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Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability

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Abstract

Recognizing the need to move towards more sustainable pavement management practices, stakeholders in the pavement sector have been seeking new pavement engineering solutions that can help them to successfully embrace this challenge. The general approaches for improving pavement sustainability include, among others, reducing virgin binder and virgin aggregate content in HMA and WMA mixtures, reducing energy consumed and emissions generated in mixtures production, applying in-place recycling techniques, and implementing preventive treatments. Despite the fact that the cost effectiveness and the environmental-friendliness of some of those solutions have started to be progressively recognized when considered individually, it is no less true that sustainability is quite context-sensitive, and the extent to which a pavement engineering solution is labelled “sustainable” will very much depend on the characteristics of the project, the specific economic and environmental goals of the highway agency and road users, and the processes included into the boundaries of the system being considered. Moreover, improving one component of sustainability is often done at the expense of another, or its effect is limited with respect to time and scope. Therefore, it is clear that assessing the role played by those solutions in improving pavement sustainability requires the use of comprehensive and wide-scope life cycle modelling approaches which enable multidimensional and conflicting decision-makers’ perspectives to be brought into the decision-making context. In this study, a comprehensive and integrated pavement life cycle costing- life cycle assessment model was developed to investigate, from a full life cycle perspective, the extent to which several pavement engineering solutions, namely hot in-plant recycling mixtures, WMA, cold in-place recycling, cold central plant recycling and preventive treatments, are efficient in improving the environmental and economic dimensions of pavement infrastructure sustainability, when applied either separately or in combination, in the construction and management of a road pavement section located in Virginia, USA.

Keywords: life cycle costing, life cycle assessment; in-place recycling techniques; sustainable pavement construction and management; multi-criteria decision analysis.

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1. Introduction

With the recent launch of the Build America Investment Initiative (White House 2014), a US government-wide initiative that aims to tackle the pressing infrastructure investment needs of the United States as well as to promote economic growth, many Departments of Transportation (DOTs) will likely renew their efforts both in the construction of new highway infrastructures and in the maintenance of those already built.

The activities underlying to the construction, operation and maintenance of highway infrastructures are notorious for the large amounts of natural materials and energy resources they consume, as well as for the considerable environmental impacts they generate (British Columbia Road Builders and Heavy Construction Association 2011). In addition, the strong and growing evidence of the environmental effects of these activities along with stringent environmental regulations has strengthened the commitment of DOTs in delivering infrastructures in a more environmentally friendly way, while also using funds in the most economically responsible manner possible. This fact has motivated DOTs, and the pavement community in general, to investigate strategies that improve the environmental performance and reduce the costs of road pavement construction and maintenance practices by using sustainable engineering solutions. Some examples of solutions commonly mentioned in the literature that possess the potential to improve pavement sustainability include (but are not limited to): (1) asphalt mixes requiring lower manufacturing temperatures, such as warm mix asphalt [WMA] (Kristjánssdóttir *et al.* 2007, Hamzah *et al.* 2010, Tatari *et al.* 2012, Vidal *et al.* 2013, Mohammad *et al.* 2014, Rodríguez-Alloza *et al.* 2015) and half-warm mix asphalt [HWMA] technologies (Rubio *et al.* 2013), (2) in-place pavement recycling (Thenoux *et al.* 2007, Robinette and Epps 2010, Santos *et al.* 2014a), (3) pavement preservation strategies and preventive treatments (Giustozzi *et al.* 2012), (4) long-lasting pavements (Lee *et al.* 2011, Sakhaeifar *et al.* 2013), (5) reclaimed asphalt pavement (RAP) materials (Lee *et al.* 2010, Aurangzeb *et al.* 2014), (6) reclaimed asphalt shingles (RAS) materials (Illinois Interchange 2012), (7) industrial wastes and byproducts (Birgisdóttir *et al.* 2006, Carpenter *et al.* 2006, Carpenter and Gardner 2009, Huang *et al.* 2009, Lee *et al.* 2010, Sayagh *et al.* 2010, Mladenović *et al.* 2015), etc.

Despite the fact that the majority of the results of those studies have to some extent corroborated the environmental benefits with which they are a-priori associated, it is not uncommon that they have been obtained by applying methodologies that disregarded the environmental burdens of some processes and pavement life cycle phases. Added to this, as the primary goal of a transportation agency still remains to provide maximum pavement performance within budgetary constraints, a solution which is found environmentally advantageous might not be preferred to another one technically equivalent if it is not economically competitive. Furthermore, there are still some questions about (1) the extent to which such solutions are cost effective throughout their life cycle, (2) which factors are the key drivers of their economic performance, and (3) who are the stakeholders that benefit most from the application of those solutions.

Facing this bicephalous challenge and providing answers to the aforementioned questions requires multidimensional life-cycle modelling approaches, such as life-cycle assessment (LCA) and life cycle costing (LCC), which enable long-term economic and environmental factors to be included in the decision-making process by providing a comprehensive and cumulative view of both the environmental and economic dimensions of a given technical solution. However, it is important to underline that life-cycle modelling approaches by themselves will not necessarily determine which solution is most suitable for a given purpose. Rather, the information that they make available should be used as one

component of a more comprehensive decision making process, which among other merits, will allow the tradeoffs between the interests of the multiple stakeholders to be assessed.

2. Objectives

The main objective of this paper is to investigate from a life cycle perspective the extent to which several pavement engineering solutions, namely hot in-plant recycling mixtures, WMA, cold in-place recycling (CIR), cold central plant recycling (CCPR) and preventive treatments, are efficient in improving the environmental and economic dimensions of pavement infrastructure sustainability, when applied either separately or in combination, in the construction and management of a road pavement structure.

For this purpose, a comprehensive and integrated pavement life cycle costing-life cycle assessment (LCC-LCA) model has been developed, which encompasses all six pavement life cycle phases into the system boundaries, including the usage phase, and accounts for the upstream impacts in the production of elements commonly disregarded by the majority of the existing pavement LCA models.

Finally, to account for the often conflicting interests of the multiple stakeholders involved in the decision making process within pavement management, the pavement construction and maintenance scenarios considered in this paper were further analyzed by employing a multi-criteria decision making analysis (MCDA) method.

3. Background to the life cycle modeling approaches adopted in the proposed framework

3.1. Life cycle assessment

LCA is a widespread, though still evolving, systematic environmental management tool used for assessing the potential environmental impacts and resources consumed throughout a product's lifecycle from a cradle-to-grave perspective, i.e., from raw material acquisition, via production and use phases, to the end-of-life phase.

The LCA approach formalized by the ISO 14040 series divides the LCA framework into four interactive stages (ISO 2006a and 2006b): (i) goal and scope definition, (ii) life cycle inventory analysis (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation. The goal and scope definition introduces the purpose for carrying out the study, the intended application, and the intended audience. It is also in this stage that the system boundaries of the study are described and the functional unit is defined. The LCI compiles the inputs (resources) and the outputs (emissions) from the product over its life-cycle in relation to the functional unit. The LCIA seeks to establish a linkage between the system and the potential to cause human and environmental damage. In the interpretation, the results from the previous phases are evaluated in relation to the goal and scope in order to identify analysis refinements and improvements, reach conclusions and recommendations, and, in general, aid in the decision-making process (Finnveden *et al.* 2009).

On the basis of the approaches for compiling the LCI, an LCA methodology can be classified into three main categories: (i) process-based LCA (P-LCA), (ii) economic input-output-based LCA (EIO-LCA), and (iii) hybrid LCA.

In the P-LCA, process-specific data for each process of the product life cycle is compiled to form a tailored process diagram that covers the whole life cycle. Each of the diverse processes within the system boundaries is then thoroughly analyzed, which leads to very accurate LCI results. However, due to the commonly high number of single processes existing in a product life cycle, accounting for all of them can be a time consuming and detail-intensive procedure. A P-LCA practitioner has to define which processes are included within the chosen system boundaries. Ideally, those that are left out should have an insignificant contribution to the results. However, due to the fact that decisions on the inclusion or exclusion of processes are commonly taken on the basis of subjective choices rather than on a scientific

basis, it might happen that significant processes are also left out of the analysis along with the insignificant ones. This problematic feature of P-LCA method is known as truncation error.

The EIO-LCA is a top-down approach that relies on the theory introduced and developed by Nobel Prize winner Wassily Leontief (Leontief 1970). It uses available sectorial monetary transaction matrixes describing complex interdependencies of industries in an economy to estimate the sector level environmental burdens and the resources consumed throughout the upstream supply-chain to deliver a certain amount of different goods and services (Suh *et al.* 2004).

Although the EIO-LCA method eliminates the truncation error by tracking all upstream processes, there are several drawbacks: (i) it uses aggregate data representing the averages of several sectors of an economy, and aggregate industry sectors may make the method unable to provide information on the particular product or activity under investigation, such as specific raw materials and energy sources, and to compare similar products within an industry sector, especially if the product falls into a sector which is broadly characterized, (ii) from the EIO-LCA practitioner's perspective it may look like a "black box", because comprehensively analyzing a specific process is always impossible, (iii) monetary value, the most commonly used representation of inter-industry transactions, can distort physical flow relations between industries due to price inhomogeneity, (iv) the proportionality assumption, according to which the inputs to a sector are assumed to be linearly proportional to its output, represent another source of errors given that in practice it is not always true, (v) available IO tables are generally several years old. Thus, assessing rapidly developing sectors and new technologies may introduce errors because of base-year differences between the product system under study and IO data, and (vi) data used in the EIO model are incomplete, with inherent uncertainties, thus, potentially, underestimating results such as environmental impacts (Suh *et al.* 2004). Quantitative evaluations of the limitations of both P-LCA and EIO-LCA models are presented by Junnila (2006), Ferrão and Nhambiu (2009), Mattila *et al.* (2010), Majeau-Bettez *et al.* (2011).

To combine the advantage of both P-LCA and EIO-LCA models while mitigating their respective limitations, three main hybrid LCA models have been developed, namely tiered, input-output-based, integrated hybrid (Suh *et al.* 2004) and augmented process-based approach (Bilec *et al.* 2006 and 2010). Although significant differences distinguish the inventory stage of those models (Suh and Huppes 2005), all are based on the principle of a disaggregated and detailed process-based description of the most important activities linked to an aggregated but complete model of the rest of the economy (Majeau-Bettez *et al.* 2011). In doing so, it allows for flows which were not included in the P-LCA to be estimated with an environmentally extended IO model. A review of LCI approaches including hybrid approaches and their advantages and disadvantages is provided by Suh and Huppes (2005) and Bilec *et al.* (2006).

3.2. Life cycle costing

Life cycle costing (LCC) is defined by the building and construction asset standard ISO15686-5 as a technique used for predicting and assessing the cost performance of constructed assets over a specific period of time while meeting all the functional and operational maintenance and other performance requirements, taking into account all relevant economic factors, both in terms of initial and future operational costs (ISO 2008).

Despite the (often) hypothetical ambiguities generated by the term "life cycle", shared by LCC and LCA, this methodology was initially developed by the US Department of Defense in the mid-sixties (Sheriff and Kolarik 1981), and to a large extent, its maturation process occurred outside the environmental context (Gluch and Baumann 2004). The abovementioned standards already allude the possibility of including inputs from other evaluation techniques (e.g. environmental assessment). Similar intents were also expressed in the revised framework ISO 14040 by claiming that "...LCA typically does not address the economic or social aspects of a product, but the life-cycle approach and

methodologies described in this International Standard may be applied to these other aspects.” (ISO 2006a). However, the most expressive step towards its integration into the environmental decision making process was taken first by Hunkeler *et al.* (2008), and, later, by Swarr *et al.* (2011), through the disclosure of a code of practice that builds on the four-phase structure of the ISO 14040 standards (ISO 2006a). This code of practice aims to provide guidance on how to define consistent system boundaries for complementary and parallel LCC and LCA studies of a given product system.

On the basis of the approach adopted to account for the externalities, Hunkeler *et al.* (2008) divide LCC into conventional, environmental or societal. Conventional LCC is a collection of all costs associated with the life cycle of a product that are directly covered by the main producer or user in the product life cycle. Environmental LCC, on the other hand, assesses the costs associated with the life cycle of a product, covered by one or more of the actors involved in the life cycle of the product, and also includes the externalities that might be internalized and reflected in real monetary flows within a foreseeable time frame. Another point that distinguishes this approach from the previous one lies with the fact that it also requires a complementary LCA with equivalent system boundaries and functional units. However, in this LCA-type LCC based on physical LCA, there is no conversion from environmental measures to monetary measures in order to avoid double counting of externalities in LCC and the complementary LCA. Finally, in the Societal LCC the scope is extended to the macro-economic system level, including costs for society overall. Environmental costs are defined as either environmental damage expressed in monetary terms (costs of external effects), or as the market-based cost of measures to prevent environmental damage. However, to avoid double counting, the monetized environmental effects of the investigated product should not be complemented by an LCA.

4. Methodology

4.1. Principle of the integrated pavement life cycle costing and life cycle assessment model

The research work presented in this paper builds on the process-based LCA and LCC models introduced by Santos *et al.* (2014, 2015a) and Santos *et al.* (2015b), respectively, to develop a comprehensive and integrated pavement LCC-LCA model. The proposed pavement LCC-LCA model relies on a hybrid inventory approach that allows the sub-models to connect with one another by data flows; specifically, the monetary flows associated with exchanges of the pavement life cycle system that are directly covered by the LCC model but for which specific process data are either completely or partially unavailable. In other cases it is available, but collection of the data and subsequent analysis is highly demanding, either in time or resource consumption (e.g. construction equipment manufacturing and maintenance, on- and off-road vehicles tires manufacturing, lubricant oil production, etc.) and, thus, was disregarded in the previous process-based LCA models (Santos *et al.* 2014 and 2015a). These are combined with the I-O methodology for deriving the underpinning environmental burdens. Thus, by interactively integrating the strengths of process-based LCI and IO-based LCI, the resources which are readily available can be used in a more efficient, consistent and rational way and with less effort, helping to reduce the “cutoff” errors and improving the consistency between the system boundaries of the pavement life cycle when analyzed concomitantly from the economic and environmental viewpoint. For this purpose, the pavement LCC-LCA model uses the EIO-LCA model developed in the Carnegie Mellon University (Carnegie Mellon University Green Design Institute [CMUGDI] 2010). This tool utilizes the Leontief’s methodology to relate the inter-sector monetary transactions sectors in the US economy, compiled in a set of matrices by the Bureau of Economic Analysis (BEA) of the US Department of Commerce, with a set of environmental indicators (e.g. consumption of fossil energy, airborne emissions, etc.) per monetary output of each industry sector of the economy. The environmental burdens at sector level associated with a particular commodity under analysis is therefore calculated by multiplying its monetary value, previously adjusted to US dollars of the EIO-LCA

model's year according to sector-specific economic indices from the US Department of Labor, by the respective sectorial environmental multipliers obtained from the EIO-LCA model.

The US 2002 EIO-LCA benchmark consumer price model for the US economy was preferred to the producer model because the monetary quantities of the commodities whose environmental burdens the study aims to quantify are better represented by retail price (e.g. construction equipment acquisition, tires acquisition, lubricating oil acquisition, etc.), which allows for further accounting of the environmental impacts associated with their distribution to wholesalers.

4.2. Goal of the study

The main goal of this study is to quantify and compare the life cycle environmental and economic performances of multiple pavement construction and maintenance practices that hold the potential for improving the environmental and economic dimensions of pavement sustainability. To this end, several scenarios involving the construction, maintenance and rehabilitation (M&R) of a flexible road pavement section in Virginia, USA, were analyzed. The scenarios include the use of hot in-plant recycling mixtures, Sasobit® WMA, CIR, CCPR and preventive treatments.

The application of the pavement LCC-LCA model to the case study presented in this paper will advance the state-of-the-art by:

- 1) comprehensively estimating the potential environmental and economic advantages resulting from applying, individually or combined, new pavement engineering solutions instead of conventional materials and construction and M&R methods;
- 2) demonstrating an integrated methodology that enables the inclusion of environmental loads and costs originated by processes and pavement LCA phases typically excluded from the system boundaries of pavement life cycle modeling approaches;
- 3) identifying the compromise solutions that best suit the often conflicting interests of the multiple stakeholders involved in the decision making process in the pavement management;
- 4) concluding how robust the suitability of the obtained compromise solutions are, when all ranges of combination of weights assigned to the criteria representing the stakeholder's perspectives are taken into account, as opposed to considering only a few sets of weights.

The results will provide an audience consisting of designers, contractors, local and state agencies and road users with an improved understanding of how materials considerations, treatment typology, design, construction, and application timing promise to enhance pavement sustainability while considering the tradeoffs between the requirements imposed by these players.

4.3. Scope of the study

The integrated pavement LCC-LCA model developed to carry out this study follows a cradle-to-grave approach, and consists in a parallel application of the LCA methodology taking into account, as far as possible and suitable, the guidelines provided by the International Standard Organization (ISO 2006a and 2006b) and the University of California Pavement Research Center (UCPRC) Pavement LCA Guideline (Harvey *et al.* 2010) and the LCC methodology based on the Swarr *et al.* (2011).

4.3.1. Functional unit

The functional unit considered in this case study for achieving these goals was defined as a 1km long one-way road pavement section of an Interstate highway in Virginia, USA, with 2 lanes, each of which is 3.66m wide. The project analysis period (PAP) was 50 years, beginning in 2011 with the construction of the pavement structure. The annual average daily traffic (AADT) for the first year was 20,000 vehicles of which 25% were trucks (5% of the truck traffic consisted of single-unit trucks and the remaining percentage of combination trucks). The traffic growth rate was set equal to 3% per year.

4.3.2. Product system- the pavement structure

4.3.2.1. Initial pavement structure design

The initial pavement structure was designed using the pavement structural design method AASHTO'93 (AASHTO 1993) for flexible pavements, as defined by the *Chapter V- Pavement Evaluation and Design* of the Virginia Department of Transportation (VDOT)'s Manual of Instructions for the Materials Division (VDOT 2014). The assumptions considered during the design process are presented in Table 1. Based on the assumptions listed in the Table a pavement structure was designed with a structural number (SN) of 6.72. The details of the interstate flexible pavement structure and hot mix asphalt (HMA) mixtures properties are described in Table 2.

Table 1. Pavement design inputs.

Pavement design variable	Value
Initial construction design (years)	30
Lanes in design direction	2
Trucks in design direction (%)	50
Lane distribution factor (%)	90
Passenger cars ESAL factor (ESALs/vehicle)	0.0002
Single unit truck ESAL factor (ESALs/vehicle)	0.46
Combination truck ESAL factor (ESALs/vehicle)	1.05
Reliability (%)	95
Z_r	-1.645
S_o	0.49
Initial PSI	4.2
Terminal PSI	3
MR subgrade (psi)	9,200
W_{18} (ESALs) applied	37,531,041
SN	6.72
W_{18} (ESALs) allowed	40,120,176

Table 2. Interstate flexible pavement structure and mixes properties.

Layer ID	Material	Thickness (cm)	Asphalt binder performance grade (PG)	Binder content (%)	Fine aggregates (%)	Coarse aggregates (%)
	SM					
1	12.5	5.08 (2 in.)	70-22	5.6	38	62
2	IM 19.0	7.62 (3 in.)	70-22	5.1	35	65
	BM					
3	25.0	17.78 (7 in.)	70-22	4.6	30	70
4	21-B	30.48 (12 in.)	-	-	-	-
5	A-7-6	30.78 (12 in.)	-	-	-	-
6	A-7-6	infinite	-	-	-	-

Notes: SM, surface material; IM, intermediate material; BM, base material; Tack coats are applied in between bound layers; prime coat is applied in between bound layer and unbound layer. All WMA mixes have a Sasobit® content of 1.5% by total weight of bitumen and an aggregate blend equal to the homologous HMA mix. RAP was assumed to consist of 50% fine particles and 50% coarse particles. It was also assumed that RAP has a binder content of 5% (benchmark value) and is 100% active, therefore requiring neither compensation for lower levels of activity nor rejuvenation. An asphalt binder PG 64-22 was used in all mixes when the RAP content is equal to 30%. In all mixes hydrated lime was used as antistripping agent at a dosage rate of 1% by total weight of bitumen in mixture.

4.3.2.2. Maintenance and rehabilitation scenarios

This study analyzed and compared the environmental and economic performance of three main groups of alternative M&R strategies (scenarios) applied over the PAP of the pavement structure presented in the previous section. The first two groups were based on the M&R plan outlined by VDOT (VDOT

2014), in which functional and structural treatments and a major rehabilitation are applied in pre-established years. Nevertheless, they were considered to differ from each other to the extent that in the first group only conventional asphalt materials and treatments were implemented, while in the second group the structural and major rehabilitations were carried out through the combination of in-place recycling techniques, namely CIR and CCPR, and conventional asphalt layers. The recycling-based M&R activities were designed in such a way that they provide equivalent structural capacity to non-recycling-based ones but take into account the VDOT's surface layers requirements for layers placed over recycling-based layers (VDOT 2013). In turn, the third group consisted of preventive maintenance strategies.

The first two groups of alternative M&R strategies, hereafter named VDOT strategy and Recycling-based VDOT strategy, respectively, were further divided into HMA and Sasobit® WMA scenarios with three distinct RAP contents (0%, 15% and 30%). As for the preventive alternative maintenance strategies, two additional scenarios were considered depending on the type of preventive treatments adopted: microsurfacing and thin hot mix asphalt overlay concrete (THMACO). A summary of the names of all considered scenarios is given in Table 3. Details on the M&R activities and M&R actions considered in the several M&R scenarios are presented in Table 4. Table 5 presents the M&R activities considered in each M&R scenario, and respective application years.

Table 3. Identification of the alternative M&R scenarios.

Type of scenario	Scenario ID	Scenario name
VDOT	1	HMA - 0% RAP
	2	HMA - 15% RAP
	3	HMA - 30% RAP
	4	Sasobit® WMA - 0% RAP
	5	Sasobit® WMA - 15% RAP
	6	Sasobit® WMA - 30% RAP
Recycling-based VDOT	7	HMA - 0% RAP
	8	HMA - 15% RAP
	9	HMA - 30% RAP
	10	Sasobit® WMA - 0% RAP
	11	Sasobit® WMA - 15% RAP
	12	Sasobit® WMA - 30% RAP
Preventive maintenance	13	Microsurfacing - 0% RAP
	14	THMACO - 0% RAP ^a

Note: THMACO, thin hot mix asphalt concrete overlay. The types of bound mixes used in the construction of the initial pavement structure are coherent with the scenario name.

^aAccording to VDOT (2012a), RAP cannot be incorporated into the THMACO formulation.

Table 4. Types of M&R activities and M&R actions.

M&R activity ID	M&R activity name	M&R actions	Thickness (cm)	Mixture name
1	Conventional functional mill and replace	Mill surface layer	5.08 (2 in.)	-
		Mill full-depth prior patching 1%	25.4 (10 in.)	-
		Surface cleaning	-	-
		Prime coat application prior full-depth patching	-	Bituminous emulsion
		Pre-overlay full-depth patching 1%	25.4 (10 in.)	BM 25.0
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of AC surface layer	5.08 (2 in.)	SM 12.5

2	Conventional structural mill and replace	Mill surface and intermediate layers	8.89 (3.5 in.)	-
		Mill full-depth prior patching 1%	21.59 (8.5 in.)	-
		Surface cleaning	-	-
		Prime coat application prior full-depth patching	-	Bituminous emulsion
		Pre-overlay full-depth patching 1%	21.59 (8.5 in.)	BM 25.0
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC intermediate layer	5.08 (2 in.)	IM 19.0
3	Major rehabilitation	Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC surface layer	3.81 (1.5 in.)	SM 12.5
		Mill surface, intermediate, base layers and 1 in. unbound layer	33.02 (13 in.)	-
		Subgrade compaction	-	-
		Prime coat application	-	Bituminous emulsion
		Lay down and compaction of the AC base layer	17.78 (7 in.)	BM 25.0
		Tack coat application	-	Bituminous emulsion
4	Recycling-based structural mill and replace	Lay down and compaction of the AC intermediate layer	10.16 (4 in.)	IM 19.0
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC surface layer	5.08 (2 in.)	SM 12.5
		Mill surface and intermediate layer	8.89 (3.5 in.)	-
		Mill full-depth prior patching 1%	21.59 (8.5 in.)	-
		Prime Coat Application Prior Full-Depth Patching	-	Bituminous emulsion
		Pre-overlay full-depth patching 1%	21.59 (8.5 in.)	BM 25.0
5	Recycling-based major rehabilitation	CIR execution and compaction	7.62 (3 in.)	CIR materials ^{a,c}
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC surface layer	8.89 (3.5 in.)	SM 12.5
		Mill surface, intermediate, base layers and 1 in. unbound layer	33.02 (13 in.)	-
		Subgrade compaction	-	-
		Lay down and compaction of CCPR materials in base course	20.32 (8 in.)	CCPR materials ^{b,c}
		Tack coat application	-	Bituminous emulsion
6	Microsurf.	Lay down and compaction of the AC intermediate layer	7.62 (3 in.)	IM 19.0
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC surface layer	5.08 (2 in.)	SM 12.5
		Surface preparation: brushing	-	-
		Surface preparation: tack coat application	-	Diluted bituminous emulsion
		Microsurf. spreading	-	Microsurf.-Type C ^d

7	Thin Overlay	Mill surface layer	1.91 (0.75 in.)	-
		Surface preparation: brushing	-	-
		Surface preparation: tack coat application	-	Bituminous emulsion
		Thin overlay placement and compaction	1.91 (0.75 in.)	THMACO ^e

Notes: BM, base material; IM, intermediate material; SM, surface material; AC, asphalt concrete; CIR, cold in place recycling; CCPR, cold central plant recycling; microsurf., microsurfacing; THMACO, thin hot mix asphalt concrete overlay.

^aA layer coefficient value of 0.35 was used for design purpose based on Diefenderfer (2014).

^bA layer coefficient value of 0.40 was used for design purpose based on Diefenderfer (2014).

^cA PG 64-22 asphalt binder at a content of 2% by weight of total mixture was used to produce the foamed asphalt mix. For each mix, 1% of hydraulic cement and 1% of moisture were added and mixed before the foamed asphalt was added (Diefenderfer 2014).

^dBased on Ducasse *et al.* (2004), a mix formulation consisting of 180 liters of emulsion per m³ aggregates, 3% of SBR by weight of asphalt binder, 2% of Portland cement by weight of aggregate and 140 liters of water by m³ of aggregate was used.

^eMix formulation consists of 58.9% coarse aggregates, 36.1% fine aggregates, 5% asphalt binder PG 70-28 and 1% hydrated lime by weight of asphalt binder (VDOT 2012a).

Table 5. M&R activities considered in each M&R scenario, and respective application years.

M&R scenario ID	M&R activity ID						7
	1	2	3	4	5	6	
1 to 6	12, 44	22	32	-	-	-	-
7 to 12	12, 44	-	-	22	32	-	-
13	-	-	32	-	-	7, 11, 16, 20, 24, 29, 39, 43	
14	-	-	32	-	-	-	7, 12, 18, 23, 28, 39, 44

In order to determine the pavement performance over time, the VDOT's pavement performance prediction models (PPPM) were used. VDOT developed a set of PPPM in units of CCI as a function of time and category of the last M&R activity applied. CCI stands for Critical Condition Index and is an aggregated indicator ranging from 0 (complete failure) to 100 (perfect pavement) that represents the worst of either load-related or non-load-related distresses. Regarding the typologies of M&R activities, VDOT classifies them into five categories: (0) Do Nothing (DN), (1) Preventative Maintenance (PM), (2) Corrective Maintenance (CM), (3) Restorative Maintenance (RM), and (4) Reconstruction/Rehabilitation (RC). Using the base form corresponding to Equation (1), VDOT defines PPPM for the last three categories (Stantec Consulting Services and Lochner 2007). The coefficients of VDOT's load-related PPPM expressed through the Equation (1) for asphalt pavements of Interstate highways are presented in Table 6 (Stantec Consulting Services and Lochner 2007).

$$, CCI(t) = CCI_0 - e^{a + b \times c \ln\left(\frac{1}{t}\right)} \quad (1)$$

where $CCI(t)$ is the critical condition index in year t since the last M&R activity, i.e. CM, RM or RC; CCI_0 is the critical condition index immediately after treatment; and a , b , and c are the load-related PPPM coefficients (Table 6).

Table 6. Coefficients of VDOT's load-related PPPM expressed by the Equation (1) for asphalt pavements of interstate highways.

M&R activity category	CCI_0	a	b	c
CM	100	9.176	9.18	1.27295

RM	100	9.176	9.18	1.25062
RC	100	9.176	9.18	1.22777

Contrary to the remaining categories, VDOT did not develop individual PPPM for PM treatments. Thus, in this case study the considered PM treatments, i.e. microsurfacing and THMACO, were respectively modelled as a 10-point and 15-point improvement in the CCI of a road segment which take place whenever the CCI falls below the trigger value of 85 (Chowdhury 2011). Once the treatment is applied, it is assumed that the pavement deteriorates according to the PPPM of a CM. On the other hand, in the case of the application of CM, RM and RC treatments, the CCI is brought to the condition of a brand new pavement (CCI equal to 100) and the age is restored to 0 regardless of the CCI value prior to the M&R activity application.

For the purpose of estimating the environmental impacts and costs incurred by road users during the pavement usage phase due to the vehicles travelling over a rough pavement surface, a roughness prediction model, expressed in terms of International Roughness Index (IRI), was determined. To this end, the thresholds of the ranges of IRI and CCI values that correspond to qualitative descriptors of ride quality (VDOT 2011) considered appropriate to represent acceptable roughness levels on Virginia highways were plotted and a function in the form of the Equation (2) was fitted to the data.

$$, IRI(t) = 34970 \times CCI(t)^{-1.915} \quad (2)$$

where $IRI(t)$ and $CCI(t)$ are the IRI (in/mile) and the critical condition index in year t , respectively.

Figure 1 shows the variation of the IRI over the PAP resulting from the implementation of the alternative M&R scenarios. One can see that the pavement deterioration pattern corresponding to M&R scenarios 1 to 12 is the same. Such an outcome is the consequence of taking as premise the fact that all mixtures perform in the same way throughout the PAP.

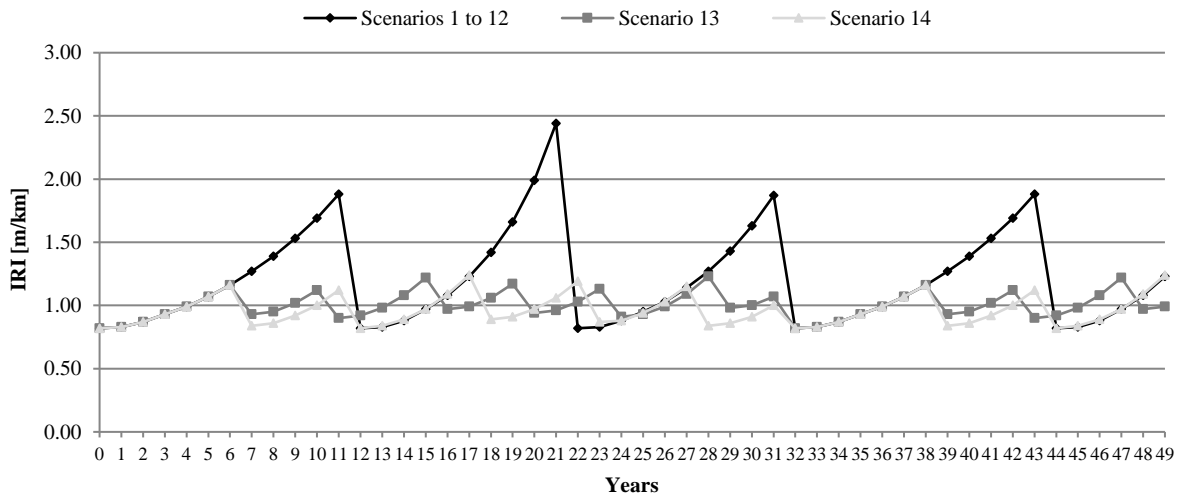


Figure 1. IRI over the PAP resulting from the implementation of the alternatives M&R scenarios.

4.3.3. System boundaries, system processes, life cycle inventory data and main assumptions

The proposed pavement LCC-LCA model entails six pavement life cycle phases: (1) materials extraction and production, (2) construction and M&R, (3) transportation of materials, (4) WZ traffic management, (5) usage, and (6) EOL. These phases were broken down into multiple components for each life cycle phase.

The environmental burdens and costs of planning, research, design activities, purchase of necessary rights-of-way, relocating utilities, constructing the roadway cuts and fills, and placing major drainage features for the mainline were not included into the system boundaries since the majority of those items regards to the whole road infrastructure and are either not exclusive to the pavement structure or entail a high level of subjectivity. Also excluded from the system boundaries were the environmental burdens due to labor. Furthermore, with regard to economic modelling performance, only real monetary flows were accounted for in order to avoid double counting the environmental impacts (Swarr *et al.* 2011).

The various models evoked while modelling each component of the pavement life cycle phases, as well as the main data required to run those models, are introduced and discussed in the following sections. Further details on the process-based LCA modelling considerations can be found in Santos *et al.* (2014). Detailed inventory data and complementary assumptions performed throughout the model application are shown in the electronic supplementary materials.

4.3.3.1. *Environmental dimension*

4.3.3.1.1 Materials extraction and production phase

This pavement LCA phase addresses the environmental burdens arising from the acquisition and processing of the materials applied during the initial construction and future M&R of a road pavement segment. This includes all materials manufacturing processes, from extraction of raw materials to their transformation into a pavement input material (material extraction sub-phase), ending with the mixture production at a mixing plant (materials production sub-phase). The latter sub-phase accounts for the environmental burdens associated with the operation of the (1) mixing plant (i.e. dryer, hot screen, mixers, etc.), (2) wheel loader during the movement of aggregates from the stockpiles to the feed bins, and (3) RAP processing unit so that the RAP ensures the required properties to be incorporated into a new asphalt mixture.

4.3.3.1.1.1 *Materials extraction sub- phase*

Process-based LCI data collected from several published LCI and LCA reports was adopted in this case study for modelling the LCI of the following materials: fine and coarse aggregates (Stripple 2001), bitumen and asphalt emulsion (Eurobitume 2011), and tap water (Weidema *et al.* 2013). On the other hand, the LCI data for the following materials was obtained through the IO-LCI approach: hydrated lime, SBR, WMA additive (Sasobit®). Information about the economic sectors responsible for manufacturing the previously mentioned materials are presented in Table 7.

As far as the system boundaries for RAP are concerned, it is assumed that prior to its utilization the material is processed via a crushing operation, which reduces the variable RAP fragments to uniform size in order to promote final blend consistency. The environmental burdens resulting from milling the pavement and hauling the RAP materials from the work site to the recycling unit were attributed to the previous pavement. To accomplish the RAP processing task, a crusher unit located within the asphalt plant facility is considered, which consists of diesel-powered crusher (model Cone LS1200 from Kolberg-Pioneer, Inc.), a diesel-powered mobile screening plant (model FNG 2612D from Kolberg-Pioneer, Inc.), an electrically-powered stackable conveyor (model 47-3050S from Kolberg-Pioneer, Inc.) and a wheel loader (model 924HZ from Caterpillar). Based on the technical features of the equipment, a RAP processing capacity of 184 tons per hour was considered. The environmental burdens from processing RAP are those resulting from the operation of the engines and were obtained by applying the methodology adopted by the United States Environmental Protection Agency's (US EPA) NONROAD 2008 model (US EPA 2010a). However, the crusher units also emit fugitive particulate matter (PM) when processing RAP. The total emissions of fugitive PM released when crushing and

screening RAP were determined from the Crushed Stone Processing and Pulverized Mineral Processing section of the U.S. EPA's AP-42: Compilation of Air Pollutant Emission Factors (US EPA 2004).

Table 7. I-O LCI data sources (CMUGDI 2008).

Pavement life cycle phase(s)	Element name	Sector ID and name	Notes
Materials	Hydrated lime manufacturing	327410 Lime and gypsum product manufacturing ^a	
	Styrene Butadiene Rubber (SBR) manufacturing	325110 Petrochemical Manufacturing ^a	
	Sasobit® manufacturing	325110 Petrochemical Manufacturing ^a	
	Setup manufacturing	333120 Construction Machinery Manufacturing ^b	Proxy
	Auxiliary equipment manufacturing	333120 Construction Machinery Manufacturing ^b	
	planned maintenance (FOG)	324191 Petroleum lubricating oil and grease manufacturing ^b	
	Repair	811300 Commercial and industrial machinery and equipment repair and maintenance ^b	
	Interest on loan	532400 Construction, Transportation, Mining, and Forestry Machinery and Equipment Rental and Leasing ^b	
	Asset insurance	524100 Insurance Carriers ^b	
	Taxes on property	541200 Accounting, tax preparation, bookkeeping, and payroll services ^b	proxy
	Manufacturing	333120 Construction Machinery Manufacturing ^b	
	Planned maintenance (FOG)	324191 Petroleum lubricating oil and grease manufacturing ^b	
	Repair	811300 Commercial and industrial machinery and equipment repair and maintenance ^b	
	Tyres manufacturing	326210 Tire Manufacturing ^b	
	special wear item manufacturing	333120 Construction Machinery Manufacturing ^b	proxy
Construction and M&R	Interest on loan	532400 Construction, Transportation, Mining, and Forestry Machinery and Equipment Rental and Leasing ^b	
	Asset insurance	524100 Insurance Carriers ^b	
	Taxes on property	541200 Accounting, tax preparation, bookkeeping, and payroll services ^b	proxy
Transportation of materials	Manufacturing	336120 Heavy Duty Truck manufacturing ^b	
	planned maintenance (FOG)	324191 Petroleum lubricating oil and grease manufacturing ^b	
	Repair	8111 Automotive repair and maintenance, except car washes ^b	proxy
	Tyres manufacturing	326210 Tire Manufacturing ^b	
	Interest on loan	532400 Construction, Transportation, Mining, and Forestry Machinery and Equipment Rental and Leasing ^b	
	Asset insurance	524100 Insurance Carriers ^b	
	Taxes on property	541200 Accounting, tax preparation, bookkeeping, and payroll services ^b	
WZ traffic management and Usage	Manufacturing	336111 Automobile manufacturing ^b	
	Maintenance and repair	8111 Automotive repair and maintenance, except car washes ^b	
	Tyres manufacturing	326210 Tire Manufacturing ^b	
	Oil manufacturing	324191 Petroleum lubricating oil and grease manufacturing ^b	
	Heavy	336120 Heavy Duty Truck manufacturing ^b	

Maintenance and repair	8111 Automotive repair and maintenance, except car washes ^b
Tyres manufacturing	326210 Tire Manufacturing ^b
Oil manufacturing	324191 Petroleum lubricating oil and grease manufacturing ^b

^aUS 2002 (428 sector) Producer Price Model. The monetary value used as input into the EIO-LCA model was obtained from the retail price but discounting 15% to account for sales markups.

^bUS 2002 (428 sector) Consumer Price Model.

4.3.3.1.1.2 Materials production sub-phase

This section addresses the LCI of the asphalt production process by considering different types of mixes, both with and without different RAP content. In this case study it was assumed that all asphalt mixes were produced through a natural gas-fired conventional drum-mix plant. In a conventional drum mix plant, RAP is not heated directly to prevent additional aging of RAP binder. Instead, the virgin aggregates are previously superheated so that when the RAP is introduced into the drum they dry and heat the RAP by conduction. However, such a superheating temperature is likely to cause additional energy consumption, which may eventually offset the economic and environmental benefits associated with the use of RAP.

In order to capture these tradeoffs along with the sensitivity of the air emissions due to the variations in composition and manufacturing temperature of the mixes and the moisture content of the raw materials, the heat energy required to produce the asphalt mixes was determined through an energy balance represented by Equation (3).

$$Q = \frac{\sum_{i=0}^M m_i \times \int_{T_{oi}}^{T_{fi}} c_i(T) dT + L_v \times (m_{wvf} - m_{wvo})}{HeatingEffF} \quad (3)$$

where Q is the heat energy required to produce the asphalt mixture (J), m_i is the mass of material i (kg), M is the total number of materials, including water, T_{fi} is the final temperature of material i (°C), T_{oi} is the initial temperature of material i (°C), $c_i(T)$ is the specific heat capacity coefficient, as a function of temperature, of material i [J/(kg°C)], L_v is the latent heat required to evaporate water (2256 J/kg), m_{wvf} is the initial mass of water vapor (kg), m_{wvo} is the final mass of water vapor (kg), and $HeatingEffF$ is a factor that represents the casing losses.

To account for the fact that specific heat capacities of minerals and fluids increase substantially with temperature, the equations presented by Waples and Waples (2004a and 2004b) were adopted, taking the temperature of 20°C as the reference temperature. The heating requirements for the aggregates applied in bound layers other than surface layers were modeled by considering the specific heat value of limestone [880 J/(kg°C)]. In the case of the surface layers, the value for quartzite [1013 J/(kg°C)] and diabase [860 J/(kg°C)] were taken to represent the aggregated used in the SM-type mixes and THMACO, respectively. With regard to binder and water, the third equation proposed by Gambill (1957) and the equation developed by Somerton (1992), both cited and displayed in Waples and Waples (2004b), were adopted, respectively. The initial moisture content of fine and coarse aggregates were assumed to be 1% and 3% (Harder 2008), whereas for RAP a value of 4% was considered. As for the $HeatingEffF$, a value of 80% was adopted for the production of all mix types after calibrating the model with the data corresponding to the HMA production in the case study of Munster, Indiana, reported by West *et al.* (2014). The HMA mixing temperature was set at 160°C (Asphalt Pavement Environmental

Council 2000) and the initial temperature of all raw materials other than bitumen was assumed to be equal to the ambient temperature of 15°C. In the case of the latter, it was considered that it remains stored at 160°C in heated tanks located in the asphalt plant facility. The volume of natural gas required to heat the insulated storage tanks was calculated based on the total quantity of binder heated, the total time the bitumen spends in the tanks throughout the paving season and the heat capacity of the tanks (Tables 1, 2 and 3 in supplementary material). As for the WMA, whose mix design was considered the same as that of the homologous HMA, it was assumed that the addition of 1.5% of Sasobit® per mass of bitumen reduces the mixing temperature by 25°C in relation to the reference temperature of 160°C. This assumption was based on the range values of reduction of temperature of 20-30°C commonly referred to in the literature (D'Angelo *et al.* 2008, Rubio *et al.* 2012, Zhao and Guo 2012). Moreover, it was also assumed that the RAP used in WMA can be blended with new asphalt binder at this lower temperature.

In order to determine the air emissions resulting from the mixing process of all mixes considered in this case study, a methodology was developed based on the emission factors (EFs) published by the AP-42 study of hot-mix asphalt (HMA) plants (US EPA 2004) corresponding to a natural gas-fired filter-controlled drum-mix plan, and the thermal energy required to produce the asphalt mixes. Firstly, the average EFs referring to the production of a HMA with 0% RAP were taken as reference. Secondly, as the CO₂ emissions primarily result from fuel combustion, the average emission of this GHG was combined with the fuel emission coefficient (53.1 Kg/MMBtu) reported by United States Energy Information Agency (EIA) to determine the quantity of natural gas whose combustion would release the same amount of CO₂ (US EIA 2013). Thirdly, for each mix an EF multiplier was determined through the ratio between the thermal energy computed with Equation (3) and the thermal energy calculated according to the procedures previously described. Finally, GHG and air pollutant EFs from mixes production were derived by multiplying the EFs taken as reference by the EF multipliers. The values of the EF multipliers as well as the natural gas consumption requirements for producing all mixes considered in this case study are shown in Table 8. The natural gas consumption reported in this table was complemented with the consumption of electricity to account for the operation of the electric components of the asphalt plant setup, e.g. conveyor, screens, etc. (Stripple 2001).

Table 8. Natural gas consumption requirements for producing the asphalt mixes and EF multiplier values.

Type of mix	Natural gas consumption ^a		EF multiplier	Natural gas consumption ^b	
	MJ	m ³		MJ	m ³
Reference mix	247	6.74	1	-	-
HMA: BM - 25.0 D, 0% RAP	217	5.93	0.880	225	6.15
HMA: IM - 19.0 D, 0% RAP	219	5.99	0.888	228	6.23
HMA: SM - 12.5 D, 0% RAP	245	6.69	0.992	254	6.94
THMACO	218	5.95	0.882	226	6.18
HMA: BM - 25.0 D, 15% RAP	229	6.26	0.929	236	6.44
HMA: IM - 19.0 D, 15% RAP	228	6.23	0.924	236	6.43
HMA: SM - 12.5 D, 15% RAP	254	6.93	1.028	262	7.16
HMA: BM - 25.0 D, 30% RAP	242	6.59	0.978	247	6.74
HMA: IM - 19.0 D, 30% RAP	244	6.65	0.987	250	6.82
HMA: SM - 12.5 D, 30% RAP	270	7.36	1.091	276	7.55
WMA: BM - 25.0 D, 0% RAP	181	4.94	0.733	189	5.15
WMA: IM - 19.0 D, 0% RAP	183	4.99	0.740	191	5.22
WMA: SM - 12.5 D, 0% RAP	203	5.55	0.823	213	5.81
WMA: BM - 25.0 D, 15% RAP	193	5.27	0.781	199	5.45
WMA: IM - 19.0 D, 15% RAP	195	5.32	0.788	202	5.52
WMA: SM - 12.5 D, 15% RAP	215	5.88	0.872	224	6.11
WMA: BM - 25.0 D, 30% RAP	205	5.60	0.830	210	5.74

WMA: IM - 19.0 D, 30% RAP	207	5.65	0.837	213	5.81
WMA: SM - 12.5 D, 30% RAP	228	6.21	0.921	235	6.40

^aIt does not include the requirements for heating the insulated bitumen storage tanks.

^bIt includes the requirements for heating the insulated bitumen storage tanks.

Emissions and energy consumption due to the operation of the wheel loader at asphalt the plant facility were estimated based on the rate at which the wheel loader can move aggregates (Santos *et al.* 2014) and the methodology adopted by the US EPA's NONROAD 2008 model (US EPA 2010a).

In addition to the process-based components described throughout this section, the IO-LCI approach was adopted to estimate the environmental burdens associated with the manufacturing, repair, maintenance, interest on loan and insurance of the asphalt plant setup and auxiliary equipment (Table 7). The amortization of the environmental burdens was done by applying the portion of the asphalt plant setup and auxiliary equipment's depreciation that was actually allocated to the quantity of asphalt mixes consumed in a given construction activity and considering the average annual production of asphalt mixes. For example, if the annual depreciation of the asphalt plant setup is \$150,000, the average annual production of asphalt mixes in 2011 is 114,000 tonnes (Hansen and Copeland 2014) and the quantity of asphalt mixes to be consumed in the construction activity is 1,000 tonnes, then $(150,000/114,000) \times 1,000 = \$1,360$ is the economic value that will be input into the EIO-LCA model to determine the environmental burdens resulting from the manufacturing of asphalt plant that will be allocated to the construction activity considered. A similar approach was adopted in the construction, M&R and transportation of materials phases for determining the environmental burdens associated with the construction equipment and hauling trucks, but taking as allocation factors the number of usage hours and hauling kilometers travelled to undertake a given construction activity.

4.3.3.1.2 Construction and M&R phase

In the construction and M&R phase, the process-based environmental burdens are due to the combustion-related emissions from construction equipment usage and were obtained by applying the methodology adopted by the US EPA's NONROAD 2008 model (US EPA 2010a). Information regarding the type and features (e.g. brand, model, engine horsepower, etc.) of each equipment used to perform the several construction and M&R activities, as well as their respective production rates were taken from the technical specifications provided by the equipment's manufacturers and complemented with the literature (US Army Corps of Engineers 2011, Caterpillar Inc. 2012).

In addition to the process-based components presented previously, the IO-LCI approach was adopted to estimate the environmental burdens associated with the equipment manufacturing, repair, maintenance, fuel, oil and greases (FOG) consumption, interest on loan, asset insurance, taxes on property, special wear items consumption and tire consumption of the equipment that define the construction or M&R process being considered (Table 7).

In this section it is worth mentioning that the operating conditions of paving machines were considered the same, regardless of the type of asphalt mix considered, i.e. HMA or WMA. Although a reduction in the number of roller passes needed to achieve a specified density was theoretically expected due to the lower viscosity of WMA (Rubio *et al.* 2012, Zaumanis 2014), there is no accurate and consistent scientific knowledge in the literature on the close relation between the reduction of the compactive effort required, in terms of roller passes, and the enhancement of WMA workability.

4.3.3.1.3 Transportation of materials phase

The process-based environmental impacts resulting from the materials and mixture transportation are due to the combustion process emissions released by the transportation vehicles. All materials and mixtures were assumed to be hauled by heavy-duty vehicles (HDVs). The US EPA's Motor Vehicle Emissions Simulator (MOVES) (US EPA 2010b) was used to determine the average fuel consumption

and airborne emissions factors for operating diesel powered, single unit short-haul trucks and long-haul combination trucks. The IO-LCI components considered in this pavement life cycle phase can be found in Table 7.

4.3.3.1.4 WZ traffic management phase

This pavement life cycle phase accounts for the fuel consumption and airborne emissions resulting from on-road vehicles traversing and detouring a work zone (WZ). It was assumed that whenever a WZ is in place, all vehicles will take a 10km detour on a lower hierarchical level road at a speed 15 mph lower than the normal operating speed of 70 mph (112 km/h). The environmental burdens were calculated by adopting a process-based two-step method. First, the US EPA's MOVES model was run multiple times to compute a set of fuel consumption factors (FCFs) and airborne EFs on an hourly basis as a function of sixteen speed ranges. Second, the changes in traffic flow were estimated using the Highway Capacity Manual 2000 (Transportation Research Board [TRB] 2000) to determine several outputs, such as the number of vehicles that traversed the WZ, the average queue length, the average queue speed in each hour, etc. Once the changes in driving patterns were determined, they were combined with the FCFs and tailpipe vehicle EFs previously computed and stored in look up tables to derive the environmental load of a WZ day.

Finally, the marginal fuel consumption and airborne emissions due to the WZ traffic management plan were calculated by subtracting fuel consumption and airborne emissions released during a WZ period from the results of an equivalent non-WZ period. The same methodology was adopted to calculate the IO-LCI components shown in Table 7.

4.3.3.1.5 Usage phase

The usage phase addresses the pavement's environmental burden resulting from the interaction of the pavement with the vehicles, environment and humans throughout its PAP. Among the factors that have been identified in past research as being worthy of consideration during the usage phase of the pavement (i.e. tire-pavement interaction, traffic flow, albedo, leachate and runoff, carbonation and lighting) only the contribution from the tire-pavement interaction, namely the pavement roughness, was taken into account in this analysis. The rationale for this decision lies with the fact that the remaining components either do not apply to the features of the case study under evaluation or lack well established and consistent scientific background. In order to determine the influence of the pavement roughness on vehicle FC and tailpipe emissions, the HDM-4 fuel consumption model (Bennett and Greenwood 2003), calibrated and validated for US conditions by Chatti and Zaabar (2012), was combined with data from the US EPA's MOVES model according to the approach proposed by Santos *et al.* (2014a). As far as the IO-LCI components are concerned, the environmental burdens related to the following items were considered: on-road vehicles manufacturing, maintenance and repair and tire consumption (Table 7).

4.3.3.1.6 End-of-life phase

Given the hierarchical level of the road under consideration the most likely EOL scenario for the pavement section in this analysis is that it will remain in place after reaching the end of the PAP, serving as the foundation for the new pavement structure. Thus, in order to model this pavement life cycle phase a 'cut-off' allocation method was adopted. According to this allocation method, each product is assigned only the burdens directly associated with it (Nicholson 2009). Therefore, no environmental burdens were assigned to the EOL phase of all alternative scenarios.

4.3.3.1.7 Energy Production

Although it is not considered a pavement life cycle phase, as are those previously introduced, energy source production and transportation is an unavoidable process that is common to all pavement life cycle phases. In this case study, the GREET model (Argonne National Laboratory 2013) was used as

the source of the LCI for the production and delivery of energy sources. For all energy sources except electricity, the GREET model default data was used. In the case of electricity, a default electricity mix was modified to reflect the electricity production in the state of Virginia (US EIA 2012).

4.3.3.2. *Economic dimension*

4.3.3.2.1 Materials extraction and production phase

This phase accounts for the costs incurred by the highway agency in producing the mixtures to be applied during the construction and M&R phases. Materials extraction and production phase costs were divided into three main categories: (1) raw materials costs, (2) energy sources costs and (3) asphalt plant operating costs. The last category was further divided into fixed and variable costs sub-categories.

In this section, it should be mentioned that a change in the price of the virgin asphalt binder was considered when a RAP percentage of 30% was used in the mixes due to the lower PG category of the asphalt binder used in those circumstances (VDOT 2012a).

4.3.3.2.2 Construction and M&R phase

The construction and M&R phase costs represent the costs incurred by the highway agency during the actual performance of a construction or M&R activity at a particular work site on a specific day and time. They include the construction equipment owning costs (depreciation, interest, insurance, taxes on property and allocation to work site), the construction equipment operation costs (fuel consumption, planned maintenance and FOG, repair, tire consumption and special wear items) and the labor costs corresponding to the wages and benefits paid to the crew members for the work performed at a work place. The materials costs, as well as the costs associated with the hauling movements required to deliver the materials from the point of production to their destinations are accounted for in individual phases. Data required for computing the various subcategories of construction equipment owning and operating costs were collected for each piece of equipment according to the information made available by equipment manufacturers, suppliers and dealers, or existing in the literature (US Army Corps of Engineers 2011, Caterpillar Inc. 2012). The number of workers needed to carry out the several M&R actions for a given M&R activity was estimated according to data gathered in the field during visits to similar recycling projects, or existing in the literature (European Asphalt Pavement Association and National Asphalt Pavement Association 2011).

4.3.3.2.3 Transportation of materials phase

The theoretical economic advantage of recycling-based construction and M&R practices is strongly affected by material transportation costs and how those costs compare to the cost of new virgin materials delivered to the construction site. Thus, unlike the majority of the LCC models existing in the literature, the proposed LCC model presents the costs incurred by the highway agencies due to the transportation of the materials separated out from the remaining categories that constitute the total delivery price.

As with construction and M&R phase costs, three main cost categories were considered: (1) hauling trucks owning costs (depreciation, interest, insurance and taxes on property), (2) hauling trucks operation costs (fuel consumption, planned maintenance and FOG, repair, tire consumption and special wear items) and (3) labor costs (hauling truck drivers' wages and benefits).

4.3.3.2.4 WZ traffic management phase

The WZ traffic management costs consist of the additional costs borne by the road users (RUC) when facing a disruption of the normal traffic flow as a consequence of the constraints imposed by a WZ traffic management plan. In this LCC model the following WZ traffic management costs categories were considered: (1) time delay costs (TDCs) and (2) vehicle operating costs (VOCs). Accident costs, typically considered as another WZ RUC category, were disregarded due to the high level of uncertainty

associated with the factors that might determine their occurrence (which are often related with driver errors and other factors not related with the WZ).

4.3.3.2.5 Usage phase

The usage phase costs, frequently named non-WZ RUC, account for the marginal VOCs supported by the vehicle drivers throughout the PAP as a consequence of the deterioration of the pavement condition. In the proposed LCC sub-model, the pavement roughness, as measured by the IRI, was used to estimate the RUC associated with the overall pavement surface condition. The following costs categories were considered to be contributors to the total usage phase costs: (1) fuel consumption, (2) tire wear, (3) vehicle maintenance and repair and (4) mileage-related vehicle depreciation. The first three costs categories were estimated by adopting the VOCs model developed by Chatti and Zaabar (2012). The effect of the pavement roughness on vehicle depreciation costs was determined according to the methodology presented by Barnes and Langworthy (2003).

4.3.3.2.6 End-of-life phase

In the case study, the most likely EOL scenario for the analyzed pavement structure is that it will remain in place after reaching the end of the PAP, serving as the foundation for the new pavement structure. Thus, the residual value of the pavement structure is given by the value of its remaining service life. The service life of the pavement was assumed to end when the CCI exceeds the value of 49, which according to the VDOT's Highway System Performance Dashboard (VDOT 2012b) corresponds to the threshold ($CCI_{Terminal}$) beyond which a ride is classified as "very poor".

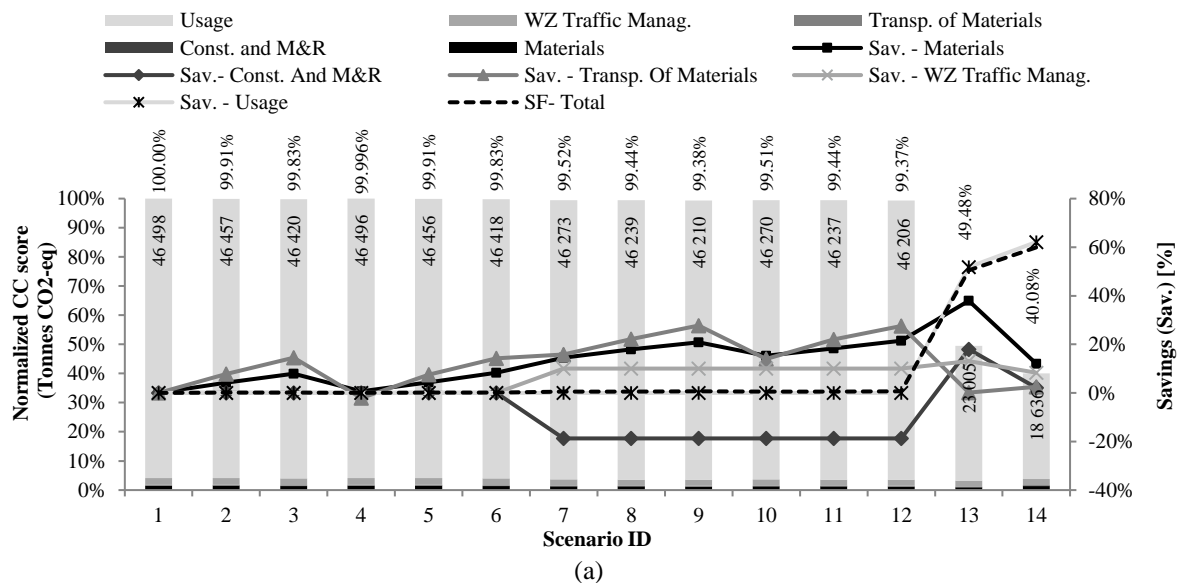
In order to compute the value of the remaining service life, and thus, the residual value of the pavement at end of the PAP, Equation (4) was adopted. It quantifies the residual value of the pavement as the proportion of the total highway agency costs incurred due to the application of the last M&R activity equal to the proportion of the remaining life of that M&R activity (Walls and Smith 1998).

$$C_{EOL\ phase} = C_{Last\ M\ \&\ R\ activity} \times \frac{CCI_{EOL} - CCI_{Terminal}}{100 - CCI_{Terminal}} \quad (4)$$

where $C_{Last\ M\ \&\ R\ activity}$ is the total highway agency cost resulting from the application of the last M&R activity. It is obtained by summing up the costs incurred by the highway agency during the materials, M&R and transportation of materials phases associated with the last M&R activity; CCI_{EOL} is the CCI of the pavement at the end of the PAP; and $CCI_{Terminal}$ is the CCI value beyond which a ride is classified as "very poor".

4.4. Life cycle impacts assessment

The US-based impact assessment methodology, the Tool for the Reduction and Assessment of Chemical and other environmental Impacts 2.0 - TRACI 2.0 (Bare *et al.* 2011) from the US EPA, was adopted in this study to conduct the impact assessment step of the LCA on the basis of obtained inventory as compiled in the previous step. The TRACI impact categories used in the analysis include: acidification air (AC), eutrophication air (EU), human health criteria pollutants (HH) and photochemical smog formation (PSF). The time-adjusted characterization model for the climate change (CC) impact category that was proposed by Kendall (2012) was used, as opposed to the traditional time-steady International Panel on Climate Change model. Furthermore, three energy-based indicators were also included in the assessment: (1) primary energy obtained from fossil resources, (2) primary energy



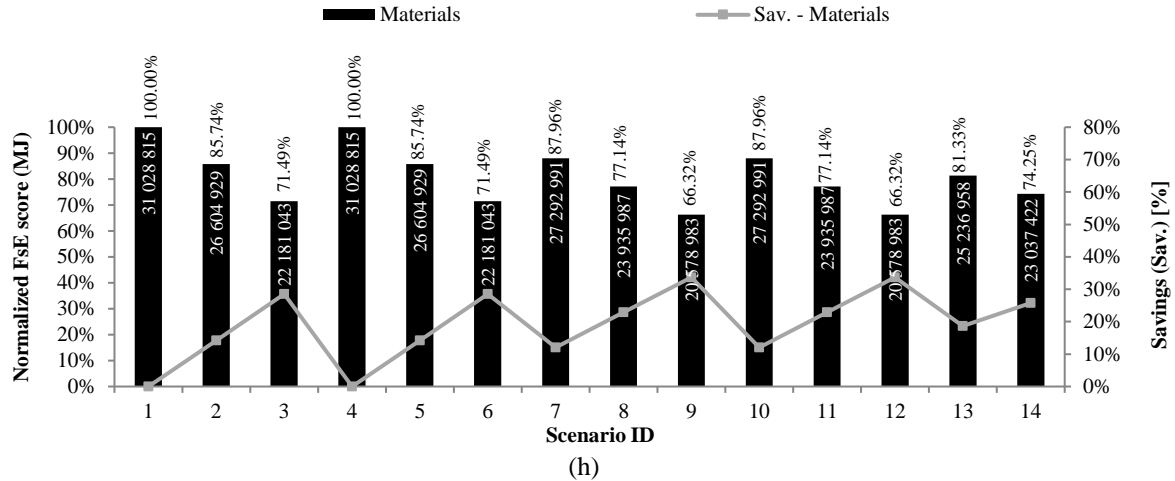


Figure 2. Life cycle impact assessment results: (a) CC, (b) AC, (c) EU, (d) HH, (e) PSF, (f) FoPE, (g) NFoPE and (h) FsE.

These results clearly indicate that scenario 14 (preventive maintenance: THMACO) is the least harmful to the environment, as it was found to be responsible for the lowest impact in seven out of eight impact categories. Compared to scenario 1, a reduction in all impacts ranging from 25.75% (FsE) to 60.09% (EU) can be achieved as a result of implementing the THMACO-based preventive M&R strategy. Similar overall reductions might be obtained through the microsurfacing-based preventive M&R scenario that denotes the second best environmental performance. Although latter preventive M&R scenario outperforms the former in all pavement life cycle phases other than the usage phase, the fact that the application of a THMACO results in a greater improvement in the pavement condition, along with the key role played by the usage phase in driving the environmental performance of a pavement system, explains the greater reduction in environmental impact associated with the implementation of scenario 14.

Contrary to the merits exhibited by the preventive maintenance scenarios, the scenarios consisting of implementing the VDOT M&R strategy are those that present the highest environmental impact. In particular, scenario 1 (VDOT M&R strategy: HMA - 0% RAP) entails the highest environmental impact for six out of eight impact and energy demand categories. However, it is worth mentioning that this result should not be seen as conclusive with regard to the disadvantage of conventional mixtures over WMA, since the environmental burdens that scenario 1 originate are quite similar to those of the scenario 4 (VDOT M&R strategy: WMA - 0% RAP) and do not show a steady pattern of improvement or deterioration of the environmental performance across all impact categories. For instance, examining the lines in Figure 2(a), which display the savings of emissions of CO₂-eq incurred during the materials phases, one can see that the difference between the aforementioned scenarios is just 0.69%. This difference might be even negative, meaning a decay of the environmental performance, if the AC impact category is taken as example (-1.08%). Such residual and contradictory values mean that for the conditions considered in this case study, the overall impacts of WMA are almost equal to those of HMA with the same RAP content, and a general conclusion on which type of mix is environmentally preferable cannot be drawn. Therefore, one noteworthy outcome of this case study is that the decrease in the impacts of WMA due to the reduction of production temperature is offset by the increase in the impacts due to the production of Sasobit®, despite its small proportion in mixture composition. Furthermore, even if the lower compacting efforts associated with the WMA were taken into account, there would be no meaningful change in the environmental performance of the system under analysis, as the environmental burdens associated with the operation of construction equipment have a relatively small impact over the life of a pavement.

Regarding the environmental benefits resulting from incorporating RAP in asphalt mixtures, the comparison of scenarios involving the application of the same type of mixture but with different RAP contents shows that the environmental impacts can be reduced by as much as 17% (AC due to materials phase) and 29% (FsE). Overall, in relative terms, the greatest advantage stems from the transportation of materials phase, while in absolute terms the materials phase plays the most important role in lowering the overall environmental impact.

As far as the potential environmental benefits of implementing recycling-based M&R activities, as opposed to the conventional M&R practices, are concerned, Figures 2(a) to 2(h) show considerable environmental impact reductions across all categories. The maximum environmental burden reduction can be as high as 18% and was observed in the EU and NFoPE impact categories of the materials phase. In absolute terms, the majority of the environmental benefits spring from WZ traffic management, followed by the materials and transportation of materials phases, respectively. Despite the overall benefits associated with the implementation of the Recycling-based VDOT strategies (scenarios 7 to 12), it should be noted that the construction and M&R phases of those scenarios present the poorest environmental performance among competing scenarios. The reason for this outcome lies with the fact that the implementation of recycling-based M&R activities requires the use of heavy construction equipment with high-rated power engines.

5.2. Life cycle costs analysis

Figures 3(a) shows the normalized highway agency life cycle costs corresponding to the alternative scenarios. Each scenario is normalized by the net highway agency life cycle cost observed in the first scenario. In addition, for each pavement life cycle phase, the relative savings in relation to the homologous phase of scenario 1 are presented. Complementarily, the absolute value of the net highway agency life cycle costs are illustrated through the labels placed right below the top of the bars.

From the analysis of Figure 3(a), it can be seen that overall, the recycling-based VDOT scenarios are the most advantageous from the highway agency's perspective. Four out of six scenarios rank in the top six of the least expensive, with scenario 9 (recycling-based VDOT strategy: HMA - 30 % RAP) being the one that allows highway agencies the greatest life cycle savings. A reduction of approximately 26% of the net highway agency life cycle costs can be achieved if this scenario is implemented instead of the first one. The contributions to the reduction of the net highway agency life cycle costs for the scenario 9 come from the materials (30%) and transportation of materials (25%) phases. Despite the overall benefits resulting from implementing recycling-based VDOT scenarios, their construction and M&R phases have the poorest performance among competing scenarios. This is because undertaking recycling-based M&R activities requires the use of heavy construction equipment which commonly incurs high owning and operating costs.

In contrast, scenario 4 (VDOT strategy: Sasobit® WMA - 0% RAP) is the least beneficial for the highway agency's interests, as it implies a slight increase in the life cycle costs of about 3% in relation to scenario 1. This result means that the benefits resulting from energy cost savings associated with the manufacturing of WMA were offset by the increased production costs related to the asphalt plant modifications, which in this case study, consisted of adding a pneumatic Sasobit® feeder to the default equipment existing in an asphalt plant facility, and the acquisition and transportation costs of the Sasobit®.

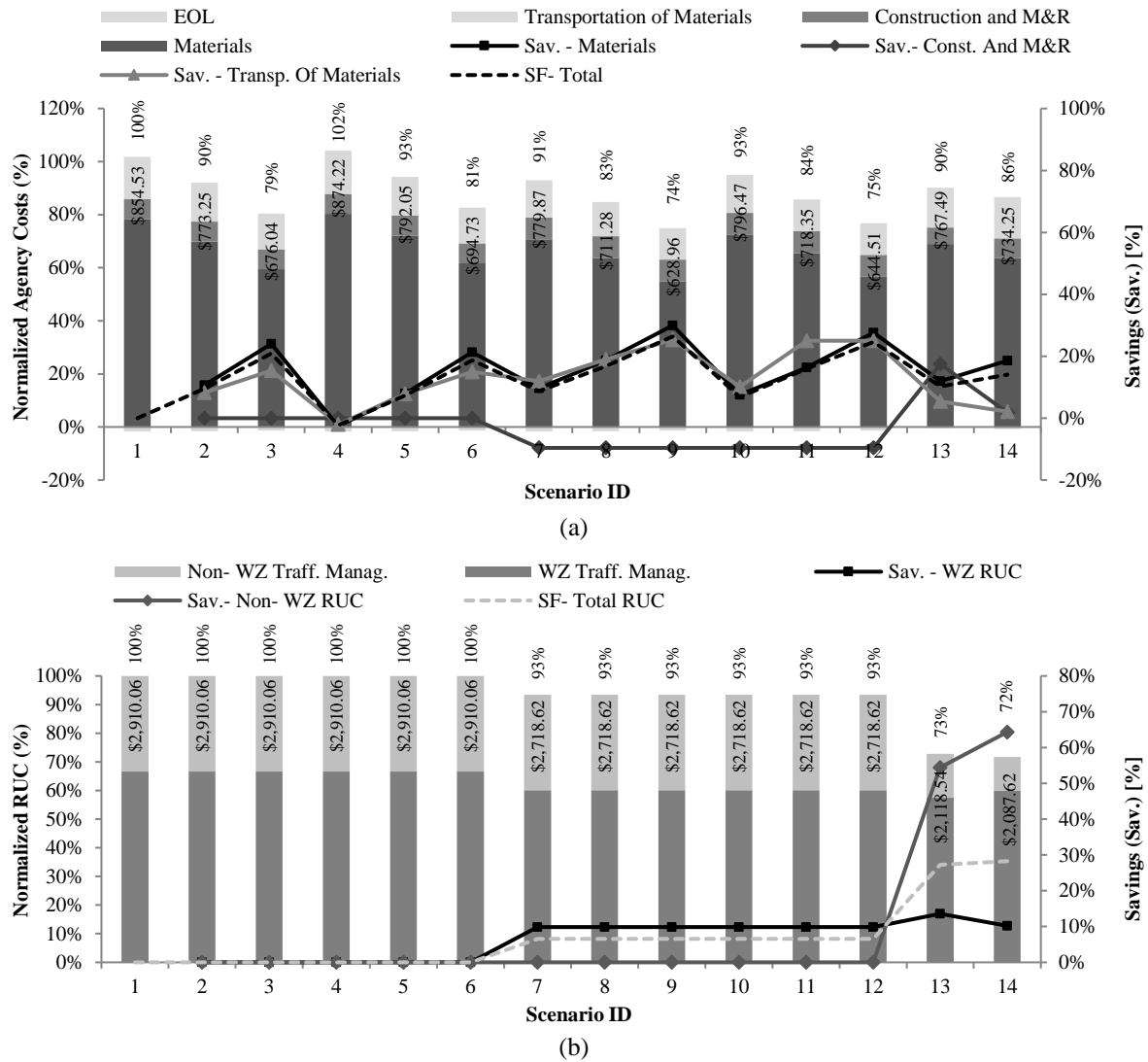


Figure 3. Life cycle costing results: (a) highway agency costs (HAC) and (b) road user costs (RUC).

As for the costs incurred by road users, Figure 3(b) shows the normalized life cycle RUC. Analogously to Figure 3(a), each scenario is normalized by the road user life cycle cost observed in the first scenario. The relative savings in relation to the homologous phase of scenario 1 and the absolute value of the road user life cycle costs, expressed in thousands of US dollars, are also presented in the same figure. Scenario 14 (preventive M&R strategy: THMACO) exhibits the lowest road user life cycle costs among alternatives, with a value of approximately \$2,087,624. This scenario is followed by the microsurfacing-based scenario, which imposes on road users a life cycle cost of about \$2,118,541. On the other hand, scenarios 1 to 6 demonstrate the highest costs for road users, with a life cycle value of approximately \$2,718,620. In comparing the contribution given by each type of RUC, Figure 3(b) shows that the percentage of non-WZ RUC in the total value incurred by these stakeholders ranges from 24 to 36%, with an average value of 27%.

5.3. Overall performance

In order to determine the preference order of alternative scenarios, a MCDA method was applied. Specifically, the TOPSIS method (Hwang and Yoon 1981) was chosen due to its (1) simple, rational and understandable concept; (2) straightforward computation; (3) ability to depict the relative performance of decision alternatives in a simple mathematical form (Anupam *et al.* 2014); and (4) broad

recognition and application in the construction sector (Jato-Espino *et al.* 2014). Three main criteria were considered: HAC, RUC and environmental impacts. The last criterion was further broken down into 8 sub-criteria, each representing one environmental impact category.

Depending on policy makers' preferences, different weights can be assigned to each criterion. This is a challenging task since there are often multiple decision-makers with different agendas and biases towards their interests. To elucidate decision-makers on the consequences of the weighting in the ranking of the alternative scenarios, a combinatorial weight assignment method was undertaken for the main criteria, while the weights assigned to the environmental sub-criteria remained unchangeable and equal to those adopted the US-based Building for Economic and Environmental Sustainability (BEES) software (Lippiatt 2007). Since the energy demand indicators considered in the proposed LCC-LCA model are not available in the BEES software, they were given a weight of 5 points each, as much as the weight assigned to the Fossil Fuel Depletion impact category considered in BEES software. All the weights assigned to the environmental sub-criteria were posteriorly rescaled, so that the sum of their values totals 100 points. Thus, in the MCDA, the final weight of each environmental sub-criterion is the value resulting from multiplying the weight of the main environmental criterion by the weight determined, as explained above.

The best scenario for all possible weighting combinations between the three main criteria is displayed in Figure 4 through a triangular diagram (Hofstetter *et al.* 1999, Graham and Midgley 2000). The axes are scaled so they increase in a clockwise direction around the diagram. Each point in the triangle area corresponds to a specific weighting set and the relative weights always add up to a total weight of 1 (or 100%). This leads to a graphical representation of superiority areas separated by indifference curves. Those curves comprise a set of points in the triangle where the scenarios being compared have the same ranking position. From the analysis of Figure 4 one can conclude that of the competing scenarios, only two (scenarios 9 and 14) have the potential to rank best. Of those, scenario 14 is the one that presents the largest area of superiority. If the decision is exclusively based on either environmental performance or RUC, scenario 14 ranks best. In turn, if the highway agency costs are the only criterion taken into account, then scenario 9 outperforms the remaining ones. This scenario is still the best compromise alternative if the highway agency costs are weighted more than approximately 60% and the RUC less than about 40%.

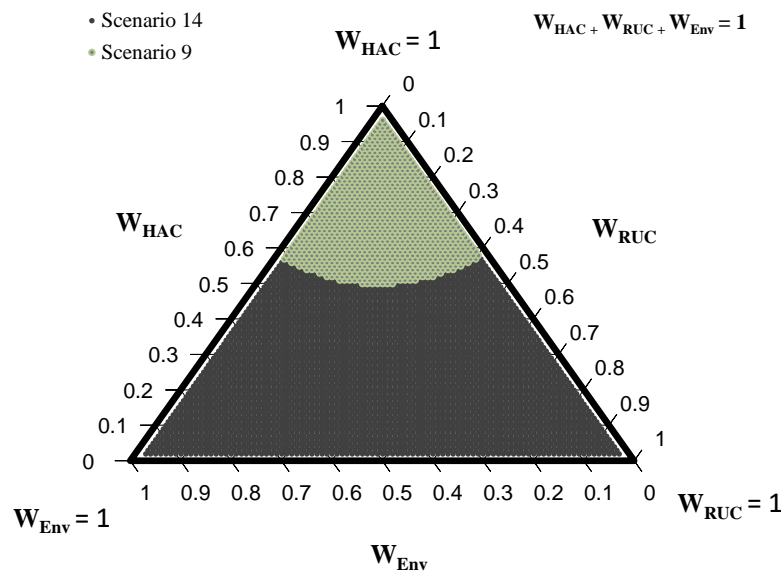


Figure 4. Best scenarios for all possible weighting combinations of the main criteria.

Note: W_{HAC} , weight assigned to highway agency costs; W_{RUC} , weight assigned to road user costs; W_{Env} , weight assigned to environmental impacts.

5.4. Key findings

From the methodology and results presented and discussed in the previous sections, the following findings are worth highlighting:

- THMACO-based preventive maintenance is the least harmful scenario to the environment, being responsible for the lowest impacts in the overwhelming majority of the categories. Compared to the scenario where only conventional materials and treatments are applied (scenario 1), a reduction in all impacts ranging from 25.75% (FsE) to 60.09% (EU) can be achieved as a result of implementing the THMACO-based preventive M&R strategy;
- The life cycle environmental impacts of WMA are identical to those of HMA with the same RAP content. The decrease in the impacts of WMA due to the reduction of production temperature is offset by the increase in the impacts due to the production of Sasobit®;
- Producing asphalt mixes with 30% of RAP allows environmental impacts to be reduced by as much as 17% (AC due to materials phase) and 29% (FsE). In relative terms, the greatest advantage springs from the transportation of materials phase, while in absolute terms the materials phase plays the most important role in lowering the overall environmental impact;
- Applying a recycling-based M&R strategy where the structural treatments are carried out through cold in-place recycling techniques leads to reduction in the environmental burdens of some pavement life cycle phases that can be as high as 18% in relation to those generated by an equivalent and conventional M&R strategy;
- Applying a conventional M&R strategy where the asphalt mixes are of type WMA with a 0% RAP content is the most costly strategy for the highway agency. On the other hand, implementing a recycling-based M&R strategy where the asphalt mixtures are of type HMA containing 30% of RAP (scenario 9) yields the greatest life cycle highway agency saving. Furthermore, these savings might be even greater than those achieved by implementing preventive maintenance strategies;
- The preventive maintenance strategies considered in this case study, i.e. THMACO and microsurfacing, bring to road users the most expressive reductions in the costs incurred by them, in addition to the greatest environmental performance;
- The recycling-based VDOT strategy, in which WMA- 30% RAP mixes are applied, is the best compromise solution if the importance given to RUC prevail over the HAC. Otherwise THMACO-based preventive maintenance is the scenario that best suits the interests of the stakeholders as a whole.

6. Summary and conclusions

A shift towards more environmentally and economically responsible behavior in the road pavement construction and management field triggered the need to develop and implement new pavement engineering solutions. Complementarily, a comprehensive and scope-wide assessment of the effectiveness of those solutions in achieving their intended objectives, requires the use of comprehensive life cycle modelling approaches, which provide valuable information for those in charge of making decisions.

Keeping this in mind, a comprehensive and integrated LCC-LCA model was developed and used to investigate the potential environmental and economic benefits resulting from applying in-plant recycling mixtures, WMA, cold in-place recycling and preventive treatments throughout the life cycle of a pavement structure. For the conditions considered in this case study, THMACO-based preventive maintenance was shown to be both more environmentally-friendly and more compliant with the road user's demands for an affordable road usage over its life cycle than the remaining technical solutions investigated. Moreover, this solution also revealed a superior overall performance when the interests of

all three stakeholders, meaning highway agency, highway users and the environment, were concomitantly taken into account in a MCDA. On the other hand, from the exclusive highway agency's point of view, implementing a recycling-based M&R strategy where the asphalt mixtures are of type HMA containing 30% of RAP was proven to be the least expensive.

Providing life cycle perspectives about the environmental and economic implications of implementing new pavement engineering solutions and management practices is doubtless an essential first step towards enhancing pavement infrastructure sustainability. However, it is no less true that decision making in a pavement management context is a much more complex exercise, where other variables and constraints came into play, so it cannot be efficiently conducted through the exclusive use of LCA and LCC approaches. Improved approaches for optimizing the selection of treatments, materials and application timings based on specific and often conflicting objectives and constraints are required. Thus, future work on this topic will focus on enhancing the potentialities and capabilities of the proposed LCC-LCA model by integrating it into a multi-objective optimization framework.

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