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# EDGAR
# Evaluation and Decision Process for Greener Asphalt Roads

## Demonstration of the methodology to assess sustainability

Deliverable D3.1
October, 2016



Project Coordinator:
BRRC – Belgian Road Research Centre

Project Partners:
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EDGAR

# CEDR Call 2013: Energy Efficiency
# EDGAR

## Evaluation and Decision Process for Greener Asphalt Roads

# Demonstration of the methodology to assess sustainability

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# Executive summary


The principal aim of the EDGAR project is to bridge the gap between innovation in the bituminous materials sector and adoption of the new technologies by national road administrations (NRAs). It aims to do this by providing road authorities with an assessment methodology that places sustainability information on the new technologies at their fingertips, enabling them to make informed decisions, by building an evidence base, and gaining reassurance to facilitate quick adoption of the technologies that provide the biggest advances towards sustainability for the highways sector and society as a whole.

In this document the utilisation of the methodology which has been previously developed in the framework of the EDGAR project (Deliverables 2.1 and 2.2) is demonstrated through a practical case study. The evaluation of the case study has been conducted using the EDGAR framework along with a multi-attribute decision making methodology (MADM). The MADM is utilised to classify the various alternatives and assist in the decision making process.

In this case study, five different alternative solutions are considered for a wearing course of a hypothetical road section. The different solutions are as follows:

1. Hot mix asphalt (HMA)
2. Warm mix asphalt (WMA)
3. Warm mix asphalt with recycled asphalt (WMA + RA)
4. Cold in-place recycled asphalt (CIR)
5. Hot mix asphalt with steel slag (HMA + steel slag)

The solutions are evaluated based on the basket of indicators proposed in Deliverables 2.1 and 2.2. The assessment tools used for some of the indicators have been slightly modified or are different from the tools recommended in Deliverable 2.2, in order to facilitate the assessment process. The flexibility of the EDGAR methodology allows this, giving each NRA the freedom to use the most appropriate assessment tools in the context of the practical application. Finally, based on the results of the analysis, the different alternatives are classified and the most sustainable solution is proposed.

It is important to emphasize that the principal aim of this case study is to demonstrate the methodology and not to make an exact or general assessment of the different alternative solutions. For example, if according to the data used in this study one alternative performs better in noise reduction than the others, this does not mean that this is always the case and the reader shall not interpret this as a general conclusion valid for any application.

Consequently, the final ranking obtained shall not be generalized either, since the ranking depends on the practical application (distance plant-work site, type of plant, traffic, …).

# 1 Introduction

## 1.1 Background

The approach to developing a sustainability assessment process of novel asphalt technologies for NRAs has been reported in previous deliverables (i.e. D2.1 and D2.2). The final methodology to assess bituminous materials and technologies has been presented in D2.2.
In D2.2, the final "basket of indicators" was identified and specific tools were proposed to measure or characterize these indicators. These indicators were chosen from a large set of potential indicators (environmental, economic and social), with their particular relevance to asphalt. Moreover the indicators that had little significance were eliminated in order to arrive at a limited and more manageable list of indicators.

## 1.2 Aim of the report

The application to a set of test cases is a necessary step to validate the methodology.

This report aims to describe the application of the methodology developed in the previous reports of the project EDGAR.

Besides demonstrating how the methodology works, the report also describes the difficulties encountered to obtain data and the critical points of the methodology. This shows how the methodology can be refined and improved for future use by NRAs.

# 2 EDGAR methodological framework

## 2.1 Basket of indicators

Deliverable D2.2 formulated the EDGAR methodology, addressing a particular decision making context that NRAs may encounter, when novel bituminous materials are proposed for use on the network. The decision making context and decision support offered by EDGAR outputs are presented in Figure 2-1 below.

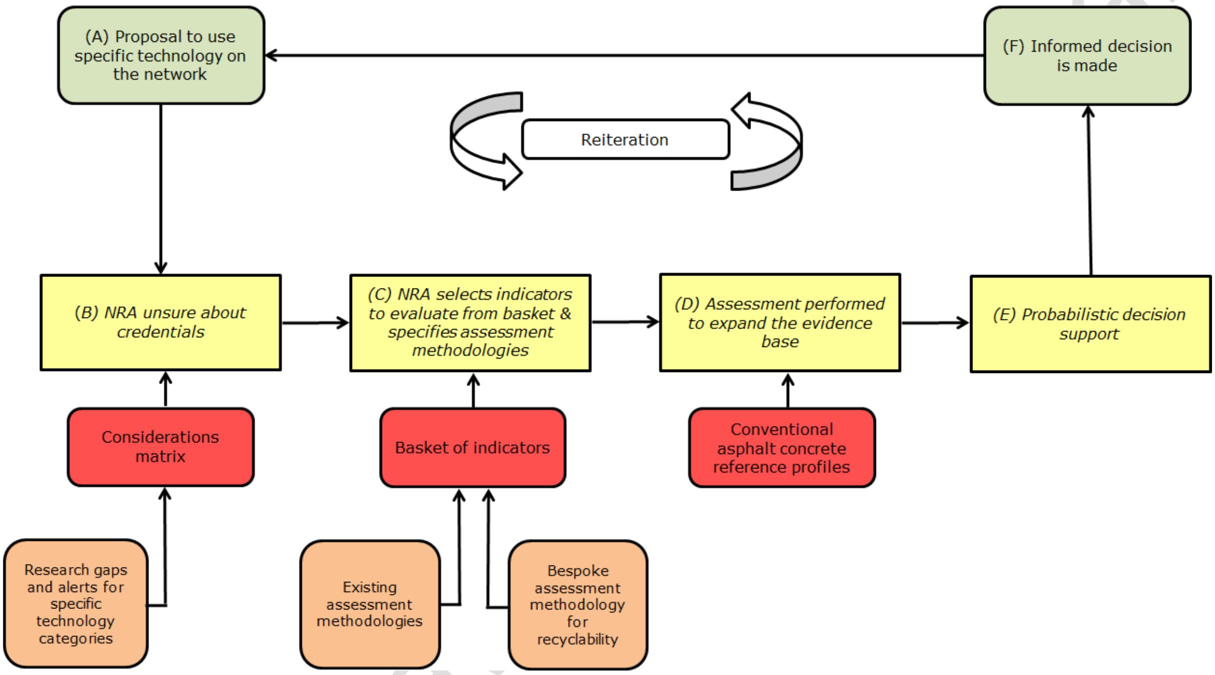



**Figure 2-1**: Decision making context and decision support from EDGAR

The 'basket of Indicators' and 'considerations matrix' were included in Deliverable D2.2.

The basket of indicators (Table 2-1) comprised eleven indicators covering environmental, social, economic and performance aspects.

**Table 2-1**: Basket of indicators

| Indicator | Description |
|---|---|
| Global warming potential | Evaluating the contribution to climate change of the used energy and materials expressed as carbon footprint |
| Depletion of resources | Assessing primary resource depletion |
| Air pollution | Assessing pollution potential on the basis of air pollution (non-$CO_2$ emissions), evaluating acidification and photochemical oxidation potentials |
| Leaching potential | Assessing pollution potential on the basis of leaching potential to groundwater |
| Noise | A health & safety consideration for road users and road neighbours related to surface characteristics |
| Recyclability | Assessing the potential for the valuable properties of asphalt's constituents to be retained into the next lifetime |
| Skid resistance | A health & safety consideration for road users related to surface characteristics |
| Responsible sourcing | Evaluating social aspects related to the supply of constituent materials |
| Financial cost | In life cycle cost (LCC) terms, measured as net present value |
| Traffic congestion | Costs related to traffic congestion due to installation of the material at the road site and the consequences for road users |
| Performance (durability) | Using a selection of test methods to assess different characteristics of bituminous materials that relate directly to how long it will last in the pavement structure |

The 'considerations matrix' suggests which indicators might be considered in relation to which families of bituminous materials. It is designed as a non-prescriptive guide that NRAs can utilise to select relevant indicators for assessment. The rows applicable to the test cases are highlighted in Figure 2-2.

| Technologies / Applicable sustainability indicator(s) | Global warming potential | Depletion of resources & waste management | Air pollution | Leaching potential | Noise | Skid resistance | Financial cost | Recyclability | Performance (durability) | Responsible sourcing | Traffic congestion |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Warm and half-warm asphalt technologies* | | | | | | | | | | | |
| Foam | ♣ | ♥ | ♣ | ♥ | ♥ | ♥ | ♠ | ♥ | ♠ | ♥ | ♣ |
| Organic additives | ♠ | ♥ | ♣ | ♠ | ♥ | ♥ | ♠ | ♠ | ♠ | ♠ | ♣ |
| Chemical additives | ♠ | ♥ | ♣ | ♠ | ♥ | ♥ | ♠ | ♠ | ♠ | ♠ | ♣ |
| *Cold and semi-cold asphalt technologies* | | | | | | | | | | | |
| Emulsion | ♣ | ♥ | ♣ | ♥ | ♥ | ♥ | ♠ | ♥ | ♠ | ♥ | ♣ |
| Foam | ♣ | ♥ | ♣ | ♥ | ♥ | ♥ | ♠ | ♥ | ♠ | ♥ | ♣ |
| *Asphalt recycling* | | | | | | | | | | | |
| Plant | ♣ | ♣ | ♣ | ♥ | ♠ | ♠ | ♣ | ♥ | ♠ | ♣ | ♥ |
| In situ | ♣ | ♣ | ♣ | ♥ | ♠ | ♠ | ♣ | ♥ | ♠ | ♣ | ♠ |
| *Secondary and open-loop recycled materials* | | | | | | | | | | | |
| Steel slag | ♠ | ♣ | ♥ | ♠ | ♠ | ♣ | ♣ | ♠ | ♠ | ♣ | ♥ |
| Fly ash | ♠ | ♣ | ♥ | ♠ | ♥ | ♥ | ♣ | ♠ | ♠ | ♣ | ♥ |
| Crumb rubber | ♠ | ♣ | ♦ | ♠ | ♣ | ♥ | ♣ | ♠ | ♠ | ♣ | ♥ |
| Shredded roofing | ♠ | ♣ | ♦ | ♠ | ♠ | ♠ | ♣ | ♠ | ♠ | ♣ | ♥ |
| Crushed glass | ♠ | ♣ | ♥ | ♠ | ♠ | ♦ | ♣ | ♥ | ♠ | ♣ | ♥ |
| *Alternative and modified binders* | | | | | | | | | | | |
| Bio-binders | ♠ | ♥ | ♠ | ♠ | ♥ | ♥ | ♠ | ♠ | ♠ | ♠ | ♠ |
| Sulphur | ♣ | ♥ | ♦ | ♠ | ♥ | ♥ | ♠ | ♠ | ♠ | ♠ | ♠ |
| PMB | ♠ | ♥ | ♥ | ♥ | ♣ | ♥ | ♠ | ♠ | ♣ | ♥ | ♣ |
| *Additives* | | | | | | | | | | | |
| Anti-stripping agents | ♣ | ♥ | ♥ | ♠ | ♥ | ♠ | ♠ | ♥ | ♣ | ♠ | ♣ |
| Pigments | ♥ | ♥ | ♥ | ♠ | ♥ | ♥ | ♠ | ♠ | ♠ | ♠ | ♠ |
| Fibres | ♥ | ♥ | ♥ | ♥ | ♥ | ♠ | ♥ | ♥ | ♣ | ♠ | ♣ |
| Rejuvenators | ♠ | ♣ | ♠ | ♠ | ♥ | ♥ | ♠ | ♠ | ♠ | ♠ | ♠ |
| | ♠ gaps in evidence; ♦ clear negative impact; ♣ potential positive; ♥ anticipated neutral | | | | | | | | | | |

**Figure 2-2**: Considerations matrix

It is anticipated that the NRAs will particularly want to investigate the 'gaps in evidence' and 'potential positive' impacts to (a) placate any doubts surrounding use of the technology and (b) potentially reinforce the claim to utilise the technologies. The 'clear negative' and 'anticipated neutral' impacts can be accepted with no further investigation required. Conventional asphalt material profiles should be used to provide a point of reference with which to compare the results obtained for the novel technologies, as indicated in Step D of the decision-making context (Figure 2-1).

## *2.2 Assessment methods*

In work package 2, a review was made of the various tools and methodologies available to assess the indicators. Based on this review, a recommendation of methodologies was presented in deliverable D2.2.

Considering the test cases in work package 3, it was found that some of the recommended methodologies were difficult to apply and it was decided to use an alternative method. Table 2.2 shows which tools or methods were finally used to assess the indicators for our practical test cases.

**Table 2-2** : List of utilised evaluation tools for each indicator

| Indicator | Evaluation tool or method |
|---|---|
| GWP | asPECT |
| Depletion of resources | Guinée Jeroen, van Oers Lauran (2002) |
| Air pollution (Acidification & photochemical oxidant formation) | ECORCE |
| Leaching potential | Milačič *et al.* (2011) (test case 5) |
| Noise | Göransson *et al.* (2013) (test case 5) |
| Skid resistance | Araujo *et al.* (2015) (test case 3); Chen and Wie (2015) (test case 5) |
| Financial cost | Nicholls *et al.* (2014) (the model) |
| Recyclability | EDGAR bespoke methodology |
| Performance (fatigue, rutting, water sensitivity) | $\varepsilon_{6,}$ rut depth and ITSR (from initial type testing) * |
| Traffic congestion | (Highways Agency, 2002) (the model) |

* note: fatigue failure strain $\varepsilon_6$ was not assessed for the test cases discussed in this report, which consider a wearing course (see chapter 3)

## *2.3 Multi-attribute decision making methodology*

A decision support methodology is required in order to rank the various alternatives and assist in the decision process. In order to provide the needed information, the utilisation of multi-attribute decision making (MADM) methods is necessary.

Multi-attribute decision making aims at assisting in the decision process, this by applying some methodologies that can be based on mathematical algorithms and/or experience. The outputs of the methods are usually a ranking of the various alternatives. MADM methods are used in a wide range of domains such as road choice, sustainability assessment, plant security assessment, etc. Basically, one can find two major trends in MADM processes: complete aggregation and partial aggregation methods. There is basically no perfect method, the choice depending on the problem to be solved. Indeed, both types of methods have their own specificities and present some advantages and disadvantages. For instance, complete aggregation methods ("American school") are very rigorous from a mathematical perspective but could sometimes appear to be a kind of simplification of the real process by applying mathematical tools in order to represent a given problem. For instance, it is quite common and comfortable to aggregate the various evaluations for each single criterion in a single normalized indicator called utility which characterizes the user preference; utility calculation is a sort of complete aggregation method. Partial aggregation methods ("European school") are less strict mathematically and more oriented in a decision process perspective. Partial aggregation methods take into account different outranking degrees and could sometimes conclude that alternatives cannot be compared. More details related to MADM methods can be found in Bueche (2011).

Based on a review of various MADM methods and on the experience of Bueche (2011), a decision support methodology has been developed. Note that the proposed methodology should finally aim at comparing different types of "green" asphalt mixtures and helping the road owner in the decision making process. The model can be divided in two phases that are the “input matrix” construction and the decision process procedure in which MADM methods will be used. These two phases are further described below.

In the first phase, the construction of the input matrix for the model consists in the data collection for the different alternatives, this for each selected criterion (*i.e.* assessment of the basket of indicators previously discussed). These various data form the so-called “input matrix”. Note that the completion of the input matrix can be time consuming and quite difficult and this should not be neglected. However, it is not compulsory to provide data for each alternative and criterion, this because some MADM methods can consider missing data in the evaluation by increasing the “unknown component” in the final alternatives ranking. In this phase, it is especially important to make a distinction between qualitative and quantitative criteria, but also to clearly identify the boundaries for the evaluation of each specific criterion.

The second phase consists in the multi-attribute decision making process that will lead to a ranking of the various alternatives. This phase has been developed in a four-level procedure in which each level provides its own contribution in the decision process with also an increase in the complexity in function of the level considered. Note that the methods applied are based on existing methods that have been adapted in the context of the present domain of analysis. A global overview of the evaluation methodology is proposed in Figure 2-; each specific level being detailed below.

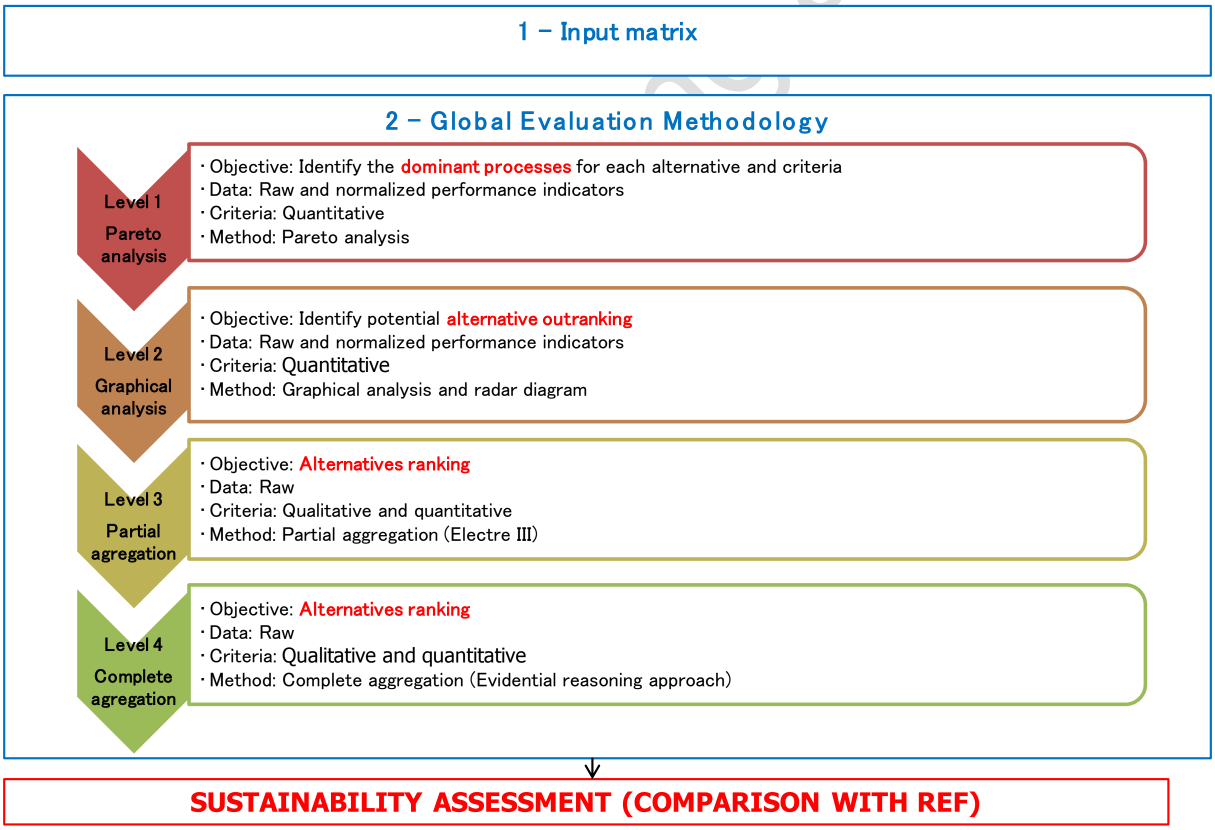



**Figure 2-3**: Overview of MADM methodology

The first level consists in a Pareto analysis in which each product is analysed separately and this for every quantitative criterion assessed in a life cycle perspective. This means that the first level will not lead to a comparison of the alternatives, this because each product is analysed separately, but will permit to identify the dominant processes and life cycle stages for a given criterion and alternative. Based on this, one can for instance assess if the allocated data collection efforts are efficient for a given life cycle stage. One can also mention that the impacts on the life cycle due to the utilization of some additives will also be highlighted in this first evaluation level this because each single contribution (for instance: bitumen extraction, additive production…) will be considered separately. Thus, depending on the considered materials, the dominant processes will be different.

The second evaluation level consists in a graphical comparison of the alternatives using some specific graphs and in particular so-called radar diagrams. In this phase, the various alternatives are compared for each criterion separately. This permits to identify a potential alternatives outranking. Thus, if a given alternative is better than the other for all the selected criteria, this will be highlighted in the second level meaning that higher level and more complex MADM methods as proposed in levels 3 and 4 are not necessary. It is however rare that an alternative proves to have better performances for all the selected criteria. The uses of such graphical representation is easy to perform and uses raw data without any specific interpretation (unless normalization), but it also presents some limitations and disadvantages. One can mention:

- Due to a normalization of the values, the difference between two alternatives cannot be quantified in a detailed manner.
- It is important to be careful with the visual interpretation of such representations, this because of the normalization factors.
- Unless there is an alternative outranking the other alternatives for all criteria, a rigorous ranking of the various alternatives cannot be provided. Some more developed MADM methods are thus required.

Multi-attribute decision making methods are introduced from the third level of the evaluation methodology. Using MADM permits in particular to consider user preference (*i.e.* weighting) and also to introduce some qualitative criteria that could not be considered in the first two evaluation steps. In MADM methods, every type of criterion can be considered (*i.e.* quantitative or qualitative), this independently of the life cycle boundaries of the criteria (*i.e.* criteria based on a life cycle evaluation as for instance GWP or on a single life cycle stage as for instance mechanical performances). Once a solution (*i.e.* ranking) is proposed, it is then necessary to perform sensitivity analyses allowing an evaluation of the ranking robustness and consequently an evaluation of the relevance of the proposed solution. Sensitivity analyses are usually performed by varying the weighting and the factors related to the MADM used (transformation matrix, preference degree …). The input data (*i.e.* evaluation of each alternative for each criterion) are usually not modified in a sensitivity analysis procedure. Based on the sensitivity analysis it is possible to assess the variations of the alternatives ranking and thus the solution robustness.

In the third evaluation level, a partial aggregation method called “Electre III” has been implemented. Electre methods are widely used, this especially in the domain of roadway and product environmental evaluation. This type of methods is particularly interesting, this because they consider different outranking degrees by comparison of two alternatives. Thus, some threshold values are considered, meaning that for a given criterion the alternative comparison can lead to an equal performance or a weak respectively strong outranking of an alternative. Using Electre III method, the various alternatives are compared by pairs in an iterative process that consists in testing all possible pairs.

The fourth evaluation level is performed using a MADM based on a complete aggregation method derived from the evidential reasoning approach (ER). This method presents the particularity of introducing some probabilistic aspects allowing to consider different confidence levels in the evaluation (data uncertainty) and also unknown data. To achieve this, the method applies so-called belief degrees (*i.e.* probability) for the different performance levels (very poor, poor, fair, good, excellent). As mentioned above, the applied algorithm consists in a complete aggregation method; a utility is finally calculated allowing a straightforward ranking of the various alternatives.

## 2.4 Model implementation

The developed methodology has been implemented in MS-Excel (VBA). This choice permits to perform easily some modification in the number of criteria and alternatives with also an access to the basic equations for the user. Note that a version of the implemented spreadsheet in the framework of the EDGAR project is freely available to NRAs by contacting the authors of this report.
A practical application of the developed methodology will be further described in chapter 3 (test case selection), 4 (assessment of the basket of indicators) and 5 (MADM analysis).

# 3 Test cases

## *3.1 Test case selection*

Deliverable D1.1 presented a review of various bituminous materials and technologies and their impact on sustainability. Based on this deliverable, test cases were selected by taking into account the following criteria:

- The relevance and importance of the test cases for today's practice;
- The evidence of a potential impact of the test cases on sustainability;
- The availability of data needed to assess the basket of selected indicators.

The project plan aimed at considering at least three test cases. For the sake of completeness, we decided to consider the following five cases:

**Case 1: HMA (reference)**
The first case to consider is classical *hot mix asphalt (HMA),* produced and paved in normal conditions using common equipment. This case will serve as a reference, since the goal of a methodology like EDGAR is usually to evaluate whether an alternative technique is more sustainable than the commonly used technique.

**Case 2: WMA**
Aiming at energy efficiency, the first idea is usually to reduce the heating in the asphalt plant by using *warm mix asphalt (WMA)* as alternative to hot mix asphalt (HMA). WMA is already used in most European countries. However, it was shown in deliverable D1.1 that there are various issues to which NRAs should remain alert. For example, the energy to produce some of the additives needed to reduce the production temperature may considerably counteract the energy gain in the heating process. Since the EDGAR methodology has been designed to encompass all these issues in the various life stages, it should be able to evaluate WMA techniques more correctly and this makes WMA a most interesting test case to consider. The test case of WMA using a synthetic wax additive was selected.

**Case 3: WMA with RA**
One of the conclusions of deliverable D1.1 was that recycling through the use of reclaimed asphalt (RA) should be among the test cases, since it is a widely used practice and the economic and environmental benefits are beyond discussion. It is also a technique that affects most of the selected indicators within the EDGAR methodology, and there is already a lot of knowledge and data available on asphalt recycling. In our third test case, using RA has been combined with WMA .

**Case 4: CIR**
A difficult but challenging test case to consider is the technique of Cold In-place Recycling (CIR). This technique was selected because the production and construction stages are very different from the other test cases considered. Deliverable D1.1 has taught us that we would probably face a lack of input data for this technique. However, CIR is generally thought of as a very sustainable technique (depending on the application and the worksite) and therefore it is important that we can at least improve the evaluation process by discerning more exactly what type of data and evidence is missing.

**Case 5: HMA with steel slag**
The use of steel slag as aggregate from a secondary source was considered as the fifth test case. It was reported in D1.1 that the higher density of the aggregates may increase the

ecological and financial costs of transport to the plant and from the plant to the worksite and the porosity of the aggregates may require more binder. These points shall be considered in the sustainability analysis. The most important issue however is the method of allocation of the impacts of steel slag (like $CO_{2eq}$) to either the steel production or the asphalt production process.

**Table 3-1**: Overview of the selected test cases

| | **Case** |
|---|---|
| 1 | HMA (*reference case)* |
| 2 | WMA |
| 3 | WMA with RA |
| 4 | CIR |
| 5 | HMA with steel slag |

## *3.2 Data and assumptions*

The test case data are partly based on test sections that have been constructed on a road in Assenede (Flanders region) in 2009, as part of a research project. The aim of these test sections was to compare two WMA sections with a reference HMA section. One of the WMA sections used a wax additive, the other used zeolites as a foaming agent. The sections with HMA and the WMA using wax were used to provide some of the data and conditions for test cases 1 and 2. The other three cases were not applied on the test sections, which were only intended to evaluate WMA techniques. In this paragraph, the test case data and additional assumptions on which the calculations in the next paragraph are based are described.

Mix compositions

The composition of each mixture is given in
Table **3-2**. Case 2 is identical to case 1, except for the replacement of 3 % by mass of the binder by wax. Case 3 is based on case 2, with 30 % of the binder and aggregate being replaced by RA. Case 4 is totally different, since it uses mainly in place milled aggregate, with the addition of bitumen emulsion, cement and fines. This composition was taken from data collected in relation to a previous CEDR project ‘CoRePaSol’ (Tabakovic, 2014). Finally, for case 5, the data are assumed to be the same as for case 1, except for the replacement of the porphyry aggregate by steel slag aggregate. Note that depending on the porosity of the steel slag used, higher amounts of bitumen may be needed. It is assumed that this is not the case here.

**Table 3-2**: Mix compositions (% by mass)

| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|
| | **HMA** | **WMA** | **WMA with 30 % RA** | **CIR** | **HMA with steel slag** |
| *Paving grade bitumen (70/100 EN 12591)* | 6.2 | 6.0 | 4.3 | | 6.2 |
| *Porphyry aggregates 2/6,3 (EN13043)* | 49.0 | 49.0 | 34.3 | | |
| *Steel slag 2/6.3* | | | | | 49.0 |
| *Porphyry aggregates 6,3/10 (EN 13043)* | 5.5 | 5.5 | 3.9 | | |
| *Steel slag 6.3/10* | | | | | 5.5 |
| *Sand (broken - nature porphyry (EN 13043)* | 8.2 | 8.2 | 5.7 | | 8.2 |
| *Sand (fluvial origin - EN13043)* | 24.6 | 24.6 | 17.2 | | 24.6 |
| *Filler (fabricated EN13043)* | 0.8 | 0.8 | 0.6 | | 0.8 |
| *Filler (baghouse)* | 5.7 | 5.7 | 4.0 | | 5.7 |
| *Wax (Sasobit®)* | | 0.2 | | | |
| *RA* | | | 30.0 | | |
| *Binder (residual from bitumen emulsion)* | | | | 2.6 | |
| *In place milled asphalt* | | | | 90.4 | |
| *Crushed rock fines* | | | | 5.9 | |
| *Cement* | | | | 1.0 | |
| **total** | **100** | **100** | **100** | **100** | **100** |

<u>Hauling distances and transport modes</u>

The data in tables 3-3 and 3-4 are taken from the Belgian test sections in Assenede (Belgium, Flanders region). The distances and transport modes can be considered as representative for the European practice in general. Return trips are also counted, but with less fuel consumption since the trucks are considered empty on the return trip.

**Table 3-3**: Transport to the plant (product stage A2)

| | Single trip distance (km) | mode |
|---|---|---|
| *Bitumen* | 60 | truck (20 tonne load) |
| *Porphyry aggregates* | 60 | truck (20 tonne load) |
| *Sand (fluvial)* | 60<br>1 | small ship<br>truck (20 tonne load) |
| *Sand (broken)* | 55 | truck (20 tonne load) |
| *Filler (fabricated)* | 210 | truck (20 tonne load) |
| *Steel slag* | 60 | truck (20 tonne load) |

**Table 3-4**: Transport from the plant to the worksite (product stage A4)

| | Distance (km) | mode |
|---|---|---|
| *Asphalt mix* | 50 | truck (20 tonne load) |

Other conditions and assumptions

The thickness of the surface course is 4 cm and the width of the lane is 3.5 m. These data are needed to convert one meter of asphalt section to one tonne of asphalt mixture (for a density of 2.4 t/m³), which is the functional unit (FU) used in the EDGAR methodology.
The mixing temperatures are shown in table 3-5. For cases 1 and 2, these were the mean temperatures actually measured after mixing at the asphalt plant.

**Table 3-5:** Mixing temperatures

| | **Case 1** | **Case 2** | **Case 3** | **Case 4** | **Case 5** |
|---|---|---|---|---|---|
| | **HMA** | **WMA** | **WMA with RA** | **CIR** | **HMA with steel slag** |
| *Mixing temperature* | 160 | 130 | 130 | 20 | 160 |

The density of HMA with steel slag is approximately 10% higher than the HMA with porphyry aggregates. Therefore, the impacts related to transport were increased by the same factor.

Except for the traffic congestion indicator, the stages of maintenance and repair (B2-B4) are not considered. This would require the prediction of future maintenance and repair scenarios and the estimation of the impact of these scenarios and there is too much lack of data and uncertainty related to these predictions. However, the EDGAR methodology indirectly accounts for this stage B2-B4 by considering the performance characteristics of the bituminous mixtures as a separate indicator. Mixtures with high performance will require less maintenance and repairs over the life time of the pavement.

The lifetime of the surface course is assumed to be 10 years. In a traditional life cycle analysis, the outcome is highly sensitive to this parameter (and to the maintenance and repair scenarios previously discussed). The EDGAR methodology on the other hand is not sensitive to this assumption, because the lifetime is indirectly assessed through the performance. For example, it can be expected that CIR will require more repairs and earlier replacement, but EDGAR does not require the user to quantify this. It is indirectly accounted for by its lesser performance.

# 4 Assessment of the basket of indicators

## 4.1 Global warming potential

_Evaluation tool_

GWP is expressed in $CO_2$e according to EN15804. It is calculated for the different test cases at the different life cycle stages using the AsPECT tool, fully Asphalt Pavement Embodied Carbon Tool. The tool is a result of collaborative research between the UK Highways Agency, Mineral Products Association, Refined Bitumen Association and TRL. AsPECT calculates the different contributions such as carbon footprint related to energy consumption during production, transport and material use.

_Input data and assumptions_

The $CO_{2e}$ of bitumen used in AsPECT (190 kg $CO_{2e}$/ tonne) originates from Eurobitume (2011), from the cradle to gate life cycle inventory of the process of bitumen production, excluding the flow associated with building of the infrastructure.
Values for stone aggregates and sand originate from the ICE database (2011). In the case of WMA the synthetic wax carbon footprint (5700 kg $CO_{2e}$/ tonne) value comes from the AsPECT database, referring to European Joint Research data. In the case of CIR, the carbon footprint of cement (913 kg $CO_{2e}$/ tonne) originates from the same source.

Transport trucks are considered charged one way, empty (at lower fuel consumption) for the return trip. Transport distances for steel slags are considered the same as for the virgin aggregates (see Table 3.3).
The aggregates for all transports are counted with an excess of 5 % to account for material losses and moisture.

Table 4-1 shows the average $CO_2$ emissions associated to transport by truck (average load of 20 tonne) and ship, according to the AsPECT database.

From asphalt plant data, a consumption of 5.8 L fuel per tonne asphalt is adopted for HMA, and estimated 1 L less for WMA production with 30 °C temperature reduction [Gonda, 2011]
For the carbon footprint due to the road use (stage B1) a pavement lifetime of 10 years for the asphalt top layer is considered, with an average traffic of 5950 cars and 1050 trucks per day (with respectively 130 and 920 g $CO_{2e}$/km).
For the steel slag asphalt it is assumed that steel slags have no carbon footprint, as being a rest product from the steel industry.

**Table 4-1** : standard $CO_{2e}$ emissions related to transport modes (AsPECT)

| | |
|---|---|
| Truck (20 tonne load) | 0.058 kg/tonne.km |
| Cargo ship | 0.0156 kg/tonne.km |

*Analysis for the considered test cases*

Table 4-2 shows the carbon footprint values for every life cycle stage for the considered cases. Additionally the bitumen and fuel consumption related to heating, transport and laying and demolition per tonne asphalt, are summarised in table 4-3 for all cases.

**Table 4-2**: Carbon footprint associated to different life stages (in kg $CO_{2e}$/tonne asphalt)

| Stage | ***1 - HMA*** | ***2 - WMA*** | ***3 - WMA with RA*** | ***4 - CIR*** | ***5 - HMA with steel slag*** |
|---|---|---|---|---|---|
| A1-raw materials | 16.9 | 26.8 | 21.8 | 18.0 | 13.9 |
| A2-transport to plant | 5.5 | 5.5 | 4.2 | 0 | 6.2 |
| A3-production in plant | 22.3 | 19.1 | 19.1 | 2.3 | 22.3 |
| A4-transport to worksite | 5.8 | 5.8 | 5.8 | 3.4 | 6.4 |
| A5-laying | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| B1-road use | 1.97e4 | 1.97e4 | 1.97e4 | 1.97e4 | 1.97e4 |
| B2-4-maintenance | 0 | 0 | 0 | 0 | 0 |
| C1-demolition | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 |
| C2-waste transport | 5.8 | 5.8 | 5.8 | 5.8 | 6.4 |
| C3-waste processing for recycling | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| C4-waste disposal | 0 | 0 | 0 | 0 | 0 |
| Total (excluding B1) | 62.7 | 69.4 | 63.1 | 33.5 | 59.6 |

**Table 4-3** : Bitumen and fuel consumption

| Consumption | ***1 - HMA*** | ***2 - WMA*** | ***3 - WMA with RA*** | ***4 - CIR*** | ***5 - HMA with steel slag*** |
|---|---|---|---|---|---|
| Bitumen [kg] | 62 | 60 | 42 | 26.2 | 62 |
| Heating [l] | 5.8 | 4.8 | 4.8 | 0.6 | 5.8 |
| Transport [l] | | | | | |
| - to plant | 1.9 | 1.9 | 1.3 | 0.29 | 2.0 |
| - to site | 2.1 | 2.1 | 2.1 | 0 | 2.3 |
| - from site (EOL) | 2.1 | 2.1 | 2.1 | 2.1 | 2.3 |
| Laying & demolition [l] | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |

Within the stage A of HMA the energy consumption in the plant takes the larger part (stage A3), in a lesser extent the embodied $CO_{2e}$ from bitumen use (stage A1) and the transport (stage A2 and A4). In the EOL stage C, transport accounts for about half of the EOL carbon footprint, more than the contribution due to demolition and processing of EOL products for recycling.

The contribution of synthetic wax, even in small quantities (in our case 0.2 m% in the mix) drastically increases the materials part within the production carbon footprint (by 60%). The reduced energy consumption due to lower production temperatures only compensates this partially (about 1/3 in our case).
Using RA in the WMA (case 3) decreases the materials carbon footprint (compared to case 2, WMA) mainly due to recycling binder from RA (and thus avoiding virgin binder with high $CO_{2e}$ content) but not to the level of HMA.

In the case of CIR (case 4) the carbon footprint linked to materials (stage A1) is almost equal to the reference case: the lower $CO_{2e}$ due to recycling is neutralised by using 1% cement with a very high $CO_{2e}$ value (Portland cement 913 kg CO2e/tonne).
The main advantage lies in saving the heating energy (1/3 of the life cycle value of the reference case (excluding road use), and in a minor extent saving on transport $CO_{2e}$ costs.

In the case of steel slag as alternative for virgin aggregates there is a (rather limited) gain in material carbon footprint but this is compensated by higher transport $CO_{2e}$ costs due to a larger (~10%) specific mass of steel slag asphalt.

In these test cases, carbon footprint due to road use (stage B1) accounts for more than 99.6% of the total carbon footprint. Although this contribution is excluded in the EDGAR decision process, the numbers are shown in table 4-2 to demonstrate that an NRA can potentially achieve large gains by acting on the use stage. For example, they can optimize rolling resistance by regular maintenance, impose the right tyre inflation, charge toll on fuel emission by vehicles…

To conclude, the global warming potential indicator expressed in carbon footprint results in a life cycle value of ~63 kg $CO_{2e}$ per tonne for the reference HMA, excluding stage B1.
Cases 3 and 5 diverge in a smaller extent from this value:

- steel slag HMA, -5%
- WMA with RA, +0,6%

Cases 2 and 4 give larger differences compared to HMA:

- WMA without RA, +11%
- CIR, -47%

It must be reminded that the considered lifetime is 10 years for all cases. In case the performance would be inferior for one of these cases, this would result in a reduction of the lifetime. In the EDGAR methodology, this will be penalised by the performance indicator. This approach was chosen by the project team, because the uncertainty of existing lifetime prediction models is at this moment still quite large. More confidence is given to the performance characteristics, which are measured as part of the initial type testing of bituminous mixtures.

Generally spoken, reducing plant energy, as well as decreasing material quantities with a high $CO_{2e}$ content, such as virgin bitumen, cement or synthetic waxes, is efficient to reduce the carbon footprint.
Recycling RA is an efficient way to reduce carbon footprint, mainly due to the reduced need for virgin bitumen.
Also transport contributes in a considerable degree to the carbon footprint. In situ techniques or measures to limit distances for sourcing materials or plant to site transport, are beneficial.

*Critical discussion on this indicator*

The GWP indicator makes it possible to compare different techniques to each other and quantify differences in terms of $CO_{2e}$. This enables to assess the relative importance of certain changes in a process of the life cycle to conventional choices such as using recycled materials, energy use changes in the production and using additives.

Calculation of the carbon footprint in a life cycle perspective is highly sensitive to the estimation of the expected life time. In these test cases, we assumed an equal lifetime for all cases. There is a lot of evidence from various research projects that WMA and the use of RA are feasible without inferior performance and thus with equal expected lifetime (if performance characteristics are equal). However, for the CIR technique, there is less evidence that this will be the case. Therefore, the very positive effect of CIR on carbon footprint (-43 %) has to be considered with higher caution.

When also the $CO_2$e emissions due to traffic in the use stage are taken into account, the related carbon footprint totally overshadows the $CO_{2e}$ contributions from the production, construction and EOL stages: Road use accounts for 99.6% of the total $CO_{2e}$ value.
This highlights the importance of all possible measures to reduce traffic $CO_2$ values. In case of a surface course, low rolling resistance is expected to have a huge impact on the total life carbon footprint. If e.g. the rolling resistance could be reduced by only 5%, resulting in an estimated 1% energy saving during the road use stage, the gain in $CO_2$ in our test cases is already exceeding by a factor three the total $CO_2$ from production, construction and EOL stage.

## *4.2 Depletion of resources*

*Evaluation tool or method*

The depletion of resources was evaluated in terms of abiotic depletion potential (ADP) according to the recommendation from the EN 15804. This method is based on the expression of the amount of resource extracted (used during the pavement life cycle in this estimation) compared to the natural reserve using the depletion of the element antimony as reference (Guinée and van Oers 2002).
As expressed in the considerations matrix (Figure 2-2), the depletion of resources is expected to positively impact the sustainability assessment of asphalt production technologies containing recycled material (both recycled asphalt and secondary materials like fly ash, crumb rubber, etc.) compared to the HMA case.

**Table 4-4** : Matrix of consideration for depletion of resources

| **Indicator** | ***1 - HMA*** | ***2 - WMA*** | ***3 - WMA with RA*** | ***4 - CIR*** | ***5 - HMA with steel slag*** |
|---|---|---|---|---|---|
| Depletion of resources | - | - | ✓ | ✓ | ✓ |

*Input data and assumptions*

The ADP of fossil fuels and heating values of oil and gas originate from Guinée and van Oers (2002). It should be noticed that the mentioned report offers three different scenarios for the evaluation of the ADP: ultimate resources, base resources and economic resources. In this evaluation the base resources scenario (it includes all the resources that have the potential of becoming economically available in the future) has been considered the most appropriate.
The ADP has been calculated only for the fossil resources, such as bitumen, gas and fuel, considered in the analysis. Other resources such as the aggregates have not been taken into account. The size of the resources for mineral aggregates is generally considered infinite and therefore negligible in the evaluation of the indicator (Guinée and van Oers 2002). Table 4-5 shows the values of ADP per kg of fossil fuel extracted which have been assigned to bitumen, gas and fuel use.

**Table 4-5** : ADP per kg of fossil material extracted

| | |
|---|---|
| Bitumen | 3,26E-06 |
| Gas (for heating) | 3,03E-06 |
| Oil (for transport, laying, demolition) | 3,26E-07 |

Since no specific ADP is found for the bitumen, the value presented in the previous table corresponds to the ADP of oil minus one decimal. This is a rough estimation, based on the low amount of bitumen in crude oil and the fact that not all crude oils are suitable for bitumen production.
In all cases the materials were considered heated in the plant with gas.

*Analysis for the considered test cases*

Table 4-6 shows the abiotic depletion due to the production of one tonne of asphalt for each of the considered test cases. These results were obtained by multiplying the ADP values in Table 4-5 to the bitumen, gas and fuel consumption that has been estimated in the previous paragraph on GWP (Table 4-3).

According to this evaluation of the depletion of resources, the indicator appears to be strongly dependent on the bitumen quantities. The case studies with recycled asphalt, and therefore a lower amount of virgin bitumen, scored the best in terms of depletion of resources. No large differences are observable among the HMA, WMA and steel slag cases.

**Table 4-6** : AD (Abiotic Depletion) per tonne of asphalt produced

| | ***1 - HMA*** | ***2 - WMA*** | ***3 - WMA with RA*** | ***4 - CIR*** | ***5 - HMA with steel slag*** |
|---|---|---|---|---|---|
| Bitumen | 2,02E-04 | 1,96E-04 | 1,37E-04 | 8,55E-05 | 2,02E-04 |
| Heating | 1,75E-05 | 1,45E-05 | 1,45E-05 | 1,82E-06 | 1,75E-05 |
| Transport | | | | | |
| - To plant | 6,07E-07 | 6,07E-07 | 4,24E-07 | 7,83E-08 | 6,52E-07 |
| - To site | 6,85E-07 | 6,85E-07 | 6,85E-07 | - | 7,50E-07 |
| - From site | 6,85E-07 | 6,85E-07 | 6,85E-07 | 6,85E-07 | 7,50E-07 |
| Laying and demolition | 4,89E-07 | 4,89E-07 | 4,89E-07 | 4,89E-07 | 4,89E-07 |
| Total | 2,22E-04 | 2,13E-04 | 1,54E-04 | 8,85E-05 | 2,22E-04 |

*Critical discussion on this indicator*

For bituminous mixtures, consumption of virgin bitumen is the main contribution to abiotic depletion, followed by gas and oil consumption for fuel. Therefore, this indicator, as evaluated in these case studies, is strongly dependent on the use of recycled material in order to reduce the use of raw resources (virgin bitumen).

## 4.3 Air pollution

In deliverable D2.2, we have defined the indicator “air pollution” as an indicator for assessing pollution potential on the basis of non-$CO_2$ emissions. It was shown that acidification and photochemical ozone creation are the two most important impacts resulting from asphalt production.

**Acidification potential (AP) (unit: kg equivalent of $SO_2$)** is due to emission of pollutants such as sulphur oxide ($SO_2$) and nitrogen oxides ($NO_x$) into the atmosphere through the combustion of fossil fuels. Acid rain occurs when $SO_2$ and $NO_x$ react in the atmosphere with water, oxygen and other chemicals to form various acidic compounds. Acidification is assessed in relation to the release of $H^+$ ions. Impact assessment factors have been

developed that relate $H^+$ production to the mass of relevant emissions and in relation to the acidification potential of sulphur dioxide (Cowell and Clift, 1999).
Emissions released from the production of asphalt could contribute to the production of localised acidification depending on prevailing weather conditions.

**Photochemical ozone creation potential (POCP) (unit: kg equivalent of ethylene)** is due to interdependent reactions between photochemical oxidants, nitrogen oxides ($NO_x$) and UV light in the atmosphere. Photochemical ozone creation is particularly prevalent in cities and can have a toxic effect on plants and human health when present in excessive concentrations. In relation to asphalt pavements, the transportation of materials is the process that contributes the most towards photochemical ozone creation (Schenck, 2000).

*Evaluation tool or method*

For assessment of these indicators in the different test cases, the ECORCE tool (French acronym for "ECO-comparator applied to Road Construction and Maintenance") developed by IFFSTAR has been used. ECORCE software is designed to evaluate environmental impacts of road construction and is inspired by the Life Cycle Analysis methods according to NF EN ISO 14040 (Jullien et al., 2014)

*Input data and assumptions*

The assumptions regarding the transport of the material and the traffic during the use stage, are identical to what has been made for the global warming potential indicator. Moreover for the case of HMA with steel slags, since steel slags have approximately 10% higher density, therefore the impact of transport has been increased by the same factor in comparison with the reference case (HMA). For the CIR case, the emissions of laying of asphalt are assumed to be 10% of the emissions of the hot mix asphalt case. In Table 4-7 the data regarding the transport stage is presented.

**Table 4-7** : Standard acidification and photochemical oxidation related to transport modes (ECORCE)

| | | |
|---|---|---|
| *Truck with 20 tonne load (road transport)* | 1.17E-04 | kg eq. SO2/tonne.km |
| | 8.90E-05 | kg eq. Ethylene/tonne.km |
| *Small ships (river transport)* | 1.08E-05 | kg eq. SO2/tonne.km |
| | 1.68E-05 | kg eq. Ethylene /tonne.km |
| *Bigger ships (sea transport)* | 5.53E-05 | kg eq. SO2/tonne.km |
| | 1.12E-05 | kg eq. Ethylene /tonne.km |

*Analysis for the considered test cases*

The input matrix concerning acidification and photochemical ozone creation is presented in Table 4-8. The reference case (HMA) has the highest acidification and photochemical ozone creation potential of all the test cases. Identical to what was observed for the GWP indicator, approximately 99.3% of the acidification is due the use phase (B1) of the pavement life. This value is chosen to be ignored in the decision making model, because it would obscure the differences due to the asphalt technology. Unfortunately, no data regarding photochemical oxidation during the use stage was found in the literature. It has to be mentioned that the details of the traffic for use stage calculations are given in chapter 4.1.
When the road use stage is not considered, for all of the cases except case 4 (CIR), the highest level of air pollution belongs to the production stage with approximately 44% to 48% of the total life cycle air pollution. The next high polluting stage, belongs to the production of the bitumen. This amount can be reduced by using more RA. For case 4, the majority of the

air pollution is divided between the production stage of cement, bitumen production and laying of the asphalt. Furthermore it has to be mentioned that the air pollution of case 4, without taking the use stage into account is approximately 25% of the reference case.

**Table 4-8**: AP and POCP (per tonne of asphalt)

| *Stage* | ***1 - HMA*** | | ***2 - WMA*** | | ***3 - WMA with RA*** | | ***4 - CIR*** | | ***5 - HMA with steel slag*** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *kg SO2 eq* | *kg Ethylene eq* | *kg SO2 eq* | *kg Ethylene eq* | *kg SO2 eq* | *kg Ethylene eq* | *kg SO2 eq* | *kg Ethylene eq* | *kg SO2 eq* | *kg Ethylene eq* |
| *A1* | 3.6E-02 | 1.5E-02 | 3.5E-02 | 1.5E-02 | 3.0E-02 | 1.2E-02 | 2.0E-02 | 7.0E-03 | 3.2E-02 | 1.4E-02 |
| *A2* | 1.0E-02 | 8.0E-03 | 1.0E-02 | 8.0E-03 | 7.0E-03 | 6.0E-03 | 1.0E-03 | 1.0E-03 | 1.1E-02 | 8.0E-03 |
| *A3* | 5.6E-02 | 3.7E-02 | 5.5E-02 | 3.6E-02 | 5.5E-02 | 3.6E-02 | - | - | 1.2E-02 | 9.0E-03 |
| *A4* | 1.2E-02 | 9.0E-03 | 1.2E-02 | 9.0E-03 | 1.2E-02 | 9.0E-03 | - | - | 1.3E-02 | 1.0E-02 |
| *A5* | 1.0E-03 | 1.0E-03 | 1.0E-03 | 1.0E-03 | 1.0E-03 | 1.0E-03 | 0.0 | 0.0 | 1.0E-03 | 1.0E-03 |
| *B1* | 1.8E+01 | - | 1.8E+01 | - | 1.8E+01 | - | 1.8E+01 | - | 1.8E+01 | - |
| *B2-4* | - | - | - | - | - | - | - | - | - | - |
| *C1* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *C2* | 1.2E-02 | 9.0E-03 | 1.2E-02 | 9.0E-03 | 1.2E-02 | 9.0E-03 | 1.2E-02 | 9.0E-03 | 1.3E-02 | 1.0E-02 |
| *C3* | - | - | - | - | - | - | - | - | - | - |
| *C4* | - | - | - | - | - | - | - | - | - | - |

*<u>Critical discussion on this indicator</u>*

As it was said before, excluding the use stage, the production stage is the most polluting stage in the life cycle of asphalt mixtures. Therefore, using alternative technologies in order to lower the production temperature can be beneficial in order to lower the air polluting emissions. Other measures, like improving the efficiency of burners at the plant, are equally beneficial to reduce air pollution.

## *4.4 Leaching potential*

The Matrix of Considerations (Figure 2-2) suggests that leaching potential should be evaluated in relation to the WMA, WMA with RA (focussing on the WMA element) and HMA with steel slag test cases, alongside the reference HMA case.

**Table 4-9 :** Matrix of consideration for leaching potential indicator

| **Indicator** | ***1 - HMA*** | ***2 - WMA*** | ***3 - WMA with RA*** | ***4 - CIR*** | ***5 - HMA with steel slag*** |
|---|---|---|---|---|---|
| **Leaching potential** | ✓ | ✓ | ✓ | **-** | ✓ |

The premise behind assessing WMA technologies for leaching potential is that the additives incorporated present an as yet unquantified potential to leach to groundwater, since environmental risk assessments are not available for the specific products used. The use of steel slag will always merit some further investigation since the composition of any given slag will vary according to the composition of the materials used in the steel production process, and the impurities present in those materials. Pig iron, the key constituent in basic oxygen steel-making, is not pure and will contain some carbon, silica and other solid impurities. If the slag results from use of an electric arc furnace, which is predominantly used for recycling steel, then the impurities present will differ. Since steel slag is the waste product that remains from the production of steel, it is the ultimate destination of any impurities that may be transferred to downstream products that utilise it as a constituent material.

*Evaluation tool or method*

The approach taken to evaluating leaching impacts was to (i) obtain the raw data from a standardised leaching test and then (ii) apply characterisation factors to equate the quantities of pollutants obtained to a potential 'number of cases' of human toxicity.

*Input data and assumptions*

Milačič *et al.* (2011) conducted leaching tests to assess the leaching potential of asphalt materials containing steel slag obtained from electric arc furnaces in Slovenia. A Dutch standard (NEN 7345, 1995) was followed in order to estimate the long-term environmental impacts of leaching using tests based on diffusion at a liquid-solid ratio of 5 $Lkg^{-1}$. Samples of asphaltic materials, in both a granular and monolithic state, containing conventional limestones aggregates and the alternative EAF slags, were tested with pure water leachate. The test results for the more toxic elements are reproduced in Table 4-10.

**Table 4-10**: Leaching test results reproduced from Milačič *et al.* (2011)

| **Chemical species** | **Concentration in pure water leachate ($mgL^{-1}$)** | | | |
|---|---|---|---|---|
| | **Compact asphalt with limestone** | **Compact asphalt with steel slag** | **Ground asphalt with limestone** | **Ground asphalt with steel slag** |
| Cr (IV) | BDL | BDL | 0.018 | 0.025 |
| Cu | 0.054 | 0.034 | 0.061 | 0.055 |
| Zn | 0.01 | 0.009 | 0.009 | 0.01 |
| V | 0.004 | 0.006 | 0.164 | 0.296 |
| Pb | 0.094 | 0.111 | 0.136 | 0.145 |

The results indicate toxicities of similar magnitude for compact and ground asphalt respectively, with the steel slag samples being slightly more toxic. The greater surface area of the ground samples gives more potential for toxic release and consequently these figures are higher than for the monoliths.

The significance of the concentrations obtained from the leaching tests could be evaluated with no further analysis by comparing the results obtained to the maximum permissible concentrations specified by national drinking water guidelines. Indeed this was the approach taken by Milačič *et al.* (2011), concluding that no pollutant thresholds had been exceeded in the leachates that they obtained from the steel slag asphalts.

However, for the purpose of the EDGAR MADM modelling approach, there was a need to normalise the concentrations of different pollutants obtained to one single measure. The measure selected was comparative toxic units (CTUh), the estimated increase in morbidity in the total human population, per unit mass of a chemical emitted. The concentrations of pollutants obtained from the leaching tests needed to be converted to this single measure. This involved:

(i) Converting leachate concentrations to absolute concentrations ('cumulative releases') in mg per kg of asphalt.
(ii) Determining human toxicity potentials for the different pollutants using the USEtox 2.0 method (Hauschild *et al*., 2008).

(iii) Applying the potentials to the cumulative releases to arrive at an overall toxicity potential for a tonne of asphalt containing slag aggregates.

By virtue of using a liquid-solid ratio of 5 $Lkg^{-1}$, Milačič *et al.* (*ibid.*) had approximated an annual infiltration of rainwater at a rate of 0.25 $Lkg^{-1}year^{-1}$ that might be expected through a bound pavement layer over a period of 20 years according to an estimate made by Bouvet *et al.* (2004). In practice, infiltration rates may be higher, depending on local climatic conditions. Conversely, surface course materials may be in place for less than 20 years in practice, so overall use of this liquid-solid ratio seemed a reasonable approximation.

The ground samples were also subject to a liquid-solid ratio of 5 $Lkg^{-1}$ in the experimental procedure of Milačič *et al.* (2011). This ratio was deemed too high to be representative of infiltration rates that stockpiles of RA might be subjected to at end-of-life, since:

- Stockpiles are much more transient in nature and would be in place for shorter periods of time (i.e. weeks) before being utilised.
- The surface area to mass ratio of stockpiles would be considerably less than for pavements *in situ*, since their depth is generally far greater.

Both of these factors would leave RA less exposed to rainfall, resulting in low infiltration rates. The leaching potential of RA in stockpiles was therefore concluded to be negligible in relation to the test case 'HMA with steel slag'. However, NRAs do have the option to test the leaching potential of stockpiles if they have a particular concern.

To arrive at human toxicity potentials for the toxic chemical species released in the leaching test, USEtox 2.0 potentials for releases to continental freshwater were obtained from Rosenbaum *et al*. (2011). The potentials and the scaled-up results for one tonne of asphalt are presented in Table 4-11.

**Table 4-11**: USEtox 2.0 potentials applied to releases from one tonne of asphalt

| **Chemical species** | **USEtox 2.0 human toxicity characterisation factor (cases/kgemitted)** | **Human toxicity potential (cases/tasphalt)** | |
|---|---|---|---|
| | | **Compact asphalt with limestone** | **Compact asphalt with steel slag** |
| Cr (IV) | 2.20E-11 | - | 2.55E-13 |
| Cu | 1.54E-03 | 5.35E-08 | 6.05E-08 |
| Zn | 3.83E-03 | 2.47E-08 | 2.23E-08 |
| V | 4.58E-03 | 1.03E-08 | 4.85E-07 |
| Pb | 5.67E-03 | 3.44E-07 | 4.98E-07 |
| **TOTAL (cases/t asphalt)** | | **4.33E-07** | **1.06E-06** |

Arriving at the overall toxicity potentials per tonne of asphalt required use of two main assumptions:

- The results of the leaching tests can be scaled-up using a linear relationship. Milačič *et al.* (2011) used a sample size of 1.55 kg of asphalt; the results are expressed per tonne.
- The leaching concentrations reached by Milačič *et al.* (2011) were assumed to be indicative of a 'maximum possible release' *in situ* in a road pavement. Ideally the results of leaching tests should have been expressed in terms of 'cumulative release' (mg) in order for the USEtox 2.0 potentials to have been applied directly, however, leachate potentials (in mg/L) were instead used. This was not an unreasonable assumption since, as previously discussed, the liquid-solid ratio of 5 $Lkg^{-1}$ adequately reflected infiltration rates of rainwater into an *in situ* road pavement over its typical lifetime. Furthermore, according to studies by Hill (2004) and Reid *et al*. (2007), much

of the leaching of the chemical species evaluated would have been expected to take place at lower liquid-solid ratios, and something close to maximum leaching would have taken place by the time 5 $Lkg^{-1}$ has been reached. If the same methodology is used by NRAs, then a recommendation would be for the results of leaching tests to be expressed in terms of ‘cumulative leaching’ to minimise any ambiguity surrounding the use of leaching concentrations.

In relation to the WMA test cases, a literature search did not yield suitable data that could be used to assess the leaching potential of the specific technologies investigated. In this situation the EDGAR methodology suggests that leaching tests should be conducted according to PD CEN/TS 16637-1:2014, PD CEN/TS 16637-2:2014 and PD CEN/TS 16637-3:2016 to determine the leaching potentials. Part 1 of the standard provides guidance for the determination of leaching tests for construction products. Part 3 applies to materials in a granular state (e.g. to simulate bituminous materials that have been planed-off the road at end-of-life and are stored in a stockpile). Part 2 of the standard applies to monoliths and could be used to simulate bituminous materials *in situ* in a pavement structure. Laboratory tests of this type, collecting cumulative leaching data at suitable liquid-solid ratios, would yield results that can be characterised using the USEtox impact potentials in the same way that has been described for the results obtained from laboratory tests on steel slag. European guidance for the impact assessment based on the leaching test methods has not yet been published, so national guidance should be used (if available) or risk assessments carried out for typical use scenarios.

*Critical discussion on this indicator*

The requirement for standardising a test method to assess the leaching potential of construction materials was realised by CEN some years ago and two test methods have now been published. These methods and the Dutch NEN 7345 standard provide suitable frameworks to assess leaching potentials of asphaltic materials. Adequate attention should be paid to ensure that the liquid-solid ratio reflects water infiltration rates that would be experienced by the pavement *in situ*. To achieve the desired liquid-solid ratios, tests will sometimes need to be lengthy (e.g. 180 days) and perhaps will be costly as a result. The lack of European guidance on risk assessment based on the test results is a potential problem and could lead to different methods being used in different countries. CEN TC351 WG1, which produced the three parts of CEN/TS 16637 is working on this aspect and guidance is expected in the next few years.

## 4.5 Noise reduction

The Matrix of Considerations (Figure 2-2) suggests that noise should be evaluated in relation to the WMA with RA (focussing on the RA element), CIR and HMA with steel slag test cases, alongside the reference HMA case. The aim is to measure the noise properties of the surfaces in use, as opposed to during construction or demolition.

**Table 4-12** : Matrix of consideration for Noise indicator

| Indicator | 1 - HMA | 2 - WMA | 3 - WMA with RA | 4 - CIR | 5 - HMA with steel slag |
|---|---|---|---|---|---|
| Noise | ✓ | - | ✓ | ✓ | ✓ |

*Evaluation tool or method*

A literature search was carried out to find relevant past research that could be used to inform the test cases. In the absence of laboratory drum measurements, the recommended methodology for quick noise tests from Deliverable 2.2, data using other methods were sought.

*Input data and assumptions*

A study by Göransson *et al.* (2013) measured the noise produced from an 8 mm SMA containing steel slag in Sweden using a microphone mounted under a car tyre, relative to an 8 mm hot-mix asphalt. Noise levels of 92.5 dB(A) were recorded for the HMA and 91.7 dB(A) for the steel-slag mixture. With such a small difference, no real significance can be asserted from these results.

In relation to the recycling test cases (WMA with RA and CIR), no data could be found from past research to evaluate noise. If noise performance associated with recycled mixtures is a concern for NRAs then laboratory tests or full-scale trials could be commissioned to evaluate tyre-pavement noise through close-proximity (CPX) method or otherwise. However, since noise from tyre-pavement interaction is fundamentally related to texture and porosity (through mechanisms as absorption and flow resistance) of the pavement surface, more attention should be paid to the type of mixture being specified rather than the presence of recycled asphalt therein.

*Critical discussion on this indicator*

It is quite difficult to measure noise levels before a bituminous material has been laid in at least a trial section and can be subjected to close proximity (CPX) or statistical by-pass (SPB) monitoring. Even if this large scale testing is undertaken, there is no guarantee that the same noise characteristics will be maintained throughout the material's lifetime, since characteristics may change with time (e.g. porous asphalt may become clogged etc.). For these reasons, measuring noise characteristics of materials prospectively is quite an undertaking and can be expensive. Laboratory drum methods of measurement may prove to be more convenient to evaluate the properties of new materials but these are not widely available at present.

## 4.6 Skid resistance

The Matrix of Considerations (Figure 2-2) suggests that skid resistance should be evaluated in relation to the WMA with RAP (focussing on the RAP element), CIR and HMA with steel slag test cases, alongside the reference HMA case.

**Table 4-13**: Matrix of consideration for skid resistance indicator

| Indicator | *1 - HMA* | *2 - WMA* | *3 - WMA with RA* | *4 - CIR* | *5 - HMA with steel slag* |
|---|---|---|---|---|---|
| Skid resistance | ✓ | - | ✓ | ✓ | ✓ |

*Evaluation tool or method*

A literature search yielded data that could inform the test cases comparing HMA to WMA with RAP and HMA to steel slag asphalt. Past research where the Pendulum Test (EN 13036-4), as the EDGAR recommended methodology, was used to assess surface frictional properties was sought.

*Input data and assumptions*

Araujo *et al.* (2015) assessed HMA and WMA with RA mixtures in field mixtures, measuring HMA with a BPN (PTV or Pendulum Test Value according to EN 13036-4) of 67 and WMA with RA with a BPN of 70.

A study by Chen and Wie (2015) evaluated the skid resistance performance, amongst other properties, of HMA and HMA with steel slag on a trial road site in Taiwan. A BPN of 65 was recorded for the HMA and 62 for the steel slag mixture. For this particular data, it was noted that the BPN was lower than anticipated because it was the initial value following construction as asphalt binder film coated the aggregate at the pavement surface. The BPN of all trial sections was expected to improve once open to traffic.

No data was determined that could inform skid resistance in the CIR test case. In some respects this is not surprising; recycling *in-situ* should not cause any skid resistance issues since it is largely the same aggregate that is returned to the road pavement in the recycled asphalt. Small additions (~10%) of crushed rock fines, even from low PSV sources, are not likely to have any significant implications for the skid resistance of the surface (Dunford, 2014).

*Critical discussion on this indicator*

According to the EN 13036-4, the reproducibility standard deviation is from 1.5 up to 4.5, depending on the nature and the surface characteristics. Hence, it is not sure whether a difference of 3 in PTV, as reported in the above mentioned sources, is significant.

The Pendulum Test has been recommended for the EDGAR methodology, because it is a simple test that can be performed on laboratory scale, as part of the initial testing of a mixture, before even laying a trial or real section. However, because of the limited precision and the impact of the laying and compaction process on the surface characteristics, an in situ test (e.g. SCRIM test) would be more accurate to characterize skid resistance. As with all the EDGAR indicators, the recommended methodologies are not prescriptive and can easily be substituted in the MADM framework.

## 4.7 Financial cost

The Matrix of Considerations (Figure 2-2) suggests that financial cost should be evaluated in relation to all five test cases; economic trade-offs exist in most scenarios. A life cycle costing approach can identify the net economic benefits from those that exist: a cheaper material may be outweighed by a longer transport distance; lower temperature mixing may justify the price of an additive.

**Table 4-14**: Matrix of consideration for financial cost

| **Indicator** | ***1 - HMA*** | ***2 - WMA*** | ***3 - WMA with RA*** | ***4 - CIR*** | ***5 - HMA with steel slag*** |
|---|---|---|---|---|---|
| Financial cost | ✓ | ✓ | ✓ | ✓ | ✓ |

*Input data and assumptions*

The financial cost was assessed for all five EDGAR mixes (see Table 4-19) by adapting a cost model developed for the Effects on Availability of Road Network (EARN) CEDR project by Nicholls *et al.* (2014). This model was initially created to evaluate the life cycle cost impacts of the recycled and lower-temperature asphalt materials trialled during EARN, assessing the costs associated with one tonne of surface material over a 60 year design life. The model needed only a few minor adaptations to be suitable for use in EDGAR. The model is a framework which discounts future cash flows in order to account for the time value of money, and arrive at costs in terms of net present value (NPV).

For this basic life cycle cost evaluation, a few assumptions were made:

- Material, transport and fossil fuel costs all remain constant throughout the 10 year analysis period.
- For transport, it is also assumed that the return journey costs the same as the original journey, despite carrying no material back.
- User delay costs were not calculated using this model but were instead evaluated separately as part of the Traffic Congestion indicator (section 4.11).

*Analysis of the test cases*

The results of the cost analysis are presented in
Table 4-15 :

**Table 4-15** : Costs of the test case materials

| | ***1 - HMA*** | ***2 - WMA*** | ***3 - WMA with RA*** | ***4 - CIR*** | ***5 - HMA with steel slag*** |
|---|---|---|---|---|---|
| Cost (€ NPV) to provide a tonne of surface course | 189 | 190 | 154 | 183 | 185 |

In practice, the life cycle costs are seen to vary little between the different mixture variations, with only the warm-mix with recycling scenario seen to perform significantly better. In the WMA scenario, the gains realised through lower expenditure on energy are countered by the cost of the additive. Installation of cold asphalt is slightly more expensive and this nullifies most of the lower cost of materials in this scenario The HMA with steel slag scenario is very similar to the reference in terms of costs, with some limited savings realised through using steel slag in the place of virgin aggregates.

*Critical discussion on this indicator*

The method adopted to measure this indicator is a well-established life-cycle costing approach. It is relatively easy to conduct and is free to use or construct from first principles. The quality of the output is wholly dependent on the quality of the input data. Those with access to accurate costs (i.e. asphalt producers) would be best placed to obtain data of the quality required.

## 4.8 Recyclability

*Evaluation tool or method*

The recyclability was assessed using the method developed within WP1 of the EDGAR project. The main objective was to evaluate in a quick way the ability of a green bituminous mixture or technology to end up as a recyclable material at the end-of-life stage.

The method consists of going through a flow chart, which was devised in WP1 task 3 (added as annex to this report). It starts with an initial ideal recyclability score of 100%. Depending on the chosen flow, penalty factors apply, reducing this recyclability score. Finally a quantitative score is obtained expressing the degree of recyclability.

*Assumptions*

Different factors influence the degree of recyclability. The most important are considered in the flow chart assessment, such as:

- Recyclability allowed? This is a pass/no pass, depending on legal issues of recycling (that could be country dependent). In our test cases, there are no legal recycling limits.
- Milling & sieving risks? This question considers risks or concerns related to milling & sieving processes. A higher risk results in a penalty (pen1=0.8). This is the case for HMA with steel slag (case 5), because of the concern of fine dust production.
- Storage risks? The same penalty factor (pen2=0.8) applies for storage risks, meaning a higher risk might occur when storing some constituents. In our test cases, it is assumed that no storage risks are present.
- Reheating H&S issues? It is assumed that for our test cases, there are no health and safety issues, for which reason hot recycling should be excluded.
- In situ recycling or plant recycling? A penalty factor (pen3=0.9) is applied to the CIR because it is assumed that there is a higher risk of reduced performance.
- EOL products fully recyclable? The percentage of recyclable products at EOL is directly the applied penalty factor, as an indicator of the degree of recyclability. In our cases, it is assumed that 100% of the EOL products can be recycled.
- Downgrading? Downgrading means that EOL products are not suitable for being reused in the same type of application as they are used in the current life cycle. Further processing of the EOL products, or recycling in lower level applications where requirements are less severe, would then be needed. For instance, when multiple recycling is applied, it is known that a highly aged binder might need a rejuvenating treatment. This is the reason why the cases in which RA is used, receive a penalty (pen4=0.8).

*Analysis of the test cases*

The cases of the HMA and WMA without RA obtain a recyclability score of 100%. No supplementary milling, storing, sieving and reheating risks compared to HMA are known for the EOL products as well as no performance decrease is proven.
The case WMA with RA obtains a reduced score of 80% because of the multiple recycling aspect. Multiple recycling is possible, but supplementary measures like using rejuvenating additives might be necessary to maintain the same performance level.
The case of HMA with steel slag also gets a 80% recyclability score, but the penalty here is due to a potential sieving & milling risk.

Finally the CIR test case results in a 72% score, taking two penalties: one for in situ recycling and one for downgrading.

**Table 4-16**: Recyclability scores of the test cases

| | ***1 - HMA*** | ***2 - WMA*** | ***3 - WMA with RA*** | ***4 - CIR*** | ***5 - HMA with steel slag*** |
|---|---|---|---|---|---|
| Recyclability (%) | 100 | 100 | 80 | 72 | 80 |

*Critical discussion*

Some factors are not considered in this flow chart, because a correct evaluation is rather difficult (premature or arbitrary) at this early assessment of the recyclability of a green product or technique, e.g.:

- Necessity and cost (environmental & financial) for additives to be added to EOL product to improve recyclability
- Supplementary costs of the recycling process
- % of recycling allowed in the future product

Performance of a product with RA, compared to a product without RA, is taken into account by the downgrading check. In the case of multiple recycling, a penalty factor applies (see above).

## 4.9 Performance

*Evaluation method*

The consideration of performance (durability related) of the constructed structure is very important, since a product might perform exceptionally well in a cradle-to-gate or cradle-to-site assessment, but fail for in-situ performance and hence require replacement within a short time after construction.

The main damage phenomena in asphalt surface courses are:
(1) appearance of surface cracks (i.e. fatigue cracking or thermal cracking in very cold climates);
(2) permanent deformation (*i.e.* rutting);
(3) ravelling

Moreover the presence of humidity in the asphalt layer can reduce the adhesion between the aggregates and the binder of the asphalt mixture and accelerate the propagation of cracks, ravelling and potholes. Some mixtures are more sensitive to these types of water induced damage mechanisms, which is why the water sensitivity of an asphalt mixture is also a very important characteristic.

Therefore, results from three different mechanical tests (i.e. resistance to fatigue; resistance to rutting; water sensitivity) have been chosen in this case study on a surface course to constitute the pavement performance indicator:

**Water sensitivity** (unit %) is a performance related characteristic, since a high sensitivity to water can lead to premature degradation of the asphalt pavement and hence of the whole pavement structure. As mentioned above, the presence of humidity in the mixture can decrease the adhesion between the aggregates and the binder, and therefore can decrease the tensile strength of the mixture. The European standard EN 121697-12 describes a test, in which the strength is measured on two sets of specimens: one set of specimens previously subjected to water conditioning, the other set unconditioned. The water sensitivity value is expressed as the tensile strength ratio between the conditioned and unconditioned specimens of a mixture.

**Resistance to rutting** (unit %) is the mixture resistance to irreversible deformation on the pavement surface, which is caused by heavy traffic loading. Resistance to rutting can be measured by different test methods (e.g. wheel track testing) as mentioned in EN 12697-22. The result of the test can be expressed in % as the ratio of the rut depth after a certain number of load cycles to the height of the specimen.

**Resistance to fatigue** (unit $10^{-6}$) can be evaluated by different tests on asphalt mixtures (e.g. 3 point bending test; 4 point bending test). The resistance to fatigue ($\varepsilon_6$) is the maximum strain level that can be applied in the test specimen in order to reach 1 million load cycles. A higher $\varepsilon_6$ thus implies a better resistance to fatigue failure. The European standard EN 12697-24 contains the details regarding the resistance to fatigue.
A poor resistance to fatigue will eventually result in fatigue cracks appearing at the surface of the pavement. However, it is important to emphasize that in most cases, the cracks are initiated within the sublayers, which are subject to high tensile stresses, and propagate from the bottom to the top. Therefore, fatigue resistance is a critical performance characteristic for sublayers only. When we are considering the case of a surface

Assumptions

In this project the values of the performances have been assumed based on existing literature.

Analysis for the considered test cases

*Case 1 (HMA)*
The performance data for the reference case are based on the data given by Bueche (2011) with a water sensitivity of 90%, rutting value of 5.6% and ε6 value of 115.

*Case 2 (WMA)*
Bueche (2011), propose the following data regarding a warm mix asphalt, including wax (3% of the containing bitumen):
Water sensitivity: 87%
Resistance to rutting 5%
Resistance to fatigue: 120

*Case 3 (WMA with RA)*
Based on different experimental studies (c.f. Zhao et al, 2012) the incorporation of 30% of RAP to the warm mix asphalt improves the material resistance to rutting as well as the material sensitivity to water. However the changes in resistance to fatigue are not significant. Based on this information the following hypothesis has been made for the performance of the case 3:
Water sensitivity: 90%
Resistance to rutting: [5% improvement compare to the WMA case]: 4.8%
Resistance to fatigue: 120

*Case 4 (CIR)*
A hypothesis has been made that the cold in place mixtures, has a lower resistance to rutting and fatigue, and a higher sensitivity to water as compared to the HMA (reference) case. Based on this hypothesis, the following values have been assumed for this case:
Water sensitivity: [15% reduction compared to the HMA case]: 77%
Resistance to rutting: [5% increase compare to the HMA case]: 5.9%
Resistance to fatigue: [10% reduction compared to the HMA case]: 103.5

*Case 5 (HMA with steel slag)*
It is assumed that using steel slags in the asphalt mixture improves the pavement resistance to rutting as compared to the reference case (Lin et al., 2015):
Water sensitivity: 90%
Resistance to rutting: [15% improvement compare to the HMA case]: 4.8%
Resistance to fatigue: 115

Critical discussion

This is a very important indicator and it has to be assessed correctly, otherwise sustainability assessment becomes very unreliable. The performance indicator could be further enhanced by considering more performance characteristics (e.g. ravelling sensitivity), provided there are reliable data and/or tests for these additional characteristics.
The set of performance indicators will depend on the application: e.g.: fatigue not relevant for surface course; rutting not relevant for a road with only light traffic; ravelling not relevant for base layer, etc.

## 4.10 Responsible sourcing

*Evaluation tool*

The BES-6001 (BRE Environmental & Sustainability Standard, 2014) has been used as a tool to evaluate the social responsibility connected to the use of a particular resource. Six requirements listed in the standard (responsible sourcing policy, supplier management system, material traceability through the supply chain, health and safety management systems in the supply chain, management of greenhouse gas emissions, local communities) have been selected based on their applicability to asphalt technologies and their independency from the other indicators considered in this project. Different amount of points are assigned to the fulfilment of each requirement for a maximum total, in this project, of 33 points as in Table 4-17.
The fulfilment of the requirements requires major effort not only at the project level: the fulfilment of each requirement depends on the accomplishments of several tasks (Table 4-17). Both companies and their suppliers are in fact required to supply documentation certified by a third party of their organizational management, supply chain and sustainability aspects necessary for the evaluation of the responsible sourcing of the construction products.
Being part of this documentation defined mandatory within the BES-601 (their absence could lead to a null score for the requirement), in order to facilitate the evaluation of this indicator, the tool was deprived of the compulsory points.

*Hypotheses*

There was no critical basis to differentiate between the cases. The maximum score was therefore considered for all cases.

**Table 4-17**: Costs of the test case materials

| Requirement | Main tasks | Maximum score |
|---|---|---|
| Responsible sourcing policy | • Written policy to address the responsible sourcing issue | 1 |
| Supplier management system | • Documented management system for the purchasing process and for approval of its suppliers | 1 |
| Material traceability through the supply chain | • Documented traceability of extraction, recovery, production or processing of at least 60% of the materials | 6 |
| Health and safety management systems in the supply chain | • Documented health and safety policy and management system<br>• At least 60% of the materials should be traceable to the suppliers with certified health and safety management systems | 10 |
| Management of greenhouse gas emissions | • Quantification of direct and indirect GHG emissions and monitoring plan<br>• Communication to the stakeholders about emissions and removal of GHG | 9 |
| Local communities | • Establish policy to identify and consult local communities' stakeholders<br>• Review and report about its performance in terms of local communities relationship, activities and incidents | 6 |

*Analysis of the test cases*

As mentioned above, all cases have been considered equal in the evaluation. A maximum score of 33 has therefore been assigned to all the asphalt production technologies.

*Critical discussion on this indicator*

Although it was not possible to properly evaluate the contribution of this indicator to the presented methodology, it could become relevant in a real setting. If this indicator would be translated into a requirement from the NRAs, it could significantly affect the whole asphalt production chain. It is in fact not only related to the asphalt producer policy but also to the social responsibility of its subcontractors and suppliers.

## 4.11 Traffic congestion

The Matrix of Considerations (Figure 2-2) suggests that traffic congestion impact should be evaluated in relation to all four of the test cases. The HMA with steel slag material is not thought to show any variation on the HMA scenario, in terms of the time it takes to install.

**Table 4-18**: Consideration matrix for traffic congestion indicator

| **Indicator** | ***1 - HMA*** | ***2 - WMA*** | ***3 - WMA with RA*** | ***4 - CIR*** | ***5 - HMA with steel slag*** |
|---|---|---|---|---|---|
| Financial cost | ✓ | ✓ | ✓ | ✓ | - |

*Evaluation tool or method*

Traffic congestion was assessed using the Queues and Delays at ROadwork (QUADRO) model. This is a Highways England sponsored program that estimates the effects of roadworks considering delays to road users, including fuel carbon emissions and accident costs associated specifically with the works. In accordance with the DfT's WebTAG guidance, all costs in QUADRO are expressed in 2002 prices and then converted into Euros (£1 = €1.25). The age of the data should not impact comparative analyses. The details of QUADRO, including all assumptions made in its calculations, are provided in the manual (Highways Agency, 2002).

Different scenarios can be input into the model spreadsheet and these are accompanied by details of a diversion route, which is defined by the QUADRO Diversion Tool. In this way the model can take account of whether the particular site in question becomes overloaded, representing both the road users that queue through the site and those that take an alternate route. Parameters, such as annual average daily traffic (AADT), road type and percentage of HGVs must be recorded. The outputs from QUADRO produce the User Time Delay Cost (€) for a particular scenario.

*Analysis of the test cases*

The following scenarios were constructed to be representative of the EDGAR test cases:

- **Reference HMA** – Shuttle working on a 0.5 km stretch of single lane A-road for 8 hours.
- **WMA** – Identical to the reference HMA test case, except that the closure lasts six hours only.
- **WMA with RA** – Identical to the WMA test case.
- **CIR** – Identical to the reference HMA test case, except a full 8-hour closure is put in place on a kilometre of A-road.
- **HMA with steel slag** – Identical to the reference HMA case.

The HMA vs. WMA comparison is designed to evaluate the potential advantage of having quicker cooling asphalt in the case of WMA, allowing the highway to be re-opened more quickly to traffic. The HMA vs. CIR comparison is designed to reflect the working practices of in-situ recycling machines that require the road to be closed-off to enable work to take place. Each intervention includes planning-off the expired material and installation of the new, with the costs split equally across life cycle steps A5 – laying of asphalt and C1 – demolition.

**Table 4-19**: User delay costs of the comparative scenarios used to explore the test cases

| | User delay cost of each maintenance intervention (€/t) |
|---|---|
| **HMA** | 23.84 |
| **WMA / WMA with RA** | 18.30 |
| **CIR** | 55.84 |

*Critical discussion on this indicator*

The method used is well established and produces clear results. However, it is quite heavily based on assumptions. More confidence can be placed in the results when the analysis is based on a particular road site and the assumptions are consequently reduced.

# 5 Results and discussion

## 5.1 Level 1 – Pareto analysis

The first level of analysis is to study each alternative separately. This is done in order to identify the critical stage in the life cycle of each alternative.
By performing the primary analysis, it was found out that for all the alternatives, while considering the climate change and air pollution indicators, the road use stage (B1) is an absolute dominant (more than 95% of the total value). However if the road use stage (B1) is not considered, the production in plant stage, for all of the alternatives except case 4 (CIR) is the dominant stage. An example of the output of this type of analysis is given in Figure 5-1 where the contribution of each product stage is given for GWP indicator. In this figure, the GWP of the road use stage has not been considered, in order to obtain a better graphical representation of the other product stages.

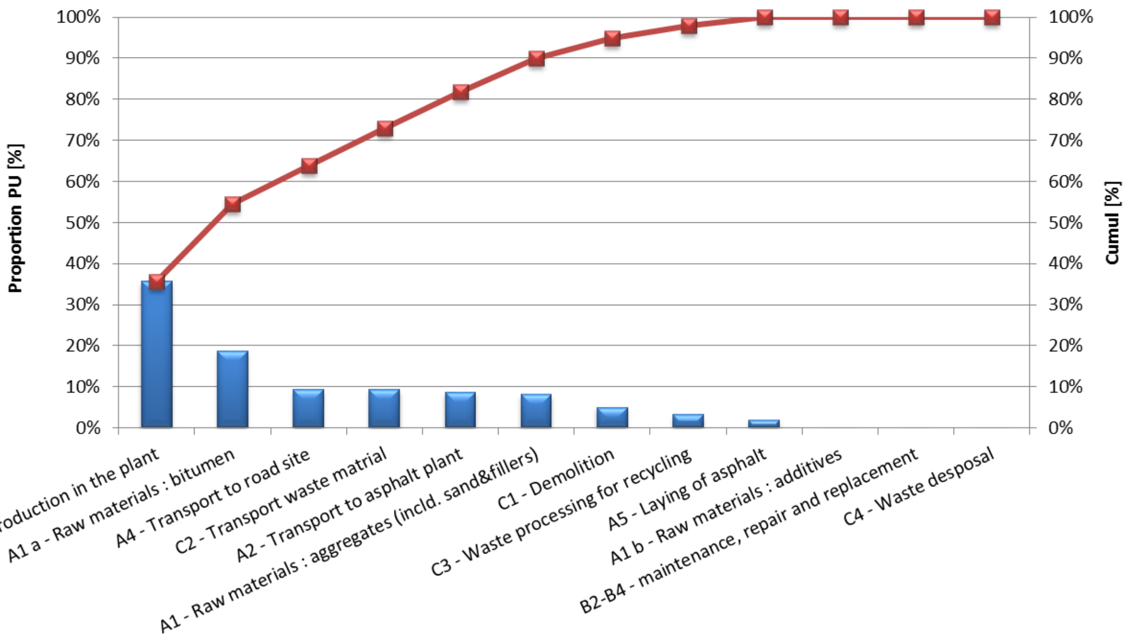



**Figure 5-1** : Dominant unit process identification for « Global warming potential » in Case 1 (HMA), excluding the use road use stage



## 5.2 Level 2 – Graphical analysis

The second level of analysis consists of a graphical analysis to identify the differences and eventual classification between different alternatives.
The performance of each alternative for each indicator is given in Table 5-1. The differences in performance for different alternatives as compared to the reference case (HMA) are normalized by the data of the reference case and depicted in Figure 5-2. Hence, the reference case shows 0% for all indicators. The smaller the radar diagram, the better the alternative performs. It may be seen that for most of the indicators (with an exception of the traffic congestion), the alternative 4 (CIR) has a better performance as compared to the other alternatives. Alternative 5 (HMA with steel slag) has approximately 150 % higher leaching potential as compared to the reference case.

In this method of analysis, in the chart, there is no point depicted in case of missing values. This can be one of the disadvantages of the graphical method. Another disadvantage of this method is that the scale of differences is shown as linear for all of the indicators. This can be a tricky point since the distribution of the values for some indicators is not linear (e.g. noise (dB) has a logarithmic scale).

As already explained in section 2.3, a disadvantage of this analysis level is that because of the normalization the exact quantitative data are not represented in the diagram. Moreover, it is difficult to interpret the magnitude of the differences. For example, alternative 5 gives the impression of being a very bad alternative, because of the extremely big difference in leaching potential. This could be misleading, because 150 % on leaching potential may be less problematic than for instance 50 % on another type of indicator. Consequently, this graphical method can only result in a decision in the exceptional case where one alternative would outrank all the others.

**Table 5-1** : Summary of the input data

| Indicators | | Sub-indicators | | Unit | 1 HMA | 2 WMA | 3 WMA+ RAP | 4 CIR | 5 HMA + steel slag |
|---|---|---|---|---|---|---|---|---|---|
| C1 | GWP/Climate change | | | kg CO2eq | 62.6815 | 69.36 | 63.055 | 33.5 | 59.626 |
| C2 | Depletion of resources | | | kg sbeq/tonne | 2.22E-04 | 2.13E-04 | 1.54E-04 | 8.91E-05 | 2.23E-04 |
| C3 | Air pollution | C3.1 | Acidification | kg SO2eq | 1.27E-01 | 1.25E-01 | 1.17E-01 | 3.35E-02 | 8.16E-02 |
| | | C3.2 | Photochemical oxidant formation | kgEthene eq | 7.93E-02 | 7.81E-02 | 7.28E-02 | 1.74E-02 | 5.23E-02 |
| C4 | Leaching potential | | | - | 4.33e-7 | - | - | - | 1.06e-6 |
| C5 | Noise | | | dB | 95.2 | 95.2 | 95.2 | - | 91.7 |
| C6 | Skid resistance | | | BPN | 65 | 65 | 70 | - | 62 |
| C7 | Financial cost | | | € | 189 | 190 | 154 | 183 | 185 |
| C8 | Recyability | | | - | 100% | 100% | 80% | 72% | 80% |
| C9 | Performance | C9.1 | Resistance to rutting | % | 6% | 5% | 5% | 6% | 5% |
| | | C9.2 | Resistance to fatigue | [10-6] | 115 | 120 | 120 | 103.5 | 115 |
| | | C9.3 | Water sensitivity | % | 90% | 87% | 90% | 77% | 90% |
| C10 | Responsible sourcing | | | - | 33 | 33 | 33 | 33 | 33 |
| C11 | Traffic congestion | | | € | 23.84 | 18.3 | 18.3 | 55.84 | 23.84 |

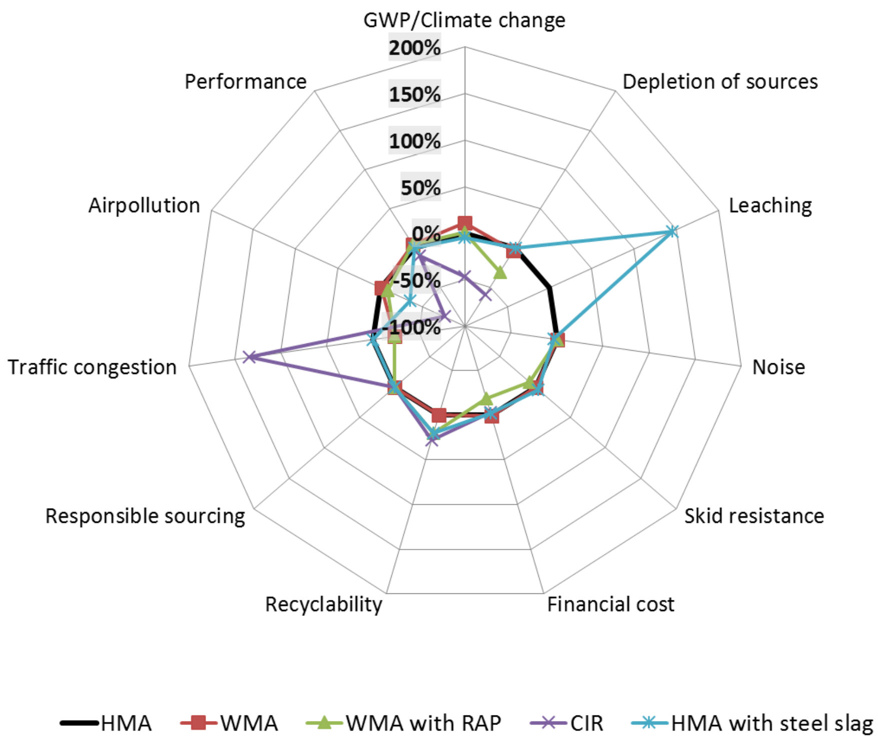



**Figure 5-2** : Comparison between different mixtures for different indicators

## *5.3 Level 3 – Partial aggregation method*

In the level 3 and 4 of the analysis, a classification of the alternatives is given as the final output, considering a weight factor and thresholds of comparison for each indicator. In the primary phase of the analysis, a default matrix of weighting and threshold values has been initially considered in order to perform a primary ranking analysis.
A summary of the input data for each case and criteria has previously been given in Table 5-1. The default weighting matrix has been determined as an average of the assigned weights to each indicator by each project-partner. This matrix can be however changed by the users during the analysis. The default weighting matrix is presented in Table 5-2. Since the evaluated mixtures in this study are surface layers, the fatigue criterion has been considered to have a zero weight in this analysis.

**Table 5-2 :** Default weighting matrix for partial and complete aggregation method

| N° | Indicator | ω | Weighting ω [0 … 1] $\omega_i$ | $\omega_{ij}$ | Final |
|---|---|---|---|---|---|
| C1 | GWP/Climate change | $\omega_1$ | 0.175 | | 0.1750 |
| C2 | Depletion of resources | $\omega_2$ | 0.050 | | 0.0500 |
| C3.1 | Air pollution- Acidification | $\omega_{31}$ | 0.075 | 0.500 | 0.0375 |
| C3.2 | Air pollution-photochemical oxidant formation | $\omega_{32}$ | | 0.500 | 0.0375 |
| C4 | Leaching potential | $\omega_4$ | 0.050 | | 0.0500 |
| C5 | Noise | $\omega_5$ | 0.063 | | 0.0625 |
| C6 | Skid resistance | $\omega_6$ | 0.050 | | 0.0500 |
| C7 | Financial cost | $\omega_7$ | 0.088 | | 0.0875 |
| C8 | Recyclability | $\omega_8$ | 0.138 | | 0.1375 |
| C9.1 | Performance-Resistance to rutting | $\omega_{91}$ | | 0.500 | 0.1125 |
| C9.2 | Performance-Resistance to fatigue | $\omega_{92}$ | 0.225 | - | - |
| C9.3 | Performance-water sensitivity | $\omega_{93}$ | | 0.500 | 0.1125 |
| C10 | Responsible sourcing | $\omega_{10}$ | 0.038 | | 0.0375 |
| C11 | Traffic congestion | $\omega_{11}$ | 0.050 | | 0.0500 |
| | | Sum ω | 1.00 | Ok | 1.0000 |
| | | Verification | Ok | | Ok |

The threshold values regarding the partial aggregation method are presented in Table 5-3 were each type of threshold is defined as below:

- $q_i$, Indifference threshold : If the difference in the evaluation of two alternatives for a given criterion is below the indifference threshold, then no difference between the two alternatives for the considered criterion (i.e. they are comparable) is considered. In this study this value has been defined as 25% of the standard deviation of the input data for each indicator. However it has to be mentioned that this value has been modified manually for some indicators, since the standard deviation is unknown for some indicators or their distribution is not normal.
- $p_j$, strict preference threshold: If the difference in the evaluation of two alternatives for a given criterion is bigger than the strict preference threshold, then a difference between the two alternatives for the considered criterion is considered. This value is chosen manually in this study based on the matrix of differences for each indicator.
- $v_j$, veto threshold : Threshold above which the non-respect of the outranking hypothesis has a high importance. Basically, this threshold corresponds to a limit of compensation between criteria. In this study this value is chosen high enough (10 times bigger than the strict preference threshold ($p_j$)) in order to eliminate the effect of this parameter on the results of the analysis.

In the Electre III methodology (Roy, (1991)), various methods can be used in order to finally obtain the ranking of the alternatives. One of these methods is the Siskos-Huber calculation which proposes a ranking of the alternatives based on the degree of creditability (*i.e.* represents the credibility that an alternative is better than another one). In this method, the non-dominance degree is finally calculated for each alternative. A higher non-dominance degree can be interpreted as a better alternative ranking (Maystre. et al., (1994)).

This method has been used for classification of the output of the partial aggregation method. The result of the classification is shown in Table 5-4. Based on the results presented in Table 5-4, alternative 4 (i.e. CIR) is ranked as the best and alternative 3 is classified as the second best. However it has to be mentioned that these output results are specific for the considered weighting matrix and threshold values. In order to study the effect of the weighting matrix, a sensitivity analysis has been performed and is presented in Section 6.

**Table 5-3** : Threshold values regarding the partial aggregation method

| Indicator | C1 | C2 | C3.1 | C3.2 | C4 | C5 | C6 | C7 | C8 | C9.1 | C9.2 | C9.3 | C10 | C11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit | kg CO2eq | kg sbeq/tonne | kg SO2eq | kgEthene eq | - | dB | BPN | € | % | % | % | [10-6] | - | € |
| $q_j$ | 1.0 | 1.0E-05 | 2.0E-03 | 2.00E-3 | 1.0e-7 | 0.5 | 1 | 5 | 0.05 | 0.001 | 2 | 0.05 | 0.5 | 4 |
| $p_j$ | 5.0 | 3.0E-05 | 1.0E-02 | 1.00E-2 | 3.0e-7 | 1 | 2 | 10 | 0.10 | 0.01 | 5 | 0.10 | 1 | 10 |
| $v_j$ | 50.0 | 3.0E-04 | 0.1 | 0.10 | 1.5e-5 | 15 | 20 | 100 | 1.00 | 1.00 | 50 | 1.00 | 10 | 100 |

**Table 5-4** : Classification based on Siskos-Huber method based on partial aggregation method

| **CASE** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| | HMA | WMA | WMA+RA | CIR | HMA+STEEL SLAG |
| **RANK** | 4 | 5 | 2 | 1 | 3 |

## *5.4 Level 4 – Complete aggregation method*

The solution based on complete aggregation method (Evidence theory) is given in this section. The default input and weighting matrix is identical to what has been used in the level 3 (partial aggregation) analysis.

The default transformation matrix regarding this study is presented in Table 5-5, for quantitative indicators, and in Table 5-6 for qualitative indicators. The values shown in the transformation matrix in Table 5-5 have been decided based on the data available for this study. It has to be noted that the input data has to be in the range of the transformation matrix (no input value can be higher/lower than the maximum/minimum value given in the transformation matrix). Moreover the transformation matrix for qualitative data is chosen based on the matrix defined in Bueche (2011). This matrix determines the degree of belief for each alternative. For example a mixture with recyclability potential of 90% has 80% chance to perform “Good” and 10% chance to perform “Excellent” (see Table 5-6).

**Table 5-5** : Transformation matrix of quantitative indicators regarding to complete aggregation method

| | Transformation matrix - quantitative indicator | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3.1 | C3.2 | C4 | C5 | C6 | C7 | C8 | C9.1 | C9.2 | C9.3 | C10 | C11 |
| | kg CO2eq | - | kg SO2eq | kgEthene eq | - | dB | BPN | € | - | % | [10-6] | % | - | € |
| Unknown | No values is assigned | | | | | | | | | | | | | |
| Very poor | 71 | 2.25E-04 | 1.30E-01 | 8.10E-02 | 4.40E-06 | 96 | 60 | 630 | Qualitative | 10.0% | 100 | 70% | 20 | 58 |
| Poor | 61.5 | 1.90E-04 | 1.05E-01 | 6.50E-02 | 3.40E-06 | 92 | 63 | 615 | | 8.5% | 105 | 75% | 22 | 48 |
| Fair | 52 | 1.55E-04 | 8.00E-02 | 4.90E-02 | 2.40E-06 | 88 | 66 | 600 | | 7.0% | 110 | 79% | 26 | 38 |
| Good | 42.5 | 1.20E-04 | 5.50E-02 | 3.30E-02 | 1.40E-06 | 84 | 69 | 585 | | 3.5% | 120 | 84% | 30 | 28 |
| Excellent | 33 | 8.50E-05 | 3.00E-02 | 1.70E-02 | 4.00E-07 | 80 | 72 | 570 | | 0.0% | 130 | 88% | 33 | 18 |

**Table 5-6**: Transformation matrix of qualitative indicators regarding to complete aggregation method

| | Transformation matrix – Qualitative indicator | | | | | | |
|---|---|---|---|---|---|---|---|
| | 100% | 90% | 80% | 70% | 60% | 50% | 40% |
| Very poor | | | | | | 0.1 | 0.8 |
| Poor | | | | | 0.7 | 0.8 | 0.1 |
| Fair | | | 0.2 | 0.9 | 0.2 | | |
| Good | 0.1 | 0.8 | 0.7 | | | | |
| Excellent | 0.8 | 0.1 | | | | | |

The output of the complete aggregation analysis, is a representation of the degree of certainty for each indicator and each case (Figure 5-3). Furthermore the utility analysis gives a classification of the alternatives as depicted in Figure 5-4.

Utility is a characterization of the satisfaction related to a given alternative. Total aggregation methods usually aim at calculating a value of total utility that will permit to determine the rank of the various alternatives. For a given alternative, the total utility is a combination of the partial utilities that correspond to each single indicator selected. Different mathematical relations can be used in order to calculate the total utility (Schärlig (1985)).

Based on the classification results shown in Figure 5-4, Case 4 (CIR) is ranked as the best alternative followed by Case 3(WMA+RA) as the second best alternative. It can be seen that the classifications from partial and complete aggregation methods lead approximately to the same ranking of the different alternatives.

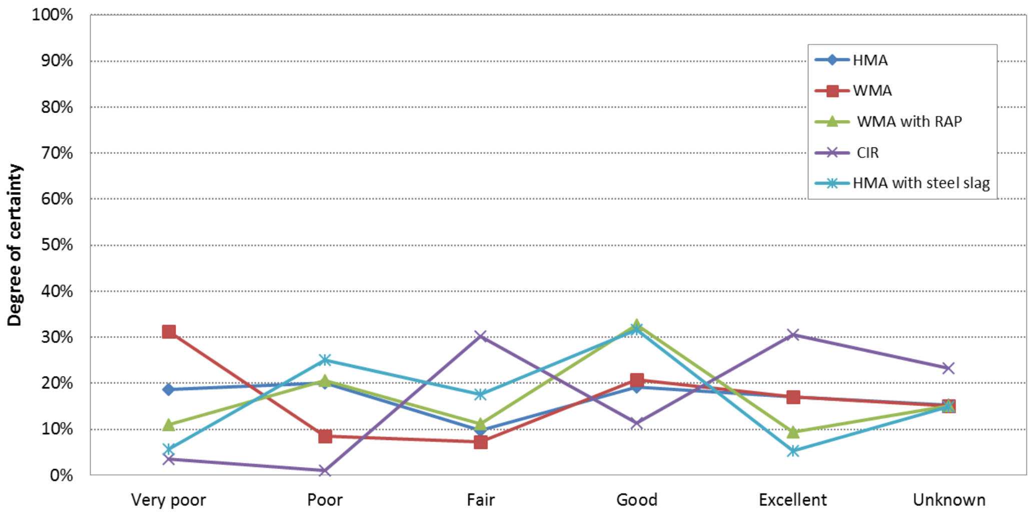
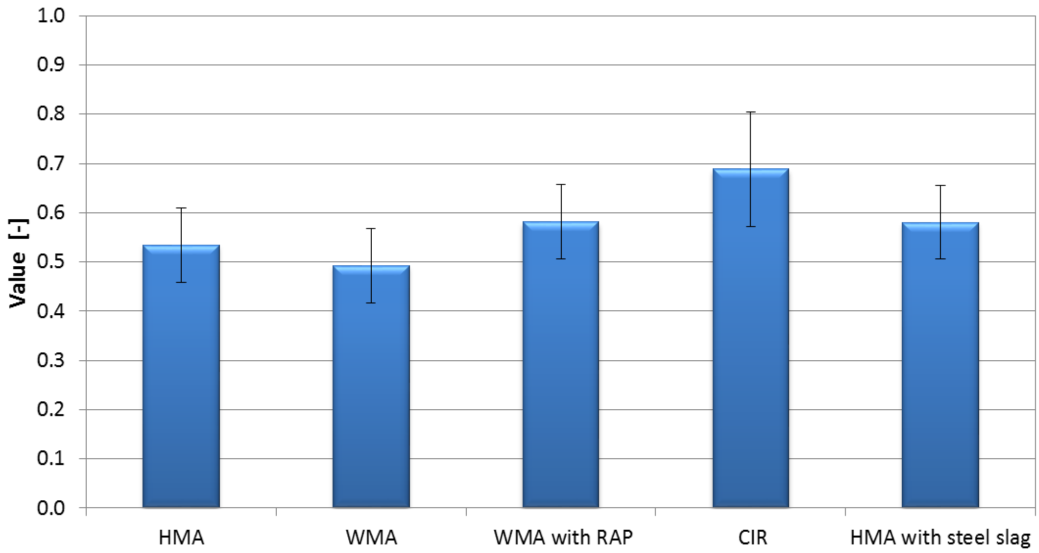



**Figure 5-3** : Results of degree of certainty for different cases based on complete aggregation method




| CASE | 1<br>HMA | 2<br>WMA | 3<br>WMA+RA | 4<br>CIR | 5<br>HMA+STEEL SLAG |
| --- | --- | --- | --- | --- | --- |
| RANK | 4 | 5 | 2 | 1 | 3 |

**Figure 5-4** : Classification results based on complete aggregation method

# 6 Sensitivity analysis

## 6.1 Effect of weighting matrix on ranking of the alternatives

A sensitivity analysis has been performed in order to investigate the robustness of the solution. Both partial and complete aggregation methods have been utilised for this study. The weighting factor ($\omega_i$) has been changed for each indicator while the input data remained unchanged. The purpose of this analysis is to investigate the effect of weight of each parameter on the final ranking of the alternatives.
The weighting factor for each indicator is increased from +20% to +50% of its initial value. It has to be mentioned that since the sum of the weighting factors has to be equal to 100%, every time that an indicator weight is changed, the weight of the rest of the indicators has to be redistributed with a ratio of their initial weighting. The alternated weighting factors can be calculated as follows:

$$\omega_{i,f} = \frac{\omega_{i,new}}{1 - \omega_{i,ini} + \omega_{i,new}}$$

$$\omega_{j,f} = \frac{\omega_{j,ini}}{1 - \omega_{i,ini} + \omega_{i,new}} , j \neq i$$

$\omega_{i,new}/\omega_{i,ini}$ : The ratio of the new weighting factor to the initial factor for the indicator to be studied
$\omega_{i,ini}$ : The initial weighting factor for the indicator to be studied
$\omega_{j,ini}$ : The initial weighting factor of the rest of the indicators

The results of the effect of alternating the weighting factors on the outcome of the ranking is given in Table 6-1 & Table 6-2 using both methods of partial and complete aggregation. The summary of the sensitivity analysis is given in Table 6-3 as the average value of each column. Note that the sensitivity analysis was not done for the indicator C10 (responsible sourcing), because all cases were equal for this indicator and consequently, the weight attributed to this indicator has no impact on the ranking.
It can be seen that the change of weight parameters has a different outcome, depending on which method of analysis is being used. For example, the weight parameter change for "depletion of resources", "skid resistance" and "traffic congestion" resulted in almost no changes in the final classifications. However, the classification showed to be sensitive for the aforementioned indicators with complete aggregation method. The "financial cost" indicator was shown to be not sensitive to the weight factor with complete aggregation analysis.
Overall, the ranking was proven to be relatively stable, and for the majority of the cases, independent of the weighting parameters, the best alternative is the Cold In place Recycling (CIR) option. The details of the sensitivity analysis for each criterion are given in Appendix B.

**Table 6-1** : Sensitivity analysis of partial aggregation method to weighting factor

| | | | Weighting factor change | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | REF | +20% | +25% | +30% | +40% | +45% | +50% |
| **GWP** | **a1** | 4 | 4 | 4 | 4 | 4 | 3 | 3 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 2 | 2 | 3 | 3 | 4 | 4 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 | 2 | 2 | 1 | 1 |
| **Depletion of resources** | **a1** | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **Air pollution** | **a1** | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Leaching potential** | **a1** | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| | **a2** | 5 | 5 | 5 | 5 | 3 | 3 | 3 |
| | **a3** | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 | 3 | 4 | 4 | 4 |
| **Noise** | **a1** | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 3 | 4 | 4 | 4 | 4 | 4 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Skid resistance** | **a1** | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **Financial cost** | **a1** | 4 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a2** | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | **a3** | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **Recyclability** | **a1** | 4 | 3 | 3 | 2 | 1 | 1 | 1 |
| | **a2** | 5 | 5 | 5 | 4 | 4 | 3 | 3 |
| | **a3** | 2 | 2 | 2 | 3 | 3 | 4 | 4 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 4 | 4 | 5 | 5 | 5 | 5 |
| **Performance** | **a1** | 4 | 4 | 4 | 4 | 3 | 3 | 3 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 | 3 | 4 | 4 | 4 |
| **Traffic congestion** | **a1** | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

**Table 6-2** : Sensitivity analysis of complete aggregation method to weighting factor

| | | | | Weighting factor change | | | | |
|---|---|---|---|---|---|---|---|---|
| | | REF | +20% | +25% | +30% | +40% | +45% | +50% |
| **GWP** | **a1** | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| **Depletion of resources** | **a1** | 4 | 4 | 4 | 4 | 4 | 5 | 5 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 4 | 4 |
| | **a3** | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **Air pollution** | **a1** | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| **Leaching potential** | **a1** | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **Noise** | **a1** | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| **Skid resistance** | **a1** | 4 | 3 | 3 | 3 | 3 | 3 | 3 |
| | **a2** | 5 | 5 | 5 | 4 | 4 | 4 | 4 |
| | **a3** | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 4 | 4 | 5 | 5 | 5 | 5 |
| **Financial cost** | **a1** | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **Recyclability** | **a1** | 4 | 4 | 4 | 3 | 2 | 2 | 1 |
| | **a2** | 5 | 5 | 5 | 4 | 5 | 5 | 3 |
| | **a3** | 2 | 2 | 2 | 2 | 3 | 3 | 4 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
| | **a5** | 3 | 3 | 3 | 5 | 4 | 4 | 5 |
| **Performance** | **a1** | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | **a3** | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | **a4** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **Traffic congestion** | **a1** | 4 | 4 | 3 | 3 | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 | 4 | 3 | 3 | 3 |
| | **a3** | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **a4** | 1 | 2 | 4 | 5 | 5 | 5 | 5 |
| | **a5** | 3 | 3 | 2 | 2 | 2 | 2 | 2 |

**Table 6-3** : Summary of the average as an output of sensitivity analysis

| | Reference ranking | | Average ranking from sensitivity analysis | |
|---|---|---|---|---|
| | Partial aggregation Method | Complete aggregation method | Partial aggregation Method | Complete aggregation method |
| **HMA** | 4 | 4 | 4 | 4 |
| **WMA** | 5 | 5 | 5 | 5 |
| **WMA+RA** | 2 | 2 | 2 | 2 |
| **CIR** | 1 | 1 | 1 | 1 |
| **HMA+Steel Slag** | 3 | 3 | 3 | 3 |

## 6.2 Effect of thresholds on ranking of the alternatives

The sensitivity analysis can also be performed to study the effect of thresholds on the classification results (level 3 analysis, partial aggregation method). The domain of variation of the threshold should be according to the law of $q_j \leq p_j \leq v_j$. In this study the effect of variation of strict preference threshold ($p_j$) for certain selected indicators has been studied.
Initially the strict preference threshold was changed for the GWP indicator. The results of this study are shown in Table 6-4. It can be seen that the best and the worst alternatives stay independent of the choice of $p_j$. However when the value of $p_j$ is lowered to 3 and 1.5, the HMA+steel slag option becomes more beneficial as compared to WMA+RAP with a $p_i$ of 5. The reason is that the difference of GWP for alternative 3 and 5 is approximately 4 kg $CO_{2eq}$ and even though having a strict preference of 5, gives a small priority to alternative 5, it is not enough to classify this option ahead of alternative 3.

**Table 6-4** : Effect of strict preference threshold of GWP indicator on the final classification

| | GWP | | | |
|---|---|---|---|---|
| **$p_j$** | *1.5* | *3* | **5** | *10* |
| | Ranking of the alternatives | | | |
| **a1** | 3 | 3 | **4** | 3 |
| **a2** | 5 | 5 | **5** | 5 |
| **a3** | 4 | 4 | **2** | 1 |
| **a4** | 1 | 1 | **1** | 1 |
| **a5** | 1 | 1 | **3** | 4 |

The second sensitivity analysis was performed while changing the value of $p_j$ for the skid resistance indicator. The results of the analysis are shown in Table 6-5. It can be seen that when the value of $p_i$ increases to 5 and 10, the HMA+steel slag becomes more beneficial than the WMA+RAP case. The reason is that when $p_i$ increases, the HMA+steel slag option is penalized less for its low skid resistance and therefore is classified higher than the WMA+RAP option.

**Table 6-5** : Effect of strict preference threshold of Skid resistance indicator on the final classification

| $p_j$ | Skid resistance | | | |
|---|---|---|---|---|
| | ***1.5*** | 2 | *5* | *10* |
| | Ranking of the alternatives | | | |
| **a1** | **4** | 4 | 4 | 4 |
| **a2** | **5** | 5 | 5 | 5 |
| **a3** | **2** | 2 | 3 | 3 |
| **a4** | **1** | 1 | 1 | 1 |
| **a5** | **3** | 3 | 2 | 2 |

## *6.3 Effect of the noise indicator on ranking of the alternatives*

The effect of the noise indicator on the final classification of the alternatives has been studied in this section. It was found out that finding exact values for the noise indicator is a difficult task, since the precision of the measurements is relatively low and noise depends not only on the type of mixture, but also for a large part on the quality of construction and paving. Therefore in the initial input matrix (see Table 5-1) the same value of noise has been assigned to case 1, 2 and 3. Since this was an assumption, the robustness of the solution needed to be investigated. In order to do so, three different cases were studied with the model. The first case (marked as “All equal” in Table 6-6) is when all the cases are assumed to have the same level of noise. In the second and third case study, it was assumed that the CIR case has 5% and 10% higher noise level as compared to the rest of the cases. This was in order to investigate that even if the CIR case has a higher level of noise, would it still get the best ranking? The analysis method used for this investigation is the complete aggregation method. The results of the analysis showed that even if we assume a higher level of noise for the CIR case, it still gets the highest ranking as compared to the other mixtures. However, it has to be pointed out that these results are obtained considering the default weighting factors, previously defined in section 5.3. This results might change if we attribute a higher weighting factor to the noise indicator.

**Table 6-6** : Results of the senstivity analysis on the noise indicator

| | Cases | All equal dB | CIR+5% dB | CIR+10% dB |
|---|---|---|---|---|
| | **a1** | 95.2 | 95.2 | 95.2 |
| | **a2** | 95.2 | 95.2 | 95.2 |
| | **a3** | 95.2 | 95.2 | 95.2 |
| | **a4** | 95.2 | 99.96 | 104.72 |
| | **a5** | 95.2 | 95.2 | 95.2 |
| **Classification** | **a1** | 4 | 4 | 4 |
| | **a2** | 5 | 5 | 5 |
| | **a3** | 2 | 2 | 2 |
| | **a4** | 1 | 1 | 1 |
| | **a5** | 3 | 3 | 3 |

## 6.4 Effect of unknown performance data on ranking of CIR case

Since the CIR case came out the best option after performing different case studies, it was decided to examine the strength of this option by focusing on the performance data. Generally, although the CIR option is beneficial when considering the cost and environmental impacts, there have been some reports on the weak performance of this technique. A surface re-built with the CIR method, could be more susceptible to ravelling, thermal cracking and can exhibit compaction problems (Thomas et al., 2002). That is why CIR is usually followed by the application of a fog seal, a slurry seal or even overlaid by a HMA surface course, to prevent surface ravelling. However, in this case study, it is considered as an alternative to a surface layer. The reason why it is so highly ranked is because the performance characteristics that were considered (rutting resistance and water sensitivity) are not adequate to represent the sensitivity to ravelling. A high water sensitivity (or a low ITSR value) may be related to ravelling sensitivity, but in this case study the ITSR of the CIR case was still fairly good (ITSR=77%).The sensitivity analysis was performed using the complete aggregation method (Level 4). As it was explained before in chapter 2 of this document, in the complete aggregation method a transformation matrix is calculated based on the input data for each case and indicator. This matrix, indicates the probability distribution of each indicator for different performance levels (very poor, poor, fair, good, and excellent). The decision matrix can be defined either based on the input data, or by the values inserted by the user. In this section, in order to perform the sensitivity analysis, the values are inserted manually for the performance indicators (Rutting and water sensitivity) of CIR case. It has to be mentioned that the decision matrix for other indicators and cases, are remained as before (calculated based on the input data (Table 5-1)).
The results of the analysis are shown in **Figure 6-1**. In the figure different case studies are shown:

- “Poor”: the performance level is assigned between “Poor” and “Unknown” (e.g. 10% “Poor” performance and 90% “Unknown” performance).
- “Very poor”: the performance level is assigned between “Very poor” and “Unknown” (e.g. 10% “Very poor” performance and 90% “Unknown performance”).
- “Poor and Very poor”: equal percentage are assigned to “Poor” and “Very poor” performance levels, and the remaining percentage is considered as “Unknown” (e.g.

10% “Poor” performance, 10% “Very poor” performance and 80% “Unknown performance”).

It can be seen in **Figure 6-1** that when the percentage of “Unknown” data is more than 80%, the CIR case becomes the top ranking in the classification. On the contrary if we are 100% sure (which means 0% uncertainty) of “Very poor” performance of the CIR case, the CIR case becomes the worst choice in the 5 available cases.

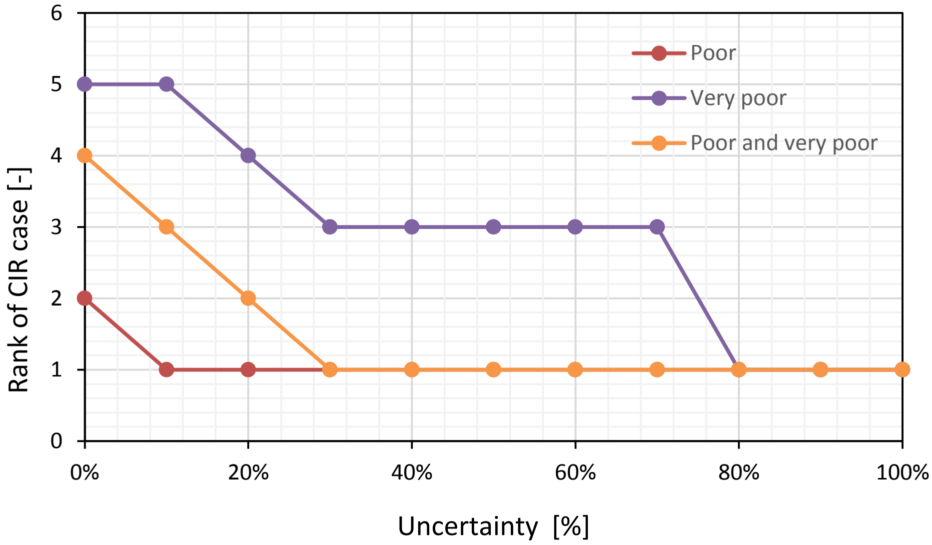



**Figure 6-1**: Results of sensitivity analysis on the performance of the CIR case

# 7 Conclusions

In this document, the methodology which has been previously developed in the framework of the EDGAR project (Deliverables D2.1 and D2.2) has been demonstrated through a practical case study. In this case study, five different alternative solutions are considered for a wearing course of a road section. The different solutions evaluated are as follows:

1. Hot mix asphalt (HMA)
2. Warm mix asphalt (WMA)
3. Warm mix asphalt with recycled asphalt (WMA + RA)
4. Cold in-place recycled asphalt (CIR)
5. Hot mix asphalt with steel slag (HMA + steel slag)

The solutions are evaluated based on the basket of indicators proposed in Deliverables D2.1 and D2.2. The assessment tools used for some of the indicators have been slightly modified or are different from the tools recommended in D2.2, in order to facilitate the assessment process. The flexibility of the EDGAR methodology allows this, giving each NRA the freedom to use the most appropriate assessment tools in the context of practical application.

Once the indicators of each alternative solution were evaluated, a decision making tool has been employed in order to classify the alternatives. The tool is based on a multi-attribute decision making methodology which was proposed by Bueche (2011).

In order to evaluate the different alternatives, four different levels of analysis were performed. The first two levels can give some interesting information before progressing to a more in-depth analysis in levels 3 and 4. For example the Pareto analysis (level 1) reveals which life cycle stages for every indicator are contributing most and hence indicates where to start for optimising the indicator's output. The graphical analysis (level 2) visualises the differences between alternatives on sustainability indicator level. Subsequent analysis in level 3 and 4 can lead to the ranking of the alternative solutions.

The stability of the ranking was investigated by performing various types of sensitivity analysis on weighting coefficients, or on the threshold values. It is logical that the ranking of the cases may change when the weighting factor of some indicators are modified. However, it is important to show that if the weighting coefficients are only slightly modified within some realistic limits, then the ranking of the alternatives shall not be completely overturned, since this would suggest 'over sensitivity'. There should be some inherent level of stability in the ranking and modifying the weighting should not lead to complete reversals in the rankings. This demonstrates one particular benefit of such decision methods. Despite this, the results of the analysis were found to be rather more sensitive to the thresholds which are defined for the partial aggregation analysis (level 3). The software tool allows the user to easily perform this type of sensitivity analysis, in order to gain a better understanding of the significance of the various MADM parameters.

Application of the methodology to the test cases showed the difficulties and challenges of the methodology:

- Firstly, it was not an easy task to find accurate data for all indicators. This is a finding in common with any type of sustainability assessment tool. Without correct and accurate input data, you cannot expect to obtain an accurate output. Even though the number of indicators has been limited to a minimum, it is still quite difficult and time consuming to obtain the input data. Within the short time scope of this project, there was not enough time to go sufficiently deep in search of literature and other data sources. However, for the purpose of this report, the quality of the input data is of less importance, since the real purpose was to demonstrate and evaluate the methodology.

- Some of the indicators, such as responsible sourcing or skid resistance, did not play a role in the ranking of the alternatives. That is because the test cases considered here were such that there is no or little variation in these indicators from one alternative to the other. However, this doesn't mean that these indicators are not important. For instance, if two alternative solutions would be proposed by two different companies, one of which is very much concerned with responsible sourcing while the other is not, the indicator responsible sourcing should be able to make a difference.

- A tool like this MADM tool shall be considered as a decision aid, not as an absolute solution. The user shall still have sufficient expertise in the field of bituminous materials and remain critical towards the outcome. For example, in the test case considered in this report, the CIR ranked as the best solution. However, it is known that CIR is not a good solution for heavy traffic roads with high shear forces at the surface, due to its sensitivity to surface ravelling. If the user is aware of this, he will realize that CIR gets a high ranking because ravelling resistance is not well covered by the performance indicator.

- It was shown, especially in the determination of GWP and air pollution, that the use stage has an overwhelming contribution. However, this doesn't mean that we should not seek to minimize the impact of the other life cycle stages. In this study, the contribution from traffic in the use stage was not considered, simply because it would mask the differences in the other stages, but it was emphasized that an NRA has the responsibility to take all possible measures to decrease the impact of the use stage. If the option of selecting a type of asphalt surface course with a low rolling resistance were available, this option should be considered because the impact on GWP or air pollution over the whole life cycle would be huge.

- In this MADM tool, the use of weighting factors is necessary to account for user preferences and the use of threshold values to account for data uncertainties and the significance of differences. The final ranking of the solutions depends on these parameters, but small changes in these parameters should not completely overturn the ranking. In other words, the solution is expected to be sufficiently stable. Therefore, sensitivity analyses are needed to check the stability or robustness of the solution.

Application of the methodology in this case study also highlighted some potential ways to improve the quality of future analyses:

- The performance indicator shall be refined, in order to better characterize the overall performance. For example, this indicator should also cover the resistance to ravelling, a very important performance characteristic for surface courses. The work done in the ongoing CEDR project DRaT (Development of the Ravelling Test), may contribute to this improvement.

- Using lifetime prediction could be a viable alternative to the evaluation of the performance indicator, provided the lifetime prediction is sufficiently accurate. Such a lifetime prediction will of course be based on the performance characteristics of the asphalt. A further improvement could then be provided by using the outcome of the CEDR project CONSISTEND, which also allows to assess the effects of construction quality on the lifetime.

- Effort should be made to refine the assessment methodologies for indicators that are outweighed by 'in use' impacts, to isolate the specific material-related contributions to the overall impact score. The justification for this would be that material choice can only influence a small fraction of overall in-use exhaust emissions through micro and macro texture. The other major contributors to overall exhaust emissions, such as the vehicle characteristics, road profile and roughness, are defined by external factors and therefore should not be included in a material-based assessment.

- The sensitivity analysis may become a very extensive and time consuming work. It is impossible to change all the parameters in all possible measures. Guidelines on how to perform such an analysis in the most efficient way may be of help to the user.

- The user friendliness, quality of graphs and interactivity of the tool can be improved, but this is beyond the scope of the present project which only aimed to develop and demonstrate the methodology.

Some supplementary challenges for future development are:

- How to deal more accurately with missing data?

  If data for an indicator is not or only partially known, assumptions can be made to obtain a value, based on preliminary lab results, experience or literature. In the case, where the data is missing and the assumptions cannot be made, the value can be left empty and the indicator will be treated as unknown. Also possible unavailability of real-life data compared to laboratory data could influence an assessment.

- How to deal more accurately with uncertainty of data?

  Even if indicator values for different cases are the same, the uncertainty could be different. The amount of laboratory or real-life tests or experience can be totally different. A way to introduce uncertainty of values into the methodology seems necessary. This expresses how an NRA deals with risks in an assessment. Preferring lower uncertainties for identical indicator values, or only accepting improved indicator values with an acceptable uncertainty, is part of an overall risk assessment that could be embedded in the methodology

- How to streamline the analysis and make it less time consuming?

  A well-informed user can easily streamline the analysis by focussing on the indicators of particular concern, if they are in possession of good, reliable data for a standard reference material (e.g. a standard hot mix) that can always be used as a baseline for comparison. Deliverable 2.2 included a 'Considerations Matrix' to indicate where the user might like to focus their analysis according to the particular type of technology they were considering. For example, the particular concerns with a new polymer-modified bitumen might be 'global warming potential', 'financial cost' and 'recyclability, with 'noise', 'performance' and 'traffic congestion' the anticipated positive impacts. The other impacts in the basket: 'resource depletion', 'air pollution', 'leaching potential', 'skid resistance' and 'responsible sourcing' would be anticipated neutral. On this basis the user might want to analyse only the 'concerns' or the 'concerns and positives' in order to make an informed decision regarding use of the new technology. To perform the streamlined analysis, the user would need to obtain data regarding the new technology for only the indicators that fall into the focussed 'basket' and default to the reference data for the remainder. The weightings could also be modified to place more emphasis on the indicators within the basket to further enhance the analysis. **Figure 7-1** indicates how this might work.

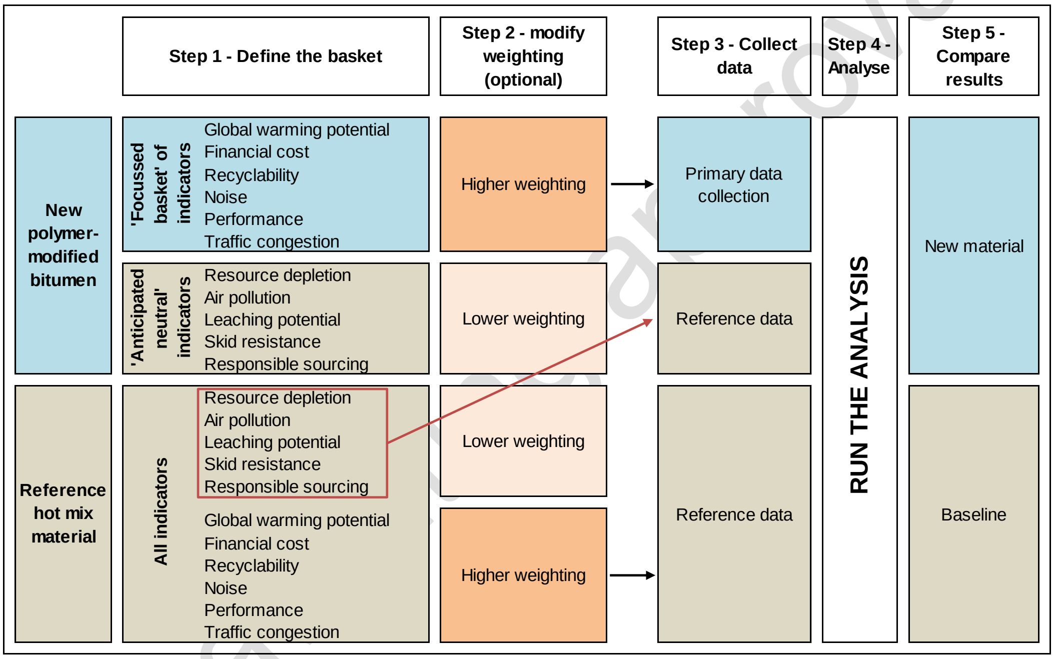



**Figure 7-1**: A streamlined analysis

If the user is in possession of a full set of data for a reference material then a benchmark will essentially be formed, providing both a point of reference with which to compare new technologies and a means to rationalise the assessment process.

As a final remark it has to be mentioned that the framework that has been utilised in this study is general and can be used by NRAs, as a tool for evaluation and assessment of different asphalt technologies in a project. This case study only demonstrates the functionality of the methodology for one particular test case.

# 8 Acknowledgements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# Annex A: Input data

| | 1 - HMA | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | GWP | Depletion of resources | Air pollution | | Leaching potential | Noise | Skid resistance | Financial cost | Recyclability | Performance | | | Responsible sourcing | Traffic congestion |
| Product stage | kg CO2eq | kg sbeq /tonne | *Acidification* kg SO2eq | *Photochemical oxidation* kgEthene eq | - | dB | PBN | € | % | % | % | [10-6] | - | € |
| A1 - Raw materials : aggregates (incld. sand&fillers) | 5.07 | - | 8.98E-03 | 4.12E-03 | | | | | | | | | | |
| A1 a - Raw materials : bitumen | 11.78 | 2.02E-04 | 2.73E-02 | 1.13E-02 | | | | | | | | | | |
| A1 b - Raw materials : additives | | | | | | | | | | | | | | |
| A2 - Transport to asphalt plant | 5.49 | 6.07E-07 | 1.01E-02 | 7.86E-03 | | | | | | | | | | |
| A3 - Production in the plant | 22.34 | 1.75E-05 | 5.57E-02 | 3.68E-02 | | | | | | | | | | |
| A4 - Transport to road site | 5.83 | 6.85E-07 | 1.17E-02 | 8.92E-03 | | | | | | | | | | |
| A5 - Laying of asphalt | 1.24 | 4.89E-07 | 8.10E-04 | 1.27E-03 | | | | | | | | | | 11.92 |
| B1 - Road use | 19682 | | 1.78E+01 | | 4.33E-07 | 95.2 | 65 | | | 90 | 5.6 | 115 | | |
| B2-B4 - maintenance, repair and replacement | 0.00 | | | | | | | | | | | | | |
| C1 - Demolition | 3.10 | 4.89E-07 | 4.70E-04 | 1.43E-04 | | | | | | | | | | 11.92 |
| C2 - Transport waste material | 5.83 | 6.85E-07 | 1.17E-02 | 8.92E-03 | | | | | | | | | | |
| C3 - Waste processing for recycling | 2.00 | | - | - | | | | | | | | | | |
| C4 - Waste disposal | 0.00 | | - | - | | | | | | | | | | |
| **Total (Excluding use stage)** | **62.7** | **2.22E-04** | **1.27E-01** | **7.93E-02** | **4.79E-04** | **95.2** | **65** | **189.00** | **100** | **90** | **5.6** | **115** | **33** | **23.84** |

| | 2 - WMA | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | GWP | Depletion of resources | Air pollution | | Leaching potential | Noise | Skid resistance | Financial cost | Recyclability | Performance | | | Responsible sourcing | Traffic congestion |
| Product stage | kg $CO_2$eq | kg sbeq /tonne | *Acidification* kg $SO_2$eq | *Photochemical oxidation* kgEthene eq | - | dB | PBN | € | % | % | % | [10-6] | - | € |
| A1 - Raw materials : aggregates (incld. sand&fillers) | 5.07 | | 8.98E-03 | 4.12E-03 | | | | | | | | | | |
| A1 a - Raw materials : bitumen | 11.44 | 1.96E-04 | 2.65E-02 | 1.10E-02 | | | | | | | | | | |
| A1 b - Raw materials : additives | 10.26 | | - | - | | | | | | | | | | |
| A2 - Transport to asphalt plant | 5.49 | 6.07E-07 | 1.01E-02 | 7.84E-03 | | | | | | | | | | |
| A3 - Production in the plant | 19.10 | 1.45E-05 | 5.47E-02 | 3.59E-02 | | | | | | | | | | |
| A4 - Transport to road site | 5.83 | 6.85E-07 | 1.17E-02 | 8.92E-03 | | | | | | | | | | |
| A5 - Laying of asphalt | 1.24 | 4.89E-07 | 8.10E-04 | 1.27E-03 | | | | | | | | | | 9.15 |
| B1 - Road use | 19682.4 | | 1.78E+01 | | - | 95 | 65 | | | 87 | 5 | 120 | | |
| B2-B4 - maintenance, repair and replacement | 0.00 | | | | | | | | | | | | | |
| C1 - Demolition | 3.10 | 4.89E-07 | 4.70E-04 | 1.43E-04 | | | | | | | | | | 9.15 |
| C2 - Transport waste material | 5.83 | 6.85E-07 | 1.17E-02 | 8.92E-03 | | | | | | | | | | |
| C3 - Waste processing for recycling | 2.00 | | - | - | | | | | | | | | | |
| C4 - Waste disposal | 0.00 | | - | - | | | | | | | | | | |
| **Total (Excluding use stage)** | **69.4** | **2.13E-04** | **1.25E-01** | **7.81E-02** | **-** | **95.2** | **65** | **190.00** | **100%** | **87** | **5** | **120** | **33** | **18.30** |

| Product stage | GWP | Depletion of resources | Air pollution | | Leaching potential | Noise | Skid resistance | Financial cost | Recyclability | Performance | | | Responsible sourcing | Traffic congestion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **3 – WMA with RAP** | | | | | | | | | | | | | |
| | kg CO2eq | kg sbeq /tonne | *Acidification* kg SO2eq | *Photochemical oxidation* kgEthene eq | - | dB | PBN | € | % | % | % | [10-6] | - | € |
| A1 - Raw materials : aggregates (incld. sand&fillers) | 3.57 | | 6.29E-03 | 2.88E-03 | | | | | | | | | | |
| A1 a - Raw materials : bitumen | 7.98 | 1.37E-04 | 1.85E-02 | 7.68E-03 | | | | | | | | | | |
| A1 b - Raw materials : additives | 10.26 | | 5.37E-03 | 1.56E-03 | | | | | | | | | | |
| A2 - Transport to asphalt plant | 4.15 | 4.24E-07 | 7.11E-03 | 5.51E-03 | | | | | | | | | | |
| A3 - Production in the plant | 19.10 | 1.45E-05 | 5.47E-02 | 3.59E-02 | | | | | | | | | | |
| A4 - Transport to road site | 5.83 | 6.52E-07 | 1.17E-02 | 8.92E-03 | | | | | | | | | | |
| A5 - Laying of asphalt | 1.24 | 4.89E-07 | 8.10E-04 | 1.27E-03 | | | | | | | | | | 9.15 |
| B1 - Road use | 19682.44 | | 1.78E+01 | | - | 95 | 70 | | | 90 | 4.8 | 120 | | |
| B2-B4 - maintenance, repair and replacement | 0.00 | | | | | | | | | | | | | |
| C1 - Demolition | 3.10 | 4.89E-07 | 4.70E-04 | 1.43E-04 | | | | | | | | | | 9.15 |
| C2 - Transport waste material | 5.83 | 6.52E-07 | 1.17E-02 | 8.92E-03 | | | | | | | | | | |
| C3 - Waste processing for recycling | 2.00 | | - | - | | | | | | | | | | |
| C4 - Waste disposal | 0.00 | | 0.00E+00 | 0.00E+00 | | | | | | | | | | |
| **Total (Excluding use stage)** | **63.1** | **1.54E-04** | **1.17E-01** | **7.28E-02** | **-** | **95.2** | **70** | **154.00** | **80%** | **90** | **5** | **120** | **33** | **18.30** |

**4 – CIR**

| Product stage | GWP | Depletion of resources | Air pollution | | Leaching potential | Noise | Skid resistance | Financial cost | Recyclability | Performance | | | Responsible sourcing | Traffic congestion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | kg CO2eq | kg sbeq /tonne | *Acidification* kg SO2eq | *Photochemical oxidation* kgEthene eq | - | dB | PBN | € | % | % | % | [10-6] | - | € |
| A1 - Raw materials : aggregates (incld. sand&fillers) | 3.86 | | 5.89E-04 | 2.72E-04 | | | | | | | | | | |
| A1 a - Raw materials : bitumen | 4.98 | 8.55E-05 | 1.15E-02 | 4.79E-03 | | | | | | | | | | |
| A1 b - Raw materials : additives | 9.13 | | 7.90E-03 | 2.23E-03 | | | | | | | | | | |
| A2 - Transport to asphalt plant | 0.00 | 7.83E-08 | 1.19E-03 | 9.09E-04 | | | | | | | | | | |
| A3 - Production in the plant | 0.00 | 1.82E-06 | | | | | | | | | | | | |
| A4 - Transport to road site | 3.36 | - | | | | | | | | | | | | |
| A5 - Laying of asphalt | 1.24 | 4.89E-07 | 8.10E-05 | 1.27E-04 | | | | | | | | | | 27.92 |
| B1 - Road use | 19682.44 | | 1.78E+01 | | - | - | - | | | 77 | 5.9 | 103.5 | | |
| B2-B4 - maintenance, repair and replacement | 0.00 | | | | | | | | | | | | | |
| C1 - Demolition | 3.10 | 4.89E-07 | 4.70E-04 | 1.43E-04 | | | | | | | | | | 27.92 |
| C2 - Transport waste material | 5.83 | 6.85E-07 | 1.17E-02 | 8.92E-03 | | | | | | | | | | |
| C3 - Waste processing for recycling | 2.00 | | | | | | | | | | | | | |
| C4 - Waste disposal | 0.00 | | | | | | | | | | | | | |
| **Total (Excluding use stage)** | **33.5** | **8.91E-05** | **3.35E-02** | **1.74E-02** | ***** | **0.0** | **0** | **183.00** | **72%** | **77** | **6** | **103.5** | **33** | **55.84** |

| | 5 – HMA with steel slag | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | GWP | Depletion of resources | Air pollution | | Leaching potential | Noise | Skid resistance | Financial cost | Recyclability | Performance | | | Responsible sourcing | Traffic congestion |
| Product stage | kg $CO_2$eq | kg sbeq /tonne | *Acidification* kg $SO_2$eq | *Photochemical oxidation* kgEthene eq | - | dB | PBN | € | % | % | % | [10-6] | - | € |
| A1 - Raw materials : aggregates (incld. sand&fillers) | 2.10 | | 3.58E-03 | 1.63E-03 | | | | | | | | | | |
| A1 a - Raw materials : bitumen | 11.78 | 2.02E-04 | 2.73E-02 | 1.13E-02 | | | | | | | | | | |
| A1 b - Raw materials : additives | 0.00 | | 1.08E-03 | 9.34E-04 | | | | | | | | | | |
| A2 - Transport to asphalt plant | 6.24 | 6.52E-07 | 1.09E-02 | 8.44E-03 | | | | | | | | | | |
| A3 - Production in the plant | 22.34 | 1.75E-05 | 1.17E-02 | 8.92E-03 | | | | | | | | | | |
| A4 - Transport to road site | 6.41 | 7.50E-07 | 1.29E-02 | 9.81E-03 | | | | | | | | | | |
| A5 - Laying of asphalt | 1.24 | 4.89E-07 | 8.10E-04 | 1.27E-03 | | | | | | | | | | 11.92 |
| B1 - Road use | 19682.4 4 | | | | 1.06E-06 | 91.7 | 62.000 | | | 90 | 4.8 | 115 | | |
| B2-B4 - maintenance, repair and replacement | 0.00 | | | | | | | | | | | | | |
| C1 - Demolition | 3.10 | 4.89E-07 | 4.70E-04 | 1.43E-04 | | | | | | | | | | 11.92 |
| C2 - Transport waste material | 6.41 | 7.50E-07 | 1.29E-02 | 9.81E-03 | | | | | | | | | | |
| C3 - Waste processing for recycling | 0.00 | | | | | | | | | | | | | |
| C4 - Waste disposal | 0.00 | | | | | | | | | | | | | |
| **Total (Excluding use stage)** | **59.6** | **2.23E-04** | **8.16E-02** | **5.23E-02** | **1.48E-03** | **91.7** | **62** | **185** | **80** | **90** | **5** | **115** | **33** | **23.84** |

# Annex B: Details of sensitivity analysis

## *Partial aggregation method*

| | | | | GWP/Climate change | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | |
| | | | | 30% | 25% | 20% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.267 | 0.233 | 0.195 | 0.327 | 0.353 | 0.377 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.044 | 0.047 | 0.049 | 0.041 | 0.039 | 0.038 |
| | Air pollution | $\omega_3$ | 0.075 | 0.067 | 0.070 | 0.073 | 0.061 | 0.059 | 0.057 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.044 | 0.047 | 0.049 | 0.041 | 0.039 | 0.038 |
| | Noise | $\omega_5$ | 0.063 | 0.056 | 0.058 | 0.061 | 0.051 | 0.049 | 0.047 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.044 | 0.047 | 0.049 | 0.041 | 0.039 | 0.038 |
| | Financial cost | $\omega_7$ | 0.088 | 0.078 | 0.081 | 0.085 | 0.071 | 0.069 | 0.066 |
| | Recyability | $\omega_8$ | 0.138 | 0.122 | 0.128 | 0.134 | 0.112 | 0.108 | 0.104 |
| | Performance | $\omega_9$ | 0.225 | 0.200 | 0.209 | 0.220 | 0.184 | 0.176 | 0.170 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.033 | 0.035 | 0.037 | 0.031 | 0.029 | 0.028 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.044 | 0.047 | 0.049 | 0.041 | 0.039 | 0.038 |
| | | | | Ranking of the variations | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 3 | 3 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 3 | 2 | 2 | 3 | 4 | 4 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 2 | 3 | 3 | 2 | 1 | 1 |

| | | | | Depletion of resources | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | |
| | | | | 30% | 25% | 20% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.140 | 0.146 | 0.152 | 0.130 | 0.125 | 0.121 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.240 | 0.208 | 0.174 | 0.296 | 0.321 | 0.345 |
| | Air pollution | $\omega_3$ | 0.075 | 0.060 | 0.063 | 0.065 | 0.056 | 0.054 | 0.052 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.037 | 0.036 | 0.034 |
| | Noise | $\omega_5$ | 0.063 | 0.050 | 0.052 | 0.054 | 0.046 | 0.045 | 0.043 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.037 | 0.036 | 0.034 |
| | Financial cost | $\omega_7$ | 0.088 | 0.070 | 0.073 | 0.076 | 0.065 | 0.063 | 0.060 |
| | Recyability | $\omega_8$ | 0.138 | 0.110 | 0.115 | 0.120 | 0.102 | 0.098 | 0.095 |
| | Performance | $\omega_9$ | 0.225 | 0.180 | 0.188 | 0.196 | 0.167 | 0.161 | 0.155 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.030 | 0.031 | 0.033 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.037 | 0.036 | 0.034 |
| | | | | Ranking of the variations | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

| | | | | Air pollution | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 20% | 25% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.143 | 0.156 | 0.149 | 0.171 | 0.132 | 0.127 | 0.123 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.041 | 0.044 | 0.043 | 0.049 | 0.038 | 0.036 | 0.035 |
| | Air pollution | $\omega_3$ | 0.075 | 0.245 | 0.178 | 0.213 | 0.098 | 0.302 | 0.327 | 0.351 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.041 | 0.044 | 0.043 | 0.049 | 0.038 | 0.036 | 0.035 |
| | Noise | $\omega_5$ | 0.063 | 0.051 | 0.056 | 0.053 | 0.061 | 0.047 | 0.045 | 0.044 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.041 | 0.044 | 0.043 | 0.049 | 0.038 | 0.036 | 0.035 |
| | Financial cost | $\omega_7$ | 0.088 | 0.071 | 0.078 | 0.074 | 0.085 | 0.066 | 0.064 | 0.061 |
| | Recyability | $\omega_8$ | 0.138 | 0.112 | 0.122 | 0.117 | 0.134 | 0.104 | 0.100 | 0.096 |
| | Performance | $\omega_9$ | 0.225 | 0.184 | 0.200 | 0.191 | 0.220 | 0.170 | 0.164 | 0.158 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.031 | 0.033 | 0.032 | 0.037 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.041 | 0.044 | 0.043 | 0.049 | 0.038 | 0.036 | 0.035 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 3 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 1 | 1 | 1 | 3 | 1 | 1 | 1 |

| | | | | Leaching potential | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.140 | 0.146 | 0.152 | 0.167 | 0.130 | 0.125 | 0.121 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Air pollution | $\omega_3$ | 0.075 | 0.060 | 0.063 | 0.065 | 0.071 | 0.056 | 0.054 | 0.052 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.240 | 0.208 | 0.174 | 0.095 | 0.296 | 0.321 | 0.345 |
| | Noise | $\omega_5$ | 0.063 | 0.050 | 0.052 | 0.054 | 0.060 | 0.046 | 0.045 | 0.043 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Financial cost | $\omega_7$ | 0.088 | 0.070 | 0.073 | 0.076 | 0.083 | 0.065 | 0.063 | 0.060 |
| | Recyability | $\omega_8$ | 0.138 | 0.110 | 0.115 | 0.120 | 0.131 | 0.102 | 0.098 | 0.095 |
| | Performance | $\omega_9$ | 0.225 | 0.180 | 0.188 | 0.196 | 0.214 | 0.167 | 0.161 | 0.155 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.030 | 0.031 | 0.033 | 0.036 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 3 | 3 | 3 |
| | WMA+RA | a3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 |

| | | | | Noise | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.141 | 0.147 | 0.154 | 0.169 | 0.131 | 0.126 | 0.122 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.040 | 0.042 | 0.044 | 0.048 | 0.037 | 0.036 | 0.035 |
| | Air pollution | $\omega_3$ | 0.075 | 0.061 | 0.063 | 0.066 | 0.072 | 0.056 | 0.054 | 0.052 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.040 | 0.042 | 0.044 | 0.048 | 0.037 | 0.036 | 0.035 |
| | Noise | $\omega_5$ | 0.063 | 0.242 | 0.211 | 0.176 | 0.075 | 0.299 | 0.324 | 0.348 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.040 | 0.042 | 0.044 | 0.048 | 0.037 | 0.036 | 0.035 |
| | Financial cost | $\omega_7$ | 0.088 | 0.071 | 0.074 | 0.077 | 0.084 | 0.065 | 0.063 | 0.061 |
| | Recyability | $\omega_8$ | 0.138 | 0.111 | 0.116 | 0.121 | 0.133 | 0.103 | 0.099 | 0.096 |
| | Performance | $\omega_9$ | 0.225 | 0.182 | 0.189 | 0.198 | 0.217 | 0.168 | 0.162 | 0.157 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.030 | 0.032 | 0.033 | 0.036 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.040 | 0.042 | 0.044 | 0.048 | 0.037 | 0.036 | 0.035 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 3 | 3 | 4 | 4 | 3 | 3 | 3 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 4 | 4 | 3 | 2 | 4 | 4 | 4 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 1 | 1 | 1 | 3 | 1 | 1 | 1 |

| | | | | Skid resistance | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.140 | 0.146 | 0.152 | 0.167 | 0.130 | 0.125 | 0.121 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Air pollution | $\omega_3$ | 0.075 | 0.060 | 0.063 | 0.065 | 0.071 | 0.056 | 0.054 | 0.052 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Noise | $\omega_5$ | 0.063 | 0.050 | 0.052 | 0.054 | 0.060 | 0.046 | 0.045 | 0.043 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.240 | 0.208 | 0.174 | 0.095 | 0.296 | 0.321 | 0.345 |
| | Financial cost | $\omega_7$ | 0.088 | 0.070 | 0.073 | 0.076 | 0.083 | 0.065 | 0.063 | 0.060 |
| | Recyability | $\omega_8$ | 0.138 | 0.110 | 0.115 | 0.120 | 0.131 | 0.102 | 0.098 | 0.095 |
| | Performance | $\omega_9$ | 0.225 | 0.180 | 0.188 | 0.196 | 0.214 | 0.167 | 0.161 | 0.155 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.030 | 0.031 | 0.033 | 0.036 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

| | | | | Financial Cost | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | |
| | | | | 30% | 25% | 20% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.144 | 0.151 | 0.157 | 0.133 | 0.128 | 0.124 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.041 | 0.043 | 0.045 | 0.038 | 0.037 | 0.035 |
| | Air pollution | $\omega_3$ | 0.075 | 0.062 | 0.065 | 0.067 | 0.057 | 0.055 | 0.053 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.041 | 0.043 | 0.045 | 0.038 | 0.037 | 0.035 |
| | Noise | $\omega_5$ | 0.063 | 0.052 | 0.054 | 0.056 | 0.048 | 0.046 | 0.044 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.041 | 0.043 | 0.045 | 0.038 | 0.037 | 0.035 |
| | Financial cost | $\omega_7$ | 0.088 | 0.247 | 0.215 | 0.180 | 0.305 | 0.330 | 0.354 |
| | Recyability | $\omega_8$ | 0.138 | 0.113 | 0.118 | 0.124 | 0.105 | 0.101 | 0.097 |
| | Performance | $\omega_9$ | 0.225 | 0.186 | 0.194 | 0.202 | 0.171 | 0.165 | 0.159 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.031 | 0.032 | 0.034 | 0.029 | 0.028 | 0.027 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.041 | 0.043 | 0.045 | 0.038 | 0.037 | 0.035 |
| | | | | Ranking of the variations | | | | | |
| Ranking | HMA | a1 | 4 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA | a2 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WMA+RA | a3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

| | | | | Recyability | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.151 | 0.157 | 0.165 | 0.182 | 0.139 | 0.133 | 0.128 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.043 | 0.045 | 0.047 | 0.052 | 0.040 | 0.038 | 0.037 |
| | Air pollution | $\omega_3$ | 0.075 | 0.065 | 0.067 | 0.071 | 0.078 | 0.059 | 0.057 | 0.055 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.043 | 0.045 | 0.047 | 0.052 | 0.040 | 0.038 | 0.037 |
| | Noise | $\omega_5$ | 0.063 | 0.054 | 0.056 | 0.059 | 0.065 | 0.050 | 0.048 | 0.046 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.043 | 0.045 | 0.047 | 0.052 | 0.040 | 0.038 | 0.037 |
| | Financial cost | $\omega_7$ | 0.088 | 0.075 | 0.079 | 0.082 | 0.091 | 0.069 | 0.067 | 0.064 |
| | Recyability | $\omega_8$ | 0.138 | 0.258 | 0.225 | 0.188 | 0.104 | 0.317 | 0.343 | 0.367 |
| | Performance | $\omega_9$ | 0.225 | 0.194 | 0.202 | 0.212 | 0.234 | 0.178 | 0.171 | 0.165 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.032 | 0.034 | 0.035 | 0.039 | 0.030 | 0.029 | 0.028 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.043 | 0.045 | 0.047 | 0.052 | 0.040 | 0.038 | 0.037 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 2 | 3 | 3 | 4 | 1 | 1 | 1 |
| | WMA | a2 | 5 | 4 | 5 | 5 | 5 | 4 | 3 | 3 |
| | WMA+RA | a3 | 2 | 3 | 2 | 2 | 2 | 3 | 4 | 4 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 5 | 4 | 4 | 3 | 5 | 5 | 5 |

| | | | | Performance | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.163 | 0.171 | 0.179 | 0.200 | 0.149 | 0.143 | 0.137 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.047 | 0.049 | 0.051 | 0.057 | 0.043 | 0.041 | 0.039 |
| | Air pollution | $\omega_3$ | 0.075 | 0.070 | 0.073 | 0.077 | 0.086 | 0.064 | 0.061 | 0.059 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.047 | 0.049 | 0.051 | 0.057 | 0.043 | 0.041 | 0.039 |
| | Noise | $\omega_5$ | 0.063 | 0.058 | 0.061 | 0.064 | 0.071 | 0.053 | 0.051 | 0.049 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.047 | 0.049 | 0.051 | 0.057 | 0.043 | 0.041 | 0.039 |
| | Financial cost | $\omega_7$ | 0.088 | 0.081 | 0.085 | 0.090 | 0.100 | 0.074 | 0.071 | 0.069 |
| | Recyability | $\omega_8$ | 0.138 | 0.128 | 0.134 | 0.141 | 0.157 | 0.117 | 0.112 | 0.108 |
| | Performance | $\omega_9$ | 0.225 | 0.279 | 0.244 | 0.205 | 0.114 | 0.340 | 0.367 | 0.392 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.035 | 0.037 | 0.038 | 0.043 | 0.032 | 0.031 | 0.029 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.047 | 0.049 | 0.051 | 0.057 | 0.043 | 0.041 | 0.039 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 |

| | | | | Traffic congestion | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.140 | 0.146 | 0.152 | 0.167 | 0.130 | 0.125 | 0.121 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Air pollution | $\omega_3$ | 0.075 | 0.060 | 0.063 | 0.065 | 0.071 | 0.056 | 0.054 | 0.052 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Noise | $\omega_5$ | 0.063 | 0.050 | 0.052 | 0.054 | 0.060 | 0.046 | 0.045 | 0.043 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Financial cost | $\omega_7$ | 0.088 | 0.070 | 0.073 | 0.076 | 0.083 | 0.065 | 0.063 | 0.060 |
| | Recyability | $\omega_8$ | 0.138 | 0.110 | 0.115 | 0.120 | 0.131 | 0.102 | 0.098 | 0.095 |
| | Performance | $\omega_9$ | 0.225 | 0.180 | 0.188 | 0.196 | 0.214 | 0.167 | 0.161 | 0.155 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.030 | 0.031 | 0.033 | 0.036 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.240 | 0.208 | 0.174 | 0.095 | 0.296 | 0.321 | 0.345 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

## *Complete aggregation method*

| | | | | GWP | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | |
| | | | | **30%** | **25%** | **20%** | **40%** | **45%** | **50%** |
| | | | **Base** | **Calculation of the weighting factors** | | | | | |
| **Weight of the criteria** | GWP | $\omega_1$ | 0.175 | 0.267 | 0.233 | 0.195 | 0.327 | 0.353 | 0.377 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.044 | 0.047 | 0.049 | 0.041 | 0.039 | 0.038 |
| | Air pollution | $\omega_3$ | 0.075 | 0.067 | 0.070 | 0.073 | 0.061 | 0.059 | 0.057 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.044 | 0.047 | 0.049 | 0.041 | 0.039 | 0.038 |
| | Noise | $\omega_5$ | 0.063 | 0.056 | 0.058 | 0.061 | 0.051 | 0.049 | 0.047 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.044 | 0.047 | 0.049 | 0.041 | 0.039 | 0.038 |
| | Financial cost | $\omega_7$ | 0.088 | 0.078 | 0.081 | 0.085 | 0.071 | 0.069 | 0.066 |
| | Recyability | $\omega_8$ | 0.138 | 0.122 | 0.128 | 0.134 | 0.112 | 0.108 | 0.104 |
| | Performance | $\omega_9$ | 0.225 | 0.200 | 0.209 | 0.220 | 0.184 | 0.176 | 0.170 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.033 | 0.035 | 0.037 | 0.031 | 0.029 | 0.028 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.044 | 0.047 | 0.049 | 0.041 | 0.039 | 0.038 |
| | | | | **Ranking of the variations** | | | | | |
| **Ranking** | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 2 | 2 | 2 | 2 | 2 | 2 |

| | | | | Depletion of resources | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | |
| | | | | **30%** | **25%** | **20%** | **40%** | **45%** | **50%** |
| | | | **Base** | **Calculation of the weighting factors** | | | | | |
| **Weight of the criteria** | GWP | $\omega_1$ | 0.175 | 0.140 | 0.146 | 0.152 | 0.130 | 0.125 | 0.121 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.240 | 0.208 | 0.174 | 0.296 | 0.321 | 0.345 |
| | Air pollution | $\omega_3$ | 0.075 | 0.060 | 0.063 | 0.065 | 0.056 | 0.054 | 0.052 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.037 | 0.036 | 0.034 |
| | Noise | $\omega_5$ | 0.063 | 0.050 | 0.052 | 0.054 | 0.046 | 0.045 | 0.043 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.037 | 0.036 | 0.034 |
| | Financial cost | $\omega_7$ | 0.088 | 0.070 | 0.073 | 0.076 | 0.065 | 0.063 | 0.060 |
| | Recyability | $\omega_8$ | 0.138 | 0.110 | 0.115 | 0.120 | 0.102 | 0.098 | 0.095 |
| | Performance | $\omega_9$ | 0.225 | 0.180 | 0.188 | 0.196 | 0.167 | 0.161 | 0.155 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.030 | 0.031 | 0.033 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.037 | 0.036 | 0.034 |
| | | | | **Ranking of the variations** | | | | | |
| **Ranking** | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 5 | 5 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 4 | 4 |
| | WMA+RA | a3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

| | | | | Air pollution | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 20% | 25% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.143 | 0.156 | 0.149 | 0.171 | 0.132 | 0.127 | 0.123 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.041 | 0.044 | 0.043 | 0.049 | 0.038 | 0.036 | 0.035 |
| | Air pollution | $\omega_3$ | 0.075 | 0.245 | 0.178 | 0.213 | 0.098 | 0.302 | 0.327 | 0.351 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.041 | 0.044 | 0.043 | 0.049 | 0.038 | 0.036 | 0.035 |
| | Noise | $\omega_5$ | 0.063 | 0.051 | 0.056 | 0.053 | 0.061 | 0.047 | 0.045 | 0.044 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.041 | 0.044 | 0.043 | 0.049 | 0.038 | 0.036 | 0.035 |
| | Financial cost | $\omega_7$ | 0.088 | 0.071 | 0.078 | 0.074 | 0.085 | 0.066 | 0.064 | 0.061 |
| | Recyability | $\omega_8$ | 0.138 | 0.112 | 0.122 | 0.117 | 0.134 | 0.104 | 0.100 | 0.096 |
| | Performance | $\omega_9$ | 0.225 | 0.184 | 0.200 | 0.191 | 0.220 | 0.170 | 0.164 | 0.158 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.031 | 0.033 | 0.032 | 0.037 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.041 | 0.044 | 0.043 | 0.049 | 0.038 | 0.036 | 0.035 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

| | | | | Leaching potential | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.140 | 0.146 | 0.152 | 0.167 | 0.130 | 0.125 | 0.121 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Air pollution | $\omega_3$ | 0.075 | 0.060 | 0.063 | 0.065 | 0.071 | 0.056 | 0.054 | 0.052 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.240 | 0.208 | 0.174 | 0.095 | 0.296 | 0.321 | 0.345 |
| | Noise | $\omega_5$ | 0.063 | 0.050 | 0.052 | 0.054 | 0.060 | 0.046 | 0.045 | 0.043 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Financial cost | $\omega_7$ | 0.088 | 0.070 | 0.073 | 0.076 | 0.083 | 0.065 | 0.063 | 0.060 |
| | Recyability | $\omega_8$ | 0.138 | 0.110 | 0.115 | 0.120 | 0.131 | 0.102 | 0.098 | 0.095 |
| | Performance | $\omega_9$ | 0.225 | 0.180 | 0.188 | 0.196 | 0.214 | 0.167 | 0.161 | 0.155 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.030 | 0.031 | 0.033 | 0.036 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

| | | | | Noise | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.141 | 0.147 | 0.154 | 0.169 | 0.131 | 0.126 | 0.122 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.040 | 0.042 | 0.044 | 0.048 | 0.037 | 0.036 | 0.035 |
| | Air pollution | $\omega_3$ | 0.075 | 0.061 | 0.063 | 0.066 | 0.072 | 0.056 | 0.054 | 0.052 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.040 | 0.042 | 0.044 | 0.048 | 0.037 | 0.036 | 0.035 |
| | Noise | $\omega_5$ | 0.063 | 0.242 | 0.211 | 0.176 | 0.075 | 0.299 | 0.324 | 0.348 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.040 | 0.042 | 0.044 | 0.048 | 0.037 | 0.036 | 0.035 |
| | Financial cost | $\omega_7$ | 0.088 | 0.071 | 0.074 | 0.077 | 0.084 | 0.065 | 0.063 | 0.061 |
| | Recyability | $\omega_8$ | 0.138 | 0.111 | 0.116 | 0.121 | 0.133 | 0.103 | 0.099 | 0.096 |
| | Performance | $\omega_9$ | 0.225 | 0.182 | 0.189 | 0.198 | 0.217 | 0.168 | 0.162 | 0.157 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.030 | 0.032 | 0.033 | 0.036 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.040 | 0.042 | 0.044 | 0.048 | 0.037 | 0.036 | 0.035 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

| | | | | Skid resistance | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.140 | 0.146 | 0.152 | 0.167 | 0.130 | 0.125 | 0.121 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Air pollution | $\omega_3$ | 0.075 | 0.060 | 0.063 | 0.065 | 0.071 | 0.056 | 0.054 | 0.052 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Noise | $\omega_5$ | 0.063 | 0.050 | 0.052 | 0.054 | 0.060 | 0.046 | 0.045 | 0.043 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.240 | 0.208 | 0.174 | 0.095 | 0.296 | 0.321 | 0.345 |
| | Financial cost | $\omega_7$ | 0.088 | 0.070 | 0.073 | 0.076 | 0.083 | 0.065 | 0.063 | 0.060 |
| | Recyability | $\omega_8$ | 0.138 | 0.110 | 0.115 | 0.120 | 0.131 | 0.102 | 0.098 | 0.095 |
| | Performance | $\omega_9$ | 0.225 | 0.180 | 0.188 | 0.196 | 0.214 | 0.167 | 0.161 | 0.155 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.030 | 0.031 | 0.033 | 0.036 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 3 | 3 | 3 | 4 | 3 | 3 | 3 |
| | WMA | a2 | 5 | 4 | 5 | 5 | 5 | 4 | 4 | 4 |
| | WMA+RA | a3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 5 | 4 | 4 | 3 | 5 | 5 | 5 |

| | | | | Financial Cost | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | |
| | | | | 30% | 25% | 20% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.144 | 0.151 | 0.157 | 0.133 | 0.128 | 0.124 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.041 | 0.043 | 0.045 | 0.038 | 0.037 | 0.035 |
| | Air pollution | $\omega_3$ | 0.075 | 0.062 | 0.065 | 0.067 | 0.057 | 0.055 | 0.053 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.041 | 0.043 | 0.045 | 0.038 | 0.037 | 0.035 |
| | Noise | $\omega_5$ | 0.063 | 0.052 | 0.054 | 0.056 | 0.048 | 0.046 | 0.044 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.041 | 0.043 | 0.045 | 0.038 | 0.037 | 0.035 |
| | Financial cost | $\omega_7$ | 0.088 | 0.247 | 0.215 | 0.180 | 0.305 | 0.330 | 0.354 |
| | Recyability | $\omega_8$ | 0.138 | 0.113 | 0.118 | 0.124 | 0.105 | 0.101 | 0.097 |
| | Performance | $\omega_9$ | 0.225 | 0.186 | 0.194 | 0.202 | 0.171 | 0.165 | 0.159 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.031 | 0.032 | 0.034 | 0.029 | 0.028 | 0.027 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.041 | 0.043 | 0.045 | 0.038 | 0.037 | 0.035 |
| | | | | Ranking of the variations | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

| | | | | Recyability | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.151 | 0.157 | 0.165 | 0.182 | 0.139 | 0.133 | 0.128 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.043 | 0.045 | 0.047 | 0.052 | 0.040 | 0.038 | 0.037 |
| | Air pollution | $\omega_3$ | 0.075 | 0.065 | 0.067 | 0.071 | 0.078 | 0.059 | 0.057 | 0.055 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.043 | 0.045 | 0.047 | 0.052 | 0.040 | 0.038 | 0.037 |
| | Noise | $\omega_5$ | 0.063 | 0.054 | 0.056 | 0.059 | 0.065 | 0.050 | 0.048 | 0.046 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.043 | 0.045 | 0.047 | 0.052 | 0.040 | 0.038 | 0.037 |
| | Financial cost | $\omega_7$ | 0.088 | 0.075 | 0.079 | 0.082 | 0.091 | 0.069 | 0.067 | 0.064 |
| | Recyability | $\omega_8$ | 0.138 | 0.258 | 0.225 | 0.188 | 0.104 | 0.317 | 0.343 | 0.367 |
| | Performance | $\omega_9$ | 0.225 | 0.194 | 0.202 | 0.212 | 0.234 | 0.178 | 0.171 | 0.165 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.032 | 0.034 | 0.035 | 0.039 | 0.030 | 0.029 | 0.028 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.043 | 0.045 | 0.047 | 0.052 | 0.040 | 0.038 | 0.037 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 3 | 4 | 4 | 4 | 2 | 2 | 1 |
| | WMA | a2 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 3 |
| | WMA+RA | a3 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 4 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
| | HMA+Steel Slag | a5 | 3 | 5 | 3 | 3 | 3 | 4 | 4 | 5 |

| | | | | Performance | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.163 | 0.171 | 0.179 | 0.200 | 0.149 | 0.143 | 0.137 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.047 | 0.049 | 0.051 | 0.057 | 0.043 | 0.041 | 0.039 |
| | Air pollution | $\omega_3$ | 0.075 | 0.070 | 0.073 | 0.077 | 0.086 | 0.064 | 0.061 | 0.059 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.047 | 0.049 | 0.051 | 0.057 | 0.043 | 0.041 | 0.039 |
| | Noise | $\omega_5$ | 0.063 | 0.058 | 0.061 | 0.064 | 0.071 | 0.053 | 0.051 | 0.049 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.047 | 0.049 | 0.051 | 0.057 | 0.043 | 0.041 | 0.039 |
| | Financial cost | $\omega_7$ | 0.088 | 0.081 | 0.085 | 0.090 | 0.100 | 0.074 | 0.071 | 0.069 |
| | Recyability | $\omega_8$ | 0.138 | 0.128 | 0.134 | 0.141 | 0.157 | 0.117 | 0.112 | 0.108 |
| | Performance | $\omega_9$ | 0.225 | 0.279 | 0.244 | 0.205 | 0.114 | 0.340 | 0.367 | 0.392 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.035 | 0.037 | 0.038 | 0.043 | 0.032 | 0.031 | 0.029 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.047 | 0.049 | 0.051 | 0.057 | 0.043 | 0.041 | 0.039 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WMA | a2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | WMA+RA | a3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | CIR | a4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | HMA+Steel Slag | a5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

| | | | | Traffic congestion | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Choice of weighting factor | | | | | | |
| | | | | 30% | 25% | 20% | 10% | 40% | 45% | 50% |
| | | | Base | Calculation of the weighting factors | | | | | | |
| Weight of the criteria | GWP | $\omega_1$ | 0.175 | 0.140 | 0.146 | 0.152 | 0.167 | 0.130 | 0.125 | 0.121 |
| | Depletion of resources | $\omega_2$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Air pollution | $\omega_3$ | 0.075 | 0.060 | 0.063 | 0.065 | 0.071 | 0.056 | 0.054 | 0.052 |
| | Leaching potential | $\omega_4$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Noise | $\omega_5$ | 0.063 | 0.050 | 0.052 | 0.054 | 0.060 | 0.046 | 0.045 | 0.043 |
| | Skid resistance | $\omega_6$ | 0.050 | 0.040 | 0.042 | 0.043 | 0.048 | 0.037 | 0.036 | 0.034 |
| | Financial cost | $\omega_7$ | 0.088 | 0.070 | 0.073 | 0.076 | 0.083 | 0.065 | 0.063 | 0.060 |
| | Recyability | $\omega_8$ | 0.138 | 0.110 | 0.115 | 0.120 | 0.131 | 0.102 | 0.098 | 0.095 |
| | Performance | $\omega_9$ | 0.225 | 0.180 | 0.188 | 0.196 | 0.214 | 0.167 | 0.161 | 0.155 |
| | Responsible sourcing | $\omega_{10}$ | 0.038 | 0.030 | 0.031 | 0.033 | 0.036 | 0.028 | 0.027 | 0.026 |
| | Traffic congestion | $\omega_{11}$ | 0.050 | 0.240 | 0.208 | 0.174 | 0.095 | 0.296 | 0.321 | 0.345 |
| | | | | Ranking of the variations | | | | | | |
| Ranking | HMA | a1 | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 4 |
| | WMA | a2 | 5 | 4 | 5 | 5 | 5 | 3 | 3 | 3 |
| | WMA+RA | a3 | 2 | 1 | 1 | 1 | 2 | 1 | 1 | 1 |
| | CIR | a4 | 1 | 5 | 4 | 2 | 1 | 5 | 5 | 5 |
| | HMA+Steel Slag | a5 | 3 | 2 | 2 | 3 | 3 | 2 | 2 | 2 |