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SUP&R DSS: A sustainability-based decision support system for road pavements

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ABSTRACT

Road pavement community members are increasingly becoming aware of the need to incorporating the principles of sustainable development into the sector. Policies are also going in this direction and as a consequence in the recent years researchers and practitioners are coming up with new materials, technologies and practices designed to reduce the negative impacts of their activities in the surroundings. Within this framework the road pavements sector is witnessing a paradigm shift towards the development of pavement technologies incorporating high-content of recycled materials, as well as best practices to decrease the overall carbon footprint. These are all promising solutions that to the most can sound as sustainable practices. However the whole road pavement community is still investigating methodologies and tools to define what actually sustainable means and thereby performing a sustainable decision-making. It is within this context that the need of a sustainability-based decision support system (DSS) that could help road pavement engineers at the design stage was identified and is here presented. The Sustainable Pavements & Railways DSS (SUP&R DSS) relies on a multi-criteria decision analysis (MCDA) method to rank the sustainability of alternatives. It applies life cycle-based approaches to quantify the values of a set of indicators purposely and methodologically selected to capture the cause-effect link between the general concepts of the three wellbeing dimensions of sustainability, i.e., environmental, economic and social, and the infrastructure construction and maintenance practice. Furthermore, the system allows selecting different weighting for the indicators but offers also a default set of values derived from a survey conducted with over 50 stakeholders in Europe and beyond. Together with the development, structure and features of the SUP&R DSS, this paper present its applicability by means of a case study aiming at identifying the most sustainable asphalt mixture for wearing courses. Several promising options for flexible road pavements were selected, ranging from low to hot temperature asphalt. The results show that a foamed warm mix asphalt mixture with a reclaimed asphalt pavement content of 50% is the most sustainable among the competing alternatives. Furthermore, a sensitivity analysis conducted to investigate the influence of the indicators weights, the parameters of the MCDA method and the long-term performance of the alternative asphalt mixtures on the stability of the ranking showed that its first position in the ranking remained unaffected.

1. Introduction

More than ever before, sustainable development is a key topic for all development activities. It can be understood as the integration of environmental, economic and social dimensions in such a way that the goods produced and the services provided do not compromise the functional integrity of environmental systems, while minimizing their vulnerability and balancing their natural recharge (World Road Association, 2016).

In view of that, the challenge lays on how to incorporate the sustainability concept in different development sectors in order to achieve their goals. The urgency of succeeding in the

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accomplishment of this challenge is particularly meaningful for the transportation sector in general, and for the road transportation mode in particular. For instance, in the Organisation for Economic Co-operation and Development (OECD) countries, CO_2 emissions from the transport sector totalled 9000 billion tonnes in 2015, representing about 18% of all man-made emissions (ITF, 2017). Yet according to ITF (2017), the emissions from road transport, both freight and passenger, are expected to increase by more than 70% between 2015 and 2050. It is not clear yet what is the specific contribution that the infrastructures have in these numbers. Surely, road pavements are a fundamental asset of the road transport system and undertaking more sustainable decisions would have a great impact. In fact, they are large in project scope and involve considerable amounts of financial resources (ERF, 2013). Furthermore, their construction involves the depletion of non-renewable resources, significant energy consumption, emissions and waste generation associated with the production of pavement materials, which not only impact negatively the environment, but also cause social perturbations (Santero and Horvath, 2009). This is further worsened by the project's long construction time and service life that, ideally, requires maintenance to be performed on a regular basis. Based on this picture, it is evident that organizations within the pavement industry cannot go on with business as in the past and need to put in practice sustainable development principles in an effort to lower and/or mitigate its negative environmental, social, and economic impacts while constructing and preserving these assets.

1.1. Sustainable asphalt technologies and sustainability assessment of road pavements

This awareness has led to meaningful research efforts to improve the conventional construction and maintenance practices by developing and implementing more sustainable technologies. In recent years several other technologies and research products have been developed with the potential to improve pavement sustainability, amongst these it is possible to enumerate: (1) in-place pavement recycling (Thenoux et al., 2007; Robinette and Epps, 2010; Santos et al., 2015a); (2) pavement preservation strategies and preventive treatments (Giustozzi et al., 2012); (3) long-lasting pavements (Lee et al., 2011; Sakhaeifar et al., 2013); (4) reclaimed asphalt shingles (RAS) materials (Illinois Interchange, 2012); (5) wearing course with very-high reclaimed asphalt pavement (RAP) content (Zaumanis and Mallick, 2015; Lo Presti et al., 2016; Pires et al., 2017); (6) industrial wastes and byproducts (Birgisdóttir et al., 2006; Carpenter et al., 2007; Carpenter and Gardner, 2009; Huang et al., 2009; Lee et al., 2010; Sayagh et al., 2010; Mladenovič et al., 2015); (7) rubberised asphalt pavement wearing courses (Lo Presti et al., 2013); (8) low-temperature asphalt mixtures containing RAP (Vidal et al., 2013; Giani et al., 2015; Dinis-Almeida et al., 2016; Santos et al., 2018); and (9) asphalt mixtures manufactured with biomass (Del Barco Carrion et al., 2017).

The technologies aforementioned are all promising but the extent to which these solutions can effectively be said to contribute to enhance pavement sustainability depends on the context in which they are applied, and on the way the sustainability is measured and evaluated. A common procedure adopted to measure and track the sustainability of transportation projects relies on rating systems (e.g., BE^2ST-in-Highways™ (Lee et al., 2011), Envision™ (Institute for Sustainable Infrastructure, 2012), Green Leadership in Transportation and Environmental Sustainability (GreenLITES) (NYSDOT, 2010), GreenPave (Lane et al., 2014), Greenroads (Muench et al., 2010), etc.). However, as pointed out by Simpson et al. (2014), there are desirable features generally lagging in transportation infrastructure rating systems, such as the choice of relevant criteria and the customizability of criteria. Additionally, aggregating all the indicators into a single score, practice commonly adopted in those rating systems, prevents decision-makers (DMs) from seeing the underlying performance across project sustainability objectives (Haider et al., 2016). Notwithstanding, choosing and judging between several alternatives and ultimately compromising on a solution requires understand the trade-offs between different criteria. Therefore, some sort of multi-criteria decision making (MCDM) method is needed to assist with that task.

By realizing this aspect, several attempts have been made recently to perform sustainability assessment of solutions intended to improve the sustainability of transportation projects. For instance, Kucukvar et al. (2014) developed a MCDM method which combines the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method and intuitionistic fuzzy sets and applied it for ranking the life cycle sustainability performance of different pavement alternatives constructed with hot mix asphalt (HMA) and warm mix asphalt (WMA) mixtures. Umer et al. (2017) developed a sustainability evaluation framework which address uncertainties in raw data during the planning phases by means of fuzzy set theory, and at the same time integrate life cycle assessment (LCA) and life cycle costs analysis (LCCA) results to compare different pavement alternatives, including asphalt, concrete and geosynthetics. Ozer et al. (2017) used a partial life cycle approach to assess the environmental and economic impacts of different pavement mixtures and pay items. Batouli et al. (2017) performed LCA and LCCA to investigate the sustainability of different pavement alternatives for a road extension project in Miami, Florida. Santos et al. (2017a) developed a MCDM framework which combines a comprehensive and integrated pavement life cycle costing (LCC)-LCA model and the TOPSIS method. The framework was used for ranking the life cycle sustainability performance of different pavement engineering solutions, namely hot in-plant recycling mixtures, WMA, cold central plant recycling (CCPR) and preventive treatments when applied, either separately or in combination, in the construction and management of a road pavement structure.

1.2. Aim and purpose of the study

The overall purpose of this study is to increase the DMs/stakeholders' capacity to make strategic and informed decisions regarding the construction, maintenance and rehabilitation (M&R) of transportation infrastructures that would ultimately enhance the sustainability of transportation systems. In fact, despite the undeniable merits and achievements of the rating systems and studies mentioned in the previous sub-section, these usually tend to narrowly focus the sustainability assessment on the economic and environmental impacts of road pavement systems and technologies, thereby overlooking the third important dimension of sustainability, i.e. social impacts, as well as the trade-off between social, environmental and economic impacts. Furthermore, they often limit the analysis to the evaluation of the criteria and thereby do not provide insights on the ranking of the alternatives based on the relative importance of the criteria. Last but not least, in the specific case of the rating systems, the sustainability assessment is usually qualitative and does not provide the DM with numeric thresholds that would allow performing less subjective choices.

Having detected this gap, this research study aims: (1) to develop a life cycle, sustainability performance-based, decision support system (DSS) which materializes the performance management framework envisioned in Bryce et al. (2017) for helping DMs/stakeholders to prioritize alternative technologies adopted in the construction and M&R of transportation infrastructures; and (2) to show the applicability of the developed DSS by means of a practical exercise.

The research approach is organized as follows. Section 2 provides the theoretical background on multi-criteria decision analysis (MCDA) methods. Section 3 describes the main features of the proposed sustainability-based DSS, including the MCDA framework, the weighting methodology and the sustainability indicators. Section 4 illustrates the capabilities of the SUP&R DSS in road pavements through the application on a case study aiming at comparing and ranking asphalt pavement technologies for wearing courses. Finally, Section 5 concludes the paper and provides recommendations for further investigations.

2. Background: multi-criteria decision making methods

MCDM is a branch of operational research dealing with decision problems involving several decision criteria and alternatives. MCDM methods can be broadly classified into two main categories (Zavadskas et al., 2014): multi-attribute decision making (MADM) and multi-objective decision making (MODM). MADM methods are adopted to compare or rank a set of pre-defined alternatives based on their performances against a set of criteria. In turn, MODM techniques are employed to determine the set of optimal alternatives, unknown a-priori, which optimize a set of objective functions while subject to a set of well-defined design constraints.

Focusing on MADM, it has been in the spotlight of several areas as it pertains to sustainability-oriented decision making due to its capacity to methodically integrate environmental, social and economic attributes, while helping to deal with the challenges of decision making under complex conditions that may involve contradictory, and not seldom incommensurate criteria, and numerous stakeholders with conflicting interests and priorities (Kiker et al., 2005; Huang et al., 2011; Reza et al., 2011; Mitropoulos and Prevedouros, 2014; Cinelli et al., 2014; Arce et al., 2015; Khishtandar et al., 2016; An et al., 2017; Cai et al., 2017). Furthermore, they promote the role of participants in decision making and provide a good platform for understanding the perception of models and analysts in a realistic scenario (Pohekar and Ramachandran, 2004).

Notwithstanding the existence in the literature of several classification theories (Linkov et al., 2004; Liou and Tzeng, 2012), in general, MADM methods can be divided into three main groups (Slowinski et al., 2002; Greco et al., 2004): (1) value-based methods; (2) outranking methods; and (3) decision rules-based methods.

The value-based methods include multi-attribute value theory (MAVT), multi-attribute utility theory (MAUT) (Keeney and Raiffa, 1993) and the analytic hierarchy process (AHP) (Saaty, 1988). In MAVT and MAUT, numerical scores are used to represent the merit of one alternative in comparison to others on a single scale. Scores are calculated from the performance of alternatives with respect to an individual criterion, after which the overall performance of one alternative is determined by aggregating the individual score of each criterion in a single overall score. MAUT quantifies individual's preferences, by creating utility functions, in order to facilitate trade-offs among several criteria. The main objective of MAVT and MAUT is to maximize the overall utility considering the given preferences of DMs (Soltani et al., 2015), making this approach a compensatory optimization approach. The main difference between MAVT and MAUT is that the latter explicitly considers uncertainty by using utility functions rather than value functions. The AHP method was developed by Saaty (1988) and evaluates alternatives using pairwise comparisons, by asking the DM his preference on a scale from 1 to 9, in a multilevel hierarchic structure. This structure breaks down the decision from the top to the bottom, in which the goal is at the top level, criteria and sub-criteria are in middle levels, and the alternatives are at the bottom. Once the criteria weights and alternatives scores have been determined with the process summarily described above, the overall performance of the alternatives can be calculated by means of a linear additive model. The final result is a value in the range of 0–1, where the weights indicate the trade-offs between the criteria (Cinelli et al., 2014).

Regarding the outranking methods, their rationale lays on performing comparisons between pairs (or more) of alternatives at a time, with respect to the criteria. The range of possible scores for different alternatives is considered within each criteria, to derive alternatives that can be combined across criteria. An alternative's relative score on a specific criterion is thus a function of how well it compares against the set of other alternatives (Huang et al., 2011). The most well-known methods belonging to this group are Preference Ranking Organisation Method for Enrichment of Evaluations (PROMETHEE) (Brans and Vincke, 1985) and Elimination and Choice Expressing the Reality (ELECTRE) (Roy, 1991).

Finally, within the decision rules-based methods the dominance-based rough set approach (DRSA) is a relatively new technique which can be employed in classification, choice and ranking problems. In the DRSA method, data tables are used, where rows are defined as alternatives, while the columns are divided into condition attributes; specifically the criteria that are required to assess the alternatives and the decision attribute, which represents an overall evaluation of the alternative (Cinelli et al., 2014). Each cell of this table indicates an evaluation (quantitative or qualitative) of the alternative placed in that row by means of the attribute in the corresponding column. This table can be seen as a set of decision rules, in the form of "*if … then …*" connecting condition and decision criteria (Slowinski et al., 2009).

3. Methodology

The methodology of the proposed sustainability-based DSS follows the diagram presented in Fig. 1 and is described in the subsections below. It comprises the following stages: (1) selection of the environmental, economic and social indicators to be adopted for sustainability assessment; (2) definition of the alternatives to be compared and evaluation matrix formulation; (3) definition of the decision-making matrix, which includes the specification of the weights to be assigned to each indicator and the assessment of the performance of each alternative with regard to each indicator; (4) performance of the MCDA through an outranking MCDM to rank the sustainability of the finite number of alternatives; and (5) sensitivity analyses of important input parameters and alternatives' scores to determine their impact on the ranking of the alternatives.

3.1. Sustainability indicators

Defining appropriate indicators that consistently measure sustainability of alternative technologies is of paramount importance and should be context sensitive. Then, the proposed sustainability-based DSS incorporates, by default, the indicators defined according to the methodology developed by Bryce et al. (2017), (Fig. 2). It builds upon and adapts the DPSIR (driver, pressure, state, impact, response) framework developed by the European Environmental Agency. Succinctly, four steps employing different criteria and used with the ultimate objective of deriving a set of indicators that maximize their significance to the principles of sustainability applied to transportation systems. This is undertaken while covering a large spectrum of aspects related to the three Wellbeing dimensions (i.e. social, environmental and economic) and also taking into account the outcomes of recent and relevant research project in the field (i.e., LCE4Roads (http://www.lce4roads.eu/))

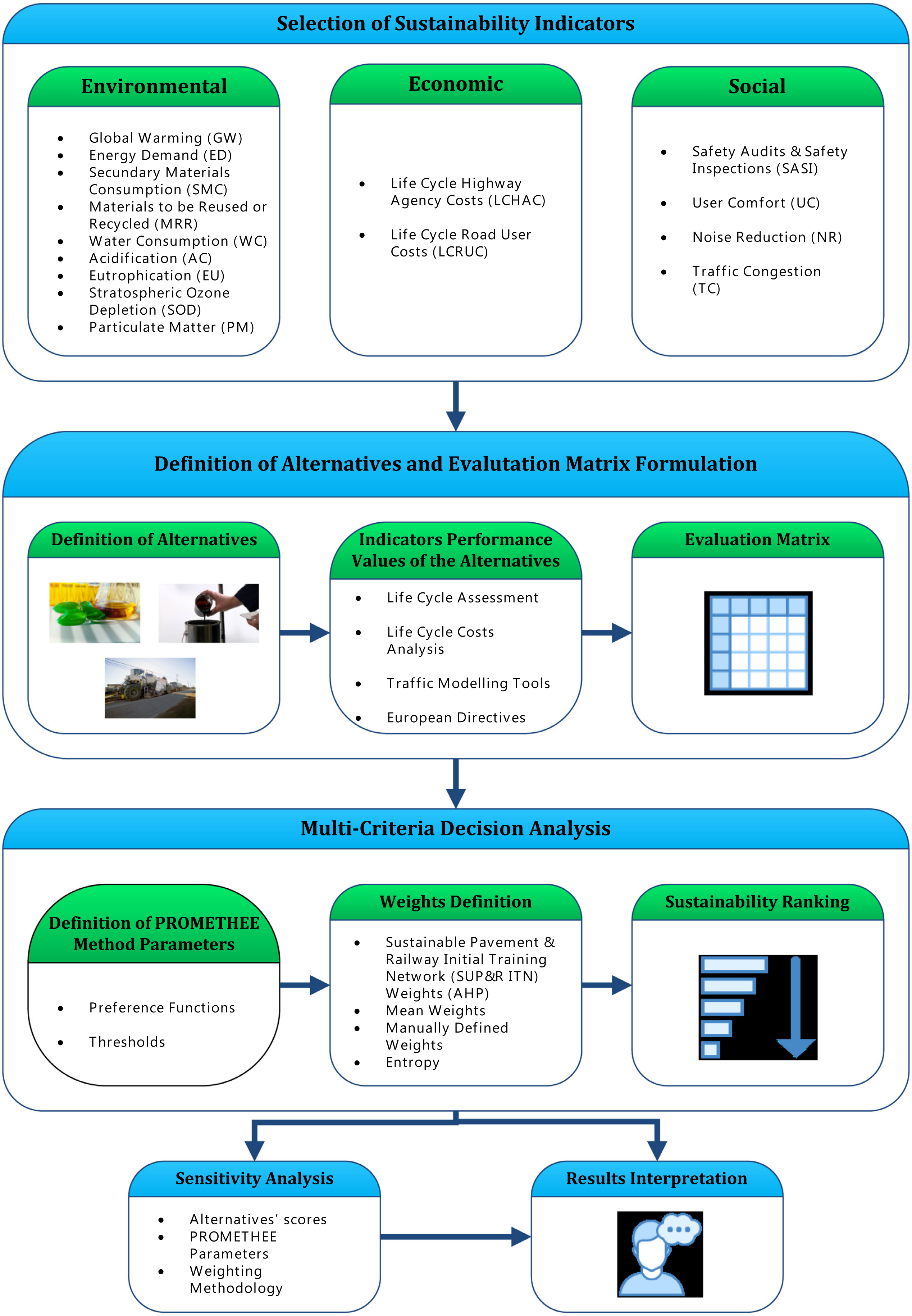

Fig. 1. Sustainability-based decision support system framework for road pavements.

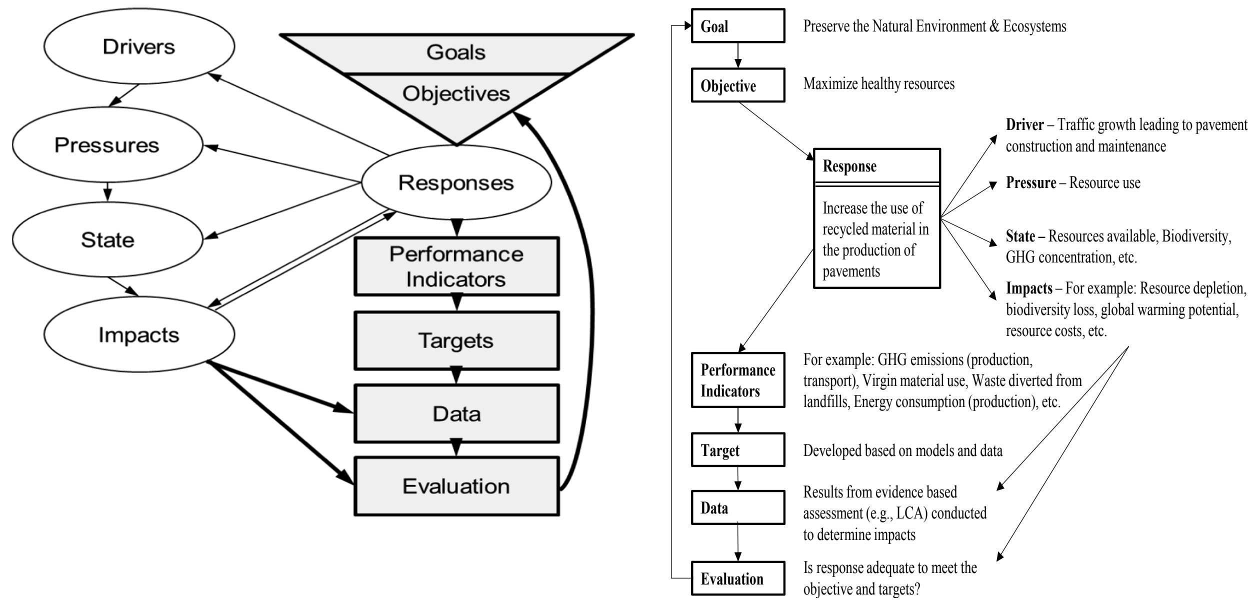

Fig. 2. The DPSIR framework and its adaptation to sustainable decision making for road pavements (adapted from Bryce et al., 2017).

and pre-standardization procedures (i.e., CEN/CENELEC Workshop Agreement (CWA) on SUSTINROADS). A wide and detailed explanation on the methodology developed to select the set of indicators will be published elsewhere and soon freely available on http://superitn.eu. Hereafter, for the sake of brevity only a concise description of that methodology as well as of each indicator belonging to the final set is presented in this section.

3.1.1. *Indicators selection methodology*

Initially, an extensive literature review was performed to identify the criteria and indicators that have been used to measure the sustainability of road pavement and railways projects. The indicators collected were posteriorly screened according two set of criteria: (1) measurability, unique and globally accepted definition and recurrence; and (2) sensitivity, updatable data, available data, and non-corruptibility. Next, each indicator was given a score based on a three-point scale (i.e., 0, 1 and 2 points) for each criterion and those that were given a score of zero in any of the individual criteria aforementioned were automatically excluded from the list of candidate indicators. The retained indicators were posteriorly reorganized to understand how they could be applied across the life cycle of a road and rail project based on the different phases characterizing it. In the next step, the third quartile (75th percentile) of the recurrence of the indicators still eligible was calculated and any indicator with a recurrence value inferior to that value was considered not to qualify for inclusion in the final list of indicators. Finally, in the last step, the eligible indicators were subject to a critical judgment that would determine their fate with regard to the inclusion in the final short-list. Complementarily, the indicators excluded throughout the selection process were given the possibility of being taken up in face of well justified reasons. The rationality for the consideration of this stage is sustained by the following points:

- To allow for the consideration of indicators belonging to misrepresented sustainability dimensions (i.e., social sustainability);
- To account for norms, reports and guidance documents published by leading authorities as well as for the outcomes of research projects with relevance in the topic;
- To ensure a balanced distribution of the indicators among the several mean-objectives and subcategories considered;
- To allow for the consideration of singularities related to specific indicators. An example that illustrate the applicability of this point pertains to the toxicity and ecotoxicity indicators.

Indeed, recent studies demonstrated that the features of the phenomena addressed by toxicity and ecotoxicity indicators make them, in general terms and apparently, interesting indicators to be included in methodologies that aim to assess the sustainability of infrastructure projects (e.g., ecotoxicity is very sensitive to construction phase; it can be used in the modelling of the end-of-life to assess the pollution after landfilling, etc.). However, a decision concerning its inclusion in methodologies intended to be used in a very short-term must take into account the following aspects: (1) these indicators require data that are not systematically collected across Europe (numerous pollutants may play a role in the variation of the toxicity and ecotoxicity scores); (2) the required data exhibit high errors associated with their collection practices; and (3) these indicators exhibit strong variation, which for the moment are not explainable at light of a scientific basis. Those were the reasons why they were considered in the list of indicators produced in the scope of the European project LCE4ROADS (http://www.lce4roads.eu/) but were excluded from the list defined by the CEN/CENELEC Workshop Agreement (CWA) on SUSTINROADS - Sustainability assessment of roads, which is supposed to be applied very shortly in standardization.

3.1.2. *Environmental indicators*

3.1.2.1. Global warming indicator (GW). This indicator refers to the impact of human emissions, namely greehouse gases (GHG), on the radiative forcing (i.e. heat radiation absorption) of the atmosphere, causing the temperature at the earth's surface to rise. It is measure in terms of kg CO_2-eq.

3.1.2.2. Energy demand (ED). This indicator refers to the amount of energy required for undertaking the processes underlying to the construction, maintenance and rehabilitation (M&R), use and end-of-life (EOL) of the road pavement. It is expressed in MJ and will be quantified through the Cumulative Energy Demand (CED) indicator

(Frischknecht et al., 2015). This indicator represents a measure of direct and indirect energy use over the entire life cycle of a product, including the conversion efficiencies. It accounts for energy produced from non-renewable sources (fossil, nuclear, and non-renewable biomass) and renewable sources (wind, solar, geothermic, hydro, and renewable biomass).

3.1.2.3. Secondary materials consumption (SMC). This indicator refers to the amount of the recycled materials used in the project as material recovered, either from previous use or from waste, which substitutes primary materials. It is measured in terms of the percentage (%) of recycled materials used related to the total material consumption. Alternatively this indicator can be expressed in any mass unit provided that it is the same when quantifying the performance of all alternatives under evaluation.

3.1.2.4. Materials to be reused or recycled (MRR). This indicator refers to the amount of waste materials or excess quantity of materials used in the project that has potential to be recycled at the EOL stage instead of being landfilled. It is measured in terms of the percentage (%) of recyclability and the percentage (%) of reusability (related to the total material sum) that could be re-used and recycled in the future. Similarly to the previous indicator, it can also be expressed in any mass unit provided that it is the same when quantifying the performance of all alternatives under evaluation.

3.1.2.5. Water consumption (WC). This indicator refers to the amount of water used for undertaking the processes underlying to the construction, M&R and EOL of the road pavement (i.e., either remain in place or be removed). It is measured in terms of m^3 of water consumed.

3.1.2.6. Acidification indicator of soil and water (AC). This indicator refers to the increase of the acidity of water and soil systems by H^+ concentration. This alters the pH of that environment, which may cause damage to the organic and inorganic materials. It is measured in terms of kg SO_2-eq.

3.1.2.7. Eutrophication indicator (EU). This indicator refers to the impacts caused by the excessive levels of macronutrients (nitrogen (N) and phosphorous (P)) in the environment due to the emissions of nutrients to air, water and soil. This may cause an elevated biomass production. It is measured in terms of kg PO_4^{3-}-eq.

3.1.2.8. Stratospheric ozone depletion indicator (SOD). This indicator addresses the thinning of the stratospheric ozone layer as a result of anthropogenic emissions, mainly chlorofluorocarbon (CFC) compounds. It is measured in terms of kg CFC-11-eq.

3.1.2.9. Particulate matter indicator (PM). This indicator refers to the amount of suspended particles with a diameter of less than 10 μm (PM_{10}) originated from anthropogenic processes such as combustion, resource extraction, etc., that may induce several health problems, especially of the respiratory tract. It is measured in terms of kg PM_{10}-eq.

3.1.3. Social indicators

3.1.3.1. Safety audits & safety inspections (SASI). This indicator refers to the verification of the accomplishment of the road safety audits (RSA) and inspections (RSI) as required by the European Directive 2008/96/EC on road infrastructure safety management. It is measured qualitatively (Yes or No) by answering to the question “Was the RSA or RSI report issued?”

3.1.3.2. User comfort (UC). This indicator evaluates the road user's level of comfort relatively to the travelled roadway. It is measured as the area under the Present Serviceability Index (PSI) curve or the area under the curve representing the pavement roughness, expressed through the International Roughness Index (IRI). The PSI is a mathematical model developed based on the mean roughness of a pavement, rated on a scale from 0 to 5 by a panel of passengers driving over the pavement in a vehicle. In turn, the IRI is an objective measurement of pavement roughness and can be obtained using vehicle-mounted high-speed inertial profilers, after applying a mathematical model to calculate it as the vehicle's suspension displacement per unit of distance travelled, expressed in unit of slope (m/km).

3.1.3.3. Noise reduction (NR). This indicator refers to the reduction of the noise level in order to decrease the acoustic impact on the users and surrounding populations. It is measured in decibel (dB).

3.1.3.4. Traffic congestion (TC). This indicator refers to the traffic congestion caused by to the execution of pavement M&R activities. It is measured as the additional road users travel time (hours).

3.1.4. Economic indicators

3.1.4.1. Life cycle highway agency costs (LCHAC). This indicator comprises the total costs incurred by the highway or transportation agency over the life of the project to construct and maintaining a pavement structure above a determined quality level. They typically include initial costs (e.g., preliminary engineering, contract administration, supervision and construction costs) and future costs (i.e., M&R costs and the EOL costs) (Santos et al., 2017b). The data required to determine the agency costs are usually obtained from historical records, current bids, and engineering judgments. This indicator can be expressed in any currency unit provided that it is the same when quantifying the performance of all alternatives under evaluation.

3.1.4.2. Life cycle road user costs (LCRUC). This indicator comprises exclusively the marginal fuel consumption (FC) costs incurred by the road users during the work-zone (WZ) traffic management phase due to the traffic perturbations caused by the execution of the M&R activities, and during the use phase due to the influence of the pavement surface properties (i.e., macrotexture and pavement roughness).

3.2. Definition of alternatives and evaluation matrix formulation

Once the alternatives have been defined, their performance with regard to each indicator is assessed by employing mostly life cycle-based methodologies. In this regard, the LCA is used for estimating the majority of the environmental indicators, whereas the LCCA is adopted to quantify the economic indicators. Finally, the social indicators are evaluated on the basis of traffic modelling tools and methodologies developed in the scope of European directives, namely the Directive 2008/96/EC on road infrastructure safety management (Directive 2008/96/EC, 2008). Excepting the case of a few indicators for road pavements (i.e., Safety audits & safety inspections and Noise reduction), which are supposed to be quantified according to European Directives, the SUP&R DSS does not specify methods or tools for quantifying the indicators, given that different users will have their own preferences. Some methodologies/tools are, however, suggested in Table 1.

3.3. Multi-criteria decision analysis (MCDA)

3.3.1. The PROMETHEE-II method

In order to rank each alternative based upon its sustainability

Table 1
Some suggested methodologies/tools for the assessment of the indicators.

Indicator	Methodologies/tool
Global warming indicator	Life cycle impact assessment (LCIA) methods implemented in LCA tools, such as SimaPro, OpenLCA, GaBi[1]
Energy demand	Cumulative Energy Demand (CED)
Secondary materials consumption	Based on the mixture formulation and type of components[2]
Materials to be reused or recycled	[2]
Water consumption	Water depletion
Acidification indicator of soil and water	[1]
Eutrophication indicator	[1]
Ozone depletion indicator	[1]
Particulate matter indicator	[1]
Safety audits & safety inspections	European Directive 2008/96/EC on road infrastructure safety management
User comfort	Area above or below the pavement performance prediction model, depending on its monotony
Noise reduction	CNOSSOS-EU method for strategic noise mapping following adoption as specified in the Environmental Noise Directive 2002/49/EC
Traffic congestion	HCM, RealCost, QUADRO, Visum
Life cycle highway agency costs (LCHAC)	Bids, authorities guidelines
Life cycle road user costs (LCRUC)	Fuel costs: Swedish National Road and Transport Research Institute (VTI)'s rolling resistance (RR) model

level, the proposed DSS implements an outranking MADA method, namely the PROMETHEE-II method.

An outranking approach was selected because of its non-compensatory nature, in the sense that a bad performance on an indicator cannot be compensated with a good performance on another indicator. According to Munda (2005), complete compensability is not desirable in a method for tackling sustainability-related decision making problems. The rationale underlying to this statement lays on the concept of "strong sustainability". According to this concept, natural capital is a set of complex systems, evolving interacting abiotic and biotic elements, whose consumption is irreversible and irreplaceable by manufactured capital and thus, no trade-offs are admissible. This concept contrasts with that of "weak sustainability", according to which natural capital and manufactured capital are substitutable and no essential differences exist between the kinds of well-being they generate (Ekins et al., 2003). Therefore, in view of the implementation of the concept of "strong sustainability", which constraint or abolish the compensation among sustainability dimensions, outranking approaches should be preferred to performance aggregation-based approaches.

Finally, as for the PROMETHEE-II method, its selection was driven by the following facts: (1) it is one of the best known outranking methods (Sultana and Kumar, 2012), with an applicability level extended to multiple domains (Behzadian et al., 2010); (2) it has a transparent computational procedure which can incorporate both quantitative and qualitative data; (3) it requires fewer parameters from the DM when compared to other outranking methods, such as the ELECTRE (Betrie et al., 2013); and (4) the comparison of the alternatives can be performed without difficulty, producing results that consist of a ranking and the identification of the best alternative, and thereby are of easy understanding for any DM/stakeholder, regardless of its expertise level.

In this outranking method, alternatives are compared pairwise on the basis of every single indicator. Let A be a set of alternatives for ranking and G be the total number of criteria (indicators). PROMETHEE method considers a function $P_j(a,b)$, that is a function of the difference (d_j) between the scores of two alternatives for every criterion (g_j), in which the difference is calculated as $d_j(a,b) = g_j(a)$ - $g_j(b)$. Brans and Mareschal (2005) defines six different functions to model the preferences of the DM. Some preference function (PF) may require a predetermined preference threshold (p) or indifference threshold (q) or both. The indifference threshold, q, represents the largest deviation which is considered as negligible by the DM. The preference threshold, p, represents the smallest deviation which is considered as sufficient to generate a total preference. Once $P_j(a,b)$ have been computed, and considering the weight assigned to criterion j (w_j), the values are converted into the multi-criteria index, $\pi(a,b)$, that expresses the degree to which a is preferred to b over all the criteria, as described in Equation (1):

$$\begin{cases} \pi(a,b) = \sum_{j=1}^{G} P_j(a,b) \times w_j \\ \pi(b,a) = \sum_{j=1}^{G} P_j(b,a) \times w_j \end{cases}, \tag{1}$$

where $\pi(a,b)$ can assume values between 0 and 1, and the greater the value of $\pi(a,b)$, the greater the preference of a over b. Furthermore, $\pi(a,b) \approx 0$ implies a weak global preference of a over b, while $\pi(a,b) \approx 1$ implies a strong global preference of a over b (Brans and Mareschal, 2005).

In order to compare an alternative a with all the other alternatives of the set A, the PROMETHEE method considers the positive ($\phi^+(a)$) and negative ($\phi^-(a)$) outranking flows of a defined as follows (Equation (2)):

$$\phi^+(a) = \frac{1}{1-n} \sum_{x \varepsilon A} \pi(a,x)$$
$$\phi^-(a) = \frac{1}{1-n} \sum_{x \varepsilon A} \pi(x,a) \tag{2}$$

Each alternative a is compared with (n-1) x other alternatives in A. The positive outranking flow measures how much alternative a is dominating the others, and thus, the higher the value of the positive outranking flow, the better the alternative. In turn, the negative outranking flow denotes how much alternative a is dominated by the others, and thus, the lower the value of the negative outranking flow, the better the alternative. The final ranking is calculated by sorting the alternatives based on its net outranking flow, $\phi(a)$, calculated according to Equation (3):

$$\phi(a) = \phi^+(a) - \phi^-(a), \tag{3}$$

The net outranking flow, $\phi(a)$, is the balance between the positive and the negative outranking flows, and the higher the net outranking flow, the better the alternative.

3.3.2. Weighting methodologies

The weight of an indicator is a measure of how much it is important with respect to the other indicators. The SUP&R DSS comprises two weighting approaches: subjective and objective. Furthermore, each approach features two alternative weighting methods. The subjective approach determine the weights of the indicators based exclusively on preference information of indicators provided by the DM, whereas in the objective approach weights are determined by employing mathematical models without any consideration of the DM's preferences.

The objective methods considered in the Sustainable Pavement & Railway Initial Training Network (SUP&R ITN) MCDA methodology include the Entropy and the Mean weight methods. In information theory, entropy is used to refer to a general measure of uncertainty. It can also measure the amount of useful information that can be obtained from the data. Thus, when the evaluated alternatives have a great difference between each other on a particular indicator, the entropy is smaller, meaning that the indicator provide more effective information, and therefore the its weight should be larger. On the contrary, when the differences are smaller, the entropy is larger, which shows that the amount of information provided by the indicator is smaller, and therefore its weight should be correspondingly smaller. Finally, according to the Mean weight method all the indicators are equally important, and therefore are given the same weight.

As for the weighting methods belonging to the subjective approach, the SUP&R ITN MCDA methodology gives the DM the possibility of considering its own weighting set, hereafter named Manually defined weighting set. Alternatively, it provides a weighting set derived from an Analytical Hierarchical Process (AHP)-based survey conducted in the framework of the SUP&R ITN research project. Public/institutional representative from the public administration, self-employed professionals, universities, enterprises and other social agents across academia, industry and consulting companies were invited to respond to a survey that was available on-line during approximately two months. In the total 52 individuals contributed to derive the weighting set hereafter named SUP&R ITN weighting set.

3.4. Sensitivity analysis

To test the robustness of the MCDA results, sensitivity analysis should be undertaken to ascertain if, and how, the ranking of the alternatives varies in face of changes of important input parameters. For these reasons the SUP&R DSS allows also to perform a sensitivity analysis on the basis of the parameters selected by the user.

4. Case study: description and results

In this section, the proposed sustainability-based DSS was applied for selecting the most sustainable road pavement construction and maintenance scenario, in which innovative asphalt mixtures are laid down in the wearing coarse of the flexible road pavement of a typical French highway section of 1-km length, composed of two independent roadways, each with two lanes with an individual width of 3.5 m. The sustainability evaluation of each alternative was performed according to a life cycle approach, for a project analysis period (PAP) of 30 years, starting in 2015, and considering all phases of the pavement life cycle, namely raw material extraction and mixtures production, construction and M&R, WZ traffic management, usage and EOL phase. Based on the real values observed in a French road section in 2015, the initial two-way average annual daily traffic (AADT) was considered to be equal to 6500 vehicles/day, of which 33% are heavy duty vehicles (HDV) (equality divided between rigid HDV and articulated HDV). The structure and composition of the French fleet of vehicles, expressed in terms of type of vehicles and European emissions standards, was that defined by CITEPA (*Centre Interprofessionnel Technique d'Études de la Pollution Atmosphérique*). The traffic growth rate was 1.5% per year (Jullien et al., 2015). The geometric characteristics of the pavement structure adopted in each of the independent roadways are presented in Fig. 3. Its initial structural number (SN_0) is equal to 5.13.

As for pavement maintenance, a pavement M&R strategy derived from French practice was considered (Jullien et al., 2014, 2015). The maintenance tasks inherent to each M&R activity, as well as the application timing are displayed in Fig. 3.

4.1. Definition of alternatives

The reference pavement structure (Fig. 3) constituted by layers made of conventional HMA without RAP content was compared to four alternative structures with equal geometry, but in which the wearing course of the initial structure, and subsequent M&R treatments, were made of WMA.

WMA represents a broad range of technologies used with asphalt concrete that allows the mixture to be produced, stay workable and compactable at lower temperatures than typical HMA. The WMA temperature reduction can be obtained by means of several technologies that involve the use of organic additives, chemical additives, and water-based or water-containing foaming processes (Rubio et al., 2012).

In this case study, the WMA was produced according with two different technologies (i.e., foaming and CECABASE® additive) and with and without the adding of a RAP content of 50%. Furthermore, the set of alternative mixtures was completed with the consideration a conventional HMA with a RAP content of 50%, thus rising to 6 the total number of pavement sections to be analysed and compared. The features of the several mixtures analysed in the case study are shown in Table 2.

4.2. Sustainability indicators and quantification of the evaluation matrix

The sustainability indicators considered in this case study are those presented in Section 3.1, excepting the MRR, SASI, UC and NR. These indicators were disregarded based on: (1) the features of the materials employed in the case study (concerning the MRR indicator), as well as its technical context (concerning the SASI indicator); (2) research studies showing that HMA and WMA pavements have comparable long-term field performance in terms of structural durability (Washington State University et al., 2017) (concerning mainly the UC indicator); (3) the assumption that initial surface properties (e.g., macrotexture) are the same for all mixtures (concerning the NR indicator); (4) inexistence of solid scientific evidences that functional properties of HMA and WMA pavements will evolve distinctively over time (concerning the UC and NR indicators). Therefore, the scores of the alternatives with regard to each one of the indicators listed above do not vary.

The midpoint level life impact assessment (LCIA) method CML 2001 (Guinée et al., 2002) was adopted to quantify the following environmental indicators: GW, AC, EU, SOD. This impact assessment methodology was developed by the Institute of Environmental Sciences (CML) at the University of Leiden in the Netherlands. It uses primarily European data to derive its impact factors. It groups the LCI results into midpoint impact categories divided into "baseline" impact categories, "study-specific" impact categories and "other" impact categories.

The ED indicator was calculated according to the definition of CED (also called "primary energy consumption") specified by Hischier et al. (2010). It represents the direct and indirect energy use in units of MJ throughout the life cycle of a product, including the energy consumed during the extraction, manufacturing and disposal of the raw and auxiliary materials. The total CED includes the fossil cumulative energy demand (i.e., from hard coal, lignite, peat, natural gas, and crude oil) and the CED of nuclear, biomass, water, wind, and solar energy in the life cycle (Huijbregts et al., 2010).

In turn, the hierarchist variant of the ReCiPe midpoint LCIA method (Goedkoop et al., 2013) was adopted to calculate the PM and WC indicators. This impact assessment methodology was developed by a set of institutions, namely the Dutch National Institute for Public Health and the Environment (RIVM), the Radboud University, the CML, and PRé, and builds on the Ecoindicator 99 and the CML Handbook on LCA (Guinée et al., 2002). The indicators can be determined at two levels (midpoint and endpoint) according to three cultural perspectives (individualist, hierarchist and egalitarian) representing a set of choices on aspects including time or prospects that future technology development can avoid future damages.

Finally, the SMC indicator was quantified according to the formulation of the mixtures, namely the RAP content.

Regarding the economic indicators, the net present value of the LCHAC was determined on the basis of the data representative of the general French conditions provided by a French construction company. The marginal FC costs incurred by the road users during the WZ traffic management were calculated according to the two-step methodology developed by Santos et al. (2015a, 2015b). First, the COPERTv5.0 air pollutants and GHG emissions model (EMISIA, 2017) was run multiple times, each considering a different speed in the "Highway" driving mode, to compute a set of FC factors representing the French vehicle fleet characteristics per type of vehicle. Next, the FC calculated for the several discrete speed values are used to derive equations that allow to determine FC factors representative of the French vehicle fleet as a continuous function of the speed. Secondly, the capacity and delay models existing in the HCM 2000 (TRB, 2000) were used to model the changes in driving patterns. They produce several outputs, such as the number of vehicles that traversed the WZ, the average queue length, the average queue speed in each hour, etc. Each section where there is a change in the driving pattern was considered to be a new road "link". The characteristics of each link (length, number of vehicles and average speed) were combined with the equations previously determined to derive the FC corresponding to a WZ hour of a given M&R activity. Finally, the marginal FC and time delay associated with the WZ traffic management plan were determined by subtracting the FC and travel time produced during a WZ period from the results of an equivalent non-WZ period.

As far as the costs incurred during the use phase are concerned, they were quantified by combining the Swedish National Road and Transport Research Institute (VTI)'s rolling resistance (RR) model (Hammarström et al., 2012) with data from the COPERTv5.0 emissions and FC model according to the two-step methodology proposed by Santos et al. (2015a).

In the first step, the VTI's RR model was used to calculate the additional FC due to the vehicles travelling over the rough pavement surface when compared to the FC of the vehicles travelling over a smooth surface. Then, an effective AADT ($AADT_E$) was used in the COPERTv5.0 emissions and FC model to relate the effect of pavement surface properties on the FC and emissions. The $AADT_E$ for a given macrotexture and roughness at time t, expressed in terms of the mean profile depth (MPD) and IRI, respectively, was calculated using Equation (4) and replaces the actual AADT.

$$AADT_E(t) = AADT(t) \times \sum_{i=0}^{N\_Veh} Veh_i \times \frac{FC_i^{IRI(t),MPD(t)}}{FC_i^{smooth}} \tag{4}$$

Where AADT is the annual average daily traffic value, N_Veh is the number of types of vehicles (in this case study it is equal to three, corresponding to passenger cars, rigid HDV and articulated HDV), Veh_i is the percentage of vehicles of type i in the AADT, $FC_i^{IRI(t),MPD(t)}$ is the FC for the type of vehicle i travelling on a pavement with a specified IRI and MPD at time t, and FC_i^{smooth} is the FC of the same type of vehicle i travelling along a typical smooth pavement.

In order to estimate the influence of RR on FC, the pavement performance prediction model of the flexible pavement design method developed by AASHTO (1993) was adopted to predict the quality of the pavement over time, expressed in terms of PSI (Equation (5)). This model was posteriorly combined with the expression proposed by Al-Omari and Darter (1994) to convert the PSI into IRI (Equation (6)). In turn, the model proposed by Lorino et al. (2008) was adopted to predict the evolution of the macrotexture over the PAP (Equation (7)).

$$PSI_t = PSI_0\text{-}(4.2\text{-}2) \times 10^{\left[\left(\log_{10}\left(W_{80_t}\right) - Z_R \times S_0 - 9.36 \times \log_{10}(SN_t+1) + 0.2\text{-}2.32 \times \log_{10}(M_R) + 8.07\right) \times \left(0.4 + \frac{1094}{(SN_t+1)^{5.19}}\right)\right]} \tag{5}$$

$$IRI_t = -\frac{1}{0.24} \times Ln\left(\frac{PSI_t}{5}\right) \tag{6}$$

$$MPD_t = 0.986 - 0.168 \times \ln(age) \tag{7}$$

Where PSI_t is the Present Serviceability Index in year t, PSI_0 is the Present Serviceability Index of a pavement immediately after construction (year 0), W_{80}^t is the number of 80 kN equivalent single axle load (ESAL) applications in year t (million ESAL/lane), Z_R is the standard normal deviate, S_0 is the combined standard error of the traffic prediction and performance prediction, SN_t is the structural number of a pavement structure in year t, M_R is the sub-grade resilient modulus (pounds per square inch), IRI_t is the International Roughness Index (m/km) in year t, MPD_t is the mean profile depth (mm) in year t, age is the age of the surface course (years).

The FC costs were calculated by considering, respectively, the following gasoline without plumb 95 and diesel unit costs (values for 2015): 1.42 €/litre and 1.15 €/litre (Ministère de la Transition Écologique et Solidaire, 2017). Moreover, the annual RUC as well as the LCHAC were brought back to the present time by considering a discount rate value equal to 4%.

Regarding the social indicators, the TC indicator was quantified by applying the capacity and delay models proposed by the HCM 2000 manual (TRB, 2000), as described in Santos et al. (2015a) and summarized previously. This manual provides a systematic basis for assessing the capacity and level of service for elements of the surface transportation system and also for systems that involves a series or a combination of individual facilities.

Taking into account the considerations aforementioned and the features of the case study, the scores of the alternatives with

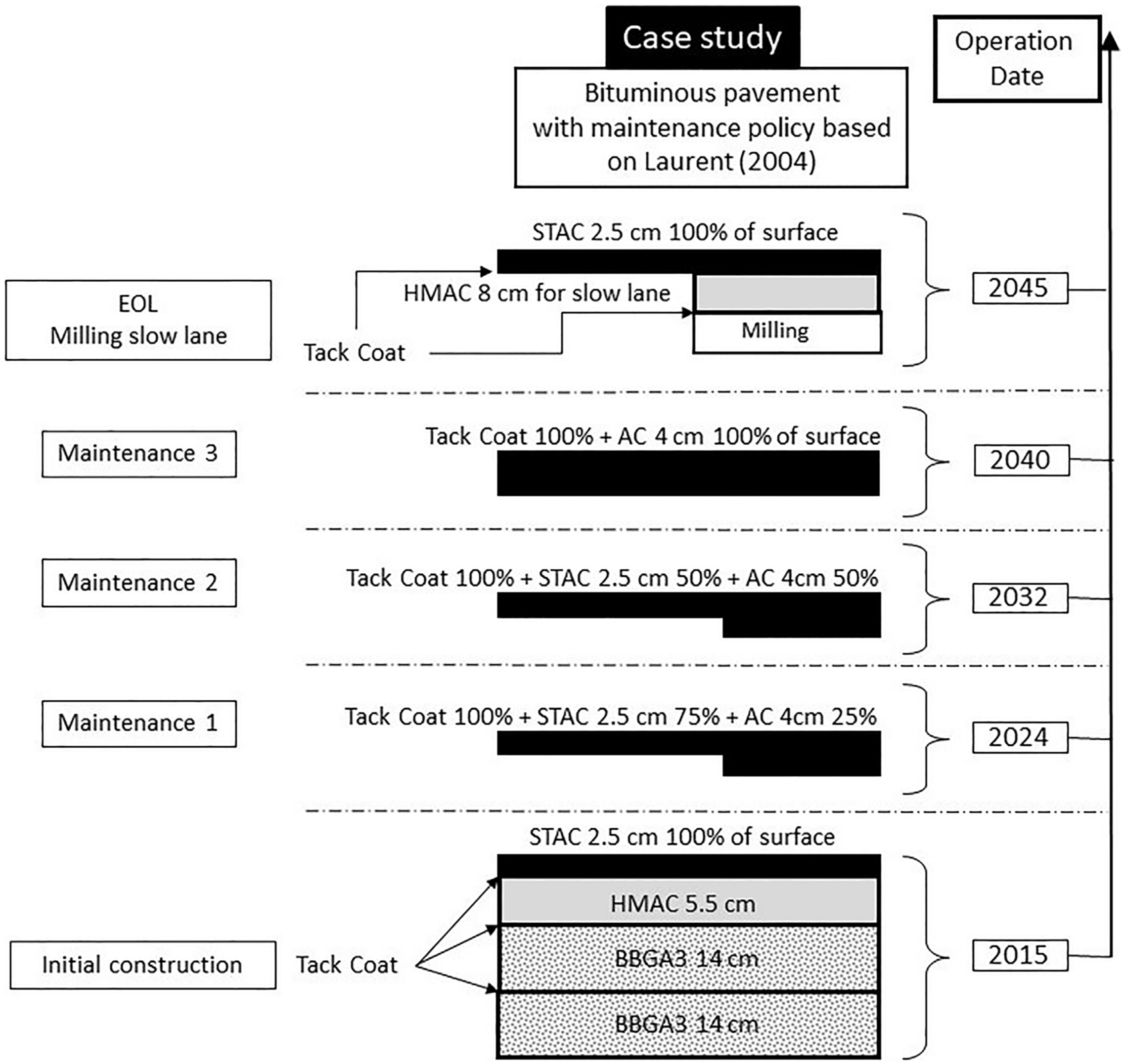

Fig. 3. Geometric characteristics of the flexible pavement structure and M&R strategy. (Note: the percentages refer to the width of the pavement layers undergoing the M&R activity being considered. Acronyms: BBGA- bituminous bound graded aggregate; HMAC – hot mix asphalt concrete; STAC- super thin asphalt concrete; AC- asphalt concrete) (Laurent, 2004).

Table 2
Summary of the features of the HMA and WMA mixtures used in the conventional and alternative scenarios.

Item	Type of mixture					
	HMA, 0% RAP	WMA- CECABASE®, 0% RAP	Foamed WMA, 0% RAP	HMA, 50% RAP	WMA- CECABASE®, 50% RAP	Foamed WMA, 50% RAP
Virgin aggregate						
Quantity (%/m)	94.4	94.4	94.4	48.4	48.37	48.36
Water content (%/a)	3	3	3	3	3	3
RAP						
Quantity (%/m)	–	–	–	48.4	48.37	48.36
Water content (%/RAP)	–	–	–	3	3	3
Bitumen						
Penetration grade	35/50	35/50	35/50	35/50	35/50	35/50
Quantity (%/m)	5.4	5.4	5.4	3.2	3.2	3.2
WMA agent						
Type	–	surfactant	water	–	surfactant	water
Quantity (%/m)	–	0.054	0.077	–	0.054	0.077
Mixture density (kg/m^3)	2360	2340	2260	2370	2360	2360

Acronyms: HMA- hot mix asphalt; WMA- warm mix asphalt; RAP- reclaimed asphalt pavement; %/m- percentage by mass of mixture; %/a- percentage by mass of aggregates; %/RAP- percentage by mass of RAP.

respect to each indicator were determined and presented in Table 3. Details on the features of the system boundaries of the case study as well as the assumptions considered can be found in Santos et al. (2018). Table 4 presents the quantity of materials applied in each

Table 3
Evaluation matrix.

Alternative scenario		Sustainability indicators										
ID	Name	GW (Kg CO_2-eq)	ED (MJ)	SMC (%)	WC (m^3)	AC (kg SO_2-eq)	EU (kg PO_4^{3-}-eq)	SOD (kg CHC_{11}-eq)	PM (kg PM_{10}-eq)	TC (Hr)	LCHAC (€)	LCRUC (€)
1	HMA, 0%RAP	1258433	69734040	0	2426	10382	4515	0.823	2873	46.142	1266306	2154
2	WMA- CECABASE®, 0% RAP	1236882	69497555	0	4124	10227	4497	0.819	2848	40.921	1270296	2050
3	Foamed WMA, 0%RAP	1224257	68735462	0	2400	10122	4433	0.811	2811	40.921	1258028	2050
4	HMA, 50%RAP	1202558	63675738	11	2236	9793	4275	0.751	2714	46.142	1204773	2154
5	WMA-CECABASE®, 50% RAP	1182016	63591181	11	3937	9651	4261	0.748	2693	40.921	1209036	2050
6	Foamed WMA, 50%RAP	1178912	63435838	11	2234	9635	4250	0.748	2681	40.921	1203225	2050

Key: HMA- hot mix asphalt; WMA- warm mix asphalt; RAP- reclaimed asphalt pavement; GW- global warming; ED- Energy demand; SMC- Secondary materials consumption; WC- Water consumption; AC- acidification; EU- Eutrophication; SOD- Stratospheric ozone depletion; PM- Particulate matter, TC- Traffic congestion; LCHAC- Life cycle highway agency costs; LCRUC- Life cycle road user costs.

Table 4
Quantity of materials consumed in the several M&R activities (ton/direction).

Initial pavement structure		ID Alternative scenario					
Type of layer	Material name	1	2	3	4	5	6
Wearing course	STAC	411.250	409.500	395.500	414.750	413.000	413.000
Tack coat	Bituminous emulsion	3.150	3.150	3.150	3.150	3.150	3.150
Base course	HMAC	904.750	904.750	904.750	904.750	904.750	904.750
Tack coat	Bituminous emulsion	3.150	3.150	3.150	3.150	3.150	3.150
Road base course	BBGA	2352.000	2352.000	2352.000	2352.000	2352.000	2352.000
Tack coat	Bituminous emulsion	3.150	3.150	3.150	3.150	3.150	3.150
Road base course	BBGA	2352.000	2352.000	2352.000	2352.000	2352.000	2352.000
Maintenance 1		ID Alternative scenario					
Type of layer	Material name	1	2	3	4	5	6
Wearing course 1	STAC	308.438	307.125	296.625	311.063	309.750	309.750
Wearing course 2	AC	164.500	164.500	164.500	164.500	164.500	164.500
Tack coat	Bituminous emulsion	3.150	3.150	3.150	3.150	3.150	3.150
Maintenance 2		ID Alternative scenario					
Type of layer	Material name	1	2	3	4	5	6
Wearing course 1	STAC	205.625	204.750	197.750	207.375	206.500	206.500
Wearing course 2	AC	329.000	329.000	329.000	329.000	329.000	329.000
Tack coat	Bituminous emulsion	3.150	3.150	3.150	3.150	3.150	3.150
Maintenance 3		ID Alternative scenario					
Type of layer	Material name	1	2	3	4	5	6
Wearing course	AC	658.000	655.200	632.800	663.600	660.800	660.800
Tack coat	Bituminous emulsion	3.150	3.150	3.150	3.150	3.150	3.150
Maintenance 4		ID Alternative scenario					
Type of layer	Material name	1	2	3	4	5	6
Wearing course	STAC	411.250	409.500	395.500	414.750	413.000	413.000
Tack coat	Bituminous emulsion	3.150	3.150	3.150	3.150	3.150	3.150
Base course	HMAC	658.000	658.000	658.000	658.000	658.000	658.000
Tack coat	Bituminous emulsion	1.575	1.575	1.575	1.575	1.575	1.575

Key: STAC- super thin asphalt concrete; HMAC- hot mix asphalt concrete; BBGA- bituminous bound graded aggregate; AC- asphalt concrete.

layer of the initial pavement structure and posterior M&R activities. Table 5 summarizes relevant M&R traffic-related. Table 6 shows for each alternative the time required per direction to perform the several M&R activities.

Table 5
M&R traffic-related inputs.

Parameter	Value
Non-WZ Conditions	
Number of lanes per direction	2
Free flow capacity (veh/lane/hour)	2297
Rural/urban capacity	rural
Maximum AADT (total for both directions)	220512
WZ Conditions	
Number lanes open in each direction	1
WZ length (km)	1
WZ speed limit (km/h)	80
WZ capacity (veh/lane/hour)	1510
Queue dissipation capacity (veh/lane/hour)	1700
Maximum queue length (km)	8

Key: WZ- work zone.

4.3. Multi-criteria decision analysis (MCDA)

In this section the alternatives described previously are ranked

Table 6
Total time required to perform the M&R activities (hours/direction).

M&R activity	ID Alternative scenario					
	1	2	3	4	5	6
Do-Nothing	0	0	0	0	0	0
STAC 2.5 cm 75% + AC 4 cm 25%	7	6	6	7	6	6
STAC 2.5 cm 50% + AC 4 cm 50%	7	6	6	7	6	6
AC 4 cm 100%	8	7	7	8	7	7
Milling 50%; HMAC 8 cm 50% + STAC 2.5 cm 100%	15	14	14	15	14	14

Key: STAC- super thin asphalt concrete; AC- asphalt concrete; HMAC- hot mix asphalt concrete.

by applying the PROMETHEE-II method. However, before using that outranking method, for each indicator, a specific PF with its thresholds as well as a weight value have to be defined. Six main types of PF can be found in the literature (Brans and Vincke, 1985): (1) *usual*, (2) *U-shape*, (3) *linear*, (4) *level*, (5) *V-shape with linear preference and indifference area*, and (6) *Gaussian*. In this case study, the *V − Shape with linear preference and indifference area* PF was selected for all indicators based on the authors' judgment as well as on the insights acquired from other studies (Geldermann and Rentz, 2005; Podvezko and Podviezko, 2010; Kilic et al., 2015; Dražić et al., 2016; Schmitt et al., 2017).

As it pertains to the thresholds values selection, no strict rule exist to govern it. However, divers research studies (e.g., Geldermann and Rentz, 2005; Gervásio and Simões da Silva, 2012; Carbone et al., 2014; Schmitt et al., 2017) adopt the Podvezko and Podviezko (2010)'s recommendation, according to which the preference (p) and indifference (q) thresholds should be between the minimum and the maximum of the differences observed within the indicators' scores.

Based on author's judgements and taking into account the values considered in other studies existing in the literature (e.g. Gervásio and Simões da Silva, 2012), in this case study the p values were defined in such way that they amount to 65% of the difference between the highest and lowest score for each indicator (d_j^p), whereas the q values were defined as 5% of the difference between the highest and lowest score for each indicator (d_j^q). A sensitivity analysis for q and p values was however performed and discussed in next section to ascertain their influence on the stability of the rankings (Rogers and Bruen, 1998).

Finally, the SUP&R ITN weighting set was adopted to weight the several indicators. The thresholds and weight values defined for each indicator are summarized in Table 7.

The positive (ϕ^+), negative (ϕ^-) and net outranking (ϕ) flows, as well as the consequent ranking of each alternative are shown in Fig. 4. From the analysis of this figure it can be seen that the construction and M&R scenario in which the mixture foamed WMA with 50%RAP is employed in the surface course ranks first, followed by the mixture WMA-CECABASE® additive with 50%RAP and the mixture HMA with 50%RAP. In turn, the construction and M&R scenario that adopts the mixture conventional HMA was found to be the least sustainable. The fact that the mixture foamed WMA with 50%RAP is the most sustainable option is not a surprise due to its better performance on all indicators, as denoted by Table 3. This result is also proved by its null negative outranking flow. Another result worthy of mention is the fact that a mixture HMA with 0% RAP is more sustainable than any WMA mixture with 0%RAP, regardless of the technology used for lowering the manufacturing temperature.

4.4. Sensitivity analysis

To investigate how variations across a set of parameters and assumptions affect the robustness of the reported ranking, and thereby the relative merits of the alternatives being considered and compared, a sensitivity analysis was performed. In particular, the “One-(factor)-At-a-Time” (OAT) sensitivity analysis method was used (Pianose et al., 2016). In this method, output variations are induced by varying one input factor at a time, while all others are held at their default values.

The sensitivity analysis was conducted at two levels. The first one focused on the determination of the influence of the weight values and PROMETHEE thresholds. The second one was intended to address the uncertainties related to the long-term perform of road pavements incorporating new pavement engineering solutions. In fact, given the lack of results obtained from comprehensive field studies it is wise to consider that new paving materials/solutions may not be as durable as the conventional materials.

4.4.1. PROMETHEE parameters

4.4.1.1. Indicators weighting. The sensitivity of the ranking to changes in the indicators weights was carried out by considering two additional weighting approaches: (1) the mean weighting method, and (2) the Entropy method.

Fig. 5 shows the weights values derived from the two alternative weighting methods as well as the relative variation in relation to the weights set of the base case scenario. Table 8 displays the ranking of alternatives for each sensitivity analysis scenario. As observed from Fig. 5, although the relative importance of the indicators changes considerably, the ranking of the alternatives proved to be robust, as no changes in the rankings were observed regardless of the weighting method considered.

4.4.1.2. PROMETHEE preference function parameters. The sensitivity of the ranking to changes in the threshold parameters was carried out by considering two alternative values for each threshold parameter (i.e., indifference and preference thresholds). The values of the threshold parameters considered in the sensitivity analysis are reported in Table 9. Table 10 displays the ranking of the alternatives for various threshold values. Likewise, the ranking of the alternatives was found to be robust, as no changes in the rankings were observed, regardless of the threshold values considered.

Table 7
Weights, preference functions and thresholds considered for each indicator.

Sustainability indicator	Weight (%)	Preference Function		
		Type	p	q
GW	3.17	V- Shape with linear preference and indifference area	51688.65	3976.05
ED	3.29	V- Shape with linear preference and indifference area	4093831.30	314910.10
SMC	4.75	V- Shape with linear preference and indifference area	7.15	0.55
WC	15.12	V- Shape with linear preference and indifference area	1228.50	94.55
AC	4.08	V- Shape with linear preference and indifference area	485.55	37.35
EU	4.08	V- Shape with linear preference and indifference area	172.25	13.25
SOD	4.08	V- Shape with linear preference and indifference area	0.04875	0.00375
PM	30.90	V- Shape with linear preference and indifference area	124.80	9.60
TC	20.76	V- Shape with linear preference and indifference area	3.39	0.26
LCHAC	4.89	V- Shape with linear preference and indifference area	43596.15	3353.55
LCRUC	4.89	V- Shape with linear preference and indifference area	67.60	5.20

Key: GW- global warming; ED- Energy demand; SMC- Secondary materials consumption; WC- Water consumption; AC- Acidification; EU- Eutrophication; SOD- Stratospheric ozone depletion; PM- Particulate matter, TC- Traffic congestion; LCHAC- Life cycle highway agency costs; LCRUC- Life cycle road user costs; p- preference threshold; q- indifference threshold.

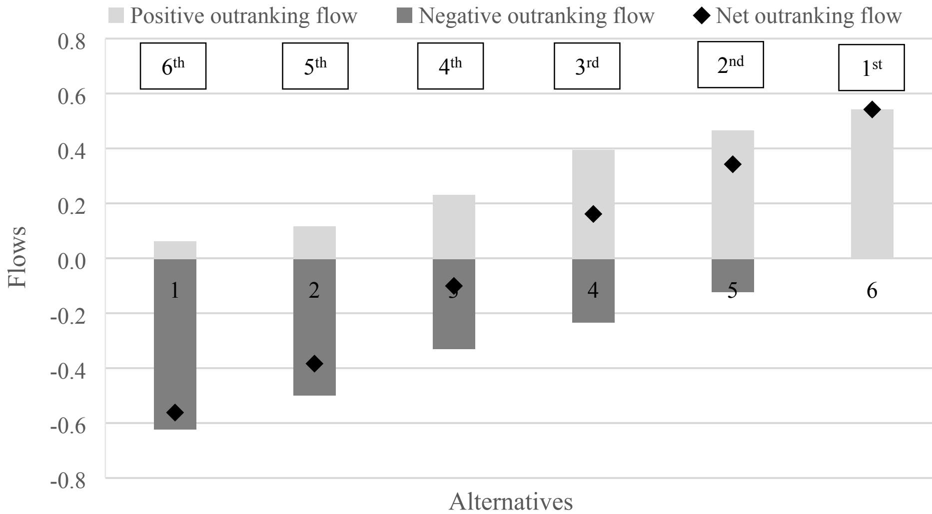

Fig. 4. Positive, negative and net outranking flows of each alternative and consequent sustainability ranking. (Key: Alternative 1: HMA, 0%RAP; Alternative 2: WMA- CECABASE®, 0% RAP; Alternative 3: Foamed WMA, 0%RAP; Alternative 4: HMA, 50%RAP; Alternative 5: WMA- CECABASE®, 50%RAP; Alternative 6: Foamed WMA, 50%RAP).

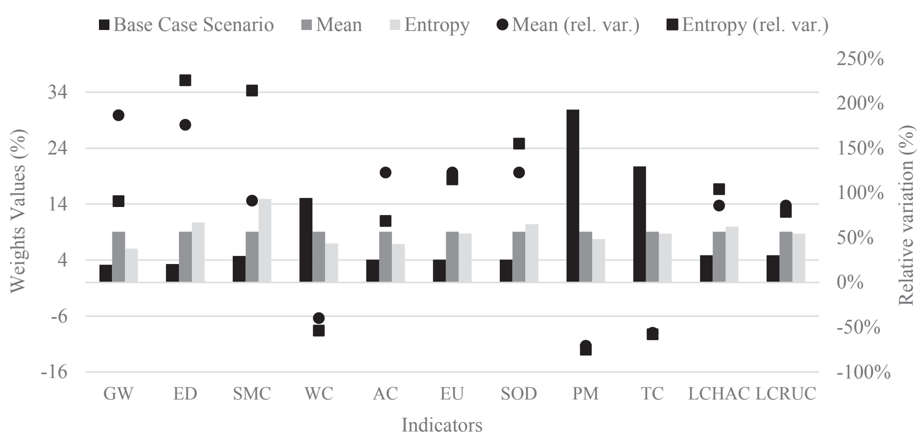

Fig. 5. Indicator weights for each alternative weighting method and relative variation in relation to the weights set of the base case scenario. (Key: GW- global warming; ED- Energy demand; SMC- Secondary materials consumption; WC- Water consumption; AC- acidification; EU- Eutrophication; SOD- Stratospheric ozone depletion; PM- Particulate matter; TC- Traffic congestion; LCHAC- Life cycle highway agency costs; LCRUC- Life cycle road user costs; rel. var.- relative variation).

Table 8
Ranking of alternatives for each sensitivity analysis scenario.

Alternative name	Weighting method											
	Base case scenario				Mean				Entropy			
	ϕ^+	ϕ^-	ϕ	Rank.	ϕ^+	ϕ^-	ϕ	Rank.	ϕ^+	ϕ^-	ϕ	Rank.
Conventional HMA	0.06063	−0.62233	−0.56169	6	0.03669	−0.64492	−0.60823	6	0.02824	−0.64555	−0.61731	6
WMA-CECABASE®, 0%RAP	0.1156	−0.49916	−0.38357	5	0.08726	−0.52625	−0.43898	5	0.08075	−0.52698	−0.44623	5
Foamed WMA, 0%RAP	0.23003	−0.33069	−0.10066	4	0.17870	−0.40708	−0.22838	4	0.15966	−0.43179	−0.27213	4
HMA, 50%RAP	0.39481	−0.23336	0.16144	3	0.44328	−0.17531	0.26797	3	0.45986	−0.16210	0.29776	3
WMA-CECABASE®, 50%RAP	0.46554	−0.12306	0.34248	2	0.51767	−0.07470	0.44297	2	0.52953	−0.05783	0.47169	2
Foamed WMA, 50%RAP	0.54199	0	0.54199	1	0.56465	0	0.56465	1	0.56622	0	0.56622	1

Key: HMA- hot mix asphalt; WMA- warm mix asphalt; RAP- recycled asphalt pavement; Rank. – ranking; ϕ^+- positive outranking flow; ϕ^-- negative outranking flow; ϕ net outranking flow.

4.4.2. Pavement performance over the PAP

The sensitivity of the ranking to changes in the assumption related to the equal long-term performance of the five alternative wearing course mixtures in relation to the conventional mixture was performed by considering that the structural capacity provided by the alternative mixtures was 75% and 50% inferior to the value considered in the base case scenario (i.e. a structural coefficient equal to 0.17323), while keeping constant the original M&R plan. Table 11 displays the ranking of the alternative solutions for the two alternative scenarios. Once again, the ranking of the alternatives was found to be robust, as no changes in the rankings were observed, regardless of the structural coefficient value considered.

Table 9
Threshold parameters considered for each sensitivity analysis scenario.

Sustainability indicator	Base case scenario				Alt. scenario 1	Alt. scenario 2	Alt. scenario 3	Alt. scenario 4
	d_j^p(%)	Abs. value	d_j^q(%)	Abs. value	d_j^p(%)	d_j^p(%)	d_j^q(%)	d_j^q(%)
GW	65	51688.65	5	3976.05	50	80	10	15
ED	65	4093831.30	5	314910.10	50	80	10	15
SMC	65	7.15	5	0.55	50	80	10	15
WC	65	1228.50	5	94.55	50	80	10	15
AC	65	485.55	5	37.35	50	80	10	15
EU	65	172.25	5	13.25	50	80	10	15
SOD	65	0.04875	5	0.00375	50	80	10	15
PM	65	124.80	5	9.60	50	80	10	15
TC	65	3.39	5	0.26	50	80	10	15
LCHAC	65	43596.15	5	3353.55	50	80	10	15
LCRUC	65	67.60	5	5.20	50	80	10	15

Key: GW- global warming; ED- Energy demand; SMC- Secondary materials consumption; WC- Water consumption; AC- acidification; EU- Eutrophication; SOD- Stratospheric ozone depletion; PM- Particulate matter; TC- Traffic congestion; LCHAC- Life cycle highway agency costs; LCRUC- Life cycle road user costs; d_j^p- preference threshold for the indicator *j*, expressed as the difference (%) between the highest and lowest score of that indicator; d_j^q- indifference threshold for the indicator *j*, expressed as the difference (%) between the highest and lowest score of that indicator.

Table 10
Ranking of alternatives for each sensitivity analysis scenario.

Alternative name	Base case scenario		$d_j^p = 50\%$		$d_j^p = 80\%$		$d_j^q = 10\%$		$d_j^q = 15\%$	
	ϕ	Rank.	ϕ	Rank.	ϕ	Rank.	ϕ	Rank.	ϕ	Rank.
Conventional HMA	−0.5617	6	−0.5822	6	−0.5485	6	−0.5448	6	−0.5336	6
WMA-CECABASE®, 0%RAP	−0.3836	5	−0.3902	5	−0.3684	5	−0.3789	5	−0.3750	5
Foamed WMA, 0%RAP	−0.1007	4	−0.1038	4	−0.0700	4	−0.1080	4	−0.1196	4
HMA, 50%RAP	0.1614	3	0.1741	3	0.1421	3	0.1665	3	0.1723	3
WMA-CECABASE®, 50%RAP	0.3425	2	0.3512	2	0.3224	2	0.3356	2	0.3329	2
Foamed WMA, 50%RAP	0.5420	1	0.5510	1	0.5224	1	0.5297	1	0.5230	1

Key: HMA- hot mix asphalt; WMA- warm mix asphalt; RAP- recycled asphalt pavement; d_j^p- preference threshold for the indicator *j*, expressed as the difference (%) between the highest and lowest score of that indicator; d_j^q- indifference threshold for the indicator *j*, expressed as the difference (%) between the highest and lowest score of that indicator; ϕ net outranking flow; Rank.- ranking.

Table 11
Ranking of alternatives for each sensitivity analysis scenario.

Alternative name	Long-term performance of the wearing course mixtures											
	Base case scenario (C = 0.17323)				75% of initial performance (C = 0.12992)				50% of initial performance (C = 0.08662)			
	ϕ^+	ϕ^-	ϕ	Rank.	ϕ^+	ϕ^-	ϕ	Rank.	ϕ^+	ϕ^-	ϕ	Rank.
Conventional HMA	0.0606	−0.6223	−0.5617	6	0,1095	−0,5762	−0,4667	6	0,1095	−0,5656	−0,4561	6
WMA-CECABASE®, 0%RAP	0.1156	−0.4992	−0.3838	5	0,0924	−0,5106	−0,4182	5	0,1168	−0,4817	−0,3649	5
Foamed WMA, 0%RAP	0.2300	−0.3307	−0.1007	4	0,2087	−0,3446	−0,1359	4	0,2015	−0,3522	−0,1507	4
HMA, 50%RAP	0.3948	−0.2334	0.1614	3	0,3965	−0,2060	0,1905	3	0,4000	−0,2072	0,1928	3
WMA-CECABASE®, 50%RAP	0.4655	−0.1231	0.3425	2	0,4496	−0,1325	0,3171	2	0,4522	−0,1325	0,3197	2
Foamed WMA, 50%RAP	0.5420	0	0.5420	1	0,5229	−0,0098	0,5132	1	0,4984	−0,0391	0,4593	1

Key: C- structural coefficient; HMA- hot mix asphalt; WMA- warm mix asphalt; RAP- recycled asphalt pavement; Rank. – ranking; ϕ^+- positive outranking flow; ϕ^-- negative outranking flow; ϕ net outranking flow.

5. Summary and conclusions

In this paper, the development of a Decision Support System intended to foster sustainability in pavement engineering is presented. The SUP&R DSS embeds several indicators methodologically selected for assessing the sustainability of road pavement technologies according to the economic, environmental and social dimensions of sustainability. PROMETHEE-II MCDM method is employed to rank the priority sequence of the alternatives being compared, with the consideration of the DMs' preferences or based on the relationship between the performance of the alternatives with respect to each indicator.

The capabilities of the proposed sustainability-based DSS were illustrated through a comparative analysis of several sustainable asphalt mixtures used in wearing courses of a flexible road pavement section. Specifically, six type of mixtures, namely (1) a conventional HMA mixture with 0%RAP, (2) a foamed WMA mixture with 0%RAP, (3) a WMA-CECABASE® additive mixture with 0%RAP, (4) a conventional HMA mixture with 50%RAP, (5) a WMA-CECABASE® additive mixture with 50%RAP, and (6) a foamed WMA mixture with 50%RAP were ranked with regard to eleven sustainability indicators. They were the following: (1) global warming; (2) energy demand; (3) secondary materials consumption; (4) water consumption; (5) acidification of soil and water; (6) eutrophication; (7) stratospheric ozone depletion; (8) particulate matter; (9) traffic congestion; (10) life cycle highway agency costs; and (11) life cycle road user costs. From the methodology and results presented and discussed in the previous sections, the following results are worth highlighting:

- All in all, by providing a computational platform embedding a representative and clear set of indicators and by allowing an easily interpretation of the results, the proposed sustainability-based DSS proved to be efficient in identifying the most sustainable alternatives according to the features of the case study presented in this paper.

- The MCDA results of the baseline scenario show that the mixture foamed WMA with 50%RAP is the most sustainable among the competing alternatives, followed by the mixture WMA-CECABASE® additive with 50%RAP and the mixture HMA with 50%RAP. In turn, the conventional HMA mixture was found to be the least sustainable.
- The sensitivity analysis conducted to investigate the influence of (1) modified weight and threshold values and (2) the assumption related to the equal long-term performance of all alternative wearing course mixtures on the stability of the ranking showed that the rankings remained unchanged regardless of the analysis scenario considered. However, it should be mentioned that the decrease in the structural coefficient might not be enough to capture the hypothetical variation in the long-term performance of a road pavement incorporating new asphalt mixtures. As such, the case study considered in this paper should be revisited once a deeper knowledge on the field long-term performance of asphalt mixtures containing RAP and WMA is available. Alternatively, an uncertainty analysis can also be conducted by assuming that uncertainties exist in the indicators performance values.
- The presented sustainability-based DSS has been structured in a way that allows DMs to apply it to several systems. It is an ambition of the authors that this methodology and tool could be adapted and used by DM to compare the sustainability of a technology already at the design stage.

Although the authors believe that the DSS presented in this paper, and soon freely available on http://superitn.eu, can already be seen as a useful tool for helping DMs striving for more sustainable transportation infrastructure, it can still benefit from further improvements. Therefore, further work concerning its development will follow three main directions. First, the number of MCDA methods available for selection will be extended. Second, the methodological context in which the MCDA is currently performed (i.e. deterministic) will be enhanced to allow a stochastic MCDA to be performed. Finally, an uncertainty analysis will be performed to ascertain the extent to which the various dimensions of uncertainty in sustainability assessment decision making can affect MCDM-assisted outcomes.

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