this study are summarized in the flowchart presented in Figure 3-1.

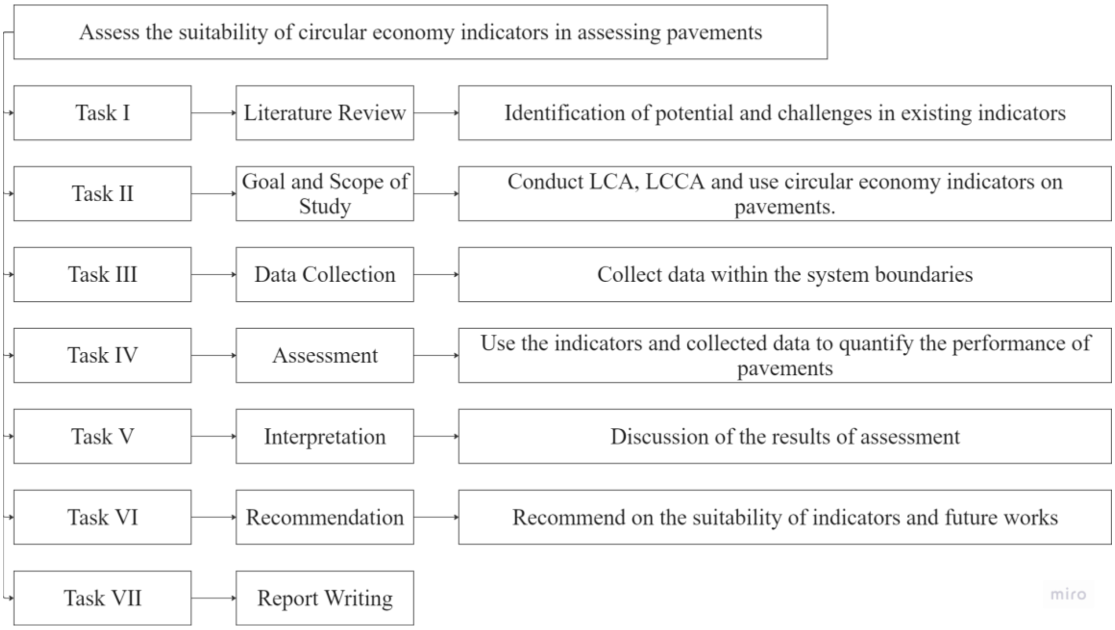

Figure 3-1 Tasks of this study

4. METHODOLOGY

4.1 General

The previous Chapter presented the problem statement as well as introduced the main research questions and objectives, and then listed the tasks that will be undertaken in this thesis. This Chapter presents the methodologies that will be adopted to answer the questions. First, the case studies selected for this study will be introduced. Then, a brief introduction of the indicators being chosen will be provided. Finally, a detailed description of the research approaches will be given.

4.2 Case studies

There are three scenarios being used as the case studies for this thesis: Resurfacing/Business as Usual (BAU), Rejuvenation, and Warm Mix Asphalt (WMA). This section provides introduction to these case studies.

4.2.1 Resurfacing/Business as Usual

The first case study was resurfacing of pavement also referred to as business as usual (BAU), where the materials from existing pavement surface are removed by milling and overlaid with virgin or recycled materials or a combination of both. Resurfacing was used as the baseline scenario as it is one of the most simple, oldest, and most commonly adopted maintenance approaches in the Netherlands and several parts of the world. In this research, the asphalt mixture used for resurfacing was hot mix consisting of 25% RAP by mass. Figure 4-1 provides an overview of the steps included in BAU.

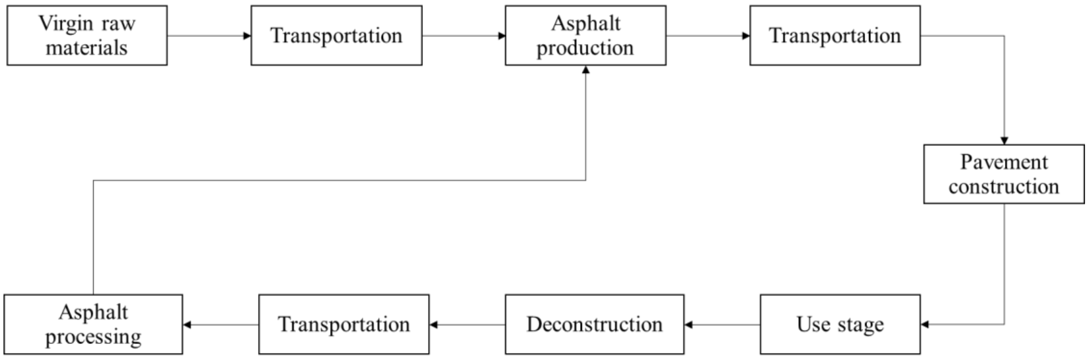

Figure 4-1 Procedures of BAU

The raw materials, including coarse aggregate, fine aggregate, bitumen, and filler were first extracted or produced and then transported to asphalt production plant, where they were mixed at high temperature to produce HMA. Then, the asphalt was transported to the construction site where paving activity took place. Figure 4-2 shows the milling process at deconstruction.

Figure 4-2 Pavement milling (Walkos, 2020)

4.2.2 Rejuvenation

In-situ rejuvenation was the second maintenance activity considered in this research. In-situ rejuvenation is a preservation maintenance method, which involves spraying a compound over the pavements' surface. This case study was selected owing to the fact that it does not require consumption of excessive virgin materials and energy for maintenance, thereby regarded as a sustainable and circular practice. Like the BAU scenario, a HMA was used to construct the pavement comprising 25% RAP by mass. Figure 4-3 shows the procedures of this scenario.

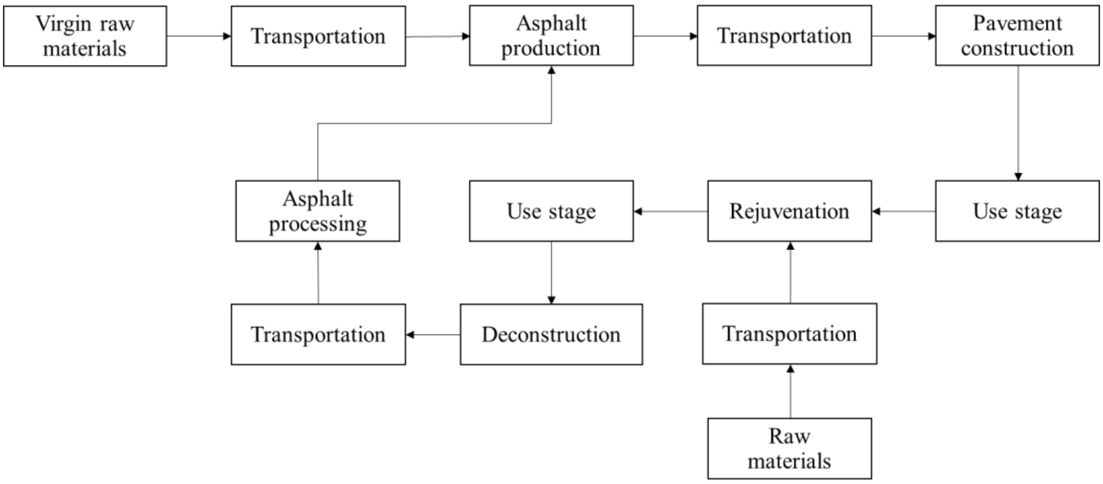

Figure 4-3 Procedures of Rejuvenation

Figure 4-4 A sprayer spraying rejuvenator on the road (Pavement Technology, n.d.)

The rejuvenator compound is sprayed on the road, which interacts with aged binder causing a change in polarity, restoring the bond between aggregates and bitumen. Figure 4-4 shows the spraying process of rejuvenator. Rejuvenator can be made from different materials, such as paraffin or bio-based materials. In this study, a paraffin-based rejuvenator was used. Sand gritting was carried out after the rejuvenation, which involves applying a thin layer of sand to the rejuvenated surface to ensure sufficient friction and maintain safe riding conditions.

4.2.3 Warm Mix Asphalt

As the Dutch government has passed the instructions to construct and maintain the pavements using low emissions technologies and mixtures having high recycled contents, the third case study considered in this research was construction of pavement using Warm Mix Asphalt (WMA) and maintain using the BAU and rejuvenation methods. The LEAB® process developed by BAM is chosen for this study as it is a popular exercise in the Netherlands by experience, and the asphalt includes 50% of RAP. Figure 4-5 provides the procedures in this scenario.

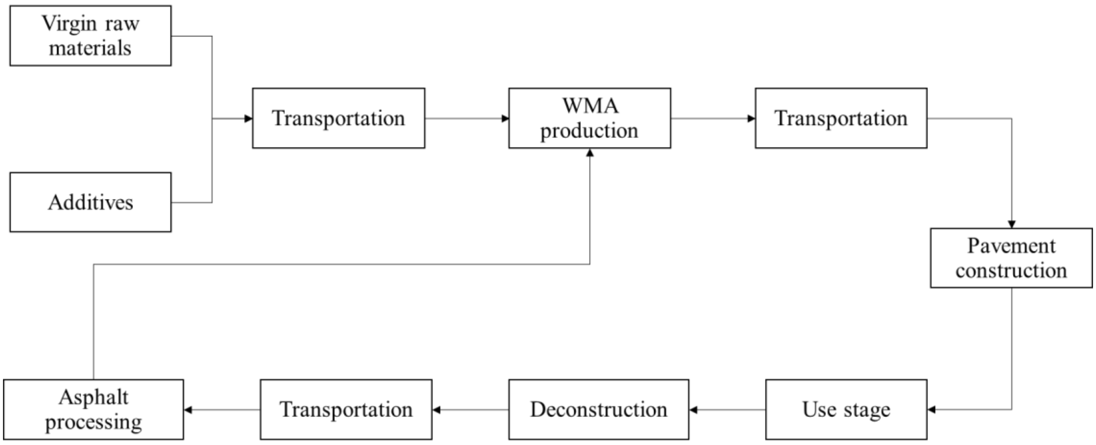

Figure 4-5 Procedures in WMA

The procedures are very similar to those of the BAU. In production, however, to enable a lower mixing temperature, foaming additives and rejuvenating agent is added in production to assist foaming and to restore the binding capability of bitumen, respectively (Huurman & Van den Beemt, 2024). The exact composition of the foaming additive and rejuvenating agent is unknown possibly due to confidential reasons. However, the mass of the foaming additive is very little compared with other components (0.1% of the mass of bitumen), and the rejuvenating agent has the same function as the rejuvenator in rejuvenation (i.e. to restore the binding capability of bitumen) (D'Angelo et al., 2008). Therefore, foaming additive is not considered in this study, and the rejuvenating agent is assumed to be the rejuvenator used for rejuvenation.

In the WMA scenarios, LEAB® process is used to produce the asphalt. Although the process is based on foaming, additives still need to be added. In this process, there are two major additives involved: rejuvenating agent and foaming additive. It is mentioned previously that both HMA and WMA in this study use RAP in production. To make the EOL asphalt pavement integrate with virgin materials, the old bitumen needs to be reactivated. In the production of HMA, this can be done with high temperature of at least 165°C. However, in the production of LEAB, the temperature only reaches about 115°C, making the reactivation by heat not possible. Instead, rejuvenation agent is added to make the old bitumen functional again (CROW, 2024). In addition to the rejuvenation function, this agent also serves as a viscosity reducer, which improves the workability of the asphalt. Since the type and amount of this rejuvenation agent is not disclosed in literatures, this study assumes it to be the wax-like rejuvenator used in rejuvenation as they have the same function, and the same amount as used in each rejuvenation activity, 2,100kg. Besides the rejuvenation agent, a foaming additive is added to improve the foaming property of the asphalt, and further reduce the viscosity and improve the adhesion between bitumen and minerals as well. The mass of this foaming additive added is typically 0.1% of the mass of bitumen (D'Angelo et al., 2008). However, since the amount of the foaming additive is so limited that it is not detectable in the LEAB® mixture, and the exact composition of this additive is not disclosed in literature, it will not be included in the assessment (CROW, 2024).

4.3 Indicators

Within the case studies described in the previous section, indicators are used to measure the performance of the pavement. This section briefly introduces the sustainability and circular economy indicators being chosen and the reasoning of choosing these indicators.

4.3.1 Sustainability indicators

As stated in the previous chapter, sustainability has three pillars: environment, economy, and society. However, since social performance is difficult to quantify at the current stage and the lack of social sustainability indicators, the sustainability study of this thesis only focuses on the environmental and economic pillars.

For environmental sustainability, this study uses the standardized lifecycle assessment (LCA) frameworks, which are capable of assessing the environmental impacts of a product, process, or service throughout its whole life cycle (USEPA, 2006). The LCA will be carried out under the standard ISO 14040:2006 and ISO 14044 (International Organization for Standardization, 1997, 2006). Further, the economic impacts were determined using the life cycle cost assessment (LCCA).

4.3.2 Circular Economy indicators

In Chapter 2, twelve of the existing indicators were reviewed and listed. To use these indicators in practice, there are various limitations. The BCI requires data such as functional separation and geometry of product edge. This indicator is originally designed for building infrastructure, and the data collection and calculation of it may not be compatible with pavements. PLCM is similar to MRS by their principles since both target at the recirculated part of the product. However, since the MRS is mass-based and the PLCM is value-based, the data requirement to calculate MRS is lower. CEI, VRE, CPI and RBR also share similar principles, which assess the preservation of materials. Among these four indicators, CPI and RBR requires data about environmental impacts, which is more difficult to collect than material quantities and costs required by CEI and VRE. Both CEI and VRE needs to be modified to become suitable for assessing pavements. Such modification is has already been completed on CEI by Varveri et al. (2023). Data availability poses a significant challenge for the RPI indicator, as the revenue and disposal costs for each component of a product, which are necessary for its calculation, are often considered business secrets and are therefore difficult to obtain. With the considerations above, only six of the twelve indicators were demonstrated in this study, and are listed in Table 4-1.

Table 4-1 Circular economy indicators used for this study.

Indicator	Source
MCI	(Ellen MacArthur Foundation, 2019)
CEI	(Di Maio & Rem, 2015)
CB'23	(Platform CB'23, 2022)
ESC_i	(Mantalovas & Di Mino, 2020)
CEIP	(Cayzer et al., 2017)
MRS	(Cradle to Cradle Products Innovation Institute, 2016)

4.4 Methodology

In the previous sections, the case studies and the indicators used for this study are introduced. This section describes how the indicators can be used in the scenarios to assess the pavement. The description is divided into three sub-sections: goal and scope, data collection, and assessment methodology.

4.4.1 Goal and scope

The goal of this study is to investigate the suitability of different indicators on assessing pavements. For consistency, all the three case studies share the same functional unit, which is a 1000 m long, 3.5 m wide, and 0.05 m thick pavement. According to the Pavement Life Cycle Assessment Framework published by the Federal Highway Administration (FHWA), the length chosen needs to comply with the goal and be representative of the study. The target of this study is on a project level instead of a micro or macro level. Therefore, 1000 m is considered to be reasonable in terms of scale (Harvey et al., 2016). The width of the functional unit is selected based on the type of road. It is suggested by the Product Category Rules (PCR) for asphalt in the Netherlands that the road chosen for lifecycle assessment should either be main or secondary road network, and single lane (Kruk et al., 2022). Since main carriageway accommodates the most important traffic flows, and has a more consistent design width than secondary carriageway, a single lane on a main carriageway, whose width is 3.5 m, is chosen (Rijkswaterstaat, 2019). Although a road has surface course, base course, and subbase course, for the consistency of materials and service life, this study will only assess the surface course. The thickness of the surface course varies according to the type of asphalt mixture. In the Netherlands, ZOAB Regular is the most commonly used mixture and is used in this study, which has a representative thickness of 0.05 m (Kruk et al., 2022).

The analysis period and timelines of the three case studies are presented in Figure 4-6. In the Netherlands, the average service life of ZOAB Regular mixture is 12 years (Kruk et al., 2022). The first case study assumes that only resurfacing takes place during the lifecycle. Since this is currently the common practice in the Netherlands, it is named 'Business as Usual (BAU)' in this study. In this scenario, one resurfacing activity happens every 12 years. On the basis of the BAU, the second case study includes two rejuvenation activities between each two resurfacing activities. Based on the experience in the Netherlands, each rejuvenation activity is expected to extend the service life by three years. Therefore, rejuvenation activities in years 5 and 10 after construction is expected to extend the service life of the pavement to 18 years. The third case study assumes the pavement to be Warm Mix Asphalt instead of Hot Mix Asphalt used in the first two case studies and is therefore named as WMA. As stated in previous sections. The LEAB® process based on foaming introduced by BAM is selected for this study as it is more common in the Netherlands. As Warm Mix Asphalt is a relatively new technology, there has not been enough experience of application to conclude an average service life of such an asphalt. As a result, the same lifespan to the Hot Mix Asphalt, 12 years, is assumed. Nevertheless, a sensitivity analysis on service life of Warm Mix Asphalt will be carried out. In the sensitivity analysis, a service life of 6, 8, 10, 12, and 15 years will be assumed and assessed. They are named as WMA6, WMA8, WMA10, WMA12, and WMA15, respectively. Given the service lives of the scenarios and the rules in the guidelines of FHWA, the analysis period of this study is 36 years, and all the periods after the 36th year are truncated (Harvey et al., 2016).

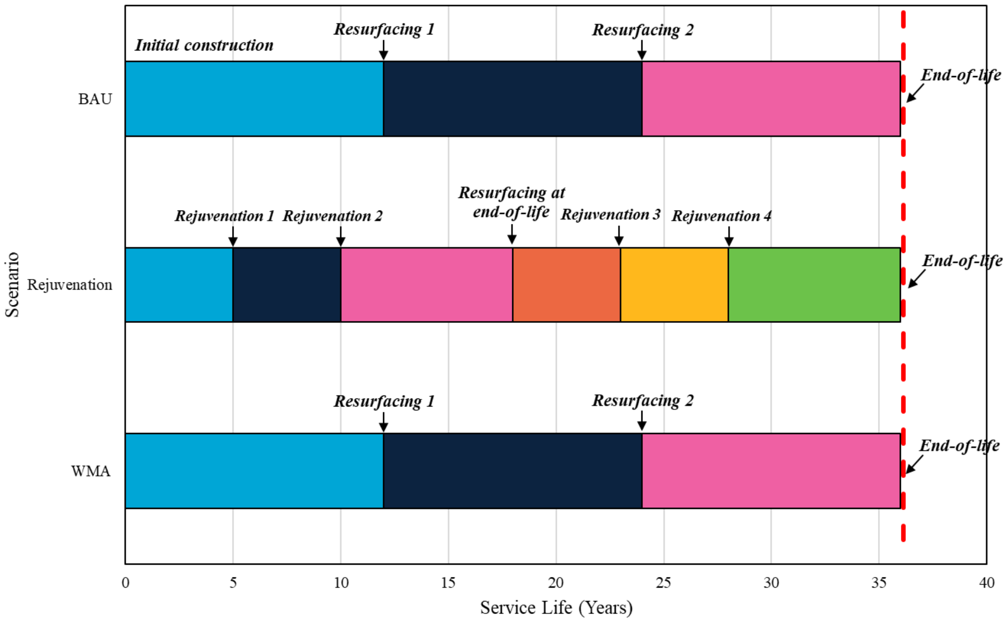

Figure 4-6 Analysis period and timelines of the case studies

As stated previously, ZOAB Regular is used as the asphalt mixture in this study. This asphalt mixture has four main components: coarse aggregate, fine aggregate, bitumen, and filler. The compositions of both 1 ton of such a mixture and the whole functional unit are presented in Table 4-2, given that the density of the asphalt is 2,000 kg/m^3 (Kruk et al., 2022).

Table 4-2 Composition of 1 ton of ZOAB Regular asphalt mixture (Kruk et al., 2022).

Mass (kg)	1 ton	Functional Unit
Coarse aggregate	860	301,000
Fine aggregate	43	15,050
Bitumen	45	15,750
Filler	52	18,200

It is a common practice to use RAP in asphalt production. In the Netherlands, by experience, the percentage of RAP for HMA is 20% to 30%. For this study, 25% is selected. WMA, however, allows for a higher RAP percentage. In this study, 50% RAP is assumed for the production of WMA according to a report published by FHWA (D'Angelo et al., 2008).

In the Rejuvenation scenario, two rejuvenation activities are carried in each lifecycle of the pavement. In each of the activities, according to the PCR of asphalt, 0.6 kg rejuvenator is applied per square meter of asphalt, resulting in a total use of 2,100 kg (Kruk et al., 2022). In the PCR, there are two types of rejuvenator available: wax-like and bio-based. This study uses the wax-like rejuvenator, which use paraffin as the main raw material, for assessment.

Figure 4-7, Figure 4-8, and Figure 4-9shows the system boundaries for the BAU, Rejuvenation, and WMA scenarios, respectively. Data collection will be conducted within these boundaries.

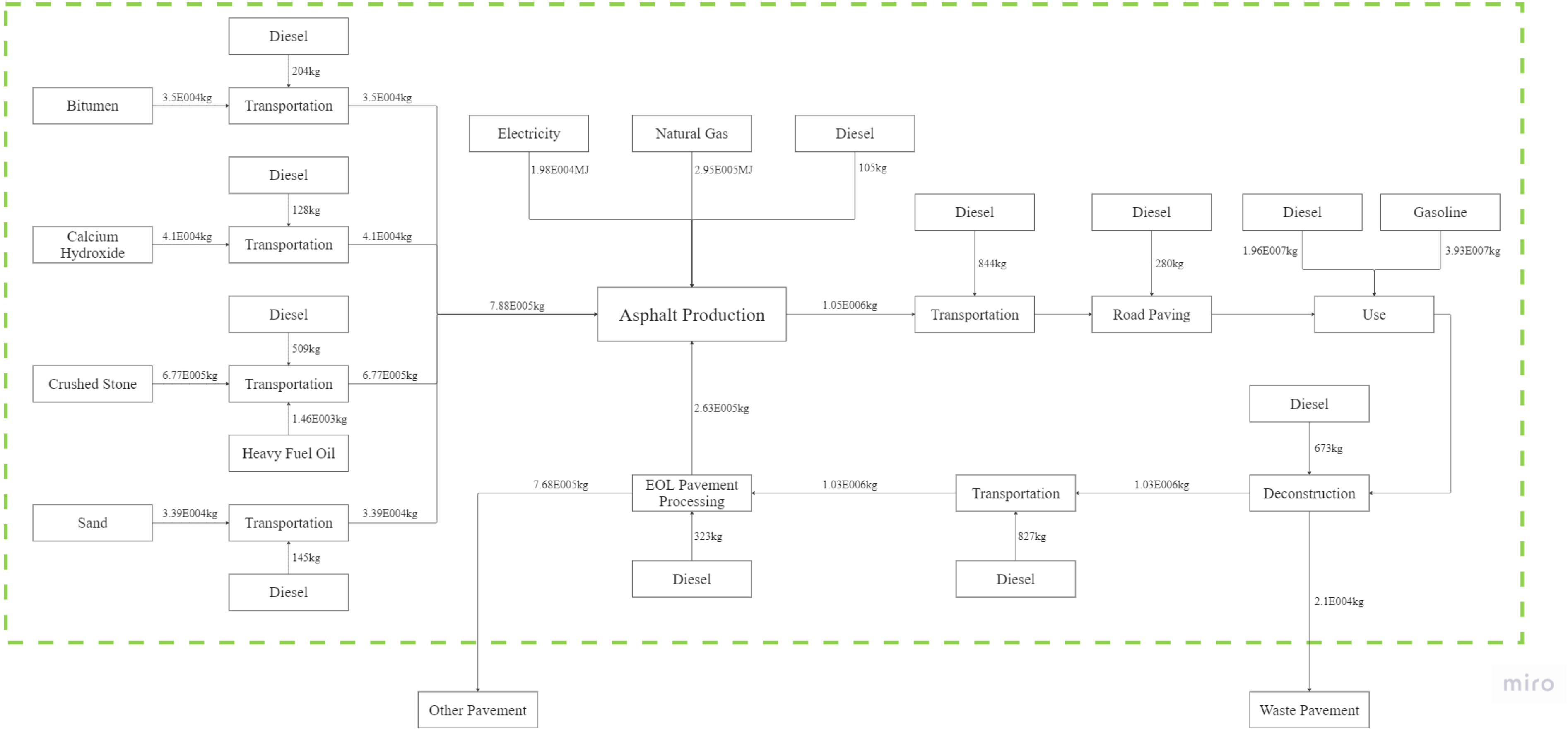

Figure 4-7 System boundary of the BAU scenario

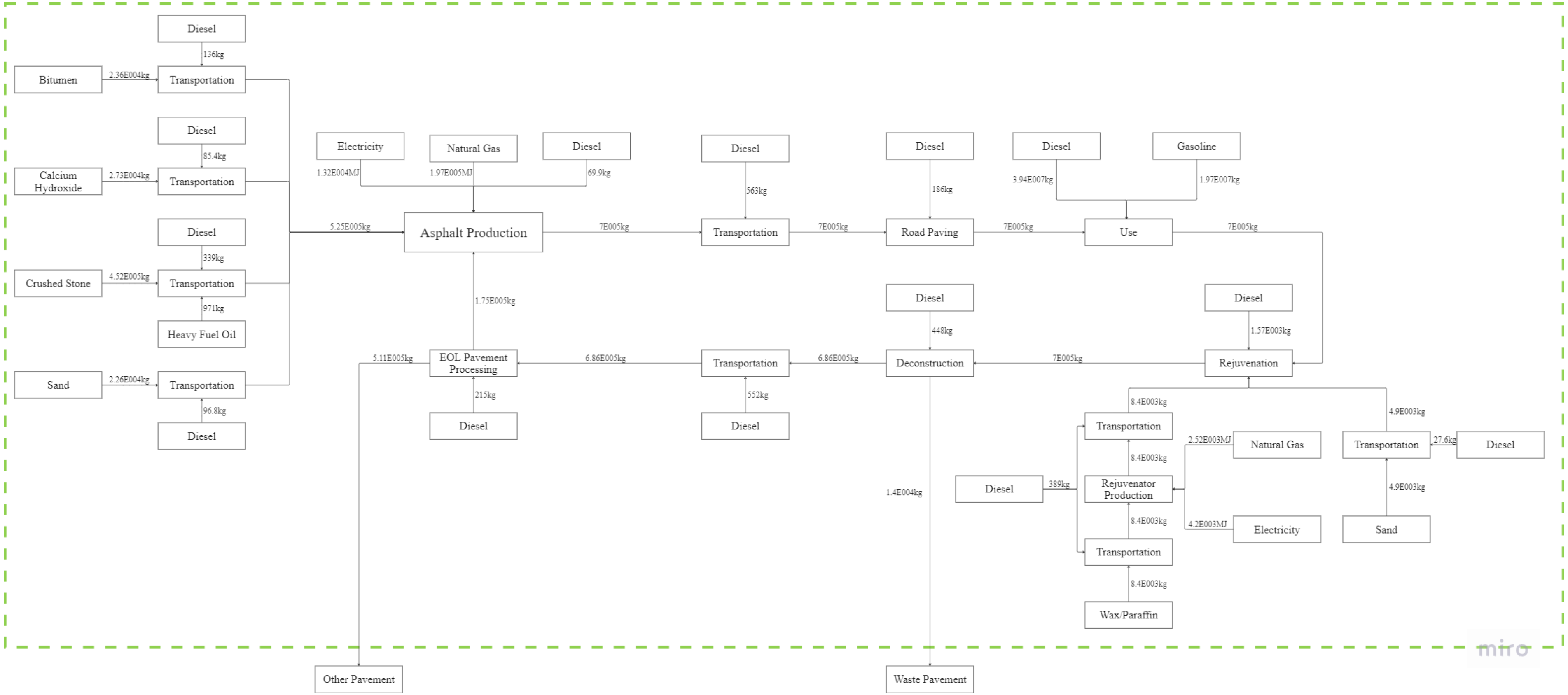

Figure 4-8 System boundary of the Rejuvenation scenario

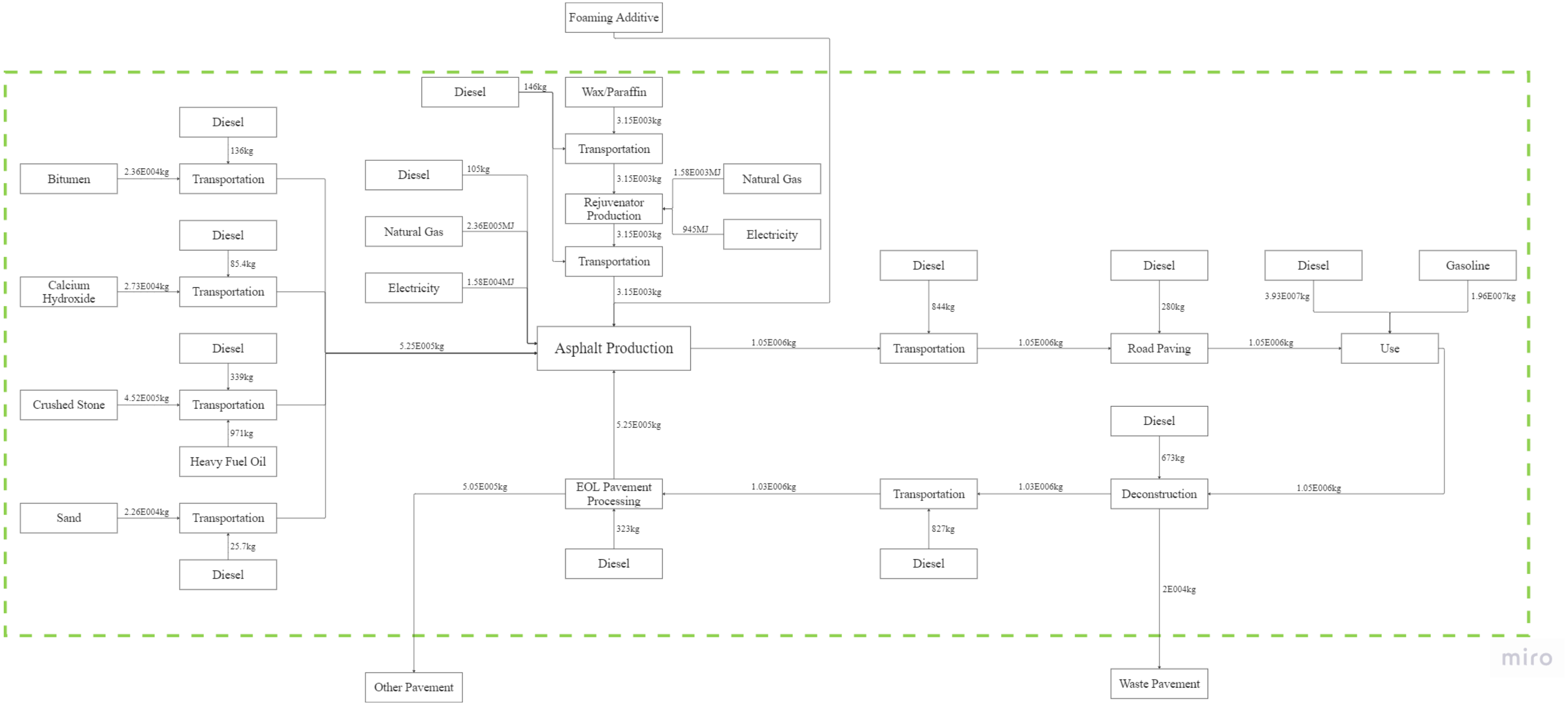

Figure 4-9 System boundary for the WMA scenario

4.4.2 Data collection

With the goals and scope defined, the lifecycle inventory was carried out with the data collected from various sources, including scientific literatures, government documents, and databases. More detailed information about the lifecycle inventory is presented in the following sections.

4.4.2.1 Sustainability

The foreground and background data used to model the case studies are shown Table A-1 in Appendix A. The data are all from the GaBi^{TM} Education Database 2020. The input data to conduct LCA such as transportation distance and material dosage are shown Table A-2 in Appendix A. Most of these data are extracted from the Product Category Rules of Asphalt in the Netherlands (Kruk et al., 2022). The data required to conduct LCCA are obtained from Singh and Varveri (2024).

4.4.2.3 Circular economy

The data needed to calculate the circular economy indicators are mainly obtained from literatures and guidelines.

4.4.3 Assessment methodology

The previous two sub-sections define the goal and scope of the study, as well as present the data needed. This sub-section explains in detail the methodology adopted to assess the pavement.

4.4.3.1 Sustainability

4.4.3.1.1 Environmental sustainability

As stated in previous sections, the environmental sustainability is carried out by performing an LCA. The ISO standards define four essential steps to carry out an LCA: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. These steps are explained in the following sections.

4.4.3.1.1.1 Goal and scope definition

Goal and scope definition is the first step of an LCA study. In goal definition, the reason of conducting the LCA study, and the target audience of the study need to be described. In scope definition, there are three elements that need to be defined: functional unit, system boundaries, and methodological choices. A functional unit is a quantified unit by which the environmental impact is measured. It is crucial that all the scenarios share the same functional unit if they are to be compared against each other. For an asphalt pavement project like this study, the functional unit is commonly defined by the dimensions and type of the road. Since this study also considers the deterioration of asphalt pavement with time, a time dimension is also included in the functional unit.

A system boundary decides the life cycle phases that are included in the study. It determines the life cycle model, e.g. cradle-to-cradle, cradle-to-gate, cradle-to-grave, being chosen. For this study, since RAP is considered in the life cycle of the pavement, a cradle-to-cradle approach is adopted. On basis of this, each of the processes, material flows, and energy flows needs to be clearly stated in this part, which is also going to be the scope for data collection in the next step, inventory analysis, that is carried out in a later stage.

For an LCA study, there are various Life Cycle Impact Assessment (LCIA) methods based on different calculation standards available. The choice of the LCIA methods affects the numerical results of the study, and hence need to be defined. In addition, the databases that the LCA study uses also need to be clearly stated in this stage.

For this study, the functional unit and the system boundary is already defined in Section 4.4.1. The LCIA method being adopted is CMLIA method designed by Leiden University (Guinée et al., 2002).

An LCA can be classified as attributional or consequential. An attributional LCA investigates the flow of materials within a chosen temporal window, and a consequential LCA investigates change of flows in response to different decisions. In this study, three case studies are assumed and compared against each other. Therefore, the LCA conducted in this study is a consequential LCA.

The environmental impacts through the life of a pavement can be classified into agency impact and user impact. The agency impact includes the impacts caused by material production, material transportation, and maintenance activities. The user impact includes the impact caused by fuel consumption of the vehicles using the road. Since the user impact is expected to be much larger than the agency impact, the LCA-involved results in this study will be presented as both agency only impact and agency-plus-user impact.

4.4.3.1.1.2 Inventory analysis

In the inventory analysis step, the data within the system boundary defined in the previous step are collected. In an LCA study, data can be distinguished as foreground data and background data. Foreground data are data that are directly measured or collected targeting the activities. As an opposite, background data are data that are collected from a third-party database. For example, in an LCA study on asphalt pavement, coarse aggregate belongs to the foreground data, and its corresponding background data is crushed stone 16/32. Currently, there are various database available, including Ecoinvent™, GaBi™, and TRACI. This study mainly uses the background process data available in GaBi™. Other data are from literatures and guidelines. Since not all data related to pavements are available, a cut-off approach is adopted. With the functional unit, the system boundary, and the data collected, a model describing the life cycle of the pavement can be created. This study uses the education version of the LCA software developed by Sphera®, GaBi™ Education to create the model (Baitz et al., 2012).

4.4.3.1.1.3 Impact assessment

With the inventory analysis complete and the data imported into the LCA model, the environmental impact of the system can be calculated and characterized into a list of impact categories. Some common categories are global warming potential (GWP), acidification, ozone depletion, and acidification. There are various methods to carry out the calculation and characterization, including CMLIA, Environmental Footprint 2.0, and ReCiPe 2016, with each may correspond to different sets of impact categories. This study adopts CMLIA method, version 2016 (Guinée et al., 2002).

Although characterizing environmental impacts into impact categories makes it explicit the quantified, specific types of impact caused by the pavement, it is difficult to compare different scenarios considering their total environmental impact because the unit of the categories are not the same and therefore the results of all impact categories are not aggregated into a single result. To enable this comparison, the Environmental Cost Indicator (ECI, or in Dutch, MKI) is used. All products have shadow prices on the environment. Therefore, it is reasonable to express the environmental impacts in a monetary form. By assigning the impact categories with different monetary price (i.e. the weighting factors) per unit, the ECI shows the relative importance of the categories, and makes calculating a weighted sum possible. With ECI, the total environmental impact of a scenario can be expressed as a single monetary value, which can then be easily compared with other scenarios. The impact categories of CMLIA method and their corresponding ECI weighting factors are listed in Table 4-3.

Table 4-3 Impact categories and the corresponding weighting factors (Harmelen et al., 2004).

Impact Categories	**Unit**	**Weighting Factors (€/ unit)**
Global Warming Potential (GWP)	kg CO2 eq	0.05
Acidification Potential	kg SO2 eq	4
Eutrophication Potential	kg PO4 eq	9
Ozone Layer Depletion Potential	kg CFC11 eq	30
Abiotic Depletion elements	kg Sb eq	0.16
Abiotic Depletion fossil	kg Sb eq	0.16
Freshwater Aquatic Ecotoxicity Potential	kg DCB eq	0.03
Human Toxicity Potential	kg DCB eq	0.09
Marine Aquatic Ecotoxicity Potential	kg DCB eq	0.0001
Photochemical Ozone Creation Potential	kg C2H4 eq	2
Terrestrial Ecotoxicity Potential	kg DCB eq	0.06

4.4.3.1.1.4 Interpretation

Interpretation is the last step of an LCA study, which identifies significant issues, evaluates completeness, sensitivity, and consistency, and draws conclusions and recommendations. The conclusions carried out from this step will be further used in decision making.

4.4.3.1.2 Economic sustainability

As state in previous sections, an LCCA is carried out to assess the economic sustainability of the pavement. In practice, it is common to use LCCA to compare pavement alternatives on their economic efficiency. There are two approaches to conduct LCCA: the deterministic approach and the probabilistic approach (or Risk Analysis Approach). The deterministic approach does not consider the variability of the inputs and is thus a simpler approach and more commonly used. The probabilistic approach, however, compute the results with changing input parameters. In this study, since for each of the scenarios, the inputs do not change, a deterministic approach is used (Diependaele, 2018).

The two most common ways to express the economic worth of the project are the Net

Present Value (NPV) and the Equivalent Uniform Annual Cost (EUAC).

NPV can be defined as the total expected cost of the project converted to present value (Zaki et al., 2021). The calculation of NPV is shown in Equation 4-1(Diependaele, 2018).

$$NPV = IC + \sum_{k=1}^{Q} FC_k \left[\frac{1}{(1+r)^{y_k}}\right] - RV\left[\frac{1}{(1+r)^{p}}\right]$$

Equation 4-1

where

IC: Initial cost.

FC_k: Future cost of activity k.

RV: Residual value of the pavement.

r: Real discount rate.

y_k: Year into the future of cash flow of activity k.

Q: Total number of activities.

p: Number of years within the analysis period.

It can be calculated with three components: the initial cost, the future cost, and the salvage value (Babashamsi et al., 2016). A discount rate is necessary in calculating costs at different time points because the value of money changes due to annual interest and inflation (Babashamsi et al., 2016). EUAC is defined as the annual cost through the life of a project that results in the same present worth as the real cost. Compared with NPV, EUAC is more suitable when annual costs are required. In this study, however, a total cost is needed. Therefore, NPV, instead of EUAC is used. To calculate the NPV of pavements, this study refers to the quantification method developed by Singh and Varveri (2024), who uses vehicle operation costs (VOC), delay costs (DC), and fuel consumption costs to calculate the future cost.

4.4.3.2 Circular economy

4.4.3.2.1 Material Circularity Indicator

Material Circularity Indicator (MCI) is an indicator developed by the Ellen MacArthur Foundation that can be used as a circular economy metric assessing material flows at product and company levels (Ellen MacArthur Foundation, 2019). This indicator is based on six principles:

- Acquire biological materials from sustainable sources.
- Utilize materials collected from reused and recycled sources.
- Extend the use phase of products (e.g., by reuse, redistribution, or durability

improvement).

- Reuse components or recycle materials collected from products after use stage.
- Increase the intensity of product usage.
- Remain biological materials uncontaminated and biologically accessible.

The result of MCI, ranging from 0 to 1, indicates the level of linearity/circularity of the material flow being assessed. The indicator is constructed based on three characteristics of a product:

- The mass of virgin material used in manufacture (V).
- The mass unrecoverable waste generated by the product (W).
- A utility factor reflecting the service life and use intensity (X).

The following sections will introduce the calculation of these three characteristics in detail.

4.4.3.2.1.1 Calculation of virgin material

In MCI, it is assumed that in the manufacture of a product, the raw materials are collected from virgin resources, recycled resources, reused resources, and biological resources from sustained production. The mass of virgin material used in manufacture can be calculated by

$$V = M(1 - F_R - F_U - F_S)$$

Equation 4-2

where

M: mass of the finished product,

F_R: fraction of feedstock from recycled resources,

F_U: fraction of feedstock from reused resources, and

F_S: fraction of biological materials from sustained production.

In Equation 4-2, the fraction of feedstock from virgin resources is calculated by $(1 - F_R - F_U - F_S)$. Therefore, the mass of the feedstock from virgin resources can be calculated by multiplying this fraction with the mass of the product.

4.4.3.2.1.2 Calculation of unrecoverable waste

In MCI, there are three waste flows in the lifecycle of a product: the waste going to landfill or energy recovery at the end of use phase, the waste generated in the recycling process, and the waste generated when producing the feedstock. The waste that will be sent to landfill or energy recovery can be calculated by

$$W_0 = M(1 - C_R - C_U - C_C - C_E)$$

Equation 4-3

where

C_R: fraction of the mass of the product collected for recycling at the end of use stage,

C_U: fraction of the mass of the product that will be reused after use stage,

C_C: fraction of the mass of the product consisting of uncontaminated biological

materials that will be composted, and
C_E: fraction of the mass of the product consisting of uncontaminated biological materials from sustained production that will be sent to energy recovery.
Regarding the fact that in the Netherlands, landfill is forbidden for construction waste, and no end-of-life materials will be sent to energy recovery, W_0 will be 0 in this study. In the recycling process and production of feedstock, it is possible that some waste will be generated. The waste generated in the recycling process can be calculated by

$$W_C = M(1 - E_C)C_R$$

Equation 4-4

And the waste from the production of feedstock can be calculated by

$$W_F = M\frac{(1 - E_F)F_R}{E_F}$$

Equation 4-5

where
E_C: efficiency of the recycling process, and
E_F: efficiency of producing the feedstock.
When adding up all the waste flows, if one simply adds W_C and W_F together, it will result in a double counting of the waste. To address this problem, a 50:50 approach, in which only 50% will be counted for both W_C and W_F, is adopted. Therefore, the total waste W generated by the product in one cycle is

$$W = W_0 + \frac{W_C + W_F}{2}$$

Equation 4-6

4.4.3.2.1.3 Calculation of Linear Flow Index

Calculated with the mass of virgin feedstock and waste derived in the previous section, the Linear Flow Index (LFI) measures the fraction of linear material flow. It can be derived by

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

Equation 4-7

The result lies between 0 and 1, where 0 means completely restorative flow and 1 indicates completely linear flow.

4.4.3.2.1.4 Calculation of utility

Two methods to improve the circularity of a product are extending the lifetime and increase the use intensity. MCI includes the effect of these two methods by introducing a parameter for utility, X. Utility can be calculated by

$$X = \left(\frac{L}{L_{av}}\right)\left(\frac{U}{U_{av}}\right)$$

Equation 4-8

where
L: lifetime of the product,
L_{av}: industry average lifetime,
U: intensity of use of the product, and
U_{av}: industry average intensity of use.
It is suggested that only one of the lifetime component L/L_{av} and intensity component U/U_{av} is used to calculate X. In this study, only the lifetime component will be used due to its relative simplicity and easiness in data collection.

4.4.3.2.1.5 Calculation of MCI

With the LFI and utility determined, the MCI can be calculated by

$$MCI_P^* = 1 - LFI \cdot F(X)$$

Equation 4-9

$$MCI_P = (0, MCI_P^*)$$

Equation 4-10

where

$F(X)$: utility factor, and is derived by

$$F(X) = \frac{0.9}{X}$$

Equation 4-11

The result of MCI is a number between 0 and 1, where 0 indicates a very linear product, and 1 indicates a very restorative one.

4.4.3.2.2 Circular Economy Index

The Circular Economy Index (CEI) is another indicator that can be used to measure circularity. Instead of adopting a mass-based approach like the MCI, the CEI introduces the economic value of the materials, which is believed to be able to cover environmental, economic, and social impacts (Di Maio & Rem, 2015). Originally, this indicator is designed for the recycling industry, and is defined as

$$CEI = \frac{Material\ value\ recycled\ from\ EOL\ product(s)}{Material\ value\ needed\ for\ (re-)producing\ EOL\ product(s)}$$

Equation 4-12

The calculation of CEI can be completed with a financial calculation method, the Gross Value Added (GVA) method. In this method, the numerator of Equation 4-12, the material value recycled from EOL product(s), can be characterized by GVA, which is defined as

$$GVA = Recycling\ firm\ revenues - non\ factor\ costs$$

Equation 4-13

Recycling firm revenues may include revenues collected from selling the recycled materials, and non-factor costs refer to costs of energy and input materials. In this way, the CEI can be defined as the ratio of the GVA to the value of input materials.

One of the reasons that this indicator is selected is its extra coverage of sustainability aspects. Unlike mass-based indicators in which only material quantities are considered, the CEI includes both quantity and quality of the materials by basing its calculation on value. On the one hand, the value of materials can reflect their environmental impact. It is reported that a positive correlation exists between the price of a material and its carbon footprint (Di Maio & Rem, 2015). Therefore, by recycling materials of higher values, the recycling companies contribute more to the environment. On the other hand, if policy makers set the recycling targets based on value using the CEI approach rather than on mass, innovation in recycling technologies will be encouraged, which is likely going to create economic benefits and new job positions.

The original definition of the CEI concentrates mainly on the recycling stage of a product. In this study, however, the goal is to assess various production and maintenance methods of a pavement road. Therefore, a modified version of CEI is necessary, and it is presented as Equation 4-14.

$$CEI = \frac{Material\ value\ added}{Material\ value\ for\ reproducing\ the\ EOL\ product}$$

Equation 4-14

The material value added here is defined as

$$Material\ value\ added = Scrap\ value - non\ factor\ cost$$

Equation 4-15

where

$$Scrap\ value = Initial\ material\ value \times (1 - depreciation\ rate)^n$$

Equation 4-16

Here, initial material value is the material value at the base year, depreciation rate is the reciprocal of design life, and n is the year after construction. The material value for reproducing the EOL product can be calculated by

$$\begin{aligned} &Material\ value\ for\ reproducing\ the\ EOL\ product \\ &\quad = Initial\ material\ value \times (1 + discount\ rate)^n \end{aligned}$$

Equation 4-17

4.4.3.2.3 Platform CB’23

Platform CB’23 is a platform initiated by the Dutch Ministry of Infrastructure and the Environment (Rijkswaterstaat), the Dutch Central Government Real Estate Agency (Rijksvastgoedbedrijf), the Royal Netherlands Standardization Institute (NEN) and De Bouwcampus in order to assist the transition to circular economy (Platform CB'23, 2022). This platform has developed a circularity measurement method that can be applied to products in the construction sector at any scale level and at any stage of the construction process. The CB’23 method proposes six main indicators that covers three goals of circular instruction defined by Platform CB’23: protecting stocks of materials, environmental protection, and value retention. And for each of the indicators, there may also be some sub-indicators. The indicators and sub-indicators are listed in Table 4-4.

Table 4-4 Indicators and sub-indicators in CB’23 (Platform CB'23, 2022).

Indicators	**Sub-indicators**		
1 Input material	1.1 Secondary material	1.1.1 Part from reuse	
		1.1.2 Part from recycling	
	1.2 Primary material	1.2.1 Part which is renewable	1.2.1a Part which is sustainably produced
			1.2.1b Part which is not sustainably produced
		1.2.2 Part which is not renewable	
	1.3 Physically scarce materials	1.3.1 Part which is physically abundant	
		1.3.2 Part which is physically scarce	
	1.4 Socio-economically scarce materials	1.4.1 Part which is socio-economically abundant	
		1.4.2 Part which is socio-economically scarce	
2 Preserved output material	2.1 Part for reuse		
	2.2 Part for recycling		
3 Lost output material	3.1 Part used for energy production		
	3.2 Part sent to landfill		
4 ECI/MPG	4.1 Climate change – overall		
	4.2 Climate change – fossil		
	4.3 Climate change – biogenic		
	4.4 Climate change – use of land and changes in use of land		
	4.5 Ozone depletion		
	4.6 Acidification		
	4.7 Eutrophication - freshwater		
	4.8 Eutrophication - seawater		
	4.9 Over-fertilization - soil		
	4.10 Smog formation		

	4.11 Depletion of abiotic raw materials – minerals and metals
	4.12 Depletion of abiotic raw materials – fossil energy carriers
	4.13 Use of water
	4.14 Emission of particulate matter
	4.15 Ionizing radiation
	4.16 Ecotoxicity (freshwater)
	4.17 Human toxicity, carcinogenic
	4.18 Human toxicity, non-carcinogenic
	4.19 Impact/soil quality related to the use of land
5 Functional value at the end of the life cycle	5.1 Functional quality
	5.2 Technical quality
	5.3 Degradation
	5.4 Reuse potential
6 Economic value at the end of the lifecycle	

In this study, the CB'23 method is used as a circular economy indicator. Therefore, only Indicator 1 to 3, which correspond to the goal of protecting stocks of materials, are used. The environmental and economic aspects covered by Indicator 4 to 6 will be assessed in separate sections.

4.4.3.2.4 Environmental Sustainability and Circularity indicator

In the transition from a linear economy to a circular economy, the assessment of environmental impacts has been absent with only the circularity assessment been carried out. To solve this issue, the Environmental Sustainability and Circularity indicator (ESC_i) has been developed to investigate the effects on environmental sustainability brought by improved circularity (Mantalovas & Di Mino, 2020). It is a composite indicator combining the results of MCI and LCA. The ESC_i can be calculated as follows:

$$ESC_i = \frac{1}{LCA_T^{(1-MCI)}} \times 100$$

Equation 4-18

where

LCA_T: The aggregated, normalized, and weighted LCA results.

MCI: The MCI result.

For a product, a higher LCA indicates a larger environmental impact, and a higher MCI indicates a higher circularity. From Equation 4-18, it can be observed that a higher LCA value or a lower MCI value result in a lower ESC_i value. Therefore, it can be concluded that a higher ESC_i value indicates that a product is more favorable in term of circularity and environmental sustainability.

The calculation of the MCI used in Equation 4-18 is already described in Section 4.4.3.2.1. The calculation of the LCA is described in Section 4.4.3.1.1, but the result cannot be directly used as LCA_T since it is presented as impact categories, while in Equation 4-18, the LCA_T is presented as a single value. To convert the results of the LCA to LCA_T, two processes are necessary: normalization and weighting, which are two optional elements of LCA suggested by ISO 14044:2006 (International Organization for Standardization, 2006). In normalization, each of the impact category result is compared against reference information to calculate the relative magnitude. Some examples for the reference information are the impact to the whole nation and the impact per person, and the values are called normalization factors. The ESC_i calculates the normalized results by dividing the LCA results by the normalization factors per person. Subsequently, in weighting, the normalized results are assigned with a weight each, and then aggregated to obtain a weighted sum. Equation 4-19 shows the calculation of LCA_T.

$$LCA_T = \sum_{i=1}^{n} \frac{LCA_i}{NFpp_i} \times W_i$$

Equation 4-19

where

LCA_i: The LCA result of the i-th impact category.

$NFpp_i$: The per person normalization factor of the i-th impact category.

W_i: Weighting of the i-th impact category.

In the original document of the ESC_i, the normalization method is ReCiPe2008 (H) Endpoint Normalization, and the weighting method is ReCiPe2008 (H) Endpoint Weighting (Mantalovas & Di Mino, 2020). In this study, since the information for both these methods cannot be obtaine, and the lifecycle impact analysis is carried out in a midpoint manner, the normalization factors are directly obtained from literatures in the context of midpoint assessment, and the weighting factors use environmental cost indicators directly.

The normalization factors are shown in Table 4-5. The factors are extracted from a normalization factor list, CML2001 - Jan. 2016, World, year 2000, incl biogenic carbon (global equivalents), in GaBi^{TM}. The normalization factor per person is derived by dividing the global equivalent values by the global population. In this study, a global population of 6,118,131,162 is used (Baitz et al., 2012).

Table 4-5 Normalization factors of the impact categories.

Impact category	**Unit**	**Normalization factor global equivalence**	**Normalization factor per person**	**Source**
Global Warming Potential	kg CO2 eq	4.22E+13	6.90E+03	GaBi^{TM}
Acidification Potential	kg SO2 eq	2.39E+11	3.91E+01	GaBi^{TM}
Eutrophication Potential	kg PO4 eq	1.58E+11	2.58E+01	GaBi^{TM}
Ozone Layer Depletion Potential	kg CFC11 eq	2.27E+08	3.71E-02	GaBi^{TM}
Abiotic Depletion elements	kg Sb eq	3.61E+08	5.90E-02	GaBi^{TM}
Abiotic Depletion fossil	kg Sb eq	1.83E+11	2.99E+01	GaBi^{TM}
Freshwater Aquatic Ecotoxicity Potential	kg DCB eq	2.36E+12	3.86E+02	GaBi^{TM}
Human Toxicity Potential	kg DCB eq	2.58E+12	4.22E+02	GaBi^{TM}
Marine Aquatic Ecotoxicity Potential	kg DCB eq	1.95E+14	3.19E+04	GaBi^{TM}
Photochemical Ozone Creation Potential	kg C2H4 eq	3.68E+10	6.01E+00	GaBi^{TM}
Terrestric Ecotoxicity Potential	kg DCB eq	1.09E+12	1.78E+02	GaBi^{TM}

The weightings of the normalized factors are also obtained from the database in GaBi^{TM}, under a weighting list, thinkstep LCIA Survey 2012, Global, CML 2016, incl biogenic carbon (global equivalents weighted). The weightings are shown in Table 4-6.

Table 4-6 CML2016 weightings of impact categories.

Impact category	Weightings	Source
Global Warming Potential	9.3	GaBi™
Acidification Potential	6.1	GaBi™
Eutrophication Potential	6.6	GaBi™
Ozone Layer Depletion Potential	6.2	GaBi™
Abiotic Depletion elements	6.4	GaBi™
Abiotic Depletion fossil	7	GaBi™
Freshwater Aquatic Ecotoxicity Potential	6.8	GaBi™
Human Toxicity Potential	7.1	GaBi™
Marine Aquatic Ecotoxicity Potential	6.8	GaBi™
Photochemical Ozone Creation Potential	6.5	GaBi™
Terrestric Ecotoxicity Potential	6.8	GaBi™

4.4.3.2.1 Circular Economy Indicator Prototype

Unlike the indicators introduced above, the Circular Economy Indicator Prototype (CEIP) uses a pointed-based questionnaire to assess the circular economy performance of the alternatives (Cayzer et al., 2017). The questionnaire contains a series of questions concerning the design/redesign, manufacturing, commercialization, use, and end-of-use phases of a product. For each of the questions, the full point may be different, which reflects their relative impacts on the circularity performance of the product. The questions and the points available are shown in Table 4-7.

Table 4-7 Questions used in CEIP.

Phases	Questions	Points
Design/Redesign	Is the product made from recycled/reused material?	20
	Is the product lighter than its previous version?	2
	Is there a complete bill of materials and substances for the product?	5
Manufacturing	Is there a complete bill of energy for the manufacturing process?	10
	Is there a complete bill of solid waste for the manufacturing process?	15
Commercialization	What packaging is being used?	5
	What is the product's warranty?	10
	Is there a rental option for the product?	15
In Use	Can the usage status and identification of the product be established?	15
	Can the product be repaired?	5
	Can the product be reused?	10
	Does the product reduce waste through its use?	5
End of Use	What take-back scheme is available for this product?	15
	Is the product separated out from other products at the end of its life?	10
	Are the product's materials passed back into the supply chain?	10

The CEIP was originally designed for home improvement product. Therefore, it is reasonable that not all the questions are suitable for assessing asphalt pavement and need to be removed in this study. The questions being excluded, and the reasoning are shown in Table 4-8. Table 4-9 shows the questionnaire that is used specifically for this study.

Table 4-8 Questions not included in this study and the reasons of being excluded.

Questions	Reason
What packaging is being used?	The asphalt arrived at the construction site is carried by trucks and does not have the packaging appears on the common commodities.
Is there a rental option for the product?	The pavement is deconstructed after use and is not transferred directly to the next use stage without processing.
Does the product reduce waste through its use?	This question assesses whether the use of the product makes other products more circular.

Table 4-9 Questions of CEIP used in this study.

Phases	Questions	Points
Design/Redesign	Is the product made from recycled/reused material?	20
	Is the product lighter than its previous version?	2
	Is there a complete bill of materials and substances for the product?	5
Manufacturing	Is there a complete bill of energy for the manufacturing process?	10
	Is there a complete bill of solid waste for the manufacturing process?	15
Commercialization	What is the product's warranty	10
In use	Can the use status and identification of the product be established?	15
	Can the product be repaired?	5
	Can the product be reused?	10
	Does the product reduce waste through its use?	5
End of use	What take-back scheme is available for this product?	15
	Is the product separated out from other products at EOL?	10
	Are the product's materials processed back into the supply chain?	10

For each question, the score may range from 0 to the available largest point. Therefore, a set of scoring criteria is necessary for assigning the scores. The criteria are shown in Table 4-10.

Table 4-10 Scoring criteria for the questions.

Questions	Criteria	Scores
Is the product made from recycled/reused material?	The percentage of recycled/reused material is r%.	20×r%
Is the product lighter than its previous version[a]?	Yes.	2
	The same.	1
	Heavier.	0
Is there a complete bill of materials and substances for the product?	Yes, and all quantities are from primary source.	5
	Yes, but some quantities are from secondary source or assumed.	3
	No.	0
Is there a complete bill of energy for the manufacturing process?	Yes, and 80% to 100% of all quantities are from primary source.	10
	Yes, and 40% to 80% of all quantities are from primary source.	7
	Yes, but only less than 40% of all quantities are from primary source.	4
	No.	0
Is there a complete bill of waste for the manufacturing process?	Yes, and 80% to 100% of all quantities are from primary source.	15
	Yes, and 40% to 80% of all quantities are from primary source.	9
	Yes, but only less than 40% of all quantities are from primary source.	4
	No.	0
What is the product's warranty?	The product's lifetime is no less than twice as long as the BAU.	10
	The product's lifetime is longer than the BAU but not twice as much.	7
	The product has the same lifetime as the BAU.	5
	The product's lifetime is shorter than the BAU but no less than half of it.	2
	The product's lifetime is shorter than half of the BAU.	0
Can the usage status and identification of the product be established?	The status[b] of the pavement can be known exactly.	15
	The status of the pavement can be estimated approximately.	8
	The status of the pavement is unknown.	0
Can the product be repaired?	Yes, and it can be repaired for more than one time.	5
	Yes, but it can only be repaired for one time.	3
	No.	0
Can the product be reused?	Yes, and it can be reused for more than one time.	10
	Yes, but it can only be reused for one time.	5
	No.	0

Does the product reduce waste through its use?	Yes, it makes other product become more circular.	5
	No.	0
What take-back scheme is available for this product?	80% to 100% of the product can be collected.	15
	40% to 80% of the product can be collected.	9
	Less than 40% of the product can be collected.	4
	No.	0
Is the product separated out from other products at EOL?	Yes, and 70% to 100% can be separated.	10
	Yes, and 40% to 70% can be separated.	7
	Yes, and 20% to 40% can be separated.	4
	Less than 20% can be separated.	0
Are the product's materials processed back into the supply chain?	Yes, and 70% to 100% can be processed back to the supply chain.	10
	Yes, and 40% to 70% can be processed back to the supply chain.	7
	Yes, and 20% to 40% can be processed back to the supply chain.	4
	Less than 20% can be processed back to the supply chain.	0
Note a. The previous version in this study refers to the asphalt pavement of the BAU scenario. b. Status refers to the remaining lifetime.		

4.4.3.2.6 Material Reutilization Score

The Material Reutilization Score (MRS) developed in Cradle to Cradle Certified^{TM} Product Standard assesses a product's circularity based on its material parts related to recycling (Cradle to Cradle Products Innovation Institute, 2016). The MRS can be calculated by

$$MRS = \frac{\begin{bmatrix} \%recycled\ or\ rapidly\ renewable \\ product\ content \end{bmatrix} + 2\begin{bmatrix} \%\ of\ product\ recyclable \\ or\ biodegradable/compostable \end{bmatrix}}{3} \times 100$$

Equation 4-20

From Equation 4-20, it can be observed that the calculation of the MRS is characterized by two parts: input materials from recycled or renewable sources and EOL materials that can be recycled or biodegraded. The Cradle to Cradle Products Innovation Institute has set four certification levels based on the MRS score of a product, which is shown in Table 4-11.

Table 4-11 MRS scores and corresponding certification levels.

Certification level	MRS score
Bronze level	≥35
Silver level	≥50
Gold level	≥65
Platinum level	100

4.5 Summary of indicators used

Following the introduction in the previous sections, a summary listing all the circular economy indicators is shown in Table 4-12.

Table 4-12 Summary of the circular economy indicators.

Indicator	Calculation	Source
MCI	$MCI_P^* = 1 - LFI \cdot F(X)$ $MCI_P = (0, MCI_P^*)$	(Ellen MacArthur Foundation, 2019)
CEI	$CEI = \frac{Material\ value\ added}{Material\ value\ for\ reproducing\ the\ EOL\ product}$	(Di Maio & Rem, 2015)
CB’23	Table 4-4	(Platform CB'23, 2022)
ESC$_i$	$ESC_i = \frac{1}{LCA_T^{(1-MCI)}} \times 100$	(Mantalovas & Di Mino, 2020)
CEIP	Table 4-9 and Table 4-10	(Cayzer et al., 2017)
MRS	$MRS = \frac{\left[\begin{matrix}\%recycled\ or\ rapidly\ renewable\\ product\ content\end{matrix}\right] + 2\left[\begin{matrix}\%\ of\ product\ recyclable\\ or\ biodegradable/compostable\end{matrix}\right]}{3} \times 100$	(Cradle to Cradle Products Innovation Institute, 2016)

4.6 Summary

This Chapter introduced several methodologies for answering the research questions and completing the research tasks. A few indicators for both the circular economy and sustainability were discussed in limited details. Moreover, methods for case studies and designing an assessment framework were briefly described. In the next Chapter, expected outcomes upon completion of the research tasks and a timeframe will be presented.

5. RESULTS

5.1 General

The previous chapter introduced in detail the environmental, economic, and circular economy indicators that will be used in this thesis. This chapter presents the results of assessing the pavements using these indicators.

5.2 Analysis and interpretation

5.2.1 Sustainability

5.2.1.1 LCA

The results of LCA considering agency impact only and the corresponding values of MKI for the BAU, Rejuvenation, and WMA scenarios are shown in Table 5-1.

Table 5-1 Agency only LCA and MKI results of the three scenarios.

		BAU		Rejuvenation		WMA	
Impact Categories	**Unit**	**Amount**	**MKI (€)**	**Amount**	**MKI (€)**	**Amount**	**MKI (€)**
Global Warming Potential (GWP)	kg CO2 eq	9.39E+04	4695.00	7.39E+04	3695.00	7.39E+04	3695.00
Acidification Potential	kg SO2 eq	2.63E+02	1052.00	2.08E+02	832.00	2.08E+02	832.00
Eutrophication Potential	kg PO4 eq	3.42E+01	307.80	2.62E+01	235.80	2.62E+01	235.80
Ozone Layer Depletion Potential	kg CFC11 eq	4.45E-10	0.00	3.25E-10	0.00	3.25E-10	0.00
Abiotic Depletion elements	kg Sb eq	1.02E-02	0.00	8.64E-03	0.00	8.64E-03	0.00
Abiotic Depletion fossil	kg Sb eq	1.12E+03	178.55	1.00E+03	160.08	1.00E+03	160.08
Freshwater Aquatic Ecotoxicity Potential	kg DCB eq	6.51E+02	19.53	6.27E+02	18.81	6.27E+02	18.81
Human Toxicity Potential	kg DCB eq	3.20E+03	288.00	3.14E+03	282.60	3.14E+03	282.60
Marine Aquatic Ecotoxicity Potential	kg DCB eq	3.60E+06	360.00	3.18E+06	318.00	3.18E+06	318.00
Photochemical Ozone Creation Potential	kg C2H4 eq	1.54E+01	30.80	1.39E+01	27.80	1.39E+01	27.80
Terrestrial Ecotoxicity Potential	kg DCB eq	2.65E+02	15.90	2.30E+02	13.80	2.30E+02	13.80
Total			**6947.58**		**5583.89**		**5583.89**

The agency impact only MKI results of the three scenarios are summarized in Figure 5-1.

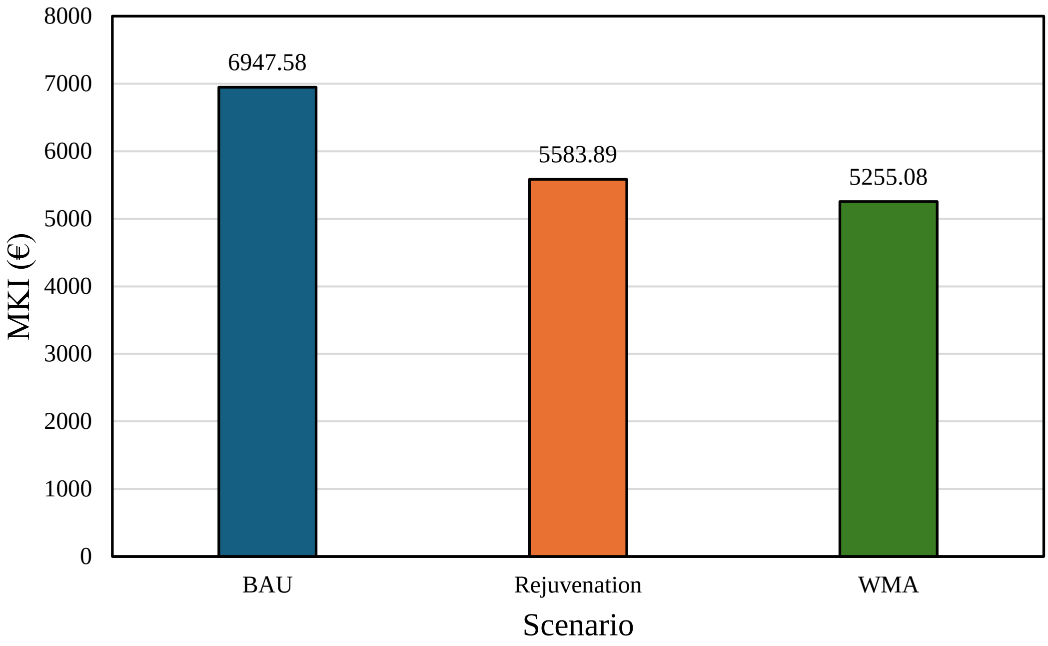

Figure 5-1 Agency only MKI results of the three scenarios

From Figure 5-1, it can be concluded that among the three scenarios, the BAU scenario has the highest environmental impact, while the Rejuvenation and the WMA scenario have lower impact with the WMA scenario having the lowest environmental impact. For the Rejuvenation scenario, this is a result of a longer service life brought by the rejuvenation activities and thus a smaller amount of total material demand within the analysis period. For the WMA scenario, the environmental benefit is due to a higher share of RAP and thus a lower demand on virgin materials, and a lower energy consumption in the production of asphalt as well. The results show that these benefits can overcome the extra burden brought by additives like rejuvenator and reduce the total environmental impact of the asphalt pavement throughout the analysis period. When comparing the Rejuvenation and the WMA scenarios, it can be observed that even though the asphalt pavement has a shorter service life in the WMA scenario, it is still more environmentally friendly than the Rejuvenation scenario, making this novel technology a promising choice considering the environmental aspect.

The sensitivity analysis of agency impact only MKI is shown in Figure 5-2.

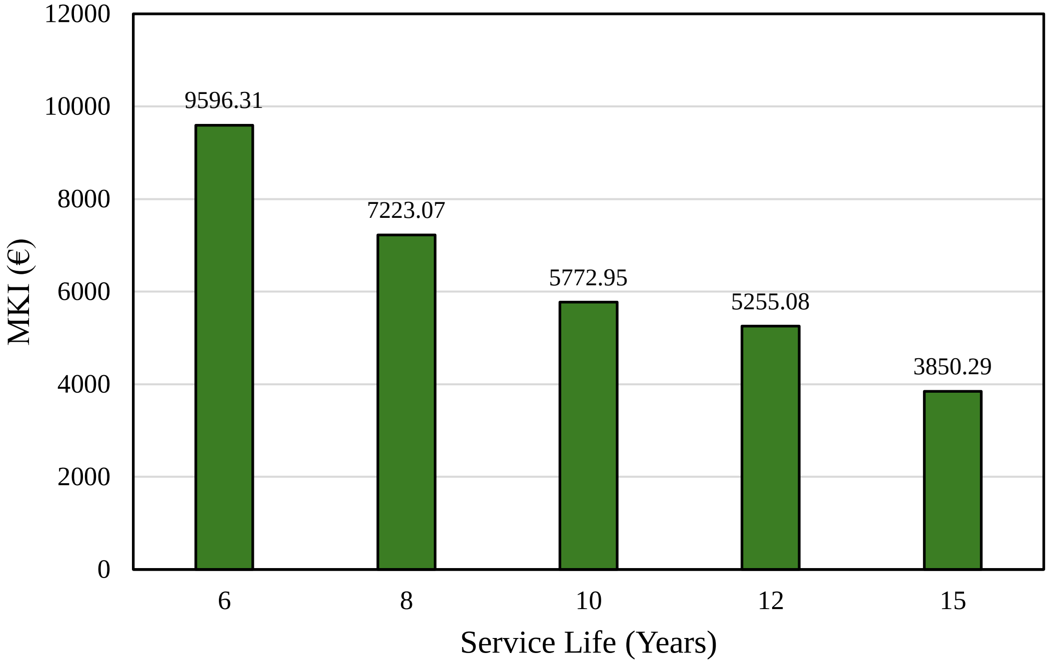

Figure 5-2 Agency only sensitivity analysis of MKI

From Figure 5-2, it can be observed that with the increase of the assumed service life, the MKI value reduces, suggesting a negative relationship between service life and environmental impact.

Table 5-2 shows the LCA and corresponding MKI results of the three scenarios when combining agency and user impacts.

Table 5-2 Agency and user combined LCA and MKI results of the three scenarios.

		BAU		**Rejuvenation**		**WMA**	
Impact Categories	**Unit**	**Amount**	**MKI (€)**	**Amount**	**MKI (€)**	**Amount**	**MKI (€)**
Global Warming Potential (GWP)	kg CO2 eq	3.19E+07	1.60E+06	3.19E+07	1.60E+06	3.19E+07	1.60E+06
Acidification Potential	kg SO2 eq	1.36E+05	5.44E+05	1.36E+05	5.44E+05	1.36E+05	5.44E+05
Eutrophication Potential	kg PO4 eq	2.08E+04	1.87E+05	2.08E+04	1.87E+05	2.08E+04	1.87E+05
Ozone Layer Depletion Potential	kg CFC11 eq	4.67E-08	1.40E-06	4.66E-08	1.40E-06	4.65E-08	1.40E-06
Abiotic Depletion elements	kg Sb eq	1.43E+01	2.29E+00	1.43E+01	2.29E+00	1.43E+01	2.29E+00
Abiotic Depletion fossil	kg Sb eq	1.40E+06	2.24E+05	1.40E+06	2.24E+05	1.40E+06	2.24E+05
Freshwater Aquatic Ecotoxicity Potential	kg DCB eq	1.12E+06	3.36E+04	1.12E+06	3.36E+04	1.12E+06	3.36E+04
Human Toxicity Potential	kg DCB eq	4.62E+06	4.16E+05	4.62E+06	4.16E+05	4.62E+06	4.16E+05
Marine Aquatic Ecotoxicity Potential	kg DCB eq	3.64E+09	3.64E+05	3.65E+09	3.65E+05	3.64E+09	3.64E+05
Photochemical Ozone Creation Potential	kg C2H4 eq	2.14E+04	4.28E+04	2.14E+04	4.28E+04	2.14E+04	4.28E+04
Terrestrial Ecotoxicity Potential	kg DCB eq	3.59E+05	2.15E+04	3.59E+05	2.15E+04	3.59E+05	2.15E+04
Total			**3.43E+06**		**3.43E+06**		**3.43E+06**

The combined MKI results considering both agency and user impacts of the three scenarios are summarized in Figure 5-3.

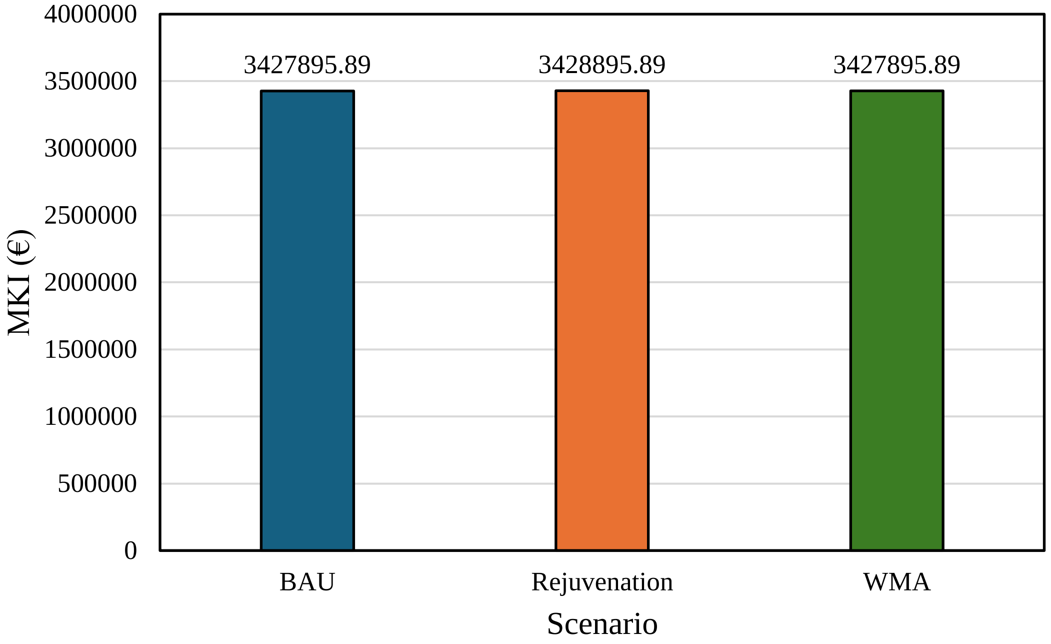

Figure 5-3 Agency and user combined MKI results of the three scenarios

In Figure 5-3, the difference between the three results is less than 0.03%, which is much smaller than that of the agency impact only results. This is because the user impacts of all scenarios are approximately the same and overwhelm the agency impacts.

The sensitivity analysis of combined agency and user MKI is shown in Figure 5-4.

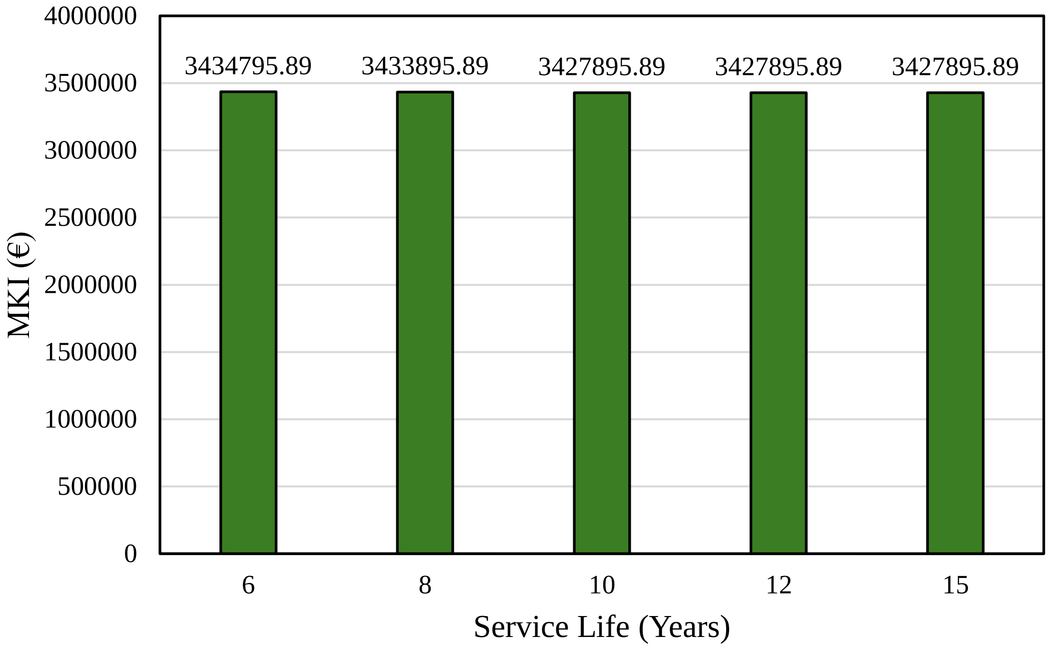

Figure 5-4 Agency and user sensitivity analysis of MKI

From Figure 5-4, it can be observed that the MKI values are approximately the same across all cases, which can also be explained by the similarly overwhelming user impacts.

5.2.1.2 LCCA

Figure 5-5 shows the NPV results of the three scenarios.

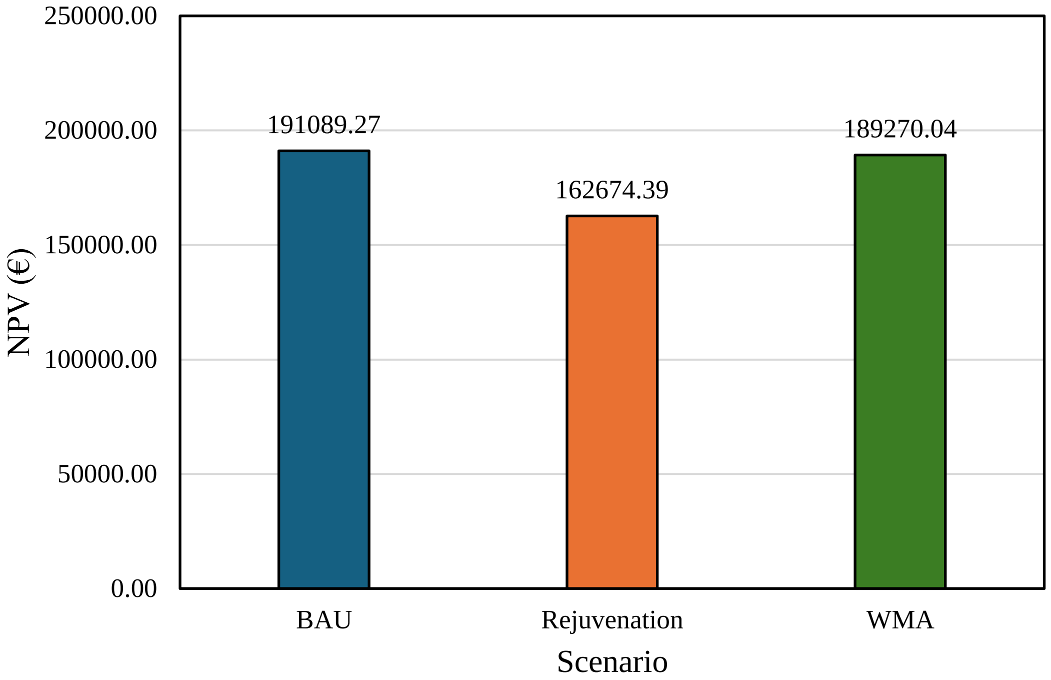

Figure 5-5 NPV of the three scenarios

It can be observed from Figure 5-5 that among the three scenarios, Rejuvenation has the lowest life-cycle cost, and the BAU and WMA scenarios have roughly the same costs. The Rejuvenation scenario has the lowest life-cycle cost mainly for the following three reasons: 1. There are fewer resurfacing activities through the analysis period, which is more expensive than rejuvenation activities, resulting in a lower initial cost. 2. The vehicle operating cost is lower due to a shorter detour length of rejuvenation activities. 3. The delay cost is lower because rejuvenation activities last shorter. The lower cost of the WMA scenario than the BAU is mainly due to a cheaper price of WMA than HMA.

Figure 5-6 presents the sensitivity analysis of NPV.

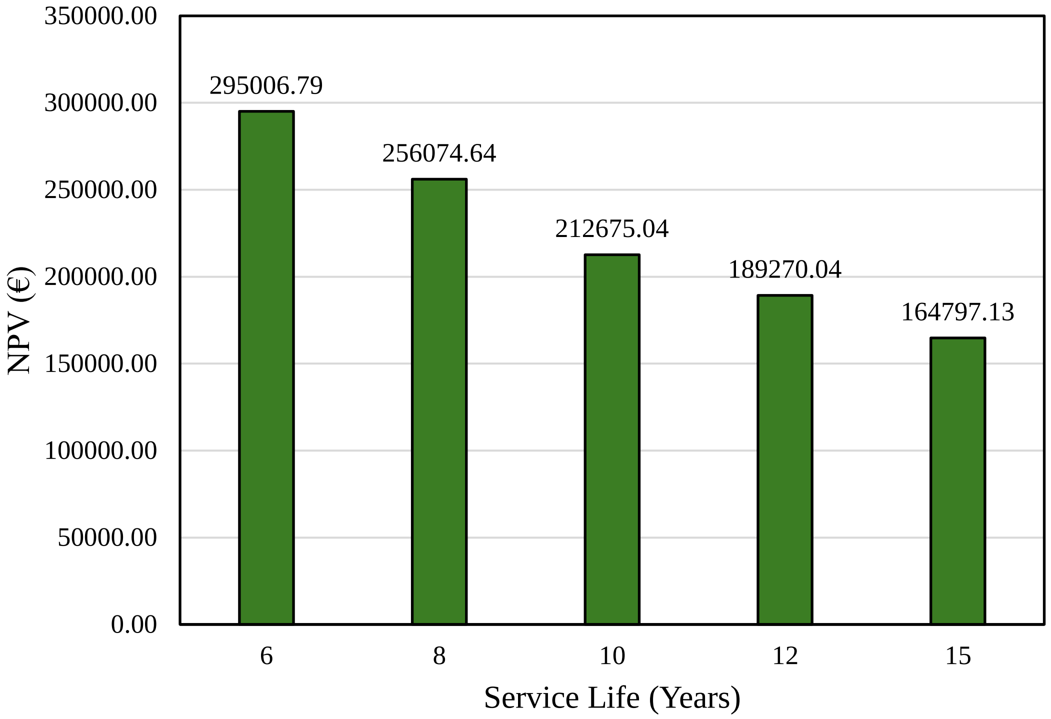

Figure 5-6 Sensitivity analysis of NPV

The sensitivity analysis shows that the life-cycle cost reduces with the increase of assumed service life, which can be explained by the lower cost resulting from the reduced number of resurfacing activities needed.

5.2.2 Circular economy

5.2.2.1 MCI

The values of the parameters for calculating MCI and the final results for the BAU, Rejuvenation, and WMA scenarios are shown in Table 5-3. The MCI results of these three scenarios are compared against each other in Figure 5-7.

Table 5-3 Results of MCI quantification.

	BAU	**Rejuvenation**	**WMA**
Cycles	3	2	3
V (kg, per cycle)	262500	269150	176050
$\mathbf{F_R}$	25%	25%	50%
M	350000	356650	351050
$\mathbf{C_R}$	100%	100%	100%
$\mathbf{W_0}$	0	0	0
$\mathbf{E_c}$	98%	98%	98%
$\mathbf{W_c}$	7000	7084	7042
$\mathbf{E_F}$	100%	100%	100%
$\mathbf{W_F}$	0	0	0
W	3500	5992	3521
LFI	0.38	0.39	0.26
X	1	1.5	1
F(X)	0.9	0.6	0.9
MCI	0.66	0.77	0.77

where

V: mass of virgin materials,

F_R: fraction of feedstock from recycled resources,

M: mass of the pavement,

C_R: fraction of the mass of the product collected for recycling at the end of use stage,

W_0: waste that will be sent to landfill or energy recovery,

E_c: efficiency of the recycling process,

W_c: waste generated in the recycling process,

E_F: efficiency of producing the feedstock,

W_F: waste from the production of feedstock,

W: waste generated in one cycle,

LFI: linear flow index,

X: utility, and

F(X): utility factor.

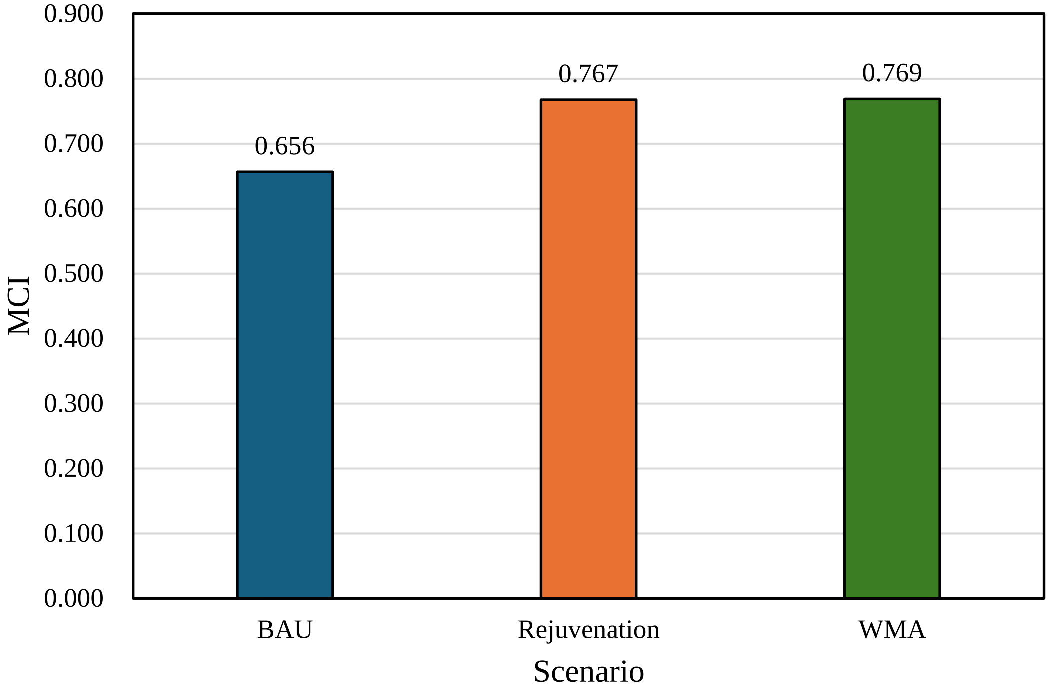

Figure 5-7 MCI results of the three scenarios

It can be concluded from Figure 5-7 that the BAU has a lower MCI score than the Rejuvenation and WMA12 scenarios, and the Rejuvenation and the WMA12 scenarios has roughly the same circularity. The reason is that the Rejuvenation scenario improves the utility by extending the service life by rejuvenation activities, and the WMA12 reduces the linearity by introducing a higher percentage of RAP.

Figure 5-8 shows a sensitivity analysis of MCI assuming various service life years for the WMA scenarios.

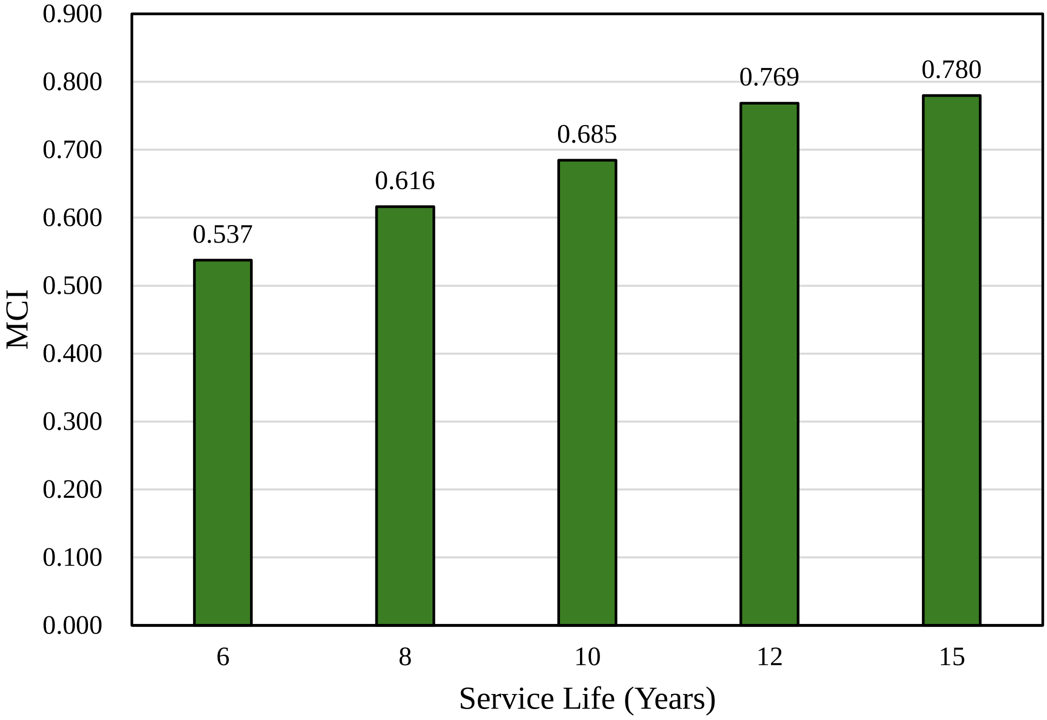

Figure 5-8 Sensitivity analysis of MCI

It can be observed from Figure 5-8 that with the increase in service life, the circularity of the asphalt improves. This improvement is believed to be a result of a longer lifespan and thus a larger utility. Compared with the BAU scenario, it can be observed that the circularity of the WMA exceeds that of the BAU when the service life is 10 years, suggesting that the benefit of using a higher percentage of RAP in production offsets the potential disadvantage of a shorter service life.

5.2.2.2 CEI

The parameters as well as the results of the CEI for the BAU, Rejuvenation, and WMA12 scenarios are shown in Table 5-4, Table 5-5, and Table 5-6, respectively. The results of the three scenarios are compared against each other in Figure 5-9.

Table 5-4 CEI for the BAU scenario.

BAU				
Original service life	12			
Depreciation	0.083			
Maintenance year	12	24	36	
Scrap value	12000.04	21550.35	7585.63	
Non-factor cost	269830.47	484576.75	324341.70	
Material value added	-257830.42	-463026.40	-316756.07	
Material value to reproduce	13090.95	23509.47	42219.64	
CEI	-19.695	-19.695	-7.503	**-46.893**

Table 5-5 CEI for the Rejuvenation scenario.

Rejuvenation							
Original service life	12						
Depreciation	0.083						
Maintenance year	5	10	18	23	28	36	
Scrap value	6125.23	5146.90	16081.20	2821.94	2371.21	1182.12	
Non-factor cost	11060.58	14116.41	361598.63	26618.59	33972.82	324341.70	
Material value added	-4935.34	-8969.51	-345517.43	-23796.66	-31601.61	-323159.58	
Material value to reproduce	9303.50	11873.88	17543.13	22389.97	28575.91	42219.64	
CEI	-0.530	-0.755	-19.695	-1.063	-1.106	-7.654	**-30.804**

Table 5-6 CEI for the WMA scenario.

WMA				
Original service life	12			
Depreciation	0.083			
Maintenance year	12	24	36	
Scrap value	11687.52	20989.11	7388.07	
Non-factor cost	269830.47	484576.75	324341.70	
Material value added	-258142.95	-463587.64	-316953.63	
Material value to reproduce	12750.02	22897.21	41120.09	
CEI	-20.246	-20.246	-7.708	**-48.201**

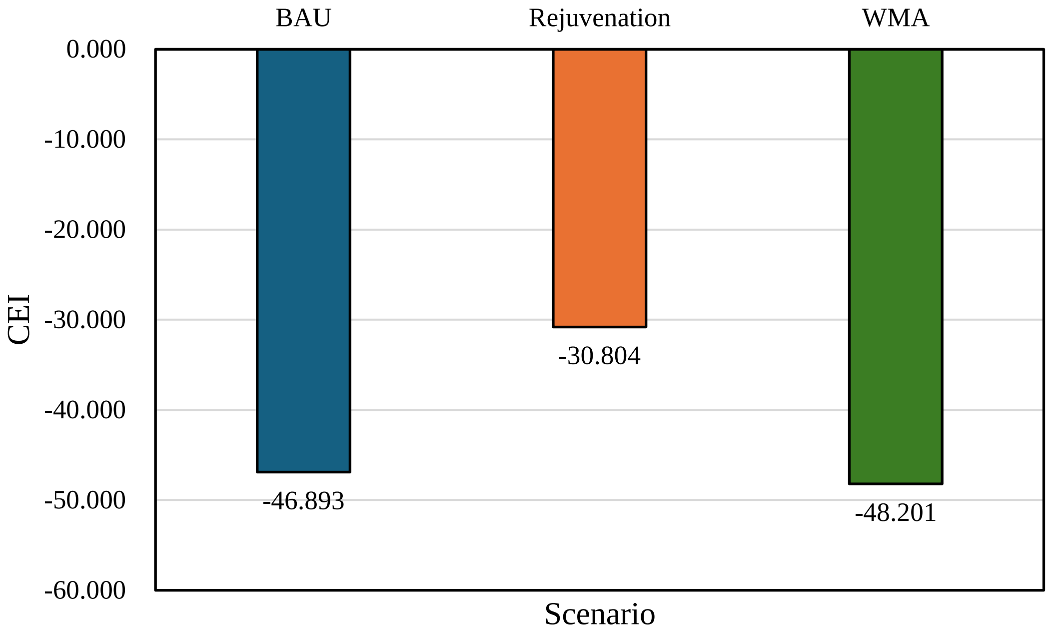

Figure 5-9 CEI results of the three scenarios

For the CEI, the higher the real value, the better the circular economy performance is. In Figure 5-9, it can be observed that the WMA12 scenario has the most negative CEI value and thus the poorest circular economy performance. Likewise, the Rejuvenation scenario has the least negative CEI value and thus the best circular economy performance. The reason that the CEI value of the WMA12 scenario is lower than that of the BAU scenario is the lower price of RAP compared with virgin materials and thus a lower scrap value on the numerator of Equation 4-14. The highest CEI value of the Rejuvenation scenario is due to the extended service life and the absence of the price of rejuvenator due to difficulty in obtaining data.

Figure 5-10 shows a sensitivity analysis of CEI assuming various service life years for the WMA scenarios.

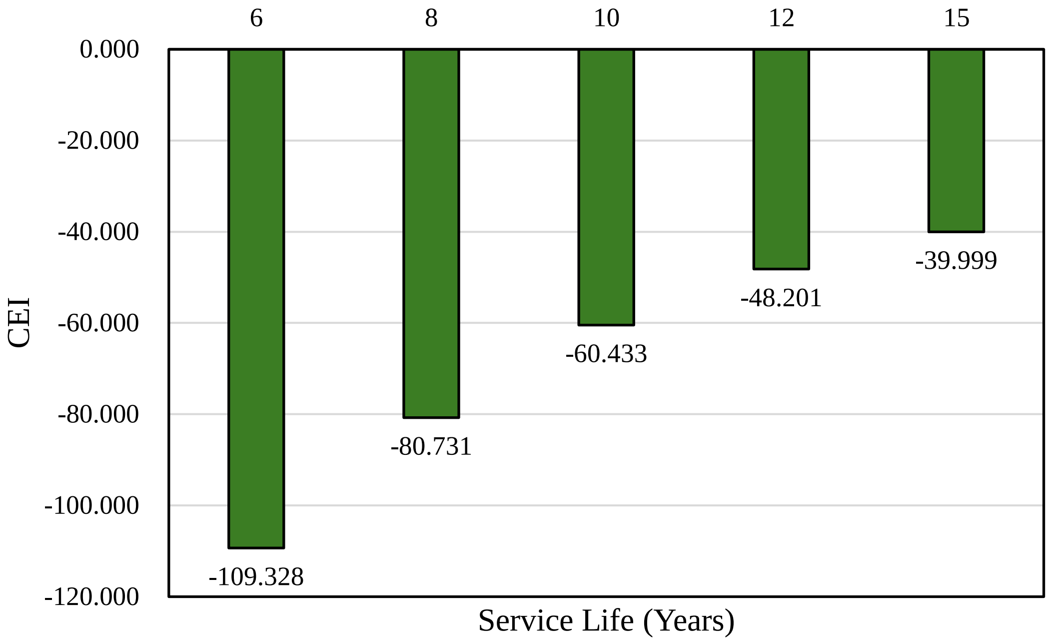

Figure 5-10 Sensitivity analysis of CEI

From Figure 5-10, an increasing trend of circularity can be observed with the extension of service life, indicating a positive correlation between circularity and lifetime. However, unlike the results from the sensitivity analysis of MCI, the CEI value only approaches that of the BAU when the service life is 15 years. As explained above, this is due to a lower scrap value.

5.2.2.3 CB'23

CB'23 is a mass-based method. As described in Section 4.4.3.2.3, the results are not presented in a single numerical form, but rather a list of figures. In the calculation of CB'23, since the definition of physically scarce materials (Indicator 1.3) is not developed yet, this study uses the results of abiotic depletion of non-fossil fuel elements obtained in LCA, which is expressed in the form of equivalent mass of antimony. Since antimony is not a part of the asphalt pavement, the percentage of it relative to the total mass is invalid. For calculating Indicator 1.4, a table containing the socio-economically scarce materials is provided in the document for CB'23 (Platform CB'23, 2022). However, due to the difficulty in quantifying all the background raw materials, this study uses the method by Bautista Carrera (2022), which considers bitumen and rejuvenator as social-economically scarce materials. The results of the CB'23 methods for the three scenarios are listed in Table 5-7.

Table 5-7 CB’23 results for the three scenarios.

Indicators		**BAU**		**Rejuvenation**		**WMA**	
1	**Input material**	Kilogram	Percentage	Kilogram	Percentage	Kilogram	Percentage
1.1	**Secondary material**	262500	25.00%	175000	24.53%	525000	49.85%
1.1.1	Part from reuse	0	0	0	0	0	0
1.1.2	Part from recycling	262500	25.00%	177500	25.00%	525000	49.85%
1.2	**Primary material**	787500	75.00%	538300	75.47%	528150	50.15%
1.2.1	Part renewable	0	0	0	0	0	0
1.2.1a	Part sustainably produced	0	0	0	0	0	0
1.2.1b	Part unsustainably produced	0	0	0	0	0	0
1.2.2	Part not renewable	787500	75%	538300	75.47%	528150	50.15%
1.3	**Physically scarce materials**	Kilogram	Percentage	Kilogram	Percentage	Kilogram	Percentage
1.3.1	Part physically abundant	1050000	100.00%	713300	100.00%	1053150	100%
1.3.2	Part physically scarce	0.0102	-	0.00832	-	0.00773	-
1.4	Socio-economically scarce	Kilogram	Percentage	Kilogram	Percentage	Kilogram	Percentage
1.4.1	Part socio-economically abundant	1002750	95.50%	673400	94.40%	1002750	95.21%
1.4.2	Part socio-economically scarce	47250	4.50%	39900	5.59%	50400	4.79%
2	**Preserved output material**	Kilogram	Percentage	Kilogram	Percentage	Kilogram	Percentage
2.1	Part for reuse	0	0	0	0	0	0
2.2	Part for recycling	1029000	98.00%	694232	97.32%	1032087	98.00%
3	**Lost output material**	Kilogram	Percentage	Kilogram	Percentage	Kilogram	Percentage
3.1	Part used for energy production	0	0	0	0	0	0
3.2	Part sent to landfill	0	0	0	0	0	0

In Table 5-7, both mass and percentage of the indicators are listed. It can be observed that compared with the BAU and Rejuvenation scenarios, the WMA12 scenarios uses a lower percentage of primary materials, which is largely brought by a higher RAP percentage. Compared with the BAU scenario, both the Rejuvenation and WMA12 scenarios use a higher percentage of socio-economically scarce materials, which is due to the addition of rejuvenator.

Table 5-8 shows a sensitivity analysis of CB’23 for different assumed service life years of the WMA scenario.

Table 5-8 Sensitivity analysis of CB'23.

Indicators		WMA6		WMA8		WMA10	
1	**Input material**	Kilogram	Percentage	Kilogram	Percentage	Kilogram	Percentage
1.1	**Secondary material**	1050000	49.85%	875000	49.85%	700000	49.85%
1.1.1	Part from reuse	0	0	0	0	0	0
1.1.2	Part from recycling	1050000	49.85%	875000	49.85%	700000	49.85%
1.2	**Primary material**	1056300	50.15%	880250	50.15%	704200	50.15%
1.2.1	Part renewable	0	0	0	0	0	0
1.2.1a	Part sustainably produced	0	0	0	0	0	0
1.2.1b	Part unsustainably produced	0	0	0	0	0	0
1.2.2	Part not renewable	1056300	50.15%	880250	50.15%	704200	50.15%
1.3	**Physically scarce materials**	Kilogram	Percentage	Kilogram	Percentage	Kilogram	Percentage
1.3.1	Part physically abundant	2106300	100.00%	1755250	100.00%	1404200	100%
1.3.2	Part physically scarce	0.0102	-	0.00832	-	0.00773	-
1.4	Socio-economically scarce	Kilogram	Percentage	Kilogram	Percentage	Kilogram	Percentage
1.4.1	Part socio-economically abundant	2005500	95.21%	1671250	95.21%	1337000	95.21%
1.4.2	Part socio-economically scarce	100800	4.79%	84000	4.79%	67200	4.79%
2	**Preserved output material**	Kilogram	Percentage	Kilogram	Percentage	Kilogram	Percentage
2.1	Part for reuse	0	0	0	0	0	0
2.2	Part for recycling	2064174	98.00%	1376116	78.40%	1032087	73.5%
3	**Lost output material**	Kilogram	Percentage	Kilogram	Percentage	Kilogram	Percentage
3.1	Part used for energy production	0	0	0	0	0	0
3.2	Part sent to landfill	0	0	0	0	0	0

Table 5-8 (cont.)

Indicators		WMA12		WMA15	
1	**Input material**	Kilogram	Percentage	Kilogram	Percentage
1.1	**Secondary material**	525000	49.85%	525000	49.85%
1.1.1	Part from reuse	0	0	0	0
1.1.2	Part from recycling	525000	49.85%	525000	49.85%
1.2	**Primary material**	528150	50.15%	528150	50.15%
1.2.1	Part renewable	0	0	0	0
1.2.1a	Part sustainably produced	0	0	0	0
1.2.1b	Part unsustainably produced	0	0	0	0
1.2.2	Part not renewable	528150	50.15%	528150	50.15%
1.3	**Physically scarce materials**	Kilogram	Percentage	Kilogram	Percentage
1.3.1	Part physically abundant	1053150	100%	1053150	100%
1.3.2	Part physically scarce	0.00773	-	0.00832	-
1.4	Socio-economically scarce	Kilogram	Percentage	Kilogram	Percentage
1.4.1	Part socio-economically abundant	1002750	95.21%	1002750	95.21%
1.4.2	Part socio-economically scarce	50400	4.79%	50400	4.79%
2	**Preserved output material**	Kilogram	Percentage	Kilogram	Percentage
2.1	Part for reuse	0	0	0	0
2.2	Part for recycling	1032087	98.00%	688058	65.33%
3	**Lost output material**	Kilogram	Percentage	Kilogram	Percentage
3.1	Part used for energy production	0	0	0	0
3.2	Part sent to landfill	0	0	0	0

It can be observed from Table 5-8 that the percentage values of all the sub-indicators are the same except for the output material for recycling. This is because the composition of input materials for the WMA scenarios is the same regardless of the assumed service life, while due to the truncation by analysis period, the output of the final cycle of some scenarios is not included.

5.2.2.4 ESC_i

With the normalization factor per person and the weightings available, the normalized results of the impact categories can be calculated. The normalized and weighted LCA results for the three scenarios are shown in Table 5-9.

Table 5-9 Agency only normalized and weighted LCA results of the three scenarios.

	BAU		**Rejuvenation**		**WMA**	
Impact categories	Normalized	Weighted	Normalized	Weighted	Normalized	Weighted
Global Warming Potential (GWP)	1.36E+01	1.27E+02	1.07E+01	9.96E+01	1.03E+01	9.61E+01
Acidification Potential	6.73E+00	4.11E+01	5.32E+00	3.25E+01	4.91E+00	3.00E+01
Eutrophication Potential	1.32E+00	8.74E+00	1.01E+00	6.70E+00	9.64E-01	6.36E+00
Ozone Layer Depletion Potential	1.20E-08	7.44E-08	8.76E-09	5.43E-08	8.49E-09	5.26E-08
Abiotic Depletion elements	1.73E-01	1.11E+00	1.46E-01	9.37E-01	1.32E-01	8.47E-01
Abiotic Depletion fossil	3.74E+01	2.61E+02	3.35E+01	2.34E+02	2.91E+01	2.04E+02
Freshwater Aquatic Ecotoxicity Potential	1.69E+00	1.15E+01	1.63E+00	1.11E+01	1.33E+00	9.06E+00
Human Toxicity Potential	7.59E+00	5.39E+01	7.45E+00	5.29E+01	6.17E+00	4.38E+01
Marine Aquatic Ecotoxicity Potential	1.13E+02	7.68E+02	9.98E+01	6.78E+02	8.69E+01	5.91E+02
Photochemical Ozone Creation Potential	2.56E+00	1.66E+01	2.31E+00	1.50E+01	1.68E+00	1.09E+01
Terrestric Ecotoxicity Potential	1.49E+00	1.01E+01	1.29E+00	8.78E+00	1.13E+00	7.67E+00
SUM		**1299.16**		**1140.35**		**999.72**

The normalized and weighted results can be denoted as LCA_T. Together with the MCI values calculated before, the ESC results can be calculated, and are shown in Table 5-10. In Figure 5-11, a summary of the results is provided.

Table 5-10 Calculation of the agency only ESC_i for the three scenarios.

	MCI	**LCA_T**	**ESC_i**
BAU	0.66	1299.16	8.51
Rejuvenation	0.77	1140.35	19.45
WMA12	0.77	999.72	20.23

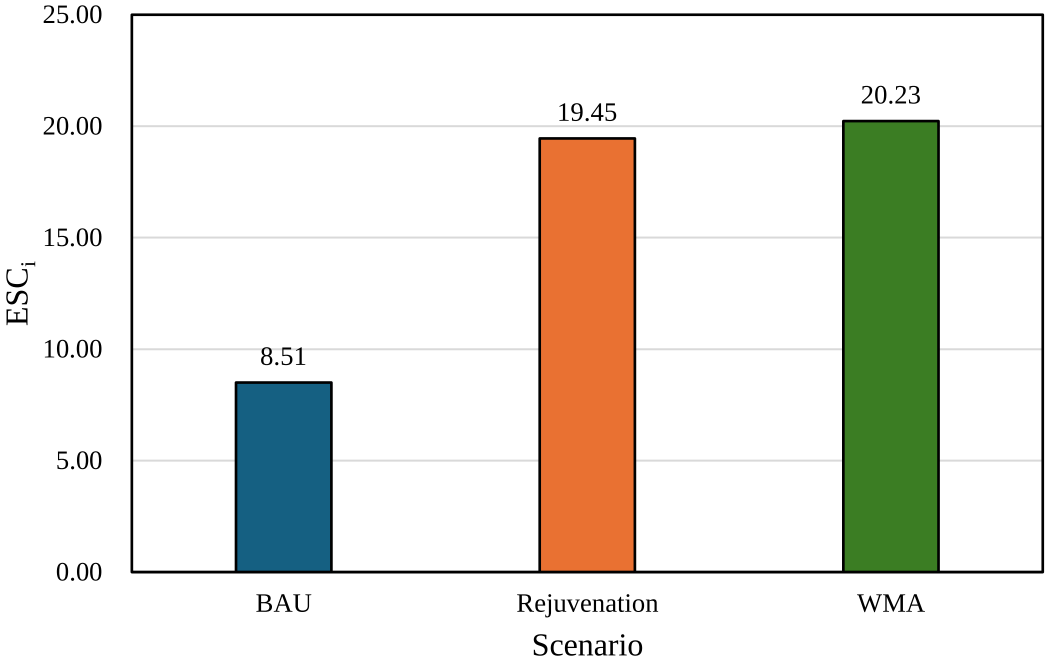

Figure 5-11 Agency only ESC_i results of the three scenarios

From Figure 5-11, it can be observed that among the three scenarios, the BAU scenario has the lowest ESC, and the Rejuvenation and WMA12 scenarios have approximately the same results with the WMA12 scenario being slightly higher. This indicates that compared with the BAU, the Rejuvenation and WMA12 have a better sustainability performance, which can be explained by the fact that the Rejuvenation scenario extends the service life and thus uses fewer materials, and the WMA12 scenario uses less energy and fewer virgin materials.

Figure 5-12 shows the sensitivity analysis of ESC_i when considering agency impact only.

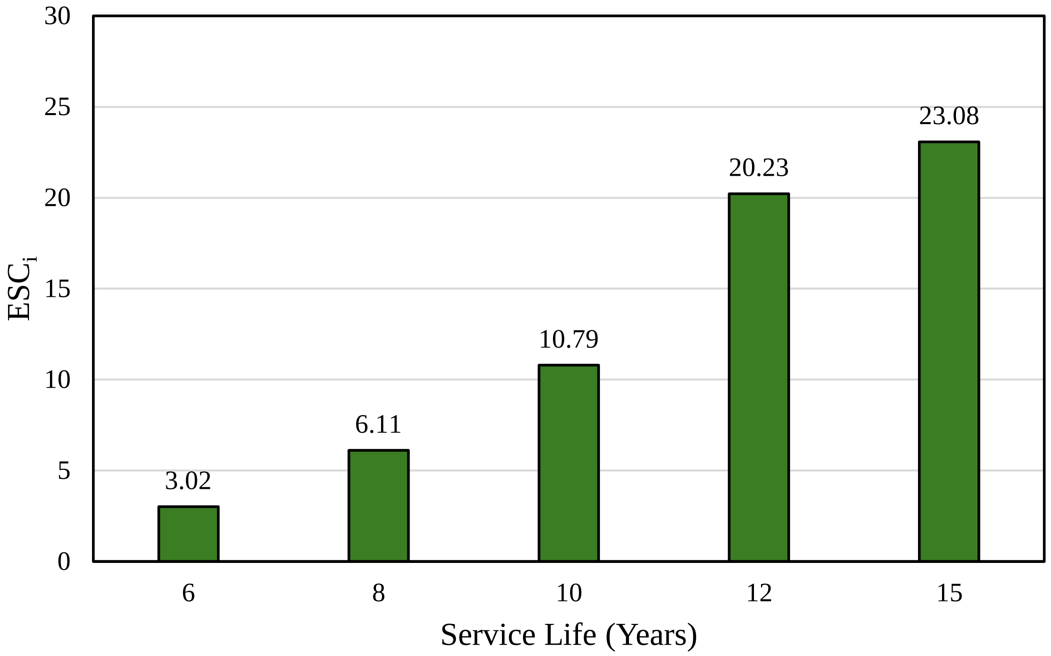

Figure 5-12 Agency only sensitivity analysis of ESC_i

Figure 5-12 shows that with the increase of the assumed service life, the ESC_i results also increase. Pavement with a longer service life experiences fewer life cycles in the analysis period, and thus needs fewer raw materials, resulting in a lower environmental impact. At the same time, the utility is also higher, leading to a higher MCI value.

Table 5-11 shows the normalized and weighted LCA results of the three scenarios when considering both agency and user impacts.

Table 5-11 Agency and user normalized and weighted LCA results of the three scenarios.

	BAU		**Rejuvenation**		**WMA**	
Impact categories	Normalized	Weighted	Normalized	Weighted	Normalized	Weighted
Global Warming Potential (GWP)	4.62E+03	4.30E+04	4.62E+03	4.30E+04	4.62E+03	4.30E+04
Acidification Potential	3.48E+03	2.12E+04	3.48E+03	2.12E+04	3.48E+03	2.12E+04
Eutrophication Potential	8.05E+02	5.32E+03	8.05E+02	5.32E+03	8.05E+02	5.32E+03
Ozone Layer Depletion Potential	1.26E-06	7.80E-06	1.26E-06	7.79E-06	1.25E-06	7.77E-06
Abiotic Depletion elements	2.42E+02	1.55E+03	2.42E+02	1.55E+03	2.42E+02	1.55E+03
Abiotic Depletion fossil	4.69E+04	3.28E+05	4.69E+04	3.28E+05	4.69E+04	3.28E+05
Freshwater Aquatic Ecotoxicity Potential	2.90E+03	1.97E+04	2.90E+03	1.97E+04	2.90E+03	1.97E+04
Human Toxicity Potential	1.10E+04	7.78E+04	1.10E+04	7.78E+04	1.10E+04	7.78E+04
Marine Aquatic Ecotoxicity Potential	1.14E+05	7.77E+05	1.15E+05	7.79E+05	1.14E+05	7.77E+05
Photochemical Ozone Creation Potential	3.56E+03	2.31E+04	3.56E+03	2.31E+04	3.56E+03	2.31E+04
Terrestric Ecotoxicity Potential	2.02E+03	1.37E+04	2.02E+03	1.37E+04	2.02E+03	1.37E+04
SUM		**1.31E+06**		**1.31E+06**		**1.31E+06**

With the weighted sum of LCA results calculated, the calculation of ESC_i for the three scenarios when considering both agency and user impacts is shown in Table 5-12. T the ESC_i results is visualized in Figure 5-13.

Table 5-12 Calculation of the agency and user ESC_i for the three scenarios.

	MCI	**LCA_T**	**ESC_i**
BAU	0.66	1.31E+06	**0.79**
Rejuvenation	0.77	1.31E+06	**3.78**
WMA12	0.77	1.31E+06	**3.84**

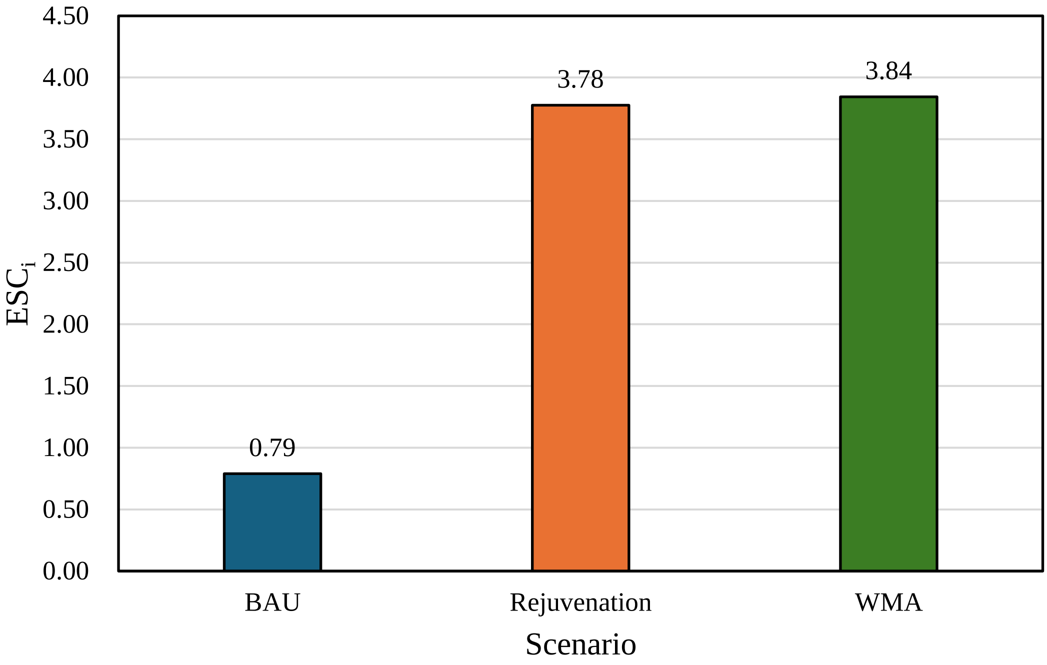

Figure 5-13 Agency and user ESC$_i$ results of the three scenarios

Figure 5-13 shows that when summing agency and user impacts, the BAU remains to have the poorest performance and Rejuvenation and WMA have approximately the same score. Table 5-12 reveals that this is mainly due to the difference in MCI since the normalized and weighted LCA results of the three scenarios are roughly the same.

Figure 5-14 provides the sensitivity analysis of ESC$_i$ when considering agency and user impacts together.

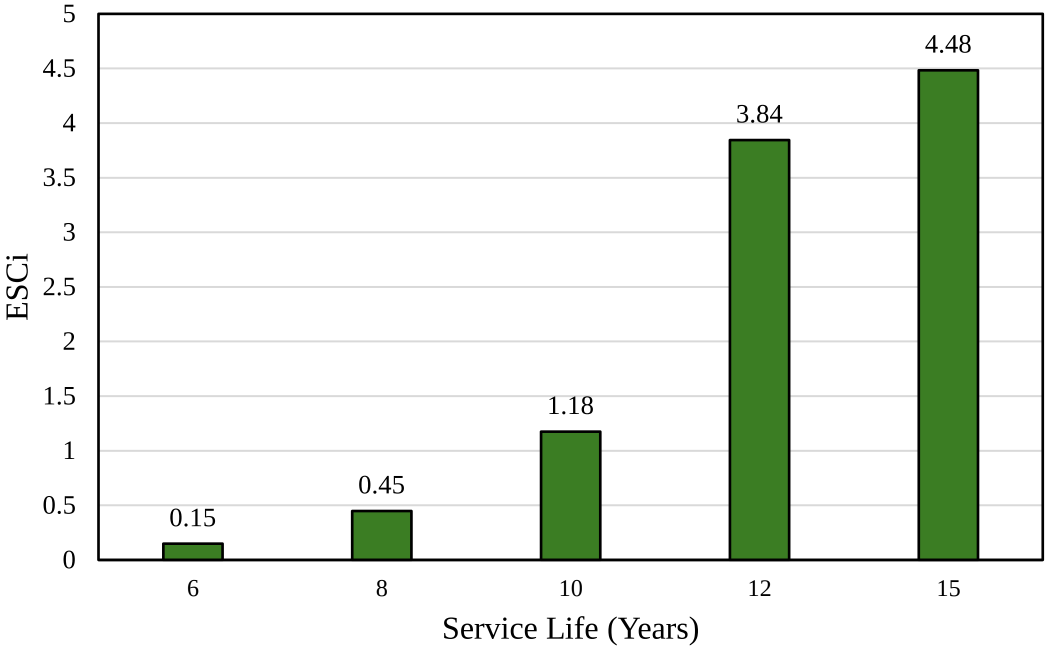

Figure 5-14 Agency and user combined sensitivity analysis of ESC_i

With the increase of the assumed service life, the ESC_i results increases, suggesting a better sustainability and circularity performance. As also explained in previous sections about LCA and MCI results, this can be explained by fewer virgin materials used and higher utility.

5.2.2.5 CEIP

The questions selected for calculating the CEIP and the scores of the three scenarios are listed in Table 5-13. Following that, the results of CEIP of the three scenarios are summarized in Figure 5-15.

Table 5-13 Questions and scores of CEIP for the three scenarios.

Questions	**Full point**	**BAU**	**Rejuvenation**	**WMA**
Is the product made from recycled/reused material?	20	5	5	10
Is the product lighter than its previous version?	2	1	2	0
Is there a complete bill of materials and substances for the product?	5	5	5	3
Is there a complete bill of energy for the manufacturing process?	10	0	0	0
Is there a complete bill of solid waste for the manufacturing process?	15	0	0	0
What is the product's warranty	10	5	7	5
Can the use status and identification of the product be established?	15	8	8	8
Can the product be repaired?	5	0	5	0
Can the product be reused?	10	0	0	0
Does the product reduce waste through its use?	5	0	0	0
What take-back scheme is available for this product?	15	15	15	15
Is the product separated out from other products at EOL?	10	0	0	0
Are the product's materials processed back into the supply chain?	10	10	10	10
Total	132	**49**	**57**	**51**

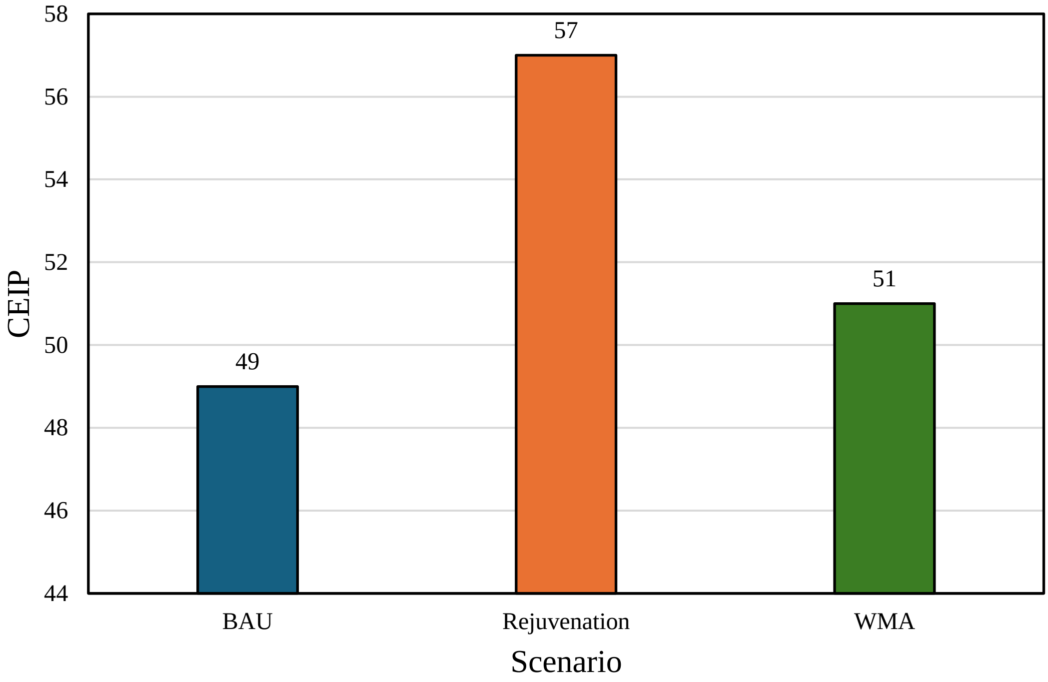

Figure 5-15 CEIP results of the three scenarios

It can be observed from Figure 5-15 that among the three alternatives, the BAU has the lowest score, and the Rejuvenation has the highest one. Compared with the BAU scenario, the pavement in the Rejuvenation scenario uses fewer materials by mass through the analysis period, has a longer lifetime, and can be repaired. These three factors contribute to the eight more points. In term of the WMA scenario, it scores only two points higher than the BAU, which is due to a higher percentage of RAP, but higher total usage of materials, and the unknown type and amount of foaming additive. The benefit brought by a lower energy usage is not reflected by the results since the questions do not concern the amount of energy used.

Figure 5-16 provides a sensitivity analysis of CEIP assuming different service life years of the WMA scenario.

Figure 5-16 Sensitivity analysis of CEIP

The sensitivity analysis shows the same CEIP results when service life is 6, 8 and 10 years. This is because in these cases, the service life is shorter than that of the BAU but still not less than half of it. When the service life is 12 and 15 years, the CEIP result is larger, which shows that the CEIP only captures the effect of service life under certain circumstances. This is a result of the definition of the scoring of the indicator. The sensitivity analysis also shows that for service life no longer than 10 years, the CEIP of the WMA scenarios is smaller than that of the BAU, suggesting that the disadvantage of a shorter lifespan offsets the benefit of a larger percentage of recycled materials used.

5.2.2.6 MRS

The calculation of the MRS for the three scenarios is shown in Table 5-14. The results are shown in Figure 5-17.

Table 5-14 Calculation and results of MRS for the three scenarios.

	BAU	**Rejuvenation**	**WMA12**
Recycled or renewable part	0.25	0.25	0.5
Recyclable or renewable part	0.98	0.98	0.98
MRS	**73.67**	**73.67**	**82**

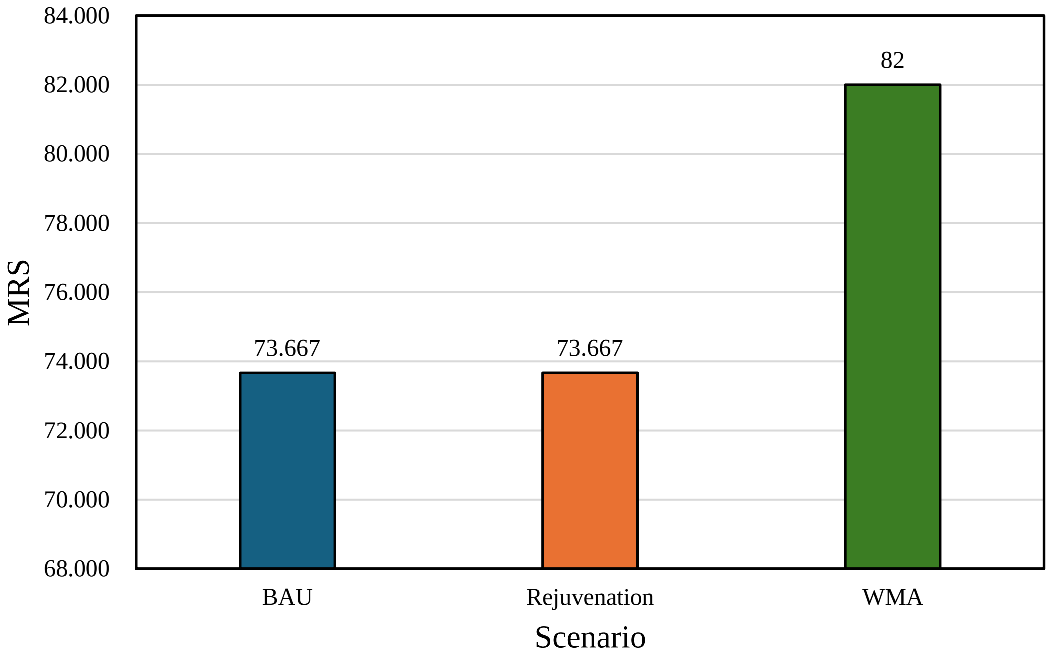

Figure 5-17 MRS results of the three scenarios

It can be observed in Figure 5-17 that the BAU and the Rejuvenation scenarios have the same MRS scores and are lower than that of the WMA12 scenario. The reason that the BAU and the Rejuvenation scores the same is that both of them use 25% RAP and can be recycled at a 98% efficiency. Similarly, the reason why the WAM12 alternatives scores higher is that although the recycling efficiency is the same, the percentage of recycled material used is higher than the other two options.

A sensitivity analysis of MRS based on different assumed service life years for the WMA scenario is shown in Figure 5-18.

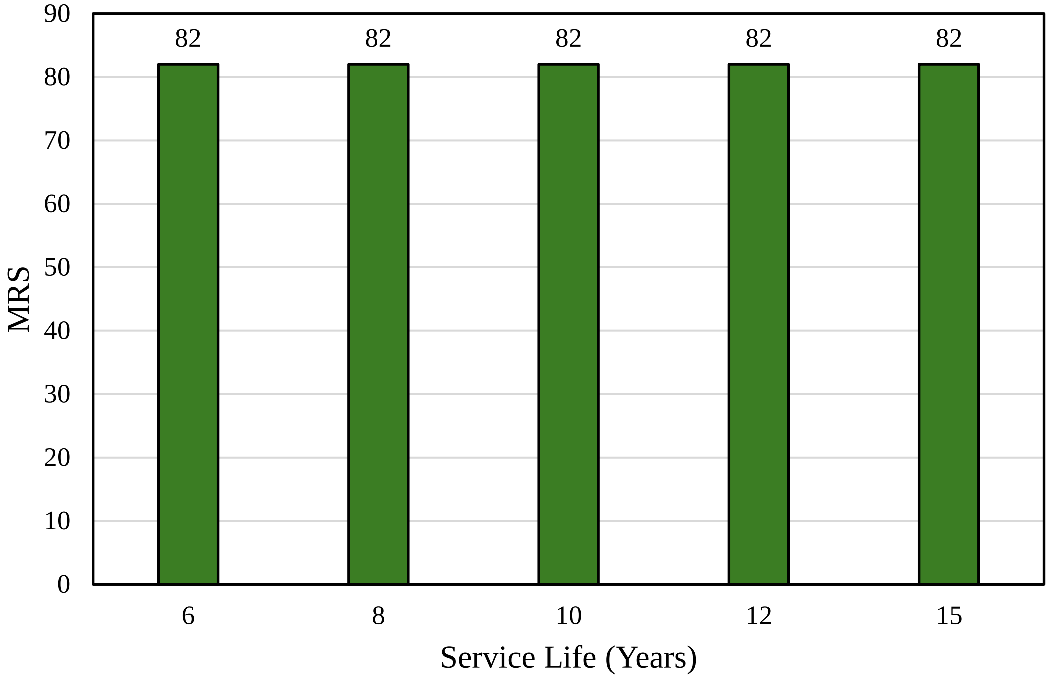

Figure 5-18 Sensitivity analysis of MRS

It can be observed from Figure 5-18 that the MRS results are the same for all alternatives, indicating that this indicator cannot capture the effect of the change in lifespan. This is a result of the definition of the indicator itself, which only considers the percentage of recycled and recyclable materials. Since for the WMA scenarios in this study, the percentage of RAP and the percentage of EOL materials to recycling are the same, the MRS results are the same.

5.3 Summary

This chapter presents the assessment results of the pavements in different case studies. The results will be summarized and discussed in the next chapter.

6. DISCUSSION

6.1 General

The previous chapter presents the results of the indicators assessed across different case studies. In this chapter, a discussion regarding the results and the suitability of indicators is carried out.

6.2 Discussion

6.2.1 Table of results

Table 6-1 summarizes the results obtained from the indicators.

Table 6-1 Summary of the results of indicators.

Field	Indicators	Scenarios		
		BAU	Rejuvenation	WMA
Sustainability	MKI (Agency only)	6947.58	5583.89	5255.08
	MKI (Agency + user)	3427895.89	3428895.89	3427895.89
	LCCA	191089.27	162674.39	189270.04
Circular Economy	MCI	0.66	0.77	0.77
	CEI	-46.89	-30.80	-48.20
	CB’23	Table 5-7		
	ESC$_i$ (Agency)	8.51	19.45	20.23
	ESC$_i$ (Agency + user)	0.79	3.78	3.84
	CEIP	49	57	51
	MRS	73.67	73.67	82

The results indicate that all the indicators have their advantages and disadvantages. The advantage of MCI is that it considers both material circularity and the utility of product including its intensity of use and service life. Therefore, the advantage of both Rejuvenation and WMA scenarios over the BAU can be identified through the results. The disadvantage of MCI is that it is a mass-based indicator, and thus environmental impact cannot be reflected. In the context of this study, the environmental benefit brought by the reduced energy usage in production of WMA cannot be captured. As can be observed from the MKI results when considering agency impact only, the environmental impact of the WMA scenario is 24.36% lower than that of the BAU case, and this benefit is not reflected by the results of MCI. It is expected that the environmental benefits brought by other measures, for instance, replacing bitumen with bio-based materials, also cannot be reflected by the results. Therefore, it is suggested by the EMF that MCI can be used along with indicators measuring CO_2 emissions, water footprint, and toxicity (Ellen MacArthur Foundation, 2019). In addition, from the results themselves, the distinction between Rejuvenation and WMA cannot be identified, which is a result of Rejuvenation extending the service life while WMA reducing linearity. When delivering the results of MCI, a table including the values of the sub-indicators required for calculating the final results can be presented so that stakeholders can better identify the specific advantages of each alternative, as it is shown in similar studies (Mantalovas & Di Mino, 2019, 2020).

CEI, being a value-based indicator, indirectly includes the environmental impacts of materials within the prices of them. However, prices are affected by the supply and demand of the market. A larger supply than demand may lead to a drop in price and vice versa. Price can affect the results. As can be observed in the results, WMA is expected to have a better performance than the BAU, but the lower price of RAP leads to a lower scrap value of WMA, which further results in a more negative CEI value than the BAU. The lower price of RAP is due to its lower quality compared with virgin materials. Concerns regarding the quality of RAP-included pavements often include the quality of the binder, and cracking due to stiffening (Copeland, 2011). These problems lead to a lower value of RAP and may shorten the service life of the pavements, leading to a lower CEI value. In this study, the WMA scenario uses 50% of RAP, which is higher than the 25% used in HMA for the BAU scenario. As a result, the CEI of the WMA is lower by 2.79% even when the service life is assumed to be the same. When the service life of WMA is assumed to be lower than 12 years, the CEI result becomes even lower. In such a case, the benefit brought by using a higher percentage of WMA, the reduction of virgin material input, may not be reflected.

In this study, only the results of Indicator 1 to 3 are presented for CB'23. Therefore, it is also mass-based indicator in this study. Without aggregating these results, it could be difficult comparing one scenario as a whole with other alternatives. However. this is expected to be helpful if stakeholders want to improve a specific part of the product, and if they strongly highlight one specific aspect, percentage of socio-economically scarce material used, for example, when deciding the best alternative. However, like MCI, a mass-based indicator cannot capture the environmental effect. Therefore, when using CB'23, Indicators 4 about environmental impacts can be included to make a more comprehensive assessment. In addition, the effect of service life is not included in the indicator, which can be observed in the sensitivity analysis results, where the percentage values are the same for all assumed service life.

ESC_i combines the results of MCI and LCA, which makes it possible to cover the environmental effect in addition to material circularity and service life. In the results, the difference between Rejuvenation and WMA is also relatively small. Therefore, as suggested for the use of MCI, when presenting the results of ESC_i the table for the sub-indicators can be presented. Moreover, a table containing the results of each LCA impact category involved in the calculation of ESC_i can be included so that the contribution of each category can be identified. Though covering the environmental aspect of sustainability, ESC_i fails to integrate economic sustainability, which is often an essential consideration in decision making. The agency and user combined ESC_i results show that the WMA scenario is 1.59% better than the Rejuvenation scenario. However, from the LCCA results, the Rejuvenation scenario is 16.35% better than the WMA scenario, which is not reflected in ESC_i. Therefore, the complementary use of economic sustainability indicators or even an integration with ESC_i can be developed if a more comprehensive assessment including circularity, environmental sustainability, and economic sustainability is desired.

CEIP is a questionnaire-based indicator, in which a broad area of questions related to circularity are asked. The original literature gives its own weighting of each question, but the weighting may vary depending on the requirements of the stakeholders. In the results of this study shows that the Rejuvenation is the most ideal alternative, leading the BAU and the WMA scenarios by 16.33% and 11.76%, respectively. This is mainly due to its less amount of material use and repairability. The full scores for the questions for the amount of material and repairability account for 1.51% and 3.79%, respectively. It is expected that if the weightings of these two questions raise the Rejuvenation scenario will lead by a larger margin. In addition, the interpretation of each question and the design of scoring criteria also have a high level of freedom. These give the indicator flexibility, but also reduces the reliability of the results due to their subjectivity. Data collection is another issue. In this study, since the amount of some materials and energy consumption could not be found, the scenarios lose points on questions about bill of materials and bill of energy. In practice, if the decision maker can obtain more complete primary data, a more accurate scoring can be derived.

MRS is a mass-based indicator that only considers the percentage of recycled and recyclable materials. Therefore, the results only show differences when the percentage of RAP is not the same. As is shown by Table 6-1, both the BAU and the Rejuvenation scenarios using 25% RAP have the same result, 73.67, while the WMA scenario using 50% RAP has 82. All the other factors that may affect circularity and sustainability performances, including but not limited to the lower energy consumption of WMA, and the longer service life and less amount of materials use of the Rejuvenation scenario is not reflected by MRS. This suggests that MRS can only be used in limited circumstances, where recycled and recyclable materials are designated to be the only considerations of selecting alternatives. Although not reflected in this study, it is possible that two alternatives with different percentage of recycled materials and recyclable materials (e.g. Alternative A has 50% recycled materials and 25% recyclable materials, and alternative B has 40% recycled materials and 30% recyclable materials) have the same results. Therefore, the percentage values need to be presented along with the results. The equation used to calculate MRS, Equation 4-20, shows that the developer of MRS assigned a higher weighting to the recyclable part than the recycled part, which may not always be the same as the preference of decision makers in practice. Hence, the equation may need to be slightly modified in use.

Given the discussion above, it is challenging at this stage to recommend a single indicator as the universally most suitable one, as each has its own advantages and limitations and may be appropriate under different circumstances. The choice of indicators leads to varying selections of alternatives. Choosing different indicators results in different choices of alternatives. In this study, if MKI, MCI, ESC_i or MRS is chosen, the WMA scenario emerges as the best choice; if LCCA, CEI or CEIP is chosen, the Rejuvenation alternative appears ideal; if CB'23 is chosen, the selection might depend on the result of a specific sub-indicator. Although the advantages and limitations of each indicator have been discussed, it is not reasonable to label any indicator as inherently right or wrong. The differences between indicators lie in their coverage and focus on circularity and sustainability. Consequently, the alternatives selected based on different indicators may lead to improvements in distinct aspects of circular economy and sustainability.

For instance, selecting the BAU scenario may not clearly enhance circularity or environmental and economic sustainability, but it requires fewer changes to the management system as it is the conventional practice, which could benefit certain aspects of social sustainability. Choosing the Rejuvenation alternative primarily improves resource efficiency and economic sustainability. Opting for the WMA scenario is expected to enhance resource efficiency and environmental sustainability. Therefore, in practice, any indicator—or the complementary use of multiple indicators—may be used to support decision-making, but it is crucial to consider, discuss, and transparently communicate the focus, implications, and results associated with each choice.

6.3 Summary

In this chapter, the results obtained from the indicators were summarized, and the suitability of the indicators were discussed. It was decided that ESC_i is the most suitable indicator but requires combination with LCCA for a more comprehensive assessment.

7. CONCLUSION

7.1 Conclusion

In response to various environmental, economic, and social issues caused by the development of the human society, the necessity for circular economy and sustainability has increased over years. Pavement, as a part of the construction sector, is believed to be resource and fund intensive, and also causes considerable environmental pollution. In recent years, also there have been developments in approaches improving circularity and sustainability of pavements, there still lacks indicators measuring the circularity and sustainability performances of pavements, which makes the implementation of these approaches difficult. To address this problem, this study first reviewed existing sustainability and circular economy indicators from literatures and selected the potentially feasible ones. For the sustainability part, MKI of LCA was selected for the environmental aspect and NPV of LCCA was selected for the economic aspect. For the circular economy part, six indicators were chosen: MCI, CEI, CB'23, ESC_i, CEIP, and MRS. Three case studies were chosen for this study: BAU, Rejuvenation, and WMA, and for the WMA scenario, various service life years were assumed for a sensitivity analysis. After collecting the necessary data, quantification of sustainability and circularity performances of pavements in the case studies was carried out using these indicators, and a series of results were obtained.

In the results, MKI, MCI, ESC_i, and MRS indicates that the WMA alternative has the best performance; LCCA, CEI, and CEIP recommends the Rejuvenation alternative; CB'23, instead of favoring one alternative, provides a table containing the quantification results of parts of the pavement classified by different circular economy principles. It was concluded that each indicator has its strengths and trade-offs. Therefore, choosing different indicators may have different implications on circularity and sustainability, which needs to be carefully considered and discussed during decision making. Using circular economy indicators does not provide enough coverage of sustainability aspects. Hence, the complementary use of environmental, social, and economic sustainability indicators can assist a more rational decision.

7.2 Limitations

Due to various reasons, there are some limitations to this study. When modelling the case studies using GaBi^{TM}, the education version of this software is used, whose database may not be inclusive. Therefore, during the modelling, some processes such as asphalt production, asphalt paving, pavement use stage, rejuvenation, pavement deconstruction, and EOL asphalt processing are created manually in the software by entering the input and output flows. The quantities of flows are taken from various sources including literatures, PCRs, and guidelines. However, it could be possible that the flow categories may not be inclusive, and the complexity of the process not being modelled. If the update of the software can include these processes in its database, the environmental impacts of the case studies are expected to be captured more accurately.

Lack of data is another issue. The composition, price and quantity of some materials are not available. For example, what substances are used as the foaming additive and rejuvenating agent in the production of WMA and the quantity cannot be found. Therefore, the foaming additive is excluded from quantification, and the rejuvenating agent is assumed to be the same as rejuvenator since they have similar function. In addition, the price of rejuvenator is unavailable, so it is not included in the calculation of CEI. Moreover, the price of materials varies with different sources. The selection of sources may also affect the results.

7.3 Recommendations

In this study, although existing circular economy indicators were adapted for application to pavements, they were originally developed for other specific or more general sectors. To more accurately reflect the impacts and to minimize potential bias introduced during the modification process, future research should focus on developing indicators specifically tailored to pavement construction and maintenance. The following recommendations are provided for developing such indicators: (a) base the new indicators on existing indicators, (b) consider combining multiple indicators while carefully addressing overlaps and complementarities in circular economy strategies and measurement scopes, and (c) prioritize the use of simpler indicators when their results consistently align with those of more complex ones.

Social sustainability was not included in the assessment due to lack of appropriate indicators and expected difficulty in data collection and quantification. However, as one of the three pillars of sustainability, it is recommended that feasible social indicators be developed and included to deliver a more comprehensive sustainability assessment. In addition, the development of a more inclusive database that can be used in LCA can be work on.

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Appendix A Lifecycle Inventory

Table A-1 Foreground data and background data used in GaBi^{TM} modelling.

Foreground Data	**Background Data**	**GEO**	**Source**
Bitumen	Bitumen at refinery	EU-28	GaBi^{TM}
Coarse aggregate	Crushed stone 16/32	DE	GaBi^{TM}
Fine aggregate	Sand 0/2	EU-28	GaBi^{TM}
Calcium hydroxide	Calcium hydroxide (Ca(OH)2; dry; slaked lime) (EN15804 A1-A3)	DE	GaBi^{TM}
Sand	Sand 0/2	EU-28	GaBi^{TM}
Rejuvenator	Wax / Paraffins at refinery	EU-28	GaBi^{TM}
Diesel	Diesel mix at refinery	EU-28	GaBi^{TM}
Electricity	Electricity grid mix	NL	GaBi^{TM}
Natural gas	Thermal energy from natural gas	NL	GaBi^{TM}
Heavy fuel oil	Heavy fuel oil at refinery (1.0wt.% S)	EU-28	GaBi^{TM}
Truck transport	Truck, Euro 5, up to 7.5t gross weight / 2.7t payload capacity	GLO	GaBi^{TM}
	Truck, Euro 5, 20 - 26t gross weight / 17.3t payload capacity	GLO	GaBi^{TM}
	Truck, Euro 5, 26 - 28t gross weight / 18.4t payload capacity	GLO	GaBi^{TM}
	Truck, Euro 5, more than 32t gross weight / 24.7t payload capacity	GLO	GaBi^{TM}
Inland shipping	Average ship, 1,500t payload capacity/ canal	GLO	GaBi^{TM}
Sea shipping	Container ship, 5,000 to 200,000 dwt payload capacity, ocean going	GLO	GaBi^{TM}

Table A-2 Input values for LCA.

Input Parameters		**Quantity**	**Source**
Rejuvenation	Dosage (kg/m^2)	0.6	(Kruk et al., 2022)
Sand gritting	Dosage (kg/ m^2)	0.35	CERCOM
Resurfacing	Asphalt density (kg/m^3)	2000	(Kruk et al., 2022)
Vehicle	Bitumen transportation distance A2 (km)	250	(Kruk et al., 2022)
	Coarse aggregate transportation distance A2 (km)	25	(Kruk et al., 2022)

	Fine aggregate transportation distance A2 (km)	25	(Kruk et al., 2022)
	Calcium hydroxide transportation distance A2 (km)	136	(Kruk et al., 2022)
	Sand transportation distance A2 (km)	25	(Kruk et al., 2022)
	Wax/paraffin transportation distance A2 (km)	500	(Kruk et al., 2022)
	Asphalt transportation A4 (km)	44.4	(Kruk et al., 2022)
	Rejuvenator transportation A4 (km)	100	(Kruk et al., 2022)
	Asphalt transportation to processing C2 (km)	44.4	(Kruk et al., 2022)
Inland shipping	Coarse aggregate transportation distance A2 (km)	53	(Kruk et al., 2022)
	Fine aggregate transportation distance A2 (km)	660	(Kruk et al., 2022)
	Snad transportation distance A2 (km)	660	(Kruk et al., 2022)
Sea shipping	Coarse aggregate transportation distance A2 (km)	933	(Kruk et al., 2022)

Table A-3 Energy consumption values in LCA.

Input Parameters		**Quantity**	**Source**
Diesel	Diesel consumption at HMA asphalt production A3 (l/ton asphalt)	0.12	(Kruk et al., 2022)
	Disel consumption at asphalt construction A5 (l/ton asphalt)	0.32[a]	(Kruk et al., 2022)
	Diesel consumption at rejuvenation A5 (l/m^2 asphalt)	0.135	(Kruk et al., 2022)
	Diesel consumption at pavement deconstruction C1 (l/ton asphalt)	0.58	(Kruk et al., 2022)
	Diesel consumption at EOL pavement processing C3 (l/ton asphalt)	0.37	(Kruk et al., 2022)
Natural gas	Gas consumption at HMA asphalt production A3 (m^3/ton)	8.88	(Kruk et al., 2022)
	Natural gas energy content (MJ/Nm^3)	31.65	(Kruk et al., 2022)
	Energy consumption from natural gas at rejuvenator production A3 (MJ/kg rejuvenator)	0.5	(Kruk et al., 2022)
Electricity	Electricity consumption at HMA asphalt production A3 (kWh/ton asphalt)	5.24	(Kruk et al., 2022)
	Electricity consumption at rejuvenator production A3 (MJ/kg	0.3	(Kruk et al., 2022)

	rejuvenator)		

Note

a. Diesel consumption depends on the construction volume per day in the PCR, and the construction volume depends on the project. The pavement construction in this study is defined as a major asphalt work and has a construction volume of 1,000 ton/day.