Conférence Européenne des Directeurs des Routes

Conference of European Directors of Roads

Pavement LCM

Pavement LCM Resources

Recommendations for Multi-Criteria Sustainability Assessment

Deliverable 5.1b

June 2021

CEDR Call 2017: New Materials

Project Nr. 128556
Project acronym: PAVEMENT LCM
Project title:

A complete package for Life Cycle Management of green asphalt mixtures and road pavement

Pavement LCM Resources
Deliverable 5.1b - Recommendations for Multi-Criteria Sustainability Analysis

Due date of deliverable: 31.05.2019
Actual submission date: 30.06.2021

Start date of project: 01.10.2018 End date of project: 30/6/2021

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Executive summary

This report describes the work performed to provide recommendations for performing Multi-Criteria Decision Analysis (MCDA) of pavement projects and asphalt mixtures under Pavement LCM project activities, task 5.4. Sustainability indicators can be categorised under three main pillars, Environment, Economy, and Society. Many indicators are available in the literature, some of the common ones include global warming, air pollution, resource depletion, energy consumption, noise, life cycle cost, pavement roughness, durability, and several others. Considering that number of indicators and the number of new green mixtures and asphalt production technologies rising to surface, it is important to use or develop a tool that is able to identify the most sustainable alternative amongst several options. This tool should be robots, simple to implement, and transparent in the calculation procedure and decisions making process.

Amongst several multi-criteria decision making (MCDM) methods available in literature, PROMETHEE method has been selected due to its transparency, practicality, and simplicity. This method was reviewed extensively in this report and a procedure to apply this method to serve the purposes of Pavement LCM aims has been developed. This method was applied to the six case studies selected in this project to demonstrate the application of this method. The sustainability indicators chosen in Deliverable D2.1 based on Pavement LCM workshop one were used in the application process. These are global warming, photochemical oxidation, eutrophication, recycled material content, cost, type-pavement noise, and durability. These indicators were quantified in deliverable D3.1 and adopted in this report to demonstrate the application of PROMETHEE method. The results show that this method is reliable and practical, but the reliability of the results depends on the indicators and their weights which must be calculated in a robust method. Therefore, NRAs, should accurately identify and quantify the important sustainability indicators, and should carefully quantify their weights. Since these are key steps towards performing a successfully MCDM. Lastly, the results showed that the durability effect is quite critical, but it must be included indirectly in the MCDM analysis by considering its impacts on other indicators rather than considering it as an evaluation criterion on its own.

- PROMETHEE II method is suitable for sustainability assessment of asphalt studies and it provide rational and justifiable MCDM results.
- User defined indicator weights is the best weighting method because it reflects the relative importance of the indicators from the decision maker point of view. If these data are not available, however, the average weight method may be an alternative solution.
- Determination of indicator weights by the entropy method is not recommended as it resulted in unrealistic weights that do not reflect the importance of the indicators.
- Asphalt durability is correlated with most indicators, so its effect on other indicators should be considered in the decision-making process rather than considering it as an independent indicator in the MCDM analysis.

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1 Introduction

The main aim of the sustainable development is to mitigate or minimise the negative impacts of industry on the three pillars of sustainability, Environment, Economy, Society (EES). Balancing these pillars is a crucial step towards achieving a more sustainable life. With respect to pavement engineering, it is paramount nowadays to provide or innovate more sustainable solutions since the processes and materials required for road construction and maintenance contribute to significant negative impacts on EES; including large CO2 emissions, consumption of energy, depletion of raw materials, air pollution, and many concerns regarding the health and safety of road users and the society in general. However, balancing the EES pillars to achieve sustainable results is not an easy task. Reducing the environmental impacts on the expense of cost may not be considered a sustainable solution; the same can be said regarding enhancing any of the EES on the expense of others.

One of the methods to balance the EES and select the most sustainable alternative among others, is to identify sustainability indicators that can reflect or quantify the impacts on the EES and optimise these indicators. This can be achieved by performing a life cycle sustainability assessment where all expected impacts are tackled from cradle to grave. This means accounting for the impacts starting from the stage of preparing raw materials, mixing process, construction activities, maintenance activities, end of life activities, and any transportation required during these stages.

However, that kind of sophisticated analysis requires a lot of data that might not be available in several cases. For instance, quantifying vehicle CO2 emissions caused by pavement deformation during the service life of a road is still a challenging task. Prediction of durability of the emerging new pavement technologies and pavement materials is also controversial process due to the lack of the available information and the limited experience with these materials. Accordingly, selecting a suitable set of indicators is an important step that must be carefully considered in order to conduct a productive sustainability analysis and make correct decisions.

2 Multi-Criteria Decision-Making methods: A brief Literature Review

2.1 Background

Decision makers face a critical challenge when deciding a best solution out of several available alternatives based on various criteria. The decision-making process involves assessing of the considered alternatives based on the selected evaluation criteria and identifying the best solution. In the real-world problems, none of the available solutions will match all considered assessment criteria. Every solution will match the criteria to a certain extent; and the decision maker must identify the best solution that match the considered criteria to the largest extent. Hence, several MCDM methods have been developed to support decision makers in their unique and personal decision process. MCDM methods provide stepping-stones and techniques for finding a compromise solution. They have the distinction of placing the decision maker at the centre of the process. However, they are not automatable methods that lead to the same solution for every decision maker, but they incorporate subjective or preference information provided by the decision maker, which leads to the compromise solution.

Considering the number of MCDA methods available, the decision maker is faced with the arduous task of selecting an appropriate decision support tool, and often the choice can be difficult to justify. None of the methods are perfect nor can they be applied to all problems. Each method has its own limitations, particularities, hypotheses, premises and perspectives. Up to now, there has been no possibility of deciding whether one method makes more sense than another in a specific problem situation.

2.2 MCDM in the field of infrastructure management

The characterization of a decision-making problem is important in order to define what types of decision-making methods are relevant to the infrastructure management field. Different problems call for different decision methods. In the Architecture and Engineering Construction (AEC) industry, a decision-making process is more likely to be embedded in a wider process of problem structuring and resolution, rather than be found as a stand-alone problem. Usually the problem of defining alternatives, factors, and criteria is as hard as deciding which alternative to select.

In the process of formulating a problem, Roy [1] identified four types of decisions:

1. Describing Problem: To explain or describe each alternative provided together with its main consequences by reference to the decision-making problem being dealt with.
2. Sorting Problem: To classify or sort all the alternatives into classes or categories. Each of these is graded based on predetermined requirements established by the decision maker.
3. Ranking Problem: To construct a ranking of all alternatives. The options are compared against one another and grouped into classes of equivalent rank, which in turn are sorted partially or fully in accordance with models of preferences.
4. Choosing Problem: To select or choose one and only one action or alternative (or a combination of these). The problem consists in choosing the best of all. Most of the Optimisation problems fall into this category.

However, Belton and Stewart [2] added two more types:

1. Selecting a Portfolio Problem: To choose a subset of alternatives from a larger set of possibilities, considering not only the characteristics of the individual alternatives, but also the manner in which they interact and produce positive and negative synergies.
2. Designing Problem: To research for, identify or create new decision alternatives to meet the goals and aspirations revealed though the decision-making process.

Each one of these types of problems occurs in the AEC industry. Accordingly, Belton and Stewart have classified MCDA methods in the following three broad categories:

1. Goal-programming and multi-objective optimisation methods,
2. Value-based methods, and
3. Outranking methods.

In addition, a fourth category called “Choosing By Advantages” (CBA) has been reported in literature and briefly [3] described in the following sections. and in the lean construction literature.

2.2.1 Goal-programming and Multi-Objective optimisation methods

Goal-programming and multi-objective optimisation methods are known as “aspiration” or “reference-point” models. They are characterised by establishing a desirable or satisfactory level of achievement for each of the considered criteria and the decision-making process then seeks to discover options that are closest to achieving them. Belton and Stewart [2] viewed these methods as the operationalisation of Simon’s ‘satisficing’ concept [4] which requires improving the most important goal, until some satisfactory level of performance is achieved, and then shifting attention to the next most important goal, and so on., so to establish desirable or satisfactory level of achievement for each of the factors.

These methods are used in situations where decision makers find it difficult to express trade-offs or assigning weights to factors, but are able to identify the aspirations or criteria (usually referred to as ‘goals’ in the literature) for the outcomes of alternatives that they would find satisfying. When many factors with their criteria are considered and no alternative complies with a satisfactory level of achievement for each of them, then the aim is to find a solution which is as near as possible to the target. In order to do that, three methods can be used [5]:

1. Rank the factors and filter alternatives according to the ranking order until only one alternative is left.
2. Weigh the factors, as done in linear goal programming.
3. Minimize the maximum weighted deviation from the criteria (goals), as done when using the reference point model.

The application of a goal-programming and multi-objective optimisation method, using ranking of factors, can be summarized in the following steps: (1) Define factors and criteria for evaluation. (2) Prioritize factors. (3) Formulate a maximization or minimization function including restrictions. (4) Solve the optimisation problem. (5) Come to a final conclusion based on the results of this process.

2.2.2 Value-Based Methods

Value-based methods are focused on representing a value or utility function to represent the preference of the decision makers. Value-based methods use explicit statements of acceptable trade-offs between different factors as a way of facilitating construction of preferences. The most used value-based methods are Analytic Hierarchy Process AHP and Weighting Rating and Calculation WRC [6]. The AHP is prevalent in AEC decision-making literature, and WRC is widespread use in AEC design practice.

The AHP method measures the relative importance of factors and preferences for alternatives through pairwise comparison matrices [7], which are recombined into an overall rating of alternatives by using the eigenvalue method [8]. The AHP method is used in cases where decision makers are not comfortable with numerical scores but prefer qualitative or semantic scales (e.g., moderately important, highly important). It uses a natural ratio scale, which implies that zero is the natural reference point and that the attributes of the alternatives can be expressed on natural ratio scales, such as mass, distance, etc. Saaty [7] summarizes the AHP method in the following steps:

1. Model the problem as a hierarchy containing the decision factors (usually referred to as 'goals' in the AHP literature), the alternatives for reaching it, and the criteria for evaluating the alternatives.
2. Establish priorities among the factors by making a series of judgments based on pairwise comparisons of the factors.
3. Establish priorities among the alternatives for each factor based on pairwise comparisons of attributes.
4. Synthesize these judgments to yield a set of overall priorities for the hierarchy.
5. Check the consistency of the judgments.
6. Come to a final decision based on the results of this process.

In step 2, when establishing priorities among factors, decision makers are asked to indicate the strength of their preferences for one factor over another on the following scale: 1 Equally Preferred, 3 Weak Preference, 5 Strong Preference, 7 Demonstrated preference, and 9 Absolute preference. After these judgments are completed, the eigenvalue method can be used to provide the weight of factors.

WRC can be described as a simplification of the AHP method. In WRC, the weighting of factors and attributes is done directly. The WRC method can be summarised as follows: (1) Identify alternatives. (2) Identify factors and criteria for evaluation. (3) Weigh the factors. (4) Rate alternatives for each factor. (5) Calculate the value of each alternative and come to a final decision.

The value-based method can be mathmatically represented as follows:

$$U(g^x) = w_1 U_1(g_1^x) + w_2 U_2(g_2^x) + \cdots + w_n U_n(g_n^x)$$

where *x* is an alternative, $U_{1,n}$ are the marginal utility functions of alternative *x* corresponding to *n* factors evaluated according to their criteria, g^x is the vector of the attributes of the alternative x for each factor, g^x = $(g_1^x, \ldots g_{1n}^x)$, and w_1,..., w_n are the weights representing the trade-offs between different factors, where $\sum_1^n w_i = 1$.

In many applications the utility function is assumed linear in value-based methods, and it can be defined as follows:

• $U(g^x)$ > $U(g^{x\prime})$↔ x > x' (alternative x is preferred to alternative x')

• $U(g^x)$ = $U(g^{x\prime})$↔ x = x'(alternative x is indifferent or equally preferred as to alternative x')

According to Belton and Stewart [2], the marginal utility functions can be obtained in three different ways:

1. Definition of a partial value function: decision makers need to define a function that gives a value to the attributes in terms of a measurable scale according to a criterion.
   a. The definition of the function can be direct:
      i. monotonically increasing according to a natural ratio scale
      ii. monotonically decreasing according to a natural ratio scale

iii. non-monotonic, i.e., an intermediate point in the scale defines the most or least referred attribute.

b. The definition of the function can be indirect when no natural scale exists [9, 10]:

i. Bisection method: the worst expected attribute is assigned the least value and the best expected attribute is assigned the most value. Then decision makers need to identify the point on the attribute scale, which is half way, in value terms, between the two extreme attributes. The next step is to find the midpoints between the two created segments.

ii. Difference method: decision makers consider increments in the attribute scale in order to assign value to those differences. This ranking gives an idea of the shape of the value function.

2. Construction of a qualitative scale: the values assigned to the attributes are assessed by reference to descriptive explanations of desirable characteristics, which represent a value scale.
3. Direct rating of the alternatives: no attempt is made to define a scale in which the values assigned to the attributes are independent of the alternatives being evaluated. The decision makers simply specify a number or a position in a visual scale, which reflects the value of the alternatives in relation to a specified reference point.

The AHP method recommends that decision makers normalise the quantitative attributes, assuming a linear function according to a natural ratio scale, and compare qualitative attributes in a pairwise fashion using a relative scale. In WRC decision makers can use any of the three approaches for finding marginal utility functions. However, in many applications decision makers use linear marginal utility functions, by following either a monotonically increasing or decreasing functions according to a natural ratio scale. The process of assigning weights to factors (w_i), "importance weights", has been the focus of extensive debate. The question is, indeed, how to assign those weights in a meaningful way. Also, the AHP method requires decision makers to establish priorities by pairwise comparison of factors; while the WRC method allows for direct weighting of factors. In both cases, decision makers are required to answer some questions such as what is more important in choosing an alternative among others [11].

2.2.3 Outranking Methods

The outranking methods differ from value-based methods because they do not have an aggregative value function, in which alternatives can be scored in an overall ranking. The result of the outranking methods is not a score for each alternative, but a determination that one alternative in a set outranks the others. For instance, "alternative *a* is said to outrank another alternative *b* if, taking account all available information regarding the problem and the decision-maker's preferences, a strong enough argument that *a* is at least as good as *b* and no strong argument to the contrary" [2]. Outranking methods use pairwise comparisons to assess preferences, indifferences, and incomparability between alternatives. For example, if alternatives *a* and *b* are compared for a factor with a criterion i, several outcomes are possible: *a* can be preferred to *b* in regard to criterion i, *b* can be preferred to *a*, *a* and *b* can be indifferent, or *a* and *b* can be incomparable due to lack of information. Even though this method requires ranking of factors, weights do not represent trade-offs. According to Doumpos and Zopounidis [12], the main two differences between value-based methods and outranking methods are:

- Outranking relation is not transitive. This means that it enables the modelling and representation of situations when transitivity does not hold.
- Because of possible incomparability, the outranking relation is not complete.

Roy [13] created and first used ELECTRE in 1965, which was one of the best-known outranking methods. He described ELECTRE as a method that provides weaker preference models than value-based methods. ELECTRE was built with less effort, and fewer hypotheses than value-based methods, but does not always allow for a conclusion to be drawn. Generally, It can be summerised in the following steps:

1. Define factors and criteria for evaluation.
2. Weigh factors.
3. Define scales for attributes and 'veto' thresholds.
4. Calculate concordance and discordance index.
5. Construct outranking relations.
6. Arrive at a final decision if enough evidence to support the superiority of one alternative exists.

The emphasis is on the strength of evidence for the assertion that alternative *a* is at least as good as alternative *b*. Decision makers need to set an *indifference threshold* [14].

Alternative *b* is weakly preferred to *a* in terms of factor *i* if:

$$Z_i(b) > Z_i(a) + q_i[Z_i(a)]$$

Alternative *b* is strictly preferred to *a* in terms of factor i if:

$$Z_i(b) > Z_i(a) + p_i[Z_i(a)]$$

For consistency, $p_i[Z_i(a)]$> $q_i[Z_i(a)]$

where $Z_i(a)$ is the partial preference function, similar to a utility function, of alternative *a* with regards to factor *i*. The outranking relation is constructed by considering the concordance and discordance indices. The concordance index between alternatives a and b, symbolised by *C (a,b)*,represents the strength of support provided by the available information, for the hypothesis that alternative *a* is at least as good as alternative *b*. This index takes a value between 0 and 1; higher values represent stronger evidence that *a* is superior to *b*.

$$c(a,b) = \frac{\sum_{i \in Q(a,b)} w_j}{\sum_{i=1}^{m} w_j}$$

Where Q$(a, \ b)$ is the set of factors in which *a* is equal or preferred to *b*, and w_j is the weight of the factor j.

The discordance index between alternatives *a* and *b*, symbolised by (a, b), represents a 'veto', in the sense that if the $Z_i(a)$ is below a minimum acceptable level or the difference between $Z_i(b)$- $Z_i(a)$ is greater than some threshold *t*, then *a* cannot outrank *b*, as follows:

$$D(a,b) = 1 \quad if\, Z_i(b) - Z_i(a) > t_i \; for\, any\, i$$

$$D(a,b) = 0 \; otherwise$$

This is analysed for every factor regardless of the weight of the factor. Then outranking relations are constructed. First, decision makers need to specify concordance and discordance thresholds, C* and D* respectively. Alternative *a* outranks alternative *b* if $C\ (a,\ b)\ \geq\ C^*$ and if $D\ (a,\ b)\ is\ \leq\ D^*$. The values of C* and D* will determine how strict the outranking relation is.

2.2.4 Choosing By Advantage

Choosing By Advantages (CBA) is a system to make decisions using well-defined vocabulary to ensure clarity and transparency in the decision-making process [3, 15]. According to this system, it is important to identify which factors will reveal significant differences between alternatives, not what factor (in the abstract) will be important in the decision. CBA decisions are based on the Importance of Advantages (IofAs), not advantages and disadvantages, thereby avoiding a common way of double counting factors. Once the advantages of each alternative are found, stakeholders need to assess the importance of these advantages making comparisons among them. The weighting process should be only on the advantages, not criteria, attributes, or other types of data. The CBA system has four principles:

1. decision makers must learn and skilfully use sound methods of decision making.
2. decisions must be based on the importance of the advantage.
3. decisions must be anchored to the relevant facts.
4. different types of decisions call for different sound methods of decision making.

In addition, CBA anchors decisions to relevant facts. As stated in Parrish and Tommelein [15], “Attributes are inherent to an alternative, so summarising them does not involve subjective judgment. Determining the advantages of each alternative does not require subjective judgment itself, though advantages may depend on the ‘want’ criteria in a given factor, which are subjective. Assigning a degree of importance to each advantage is the first task that requires decision makers to make value judgments about alternatives, and CBA postpones it as long as possible”. CBA includes methods for all types of decisions, from very simple to very complex. Suhr [3] presents instant CBA for simple decisions involving two mutually exclusive alternatives, two-list method for two mutually exclusive alternatives of equal cost, and the *tabular method* for moderately complex decisions involving more than two mutually exclusive alternatives.

CBA Tabular method divides the decision-making process in five phases: (1) the stage setting phase, (2) the innovation phase, (3) the decision-making phase, (4) the reconsideration phase, and (5) the implementation phase. For moderately complex decisions, the method can be summarized in 7 steps:

1. Stakeholders identify alternatives likely to yield important advantages over other alternatives
2. Stakeholders must define factors to evaluate attributes of alternatives.
3. Stakeholders need to agree on the criteria for each factor. Criteria can be either a desirable (want) or a mandatory (must) decision rule
4. Stakeholders summarize the attributes of each alternative.
5. Stakeholders decide the advantages of each alternative.
6. Stakeholders decide the importance of each advantage. They need to explicitly state their preferences for the advantages. They have also to select the paramount advantage, which is the most important advantage and is used as a reference point to compare to other advantages. Then stakeholders need to assign importance of other advantages based on a scale defined by the selection of the paramount advantage. It is not assumed that advantages are independent; therefore, similar advantages can be grouped. The importance of advantages for each alternative is summed, and finally,
7. Stakeholders evaluate cost data.

In order to apply CBA correctly, decision makers need to have a clear understading of each advantage. Suhr [3] proposed some guide lines to help in weighting the advantages. According to him no such thing as zero advantage exists and to all the advantages of all the alternatives must be assigned a weight on the same scale of importance; choosing the paramount sets a scale of importance for the decision. Decision-making is not a branch of mathematics. Therefore the importance of each advantage must consider the purpose and circumstances of the decision; CBA is context based: it is fundamental to understand customer needs and other stakeholder needs, including those who will be affected by the decision and others who will be interested in the decision. Moreover, the magnitudes of the advantages and magnitude of scales associated with attribute are a crucial point.

A practical way of assigning IofAs to advantages is to draw a convenient scale, as defined by the paramount advantage (for example from 0 to 100), and identify the most important advantage for each criterion and then choose the paramount advantage from them. By using the CBA method, the decision team can develop an assessment cost vs. importance of advantages. The decision team needs to make trade-offs between the cost of the alternatives and the Importance of the Advantages (IofA) and analyse if it is worth it to spend extra money to obtain the most Advantageous Alternative. This process is highly collaborative; the team should be involved at every stage and consider interactions with other systems. As mentioned before, the emphasis of CBA method is on the positive differences (advantages) between alternatives. An advantage is the beneficial difference between attributes of two alternatives (one of which is the least preferred) and can be calculated as follow:

$$Ag_i^x = \left|g_i^x - g_i^0\right|$$

Advantage of alternative X over the worst alternative for factor i. where g_i^0 is least preferred attribute for factor *i*. In contrast with most other methods, CBA only requires making trade-offs between advantages, which is based on the particular decision-making context. The total importance of advantages of alternative x is described by:

$$I(g^x) = I_1(Ag_1^x) + I_2(Ag_2^x) + \cdots + I_n(Ag_n^x)$$

In order to obtain $I_i(Ag_i^x)$, stakeholders are asked to set the *paramount advantage I(Ag)** as a reference point so to compare all of them:

$I(Ag^x) > I(Ag^{x'})$ ↔x > x' (alternative x is preferred to alternative x')

$I(Ag^x) = I(Ag^{x'})$ ↔x = x' (alternative x is indifferent to alternative x').

2.3 Conclusions

In light of the differences between MCDM methods, the study concludes that [6, 16-18]:

- **Multi-objective optimisation** methods that rank factors do not seem to create transparency because they do not make explicit trade-offs. Achieving consensus on the ranking of factors may be challenging. These methods do not provide enough guidance to make an analysis of value vs. cost, which would be helpful for continuous learning. Therefore, these methods are not recommended for choosing a sustainable alternative, when few alternatives are evaluated and where attributes are known [18]. This statement agrees with Belton and Stewart [2], who recommend multi-objective optimisation methods to identify a small set of alternatives from a large or even infinite set for more detailed evaluation. However, decision makers need to be aware that the ranking of factors and criteria will affect the outcomes.
- **Value-based methods** may not create transparency, especially when assuming linear trade-offs. Also, value-based methods may not help in building consensus if when assigning weights to factors decision makers do not consider the differences between alternatives. These methods allow for an analysis of value vs. cost, which is important for continuous learning and for comparing multiple decisions.
- **Outranking methods**, these methods may help in building consensus because the weight of factors is used for constructing concordance and discordance indices and not for directly assigning weights to attributes. However, the decision team still needs to agree on the weighting of the factors.

- **CBA** methods help in creating transparency in the trade-offs by focusing on the advantages of the alternatives. CBA methods help in building consensus because they base judgments on differences between alternatives. However, the weighting of advantages can still be challenging. CBA provides a good basis for continuous learning because it is possible to construct an analysis of value vs. cost. CBA also allows comparing multiple decisions if the scale of IofAs is adjusted.

3 Selection of MCDM tool for pavement sustainability assessment

3.1 Introduction

Pavement sustainability assessment is a multi-criteria problem since this process is performed with respect to a number of sustainability indicators. Such as global warming, air pollution, resource depletion, energy consumption, noise, life cycle cost, pavement roughness, durability, and several others. Some of these indicators rerquire maximisation and other require minimisation. In practical applications, it is almost impossible to find an alternative that satisfy all of these requirements. An optimum or comprimise solution, however, can be selected by identifying the alternative that best satistfies these requirements. This can be accopmlished by using the right MCDM method.

To select a suitable method for asphalt sustainability studies a number of criteria was developed to consider when implementing a MDCM method, as presented in Table 1. This list ensures that the method: provides transparent and rational analysis procedure with clear steps; easy to implement by decision makers and does not require a lot of experiance and extensive skills to apply; prevents compensation between good and bad indicators; does not require a lot of input data from decision makers; has the ability to adopt quantified and qualified indicators as well; has a rational outcome that can easly interpreted; and lastly the outcome should be defendable and jutifyable in order to have a general agreement on the decision amongst decision makers.

By Considering these critiera, an outranking method, PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluations), has been selected. This method has been developed by professor Brans in 1982 [19, 20]. It has several advantages such as:

- It depends on a clear and rational ranking procedure which makes it a transparent method [21].
- It is simple to adopt; decision makers do not need a lot of skills to apply this method
- It does not require a lot of input data; decision makers need to input assessment indicators and their weights to define a compromise solution. However, quantification of the indicator weights must be done accurately.
- It has a non-compensatory nature [22].
- It provides an uncomplicated comparison amongst alternatives which makes the selection of the best alternative straightforward process [21].
- Due to its friendly mathematical computations and the full ranking it provides, It has been applied in many areas such as environment management, hydrology and water management, business management, chemistry, logistic and transportation, manufacturing and assembly, energy management and several other topics [23].

Accordingly, this method has been adopted in this project and it is recommended for asphalt sustainability assessment studies. The description of this method is detailed in the following section.

Table 1. The criteria considered when selecting a MCDM method for aspahlt sustainability

Criterion	Decsription
Transparency	A clear and understandable analysis method and computational procedure

Applicability	Easy to apply and does not require a lot of extertise and mathmatical skills
Compensation	Compensation between good and bad indicators is not desriable. This means that a bad performance of an indicators shall not be compensated with a good performance of another indicator
Amount of input data	Does not require significant input data from the decision makers
Flexibility	Quantified and Qualified indicators can be adopted
Interpretation	Easy to analyse the outcomes and select the best alternative accordingly
Building consensus	The identification and selection of the best alterative shall be defendable and fully justifyable in order to building consensus amongst decision makers

3.2 PROMETHEE Description

There are several forms of the PROMETHEE starting from PROMETHEE I up to PROMETHEE VI, these forms are designed for various applications; but PROMETHEE II represents the foundation for the other method forms [23]. The difference between PROMETHEE I and II is that the former provides partial outranking based on the positive outranking flow, whereas the latter provides a full outranking based on the positive and negative outranking flow. Accordingly, PROMETHEE II is described in this report. This method has been developed to provide an overall or net ranking for a set of alternatives based on the balance between the positive outranking, which shows how well an alternative is better than other alternatives, and the negative outranking which shows how bad an alternative is outscored by other alternatives. By sorting the net outranking of a set of alternatives, the best alternative can be identified straightforward as the alternative with the highest outrank.

Let's assume we have a set of alternatives A (a_1, a_2, a_3, …, a_n) and a set of evaluation criteria (g_1, g_2, g_3, …, g_n) and the weights of these criteria (w_1, w_2, w_3, …, w_n); we want to apply this method to identify the best alternative that best satisfies the required indicators, then this method can be applied as follows:

1. The deviations between each pair of alternatives are calculated using the following equations:

   $d_i(a,b) = g_i(a) - g_i(b)$

2. The preference function is used to calculate the preference of an alternative over anther as follows:

   $P_i(a,b) = Fi\ [d_i(a,b)]$ if the criterion to be maximised

   $P_i(a,b) = Fi\ [-d_i(a,b)]$ if the criterion to be minimised

   where *Pi* represents the preference of a over b and has a value of $0 \leq P_i(a,b) \leq 1$, and Fj represents a preference function which can have one of the six forms shown in Table 2. This Table presents different scoring types; type 1 gives one score to alternative a as far as $d_i(a,b) > 0$. Type 2 gives one scor to alternative a as fas as $d_i(a,b) > q$ and q can be considered as a certain certainty level that the difference function should cross in order to give the score. Types 3 to 6 have different conditions to scoring but fundementally they are similar to type 2; a score is given to an alternative if the preference function passess a certain conditions. The score could be (0 or 1), (0, 0.5, 1), a linear function between 0 and 1, or a sigmoidal function such as type 6.

3. Determine the preference index as follows:

$$\pi(a,b) = \sum_{i=1}^{n} P_i(a,b) \times w_i$$

where $\pi(a,b)$ repersents the level that alternative a is prefered over b. It can be seen that if the index function equals zero then alternative a has a weak preference ov b and vice versa.

4. Calculate the complete positive, negative and complete outranking flow for each alternative against others using the following equations:

$$\Phi^{+}(a) = \frac{1}{n-1} \times \sum_{x \in A} \pi(a,x)$$

$$\Phi^{-}(a) = \frac{1}{n-1} \times \sum_{x \in A} \pi(x,a)$$

$$\Phi(a) = \Phi^{+}(a) - \Phi^{-}(a)$$

where $\Phi(a)$ indicates the balance between the posative and negative outranking fllows of alternative a. It has a value between -1 and +1, where the upper limit means that this laternative is outranking the others on all criteria, the lower limit means the alternative; and as mentioned earlier, the best alternative can be easly identified as it is the one with the largest net outranking.

4 Application of MCDM for sustainability assessment of asphalt mixtures

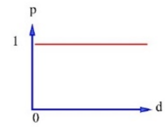
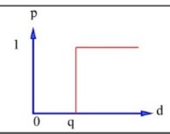
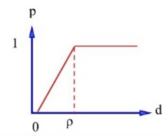
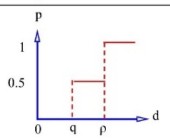
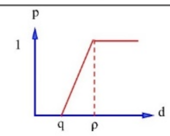
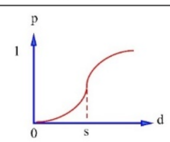
In order to demonstrate the application of the selected MCDM method, it was applied on the selected six case studies reported in deliverable D.3.1 under pavement LCM project. the following sections briefly describe the case studies, the selected sustainability indicators, some weighting methods of the indicators, and the application results and interpretation.

4.1 Brief description of the case studies

Six case studies have been identified to demonstrate the application of the different methodologies developed within Pavement LCM project activities, as reported in Deliverable D3.1. The case studies consisting of:

1. A reference asphalt mixture denoted by SMA16,
2. An SMA mix containing 40% reclaimed asphalt pavement (RAP) produced using polymer modified bitumen (PMB) denoted by SMA11,
3. An SMA mix containing 60% RAP and PMB denoted by SMA8,
4. A long service life mix denoted by SMA11-LSL,
5. A porous asphalt mix containing PMB denoted by PA8,
6. A long service life porous asphalt mix denoted by PA16.

Table 2. Forms of the preference function.

Type	Function shape	Definition	Parameters to fix
1		$P(d)=\begin{cases}0, if\ d\leq 0\\1, if\ d>0\end{cases}$	-
2		$P(d)=\begin{cases}0, if\ d\leq q\\1, if\ d>q\end{cases}$	q
3		$P(d)=\begin{cases}0, \quad if\ d\leq 0\\\frac{d}{\rho}, if\ 0<d\leq\rho\\1, if\ d>\rho\end{cases}$	ρ
4		$P(d)=\begin{cases}0,\ if\ d\leq q\\0.5, if\ q<d\leq\rho\\1,\ if\ d>\rho\end{cases}$	ρ, q
5		$P(d)=\begin{cases}0,\ if\ d\leq 0\\\frac{d-q}{\rho\text{-}q}, if\ 0<d\leq\rho\\1, if\ d>\rho\end{cases}$	ρ, q
6		$P(d)=\begin{cases}0,\ if\ d\leq 0\\1-e^{-\frac{d^2}{2s^2}},\ if\ d>0\end{cases}$	s

4.2 Sustainability Indicators

Sustainability indicators of asphalt and asphalt construction and maintenance activities varies considerably. Deliverable 2.1 of EDGAR project [24] lists thirteen environmental indicators and six socio-economic indicators. However, the importance of these indicators varies between highway agencies. Selection of suitable set of indicators that reflect the needs of beneficiaries and sponsoring agencies is vital. This process is also dependent on other factors such as the nature of the indicators whether they can be quantified or not, the availability of the tools and equipment to quantify the indicators. Therefore, a screening process is required to select the set of indicators that meets these criteria and reflects the needs of the NRAs.

In this project, the final set of indicators was selected in Deliverable 2.1 [25], as shown in Table 3. This set of indicators have been selected to reflect the priorities of NRAs and based on the selection criteria described in Deliverable 2.1. These indicators have quantified in Deliverable 3.1 [26], as presented Table 4. The Photochemical oxidation has been selected to assess the air pollution, whereas the Eutrophication has been selected to assess the pollution of the marine ecosystem. However, it can be seen in Table 3 that the durability affects all other indicators which means this is a correlation between the durability and other indicators. This is an undesirable situation in the MCDM because the effect of the durability may be double counted which can change the scoring results. To avoid this situation the durability effect is considered indirectly in the analysis by accounting for its impact on the other indicators. This is accomplished as follows:

1. A period of 40 years is considered in this analysis.
2. The total quantity of asphalt per the analysis period is calculated based asphalt durability as follows:

   $$ATQ = L \times W \times TH \times Den \times (1 + \frac{AP}{Dur})$$

   where *L, W, TH* are length, width and thickness of a road section being analysed, *Den* is asphalt density, *AP* is an analysis period in years, *Dur* is asphalt durability in years, and *ATQ* is asphalt total quantity.
3. The last step is to multiply the indicators by *ATQ* to calculate the absolute value of the affected indicators.

Table 5 presents the indicator results after considering the impact of asphalt durability. This Table demonstrates that if the effect of durability on other indicators is included, the difference in the indicator values will be quite critical. For example, Figure 1 and Figure 2 show a comparison of global warming results per one ton of asphalt and per expected total asphalt quantity over the design period. It can be seen than the global warming results were dramatically changed when the total asphalt quantity included in the assessment process based on the durability of each mix. Accordingly, the durability is not considered as direct indicator in the MCDM analysis, but its effects on other indictors is definitely considered.

Table 3. The final set of sustainability indicators considered in Pavement LCM project

N.B. The table of indicators has been updated in July2021, hence in this exercise some indicators might not present since the exercise refers to a previous version of the framework

Indicator	Pillar	Description
Global warming potential	Environment	Generally accepted equivalent of GHG accumulation, describes the relevance of

		emissions for the global warming effect and is the characterisation factor describing the radiative forcing impact of one mass-based unit of a given GHG relative to that carbon dioxide over a given period. It shall be expressed in kg CO2 equivalent, see EN 15804
Energy use	Environment	Includes a quantification of the energy required during the life cycle of the object of assessment. It should be divided in renewable and non-renewable, and can be split as defined in EN 15804
Secondary material consumption	Environment	Includes a quantification of the material recovered from previous use or from waste which substitutes primary materials. It can be expressed by mass units or as percentage of recycled materials used related to the total consumption
Cost	Economy	All costs related to the object of assessment during the product stage
Whole-life cost	Economy	All significant and relevant costs and benefits of the object of assessment, throughout life cycle, while fulfilling the performance requirements, see CWA 17089
Tyre-pavement noise	Society	The type of pavement used has an impact on the tyre/road noise level on a given road. This indicator is expressed as reduction of tyre-pavement noise level in dB compared to the reference pavement
Durability, performance related properties	Society	Durability performance-related properties of pavement materials measured in the laboratory
Durability	all	Estimated Service Life of the pavement, WP4 of Pavement LCM
Air pollution	Environment	Assessing pollution potential on the basis of air pollution (non-CO2 emissions), evaluating particulate matter and photochemical oxidation potentials

Table 4. Quantities of the selected sustainability indiactors of all alternatives

Indicator	**SMA 16**	**SMA 11**	**SMA 8**	**SMA 11 - LSL**	**PA 8**	**PA 16**

Global Warming Potential **kg CO2 eq/ton of asphalt**	96.566	106.472	101.541	101.951	110.740	95.959
Air pollution, Photochemical oxidation kg C2H4 eq/ton of asphalt	0.0272	0.0266	0.0237	0.0300	0.0279	0.0266
Eutrophication kg PO4 eq/ton of asphalt	0.1164	0.1664	0.1458	0.1222	0.1753	0.1158
Energy use MJ/ton of asphalt	74.88	67.68	74.88	74.88	74.88	74.88
Secondary materials consumption (kg/ton of asphalt)	0	382	600	0	0	0
Cost €/ton of asphalt	56.69	54.83	54.32	65.79	58.45	56.06
Tyre-pavement noise reduction dB	0	0	-0.6	0	-4.8	-2
Durability years	16	12	12	20	10	14

Table 5. Absolute values of the selected sustainability indicators per the considered analysis period

Indicator	SMA 16	SMA 11	SMA 8	SMA 11 - LSL	PA 8	PA 16
Global Warming Potential kg CO2 eq	170342.42	232534.85	221765.54	154149.91	279064.80	186544.30
Photochemical oxidation kg C2H4 eq	47.98	58.09	51.76	45.36	70.31	51.71
Eutrophication kg PO4 eq	205.33	363.42	318.43	184.77	441.76	225.12
Energy use MJ	132088.32	147813.12	163537.92	113218.56	188697.60	145566.72

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Secondary materials consumption ton	0	834288	1310400	0	0	0
Cost (€/ton of asphalt)	100001	119749	118635	99474	147294	108981
Tyre-pavement noise reduction (dB)	0.00	0.00	-0.60	0.00	-4.80	-2.00
ATQ ton of asphalt	1764.00	2184.00	2184.00	1512.00	2520.00	1944.00

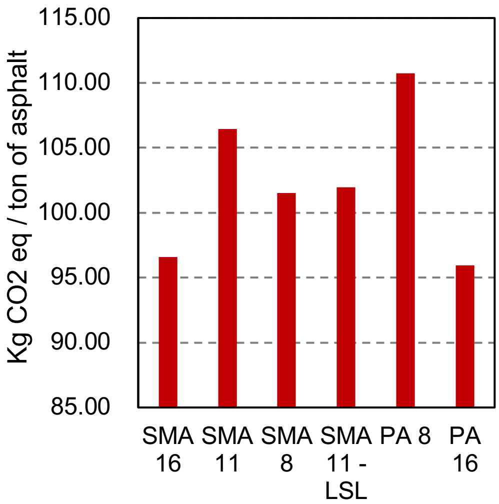

Figure 1. Global warming per one ton of asphalt.

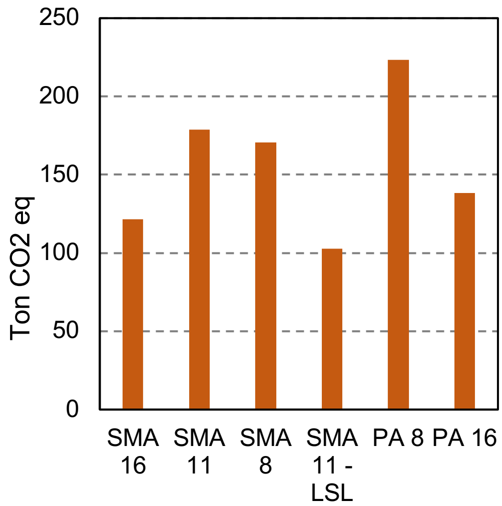

Figure 2. Global warming per analysis period of 40 years.

4.3 Weighting methods

Weighting of indicators is an important part of the MCDM analysis. Weights of the indictors reflect their importance. Indicators with larger weights will have more effect on the outranking processes than indicators with small weights. To calculate the weights of a set of indicators, various methods are exits in literature. In this report, three methods were reviewed due to their relevance, as follows:

4.3.1 Entropy weighting method (EWM)

This method quantifies indicator weights based on the dispersion of indicator values amongst the alternatives. The dispersion is used to quantify the differentiation level between alternatives, the larger the differentiation level the greater the information that can be derived from the data. Hence, more weight is given to indictors shows larger entropy than others. By this method, weighting of indicators can be done as follows:

1. The evaluation matrix is transformed into a normalised field using the following equation

$$P_{i,j} = \frac{g_{i,j}}{\sum_{j=1}^{n} g_{i,j}}$$

2. The entropy value of an indicator is then calculated as follows:

$$E_i = \frac{\sum_{j=1}^{n} P_{i,j} .\ln (P_{i,j})}{\ln (n)}$$

3. E_i has a range of (0,1) where one zero is associated with no differentiation and one with large differentiation. Accordingly, the weight on indicator i can be calculated as follows:

$$w_i = \frac{1-E_i}{\sum_{i=1}^{m}(1-E_i)}$$

where n is the number of alternatives and m is the number of indicators. This method was applied in this study to quantify the weights of the indictors presented in Table 6.

4.3.2 Average weight method (AWM)

By this method, the importance of all indicators is assumed equal. This means that the weights of the indicators are equal as well, and accordingly can be calculated as follows:

$$w_i = 100/n$$

The indicator weight calculated by AWM are reported in Table 6.

4.3.3 User defined weights (UDW)

The previous two methods do not depend on user inputs and therefore they do not reflect the importance of the indicators from the user's point of view. However, the user can define indicator weights that reflect the preference of the indicators to the user. The main drawback of this approach is that the weights are not calculated based on a scientific method. In response to this point, however, highway agencies usually conduct surveys to quantify the weights of a set of indicators based on expert judgements of many asphalt professionals and NRAs as this step enhances the robustness of the weighting process. This approach has been followed in the SUP&R ITN project [22]. The indicator weights based on the results of that project are adopted in this study, as shown in Table 6. The SUP&R ITN includes fifteen sustainability indicators for roads and pavements, therefore, only the values of the seven indicaors considered in this study are selected and normalised as reported in the Table.

Table 6. Indicator weight results by the described wrighting methods

Indicator \ weight %	EWM	AWM	UDW
Global warming	0.93	14.29	8.83
Photochemical oxidation	0.50	14.29	11.27
Eutrophication indicator	2.31	14.29	11.27
Energy demand	0.58	14.29	9.16
Secondary materials consumption	51.51	14.29	13.24

Costs	0.43	14.29	13.08
Noise reduction	43.73	14.29	33.15
Total weight	100%	100%	100%

4.3.4 Comparison of the weighting methods

By comparing the weighting results in Table 6, it can be seen that there are large variations between results of the three methods. The EWM depends on the dispersion of the indictors from one alternative to another. Therefore, the indicators that show low variations such as global warming or costs have low eights. On the other hand, indictors with large variations such as the secondary material consumption have high weights. Hence, this method may not be preferable as it is pure mathematical and does not reflect realistic indicator weights. The AWM showed closer results to the UDW, but it is also does not reflect the actual importance of the indicators. Accordingly, UDW method is recommended as it reflects the importance of the indicators from the NRAs and highway agencies point of view. In the instance where these data are not available, the AWM is seems a better choice than the EWM.

4.4 PROMETHEE application

To apply the PROMETHEE procedure explained above, a matlab code was developed. The logical steps of the code are explained in Figure 3. The first step is to read the input matrix, the code then asks the user to chose either to input the weights or let the code calculate the weights whcih is done by the AWM. After that the code applies the Promethee method to outrank the alternatives. Lastly, the code developes one figure shows the outranking results sorted in decesning order.

By implementing this code, the indictor values in Table 5 and the UDW in Table 6 were used. The outranking results are presented in Figure 4. These results show that SMA11-LSL is the most sustainable alternative amongst other alternatives. This result correlate well with the durability of this mix since it has the longest service life of 20 years. For the second and third best alternatives, despite that PA16 has 14 years durability and SMA16 has 16 years durability, PA16 outranked SMA 16 because it has less noise whcih is not affected by the durability, also it has less global warming, less air pollution, less eutrophication and less cost. Furthmore, in terms of the posative outranking, it can be seen that PA16 has the highest value but when considering the negative outranking of this alternative we conclude that this mix has been outranked by 0.334 points whcih is ~32% higher than SMA11-LSL. Accordingly, the best alternative should be selected based on the posative and negative outranking results.

Generaly, it can seen that this MCDM method can give resnable and justifyable results. The results Figure 4 are fully aligned or compatable with the values and the weights of the input indicators. This point is actualy one of the important features of the PROMETHEE method. However, to make reliable and accurate decosions, the sustainability indicators and their weights must be accurately quantified. Furthermore, another limitation of this method is the inability to include the variability of the selected impacts in the decision making a process. Deliverable D3.1 of this project showed that there is a large variability in the results of the selected sustainability impacts. By considering this factor, one can rationally expect that all other sustainability indicators shcu as cost or drvier comfort have high variabilitites which need to considered in the decision making process to make reliable decision. One method to overcome this obistical is to develop a new probabilistic decision making method capabale of incorporating the variability of the considered indicators and make a reliable “probabilistic“ decosions.

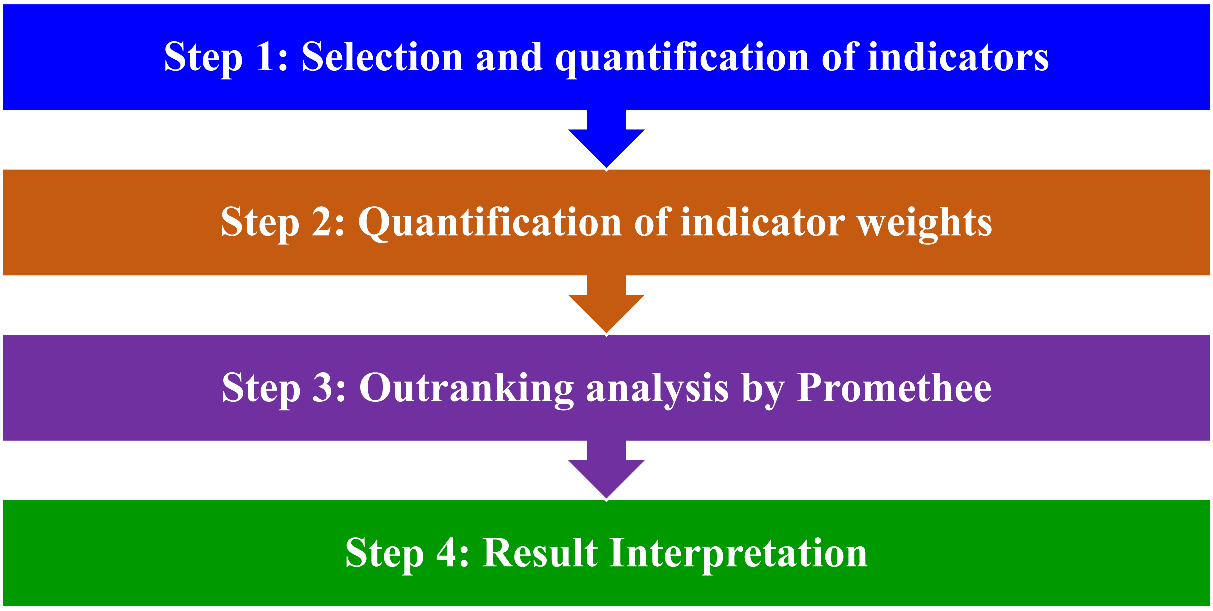

Figure 3. Application steps of MCDM analysis by the Ptomethee method

Table 7. MCDM Outranking results

Mix Type	Q+	Q-	Net Q
SMA11 - LSL	0.536	0.251	0.284
PA16	0.586	0.333	0.253
SMA16	0.428	0.359	0.069
SMA8	0.520	0.472	0.055
PA8	0.331	0.589	-0.258
SMA11	0.231	0.635	-0.404

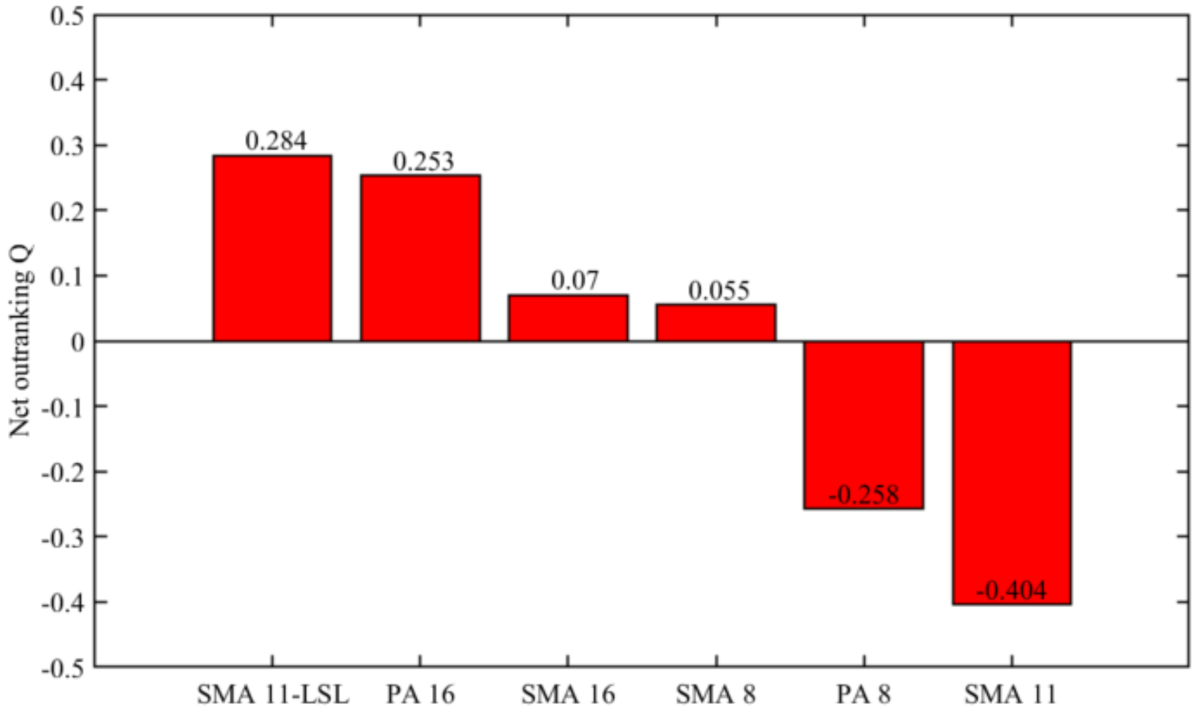

Figure 4. MCDM Net outranking results of the selected case studies

5 Summary and Conclusions

Sustainability assessment is a multi-criteria evaluation problem. Various sustainability indicators are existing, these can be grouped in three broad categories, Environmental, economic, and social indicators. The first category includes sustainability indicators affecting the environment, such as global warming or air pollution. The second category includes the indicators impacting the economy such as construction cost or maintenance cost of roads. The last one includes the indicators influencing the quality of the social life such as the Tyre-pavement noise. Optimisation of these indicators leads to identifying sustainable solutions. However, in reality, there is no alternative that have all of these indicators optimised. Therefore, it is necessary to find a compromise solution that is as close as possible to the optimum solution.

In this study, various MCDM methods were reviewed; the drawbacks and benefits of each method were also discussed. One of the frequently used methods is PROMETHEE; this method was reviewed comprehensively in this report and selected as practical and reliable method to solve multi criteria sustainability assessment problems of pavement alternatives. This method has also been selected in the SUP&R ITN project and used in the decision support system (DSS) developed in that project.

To demonstrate the application of solving a multi criteria decision making problem using the PROMETHEE method, the six case studies adopted in the Pavement LCM project were used. The sustainability indicator basket identified in deliverable D2.1 and quantified in deliverable D3.1 were used as inputs. The weights of these indicators were determined based on the SUP&R ITN project. Based on the results of this report, the following conclusions can be drawn:

1. PROMETHEE is a reliable and practical MCDM method with transparent outranking procedure. It can be used to outrank the considered alternatives based on their matching to the considered criteria and their weights.
2. Despite the reliability and practicality of PROMETHEE, this method depends on the reliability of the inputs. If the input indicators are correctly quantified and their weights are representative, then the outcome of the MCDM process will be reliable. Accordingly. NRAs should carefully select sustainability indicators based on the importance of the indicator and should accurately quantify their weights.
3. The UDW is the best alternative to weighting sustainability indicators because this method reflects the importance of the indicators from the user point of view. If weight data are not available, then the AWM can be a good second option.
4. Asphalt durability is strongly correlated with various sustainability indicators. Therefore, to avoid double counting its weight in the decision-making process, it is recommended to consider the durability effects on other indicators rather than considering it as a sustainability indicator.

References

1. Roy, B., *Critères multiples et modélisation des préférences (L'apport des relations de surclassement).* Revue d'Economie Politique, 1974. **84**(1): p. 1-44.
2. Belton, V. and T. Stewart, *Multiple criteria decision analysis: an integrated approach*. 2002: Springer Science & Business Media.
3. Suhr, J., *The choosing by advantages decisionmaking system*. 1999: Greenwood Publishing Group.
4. Simon, H., *Administrative Behavior, 3rd edn Free Press.* New York, 1976.
5. Stewart, T.J., *A critical survey on the status of multiple criteria decision making theory and practice.* Omega, 1992. **20**(5-6): p. 569-586.
6. Arroyo, P., I. Tommelein, and G. Ballard. *Deciding a sustainable alternative by 'choosing by advantages' in the AEC industry*. in *Proc. 20th Conf. of the International Group for Lean Construction (IGLC), San Diego, CA*. 2012.
7. Saaty, T., *Decisions, Structure and Judgment, and Natural Law*, in *International Symposium on the Analytic Hierarchy Process*. 2007: Chile.
8. Saaty, T.L., *The Analytic Hierarchy Process, Mac Gray-Hill, New York* 1980.
9. Von Winterfeldt, D. and W. Edwards, *Decision analysis and behavioral research.* 1993.
10. Watson, S.R., D.M. Buede, and D.M. Buede, *Decision synthesis: The principles and practice of decision analysis*. 1987: Cambridge University Press.
11. Aragon, T. and F. Dalnoki-Veress. *Applying the Analytic Hierarchy Process to HealthDecision Making: Deriving Priority Weights*. 2016 [cited 2020 October]; Available from: https://silo.tips/download/applying-the-analytic-hierarchy-process-to-health-decision-making-deriving-prior#.
12. Doumpos, M. and C. Zopounidis, *Multicriteria decision aid classification methods*. Vol. 73. 2002: Springer Science & Business Media.
13. Roy, B., *The outranking approach and the foundations of ELECTRE methods. Theory and decisions 31 (1): 49–73*. 1991.
14. Rogers, M. and M. Bruen, *Choosing realistic values of indifference, preference and veto thresholds for use with environmental criteria within ELECTRE.* European Journal of Operational Research, 1998. **107**(3): p. 542-551.
15. Parrish, K. and I. Tommelein. *Making design decisions using choosing by advantages*. in *17th Annual Conference of the International Group for Lean Construction, IGLC17*. 2009.
16. Arroyo, P., *Exploring Decision-Making Methods for Sustainable Design in Commercial Buildings*, in *Civil and Environmental Engineering*. 2014, University of California, Berkeley.
17. Arroyo, P., I.D. Tommelein, and G. Ballard. *Comparing weighting rating and calculating vs. choosing by advantages to make design choices*. in *Proc. 22nd Annu. Conf. Int. Gr. Lean Constr*. 2014.
18. Arroyo, P., I. Tommelein, and G. Ballard. *COMPARING WEIGHTING RATING AND CALCULATING VS. CHOOSING BY ADVANTAGES TO MAKE DESIGN CHOICES*. in *IGLC-22,*. 2014. Oslo, Norway.
19. Brans, J.P., *Lingenierie de la decision. Elaboration dinstruments daide a la decision. Methode PROMETHEE.* , in *In: Nadeau, R., Landry, M. (Eds.), Laide a la Decision:*

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Nature, Instrument s et Perspectives Davenir. Presses de Universite Laval, Qu ebec, Canada, pp. 183–214. 1982.

20. Brans, J.-P., *PROMETHEE methods.* In Multiple criteria decision analysis (pp. 187-219). Springer, New York, NY., 2016.
21. Santos, J., et al., *SUP&R DSS: A sustainability-based decision support system for road pavements.* Journal of Cleaner Production, 2019. **206**: p. 524-540.
22. Santos, J.O.D., et al., *SUP&R ITN Sustainability Assessment Methodology*. 2017.
23. Behzadian, M., et al., *PROMETHEE: A comprehensive literature review on methodologies and applications.* European Journal of Operational Research, 2010. **200**(1): p. 198-215.
24. Wayman, M., et al., *Evaluation and Decision Process for Greener Asphalt Roads, Deliverable D2.1, Recommended Product Category Rules for bituminous materials and technologies.* 2015.
25. Carrión, A.J.d.B., et al., *Pavement Life Cycle Management, Deliverable D2.1, Pavement LCM State-of-the-Art and framework*. 2019.
26. Bizarro, D.G., et al., *Pavement Life Cycle Management, Deliverable D3.1 – Sustainability Data Analysis*. 2020.
27. Visscher, J.D., et al., *Evaluation and Decision Process for Greener Asphalt Roads, Deliverable D4.6.* 2016.