INTEGRATED CIRCULARITY AND ENVIRONMENTAL SUSTAINABILITY ASSESSMENT FOR IN PLACE PAVEMENT RECYCLING TECHNIQUES

THESIS

AUTHOR: JHEAN MARCOS BAUTISTA CARRERA

STUDENT NUMBER: 2210371

SUPERVISORS (UT): SERGEI MILLER, JOAO OLIVEIRA DOS SANTOS

SUPERVISORS (DURA VERMEER): ROBBERT NAUS, RUDI DEKKERS

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DURAVERMEER

UNIVERSITY OF TWENTE.

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Abstract

This research presents the development of an integrated framework that assesses concomitantly the environmental sustainability and circularity performances of in-place pavement recycling techniques. The application of this framework contributes to road companies and stakeholders making the appropriate decision for a given analysis period. This can help these innovative treatments to account for all the side effects or possible impacts when using circular strategies or being more sustainable.

In the Netherlands, the goal is to achieve a circular economy transition in the construction sector. Similar research has been performed but focused individually on circularity or environmental sustainability. Therefore, the importance of integrating these terms to analyze the trade-offs between them, for instance, the technical performance of the asphalt could be affected by increasing the degree of circularity and not necessarily assures the reduction of environmental impacts. Moreover, encouraging the use of circular strategies such as the use of in-place pavement recycling techniques has many advantages such as limiting the extraction of raw materials, minimizing truck operations, and reducing the construction time.

The core measurement methodology is used based on the goals for a circular construction: protecting stocks of materials and environmental protection. These two goals provide circularity and environmental impact indicators that are the base for performing the integrated framework. The environmental impact indicators are translated into a single environmental cost indicator known as MKI (Milieukostenindicator), this indicator is considered as criteria for the integrated assessment. Similarly, the depletion of abiotic raw materials ADP and other circular indicators are part of the criteria but with different weights. The MKI and ADP share the same weight due to their importance for the assessment. For integrating these criteria and assessing in-place recycling techniques, a Multi-Criteria Decision Analysis tool is proposed i.e. TOPSIS method (Technique for Order of Preference by Similarity to Ideal Solution). A ranking of the techniques with better performance can be visualized after calculating the results.

Based on the study case, Dura Vermeer tested HIR (Hot In-place Recycling) techniques by using the ART (Asphalt Recycling Train). A road section located on the A73 highway is subject to its application and then compared to a hypothetic use of a conventional hot recycling treatment using 30% of RAP (Reclaimed Asphalt Pavement). The assessment is carried out for an analysis period of 100 years, in which, the road has to remain in good condition. In this way, the lifespan of using each technique varies and so the number of repetitions of each treatment to cover the analysis period. Considering HIR an innovative technology, the lifespan is not determined specifically but a range, where the best and worst lifespan scenarios are analyzed.

In conclusion, it is demonstrated that the main sources that contribute to the environmental impact are electricity production for the asphalt plant and transport of materials for conventional hot recycling, consequently increasing the MKI value and doubling the value of HIR. In terms of circularity, HIR represented a low indicator for the ADP, meaning a high circularity degree. All in all, after the 100 years analysis period, the convention hot recycling method ranked the lowest among the alternatives, being HIR positioned with the better ideal best values for circularity and environmental sustainability criteria.

Abstract

Dit onderzoek presenteert de ontwikkeling van een geïntegreerd raamwerk dat gelijktijdig de ecologische duurzaamheid en circulariteitsprestaties van in-place recyclingtechnieken voor bestrating beoordeelt. De toepassing van dit raamwerk draagt bij aan de juiste beslissingen die wegbedrijven en belanghebbenden nemen voor een bepaalde analyseperiode. Dit kan ertoe bijdragen dat deze innovatieve behandelingen rekening houden met alle bijwerkingen of mogelijke effecten bij het gebruik van circulaire strategieën of bij het verduurzamen.

Het doel in Nederland is het realiseren van een circulaire economie transitie in de bouwsector. Er is soortgelijk onderzoek gedaan, maar individueel gericht op circulariteit of ecologische duurzaamheid. Daarom kan het belang van de integratie van deze termen om de onderlinge compromissen te analyseren, bijvoorbeeld de technische prestaties van het asfalt worden beïnvloed door de mate van circulariteit te vergroten en niet noodzakelijkerwijs de vermindering van de milieueffecten garanderen. Bovendien heeft het aanmoedigen van het gebruik van circulaire strategieën, zoals het gebruik van in-place recyclingtechnieken voor bestrating heeft veel voordelen. Zoals het beperken van de winning van grondstoffen, het minimaliseren van vrachtwagenactiviteiten en het verkorten van de bouwtijd.

De kernmeetmethodiek wordt gehanteerd op basis van de doelstellingen voor circulair bouwen: het beschermen van materiaalvoorraden en het beschermen van het milieu. Deze twee doelen bieden circulariteit en milieu-impact indicatoren die de basis vormen voor het uitvoeren van het integrale raamwerk. De milieu-impactindicatoren worden vertaald naar één milieukostenindicator die bekend staat als MKI (Milieukostenindicator), deze indicator wordt beschouwd als criteria voor de integrale beoordeling. Daarom maken de uitputting van abiotische grondstoffen ADP en andere circulaire indicatoren deel uit van de criteria, maar met een ander gewicht. De MKI en ADP delen hetzelfde gewicht vanwege het belang voor de beoordeling. Voor het integreren van deze criteria en het beoordelen van in-place recyclingtechnieken, wordt een Multi Criteria Decision Analysis-tool voorgesteld. D.w.z. de TOPSIS-methode (Technique for Order of Preference by Similarity to Ideal Solution). Een rangschikking van de technieken met betere prestaties kan worden gevisualiseerd na berekening van de resultaten.

Op basis van de studiecase testte Dura Vermeer HIR (Hot In-place Recycling) technieken met behulp van de ART (Asphalt Recycling Train). Een weggedeelte in de snelweg A73 is onderworpen aan de toepassing ervan en wordt vervolgens vergeleken met een hypothetisch gebruik van een conventionele behandeling voor warme recycling waarbij 30% RAP (Reclaimed Asphalt Pavement) wordt gebruikt. De beoordeling wordt uitgevoerd voor een analyseperiode van 100 jaar, waarin de weg in goede staat moet blijven. Op deze manier varieert de levensduur van het gebruik van elke techniek en dus het aantal herhalingen van elke behandeling om de analyseperiode te dekken. Beschouw HIR als een innovatieve technologie, de levensduur wordt niet specifiek bepaald maar een range, waarbij het beste en slechtste levensduurscenario wordt geanalyseerd.

Concluderend wordt aangetoond dat de belangrijkste bronnen die bijdragen aan de milieu-impact de elektriciteitsproductie voor de asfaltcentrale en het transport van materialen voor conventionele hot recycling zijn. Waardoor de MKI-waarde stijgt en de waarde van HIR verdubbelt. In termen van circulariteit vertegenwoordigde HIR een lage indicator voor de ADP, dus een hoge mate van circulariteit. Al met al, na de analyseperiode van 100 jaar, scoorde de conventionele hot-recyclingmethode de laagste van de alternatieven, omdat HIR gepositioneerd was met de betere ideale beste waarden voor circulariteit en ecologische duurzaamheidscriteria.

Table of Contents

Acknowledgements .... *I*

Abstract .... *II*

List of figures .... *VII*

List of tables .... *VIII*

1 Introduction *1*

2 Project framework *2*

2.1 Context **2**

2.2 Problem statement **2**

2.3 Research objectives **3**

2.4 Research questions **3**

3 Background *4*

3.1 Circularity **4**

3.2 Sustainability **4**

3.3 In-place asphalt recycling techniques **5**

3.3.1 Asphalt Recycling Train (ART) 5
3.3.2 Hot In-Place Recycling (HIR) 5
3.3.3 Cold In-Place Recycling (CIR) 5

3.4 Other recycling methods **6**

3.4.1 Hot Recycling (HMA and WMA containing Recycled Asphalt Pavement) 6
3.4.2 Cold Central Plant Recycling (CCPR) 6

4 Literature Review *6*

5 Assessment methodology *7*

5.1 Core measurement methodology **7**

5.1.1 Protection of stock materials: Circularity assessment indicators 8
5.1.2 Environmental Protection: LCA methodology 9

5.2 Integrated Assessment Framework **11**

5.2.1 TOPSIS method 11

6 Case study *13*

6.1 Description **13**

6.1.1 Asphalt Recycling Train (ART) by using hot in-place recycling (HIR) 14

6.2 Framework application **15**

6.2.1 LIFE CYCLE ASSESSMENT (LCA) 16
.... 20
6.2.2 Circularity assessment 20

6.3 Results **22**

6.3.1 Life Cycle Assessment (LCA) 22

6.3.2 Circularity assessment 25
6.3.3 Integrated assessment 26
6.3.4 Sensitivity Analysis 28

7 Discussion 30

8 Summary and conclusions 31

9 Recommendations........ 33

10 Bibliography........ 34

11 Appendix 36

11.1 LCA Modelling 36

11.1.1 LCA Model Hot In-place Recycling 37
11.1.2 LCA Model Hot Conventional Recycling 38
11.1.3 LCA Modelling HIR for 100 years (best scenario) 39
11.1.4 LCA Modelling HIR for 100 years (worst scenario) 40
11.1.5 LCA Modelling Hot Conventional Recycling for 100 years 41
.... 41

List of figures

Figure 1 Aerial view of the road section in A73 (Google Earth 2022)....................................13
Figure 2 Wirtgen Panel Heating HM 4500 before starting operation......................................14
Figure 3 Wirtgen Remixer 4500 15
Figure 4 ART in operation...15
Figure 5 LCA system boundary...17
Figure 6 Main sources of climate change by conventional hot recycling method..................22
Figure 7 Main sources of climate change by HIR method 22
Figure 8 LCA Model of Hot In-place Recycling...37
Figure 9 LCA Model of Conventional Hot Recycling 38
Figure 10 LCA Model of Hot In-place Recycling (HIR) for analysis period of 100 years (best scenario-lifespan 16 years) 39
Figure 11 LCA Model of Hot In-place Recycling (HIR) for analysis period of 100 years (worst scenario-lifespan 10 years) 40
Figure 12 LCA Model for Conventional Hot Recycing method for the analysis period of 100 years 41

List of tables

Table 1 Input and output materials indicators for protection of stock materials (Platform CB’23 2020)....8
Table 2 Environmental impact indicators (Platform CB’23 2020)....10
Table 3 Dimension of A73 road section....13
Table 4 Number of treatments repetitions during the analysis period....16
Table 5 Lifecycle stages used in the SBK method....16
Table 6 LCI of materials for hot in-place recycling (HIR)....18
Table 7 LCI of energy resources for hot in-place recycling (HIR)....18
Table 8 LCI of materials for conventional hot recycling method....18
Table 9 LCI of energy resources for conventional hot recycling method....19
Table 10 Material transportation information....20
Table 11 Material classification for HIR....21
Table 12 Material classification for conventional hot recycling method....21
Table 13 Environmental impact results of recycling techniques in the analysis period....23
Table 14 Weighting of environmental impacts....24
Table 15 MKI calculation for the three recycling techniques....24
Table 16 Circularity indicators assessment for HIR and Conventional hot recycling....25
Table 17 Evaluation matrix with recycling alternatives and weighted criteria....26
Table 18 Normalized evaluation matrix....27
Table 19 Weighted normalized matrix....27
Table 20 Ideal best/worst value selection....27
Table 21 Euclidean distance between target and best/worst alternatives, similarity to the worst alternative and ranking of methods....28
Table 22 Original criteria weight and variation of weights per criteria for sensitivity analysis....28
Table 23 Sensitivity analysis results....29

1 Introduction

Circularity and sustainability are terms commonly used in the infrastructure system domain. However, there are misconceptions regarding their relation, usability, and application (Geissdoerfer et al. 2017). Circularity is considered a take-back system, focused on slowing the cycle and ensuring resource efficiency that can prolong the product lifecycle while also reducing process loss and material demands (Antwi-Afari, Ng, and Hossain 2021). In other words, the used or discarded products serve as raw materials for new products or materials. In turn, environmental sustainability focuses on conserving natural resources and protecting global ecosystems, meeting today's needs without compromising the ability of future generations (Sphera 2020). The mismatches that can be found are mainly because of wrong attempts of companies to apply a circular economy model that end up exhibiting adverse effects (Mantalovas and Mino 2020). These attempts of adopting circular strategies during their activities can provoke side effects like rebound effects that impact the sustainability of the environment or vice versa (Köhler, Thorenz, and Tuma 2021). Several examples can be found in different products and processes, the recycling of asphalt pavement is one of them. Moreover, there are methodologies that measure the terms mentioned before independently.

In the road industry, the rehabilitation of road pavements contributes to the extension of pavement life and also the limitation of raw materials extraction, being considered a circular strategy. For example, in-place recycling techniques whose main function is to rehabilitate the pavement in the project site itself. There are several techniques such as Hot In-Place Recycling (HIR), Cold In-Place Recycling (CIR), etc. Among their potential advantages, they intend to extend pavement life, require limited new material, minimize trucking operations, and also can be cost-effective. Therefore, it is important to assess the contribution to circularity and environmental sustainability of these techniques for a determined lifespan.

Dura Vermeer is a major Dutch construction company with 165 years of experience that focuses on creating long-term value and establishing sustainable relationships with its customers. Their ambitions highlight the importance of leading sustainability through innovation. Therefore, this project research matches their sustainable ambition of encouraging the reuse of products as often as possible, limiting CO_2 emissions and the use of raw material (Dura Vermeer 2022). The integrated assessment is elaborated and then applied to a study case provided by the company.

2 Project framework

2.1 Context

In the Netherlands, the construction sector is one of the key sectors in the transition to a Circular Economy and wants to achieve a circular construction economy by 2050 (Leffers, Moustafa, and Vorstman 2022). This transition has to follow an equilibrium with the terms circularity and environmental sustainability. In the road engineering industry, there are several attempts to include these factors together. Unfortunately, there might be a mismatch between efforts intended to increase circularity and environmental sustainability, which represents a challenge for any system. Indeed, Antwi-Afari et al. (2021) and Lonca et al. (2018) agree that increasing circularity does not lead to a sustainable product or that a sustainable strategy does not always deliver a circular result due to potential side effects such as rebound effects or burden-shifting. This means that any improvement activity taken in a phase can reduce the environmental impact in that phase but increase it in other phases of the life cycle. Therefore, recycling or reusing waste from one production stream to another would be of no benefit if it happens to transfer hazardous substances or increase the impact in other phases of the product. Moreover, Mantalovas and Mino (2020) also support that the technical performance of a product could be affected by the increase of its circularity level that not always, in the end, assure the reduction of environmental impacts. The integration of these two methods allows us to assess the potential environmental impacts of the transition to a circular approach. An example of this integration can be found in Mantalovas and Mino (2020), who combined the circularity and sustainability assessment of asphalt mixtures with Reclaimed Asphalt Pavement (RAP) materials. However, it focuses only on the integration of a closed-loop product into the manufacturing process for a new product, without considering, how the intended functional lifespan of this product can affect the sustainability and circularity indicators. According to Leffers, Moustafa, and Vorstman (2022), the development of this improved way to assess circularity can be useful for stakeholders to make informed decisions.

Using in-place recycling techniques is considered a circular strategy since it is based on a material sourcing approach while recycling pavement (Alejandrino, Mercante, and Bovea 2022). So, assessing these techniques concomitantly in terms of sustainability and circularity by the corresponding indicators can contribute significantly to evaluating its performance, in a given lifespan of the final product.

2.2 Problem statement

Nowadays, the concepts of circularity and sustainability are increasingly important for the activities of many industries. For instance, in the case of the paving industry, in-place pavement recycling treatments are commonly presented as measures able to improve the circularity and environmental sustainability of road pavement systems. Such claims are often based on the results of life cycle assessment (LCA) studies. However, increasing the circularity of a product might not lead to an environmentally sustainable product and vice versa. This is because of potential side effects, such as rebound effects or burden shifting that may occur during the intention of being circular. Therefore, there is a need for an integrated framework that allows for evaluation and understanding of (i) whether the claimed environmental and circularity benefits of in-pavement recycling strategies are achieved, (ii) to what extent, and (iii) what factors play the most important roles in driving their environmental and circularity performances.

2.3 Research objectives

The aim of this research is to develop an integrated framework to assess the environmental sustainability and circularity performances of in-place pavement recycling practices. This research can contribute to road companies and stakeholders to make appropriate decisions for short and long-term because the circular and sustainable performance of these innovations can be previously evaluated.

2.4 Research questions

In order to enhance the circularity and environmental sustainability of road pavement maintenance and rehabilitation practices this investigation is led by the following main research question:

To what extent do in-place pavement recycling techniques contribute concomitantly to circularity and environmental sustainability?

The main research question will be answered with the next sub-questions:

- What types of in-place recycling techniques exist and how do they fit into the Circular Economy principles?
- What methodologies can be used to assess the circularity and environmental sustainability performances of in-place pavement recycling techniques?
- How can those methodologies and indicators be integrated into a holistic assessment framework that can capture and quantify the eventual trade-offs between the circularity and environmental sustainability concepts?
- What are the assessment results for the different in-place pavement recycling techniques in a determined lifespan?

The first sub-question is posed to explore the existing in-place recycling techniques that can be used to rehabilitate pavements. When answering this question, a number of techniques will be defined for which the integrated assessment could be applied. Moreover, it is important to relate these techniques with the Circular Economy Principles.

The second sub-question aims to explore the literature and then, select the most appropriate methodologies and indicators to measure circularity and environmental impacts.

The third sub-question intends to determine the way in which the indicators defined in the previous questions can be integrated into a holistic approach to capturing the eventual trade-offs between circularity and environmental sustainability.

The last sub-question aims to apply the framework to a case study and get insights into the performance of the different recycling techniques in terms of circularity and sustainability. This will consider an analysis period for which the road has to be serviceable and determine with the mentioned indicators if a technique is suitable for short (20-30 years) or long (80-100 years) term rehabilitation. The outcome of the result will guide stakeholders to choose the most appropriate recycling technique depending on the road requirements.

By combining these sub-questions the main research question can be answered since the sub-questions were designed and articulated according to a bottom-up approach.

3 Background

3.1 Circularity

Circularity is a principle of Circular Economy in which products and materials circulate at their highest value and is complemented by other principles such as: eliminate waste and pollution and regenerate nature (Ellen Mac Arthur Foundation 2022). According to Platform CB’23 (2020), which is a guide for measuring circularity, it has three goals: protect stocks of materials, environmental protection and value retention. The aim of applying this concept is to maximize resource efficiency by keeping the highest value of the material at all times and can be achieved by the use of circular strategies such reuse, remanufacturing, refurbishment of products, and recycling of raw materials (Köhler et al. 2021). Moreover, Korhonen, Honkasalo & Seppälä (2018), as cited in (Köhler et al. 2021), highlights that for achieving the highest resource efficiency, the original function of a product has to be maintained, implying the prioritization of reuse over other Circular Economy strategies. In this way, wastes can be reduced by closing loops of products while striving for sustainable environment. As a result of ensuring resource efficiency and also slowing the product cycle, the product lifespan can be prolonged and also the process loss and material demands can be reduced (Antwi-Afari et al. 2021).

There are several methodologies to measure circularity of a product and they are essential to make informed decisions. These methods could be adopted in some phases of the product lifecycle such as design and procurement or even to monitor progress (Leffers et al. 2022).

3.2 Sustainability

Sustainability is a term that englobes different dimensions, namely social, economic and environmental. Sustainability development can be defined as the development that meet needs of the present without compromising the ability of future generations to meet their own needs (Plati 2019). This sustainable development refers to the processes and pathways to achieve sustainability (UNESCO 2015). Environmental sustainability is defined as the responsibility to conserve natural resources and protect global ecosystems that ensure the wellbeing and health of present and future generations (Sphera, 2020). Regarding pavements, the environmental sustainable principles are often those involving the selection of eco-friendly materials at low costs, utilization of waste materials, appropriate selection of materials and recycling practices (Plati 2019)

3.3 In-place asphalt recycling techniques

These techniques are referred to strategies that are applied on site by road construction companies to rehabilitate pavements with the purpose of lowering costs and also extend the life of roadways by means of innovations in technology. These techniques have been increasing their impact due to the change of scope when preferring maintenance and rehabilitation (M&R) instead of construction(Cao, Leng, and Hsu 2019). Caltrans (2022) states that these techniques might originate long term economic benefits, as well as other benefits such as the need for limited new material, minimizes truck operations and shorter construction time. An example of this technology innovation is the concept of Asphalt Recycling Train (ART).

3.3.1 Asphalt Recycling Train (ART)

Asphalt Recycling Train is the name for the pieces of equipment that successively are in charge of the asphalt recycling process in-situ. This concept has been emerging due to the need of adopting economical and sustainable solutions that increases the value of in-place materials while minimizing traffic congestion and environmental impact, encouraging the application ART (Stroup-Gardiner 2011). Currently, there are three types of ART, they are able to recycle asphalt in its original location, however, they have their own application situations (Cao et al. 2019), as explained next:

- Hot in-place recycling (HIR): applied when the distresses in the pavement are limited to the upper part of the surface layer, and when there are no structural failure like cracking.
- Cold in-place recycling (CIR): applied when the damage has been extended further into the surface.
- Full depth reclamation (FDR): applied when roads are completely reconstructed

The process of the first two techniques HIR and CIR are detailed in the next subsections.

3.3.2 Hot In-Place Recycling (HIR)

The hot in-place recycling technique applies in situ heating during the construction process when restoring the damaged surface to its original condition (Ma et al. 2020). This process consists of surface recycling by using heater scarification besides mixing and paving. During the mixing stage, rejuvenating agents are involved to reverse the impact of aging on asphalt performance, restore binder properties and durability, protecting the pavement of oxidation, moisture damage and raveling for the future. It is applied for correcting hot mix asphalt pavements with shallow-depth surface distress and cracking on roadways (Cao et al. 2019).

3.3.3 Cold In-Place Recycling (CIR)

As opposite to the HIR, this technique treats the existing asphalt pavements without heating. This technique involves five basic steps: milling, gradation control, incorporation of binding additives, placement of the mixture on the milled pavement and compaction. (Orosa, Pérez, and Pasandín 2022) highlights the main constituents of a CIR asphalt mixture which are reclaimed asphalt pavement (RAP), a bituminous binder that acts as a stabilizer in the mix in form of an emulsion or foamed bitumen and a specific amount of water for facilitating the blending process while ensuring the proper moisture content. Its application is focused on stabilizing the base course of hot mix asphalt pavements (Cao et al. 2019)

3.4 Other recycling methods

3.4.1 Hot Recycling (HMA and WMA containing Recycled Asphalt Pavement)

In this process the Reclaimed Asphalt Pavement (RAP), obtained from milling or crushing operations, is added with new materials to produce HMA/HWA mixes in an asphalt plant. Considering that the RAP percentage ranges from 10 to 50 %, (Virginia Asphalt Association 2020) , assures that one of the advantages of hot mix recycling include equal or better performance compared to conventional HMA/WMA due to the capability to correct most surface defects, deformation and cracking. For the stage of mix placement and compaction, the equipment and procedures are the same.

3.4.2 Cold Central Plant Recycling (CCPR)

The material is removed and then transported to the asphalt plant, followed by crushing and screening to make an uniform product before feeding the cold plant. The products added in the process are similar to those of the CIR. These are either asphalt emulsion or foamed asphalt as a binding agent. Once the mixing is completed, the final product can be taken to the project site for paving (Virginia Asphalt Association 2020).

4 Literature Review

Circularity and sustainability are terms commonly used in the infrastructure system domain. However, there are misconceptions regarding their relation, usability, and application (Geissdoerfer et al. 2017). Circularity is focused on slowing the cycle and ensuring resource efficiency that can prolong the product lifecycle while also reducing process loss and material demands (Antwi-Afari et al. 2021). In other words, the used or discarded products serve as raw materials for new products or materials. Similarly, environmental sustainability focuses on conserving natural resources and protecting global ecosystems, meeting today’s needs without compromising the ability of future generations (Sphera 2020). There are methodologies for which the elements mentioned above can be evaluated. These include, among others, Material Circularity Index (MCI) and Life Cycle Assessment (LCA) but there are also concepts excluded when applied individually. The former methodology is proposed by Ellen Mac Arthur foundation (Ellen Mac Arthur Foundation 2019) and intends to measure the degree of circularity by considering flows during the entire lifecycle of an object as a starting point (Platform CB’23, 2020). This method is only able to provide an end product label that characterizes the product itself (Mantalovas and Mino 2020) and focuses on the technical cycles (as opposed to biological cycles) (Lonca et al. 2018), meaning that this involves the management of stocks of non-renewable abiotic resources that cannot be appropriately returned to the biosphere, in contrast to biological cycles that involve flows of renewable biotic resources that can safely cycle in and out of the biosphere (Navare et al. 2021). In turn, the LCA Framework (ISO 14044/40), is used to measure the environmental lifecycle (cradle to grave) consequences of a product or process by quantifying energy, materials consumed, wastes, and emissions discharged to the environment (Rosen 2018). When applied alone this methodology only accounts for evaluating a product from an environmental viewpoint, ignoring circularity, economic, social, and technical aspects (Lee 2004), highlighting the importance to integrate this method with other techniques and facilitating trade-offs between them. Consequently, there might be a mismatch between efforts intended to increase circularity and sustainability, which represents a challenge for any system. Indeed, Antwi-Afari et al. (2021) and Lonca et al. (2018) agree that increasing circularity does not lead to a sustainable product or that a sustainable strategy does not always deliver a sustainable result due to side effects such as rebound effects or burden-shifting. Therefore, recycling or reusing waste from one production stream to another would be of no benefit if it happens to transfer hazardous substances. Moreover, Mantalovas and Mino (2020) also support that the technical performance of a product could be affected by its increase of circularity that not always, in the end, assures the reduction of environmental impacts. The integration of these two methods can lead to assessing the environmental potential impacts of the transition to a circular approach. An example of this integration can be found in Mantalovas and Mino (2020), where it includes the concomitant circularity and sustainability assessment of asphalt mixtures with Reclaimed Asphalt percentages. However, its technical performance was poor in some mixtures, in terms of fatigue and permanent deformation, and this factor should be considered essential in the framework for assessing the final product. According to Leffers, Moustafa, and Vorstman (2022), the development of this improved way to assess circularity can be useful for stakeholders to make informed decisions.

5 Assessment methodology

For achieving a circular economy transition in the construction sector by 2050 in the Netherlands, the Platform CB’23 guide offers a circularity measurement method that can be applied either nationally or internationally. This is the core measurement method and fits the purpose of this research when assessing circularity and environmental sustainability. Then, an integrated assessment framework of circularity and environmental sustainability is proposed.

5.1 Core measurement methodology

As a way to encourage the transition to a circular economy, this method intends to measure the degree of circularity considering three key goals of a circular construction: to protect stocks of materials, environmental protection and value retention (Platform CB’23 2020). There are set of indicators for each of the goals mentioned. This research will use the core indicators for protecting existing stocks of material and will be complemented with the LCA methodology that will assess the environmental protection. The value retention indicators are excluded from this research since the techno-functional indicators are still being developed and the economic value indicators go beyond the scope of this project. This method can be applied anywhere in the construction sector and also share the same scope and conceptual framework as LCA method, besides that the data needed is similar. This method enables the impacts of different circular strategies to be compared (Platform CB’23 2020). Before starting with the core measurement method and also the calculation of its indicators, the LCA analysis has to be performed, as suggested in Platform CB’23 (2020).

5.1.1 Protection of stock materials: Circularity assessment indicators

When assessing the product in terms of protecting stocks materials, it is meant to ensure that these stocks of materials are not exhausted and will continue to be available for use (Platform CB’23 2020). The two basic principles highlighted by the guide when applying circular strategies are: reducing use and limiting loss. The first example employs a minimum amount of materials for construction while the second one refers to the availability of materials after a little degradation during its previous lifecycle. Therefore, it is important have a clear overview of the materials balance in which inputs and outputs flows of an object or sub-object are detailed.

This section is divided in three indicators: the quantity of materials used (input), the quantity of materials available for the next cycle (output) and the quantity of materials lost (output). These indicators are subdivided depending on the classification of the materials involved in the process and their descriptions are displayed in Table 1.

Table 1 Input and output materials indicators for protection of stock materials (Platform CB’23 2020)

1	**Quantity of materials used (input)**	**Description**
1.1	Quantity of primary materials	Degree to which materials produced from primary raw materials have been used
1.1.1	Quantity of non-renewable primary materials	Degree to which primary materials of abiotic or biotic origin are used which are grown, naturally replenished or naturally cleansed, beyond human time scale
1.1.2	Quantity of renewable primary materials	Degree to which primary materials of abiotic or biotic origin are used which are grown, naturally replenished or naturally cleansed, on a human time scale
1.1.2a	Quantity of sustainable produced, renewable primary materials	Degree to which materials of abiotic or biotic origin are used that originate from a production unit that is managed sustainably
1.1.2b	Quantity of unsustainable produced renewable primary materials	Degree to which materials of abiotic or biotic origin are used that do not originate from a production unit that is managed sustainably
1.2	Quantity of secondary materials used	Degree to which materials recovered from previous use, or from residual flow from another product system which substitute primary materials or other secondary materials, are used
1.2.1	Quantity of secondary materials from reuse	Degree to which reused parts are used
1.2.2	Quantity of secondary materials from recycling	Degree to which recycled materials are used

1.3	Quantity of physically scarce materials	The degree to which raw materials are used that are physically scarce or, to put it another way, are only available in natural resources to a limited extent, i.e. scarcity based on the geological availability of stocks of raw materials and the risk of their becoming depleted
1.4.1	Quantity of socio-economically scarce raw materials used	Degree to which raw materials are used that are scarce as regards their economic relevance and where there are risks to their security of supply
1.4.2	Quantity of socio-economically abundant raw materials used	Degree to which raw materials are used that are abundant as regards their economic relevance and in terms of risks to their security supply
2	**Quantity of materials available for the next cycle (output)**	**Description**
2.1	Quantity of end-of-life materials available for reuse	Degree to which the reuse of the objects or sub-objects is the most realistic end-of life treatment
2.2	Quantity of end-of-life materials available for recycling	Degree to which recycling the materials is the most realistic end-of-life treatment
3	**Quantity of materials lost (output)**	**Description**
3.1	Quantity of end-of-life materials used for energy production	Degree to which processing materials in an incinerator for energy production is the most realistic end-of-life treatment
3.2	Quantity of end-of-life materials sent to landfill	Degree to which sending materials to landfill is the most realistic end-of-life treatment

5.1.2 Environmental Protection: LCA methodology

The environmental protection ensures the good quality of living environment for people and animal (Platform CB’23 2020). The LCA methodology is used to assess the environmental performance of a product or system throughout its lifecycle. Moreover, it can also be used to identify opportunities to improve environmental performance of products at different stages of their lifecycle. This can be performed at stages from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal, following ISO 14040 (2006) and ISO 14044 (2006). According to the aforementioned standards, a LCA study consists of the following phases: goal and scope definition, life cycle inventory, impact assessment and interpretation.

The goal and scope definition phase defines exactly what is going to be analyzed, including the level of detail and system boundary. The depth of the LCA depends on the goal of the LCA, where also impact categories has to be defined based on the focus of the assessment.

The life cycle inventory (LCI) phase involves the collection of the data needed to meet the goals of the study. In this case, an inventory of input/output data with regard the system defined.

The impact assessment phase provides additional information to help assess a product system to understand their environmental significance. This is based on the previously impact categories defined. Moreover, the overall impact measurement can be calculated adding all the impacts up, an example of this measurement is the Environmental Cost Indicator (ECI), also known as Milieukostenindicator (MKI).

The interpretation is the final phase of LCA, in which the results are summarized and discussed, being the basis for conclusions, recommendations and decisions making according to the goal and scope definition previously defined in the first phase.

Considering that LCA methodology share the same scope and inputs needed for the calculation of circularity indicators, the Platform CB'23 suggests the calculation of the Environmental Footprint or product system impact categories from the SBK method (Stichting Bouwkwaliteit 2019). This consist of the following indicators with their description (see Table 2).

Table 2 Environmental impact indicators (Platform CB'23 2020)

4	**Environmental impact Indicators**	**Description**
4.1	Climate change - overall	Degree to which objects or sub-objects contribute to climate change
4.2	Climate change - fossil	Degree to which objects or sub-objects contribute to climate change due to the use of fossil fuels
4.3	Climate change - biogenic	Degree to which objects or sub-objects contribute to climate change due to the use of plant-based materials
4.4	Climate change - use of land and changes in use of land	Degree to which objects or sub-objects contribute to climate change due to the use of land and changes in the use of land
4.5	Ozone depletion	Degree to which objects or sub-objects contribute to the depletion of the ozone layer
4.6	Acidification	Degree to which objects or sub-objects contribute to the acidification of soil or water
4.7	Eutrophication - freshwater	Degree to which objects or sub-objects contribute to enriching freshwater with nitrogen and phosphorus
4.8	Eutrophication - seawater	Degree to which objects or sub-objects contribute to enriching seawater with nitrogen and phosphorus
4.9	Over-fertilization - soil	Degree to which objects or sub-objects contribute to enriching soil with nitrogen and phosphorus
4.10	Occurrence of smog	Degree to which objects or sub-objects contribute to the formation of tropospheric ozone (part of smog)
4.11	Depletion of abiotic raw materials - minerals and metals	Degree to which objects or sub-objects contribute to the depletion of abiotic raw materials, excluding fossil energy carriers
4.12	Depletion of abiotic raw materials - fossil energy carriers	Degree to which objects or sub-objects contribute to the depletion of fossil energy carriers
4.13	Use of water	Degree to which objects or sub-objects contribute to the depletion of the sources of water
4.14	Emission of particulate matter	Degree to which objects or sub-objects contribute to diseases related to particulate matter
4.15	Ionizing radiation	Degree to which objects or sub-objects contribute to humans being exposed to ionizing radiation
4.16	Ecotoxicity (freshwater)	Degree to which objects or sub-objects contribute to adverse toxicological effects for freshwater organisms

4.17	Human toxicity, carcinogenic	Degree to which objects or sub-objects contribute to adverse carcinogenic effects for people
4.18	Human toxicity, non-carcinogenic	Degree to which objects or sub-objects contribute to adverse toxicological effects for people (non-carcinogenic)
4.19	Impact/Soil quality related to the use of land	Degree to which objects or sub-objects contribute to changes to the soil quality due to the use of land

All these scores can be weighted into a final score indicator for measuring the environmental impact using the SBK method (Stichting Bouwkwaliteit 2019).

5.2 Integrated Assessment Framework

Once the circularity and environmental impact criteria were defined in several indicators, this research integrates them in an assessment framework by using a Multi-Criteria Decision Analysis (MCDA). Therefore, to see the trade-offs among the alternatives and also to choose the best solution, the TOPSIS method is applied. Before starting with the steps involved in the TOPSIS method, the alternatives and criteria for the assessment must be determined.

5.2.1 TOPSIS method

TOPSIS, known as, Technique for Order of Preference by Similarity to Ideal Solution, is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution (Li et al. 2022). The TOPSIS method is mainly divided into the following steps:

Step1: Create a matrix consisting of M alternatives and N criteria. This is called "evaluation matrix".

Equation 1 Evaluation matrix

$$(a_{ij})MxN$$

Step 2: Normalize the evaluation matrix.

Equation 2 Normalization of evaluation matrix

$$a_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{M} (a_{ij})^2}}$$

Each metric j for each recycling treatment i is normalized to be in between 0 and 1.

Step 3: Calculate the weighted normalized matrix.

Equation 3 Weighted normalized matrix

$$X_{ij} = a_{ij} * w_j$$

The weights for each criteria had to be determined beforehand and also when added up, they have to equal to 1 or 100%.

Step 4: Determine the best and the worst alternative for each criterion

Equation 4 Best alternative for each criterion

$$X_j^b = max_{i=1}^{M} X_{ij}$$

Equation 5 Worst alternative for each criterion

$$X_j^w = min_{i=1}^{M} X_{ij}$$

In this way, the maximum and minimum value can be found among the alternatives for each criterion.

Step 5: Calculate the Euclidean distance between the target alternative and the best/worst alternative.

Equation 6 Euclidean distance between target and best alternative

$$d_i^b = \sqrt{\sum_{j=1}^{N} (x_{ij} - x_j^b)^2}$$

Equation 7 Euclidean distance between target and worst alternative

$$d_i^w = \sqrt{\sum_{j=1}^{N} (x_{ij} - x_j^w)^2}$$

This calculation shows the geometric distance between a value of an alternative with respect of the best/worst value of the criterion.

Step 6: For each alternative calculate the similarity to the worst alternative. The results are the TOPSIS scores.

Equation 8 Similarity to the worst alternative

$$S_i = \frac{d_i^w}{d_i^w + d_i^b}$$

The scores are computed for each alternative based on the distances calculated before.

Step 7: Rank alternatives using the TOPSIS scores by descending order. The highest scores will be the most appropriate alternative.

6 Case study

6.1 Description

After simulating the process of using ART in the Central Laboratory of Dura Vermeer, in Eemnes, Dura Vermeer intends to test the hot in-pace recycling technique on the Dutch road network. In this case, the road section corresponds to the A73 highway, where the application of HIR with the ART is performed only in the left lane of this road (see Figure 1). The dimensions are displayed in Table 3.

Figure 1 Aerial view of the road section in A73 (Google Earth 2022)

Table 3 Dimension of A73 road section

Dimensions road section	**Quantity (m)**
Width	4,2
Length	700
Thickness	0,050

In the Netherlands, the majority of highways are paved with ZOAB (Rijkswaterstraat 2022), which is an asphalt mixture a high percentage of hollow space, about 20% (Rijkswaterstraat 2022). In order to promote a circular transition, Rijkwaterstraat, wish to reduce CO2 emission in the asphalt mixtures by replacing the currently old Porous Asphalt ZOAB-16 by new Porous Asphalt DAZOAB-16. The main difference between the two is the amount of bitumen present in the mixture, which is higher in the later case. Therefore, Dura Vermeer aims to recycle in situ 100% of existing ZOAB layer into a more durable alternative of DZOAB with approximately 5,1 tons of new binder (bitumen) using ART.

6.1.1 Asphalt Recycling Train (ART) by using hot in-place recycling (HIR)

This ART concept was introduced by Cutler (1978), who defines as a method of restoring asphalt roadway by means of heating the upper layer of the existing road to loose existing road material, which then is collected by scraping off this layer, followed by mixing the hot mix of asphalt with new materials that finally, will be placed in the roadway surface as new asphalt

In the Netherlands, Dura Vermeer has introduced to the concept of the Asphalt Recycling Train to Rijkswaterstraat, being the winner of the 'Sustainable Asphalt' competition, with the purpose of reducing CO2 emissions in a cost-effective way (van del Vliet 2018). The use of the ART concept by using HIR is a proven process for warm in-situ recycling of old asphalt into new asphalt, both in the Netherlands and abroad (Dura Vermeer 2022a). This technology has the following equipment: one or more heaters (usually infrared) that heat the old asphalt, another special heater that heats and tosses the material to loose it and keep the grading intact, subsequently raw materials are added, and if necessary the mixture is heated to the desire temperature. Finally, the asphalt is processed with an integrated spreading beam or a separate conventional spreading machine and then compacted with rollers (Dura Vermeer 2022a). For visualizing the ART process, see Figure 2, Figure 3 and Figure 4.

Figure 2 Wirtgen Panel Heating HM 4500 before starting operation

Figure 3 Wirtgen Remixer 4500

Figure 4 ART in operation

6.2 Framework application

The framework described in the previous sections will be used to assess and compare the circularity and environmental sustainability performance of HIR using ART and the conventional hot recycling in an asphalt plant using 30% of RAP. The analysis is performed for a period of 100 years in which the road section should be in good condition. This period is considered since a difference in the number of repetitions can be appreciated in a longer term rather than short term. The lifespan of the conventional hot recycling method is 14 years while for HIR ranges from 10 to 16 years (R. Naus, personal communication 2022). Given that the application of HIR with ART is a new technology, its lifespan is not yet very well known. Thus, in the analysis two durations will be considered: a best-case scenario (16 years) and a worst-case scenario (10 years). The number of repetitions of these treatments during the analysis period is shown in Table 4.

Table 4 Number of treatments repetitions during the analysis period

Analysis period 100 years	**HIR (best scenario)**	**HIR (worst scenario)**	**Conventional Hot Recycling**
Number of repetitions	6	10	7

6.2.1 LIFE CYCLE ASSESSMENT (LCA)

Goal and scope

The LCA will be conducted using the software and databases from GaBi, a software to assess sustainability provided by Thinkstep, a Sphera company. The data will be collected from literature and available inventories of asphalt pavement companies. The goal of the LCA study is to quantify the environmental impacts of the application of HIR and conventional recycling techniques along the analysis period for which the road is expected to be serviceable. The functional unit is the road section where the techniques are applied and whose dimensions are present in Table 3. The adopted approach for the system boundaries is “cradle-to-cradle” since it is referred to within Circular Economy, and it is also known as closed-loop recycling (Ecochain 2019). The boundaries for the lifecycle of the road pavement section are established based on ‘SBK Bepalingsmethode’ lifecycle phases (Stichting Bouwkwaliteit 2019). Table 5 shows the available phases.

Table 5 Lifecycle stages used in the SBK method

Stage (A1-A3): Production	
A1	Raw material supply
A2	Transport
A3	Manufacturing
Stage (A4-A5): Construction	
A4	Transport gate to site
A5	Assembly/ Construction installation process
Stage (B1-B7): Use	
B1	Use
B2-B5	Maintenance, Repair, Replacement, Refurbishment
B6-B7	Operational energy use, Operational water use
Stage (C1-C4): End of life stage	
C1	De-construction demolition
C2	Transport
C3-C4	Waste processing, Disposal
Stage(D): Benefits and loads beyond the system boundaries	

For this project, the stages accounted for are the production and construction stage (A1-A5), end-of-life stage (C1-C2), and benefits and loads beyond the system boundaries (D). The use stage (B1) requires extra modeling and information for instance, working zone management and pavement-vehicle interaction effects (Santos et al. 2015). Moreover, Platform CB'23 (2020) agrees that the user-related impacts must not be taken into account, the impact caused in this phase must be addressed to the service life of parts that need to be replaced. The stages related to maintenance (B2-B5) are excluded since it is difficult to predict when the road will need maintenance. The stages B6-B7 are ignored since it does not apply to asphalt. Stage C1 (Deconstruction) is attributed to the material production supply stage (A1) since in the case of the conventional recycling method, the milled asphalt is turned into usable asphalt aggregate. The waste processing and disposal stages (C3-C4) are excluded. They are not considered because all the materials are recycled or reused within the system boundaries. An overview of the system boundary can be found in Figure 5.

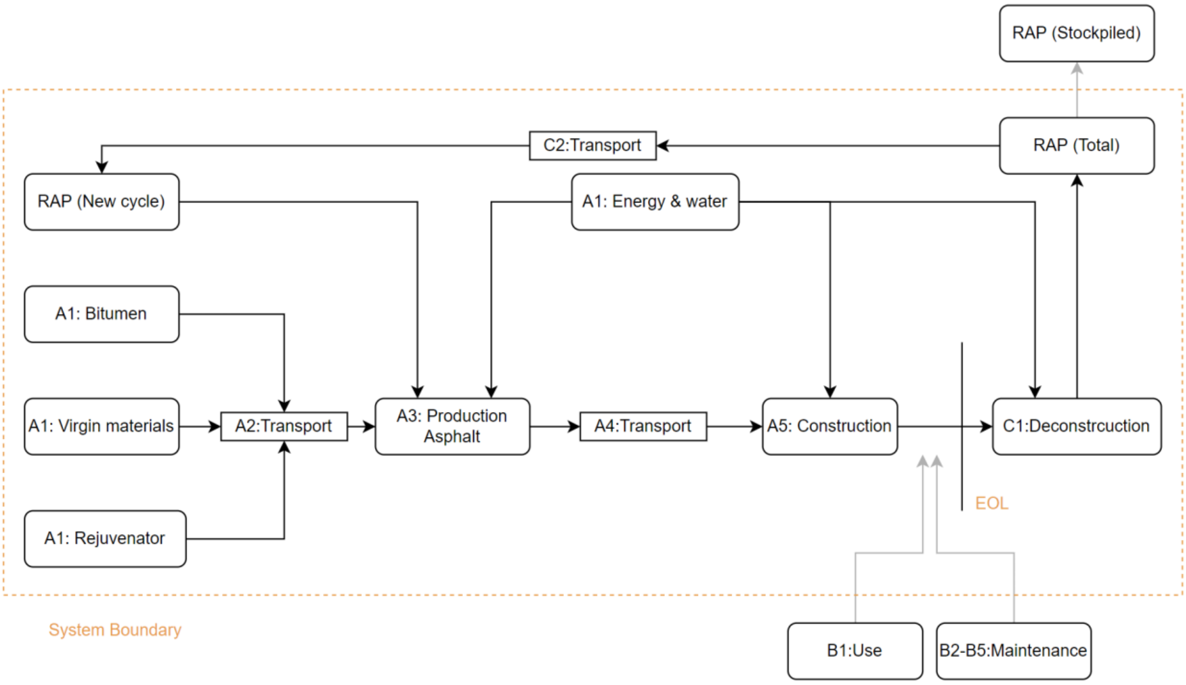


Figure 5 LCA system boundary

Life Cycle Inventory

In this phase, the data of all flow materials associated with the production of recycled asphalt pavement is collected. For collecting all the information required, it is important to understand the process of HIR techniques and also conventional recycling methods. Therefore, a deeper review must be performed to check the materials, procedures, and machinery involved. For the use of HIR using ART, and hot recycling conventional method, the machinery and materials involved have to be determined. In Table 6 and Table 8, the input materials for one treatment of each technique with the machinery and the corresponding number of materials are shown. Additionally, in Table 7 and Table 9, the inputs of energy resources needed for each machinery are detailed. All the mentioned tables have the also the name of the GaBi Objects/Flows of the materials and energy resources where they can be recognized in the LCA Model, see section 11.1.

Table 6 LCI of materials for hot in-place recycling (HIR)

	Machinery	Materials	GaBi Object/Flow	Amount
HIR	Surface cleaner (x1)	Water	EU-28: Water (deionized) ts	5880 l
	Remixer 4500 (x1)	Bitumen (binder)	EU-28: Bitumen at refinery ts	4741 kg
		Asphalt (100% recycled)	Asphalt	309412,7 kg
		Rejuvenator (Latexfalt Neomex HR)	EU-28: Bitumen at refinery ts	1896,3 kg

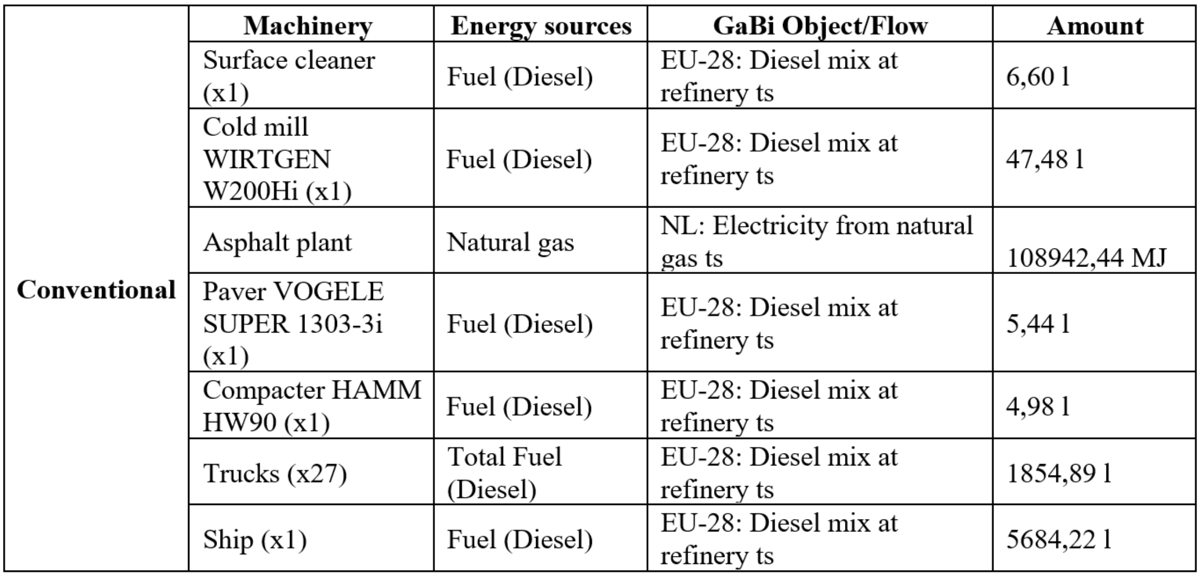
Table 7 LCI of energy resources for hot in-place recycling (HIR)

	Machinery	Energy sources	GaBi Object/Flow	Amount
HIR	Surface cleaner (x1)	Fuel (Diesel)	EU-28: Diesel mix at refinery ts	12,20 l
	Panel heating machine HM 4500 (x2)	Gas (Propane)	GB: Propane at refinery ts	2835 l
		Fuel (Diesel)	EU-28: Diesel mix at refinery ts	58,9 l
	Remixer 4500 (x1)	Gas (Propane)	GB: Propane at refinery ts	1732,5 l
		Fuel (Diesel)	EU-28: Diesel mix at refinery ts	268 l
	Compacter HAMM HW90 (x1)	Fuel (Diesel)	EU-28: Diesel mix at refinery ts	4,98 l
	Trucks (x2)	Total Fuel (Diesel)	EU-28: Diesel mix at refinery ts	46,98 l

Table 8 LCI of materials for conventional hot recycling method

	Machinery	Materials	GaBi Object/Flow	Amount
Conventional	Surface cleaner (x1)	Water	EU-28: Water (deionized) ts	2940,0 l
	Cold mill WIRTGEN W200Hi (x1)	Asphalt	Asphalt integrated	94815 kg
	Asphalt plant	Asphalt milled (30% RAP)	Asphalt	94815 kg
		Aggregates (Bistone and filler)	Aggregates Production	195192,48 kg
		Sand	EU-28: Sand 0/2 ts	11725,46 kg
		Bitumen	EU-28 Bitumen at refinery ts	13369 kg
		Anti-dripping agent	Anti-dripping production	948 kg
	Paver VOGELE SUPER 1303-3i (x1)	Asphalt Recycled	Asphalt recycled	316050 kg

Table 9 LCI of energy resources for conventional hot recycling method



	Machinery	Energy sources	GaBi Object/Flow	Amount
Conventional	Surface cleaner (x1)	Fuel (Diesel)	EU-28: Diesel mix at refinery ts	6,60 l
	Cold mill WIRTGEN W200Hi (x1)	Fuel (Diesel)	EU-28: Diesel mix at refinery ts	47,48 l
	Asphalt plant	Natural gas	NL: Electricity from natural gas ts	108942,44 MJ
	Paver VOGELE SUPER 1303-3i (x1)	Fuel (Diesel)	EU-28: Diesel mix at refinery ts	5,44 l
	Compacter HAMM HW90 (x1)	Fuel (Diesel)	EU-28: Diesel mix at refinery ts	4,98 l
	Trucks (x27)	Total Fuel (Diesel)	EU-28: Diesel mix at refinery ts	1854,89 l
	Ship (x1)	Fuel (Diesel)	EU-28: Diesel mix at refinery ts	5684,22 l

Another point to consider in the LCI is the purpose of the trucks for both techniques, which is basically, the transportation of materials. For the HIR technique, it uses one truck to transport the bitumen from the closest oil refinery Shell to the project site and another truck to transport the rejuvenator from Latexfalt to the project site. On the other hand, for the conventional hot recycling method, 13 trucks are used for the transportation of milled asphalt from the project site to the asphalt production plant and vice versa with the transportation of the new asphalt instead. Additionally, four trucks and one ship for the transportation of bitumen, aggregates, and anti-dripping agent. All of them have as final destination the asphalt plant but the initial destination varies, even being transported from other countries such as: Scotland and Norway. The fuel consumption is based on the number of kilometers and type of vehicle, calculated automatically by the database. The distances for the transportation of the mentioned materials were taken from Google Maps (2022) and are shown in Table 10.

Table 10 Material transportation information

Material transported	**Type of vehicle**	**Initial point**	**Final point**	**Distance**
Bitumen (HIR)	Truck Euro 5, 9,3t payload capacity	Shell oil refinery Pernis	A73 project location	134 km
Rejuvenator (HIR)	Truck Euro 5, 2,7t payload capacity	Latexfalt	A73 project location	133 km
Bitumen (Conventional)	Truck Euro 5, 11,4t payload capacity	Shell oil refinery Pernis	Dura Vermeer Asphalt Production plant Eemnes	101 km
Sand (Conventional)	Truck Euro 5, 17,3t payload capacity	Scotland	Dura Vermeer Asphalt Production plant Eemnes	1091 km
Bestone (Conventional)	Average ship 1500t payload capacity	Norway	Dura Vermeer Asphalt Production plant Eemnes	1327 km
Filler – Hydrated lime (Conventional)	Truck Euro 5, 17,3t payload capacity	Winterswijk	Dura Vermeer Asphalt Production plant Eemnes	127 km
Anti-dripping agent (Conventional)	Truck Euro 5, 2,7t payload capacity	Zutphen	Dura Vermeer Asphalt Production plant Eemnes	73,8 km
Milled Asphalt (Conventional)	Truck Euro 5, 24,7t payload capacity	A73 project location	Dura Vermeer Asphalt Production plant Eemnes	110 km
New Asphalt (Conventional)	Truck Euro 5, 24,7t payload capacity	Dura Vermeer Asphalt Production plant Eemnes	A73 project location	103 km

6.2.2 Circularity assessment

The material collected in the previously elaborated Life Cycle Inventory (LCI) are labelled to use the core measurement method and measure the degree of circularity. According to Platform CB’23 (2020), the materials have to be detailed with the following information:

- Quantity in kilograms
- Scarce/ abundant based on the list of Critical Raw Materials (CRM, see European Commission, 2017)
- Physically scarce/physically abundant determined according to NEN-EN 15804:2012+A2:2019 (NEN 2019) (abiotic depletion potential, ADP)
- Primary/secondary
    - If secondary: reuse/recycling

    - If primary: sustainable renewable/non-sustainable renewable
- Most probable end-of-life treatment: available for the next cycle/ not available for the next cycle
    - If available for the next cycle: reuse/recycling
    - If not available for the next cycle: energy production/landfill

The classification for each method are shown in Table 11 and Table 12, where the materials and its percentages of newness and recycled in relation with the final mixture can be identified.

Table 11 Material classification for HIR

HIR	Quantity (kg)	Critical Raw Material	ADP (kg Sb eq)	Primary/Secondary	End-of-life treatment
Bitumen (1,5 % new)	4741	Scarce	0,000446	Primary-Non-renewable	Recycling
Rejuvenator (0,6% new)	1896,3	Scarce	0,000178	Primary-Renewable	Recycling
Asphalt (100% recycled)	309412,7	Abundant	0	Secondary-Recycling	Recycling
Total	316050				

Table 12 Material classification for conventional hot recycling method

Conventional	Quantity (kg)	Critical Raw Material	ADP (kg Sb eq)	Primary/Secondary	End-of-life treatment
Anti-dripping agent	948,15	Scarce	0,000531	Primary-Renewable	Recycling
Bitumen (4,23% new)	13369	Scarce	0,00126	Primary-Non-renewable	Recycling
New aggregates (58,01% bestone, 3,71% sand and 3,75% filler)	206918	Abundant	0	Primary-Non-renewable	Recycling
Asphalt (30% recycled)	94815	Abundant	0	Secondary-Recycling	Recycling
Total	316050				

Based on the data collected the indicator calculation rules have to be followed to obtain the results and analyze the circularity of mentioned techniques. The ADP indicator was summoned from the GaBi database per material. An special case is the rejuvenator and anti-dripping agent, which were chosen based on its derivatives.

6.3 Results

6.3.1 Life Cycle Assessment (LCA)

For the LCA modeling, the analysis was carried out in two ways: analyzing the application of one treatment only per technique and also for the analysis period of 100 years, in which those techniques were repeated in order to cover the whole period, the number of repetitions was mentioned in Table 4.

The first analysis was useful to determine the responsibility for which these two techniques differ in environmental impact and the second analysis corresponds to provide an insight into the impact in a given analysis period. The diagram modeling for all the cases can be found in the section 11.1. Given the importance of Dura Vermeer to mitigate climate change, the first analysis is based on the emissions of kg CO_2 eq. produced by each method. From Figure 6 and Figure 7, it can be seen how the amount of kg CO_2 eq. differs considerably.

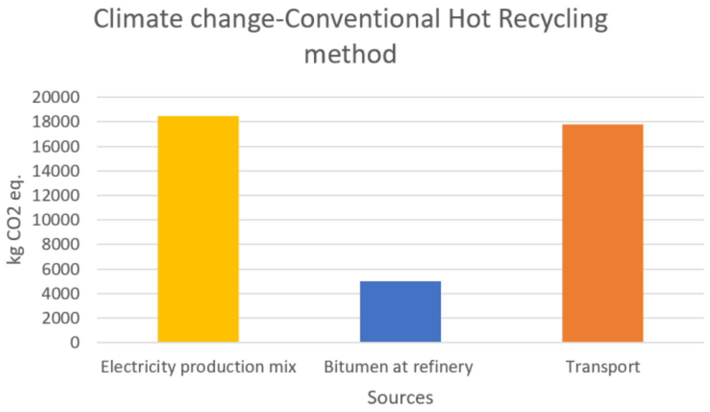


Figure 6 Main sources of climate change by conventional hot recycling method

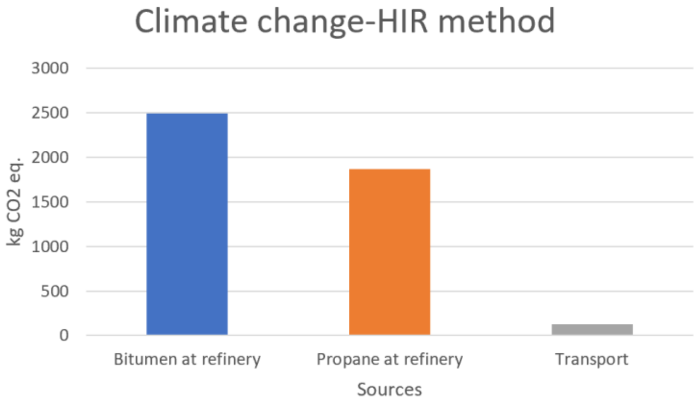


Figure 7 Main sources of climate change by HIR method

In the conventional method, the two main sources are electricity production and transport, these correspond to the asphalt plant and aggregates production, besides the transportation of materials. On the other hand, the two main sources of HIR are bitumen and propane production at the refinery. The significant differences between these two methods are the number of vehicles needed for material transportation.

In the second analysis, following Platform CB’23 (2020), the impact indicator explained in Table 2 was considered, and also the analysis period of 100 years for which the road section has to remain serviceable. Since the HIR does not have a determined lifespan, a best/worst scenario is calculated given the number of repetitions, the results are shown in Table 13.

Table 13 Environmental impact results of recycling techniques in the analysis period

4	**Environmental impact (unit)**	**Conventional Recycling**	**HIR Best Scenario**	**HIR Worst Scenario**
4.1	Climate change – overall (kg CO2 eq.)	$3,06 * 10^{5}$	$2,27 * 10^{4}$	$3,23 * 10^{4}$
4.2	Climate change – fossil (kg CO2 eq.)	$3,03 * 10^{5}$	$2,25 * 10^{4}$	$3,2 * 10^{4}$
4.3	Climate change – biogenic (kg CO2 eq.)	984	163	232
4.4	Climate change - use of land and changes in use of land (kg CO2 eq.)	$1,31 * 10^{3}$	56,1	79,7
4.5	Ozone depletion (kg CFC-11 eq.)	$1,68 * 10^{-10}$	$0,223 * 10^{-10}$	$0,317 * 10^{-11}$
4.6	Acidification (mole of H+ eq.)	$1,48 * 10^{3}$	93	132
4.7	Eutrophication – freshwater (kg P eq.)	0,556	0,0561	0,0797
4.8	Eutrophication – seawater (kg N eq.)	673	15	21,3
4.9	Over-fertilisation – soil (mole of N eq.)	$7,42 * 10^{3}$	167	237
4.10	Occurrence of smog – POCP (Kg NMVOC Equiv.)	$1,96 * 10^{3}$	72	102
4.11	Depletion of abiotic raw materials - minerals and metals (Kg Sb eq.)	0,0264	0,00417	0,00593
4.12	Depletion of abiotic raw materials - fossil energy carriers (MJ)	$8,226 * 10^{6}$	$2,4 * 10^{6}$	$3,41 * 10^{6}$
4.13	Use of water (M3 eq.)	$5,75 * 10^{3}$	$1,54 * 10^{3}$	$2,18 * 10^{3}$
4.14	Emission of particulate matter (PM2.5 eq.)	0,0378	0,000578	0,000822
4.15	Ionising radiation (kBq U235 eq.)	$2,62 * 10^{3}$	341	485
4.16	Ecotoxicity (freshwater) (CTUe)	$6,68 * 10^{4}$	$1,62 * 10^{4}$	$2,31 * 10^{4}$
4.17	Human toxicity, carcinogenic (CTUh)	$3,2 * 10^{-3}$	$0,807 * 10^{-3}$	$1,15 * 10^{-3}$
4.18	Human toxicity, non-carcinogenic (CTUh)	0,0306	0,00587	0,00834
4.19	Impact/Soil quality related to the use of land (Pt)	$1,52 * 10^{6}$	$6,91 * 10^{4}$	$9,82 * 10^{4}$

For having a single indicator impact of the recycling techniques in the analysis period. The Platform CB’23 (2020) suggests calculating a weighted single final score for indicator 4 using the SBK method (Stichting Bouwkwaliteit 2019). This method allows to calculate the environmental cost indicator (Milieukostenindicator - MKI) that summarizes all environmental effects in one score and is expressed in euros (see Table 14).

Table 14 Weighting of environmental impacts

Impact category	**Unit**	**Weighting Factor**
Depletion of abiotic raw materials (excluding fossil energy carriers) ADP	kg sb eq.	€ 0,16
Depletion of fossil energy carriers ADP	kg sb eq eq.	€ 0,16
Global Warming Potential (GWP)	kg CO2 eq.	€ 0,05
Ozone layer depletion (ODP)	kg CFC-11 eq.	€ 30,00
Photochemical oxidant formation POCP	kg C2H4 eq.	€ 2,00
Acidification (AP)	kg SO2 eq.	€ 4,00
Fertilization (EP)	kg PO4 eq.	€ 9,00
Human Toxicity (HTP)	kg 1,4-DCB eq.	€ 0,09
Freshwater aquatic ecotoxicity (FAETP)	kg 1,4-DCB eq.	€ 0,03
Marine Aquatic Ecotoxicity (MAETP)	kg 1,4-DCB eq.	€ 0,0001
Terrestrial Ecotoxicity (TETP)	kg 1,4-DCB eq.	€ 0,06

The values calculated corresponding to every impact category for each technique are multiplied with the weighting factor and then, summed up to have the total environmental cost MKI, see Table 15.

Table 15 MKI calculation for the three recycling techniques

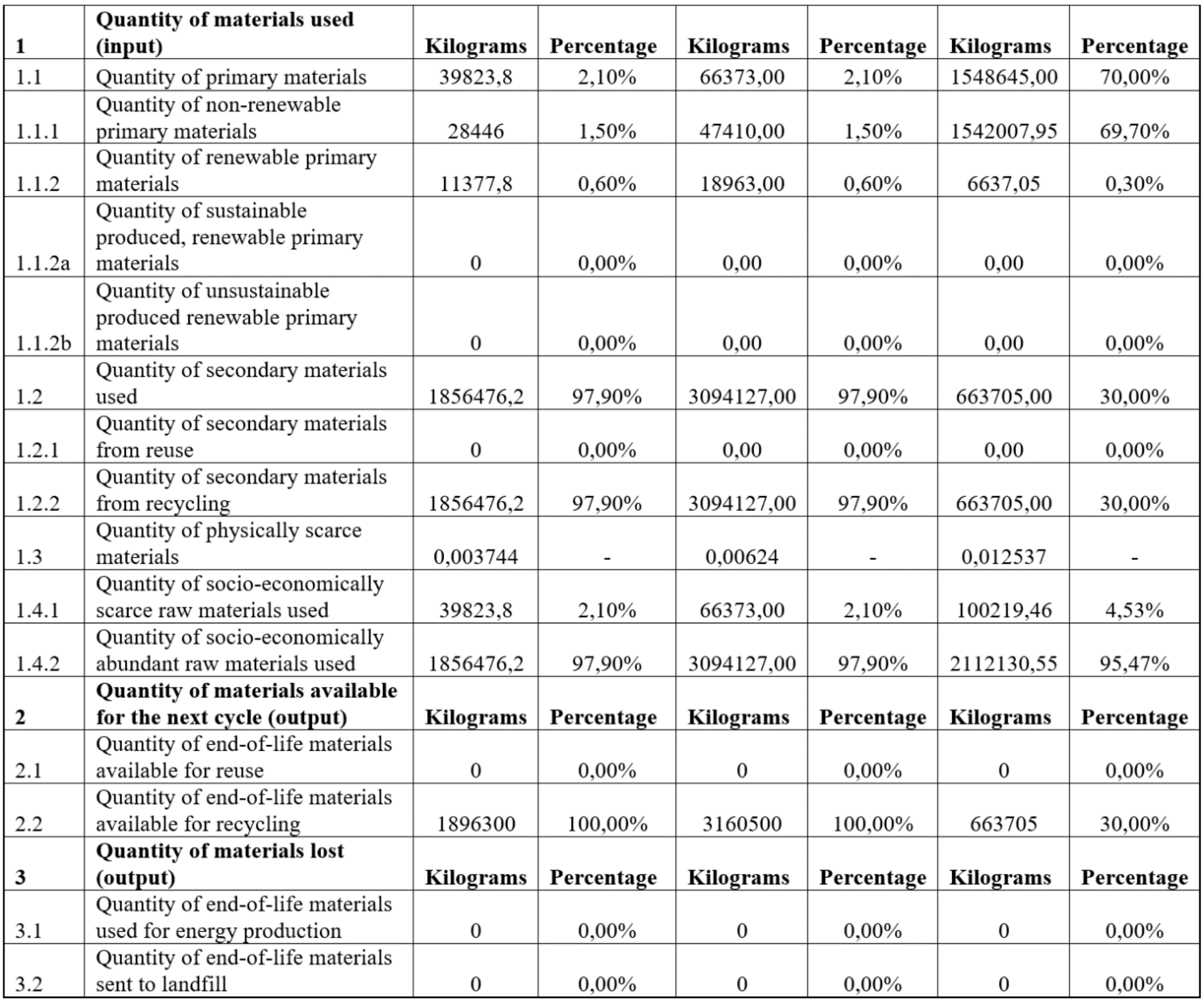
Impact category (unit)	**Conventional recycling**	**HIR best scenario**	**HIR worst scenario**
Depletion of abiotic raw materials (excluding fossil energy carriers) ADP - sb eq.	0,0309	0,00476	0,00677
Depletion of fossil energy carriers ADP - sb eq.	8220000	2400000	3410000
Global Warming Potential (GWP) - CO2 eq.	353000	20800	29500
Ozone layer depletion (ODP) - CFC-11 eq.	2,24E-10	2,89E-11	4,23E-11
Photochemical oxidant formation POCP - C2H4 eq	89,3	13,9	19,8
Acidification (AP) - SO2 eq.	1050	78,9	112
Fertilization (EP) - PO4 eq.	236	6,82	9,68
Human Toxicity (HTP) - 1,4-DCB eq.	12100	2750	3900
Freshwater aquatic ecotoxicity (FAETP) - 1,4-DCB eq.	2380	578	821
Marine Aquatic Ecotoxicity (MAETP) - 1,4-DCB eq.	9360000	2910000	4130000
Terrestrial Ecotoxicity (TETP) - 1,4-DCB eq.	711	123	175
MKI Total	€ 1.341.491,66	€ 386.008,00	€ 548.448,85

The table shows that even the worst scenario of HIR does not cause a significant environmental impact in comparison with conventional hot recycling using 30% of RAP, which doubles the worst scenario of HIR. As analyzed previously, this considerable impact of the conventional method is mainly caused by the electricity production and transportation of materials which is reiterative during the analysis period.

6.3.2 Circularity assessment

Using the explanation of each indicator (see Table 1) and following the calculation rules presented in Platform CB'23 (2020), the circular indicators are listed in Table 16 with the corresponding amount of material in kilograms present in given conditions and for the analysis period of 100 years. Moreover, the percentage of material proportions for each sub-indicator compose the main indicators: primary and secondary materials, socio-economic scarce materials, material availability for the next cycle, and materials lost. The physically scarce material (indicator 1.3) does not have a percentage since it is measured in kg Sb equivalent. These results can provide an insight into the flow of materials that acts as inputs and outputs.

Table 16 Circularity indicators assessment for HIR and Conventional hot recycling



1	**Quantity of materials used (input)**	**Kilograms**	**Percentage**	**Kilograms**	**Percentage**	**Kilograms**	**Percentage**
1.1	Quantity of primary materials	39823,8	2,10%	66373,00	2,10%	1548645,00	70,00%
1.1.1	Quantity of non-renewable primary materials	28446	1,50%	47410,00	1,50%	1542007,95	69,70%
1.1.2	Quantity of renewable primary materials	11377,8	0,60%	18963,00	0,60%	6637,05	0,30%
1.1.2a	Quantity of sustainable produced, renewable primary materials	0	0,00%	0,00	0,00%	0,00	0,00%
1.1.2b	Quantity of unsustainable produced renewable primary materials	0	0,00%	0,00	0,00%	0,00	0,00%
1.2	Quantity of secondary materials used	1856476,2	97,90%	3094127,00	97,90%	663705,00	30,00%
1.2.1	Quantity of secondary materials from reuse	0	0,00%	0,00	0,00%	0,00	0,00%
1.2.2	Quantity of secondary materials from recycling	1856476,2	97,90%	3094127,00	97,90%	663705,00	30,00%
1.3	Quantity of physically scarce materials	0,003744	-	0,00624	-	0,012537	-
1.4.1	Quantity of socio-economically scarce raw materials used	39823,8	2,10%	66373,00	2,10%	100219,46	4,53%
1.4.2	Quantity of socio-economically abundant raw materials used	1856476,2	97,90%	3094127,00	97,90%	2112130,55	95,47%
2	**Quantity of materials available for the next cycle (output)**	**Kilograms**	**Percentage**	**Kilograms**	**Percentage**	**Kilograms**	**Percentage**
2.1	Quantity of end-of-life materials available for reuse	0	0,00%	0	0,00%	0	0,00%
2.2	Quantity of end-of-life materials available for recycling	1896300	100,00%	3160500	100,00%	663705	30,00%
3	**Quantity of materials lost (output)**	**Kilograms**	**Percentage**	**Kilograms**	**Percentage**	**Kilograms**	**Percentage**
3.1	Quantity of end-of-life materials used for energy production	0	0,00%	0	0,00%	0	0,00%
3.2	Quantity of end-of-life materials sent to landfill	0	0,00%	0	0,00%	0	0,00%

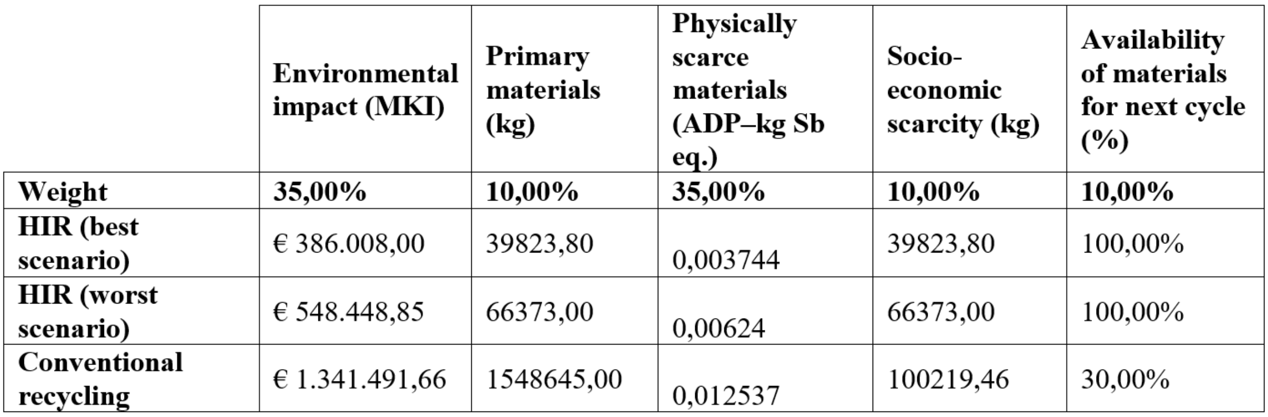
From the table, the input materials display a significant use of primary materials when using conventional recycling processes, this is mainly caused by the number of aggregates needed to assuring the quality performance of the asphalt recycled pavement. Regarding the outputs, it can also be deducted that no materials are lost during both processes. Materials that were consumed but did not end up in the recycled asphalt pavement are not considered since they are considered production waste. The fact of not losing material is mainly because of the defined system boundaries, in which, all the materials were accounted for only in the recycling process or even when using conventional recycling, the other 70% of material that was not used in asphalt production, was allocated in RAP stockpiles. The depletion of abiotic materials (ADP) is a crucial indicator of how circular the product is working and it is different per material (B. Mentink, personal communication 2022). In this case, the total ADP indicator was summoned from the results calculated by GaBi for each technique. The more circular the lower the depletion impact, hence, the more circular technique is HIR.

6.3.3 Integrated assessment

For the development of an integrated assessment of circularity and environmental impact, the TOPSIS method is chosen and was explained in section 5.2.1. The objective of this research is to assess concomitantly the environmental sustainability and circularity performance of in-place recycling techniques. However, adjusting the scope of the research to the case study and the application of the integrated framework, the HIR and conventional hot recycling methods are assessed together concomitantly by establishing circular and environmental criteria that allow choosing the best alternative for a determined analysis period.

The criteria are selected based on the indicators and previous results. The MKI and physically scarce materials (ADP) are the most relevant due to their importance in sustainability and circularity, hence their weight is 35%, which is higher than the others. The rest of the criteria are: the amount of primary and socio-economic scarcity materials and the availability of materials for the next cycle, all of them have a weight of 10%. These weights were discussed with the experts of the company and also are part of a sensitivity analysis. In Table 17, the evaluation matrix can be seen with all its components: alternatives and criteria with the corresponding metrics.

Table 17 Evaluation matrix with recycling alternatives and weighted criteria



	Environmental impact (MKI)	**Primary materials (kg)**	**Physically scarce materials (ADP–kg Sb eq.)**	**Socio-economic scarcity (kg)**	**Availability of materials for next cycle (%)**
Weight	**35,00%**	**10,00%**	**35,00%**	**10,00%**	**10,00%**
HIR (best scenario)	€ 386.008,00	39823,80	0,003744	39823,80	100,00%
HIR (worst scenario)	€ 548.448,85	66373,00	0,00624	66373,00	100,00%
Conventional recycling	€ 1.341.491,66	1548645,00	0,012537	100219,46	30,00%

Using Equation 2, the normalized evaluation matrix can be obtained, see Table 18. This normalized evaluation matrix is then multiplied by the established weights of Table 17 and a weighted normalized is displayed as a result in Table 19.

Table 18 Normalized evaluation matrix

	Environmental impact (MKI)	**Primary materials (kg)**	**Physically scarce materials (ADP-kg Sb eq.)**	**Socio-economic scarcity (kg)**	**Availability of materials for next cycle (%)**
HIR (best scenario)	0,26	0,03	0,26	0,31	0,69
HIR (worst scenario)	0,37	0,04	0,43	0,52	0,69
Conventional recycling	0,89	1	0,86	0,79	0,21

Table 19 Weighted normalized matrix

	Environmental impact (MKI)	**Primary materials (kg)**	**Physically scarce materials (ADP-kg Sb eq.)**	**Socio-economic scarcity (kg)**	**Availability of materials for next cycle (%)**
HIR (best scenario)	0,0901	0,0026	0,0904	0,0314	0,0692
HIR (worst scenario)	0,1280	0,0043	0,1507	0,0524	0,0692
Conventional recycling	0,3131	0,0999	0,3027	0,0791	0,0208

The ideal best and worst values are collected from Table 19 and displayed in Table 20. For the MKI criteria, the lower the value, is better, hence, the minimum is chosen as the ideal best value. This is also the case for the rest of the criteria, except for the availability of materials for the next cycle where the higher the value is preferred, so the maximum value is chosen as the ideal best value.

Table 20 Ideal best/worst value selection

X_j^b **(ideal best value)**	0,0901	0,0026	0,0904	0,0314	0,0692
X_j^w **(ideal worst value)**	0,3131	0,0999	0,3027	0,0791	0,0208

As mentioned before, the Euclidean distance represents the geometric distance between a value of an alternative with respect to the best/worst criterion. Equation 6 and Equation 7 were applied for its calculation. Additionally, the similarity to the worst alternative is also calculated with Equation 8 and finally, the TOPSIS scores can be ranked by descending order, see Table 21.

Table 21 Euclidean distance between target and best/worst alternatives, similarity to the worst alternative and ranking of methods

Alternatives	d_i^b	d_i^w	S_i	**Rank**
HIR (best scenario)	0,0000	0,3300	1,00	1
HIR (worst scenario)	0,0742	0,2637	0,78	2
Conventional recycling	0,3300	0,0000	0,00	3

The ranking shows that the best alternative in terms of environmental sustainability and circularity performance is HIR, even considering a lower lifespan of 10 years (worst scenario) shows a superiority in comparison to the conventional hot recycling with 30% of RAP. For evaluating the weights assigned to the criterion a sensitivity analysis is performed in the next section

6.3.4 Sensitivity Analysis

The sensitivity analysis determine how different values of an independent variable affect a particular variable. The original weights from the previous section are used. For performing the analysis, the weight assigned to one criterion is increased by 10% and then, the rest of the weights are divided proportionally among the other criterions. Therefore, TOPSIS method is performed repeatedly with different weights for each criteria to see how it differs from the original results. In , the original weight and also the increased weights by each criterion can be seen.

Table 22 Original criteria weight and variation of weights per criteria for sensitivity analysis

	Environmental impact	**Primary materials**	**Physically scarce materials**	**Socio-economic scarcity**	**Availability of materials for next cycle**
Original weight	35%	10%	35%	10%	10%
Environmental impact (+10%)	45%	8,46%	29,62%	8,46%	8,46%
Primary materials (+10%)	31,11%	20%	31,11%	8,89%	8,89%
Physically scarce materials (+10%)	29,62%	8,46	45%	8,46%	8,46%
Socio-economic scarcity (+10%)	31,11%	8,89%	31,11%	20%	8,89%
Availability of materials for next cycle (+10%)	31,11%	8,89%	31,11%	8,89%	20%

After defining the new weights, the TOPSIS method was calculated again for each criterion that was increased. The results are shown in Table 23 and demonstrate that after altering the assumed weights are robust since the final results or interpretations are almost equal.

Table 23 Sensitivity analysis results

	Original weight	**Environmental impact (+10%)**	**Primary materials (+10%)**	**Physically scarce materials (+10%)**	**Socio-economic scarcity (+10%)**	**Availability of materials for next cycle (+10%)**
HIR (best scenario)	1	1	1	1	1	1
HIR (worst scenario)	0,78	0,8	0,76	0,76	0,76	0,79
Conventional recycling	0	0	0	0	0	0

7 Discussion

Considering the importance of circularity and sustainability for the activities of many industries. The application of this integrated assessment framework in the paving industry, that adopt the application of in-place recycling techniques can improve circularity and environmental sustainability in the road system. In addition, side effects can be identified, besides important indicators that influence the environmental and circularity performances. The scope of the research was to compare in-place recycling techniques between them. However, it was adjusted given the limited data of other techniques such as cold in-place recycling techniques. Then, the conventional recycling method was used instead for analysis in the case study.

The findings after performing the circularity, environmental impact and TOPSIS calculation showed an expected favoritism for the HIR technique, even consider the worst scenario in which its lifespan is 10 years. The results can be different given the comparison with a conventional hot recycling method where RAP percentage is higher i.e. 50%. Nevertheless, Dura Vermeer is still analyzing asphalt mixtures with that percentage of RAP and hence, data for the analysis were not be available for the modelling and calculations. Similarly, analyzing it with another in-place recycling technique could show a more equated comparison.

Similarly, the case study was not realistic at all since other maintenance methods in between the lifespan of each technique are required, however, it was difficult to predict when needed and the amount, for instance, the application of rejuvenator agents. Moreover, the recycling only of the surface layer is not realistic since the other layer can be affected given such a long analysis period as 100 years.

As this research was based on the Platform CB’23 (2020) guide and it is still being developed in terms of value retention indicators. The inclusion of these indicators can provide more criteria to be added in the MCDA method for widening the criteria selection of the most appropriate technique in a given analysis period. Nonetheless, the fact that these terms are continuously under the revision, it is possible that the weighting factors can be incremented and updated. Therefore, this research needs to be updated depending on the more current guidelines.

In conclusion, this integrated assessment framework can be applied for any asphalt pavement recycling strategy and can visualize the trade-off between circularity and environmental sustainability, being important for stakeholders to facilitate the transition to a circular economy.

8 Summary and conclusions

The misconception of circularity and environmental sustainability, in terms of usability and application, has provoked side effects such as rebound effects when adopted in practices of the lifecycle of a product. Therefore, the importance of having a framework that not only measures circularity and environmental sustainability individually but together concomitantly. This research has developed an integrated assessment framework to assess the performance of in-place recycling techniques and then, applied it to a case study. Firstly, in-place recycling techniques were explored to understand the process and their characteristics, then appropriates methodologies for assessing circularity and environmental sustainability performances were chosen and applied for calculating the results, followed by the integration of their indicators in an integrated assessment by using a MCDA tool and finally, the results for a specific analysis period can be obtained.

In-place recycling techniques changed the scope when preferring maintenance & rehabilitation instead of construction, they limit new raw material, minimize truck operation and have a shorter construction time. The Asphalt Recycling Train (ART) consist of pieces of equipment that are in charge of the asphalt recycling process in-situ. Dura Vermeer implement this concept using Hot In-Place Recycling (HIR). HIR applies in situ heating during the construction process when restoring the damaged surface. The surface recycling started using heater scarification, then mixing the recycled asphalt with new bitumen and rejuvenating agents for restoring its properties, and finally, the paving process.

The core measurement methodology, proposed by the Platform CB’23 guide, consider three goals of a circular construction: protecting stocks of materials, environmental protection and value retention. The two first goals contain circularity and environmental impact indicators that are used and calculated in this report meanwhile for the last goal, its indicators are still being developed. All the indicators are listed in Table 1 and Table 2. The platform highlights that the Life Cycle Assessment (LCA) share the scope with circularity indicators, for instance, when developing a life cycle inventory. The results of these indicators were calculated for the analysis period of 100 years, comparing HIR and conventional hot recycling method.

The LCA results show that the conventional hot recycling method is responsible of the greatest emissions of CO_2 eq. which contributes to the climate change and also reflects all the environmental impacts with the highest environmental cost indicator (MKI) value. When analyzed deeply, the main sources for which the conventional method is emitting that quantity is because of the electricity production and also the transportation of materials. As opposite to HIR, where the transportation is limited. In terms of circularity, an important number of primary materials are considered when using the conventional method since the quality performance of the asphalt has to be assured. For both methods, no materials are lost during the process because some of them are allocated in RAP stockpiles or used in a different process since they were downgraded after recycling. Moreover, the ADP indicator, an important indicator to measure the degree of circularity, showed that the more circular technique is HIR, even considering the worst scenario of a lifespan of 10 years. This is because of the lower depletion impact that it has in comparison with the conventional method.

Finally, TOPSIS method tool is used for the integrated assessment framework where circularity and environmental sustainability indicators are proposed and combined as criteria, each of them was assigned a weight. The highest weights of 35 % corresponds to the environmental impact (MKI) and the physically scarce material (ADP) since they are considered crucial factors. After the whole calculation, it is found that HIR is the best alternative for maintaining the road section in usable conditions during the analysis period of 100 years. Even considering the best or worst scenario in terms of lifespan for one treatment. The sensitivity analysis demonstrates that the assumed weights for the criteria are robust, hence, when varied the results were similar.

9 Recommendations

After analyzing the results of this research, discussion, and conclusion, recommendations can be drawn up for further analysis or related projects.

Considering that one of the main sources that contribute to the environmental impact is the transportation of material, and that all the trucks modeled in the system are Euro 5 trucks. It could be interesting to assess how the inclusion of innovation in vehicles helps to reduce the emissions of carbon monoxide, hydrocarbon, nitrogen oxide, and particular matter per vehicle driven. For example, using Euro 6 vehicles, which are cleaner and more fuel efficient, in certain cases even more powerful. Another advantage of it is that it can improve the air quality by switching to the use of these vehicles.

Since the framework was elaborated in a way that can be used for comparison with other in-place recycling techniques, it can also be applied for emerging techniques to capture all the consequences and trade-offs between circularity and sustainability. An example of these emerging techniques can be the combination of existing in-place recycling techniques. Dura Vermeer finds interesting the use of hybrid in-place recycling, especially for porous asphalt, where infrared preheating and cold recycling are involved, besides the inclusion of foamed bitumen or bitumen emulsion.

As mentioned in the discussion, section 7, the guidelines can be subject to updates and to have more realistic and accurate results, the criteria indicators used in this research must be updated.

10 Bibliography

Alejandrino, Clarisa, Irma T. Mercante, and María D. Bovea. 2022. 'Combining O-LCA and O-LCC to Support Circular Economy Strategies in Organizations: Methodology and Case Study'. *Journal of Cleaner Production* 336:130365. doi: 10.1016/j.jclepro.2022.130365.

Antwi-Afari, Prince, S. Thomas Ng, and Md. Uzzal Hossain. 2021. 'A Review of the Circularity Gap in the Construction Industry through Scientometric Analysis'. *Journal of Cleaner Production* 298:126870. doi: 10.1016/j.jclepro.2021.126870.

Caltrans. 2022. 'In-Place Recycling (IPR) for Asphalt Pavements | Caltrans'. Retrieved 8 June 2022 (https://dot.ca.gov/programs/maintenance/pavement/local-agencies/in-place-recycling-main).

Cao, Ruijun, Zhen Leng, and Shu-Chien Hsu. 2019. 'Comparative Eco-Efficiency Analysis on Asphalt Pavement Rehabilitation Alternatives: Hot in-Place Recycling and Milling-and-Filling'. *Journal of Cleaner Production* 210:1385–95. doi: 10.1016/j.jclepro.2018.11.122.

Cutler, Earl F. 1978. 'Asphalt Pavement Recycling Apparatus'.

Dura Vermeer. 2022a. 'Asphalt Recycling Train'. *Dura Vermeer*. Retrieved 17 May 2022 (https://www.duravermeer.nl/infrastructuur/producten/asfalt/asphalt-recycling-train/).

Dura Vermeer. 2022b. 'Dura Vermeer Werkt Duurzaam En Circulair'. *Dura Vermeer*. Retrieved 4 April 2022 (https://www.duravermeer.nl/duurzaamheid/).

Ecochain. 2019. 'Life Cycle Assessment (LCA) - Complete Beginner's Guide'. *Ecochain*. Retrieved 11 May 2022 (https://ecochain.com/knowledge/life-cycle-assessment-lca-guide/).

Ellen Mac Arthur Foundation. 2019. 'Circularity-Indicators-Methodology | An Approach to Measuring Circularity'. Retrieved 15 March 2022 (https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o).

Ellen Mac Arthur Foundation. 2022. 'Circular Economy Introduction'. Retrieved 25 June 2022 (https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview).

Geissdoerfer, Martin, Paulo Savaget, Nancy M. P. Bocken, and Erik Jan Hultink. 2017. 'The Circular Economy – A New Sustainability Paradigm?' *Journal of Cleaner Production* 143:757–68. doi: 10.1016/j.jclepro.2016.12.048.

Google Maps. 2022. 'Google Maps'. *Google Maps*. Retrieved 7 July 2022 (https://www.google.nl/maps/dir/Zutphen/52.2231541,5.3114665/@52.2001846,6.288445,8.51z/data=!4m9!4m8!1m5!1m1!1s0x47c7940b75ecc3ab:0xc4f2a91150249d3c!2m2!1d6.1960584!2d52.142736!1m0!3e0).

Guinée et al. 2002. 'CML-IA Characterisation Factors'. *Leiden University*. Retrieved 27 June 2022 (https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors).

ISO 14040. 2006. 'ISO 14040:2006(En), Environmental Management — Life Cycle Assessment — Principles and Framework'. Retrieved 31 January 2022 (https://www.iso.org/obp/ui#iso:std:iso:14040:ed-2:v1:en).

ISO 14044. 2006. 'ISO 14044:2006(En), Environmental Management — Life Cycle Assessment — Requirements and Guidelines'. Retrieved 31 January 2022 (https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en).

Köhler, Sandra, Andrea Thorenz, and Axel Tuma. 2021. 'Does Increased Circularity Lead to Environmental Sustainability?: The Case of Washing Machine Reuse in Germany'. *Journal of Industrial Ecology* 25. doi: 10.1111/jiec.13104.

Lee, Kun-Mo. 2004. 'Life Cycle Assessment Best Practices of ISO 14040 Series'. 96.

Leffers, Jessica, Abdulla Moustafa, and Claartje Vorstman. 2022. 'Circular Infrastructure: The Road towards a Sustainable Future'.

Li, Zhao, Zujiang Luo, Yan Wang, Guanyu Fan, and Jianmang Zhang. 2022. 'Suitability Evaluation System for the Shallow Geothermal Energy Implementation in Region by Entropy Weight Method and TOPSIS Method'. *Renewable Energy* 184:564–76. doi: 10.1016/j.renene.2021.11.112.

Lonca, Geoffrey, Romain Muggéo, Hugues Imbeault-Tétreault, Sophie Bernard, and Manuele Margni. 2018. 'Does Material Circularity Rhyme with Environmental Efficiency? Case Studies on Used Tires'. *Journal of Cleaner Production* 183:424–35. doi: 10.1016/j.jclepro.2018.02.108.

Ma, Yuetan, Pawel Polaczyk, Hong Park, Xi Jiang, Wei Hu, and Baoshan Huang. 2020. ‘Performance Evaluation of Temperature Effect on Hot In-Place Recycling Asphalt Mixtures’. *Journal of Cleaner Production* 277:124093. doi: 10.1016/j.jclepro.2020.124093.

Mantalovas, Konstantinos, and Gaetano Mino. 2020. ‘Integrating Circularity in the Sustainability Assessment of Asphalt Mixtures’. *Sustainability* 12. doi: 10.3390/su12020594.

Navare, Kranti, Bart Muys, Karl C. Vrancken, and Karel Van Acker. 2021. ‘Circular Economy Monitoring – How to Make It Apt for Biological Cycles?’ *Resources, Conservation and Recycling* 170:105563. doi: 10.1016/j.resconrec.2021.105563.

NEN. 2019. ‘NEN-EN 15804:2012+A2:2019 En’. Retrieved 26 June 2022 (https://www.nen.nl/nen-en-15804-2012-a2-2019-en-265036).

Orosa, P., I. Pérez, and A. R. Pasandín. 2022. ‘Short-Term Resilient Behaviour and Its Evolution with Curing in Cold in-Place Recycled Asphalt Mixtures’. *Construction and Building Materials* 323:126559. doi: 10.1016/j.conbuildmat.2022.126559.

Platform CB’23. 2020. ‘Guide Measuring Circularity’.

Plati, Christina. 2019. ‘Sustainability Factors in Pavement Materials, Design, and Preservation Strategies: A Literature Review’. *Construction and Building Materials* 211:539–55. doi: 10.1016/j.conbuildmat.2019.03.242.

Rijkswaterstraat. 2022. ‘Zeer open asfaltbeton (zoab)’. Retrieved 15 June 2022 (http://www.rijkswaterstaat.nl/wegen/wegbeheer/aanleg-wegen/zoab).

Rosen, Marc A. 2018. ‘Environmental Sustainability Tools in the Biofuel Industry’. *Biofuel Research Journal* 5(1):751–52. doi: 10.18331/BRJ2018.5.1.2.

Santos, João, James Bryce, Gerardo Flintsch, Adelino Ferreira, and Brian Diefenderfer. 2015. ‘A Life Cycle Assessment of In-Place Recycling and Conventional Pavement Construction and Maintenance Practices’. *Structure and Infrastructure Engineering* 11(9):1199–1217. doi: 10.1080/15732479.2014.945095.

Sphera. 2020. ‘What Is Environmental Sustainability?’ *Sphera*. Retrieved 9 March 2022 (https://sphera.com/glossary/what-is-environmental-sustainability/).

Stichting Bouwkwaliteit. 2019. ‘Bepalingsmethode’. *Nationale Milieudatabase*. Retrieved 19 May 2022 (https://milieudatabase.nl/milieuprestatie/bepalingsmethode/).

Stroup-Gardiner, Engineering. 2011. *Recycling and Reclamation of Asphalt Pavements Using In-Place Methods*.

UNESCO. 2015. ‘Sustainable Development’. *UNESCO*. Retrieved 25 June 2022 (https://en.unesco.org/themes/education-sustainable-development/what-is-esd/sd).

Virginia Asphalt Association. 2020. ‘Pavement Recycling’. Retrieved 13 June 2022 (https://vaasphalt.org/pavement-recycling/).

van del Vliet, Sanne. 2018. ‘Dura Vermeer Wint Prijsvraag Duurzaam Asfalt’. *Dura Vermeer*. Retrieved 15 June 2022 (https://www.duravermeer.nl/nieuws/dura-vermeer-wint-prijsvraag-duurzaam-asfalt/).

11 Appendix

11.1 LCA Modelling

In this section, the modelling elaborated in the GaBi software for the recycling techniques: Hot In-place and conventional hot recycling are shown in and However, for answering the questions of the study case regarding the environmental impact of mentioned techniques given the analysis period of 100 years, three different models are presented, these are displayed in , and The first two models were the base to develop all the scenarios where the treatments were repeated according to

11.1.1 LCA Model Hot In-place Recycling

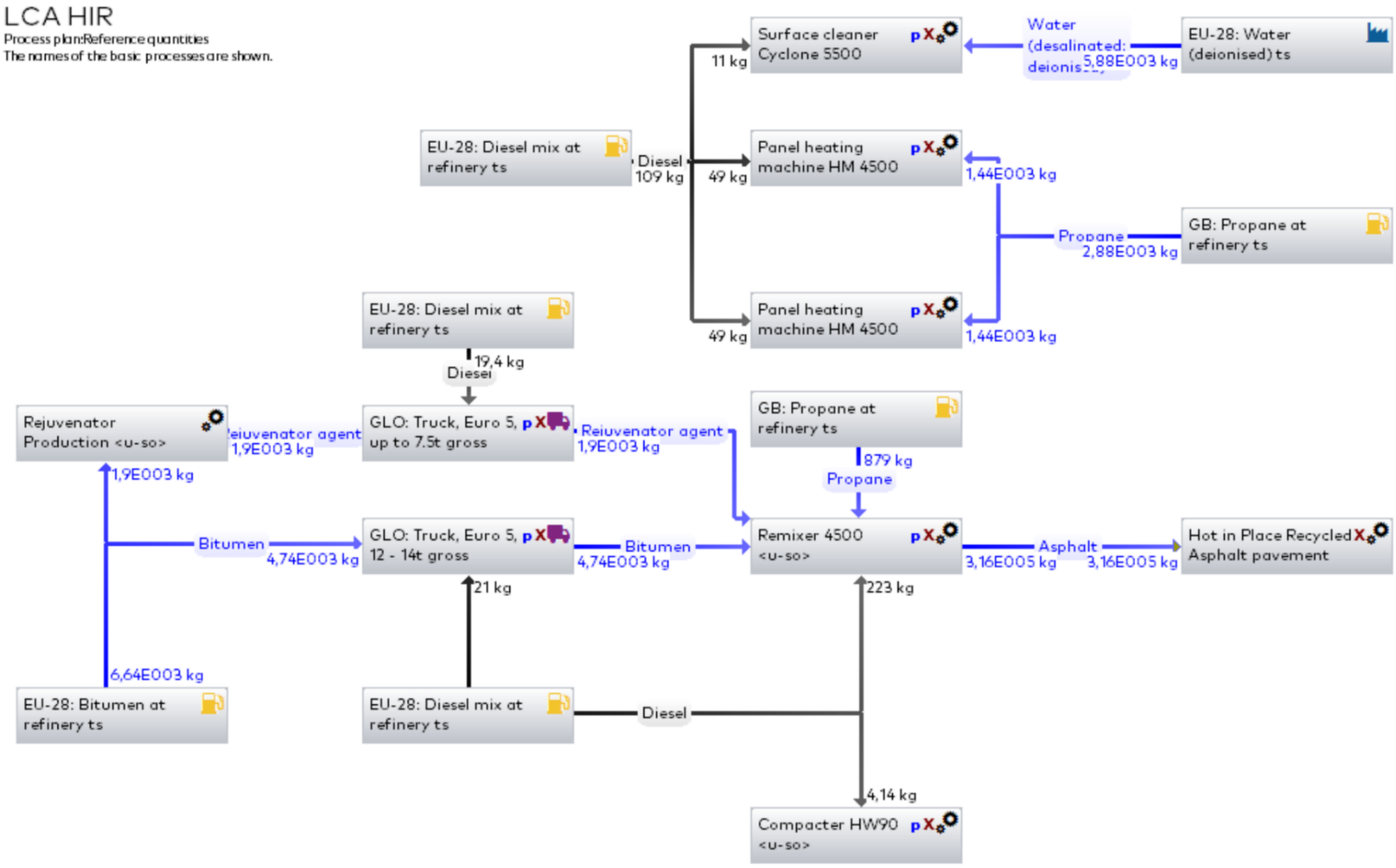


Figure 8 LCA Model of Hot In-place Recycling

11.1.2 LCA Model Hot Conventional Recycling

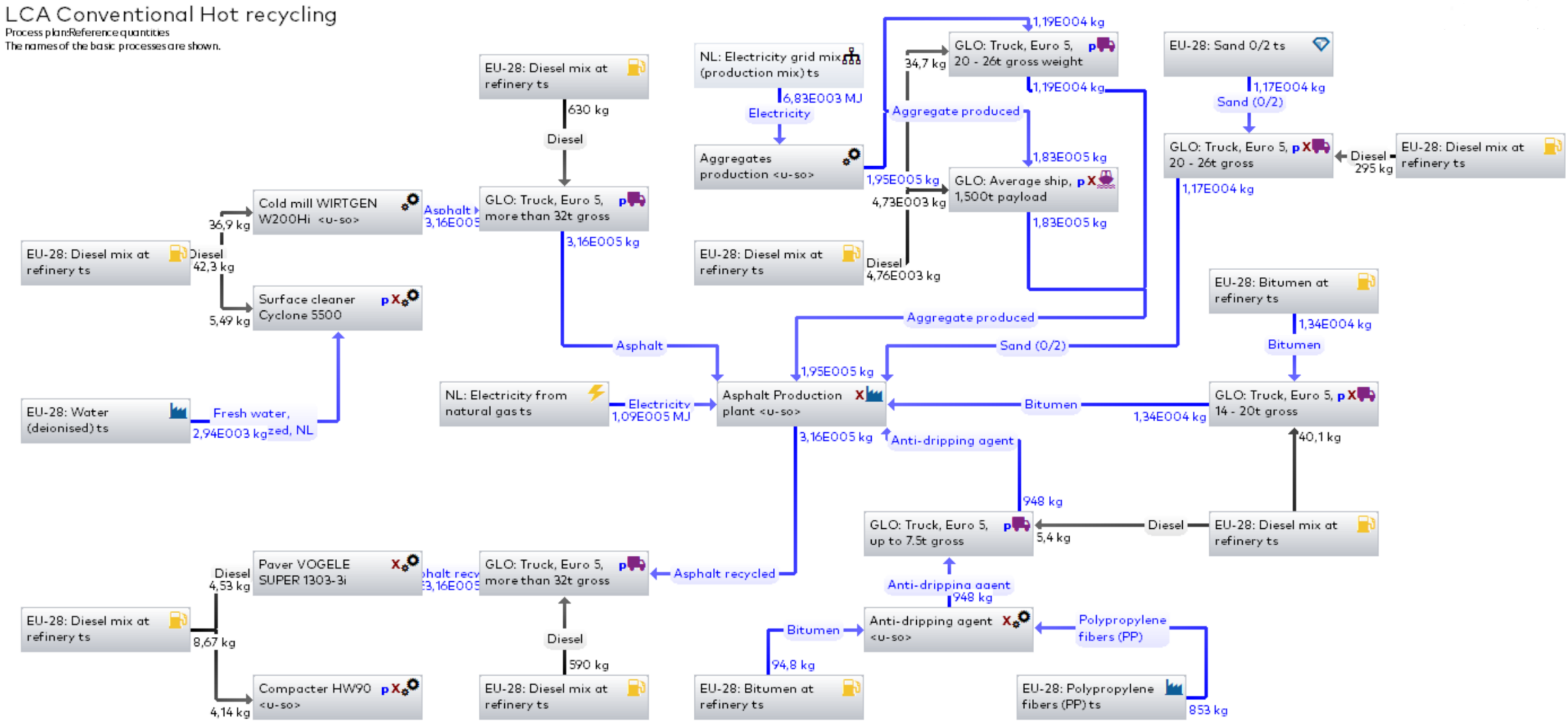


Figure 9 LCA Model of Conventional Hot Recycling

11.1.3 LCA Modelling HIR for 100 years (best scenario)

Figure 10 LCA Model of Hot In-place Recycling (HIR) for analysis period of 100 years (best scenario-lifespan 16 years)

11.1.4 LCA Modelling HIR for 100 years (worst scenario)

Figure 11 LCA Model of Hot In-place Recycling (HIR) for analysis period of 100 years (worst scenario-lifespan 10 years)

11.1.5 LCA Modelling Hot Conventional Recycling for 100 years

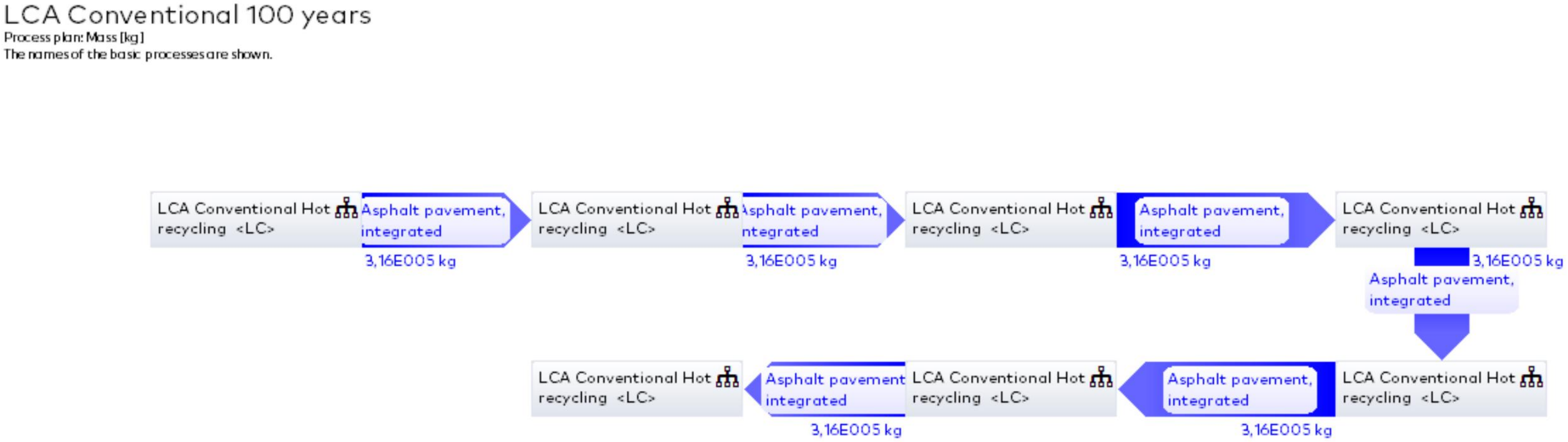


Figure 12 LCA Model for Conventional Hot Recycing method for the analysis period of 100 years