João Miguel Oliveira dos Santos

A COMPREHENSIVE LIFE CYCLE APPROACH FOR MANAGING PAVEMENT SYSTEMS

PhD Thesis in Doctoral Program in Transport Systems, supervised by Professor Adelino Ferreira and Professor Gerardo W. Flintsch, presented to the Department of Civil Engineering of the Faculty of Sciences and Technology of the University of Coimbra

December, 2015

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Universidade de Coimbra

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UNIVERSIDADE DE COIMBRA

To my parents

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POPH QUALIFICAR É CRESCER.

QREN QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL PORTUGAL 2007.2013

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List of Abbreviations

AADT - Annual Average Daily Traffic
$AADT_h$ - Annual Average Daily Heavy-Traffic
$AADT_0$ - Initial Annual Average Daily Traffic
AC - Asphalt Concrete
Ac - Acidification
ACO - Ant Colony Optimization
ADP FF - Abiotic Depletion Potential of Fossil Fuels
ADP MR - Abiotic Depletion Potential of Mineral Resources
AE - Accumulated Exceedance
AHGA - Adaptive Hybrid Genetic Algorithm
ALSOS - Adaptive Local Search Operator Selection
AM - Asset Management
AP - Adaptive Pursuit
ARD FF - Abiotic Resource Depletion of Fossil Fuels
ARD MR - Abiotic Resource Depletion of Mineral Resources
ASCE - American Society of Civil Engineers
ATRI - American Transportation Research Institute
BEA - Bureau of Economic Analysis
BEES - Building for Economic and Environmental Sustainability
BM - Base Mixture
BMC - Bituminous Materials Costs
BSFC - Brake Specific Fuel Consumption
BSM - Backward Shift Mutation
CaDM - Cauchy Distribution-based Mutation
CBR - California Bearing Ratio
CC - Climate Change
CCI - Critical Condition Index
CCPR - Cold Central Plant Recycling
CED - Cumulative Energy Demand
CED F - Cumulative Energy Demand: Fossil
CED PF - Cumulative Energy Demand: Primary Forest
CED RR - Cumulative Energy Demand: Renewable Resources
CF - Condition Factor
CH_4 - Metane

ChDM	- Chaotic Dynamic-based Mutation
CIR	- Cold In-place Recycling
CM	- Corrective Maintenance
CO	- Carbon Monoxide
CO_2	- Carbon Dioxide
CPI	- Consumer Prices Index
CUT	- Combination-Unit Truck
DBX	- Direction-based Crossover
DbC	- Database Class
DE	- Differential Evolution
DEEC	- Department of Energy & Climate Change
DelMut	- Delete Mutation
DGAB	- Dense Graded Aggregate Base
DM	- Decision-Maker
DN	- Do Nothing
DOT	- Department of Transportation
DRM	- Dynamic Random Mutation
DSS	- Decision-Support System
EA	- Evolutionary algorithms
EC	- European Commission
ECC	- Engineered Cementitious Composites
EF	- Emission Factor
EIO-LCA	- Economic Input-Output Life Cycle Assessment
EOL	- End-of-Life
EP	- Evolutionary Programming
ESAL	- Equivalent Single Axle Load
EU	- European Union
FC	- Fuel Consumption
FCF	- Fuel Consumption Factor
FDR	- Full Depth Reclamation
FHWA	- Federal Highway Administration
FIFO	- First-In First-Out
FIR	- Fitness Improvement Rate
FOG	- Filters, Oil and Greases
FoPE	- Fossil Primary Energy
FSM	- Forward Shift Mutation
FsE	- Feedstock Energy
GA	- Genetic Algorithm
GP	- Genetic Programming
GHG	- Greenhouse Gas

GREET - The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP - Global Warming Potential
HAC - Highway Agency Costs
HC - Hydrocarbons
HCM - Highway Capacity Manual
HDV - Heavy-Duty Vehicle
HERS-ST - Highway Economic Requirements System - State Version
HH - Human Health Criteria Pollutants
HMA - Hot-mix Asphalt
HT - Human Toxicity
HTP - Human Toxicity Potential
HWMA - Half-Warm Mix Asphalt
IEA - International Energy Agency
ILCD - International Reference Life Cycle Data System
IM - Intermediate Mixture
IPCC - Intergovernmental Panel on Climate Change
IRI - International Roughness Index
ISO - International Standard Organization
I-O - Input-Output
I-O LCA - Input-Output Life Cycle Assessment
I-O LCI - Input-Output Life Cycle Inventory
LCA - Life Cycle Assessment
LCC - Life Cycle Costs
LCCCsc - Life Cycle Climate Change Score
LCC-LCA - Life Cycle Costs - Life Cycle Assessment
LCCA - Life Cycle Costs Analysis
LCEI - Life Cycle Environmental Impacts
LCHAC - Life Cycle Highway Agency Costs
LCI - Life Cycle Inventory
LCIA - Life Cycle Impact Assessment
LCRUC - Life Cycle Road User Costs
LHV - Lower Heating Values
LPG - Liquefied Petroleum Gas
LS - Local Search
MA - Memetic Algorithms
MaOO - Many-objective Optimization
MCDM - Multi-Criteria Decision Making
MIRIAM - Models for rolling resistance In Road Infrastructure Asset Management Systems

MOGA	- Multi-Objective Genetic Algorithm
MOO	- Multi-Objective Optimization
MOVES	- Motor Vehicle Emissions Simulator
MPD	- Mean Profile Depth
MSI	- Modified Structural Index
MTD	- Mean Texture Depth
M&R	- Maintenance and Rehabilitation
NHS	- National Highway System
NMVOC	- Non-methane Volatile Organic Compounds
NO_x	- Nitrogen Oxide
NoPE	- Non-Fossil Primary Energy
NPV	- Net Present Value
N_2O	- Nitrous Oxide
O_3	- Ozone
OA	- Orthogonal Array
OC	- Other Classes
OFP	- Ozone Formation Potential
OGB	- Open Graded Base
OMB	- Office of Management and Budget
PAP	- Project Analysis Period
Pb	- Lead
PC	- Passenger Car
PLCPC	- Pavement Life Cycle Phase Class
PM	- Particulate Matter
$PM_{2.5}$	- Particulate Matter up to 10 micrometers in size
PMS	- Pavement Management System
POCP	- Photochemical Ozone Creation Potential
POF	- Photochemical Ozone Formation
PPI	- Producer Price Index
PPPM	- Pavement Performance Prediction Models
ProMat	- Probability Matching
PrM	- Preventative Maintenance
PSF	- Photochemical Smog Formation
PSI	- Present Serviceability Index
PSO	- Particle Swarm Optimization
PV	- Present Value
P-LCA	- Process-based Life Cycle Assessment
P-LCI	- Process-based Life Cycle Inventory
RAS	- Reclaimed Asphalt Shingles
RAP	- Reclaimed Asphalt Pavement

RC - Reconstruction
RL - Remaining Life
RM - Restorative Maintenance
RR - Rolling Resistance
RS - Ranking-based Selection
RUC - Road User Costs
Sb - Antimony
SBR - Styrene-Butadiene Rubber
SCI - Structural Capacity Index
SM - Surface Mixture
SMA - Stone Mastic Asphalt
SN - Structural Number
SOO - Single-Objective Optimization
SO_2 - Sulfur Dioxide
SPMS - Sustainable Pavement Management System
SRA - Strategic Research Agenda
SUT - Single-Unit Truck
SWM - Swap Mutation
TAWP - Time Adjusted Warming Potential
TDC - Time Delay Costs
TE - Terrestrial Eutrophication
THMACO - Thin Hot-mix Asphalt Concrete Overlay
TRACI - Tool for the Reduction and Assessment of Chemical and other environmental Impacts
UCPRC - University of California Pavement Research Center
UHV - Upper Heating Value
US - United States
US DOT - United States Department of Transportation
US DL - United States Department of Labour
US EIA - United Sates Energy Information Agency
US EPA - United States Environmental Protection Agency
US GS - United States Geological Survey
VB.NET - Visual Basic .NET
VDOT - Virginia Department of Transportation
VehOperC - Vehicle Operation Costs
VOC - Volatile Organic Compounds
WMA - Warm-mix Asphalt
WZ - Work-zone

Abstract

In a society where the public awareness of environmental protection is increasing remarkably and the availability of resources and funding is limited, it is more vital than ever that highway agencies and decision-makers (DMs) seek new tools that enable them to make the best and most rational use of these resources, taking into account environmental and social factors, along with economic and technical considerations. However, the traditional practices adopted by highway agencies with regards to pavement management, have mostly consisted of employing life cycle costs analysis (LCCA) systems to evaluate the overall long-term economic efficiency of competing pavement design and maintenance and rehabilitation (M&R) activity alternatives. This way of supporting the decision-making process, as it relates to pavement management, in which little or no importance is given to environmental considerations, does not seem to be effective in advancing sustainability in pavement systems. In view of this, it is clear there is an urgent need for pavement management decision-support systems (DSSs), which, by integrating multi-disciplinary and complementary pavement life cycle approaches, will enable the DMs to properly account for, consider and assess the cumulative and long-term impacts of their decisions and practices regarding sustainability goals and targets. This can only be achieved by employing techniques and tools with a comprehensive and wide-scoped cradle-to-grave analysis capacity.

This thesis presents a project-level optimization-based pavement management DSS, which includes several comprehensive stand-alone but logically interconnected pavement life cycle approaches. The following appraisal methods are presented: a life cycle assessment (LCA) model, a life cycle costs (LCC) model, an integrated LCC-LCA model, a single-objective life cycle optimization model and a multi-objective life cycle optimization model.

Initially, individual pavement LCA and LCC models are developed to quantify the environmental impacts and the costs incurred by highway agencies and road users throughout six pavement lifecycle phases: materials extraction and production, construction and M&R; transportation of materials; work zone (WZ) traffic management; usage; and end-of-life (EOL). Subsequently, a comprehensive and integrated pavement LCC-LCA model is developed, in order to improve the consistency between the system boundaries of the pavement life cycle when analyzed concomitantly from the economic and environmental viewpoints.

In view of the progressive enhancement of the capability of analysis of the DSS, a single-objective life cycle optimization model is developed to tackle the pavement M&R strategy selection problem. The proposed approach relies on a non-linear discrete optimization model that is solved through an Adaptive Hybrid Genetic Algorithm (AHGA). The developed algorithm contains two dynamic learning mechanisms to adaptively guide and combine the exploration and exploitation search processes. The new AHGA is compared to a non-hybridized version of the GA by applying the algorithms to several case studies with the objective of determining the best pavement M&R strategy that minimizes the PV of the total M&R costs.

Finally, to enhance the prospect of simultaneous accomplishment of both cost and environmental objectives, a multi-objective life cycle optimization methodology is proposed. The methodology contains three main components: (1) a multi-objective optimization (MOO) model; (2) a comprehensive and integrated pavement LCC-LCA model; and (3) a decision-support module. The proposed multi-objective optimization methodology is applied to determine the optimal M&R strategies for a flexible pavement section of a highway which yields the best tradeoff between the following three, often conflicting, objectives: (1) minimization of the PV of the total life cycle highway agency costs (LCHAC); (2) minimization of the PV of the life cycle road user costs (LCRUC); and (3) minimization of the life cycle environmental impacts (LCEI).

All the pavement life cycle approaches are applied to either real or academic case studies based on highway agencies' real practices, which, in addition to meeting the technical requirements, strive to enhance pavement sustainability by providing potential LCHAC and LCRUC savings and reduced environmental impacts. The results show the usefulness of the pavement life cycle-based methodologies integrating the DSS as viable tools to help highway agencies and DMs in making decisions that are more sustainable for meeting the cumulative and long-term economic and environmental goals and targets.

Resumo

Numa sociedade em que consciência pública sobre a protecção do ambiente é cada vez mais notória, e a disponibilidade de recursos naturais e de financiamento é limitada, as concessionárias rodoviárias e os decisores procuram, hoje, mais do que nunca, ferramentas que lhes possibilitem utilizar esses recursos de forma mais racional, tendo em conta factores ambientais e sociais juntamente com considerações económicas e técnicas. No entanto, as práticas tradicionalmente adoptadas pelas concessionárias rodoviárias no que diz respeito à gestão de pavimentos tem consistido essencialmente na aplicação de sistemas de Avaliação dos Custos do Ciclo de Vida (ACCV) com o objectivo de avaliar o valor económico de longo prazo de opções alternativas de investimento para novos projectos de construção, manutenção e reabilitação (M&R). Esta forma de apoio à tomada de decisão, em que nenhuma ou reduzida importância é dada às considerações ambientais, não é eficaz na promoção da sustentabilidade dos sistemas de pavimentos rodoviários. Nessa perspectiva, é evidente a necessidade urgente de Sistemas de Apoio à Decisão (SAD) para a gestão de pavimentos, que através da integração de abordagens complementares e multidisciplinares de ciclo de vida de pavimentos, permitam aos decisores contabilizar os efeitos cumulativos e de longo prazo das suas decisões e procedimentos, no que diz respeito à concretização dos objectivos e metas de sustentabilidade. Tal só será possível através da utilização de técnicas e ferramentas dotadas de uma capacidade de análise abrangente e com um âmbito alargado.

Esta tese apresenta um SAD para optimizar a gestão de pavimentos ao nível de projecto que inclui várias abordagens de ciclo de vida de pavimentos, com uma natureza abrangente e autónoma, mas interligadas de forma lógica. Especificamente, os seguintes métodos de avaliação são apresentados: um modelo de Avaliação do Ciclo de Vida (ACV), um modelo de CCV, um modelo integrado de CCV-ACV, um modelo de optimização mono-objectivo do ciclo de vida e um modelo de optimização multi-objectivo do ciclo de vida.

Inicialmente são desenvolvidos modelos individuais de ACV e CCV de pavimentos, que visam quantificar os impactes ambientais e os custos suportados pelas concessionárias rodoviárias e pelos utilizadores ao longo das seis fases do ciclo de vida de um pavimento rodoviário: extracção e produção de materiais; construção e M&R; transporte de materiais; gestão do tráfego nas zonas de trabalhos; utilização; e fim do ciclo de vida. Posteriormente, um modelo abrangente e integrado de CCV-ACV de pavimentos é desenvolvido, a fim de se melhorar a consistência das fronteiras do sistema do ciclo de vida de um pavimento, quando analisado concomitantemente dos pontos de vista ambiental e económico.

Tendo em vista a melhoria progressiva da capacidade de análise do SAD, um modelo de optimização mono-objectivo do ciclo de vida é desenvolvido para lidar com o problema da selecção de estratégias de M&R dos pavimentos. A abordagem proposta assenta num modelo de optimização discreta e não-linear que é resolvido através de um algoritmo genético híbrido adaptativo (AGHA). O algoritmo desenvolvido possui dois mecanismos de aprendizagem dinâmica que tem como objectivos conduzir e combinar, de forma dinâmica, os processos de refinamento e exploração das soluções do problema. O novo AGHA é comparado com uma versão não híbrida do algoritmo genético através da aplicação dos algoritmos a vários casos de estudo.

Por último, para melhorar a expectativa de realização simultânea dos objectivos ambientais e de custos, uma metodologia de optimização multi-objectivo do ciclo de vida é proposta. A metodologia possui três componentes: (1) um modelo de optimização multi-objectivo; (2) um modelo abrangente e integrado de CCV-ACV de pavimentos; e (3) um modelo de apoio à decisão. A metodologia de optimização multi-objectivo proposta é aplicada na identificação da estratégia óptima de M&R de um pavimento rodoviário flexível, que resulte no melhor compromisso entre os três objectivos seguintes: (1) minimização do valor actual dos CCV suportados pelas concessionárias rodoviárias; (2) minimização do valor actual dos CCV suportados pelos utilizadores; e (3) minimização dos impactes ambientais do ciclo de vida.

Todas as abordagens de ciclo de vida de pavimentos são aplicadas a casos de estudo reais ou a casos de estudos académicos baseados nas práticas reais adoptadas pelas concessionárias rodoviárias, que visam não só o cumprimentos dos requisitos técnicos, mas também a melhoria da sustentabilidade dos pavimentos através da redução dos impactes ambientais e dos CCV suportados pelas concessionárias rodoviárias e pelos utilizadores. Os resultados mostram a utilidade das metodologias de ciclo de vida que integram o SAD como ferramentas viáveis para ajudar as concessionárias rodoviárias e os decisores a concretizar os objectivos e as metas económicas e ambientais cumulativas e de longo prazo.

A COMPREHENSIVE LIFE CYCLE APPROACH FOR MANAGING PAVEMENT SYSTEMS

Chapter 1

Introduction

1.1 Motivation

It has been recognized for a long time that road infrastructure systems play an important role in ensuring the delivery of goods and services that promote prosperity and growth and contribute to the quality of life, including the social well-being, health and safety of citizens, and the quality of their environments. Therefore, on-going investment in these systems will continue to be a pivotal requirement for countries aspiring to be, or to remain, fully and competitively integrated in a world economy, although the way the investment is applied will vary depending on the country's level of development (OECD, 2007).

Developing countries are still going through a phase of strong investment in the construction of new road infrastructures, whereas the majority of developed countries have just started to experience a change in their investment needs. While in the past we saw a considerable amount of financial resources being allocated to the expansion of their road network, the future trend will be towards making the best possible use of the available infrastructures in order to accommodate growing transport demands, while ensuring that traffic density and the condition of road infrastructures remain at desirable levels, and that the road network is adaptable, automated and resilient (ERTRAC, 2010).

Nevertheless, for some countries, such as the United States (US), challenges that had been envisioned for the short/medium term are currently becoming realities that require an urgent and effective response. According to the most recent American Society of Civil Engineers' (ASCE's) report card, a considerable percentage of the country's core public road infrastructures are showing signs of continued and accelerated deterioration or have even already reached the end of its expected service life (ASCE, 2013). Failure to make significant progresses towards fulfilling the road infrastructure investments needs could prove costly in terms of congestion, costing the economy an estimated $101 billion a year in wasted time and fuel, growing environmental problems, with all the implications this has for living standards and quality of life, or maybe even lead to a permanent and irreversible partial loss of this important asset.

During the last decade, practitioners and decision-makers (DMs) have responded to the needs of addressing road infrastructure issues by putting pressure on governments to increase the investment in road infrastructure with public budgets coming mostly from tax receipts. However, either due to the economic crisis, which has lead to a reduction of the consumption-based and income-based tax revenues, or simply due to a shift in the government policies, the solutions adopted in the past cannot be employed to solve the problems of the present.

Moreover, the increasing global awareness of sustainability and climate change have motivated an ever-growing number of organizations and governing bodies to embrace the principles of sustainability in managing their activities and conducting business. For instance, in its Strategic Plan for the fiscal years 2014-2018, the United States Department of Transportation (US DOT) includes a separate strategic goal to "*Advance environmentally sustainable policies and investments that reduce carbon and other harmful emissions from transportation sources"* (US DOT, 2014). Similarly, the European Union (EU), in an effort to improve sustainability in the European community, released a Strategic Research Agenda (SRA), which defines the research and innovation priorities, with the goal of increasing the current efficiency of the European road transport system by 50% by 2030 (ERTRAC, 2010). The approach taken by the SRA recognizes, in particular, the societal demand for both increasing the energy efficiency of road transport activities and decarbonizing the energy they consume.

Highways are ideal targets for effective sustainable design and construction initiatives. Frequently, they are large in project scope and involve considerable amounts of financial resources (ERF, 2013). Also, highway road pavement construction and maintenance consume significant amounts of materials and energy and produce large amounts of waste, which may have adverse effects on the environment and 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. Therefore, to advance the integration of the road pavement infrastructures into the concept of sustainable development in a progressive and balanced manner, infrastructure owners should add sustainability considerations to the construction and maintenance concepts.

Sustainability considerations are not new, and in fact have often been considered indirectly or informally, but in recent years increased efforts are being made to assess the sustainability of road projects and to incorporate the results of that assessment into the road pavement decision-making process in a more systematic, organized and comprehensive fashion. An example of the endeavors undertaken at the forefront of the sustainable movement is the development of sustainability rating systems to qualitatively assess the sustainability of construction practices. Taking the Greenroads rating system as an example, it identifies the attributes of a road project that may contribute to enhancing sustainability, and then it sets sustainability best practices for each attribute (Greenroads, 2011). However, because the rating systems are mostly focused on environmental issues related to materials and construction processes rather than the usage phase (Bueno et al., 2015), it may be that a road project awarded with a "green" label is not always synonymous with a project that is globally "green" (Harvey et al., 2011). In fact, the most environmentally-friendly strategy may not be the one with the highest performance. In other words, simply using “greener” materials than others, or blindly performing recycle-related practices may lead to an increase in the amount of M&R treatments needed, due to a hypothetically lower performance over the life cycle, which may in turn result in higher total emissions produced and network congestion due to work-zones (WZs) (Giustozzi et al., 2012). Furthermore, while these systems may be promising in pointing out areas where sustainability can be enhanced during the construction and maintenance phases, they lack an analytical approach that enables the benefits associated with sustainable design and construction procedures to be quantified.

A pro-active consideration of sustainability goals for managing pavement assets therefore requires the setting of targets and the development of tools and methodologies that will allow DMs, owners and operators to assess the current state of road pavement infrastructures, report on their technical, economic, environmental and social performances, and predict future conditions and performances from a cradle-to-grave perspective. This multi-dimensional and life cycle thinking-based approach goes well beyond the traditional single-discipline evaluation of performance prevailing in some rating systems and “Report Cards”. It provides a more consistent platform for improving pavement management in a holistic way by helping to put decisions in context with facts from all stages of the system’s life cycle, and thereby avoids shifting the environmental, economic and social burdens from one life cycle phase or stakeholder to another. These attributes are important features which enable the benchmarking and assessment of the level of achievement of the highway agency’s goals and objectives towards sustainability.

Two instruments with a life cycle thinking-based philosophy that can be used to quantify the economic and environmental performances of sustainability considerations are life cycle assessment (LCA) and Life Cycle Costs Analysis (LCCA). While LCCA provides an effective evaluation to pinpoint long-term cost-effective solutions for the design and maintenance of pavement systems (Walls and Smith, 1998), the environmental impacts associated with their life cycle are best characterized using a LCA approach (Santero et al., 2011). LCA is an objective methodology for evaluating the environmental loads associated with a product, process, or activity over their entire life cycle (Guinée et al., 2002). This method is based on identifying and quantifying the energy and materials used in a process in order to translate them into a set of meaningful environmental indicators that inform users about the impact caused in different categories. The performance achieved in these damage categories can then be employed to assess different process alternatives that can be implemented to achieve environmental improvements.

Neither LCCA nor LCA are synonymous with a sustainability assessment but they provide critical information and metrics, which, when complemented with other appraisal techniques, can be used either to find the most cost-effective paving solutions to reduce environmental impacts or, at a higher decision level, to measure progress towards sustainability targets.

One of the techniques that can further extend the achievements obtained through the conjoint application of the aforementioned life cycle-based approaches is the multi-objective optimization (MOO) technique. MOO is well suited to incorporating environmental concerns in the optimization of sustainable processes, since it allows them to be treated as decision-making objectives to be optimized in conjunction with the traditional economic-based criteria. Therefore, by embracing these concepts and incorporating them into decision-support systems (DSSs) for pavement management, those in charge of deciding how sustainable pavement systems will be tackled, will be in a much better position to adapt and advance current pavement management practices towards enhancing pavement sustainability.

1.2 Problem statement

In a society where the public awareness of environmental protection is increasing remarkably and the availability of resources and funding is limited, it is more vital than ever that DOTs and DMs seek new tools that enable them to make the best and most rational use of these resources, taking into account environmental and social factors, along with economic and technical considerations. However, the practices adopted by highway agencies with regards to pavement management have mostly consisted of employing LCCA systems to evaluate the overall long-term economic efficiency of competing pavement design and maintenance and rehabilitation (M&R) activity alternatives. This way of supporting the decision-making process for pavement management does not seem to be effective and efficient in advancing sustainability in pavement systems.

In view of this, it is clear there is an urgent need for pavement management DSS, which, by integrating multi-disciplinary and complementary pavement life cycle modelling approaches, will enable the DMs to properly account for, consider and assess the cumulative and long-term impacts of their decisions and practices regarding sustainability goals and targets. This can only be achieved by employing techniques and tools provided with a comprehensive and wide-scoped cradle-to-grave capacity of analysis.

In this context, LCCA has the potential to contribute to enhancing the sustainability of road pavement systems, since it provides a means to minimize the costs incurred by the several pavement stakeholders throughout the project analysis period (PAP) (Santos and Ferreira, 2013). However, contrary to what an effective application of LCCA techniques requires (Ozbay et al., 2003), the state of practice reveals that the LCCA rarely incorporates non-highway agency costs (HAC) (Chan et al., 2008; Rangaraju et al., 2008; Hallin et al., 2011), and may thus favor non-optimal alternatives if the long-term pavement performance is taken into account. In turn, if the common shortcomings of existing pavement LCA models, namely the omission of some of the potentially most important pavement life cycle phases (i.e., usage and WZ traffic management) are properly addressed and corrected (Santero et al., 2010), a comprehensive LCA approach with wide system boundaries is well suited to estimate the long-term environmental performance of road pavement systems.

Notwithstanding the recognized merits of LCCA and LCA methods in evaluating the economic and environmental dimensions of sustainability, respectively, these methods applied individually are inefficient to optimally address the common tradeoff relationships and interactions between life cycle sustainability indicators. Rather, they are better employed when a wide-scoped LCCA system is integrated with a comprehensive LCA model into an optimization-based pavement life cycle management framework accounting for various objectives and constraints, and allowing LCCA and LCA to be carried out in parallel.

However, the traditional practice in optimized decision-making in pavement management has been based on the optimization of a single objective, mostly the minimization of life cycle costs (LCC), which can be either the total highway agencies, or less often, the summation of the total HAC and road user costs (RUC). It is therefore evident that the steady and effective implementation of a sustainable pavement management system (SPMS), by way of the addition of the environmental dimension to the traditional cost-based optimization framework, requires the mathematical formulation of the decision problems to migrate from the single-objective optimization (SSO) to the MOO domain, in which the DMs are provided not with a single preferred solution, but with a set of potentially preferred solutions. In this way, a tradeoff analysis can be performed in a flexible manner, with respect to objectives that are deemed important for the perspective of the DM tackling the problem.

Therefore, to enable such a holistic approach, many different modeling, appraisal and operational research techniques need to be advanced and properly coupled to enable DMs to identify the procedures that they should implement to positively define the overall sustainability of the current and future road pavement systems by appropriately selecting, designing and optimizing the management of those assets.

1.3 Research objectives

The main objective of this thesis is to develop an optimization-based pavement management DSS which includes several comprehensive stand-alone but logically interconnected pavement life cycle approaches. The system represents a tool for DMs, (1) to evaluate the current pavement management practices and policies as it pertains to the technical and economic effectiveness and the associated impacts on the natural environment and, (2) to identify more sustainable paving engineering solutions resulting from either a comprehensive MOO-based or a non-optimization-based decision-making process, depending on the DM’s interests and scope of analysis.

The fulfillment of this objective requires the following research tasks to be undertaken:

1. To draw up a conceptual framework for a project-level pavement LCA model tailored for both US and European conditions, namely for the Portuguese context, which covers all of the six pavement life cycle phases: materials extraction and production; construction and M&R; transportation of materials; WZ traffic management; usage and end-of-life (EOL);
2. To develop a comprehensive project-level pavement LCC model that accounts for the different categories of costs incurred by highway agencies and road users in every phase of the pavement life cycle;
3. To develop a comprehensive and integrated project-level pavement life cycle costs-life-cycle assessment (LCC-LCA) model, 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;
4. To investigate from a life cycle perspective the extent to which several pavement engineering solutions, namely hot in-plant recycling mixtures, Warm-mix Asphalt (WMA), 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;
5. To develop (1) a project-level single-objective-based life cycle optimization model to address the pavement M&R strategy selection problem and (2) a genetic algorithm (GA) to solve the abovementioned model;

6. To develop a comprehensive and modular MOO-based pavement management DSS, which integrates a comprehensive pavement LCC-LCA model, along with a decision-support module, within a MOO framework;
7. To foster the sustainability of the pavement management policies and practices adopted by a highway agency through: (1) the identification of pavement M&R strategies that optimally account for the tradeoff relationship between life cycle highway agency costs (LCHAC), life cycle road user costs (LCRUC) and life cycle environmental impacts (LCEI); (2) the quantification of the economic and environmental benefits that can be achieved by implementing those optimal M&R strategies in lieu of pre-defined ones; and, (3) the assessment of how new pavement engineering solutions can potentially amplify the economic and environmental benefits obtained with the implementation of optimal M&R strategies.

To sum up, this thesis provides a practical, scientifically-based, comprehensive and wide-scoped pavement management DSS to help and guide DMs in promoting economically and environmentally sustainable decision-making processes related to pavement construction and maintenance management. The feasibility and practicality of the components integrating the DSS are illustrated with various case studies.

1.4 Structure of the thesis

This thesis is organized into nine chapters. Excluding Chapter 1 (Introduction) and Chapter 9 (Summary, conclusions and future work), all chapters are written in the format of a scientific article and can be considered as an independent element. Consequently, they may be read independently or in sequence. For this reason, some sections, namely the background information, the description of the pavement life cycle approaches and the features of some case studies are partially repeated in several chapters.

Even though each chapter can be read independently, this thesis is not a simple assembly of scientific articles, as they were conceived to portray the planned evolution of the research work developed throughout the doctoral studies. The relationship between chapters is displayed in Figure 1.1.

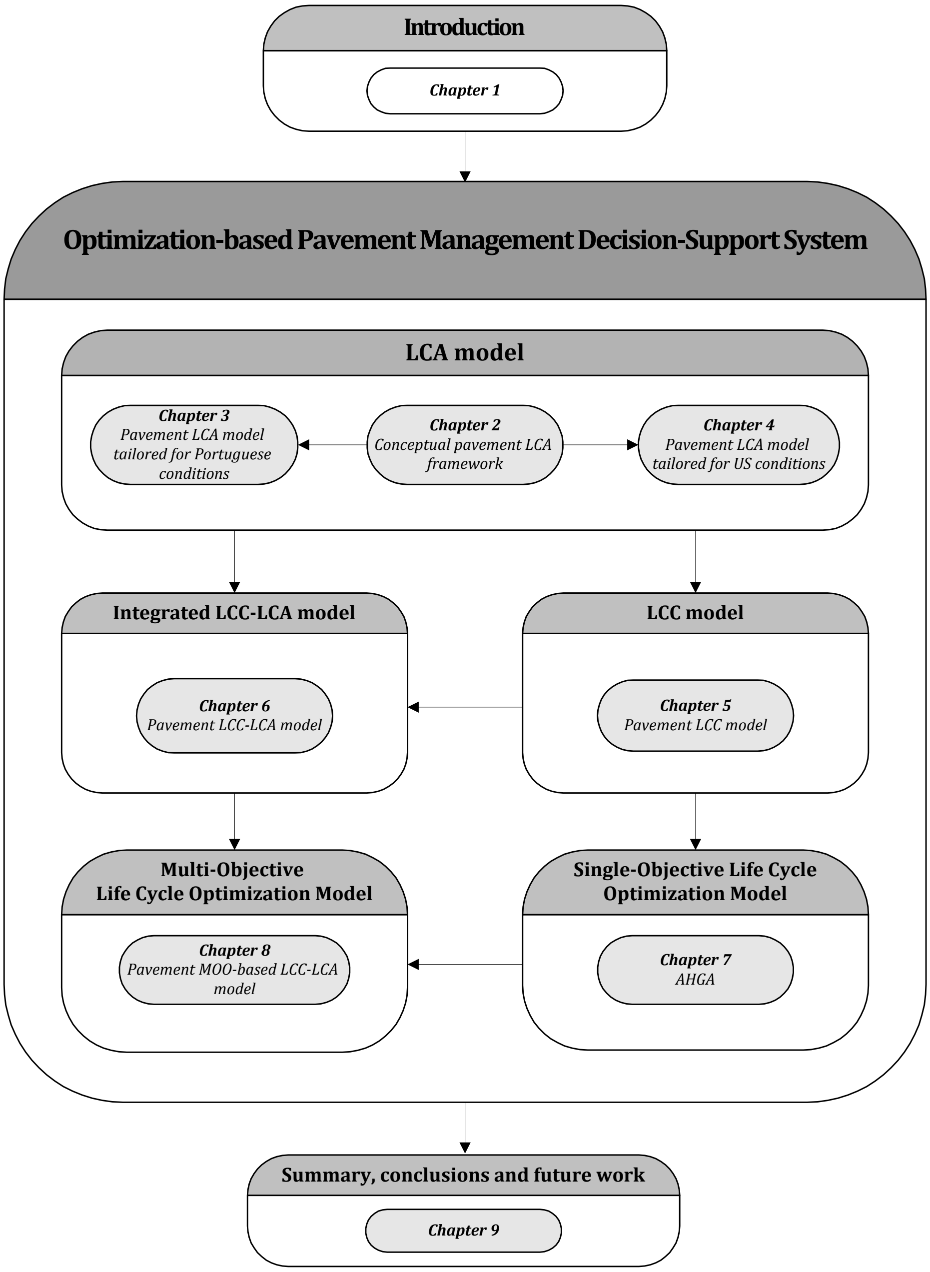

Figure 1.1- Schematic diagram of the research outline.

Chapter 1 provides an introduction to the thesis. It presents the motivation, the problem statement, the research objectives, and the organization of this thesis.

Chapter 2 presents the development of both a conceptual pavement LCA framework and a highly customizable LCA tool that provides an integrated, project-level approach that includes all six pavement life cycle phases: extraction of raw materials and production; construction and M&R; transportation of materials; WZ traffic management; usage; and EOL. It also describes in detail the models developed or selected for modelling the processes that occur in each pavement life cycle phase. Finally, it suggests several data sources with potential relevance for a LCA conducted in the Portuguese context.

Chapter 3 illustrates the potential and usefulness of the pavement LCA model introduced in the previous chapter for conducting a comprehensive and attributional LCA. For that purpose, we present the results of a study aiming to estimate and compare the LCEI of the flexible pavement structures defined in the Portuguese pavement design catalogue (JAE, 1995). The analysis assesses the functional units over a 40-year PAP considering all pavement life cycle phases.

Chapter 4 describes the development of a comprehensive pavement LCA model tailored for US conditions, according to the conceptual framework introduced in Chapter 2. It also presents the results of a pavement LCA conducted for an in-place pavement recycling rehabilitation project in the state of Virginia, USA. The project under consideration incorporated several in-place pavement recycling techniques and a unique traffic management approach. The results for the recycling-based project are compared to two other pavement management alternatives: (1) a traditional pavement reconstruction and, (2) a corrective maintenance approach.

Chapter 5 presents the development of a comprehensive pavement LCC model intended to give DMs a systematic framework that provides an in-depth perspective of the costs incurred by highway agencies and road users during the materials, construction and M&R, WZ traffic management, usage and EOL pavement life cycle phases. It also presents the results from an extensive (cradle-to-grave) LCCA of the in-place pavement recycling rehabilitation project detailed in Chapter 4.

Chapter 6 introduces a comprehensive and integrated pavement LCC-LCA model that builds on the process-based LCA and LCC models presented in Chapters 4 and 5, respectively. The proposed pavement LCC-LCA model relies on a hybrid life cycle inventory (LCI) 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-based LCI data are either completely or partially unavailable. Like the preceding models, it also encompasses all six pavement life cycle phases into the system boundaries and accounts for the upstream impacts in the production of elements commonly disregarded by the majority of the existing pavement LCA models. Finally, the applicability of the model is illustrated through its application to a case study that aims to investigate, from a life cycle perspective, the extent to which several pavement engineering solutions, namely hot in-plant recycling mixtures, WMA, 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 section located in Virginia, USA.

Chapter 7 focuses on the work undertaken to develop a new adaptive hybrid GA (AHGA), which combines a traditional GA with a Local Search (LS) mechanism for optimally solving the pavement M&R strategy selection problem. The proposed AHGA framework contains two dynamic learning mechanisms to adaptively guide and combine the exploration and exploitation search processes. In this way, it improves the overall efficiency of the search, either by accelerating the discovery of good solutions, for which evolution alone would take too long to find, or by reaching solutions that would otherwise be unreachable either by evolution or a local method alone. The first learning mechanism aims to reactively assess the worthiness of conducting an LS, and to efficiently control the computational resources allocated to the application of this search technique. The second learning mechanism uses instantaneously learned probabilities to select which one, from a set of pre-defined LS operators which compete against each other for selection, is the most appropriate for a particular stage of the search to take over from the evolutionary-based search process. The new AHGA is compared in terms of efficiency and effectiveness to a non-hybridized version of the GA by applying the algorithms to several case studies with the objective of determining the best pavement M&R strategy that minimizes the present value (PV) of the life cycle M&R costs.

Chapter 8 presents a comprehensive and modular MOO-based pavement management DSS. The main novelty of the DSS lies in the incorporation of the comprehensive and integrated pavement LCC-LCA model introduced in Chapter 6, along with a decision-support module, within a MOO framework applicable to pavement management. The capabilities of the proposed DSS are demonstrated by its application to two case studies consisting of determining the optimal M&R strategy, which yields the best tradeoff between the following three, often conflicting, objectives: (1) minimization of the PV of the total LCHAC; (2) minimization of the PV of the LCRUC; and (3) minimization of the life cycle climate change score (LCCCsc), when implemented, respectively, on two one-way flexible pavement sections of a typical Interstate highway in Virginia, USA. Furthermore, for each case study two scenarios are considered, depending on the features of the M&R activities available for employment throughout the PAP. They differ from each other in that the former comprises exclusively conventional asphalt layers, whereas, in the latter, the most structurally robust M&R activity available for employment combines conventional asphalt layers with in-place recycling layers. The model is solved through the augmented weighted Tchebycheff method using an adapted version of the AHGA presented in Chapter 7.

Chapter 9 summarizes the research work described in this thesis, highlights its contributions, and delineates a set of research lines and DSS improvements for future development.

1.5 Publications

As mentioned in the previous section, this thesis is based on the scientific articles drawn up on the basis of the research work developed during the doctoral studies. Some of the scientific articles have been submitted to international peer-reviewed journals and are either published or under review, and others will be submitted soon. Apart from eventual minor layout-specific issues they have not been meaningfully changed. Below, the list of references for the thesis chapters is presented:

1) **Scientific articles already published:**

   a. **Chapter 2:** Santos, J., Ferreira, A. and Flintsch, G., 2015. A life cycle assessment model for pavement management: methodology and computational framework. *International Journal of Pavement Engineering*, 16 (3), 268-286. DOI:10.1080/10298436.2014.942861

   b. **Chapter 3:** Santos, J., Ferreira, A. and Flintsch, G., 2015. A life cycle assessment model for pavement management: road pavement construction and management in Portugal. *International Journal of Pavement Engineering*, 16 (4), 315-336. DOI:10.1080/10298436.2014.942862

   c. **Chapter 4:** Santos, J., Bryce, J., Flintsch, G., Ferreira, A. and Diefenderfer, B., 2015. A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, 11 (9), 1199-1217. DOI:10.1080/15732479.2014.945095

   d. **Chapter 5:** Santos, J., Bryce, J., Flintsch, G. and Ferreira, A. A comprehensive life cycle costs analysis of in-place recycling and conventional pavement construction and maintenance practices. *International Journal of Pavement Engineering* (available online), DOI: 10.1080/10298436.2015.1122190

2) **Scientific articles under review:**
    a. **Chapter 6:** Santos, J., Flintsch, G. and Ferreira, A. Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability. *Resources, Conservation & Recycling*.

3) **Scientific articles to be submitted soon:**
    a. **Chapter 7:** Santos, J., Ferreira, A. and Flintsch, G. An adaptive hybrid genetic algorithm for pavement management. The submission to *Engineering Optimization* is currently being considered.
    b. **Chapter 8:** Santos, J., Ferreira, A. and Flintsch, G. A multi-objective optimization-based pavement management decision-support system for considering life cycle agency costs, user costs and environmental impacts. The submission to *Journal of Cleaner Production* is currently being considered.

Complementarily, a considerable number of scientific articles have been presented and discussed in several international and national conferences. The complete list of conferences is as follows:

1) **Conference articles:**
    a. **Chapters 2 and 3:** Santos, J., Ferreira, A. and Flintsch, G., 2014. Development and application of a life-cycle assessment model for pavement management. *Proceedings of the Transport Research Arena*, CD Ed., TRA2014_Fpaper_18702.pdf, 1-10, Paris, France.
    b. **Chapter 4:** Santos, J., Bryce, J., Flintsch, G., Ferreira, A. and Diefenderfer, B., 2014. A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. *Papers from the International Symposium on Pavement Life Cycle Assessment 2014*, Harvey, Jullien and Jones (Eds), SBN 978-0-692-29357-7, Davis, CA, USA.
    c. **Chapter 5:** Santos, J., Bryce, J., Flintsch, G. and Ferreira, A., 2014. A comprehensive life cycle costs analysis of in-place recycling and conventional

pavement construction and maintenance practices. *10th Annual Inter-University Symposium on Infrastructure Management (AISIM),* Virginia Tech Transportation Institute, Blacksburg, VA, USA.

- **d.** **Chapter 5:** Santos, J., Bryce, J., Flintsch, G. and Ferreira, A., 2015. A comprehensive life cycle costs analysis of in-place recycling and conventional pavement construction and maintenance practices. *9th International Conference on Managing Pavement Assets (ICMPA)*, Alexandria, VA, USA.
- **e.** **Chapter 5:** Santos, J., Bryce, J., Flintsch, G. and Ferreira, A., 2015. A comprehensive life cycle costs analysis of pavement maintenance and rehabilitation practices. *Workshop on Assessment Methodologies 2015*, Coimbra, Portugal.

Finally, the author has also been involved in other research work and contributed to the following publications:

1) Scientific articles already published:

- **a.** Bryce, J., Katicha, S., Flintsch, G., Sivaneswaran, N. and Santos, J., 2014. Probabilistic lifecycle assessment as a network-Level evaluation tool for the use and maintenance phases of pavements. *Transportation Research Record: Journal of the Transportation Research Board*, 2455 (1), 44-53. DOI:10.3141/2455-06

2) Conference articles:

- **a.** Bryce, J., Santos, J., Flintsch, G., Katicha, S., McGhee, K. and Ferreira, A., 2014. Analysis of rolling resistance models to analyze vehicle fuel consumption as a function of pavement properties. *Proceedings of the 3rd International Symposium on Asphalt Pavements and Environment*, in Asphalt Pavements, Y. Richard Kim, CRC Press 2014, 263–273, Print ISBN: 978-1-138-02693-3, eBook ISBN: 978-1-315-73675-4, DOI: 10.1201/b17219-39, Raleigh, North Carolina, USA.

1.6 References

American Society of Civil Engineering (ASCE), 2013. *2013 Report card for America's infrastructure*. Available at: http://www.infrastructurereportcard.org/a/#p/roads/overview

Bueno, P., Vassalo, J. and Cheung, K., 2015. Sustainability assessment of transport infrastructure projects: a review of existing tools and methods. *Transport Reviews*, 35(5), 622-649.

Chan, A., Keoleian, G., and Gabler, E., 2008. Evaluation of life-cycle cost analysis practices used by the Michigan department of transportation. *ASCE-Journal of Transportation Engineering*, 134(6), 236-245.

European Road Transport Research Advisory Council (ERTRAC), 2010. *ERTRAC Strategic Research Agenda 2010: towards a 50% more efficient road transport system by 2030*. Available at: http://www.ertrac.org/index.php?page=ertrac-research-agenda-and-plans

European Union Road Federation (ERF), 2013. *ERF 2012 European Road Statistics*. European Union Road Federation, Brussels. Available at: http://www.irfnet.eu/index.php/publications/publications

Giustozzi, F., 2012. *Life cycle assessment of sustainable road pavements: carbon footprinting and multi-attribute analysis*. PhD thesis, Virginia Tech, Blacksburg, VA.

Greenroads, 2011. *Greenroads manual v1.5*. Available at: https://www.greenroads.org/files/236.pdf

Guinée, J., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., et al., 2002. *Handbook on life cycle assessment. Operational guide to the ISO standards*. Dordrecht: Kluwer Academic Publishers.

Hallin, J., Sadasivam, S., Mallela, J., Hein, D., Darter, M. and Von Quintus, H., 2011. *Guide for pavement-type selection* (National Cooperative Highway Research

Program Report No. 703). Available at: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_703.pdf.

Harvey, J., Kendall, A., Santero, N., Van Dam, T., Lee, I.-S., and Wang, T., 2011. Pavement life cycle assessment workshop, May 5-7, 2010 in Davis, California, USA. *International Journal Life Cycle Assessment*, 16(9), 944-946.

JAE, 1995. *Manual of pavement structures for the Portuguese road network*. Junta Autónoma de Estradas, Lisboa, Portugal, 1-54 (in Portuguese).

Organization for Economic Co-operation and Development (OECD), 2007. *Infrastructure to 2030 (Volume 2): mapping policy for electricity, water and transport*. Organization for Economic Co-operation and Development, ISBN 978-92-64-03131-9, Paris, France. Available at: http://www.oecd.org/futures/infrastructureto2030/infrastructureto2030volume2mappingpolicyforelectricitywaterandtransport.htm

Ozbay, K., Parker, N., Jawad, D. and Hussain, S., 2003. *Guidelines for life cycle cost analysis* (Report No. FHWA-NJ-2003-012). Center for Advanced Infrastructure and Transportation, Rutgers University. Available at: http://cait.rutgers.edu/researchreports/guidelines-life-cycle-cost-analysis

Rangaraju, P., Amirkhanian, S. and Guven, Z., 2008. *Life cycle cost analysis for pavement type selection* (Report No. FHWA-SC-08-01). Clemson University for the South Carolina, Department of Transportation, Columbia, South Carolina, USA, 1-141. Available at: http://www.clemson.edu/t3s/scdot/pdf/projects/SPR656Final.pdf

Santero, N. and Horvath, A., 2009. Global warming potential of pavements. *Environmental Research Letters*, 4(3), 1-7.

Santero, N., Masanet, E., and Horvath, A., 2010. *Life-cycle assessment of pavements: a critical review of existing literature and research* (Report SN3119a). Portland Cement Association, Skokie, Illinois, USA, 1-81. Available at: http://www.osti.gov/scitech/servlets/purl/985846.

Santero, N., Masanet, E. and Horvath, A., 2011. Life-cycle assessment of pavements. Part I: critical review. *Resources, Conservation and Recycling*, 55(9-10), 801-809.

Santos, J. and Ferreira, A., 2013. Life-cycle cost analysis for pavement management at project level. *International Journal of Pavement Engineering*, 14 (1), 71-84.

United States Department of Transportation (US DOT), 2014. *Transportation for a new generation. Strategic plan for fiscal years 2014-2018.* Available at: https://www.transportation.gov/administrations/office-policy/fy-2014-2018-strategic-plan

Walls, J. and Smith, M., 1998. *Life-cycle cost analysis in pavement design - in search of better investment decisions* (Report No. FHWA-SA-98-079). Available at: http://isddc.dot.gov/OLPFiles/FHWA/013017.pdf

Chapter 2

A Life Cycle Assessment Model for Pavement Management: Methodology and Computational Framework

2.1 Introduction

The road transportation infrastructure is vital for the movement of people and goods. In 2010, total amount of transported goods in the EU-27 was estimated to have come to 3,831 billion tonne-kilometers, with road transport accounting for 45.8% of this total. In the passenger sector, the road transport accounted for 73.7% of the 12,869 km travelled on average per person (EC, 2012).

The challenges of satisfying this rising demand for accessibility and mobility can be framed using the concept of sustainability. Many organizations have focused on reducing greenhouse gas (GHG) and pollutant emissions. Recently, the EU targeted a reduction of GHG for the transport sector of at least 60% from 1990 levels by 2050 (EC, 2011). Similar to GHG emissions, the energy use due to transportation is also considerable, accounting for approximately 30% of the overall energy use in Europe

(EC, 2012). Road transportation is responsible for more than 80% of this energy consumption, and since mainly fossil fuels are used, the emissions of both GHG and air pollutants are considerable. For instance, in 2009, the European transport sector accounted for 25% of all carbon dioxide (CO_2) equivalent emissions, with road transport generating 71.7% of this total (EC, 2012). Current practices intended to reduce the environmental footprint of the transportation sector include new powertrains and improvements in vehicle technology, fuel refinements, a reduction in the consumption of non-renewable fossil fuel resources, optimization of urban traffic management, and the implementation of tighter emission standards (EC, 2012). However, with a 97% dependence on fossil fuels, the transportation sector has not significantly reduced its GHG intensity by switching to cleaner energy sources.

Pavement management decisions taking into account the potential environmental impacts over the road pavement's whole life cycle can contribute to sustainable development (Santero and Horvath, 2009). Those decisions are not all about applying recycling techniques and recycled materials, secondary products, low temperature mixtures, environmentally-friendly construction methods, etc. (Miller and Bahia, 2009). Indeed, for specific conditions, the impacts related to on-site equipment operation, have been shown to represent a minimal part of the environmental burden of a road pavement. Even modest reductions in vehicle energy consumption could offset the energy consumption in the pavement construction process (Santero and Horvath, 2009).

Pavement condition has been identified in published literature as having an influence on vehicle fuel consumption (FC) due to its relationship with rolling resistance, one of the resistive forces acting on the vehicle that can be roughly defined as the energy lost through pavement-tire contact. Results from a research project carried out by European and US partners, "Models for rolling resistance In Road Infrastructure Asset Management Systems (MIRIAM)", have shown that when road surface evenness expressed by the International Roughness Index (IRI) is increased by one unit (1 m/km), rolling resistance increases by approximately 4.6%, 7.1%, and 7.9%, respectively, for a car, heavy truck, and heavy truck with trailer travelling at 90 km/h. Further, this project has shown that when pavement surface texture, expressed as Mean Profile Depth (MPD), increases one unit (1 mm), rolling resistance increases by 15.1%, 18.4%, and 20.3%, respectively, for a car, heavy truck, and heavy truck with trailer travelling at the same speed (Hammarström et al., 2012).

There is also evidence that the stiffness of the pavement structure and its viscoelastic properties contribute to rolling resistance. Akbarian and Ulm (2012) presented a mechanistic model that estimates the change in FC due to pavement deflection as a function of the pavement's structural capacity and material properties. However, given the small number of studies performed, it is still unadvisable to draw a general conclusion on the relationship between fuel efficiency and the structural behavior of pavements.

In order to effectively understand how pavements impact the environment and to allocate significant efforts to increase their environmental performance, it is necessary to introduce a methodology that is able to analyze every phase of a pavement's life and provide the required metrics to set benchmarks that can be used to encourage continuous improvement. LCA, due to its flexibility, versatility, and comprehensiveness in investigating all the environmental aspects of a product system, has often been chosen to establish an effective path towards reaching environmental goals (ISO, 2006a).

2.2 Literature review on pavement life cycle assessment

In recent years, the LCA methodology has received increasing attention from academia (Carlson, 2011). Despite such interest, its effective application to road pavement is still at an embryonic stage. Some reasons for this scarce implementation include (1) a sense that environmentally-friendly solutions have a high initial cost even though they might be cost-effective when assessed under the PAP time frame; (2) the pavement practitioners' aversion to trust a methodology that entails several sources of uncertainty; (3) the lack of customizable and pavement-tailored tools that allow LCA to be carried out quickly; and (4) the lack of pavement-specific guidelines.

In general, the standards of the International Standard Organization (ISO) 14040 series have been adopted as guidelines for conducting pavement LCA. However, these standards only provide generic guidance for conducting well-documented and transparent LCAs of different products and services, leaving a considerable degree of freedom in the hands of the analysts and decision makers. Consequently, several initiatives have focused on identifying inconsistencies and proposing solutions for a standardized LCA protocol for pavement. The 2010 Pavement LCA Workshop (Harvey et al., 2011), held in California, introduced system definitions for elements of pavement LCA and provided a guide on how to conduct pavement LCA studies. Huang et al. (2013) assessed the impact of methodological choices (allocation among co-products or at EOL) concerning LCA and the footprint evaluation of road pavements. Santero et al. (2011a) and Santero et al. (2011b) provided a critical review of the strengths and weaknesses of the body of work, and developed future research directions for improving the credibility and utility of pavement LCAs for decision-making in policy-setting and transportation engineering contexts. According to Santero et al. (2011a) most existing studies are focused on the comparison of asphalt and concrete materials. However, framework gaps and inconsistencies in the functional unit, system boundaries, data quality, and environmental metrics have made the results of the different studies incomparable. Moreover, Santero et al. (2011a) identified the omissions of the usage phase from nearly all studies as "*the most significant shortfall from a system boundary perspective*". This stresses the need for developing LCA methodologies that broaden the system boundaries, particularly by including the effects on traffic energy due to the surface characteristics and eventual traffic delays imposed by M&R activities. Although literature already includes some LCA approaches moving in this direction (Huang et al., 2009a; Zhang et al., 2010; Wang et al., 2012; Yu and Lu, 2012), new studies and methodologies are needed because the existing ones tend to exhibit at least one of the following drawbacks: (1) they incorporate both outdated and closed data and irreproducible methodologies (e.g., fixed mixtures recipes, procedures, etc.), which make them unsuitable for use in geographic and technical contexts different from those for which they have been developed; (2) the boundaries exclude important phases; (3)

they contain only LCIs and do not provide life cycle impact assessment (LCIA); or (4) they are not available in user-friendly and customizable software able to be applied to any number of different scenarios and functional units.

Currently, LCA-based software encompasses a set of tools for supporting DMs in evaluating the environmental performance of their pavement-related decisions. For instance, pavement-related tools, such as Athena Impact Estimator for Highways (ASMI, 2012), AggRegain CO2 Tool (TRL, 2010), PaLATE (Horvath, 2007), ROAD-RES (Birgisdóttir et al., 2006), ROADEO (The World Bank, 2010), CHARGER (Zammataro, 2011), asPECT (TRL, 2011), PE-2 (Mukherjee and Cass, 2012), CFET (Melanta et al., 2013), and the CMS RIPT (Fox et al., 2011), provide life cycle emissions predictions, essentially life cycle GHG, resulting from material production, material transport, and construction phases. NONROAD 2008 (US EPA, 2010a) estimates the emissions released during the use of construction equipment, whereas MOVES (US EPA, 2010b), EMFAC 2007 (CARB, 2007), and COPERT 4 (Gkatzoflias et al., 2012) predict on-road vehicle emissions. However, all these tools remain fragmented in terms of pavement life cycle coverage and limited in terms of the environmental indicators taken into account.

In an attempt to address some of the scope and customization limitations evidenced by the current state-of-the-practice LCA approaches and tools, this chapter presents the development of a fully integrated and highly customizable DSS that hosts a project-level pavement LCA model intended to give DMs a computational and systematic platform to organize and cross their “in-house” data (e.g., inventories of materials, equipment, construction activities, etc.) in order to facilitate the benchmarking of their designs, construction and management options at the early design phase of a pavement project. The DSS includes all six pavement life cycle phases (e.g., materials extraction and production; construction and M&R; transportation of materials; WZ traffic management; usage; and EOL) and user-friendly communication platforms between the user and the model.

2.3 Pavement life cycle assessment model description

2.3.1 Model structure

Modeling the LCA of a complex system requires a modeling approach and a computational platform able to keep the integrity of all data within the system without constraining the movement of inputs and outputs across the life cycle phases. Another important feature is the ability to enable users to improve the accuracy of all estimates by introducing their own data. Such a customization property, by allowing easy modification of the default values of process parameters and data, can be beneficial to evaluate the results of different decision-making scenarios, as well as to perform sensitivity analysis on the results due to variations of design and operational parameters, assumptions, and methodological choices.

Microsoft's Excel software has been used by some pavement LCA models (Horvath, 2007; Huang et al., 2009b). While the spreadsheet approach allows for easy sharing of information between system components and quick response to changes in many system parameters, it imposes several limitations (1) in managing and storing a large amount of data; (2) in dealing with information and processes that tend to change and evolve over the PAP; and (3) in modeling the intrinsic complexity of some processes, such as vehicle FC modeling, even using macros. In some types of analysis, such limitations do not inhibit spreadsheet-based models from being used; however, other tools can conduct the analyses more efficiently and provide greater customization. Therefore, the DSS that hosts the process-based pavement LCA model described in this chapter was written in Visual Basic .NET (VB.NET) (Loureiro, 2010) and SQL programming languages (Damas, 2005), the latter being used for managing the data introduced and held in the system.

Figure 2.1 provides an overview of the architecture of the pavement LCA model. It encompasses three types of VB.NET Classes: Pavement Life Cycle Phase Class (PLCPC), Database Class (DbC), and Other Classes (OC), those not covered by the two classes previously mentioned. Each PLCPC is linked to several classes, including a

Main Class that is the hub of the model. Apart from other functions, the hub is responsible for the interaction between all classes, so that the system is automatically updated whenever the user makes a decision that affects the remaining system components. For example, assuming that the user deletes a single material (e.g., bitumen 50/70, etc.) from the database, all downstream materials (e.g., Hot-mix Asphalt [HMA], etc.) and processes (i.e., bitumen 50/70 transportation from the refinery to mixing plant and HMA transportation from the mixing plant to the work site) related in some way to that single material are automatically deleted, avoiding future errors and lack of coherence when executing the model.

The majority of the data required to run the model is input through windows, either by scrolling through the classes representing the pavement life cycle phases or directly accessing the classes existing in the database. The exception is the data regarding the evolution over time of both the on-road vehicle fleet composition and pavement quality. In these cases, due to the extensive amount of data involved, the data must be imported from a Microsoft Excel file. Once the data is entered into the DbC, it becomes available for all future analysis, unless it is directly or indirectly (due to the reasons mentioned above) deleted by the user. Moreover, given the open nature of the database, project-specific data can be added and pre-existing data can be edited to fit the characteristics and particularities of the analysis being performed.

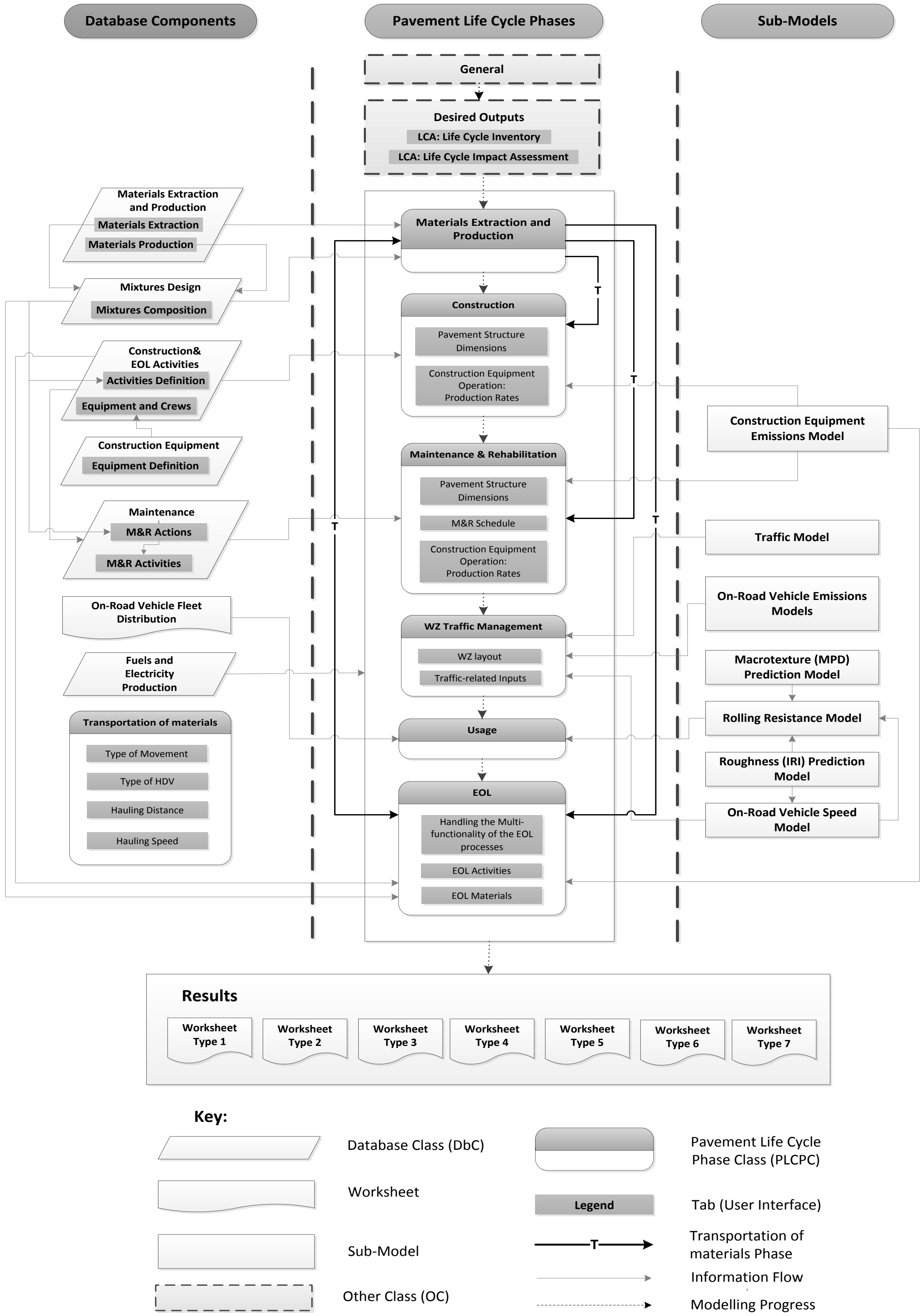

Figure 2.1- Pavement LCA model: computational framework.

The LCA model is intended to be applicable for a wide range of deliverables, for different scenarios, and for a wide variety of questions addressed during the project planning stage (e.g., types of mixtures and compositions to be adopted in a specific layer, selection of M&R actions, etc.). However, to properly use the model, users must first elucidate the processes occurring in each pavement life cycle phase, the model's potentialities and limitations, and the interdependencies between the components. The following sections describe the pavement life cycle phases, as well as the sub-models and database components linked to those phases. They also introduce the default data potentially suitable for use in studies carried out in the Portuguese context.

2.3.2 Goal and scope definition

The model presented in this chapter is intended to give highway agencies a highly customizable tool to assist them in quantitatively assessing the total environmental footprint of their procedures, strategies, and decisions regarding the construction and maintenance of flexible pavements used for a rural/interurban highway at project level. The target audience for using the methods, data, and results made available by the model includes LCA practitioners, pavement engineers, and other technical experts. The model enables the user to assess the environmental impacts and resources consumption (energy sources and materials) of alternative solutions for pavement design and maintenance throughout the different phases of the PAP of alternative solutions for pavement design and maintenance. The user can track where in the life cycle of the pavement's PAP environmental impacts are greatest and which materials, energy sources, equipment and processes contribute to the impact on the environment. After acknowledging the environmental consequences of their potential decisions, they will be more prepared to adopt more sustainable pavement design and management practices.

2.3.2.1 Functional unit

The functional unit is the physical unit on which all measures are computed. It allows for the comparison between systems with the same utility for the same function. Regarding the pavement domain, this means a unit of pavement that can safely and efficiently carry the same traffic over the same PAP. In order to define the functional unit, the user is asked to identify and quantify the relevant quantifiable properties and the technical/functional performance of the system, such as PAP length, beginning year of the PAP, traffic-related data, characteristics of the pavement structure, pavement dimensions, and type of M&R activities, etc.

Setting the system boundaries is an indispensable procedure in conducting any LCA. It consists of defining which parts of the life cycle and which processes belonging to the analyzed system are required for providing its function as defined by its functional unit. Therefore, these boundaries are drawn in such a way that only elements of minor importance or elements for which there is either no sufficient or solid knowledge are left out. This selection criterion contributes to ensuring that the quality of data is sufficient to provide trustable results for the intended applications.

2.3.2.2 System boundaries and system processes

The system boundaries of the proposed pavement LCA model entail six pavement life cycle phases, modeled through individual but interconnected modules. They are the following: (1) extraction of materials and production, consisting of the acquisition and processing of raw materials, and the mixing process of asphalt mixtures in plants; (2) construction and M&R, including all construction and M&R procedures and related construction equipment usage; (3) transportation of materials, accounting for the transportation of materials to and from the construction site and between intermediate facilities (e.g., transportation of aggregates from the quarries to asphalt mixing plants, etc.); (4) WZ traffic management, which models the traffic delays resulting from the application of M&R activities; (5) usage, which addresses the interactions of the pavement with vehicles and environment throughout the PAP; and (6) EOL, which models the destination of the pavement structure after the PAP. Various supplementary sub-models that are attached to the corresponding modules, as well as the data required to run those models, are introduced and discussed in the following sections.

Apart from the general system boundaries, there are less embracing scope-related decisions that must be made, which might result in the exclusion of certain processes. The processes for which the current version of the proposed model is not able to account are the following: (1) manufacturing and maintenance of production asphalt mixing plants and construction equipment necessary for the construction and M&R of road pavements; (2) road related safety and signaling equipment; (3) transportation of equipment and workers to the construction site; and (4) capital investments attributable to the construction and maintenance phase. The exclusion of those processes was governed by one of the following reasons: (1) the uniqueness of the condition to which it refers; (2) the lack of reliable information; or (3) unsuitability for the model's global scope (pavement LCA rather than a roadway LCA).

2.3.2.2.1 Materials extraction and production phase

Most materials used in asphalt pavement construction and M&R processes consist of aggregates of various gradations and asphalt binders of different performance grades. Pavement-related environmental burdens assigned to this phase are due to material acquisition and processing, which include the manufacturing processes of all materials, from extraction of raw materials to their transformation into a pavement input material (material extraction sub-phase), and ending up with the mixture production at a mixing plant (materials production sub-phase). The manufacture of facilities, such as mixture production plants, is excluded from the system boundaries.

Until becoming a pavement input material (e.g., aggregate, bitumen, etc.), all environmental burdens stemming from transportation between facilities are assigned to the materials extraction and production phase. Isolating transportation from other manufacturing steps can become complex and often depends on the boundary conditions of the cradle-to-gate LCI considered as the data source. Therefore, transportation activities taking place after pavement input material has been produced are calculated in the transportation of materials phase.

Available literature includes various sets of data sources for the various materials, representing different geographic conditions, procedures, technologies, and system boundaries. Ideally, before inclusion in the database of an LCA model, the process system underlying the material under assessment should be broken down into lower-level processes (unit processes), which may occur within and/or between facilities, in such a manner that inputs and outputs at its boundary are elementary and product flows. These processes should be recalculated based on unit process data that best suit the goal and scope of the study being performed. While such a level of discretization may be useful to meet the ISO data quality requirements (temporal, geographical, and technological representativeness, precision, completeness, consistency) for the goal and scope being considered in the analysis, there is a point in this procedure of data disaggregation where it is necessary to truncate some processes and to exclude other ones.

The cradle-to-gate LCIs referring to bitumen and bitumen emulsion are perhaps the best examples to illustrate the previous statement. Emissions from bitumen should include emissions due to oil extraction, transportation to the plant, refinement of crude oil into bitumen, transportation, and storage in depots, etc. As bitumen is one of the many products that come from crude oil, a proper allocation of the environmental flows from crude oil acquisition through the refining process to bitumen production is a difficult task. Therefore, the data with regard to bitumen, as well as bitumen emulsion production, has been collected from the Eurobitume report (Eurobitume, 2011) without performing any reanalysis of the bitumen and bitumen emulsion cradle-to-gate LCIs.

Although it is considered to be a construction material by the road pavement construction and management sector, bitumen may also be considered an energy source from a broader point of view. However, due to its highly impure organic nature, burning or processing of bitumen is associated with extra environmental burdens compared with those of alternative and conventional fuels. This fact means that in practical terms the applicability of bitumen is constrained to the condition of construction material. Therefore, in the case of bitumen, the feedstock energy (FsE), which represents the heating value of a material when burned, was dealt with differently from that of conventional energy sources. This analysis procedure is advocated by the University of California Pavement Research Center's (UCPRC's) Pavement LCA Guideline (Harvey et al., 2010). Following this recommendation, the FsE of bitumen is presented separately from other primary energy usage. The pavement model assumes a value of 40.2 MJ/kg by default (Garg et al., 2006), although that value can be edited by the model's user.

With respect to aggregates cradle-to-gate LCI, the data has been collected from a study carried out in a French quarry (Jullien et al., 2012). The pollutants released into the air at a quarry site stem from emissions produced during explosions and from operating quarry vehicles. Those emissions are allocated to different grading outputs at the plant. The energy consumption accounted for includes the electricity demand of the equipment in the production lines and the fuel consumed by non-road vehicles.

Supplementary materials that may be used in the construction and maintenance activities of flexible pavements include additives, fibers, waxes, pigments, etc. As these materials only represent a small percentage of the total mass of a given mixture, and the number of cradle-to-gate LCIs existing in literature is scarce or even non-existent, no data with regard to those materials have been inserted by default into the database.

After being produced, the pavement input materials intended for producing, for instance, a HMA are transported to an asphalt mixing plant. Asphalt mixing plants are commonly classified as a batch mixing plant or a drum mixing plant. The default data entered into the database concerning the performance of an asphalt mixing plant has been gathered from a Portuguese company that owns and operates a batch plant powered by natural gas. The FC during one year of operation has been divided by the total output of HMA produced during an equal period of time. Data on the average amount of natural gas consumed per tonne of HMA produced has been combined with the emissions factors published by the AP-42 study of HMA plants (US EPA, 2004) for a batch mixing plant powered by natural gas.

Data for the materials extraction and production phase are input into the database through the "*Materials Extraction and Production*" DbC, which has two tabs named as follows: "*Materials Extraction*" and "*Materials Production*". The "*Materials Extraction*" tab is allocated to defining the features of the individual materials. The user is asked to identify the material category by picking a label from a drop-down list, and then to enter a name, a description, a data source, an energy source, respective consumption (up to five different energy sources, picked from those available in the LCA model database), and an emission factor (EF) per tonne of material extracted for each of the substances inventoried. The "*Materials Production*" tab plays a similar role to the "*Materials Extraction*" tab but with respect to the production of mixtures. Beyond entering the type of information required in "*Materials Extraction*", the user has to identify the plant location, the type of plant (batch or drum plant), and the annual and hourly production rates. The new material and the new mixture will then become a permanent item in the LCA model database and can be chosen for future mix designs, pavement layers, and M&R actions. For computer modelling purposes, whenever a new mixture is defined, the user is directed to the "*Mixtures Composition*" tab in the "*Mixtures Design*" DbC in order to identify the materials that integrate the mixture composition and to type in its percentage by mixture weight.

2.3.2.2.2 Transportation of materials phase

The transportation of materials phase is directly linked to the materials extraction and production, construction and M&R, and EOL phases. For instance, materials for a new pavement or for an existing pavement subject to M&R interventions need to be hauled from a mixing plant or quarry to the work site, whereas the waste materials resulting from M&R interventions need to be hauled from the work site to a disposal facility or to a mixing plant. The environmental impacts resulting from the transportation of materials are influenced by five primary characteristics: (1) engine technology; (2)

payload capacity of the transportation mode; (3) transportation distance; (4) transportation speed; and (5) the mass of materials being transported. As FC and emissions profile vary with the load scenario, in the proposed LCA model all materials and wastes are assumed to be hauled by heavy-duty vehicles (HDVs) that run at their maximum legal capacity when loaded and empty on return journeys. Emissions data associated with the operation of those vehicles have been obtained from the EMEP/EEA Emission Inventory Guidebook 2013 (EEA, 2013). More details on this methodology are provided in Section 2.3.2.2.3.

In the "*Transportation*" PLCPC, the user is asked to assign a set of data for each material and mixture being transported: (1) type of movement (transport of materials from source/extraction place to mixing plant; transport of mixtures from mixing plant to work site; transport of materials directly from source/extraction place to work site; transport of materials from work site to landfill; transport of materials from work site to mixing plant or recycling facility); (2) type of HDV (fourteen categories available) and engine technology (seven Euro legislation classes available); (3) average distance in kilometers from the origin to the destination (only one direction); and (4) average speed that the HDV is supposed to travel at from the origin to the destination (km/h) and vice-versa. The payload capacity of each HDV has been defined according to (Hausberger et al., 2009).

2.3.2.2.3 Construction and maintenance and rehabilitation phase

In the construction and M&R phase, the environmental burdens are due to the combustion-related emissions from construction equipment usage. Environmental impacts resulting from traffic congestion and detouring occurring during M&R interventions are dealt with in the WZ traffic management phase. The consumption-related emissions associated with the operation of construction equipment have been obtained by applying a methodology based on the Tier 3 approach described in the EMEP/EEA Emission Inventory Guidebook 2013 for non-road mobile sources and machinery (EEA, 2013). The expression used for this methodology is as follows (Expression (2.1)):

$$E_{i,e,w}^{construction\ equipment} = HRS_{e,w} \times HP_e \times LF_e \times EF_{i,e}^{construction\ equipment} \times DF_{i,e} \tag{2.1}$$

Where $E_{i,e,w}^{construction\ equipment}$ is the environmental burden *i* resulting from the operation of the construction equipment *e* during the construction, M&R, or EOL activity *w*; $HRS_{e,w}$ is the operation time of the construction equipment *e* for completing the activity *w*; HP_e is the average rated horsepower (kWh) of the construction equipment *e*; LF_e is the average load factor of construction equipment *e*; $EF_{i,e}^{construction\ equipment}$ is the average emissions factor of the environmental burden *i* (or FC) per unit of use of construction equipment *e* (g/kWh); $DF_{i,e}$ is the degradation rate of the emission factor of environmental burden *i* (or FC) due to aging of construction equipment *e*.

As default, the average rated horsepower value has been taken from the technical specifications of the construction equipment. The load factor is applied to indicate the average proportion of rated power used, due to the effect of operation at idle and partial load conditions, as well as transient operation. Those values have been obtained from US EPA (2010c). The baseline emissions factors are given by EEA (2013) based on the EU directive emission limits. The degradation rates take into account the change of emissions with the aging of the construction equipment. Those values have been taken from EEA (2013).

The parameters in the previous expression are inputted in the "*Construction Equipment*" DbC. A new data file is created each time the user stores information about a new piece of equipment. Beyond the parameters above, the user is asked to insert the name, brand, type of equipment, type of fuel consumed, Euro legislation class compliance, year of manufacture, and age of the construction equipment at the beginning of the PAP. The EFs and FC fields are automatically filled in, as long as the year of manufacture, engine power, and Euro legislation class data are entered by the user. Once in the database, the information on the construction equipment is available to be allocated to any sort of construction, M&R, or EOL activity, either pre-existing or customized by the user. In the "*Equipment and Crews*" tab existing in the "*Construction & EOL Activities*" DbC, the names of all construction, M&R, and EOL activities, and the construction equipment are displayed. The user is then able to match the construction equipment with the activities by specifying an assignment factor between 0 and 1 that represents the effective construction equipment operation time during one hour of a determined activity. For example, if the assignment factor of a tandem roller allocated to "Asphalt Paving: laying and compacting" is equal to 0.8, then during one hour of that activity, the tandem roller's operation time will be 48 minutes.

2.3.2.2.4 Work-zone traffic management phase

In this pavement LCA model, the FC and airborne emissions resulting from traversing and detouring a WZ have been determined by adopting a two-step method. In the first step, changes in traffic flow are modeled using the capacity and delay models proposed by the Highway Capacity Manual (HCM) 2000 (TRB, 2000) to determine several outputs, such as the number of vehicles that changed speed, the number of queued vehicles, the number of vehicles that traversed the WZ, the average length of the queue, and the average vehicle speed in the queue, which are recorded by the "*WZ traffic management*" PLCPC. In the second step, those traffic outputs are then fed into two hot exhaust emissions models. The FC resulting from acceleration and deceleration movements associated with speed changes in between homogeneous driving patterns are estimated through the macroscopic four-mode "elemental model" as described by Akçelik et al. (2012), in a recalibration of Bowyer et al. (1985). It consists of a set of FC expressions derived from a microscopic FC model that comprises a polynomial model of acceleration and deceleration profiles. The FC estimations based on the acceleration and deceleration models are later combined with the Tier 1 FC-dependent EFs (minimum values) defined in the EMEP/EEA Emission Inventory Guidebook 2013 (EEA, 2013). The Tier 3 approach presented in the EMEP/EEA Emission Inventory

Guidebook 2013 (EEA, 2013) is adopted to estimate the emissions released by on-road vehicles during driving patterns characterized by a constant average speed.

The basic formula for estimating the FC and hot emissions released by on-road vehicles approaching a WZ is as follows (Expression (2.2)):

$$E_{i,j}^{on-road} = \sum_{k}^{vehicle\ technology} EF_{i,k,j}^{on-road} \times NVeh_{k,j} \times L_j \tag{2.2}$$

Where $E_{i,j}^{on-road}$ is the total environmental burden *i* resulting from the operation of all on-road vehicles at operation condition *j* (e.g., decelerating, accelerating, queuing, etc.); $EF_{i,k,j}^{on-road}$ is the average emission factor of environmental burden *i* (or FC) released by an on-road vehicle of technology *k* while driving along a segment of road 1 kilometer in length at operation condition *j* (g/km); $NVeh_{k,j}$ is the number of on-road vehicles of technology *k* facing the operation condition *j*; L_j is the length (km) of a road segment under the operation condition *j*.

The development of the Tier 3 approach was based on on-road European studies and can be found in COPERT 4 software (Gkatzoflias et al., 2012). It is an EFs model used to estimate the FC, air pollutant emissions, and GHG produced by various vehicle categories as a function of the speed, according to technological classification and European legislation. Baseline EFs are estimated for every major pollutant for every country and region in Europe. For FC and regularly studied pollutants, such as carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxide (NO_x), and particulate matter (PM), detailed EFs are available, whereas for other pollutants, more simple bulk EFs and expressions are used. Bulk emissions factors represent three driving modes: “Urban”, “Rural”, and “Highway”. In the proposed model, “Urban” bulk factors have been assumed to represent the emissions released by vehicles queuing, “Rural” bulk factors have been considered to model the emissions released by vehicles traversing the WZ segment, and “Highway” bulk factors account for emissions released during normal operating conditions. There are other substances, namely CO_2, sulfur dioxide (SO_2), and heavy metals, whose emissions estimation methods do not fall into the previous methodologies. The emissions of those substances are calculated on the basis of the FC. The adopted model is still able to account for factors like vehicle age, fuel improvements (e.g., changes in fuel properties, such as sulfur content, eyc.), gradient, and vehicle loads by using correction factors defined in EEA (2013).

Apart from the "*On-Road Vehicles Emissions Models*", predicting the marginal emissions due to congestion requires knowledge of both the distribution of the vehicle fleet into different exhaust emission legislation classes and traffic conditions during M&R activities. Regarding the former, the "*On-Road Vehicle Fleet Distribution*" DbC has been filled in with detailed data on Portuguese vehicle stocks, which are available for order on the EMISIA SA website (EMISIA SA, 2009). The default data in this worksheet-based DbC comprises the Portuguese fleet distribution per vehicle category, type, and legislation/technology (Euro legislation class), from 2010 to 2030. For years beyond the period 2010 to 2030, the tendency observed in the aforementioned period of time is extrapolated.

Using these inputs, the annual average daily traffic (AADT) is proportionally distributed into different vehicle classes and technologies, according to the vehicle population observed in each year of the "*On-Road Vehicle Fleet Distribution*" DbC. With respect to WZ traffic conditions, in the "*WZ traffic management* " PLCPC, the user is asked to provide a set of inputs such as the number of open lanes in each direction, speed limit, WZ hourly schedule, WZ length, detour rate, detour length, driving speed on the detour road, etc. The fuel consumed and vehicle emissions from detoured vehicles are added to the remaining components of WZ traffic management phase after the on-road vehicles emissions model has been run for the detour conditions. Finally, the marginal FC and airborne emissions due to WZ delays are calculated by subtracting FC and emissions released during a WZ period from the results of an equivalent non-WZ period (Expression (2.3)):

$$
\begin{aligned}
E_{Total_i}^{on-road} &= \left[E_{i,acceleration}^{on-road} + E_{i,deceleration}^{on-road} + E_{i,queuing}^{on-road} + E_{i,goingthroughWZ}^{on-road} + E_{i,detouring}^{on-road} \right] \\
&- E_{i,normaloperatingconditions}^{on-road}
\end{aligned}
\tag{2.3}
$$

Where $E_{Total_i}^{on-road}$ is the total marginal value of the environmental burden *i*, such as FC or airborne emissions. The remaining variables have the same meaning as in Expression (2.2).

2.3.2.2.5 Usage phase

The usage phase of a pavement life cycle accounts for the impacts resulting from the interaction of the pavement with the vehicles and environment throughout its PAP. These impacts include additional FC for vehicle operation due to the deterioration of the pavement (increased RR), the albedo, the roadway lighting effect, the carbonation of concrete pavement, the non-GHG climate change effect, and water pollution from leachate and runoff (Harvey et al., 2010). Only the RR effect has been included in the proposed pavement LCA model. Roads in rural/interurban areas generally do not require lighting (except at intersections). Carbonation is a process that only occurs in pavements with cement in their composition, which is not the case with the flexible pavements for which this model is intended. The albedo should only be taken into account for locations where air conditioning is used, such as in the city (Harvey et al., 2010). Although Akbari et al. (2009) have proposed a mathematical expression to estimate the radiative forcing in pavement LCAs, there are still great uncertainties about how to consider several factors, e.g. pavement aging, which have been shown to influence this phenomenon. Lastly, there is general agreement in published literature that most contaminants found in runoff water originate from vehicle sources rather than pavement materials (Santero et al., 2011b). This is due to most pavement materials being inert, so leachates do not occur, at least not at a level significant enough to deserve to be accounted for in a pavement LCA.

The RR force describes the energy loss associated with pavement-vehicle interaction. Pavement deterioration increases RR, which in turn lowers fuel economy and increases the energy consumed by traffic. Additional FC due to the deteriorated pavement can be evaluated through the change in pavement condition over the PAP. In this pavement LCA model, the additional FC originated by RR has been estimated through the MIRIAM models (Hammarström et al., 2012). Derived FC function for a car (similar models exist for heavy trucks and heavy trucks with trailers) is as follows (Expression (2.4)):

$$F_{cs} = 0.0286 \times \left[\begin{pmatrix} 1.209 + 0.000481 \times IRI \times v + 0.0394 \times MPD + \\ 0.000667 \times v^2 + 0.0000807 \times ADC \times v^2 + \\ -0.00611 \times RF + 0.000297 \times RF^2 \end{pmatrix}^{1.163} \right] \times v^{0.056} \tag{2.4}$$

Where F_{cs} is the FC due to RR (l/km); IRI is the pavement roughness, measured using the IRI (m/km); v is the vehicle speed (m/s); MPD is the pavement's macrotexture, represented by the parameter MPD (mm); ADC is the road curvature (rad/km), and; RF is the road slope (m/km).

As one can see from Expression (2.4), the influence of pavement condition on RR comes partially from changes in the pavement's roughness and macrotexture. Therefore, the first step in estimating the influence of rolling resistance on FC requires prediction of the IRI and MPD progression over the PAP. For each year of the PAP, the values of those pavement surface quality indicators are compared with their values at initial construction, taken as the baseline scenario. FC and emissions are then calculated based on the progressive deviation from that initial scenario.

Apart from the direct effect on rolling resistance, IRI has long been recognized as a factor able to affect the vehicle operating speed (Watanatada, 1981). In order to account for this effect, the speed-IRI relationship described by Yu and Lu (2014) has been included into the LCA model. According to Yu and Lu (2014), the average vehicle speed decreases linearly with the increase of IRI at a rate of -0.84 km/h. However, due to the increased frequency of "cruise control" equipment, the IRI effect on speed might not be verified in practice. Therefore, in this model the inclusion of this effect into the analysis depends on the model user's decision.

In Portugal, the Pavement Management System (PMS) of the Portuguese Road Administration (Picado-Santos and Ferreira, 2008; Ferreira et al., 2011) and other municipal PMSs (Ferreira et al., 2009a; Ferreira et al., 2009b) use the pavement performance model of the flexible pavement design method developed by AASHTO (1993) to predict the future quality of pavements. Integrating this new pavement LCA model with current Portuguese practice on pavement management requires the transformation the Present Serviceability Index (PSI) to the IRI. From the conceptual point of view, such conversion does not seem to represent an obstacle, as roughness is widely recognized as the main contributor to PSI. Thus, several expressions relating those indicators are included in the usage module and made available for choice according the model user's preference (Patterson, 1987; Al-Omari and Darter, 1994; Gulen et al., 1994). Additionally, since the relation between PSI and IRI is commonly described by a standard expression whose formulation is presented below (Expression (2.5)), users are given the option to insert their own calibration parameters.

$$IRI = a \times Ln\left(\frac{PSI}{b}\right) \tag{2.5}$$

Where IRI is the International Roughness Index (m/km); *PSI* is the Present Serviceability Index, and; *a* and *b* are calibration parameters.

Once the additional FC due to rolling resistance is calculated, those values are coupled with the Tier 1 FC-dependent EFs (minimum values) defined in the EMEP/EEA Emission Inventory Guidebook 2013 (EEA, 2013).

2.3.2.2.6 End-of-life phase

When a road pavement reaches the end of the PAP, it can be given two main destinations: (1) remain in place, serving as support for a new pavement structure, and; (2) be removed. If the pavement is removed, the debris can be landfilled or recycled in a central plant. Once recycled, those materials can be used again as a replacement for virgin aggregate sub-bases/bases or as a replacement for virgin asphalt and aggregate in new asphalt mixtures. An in-situ recycling process will not be considered by the model as an EOL treatment; rather it is more accurately considered an M&R activity (Levis et al., 2011).

Regardless of whether the pavement is landfilled or recycled, whatever the fate of the pavement, it will imply carrying out a set of actions which will have some sort of environmental impact. By definition, the environmental performance of those activities would be accounted for in other phases of the pavement LCA, namely in the construction and M&R (construction equipment operation), and transportation of materials phases. However, for the purpose of assessing the contribution of the EOL to the pavement LCA, the environmental burdens of those activities were assigned to the EOL phase.

In the pavement LCA model, the "*EOL*" PLCPC prompts the user to define the pavement's final destination: either to remain in place, or to be removed and the materials transported to either a recycling center (e.g., asphalt mixing plant, etc.) or a landfill. This PLCPC contains three tabs. The first one, designated "*Handling the multi-functionality of the EOL processes*", requires the user to define the assignment approach that would govern the share of the environmental burdens and credits between the pavement system producing the recyclable materials, or providing support capacity for a new pavement structure, and the one taking advantage of those exported functions.

Taking into account the multiplicities of scenarios involving the EOL, the uncertainties and the scope of an LCA, the pavement LCA model features two different approaches to handle the multi-functionality of the EOL phase: (1) the cut-off; and (2) the substitution variant of the system expansion approach. The cut-off approach, commonly applied in LCA of open recycling systems, follows the principle that each product is assigned only the burdens directly associated with it. On the other hand, the substitution approach, also called "avoided burden approach" or "crediting approach", consists of expanding the boundaries of the current pavement system to account for the environmental burdens that would be generated within the next pavement system to deliver a new pavement structure that incorporates either the recycled materials or the remaining pavement structure. The avoided environmental burdens are later “credited” or subtracted from those produced during the pavement system under analysis.

In both scenarios the model’s user is later directed to the tabs *“EOL Activities*” and “*EOL Materials”* either to set where in the interface of the two pavement systems the cut-off is located (i.e., to define which activities belong to the current system and, thus, requiring accounting), or to set the system boundaries of the processes whose environmental burdens are avoided.

The tab labeled “*EOL Materials*”, asks the user to define the types of pavement layers (bounded or unbounded, and respective mixtures/material) and the dimensions of the pavement section (width, length, and depth) that is to undergo the activities inherent to the selected EOL modeling approach. They can be considered either an avoided activity or an effective activity depending on the selected EOL modeling approach. In the second tab, designated “*EOL Activity*”, the user must pick the type of work to be performed (e.g., pavement milling, materials transportation, etc.) and input the production rates. Along with the previous steps, the user is also directed to the “*Transportation of materials*” PLCPC in order to define the input variables required by this PLCPC (see section 2.3.2.2.2) to model the transportation processes in case they are required.

2.3.2.3 Other modules

2.3.2.3.1 Fuel and electricity production

The overall environmental impact of a process depends on both the combustion of energy for operating equipment and vehicles, and the upstream energy requirements for producing and delivering the energy source. In that sense, it is important not to constrain the EFs related to energy sources to pre-established values that might not comply with the scope of the analysis. For this reason, model users are given the freedom to enter their own inventory data into the “*Fuels and Electricity Production*”

DbC. The required information includes the type of fuel/electricity (nine types are available: coal, crude oil, gasoline, diesel, fuel oil, burning oil, natural gas and liquefied petroleum gas [LPG], and electricity), name, description, data source, input date, airborne EFs, eight cumulative energy demand (CED) indicators (fossil, nuclear, primary forest, biomass, wind, solar, geothermal, and hydro energy), and the consumption of non-energetic resources per unit of energy source (depending on the type of energy source it can be given in g/kWh, g/kg, or g/m^3). The energy source data becomes a permanent item in the LCA model database and is used to compute the environmental impacts coming from the upstream processes associated with the energy sources consumed by the various modeled processes over the pavement life cycle.

For computation, all energy sources are converted into a universal energy unit (MJ), according to the lower heating values (LHVs) presented in Table 2.1. The default pavement LCA database was mostly populated with EFs derived from the ELCD 2.0 databases (EC, JRC - IES and DGE - DG, 2008).

Table 2.1- LHVs of the energy sources.

Energy source	Unit	Value	Data source
Burning oil	MJ/kg	43.9	DECC (2013)
Mine gas	MJ/ m^3	18.9	
Crude oil	MJ/kg	43.2	Frischknecht et al. (2007)
Diesel	MJ/kg	42.8	
Electricity	MJ/kWh	3.6	
Fuel oil	MJ/kg	41.2	
Gasoline	MJ/kg	42.5	
Hard coal	MJ/kg	28.9	
Soft coal	MJ/kg	8.4	
Natural gas	MJ/m^3	36.32	
LPG	MJ/kg	46.15	IEA (2005)

Legend: LPG- liquefied petroleum gas.

2.3.3 Life cycle impact assessment

In the LCIA, the inventory results are assigned to different impact categories based on the expected types of impacts on the environment. The first step of LCIA consists of classifying the environmental loading into various categories, known as classifications. Characterization factors are then used to quantify the magnitude of the contribution that an LCI analysis result may have in producing the associated impact. In this model, the impact categories were set at the midpoint of the impact pathway rather than at the endpoint. Application of the latter is still not seen as mature in terms of fulfilling the criteria for scientific and stakeholder acceptance due to the insufficient level of scientific quality, the uncertainties and complexities surrounding the methodological assumptions, and a lack of completeness of scope (Hauschild et al., 2013). On the other hand, the application of a midpoint method in the interpretation of LCA results provides several advantages (Mizsey et al., 2009): (1) it exposes the multidimensionality of the problem of environmental assessment; (2) it does not require additional steps for data collection, modeling, and computation; and (3) it makes possible the iterative evaluation of impact indicators and the exclusion of indicators with excessively high uncertainty.

According to the LCI results and the impact categories commonly recognized as the most representative of the three protection areas (human health, natural environment, and natural resources), the following impact categories have been selected to be modeled in LCIA: CC, acidification (Ac) due to airborne emissions, terrestrial eutrophication (TE), human toxicity (HT) due to airborne emissions, photochemical ozone formation (POF), and abiotic resource depletion in terms of fossil fuels (ARD FF) and mineral resources (ARD MR). Characterization models and associated characterization factors proposed to quantify the contribution of each LCI element to the aforementioned impact categories have been selected according to the recommendations of the International Reference Life Cycle Data System (ILCD) handbook (Hauschild et al., 2013), but taken into account the compatibility between the LCI detail level promoted by the pavement LCA model and those required by the methods suggested in the ILCD handbook, as well as the recent literature addressing emissions timing in LCA. The energy intensity of the processes was evaluated through the CED indicator, which calculates the primary energy use throughout the life cycle of the product under assessment (Hischier et al., 2010).

Current state-of-the-practice consists of providing characterization factors that linearly represent the contribution of a mass of a given substance to a specific impact category.

Emissions occurring at different points in time are added together as if they occurred at the same time, which means that emissions profiles with different effects at different times are treated equally (Kendall, 2012). The adoption of such procedures has been demonstrated to potentially overestimate the system contribution for certain impact categories (Kendall, 2012; Collinge et al., 2013). Therefore, in this model the user is given the option to choose between the Intergovernmental Panel on Climate Change's (IPCC) Global Warming Potentials (GWPs) and the time-adjusted warming potentials (TAWPs) proposed by Kendall (2012). The lack of either consistent or geographically suitable sets of other time-adjusted characterization factors across multiple impact categories does not allow for the accounting of time effects in impact categories other than CC. If dynamic characterization factors for other impact categories are developed in the future, these can be incorporated into the LCA model. Impact categories and respective characterization factors selected for the model are summarized and exhibited in Table 2.2.

Lastly, according to ISO (2006b) normalization, grouping, and weighting steps in LCA are optional. While they might be useful in translating the impact scores of different impact categories into a more understandable and somehow digestible form (Dahlbo et al., 2013), they also entail a risk of oversimplifying the results. Therefore, this first version of the pavement LCA model does not include those three optional steps, although its modular nature will allow easy integration into a future version of the model.

Table 2.2- Environmental impact categories, and respective characterization factors.

Impact category	Impact category indicator	Characterization factor name	Characterization factor unit	Inventory loading	Characterization factor value	Model
CC	Infrared Radiative Forcing	GWP_{100}	CO_2-eq/kg	CO_2 CH_4 N_2O	-[a]	Kendall (2012)
Ac: emissions to air	Accumulated Exceedance (AE)	Acidification Potential	molc H^+-eq/kg	SO_2	0.6	Seppala et al. (2006); Posch et al. (2008)
				NO_2	0.2	
				NH_3	1	
TE: emissions to air	AE	Eutrophication Potential	molc N-eq/kg	NO_2	2.6	Seppala et al. (2006); Posch et al. (2008)
				NH_3	9.4	
HT: emissions to air	Acceptable Daily Intake	Human Toxicity Potential (HTP_{100})	kg 1.4-dichlorobenzene eq/kg (kg 1.4-DB-eq/kg)	NO_x	1.2	Guinée et al. (2002)[c]
				SO_2	0.096	
				NH_3	0.100	
				Lead	29.136	
				$PM_{2.5}$	0.82	
POF	Photochemical Ozone Creation Potential (POCP)	Ozone Formation Potential	kg NMVOC-eq/kg	NO_x	1	van Zelm et al. (2008) as applied in ReCiPe 2008 (Goedkoop et al., 2013)
				NMVOC	1	
				CH_4	0.0101	
				CO	0.0456	
				SO_x	0.0811	
					0.235	
				VOC		
ARD MR	Scarcity	Abiotic Depletion Potential: mineral resources (ADP MR)	kg Antimony eq/kg (kg Sb-eq/kg)	Mineral resources	1.40E-11[b]	Guinée et al. (2002)[c]
ARD FF	Scarcity	Abiotic Depletion Potential: fossil fuels (ADP FF)	MJ/kg or MJ/m^3	Fossil fuels	LHVs[d]	Guinée et al. (2002)[c]

Legend: CC- climate change; Ac- acidification; TE- terrestrial eutrophication; HT- human toxicity; POF- photochemical ozone formation; ARD FF- abiotic resource depletion in terms of fossil fuels; ARD MR- abiotic resource depletion in terms of mineral resources; AE- accumulated exceedance; POCP- photochemical ozone creation potential; LHV- lower heating value.

Notes: [a] The value depends on time and type of GHG.

[b] Figure for Silicium. For the remaining mineral resources accounted for, the recommended characterization factor values were considered.

[c] Characterization factors according to the updated version of the Center Environmental Studies of the University of Leiden´s "CML" factors (CML, 2013).

[d] The ADP FF are given by the LHVs of the fossil fuels.

2.3.4 Calculation and model outputs

The proposed pavement LCA model is able to deal efficiently with a significant amount of information and related models. Most of that information is further broken down and differentiated into several emissions sources within each pavement life cycle phase. From this exhaustive analysis might result a set of detailed outputs that exceed the real users' needs. Such usage of unnecessary computational resources increases the computation time and, depending on the user's experience, might cause some difficulties in handling and interpreting the model's outputs. Thus, in order to make the model supportive of the decision-making process, the user is able to choose the exact outputs and level of disaggregation displayed. Outputs are customized using the "*LCA: Life Cycle Inventory*" and "*LCA: Life Cycle Impact Assessment*" tabs hosted in the "*Desired Outputs*" OC.

Each pavement life cycle phase has its own mode of exhibiting outputs. For each life cycle phase, the results are split into emissions related to the process energy combustion and emissions related to the upstream energy requirements. The emissions due to both sources are further displayed with different levels of discretization depending on the pavement life cycle phase. The desired impact categories and the analytical time horizon are selected in the *"LCA: Life Cycle Impact Assessment"* tab. For the impact categories enabled to account for the temporal variation, in this case CC, the user selects between time-adjusted characterization factors, and respective time horizon, and non-time-sensitive characterization factors.

The selected LCI and LCIA results are then exported to a Microsoft Excel file and displayed in individual life cycle phase worksheets through tables and charts. Apart from the individual treatment given to each phase, the Excel file also contains several worksheets aimed at comparing the environmental performance of each phase against the remaining phases. Table 2.3 summarizes the features of the worksheets hosted by the Microsoft Excel file that gathers the LCA model outputs.

Table 2.3- Features of the worksheets hosted by the Microsoft Excel generated to export the LCA model outputs.

Worksheet type	LCA stage	Worksheet	Description	Sub worksheet name	Notes
1	Goal and scope definition	Project description	Project general data: descriptive data identifying the project Analysis data: PAP; pavement life cycle phases selected Project detail data: traffic over PAP Construction: layers dimensions; mixtures typology Maintenance: schedule; WZ dimensions; type of M&R activity; traffic-related inputs	‘Project Description’	
2	LCI	Process energy combustion	Inventory outputs resulting from the process energy combustion in each pavement life cycle phase	‘LCI_MaterialsExtraction_and_Production‘ ‘LCI_Construction_and_Maintenance’; ‘LCI_Transportation’; ‘LCI_WZ_Traffic_Manag.’ ’LCI_Usage’; ‘LCI_EOL’	Lowest discretization level: pavement layer and M&R activity
			Inventory outputs resulting from the process energy combustion per unitary processes of several pavement life cycle phases	‘LCI_UnitProcess_MaterialsExtraction_and_Production’ ‘LCI_UnitProcess_Construction_and_Maintenance’; ’LCI_UnitProcess_Transportation’ ‘LCI_UnitProcess_WZ_Traffic_Manag.’ ’LCI_UnitProcess_Usage’; ‘LCI_UnitProcess _EOL’	Lowest discretization level: pavement materials
3		Pre-combustion energy-related processes	Inventory outputs associated with the pre-combustion energy-related processes corresponding to the process energy consumed in each pavement life cycle phase	‘LCI_MaterialsExtraction_and_Production’ ’LCI_Construction_and_Maintenance’; ‘LCI_Transportation ’ ‘LCI_WZ_Traffic_Manag.’; ‘LCI_Usage’; ‘LCI_EOL’	Lowest discretization level: pavement layer and M&R activity
			Inventory outputs associated with the pre-combustion energy-related processes corresponding to the process energy consumed per unitary processes of several pavement life cycle phases	‘LCI_UnitProcess_MaterialsExtraction_and_Production’ ‘LCI_UnitProcess_Construction_and_Maintenance’ ‘LCI_UnitProcess_Transportation’; ‘LCI_UnitProcess_WZ_Traffic_Manag.’; ‘LCI_UnitProcess_Usage’; ‘LCI_UnitProcess _EOL’	Lowest discretization level: pavement materials

Legend: LCI- life cycle inventory; WZ- work-zone; EOL- end-of-life.

(continued)

Worksheet type	LCA stage	Worksheet	Description	Sub worksheet name	Notes
4	LCI	Comparative worksheets	The results displayed by worksheets type 2 and 3 are gathered and exhibited in comparative tables and charts	‘LCI_MaterialsExtraction_and_Production_Comparison’; ‘LCI_Construction_and_Maintenance_Comparison’; ‘LCI_Transportation_Comparison’; ’LCI_WZ_Traffic_Manag._Comparison’; ’LCI_Usage_Comparison’; ‘LCI_EOL_Comparison’; ‘LCI_UnitProcess_MaterialsExtraction_and_Production_Comparison’; ‘LCI_UnitProcess_Construction_and_Maintenance_Comparison’; ’LCI_UnitProcess_Transportation_Comparison’; ’LCI_UnitProcess_WZ_Traffic_Manag._Comparison’; ’LCI_UnitProcess_Usage_Comparison’; ‘LCI_UnitProcess_EOL_Comparison’	Lowest discretization level in accordance with worksheets types 2 and 3
5	LCIA	Process energy combustion	For each worksheet type 2, the inventory loads are assigned to the defined impact categories and characterized according to the information presented in Table 2.2	Names are equal to those adopted in the worksheet types 2, 3 and 4 but start with “LCIA” instead of “LCI”	Lowest discretization level in accordance with worksheets type 2
6		Precombustion energy-related processes	For each worksheet type 3, the inventory loads are assigned to the defined impact categories and characterized according to the information presented in Table 2.2		Lowest discretization level in accordance with worksheets type 3
7		Comparative worksheets	The results displayed by worksheets type 5 and 6 are gathered and exhibited in comparative tables and charts		Lowest discretization level in accordance with worksheets types 5 and 6

Legend: LCI- life cycle inventory; LCIA- life cycle impact assessment; WZ- work-zone; EOL- end-of-life.

2.3.5 Uncertainties and limitations

The LCA methodology requires multiple choices, many of which are constrained by uncertainties and limitations of several types, making problems less tangible and decision-making difficult (Funtowicz et al., 1999). According to the scope of the LCA study, some of these factors might represent additional difficulties in achieving the desired goals. Overall, the main sources of uncertainties and limitations in conducting an LCA study come from the decision-making process related to data, models, and the practitioner's choices and assumptions. This section addresses the sources of uncertainty, the limitations of the LCA model, and provides justifications that support several choices made during the development of the model that have introduced some type of uncertainty.

According to the EC, JRC - IES (2010) the quality of LCI data quality can be characterized by representativeness (technological, geographical, and time-related), completeness (regarding impact category coverage in the inventory), precision/uncertainty (of the collected or modeled inventory data), and methodological appropriateness and consistency. The presented LCA model uses, when feasible, recognized data sources, peer-reviewed studies and reports from recognized institutions, that are geographically and technologically compatible, to meet these criteria. However, even recognized sources do not always describe all the processes accounted for in the cradle-to-gate LCI of some materials. This introduces difficulties in assessing whether the system boundaries associated with the cradle-to-gate of such materials fully match the system boundaries set by the user.

The time-related issues are certainly significant sources of uncertainty when conducting an LCA, especially for a long PAP. During a long PAP, such as the one typically considered in both pavement LCA and pavement LCCA, what is now at the cutting-edge technologically might be out-of-date ten years from now or even sooner. This fact is valid not only for technology but also for knowledge, as well as pavement construction and M&R-related practices. In the materials extraction and production phase, the FC and emissions factors associated with the several processes accounted for are kept constant over the PAP. Factors could be included to account for technological improvement, but what values would be considered is an issue that by itself represents a source of uncertainty. In the construction model, this issue was addressed by considering the degradation rates of airborne EFs and the average lifespan of construction equipment. Whenever a construction vehicle reaches its life expectancy, the LCA model replaces it with a new one possessing an engine that meets the Euro legislation class in force at the time. Though new and increasingly constrained regulations are expected to come into force in the future, all new construction equipment has been assumed to be powered by an engine meeting Euro Stage IV standards because at this moment there is no way to quantitatively measure such improvements. Still, the airborne emission model considered for construction equipment is a static one. Although the load factor attempts to represent average engine performance during the operation time, it is not truly able to model the diversity of scenarios experienced by the engine. In the case of on-road vehicles, no additional or improved engine technologies, apart from those known right now and recognized by the COPERT model, have been considered.

With respect to the usage phase, several projects have acknowledged the importance of the pavement on vehicle FC. For example, the structural deflection effect, although it may be significant, was not added to the usage phase model. Concerning the marginal FC due to this resistive force, the MIRIAM models have been used. Those models, part of an ongoing research project, have been developed only for three categories of vehicles and are based on a restrictive spectrum of pavement conditions, types of tires, and climatic conditions. Moreover, MPD and IRI, which have been found to be the pavement surface characteristics with the most influence on FC, are difficult to predict and control during the PAP. Few MPD/mean texture depth (MTD) prediction models are available in published literature, and those which do exist have been developed for particular road sections and climates, and only address short periods of time. Therefore, the usage of up-to-date and road-section-customized models is desirable and welcome as soon as new models are available.

Lastly, in the proposed pavement LCA model, the environmental burdens assessed do not represent all the flows. Other emissions outside the scope of this study, or even inside the scope but for which there is no data, could result in additional environmental impacts. As many of the meaningful flows as possible were captured, but due to the diversity of models integrated in the proposed LCA model, it has not been possible to collect exactly the same outputs in all of them. In addition, some models either overlap or do not report the emissions classified as hydrocarbons (HC) or VOC explicitly enough. These are compounds containing combinations of carbon and hydrogen, and may also contain oxygen, sulfur, nitrogen, and halogens like fluorine and chlorine (Petchers, 2003). Such a lack of clarification in the LCIA stage may lead to under- or over-estimation in some impact categories due to an inaccurate characterization.

2.4 Summary and conclusions

Over the past decades the LCA methodology has been used intensively to assess the environmental performance of multiple systems in diverse fields. For the specific case of pavement, the effective integration of LCA into pavement infrastructure decision-making is still in its infancy. Some highway agencies feel that the environmental concerns are somehow negligible or do not fall under their responsibility. Others believe that environmental analyses imply further expenses. In addition, the lack of available tools that allow DMs to use their own data and to model their own procedures, instead of imposing a “black-box” with a set of incomplete, subjective, and unclear data and methods, hinders change.

To enhance the current state-of-practice, this chapter has presented the development of a VB.NET-based pavement LCA model able to consider the pavement cycle as an integrated whole, from materials extraction and production to construction, to usage and EOL. Various models, research papers, reports, and guidelines have been analyzed in order to determine appropriate methods that broaden our awareness of the impacts caused by the entire life cycle, typically estimated in the state-of-the-practice methodologies applied in the pavement field. The developed model expands the LCIA to categories other than CC and upgrades the impact assessment techniques typically incorporated in the majority of pavement LCA tools through the inclusion of dynamic characterization factors. Additionally, thanks to the open and customizable database that comes with the pavement LCA model, the approach can be applied to a diversity of case studies and projects while providing trust and credibility to the geographical and temporal context of the results.

Because the highly customizable nature is present throughout the various steps of the model, the user is not constrained to a set of pre-established and imposed conditions and assumptions. The software allows the user to handle the singularity of road pavement projects and the remarkable diversity of the materials, structures, construction techniques, and M&R plans associated with them. Therefore, the more relevant areas and related key points of the pavement life cycle can be measured and benchmarked against other solutions and projects.

In the near future, the development of this model will proceed in five main directions. First, the applicability of this LCA model will be illustrated through its application to a case study representative of the current Portuguese practice on pavement construction and management. Second, the geographical applicability of the LCA model will be extended, in a first stage, by including sub-models tailored for other countries, namely the US, and in a second stage by fully applying the model to a case study. Third, the methodologic approach of this LCA model will be upgraded from the process-based approach to the hybrid approach. This improvement in the model’s approach will be performed by integrating it with a comprehensive pavement LCC model that allows the several sub-models to connect with one another by monetary flows associated with exchanges of the pavement life cycle system that are directly covered by the LCC model but for which specific process-based LCI (P-LCI) data are either completely or partially unavailable. Fourth, the comprehensive pavement LCC-LCA model will be incorporated, along with a decision-support module, within a MOO framework to identify optimal pavement M&R strategies that yield the best tradeoff between conflicting objectives. Fifth, the analysis level of the optimization-based LCC-LCA model will be updated from the project to the network level to ensure that the decisions taken at project level end up in optimal sustainable solutions for the whole road pavement network.

2.5 References

Akbari, H., Menon, S. and Rosenfeld, A., 2009. Global cooling: increasing world-wide urban albedos to offset CO. *Climatic Change*, 9(3-4), 275-286.

Akbarian, M. and Ulm, F., 2012. *Model based pavement- vehicle interaction simulation for life cycle assessment of pavements*. Available at: http://web.mit.edu/cshub/publications/reports.html.

Akçelik, R., Smit, R. and Besley, M., 2012. Calibrating fuel consumption and emission models for modern vehicles. *In: Proceeding of the IPENZ Transportation Group Conference*, Rotorua, New Zealand.

Al-Omari, B. and Darter, M., 1994. Relationships between international roughness index and present serviceability rating. *Transportation Research Record: Journal of the Transportation Research Board*, 1435, 130-136.

American Association of State Highway and Transportation Officials (AASTO), 1993. *Guide for design of pavement structures*. 4th ed. Washington, DC: American Association of State Highway and Transportation Officials.

Athena Sustainable Materials Institute (ASMI), 2012. *The Athena impact estimator for highways- user guide*. Available at: http://www.athenasmi.org/.

Birgisdóttir, H., Pihl, K., Hauschild, M. and Christensen, T., 2006. Environmental assessment of roads constructed with and without bottom ash from municipal solid waste incineration. *Transportation Research Part D: Transport and Environment*, 11(5), 358-368.

Bowyer, D., Biggs, D. and Akçelik, R., 1985. *Guide to fuel consumption analysis for urban traffic management* (Special Report SR No.32). ARRB Transport Research Ltd, Vermont South, Australia.

California Air Resources Board (CARB), 2007. *EMFAC2007- calculating emissions inventory for vehicles in California*. Available at: http://www.arb.ca.gov/msei/onroad/downloads/docs/user_guide_emfac2007.pdf.

Carlson, A., 2011. *Life cycle assessment of road and pavements- studies made in Europe* (VTI report 736A). Available at: http://www.vti.se/en/publications/life-cycle-assessment-of-roads-and-pavements--studies-made-in-europe/

CML, 2013. *CML-IA characterisation factors (updated April 2013).* Available at: http://cml.leiden.edu/software/data-cmlia.html#downloads

Collinge, W., Landis, A., Jones, A., Schaefer, L. and Bilec, M., 2013. Dynamic life cycle assessment: framework and application to an institutional building. *International Journal of Life Cycle Assessment*, 18(3), 538-552.

Dahlbo, H., Koskela, S., Pihkola, H., Nors, M., Federley, M. and Seppälä, J., 2013. Comparison of different normalised LCIA results and their feasibility in communication. *International Journal of Life Cycle Assessment*, 18(4), 850-860.

Damas, L., 2005. *SQL- Structured Query Language.* Lisboa: FCA- Editora de Informática Lda. (in Portuguese).

Department of Energy & Climate Change (DECC), 2013. *DUKES 2013: Calorific values*. Available at: https://www.gov.uk/government/statistical-data-sets/dukes-2012-calorific-values.

EMISIA SA, 2009. http://www.emisia.com/

Eurobitume, 2011. *Life cycle inventory: bitumen*. Available at: http://www.eurobitume.eu/hse/sustainability

European Commission (EC), 2011. *White paper. Roadmap to a single European transport area - towards a competitive and resource efficient transport system*. COM(2011) 144 final, Brussels: European Commission, Brussels. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0144:EN:NOT.

European Commission (EC), 2012. *EU transport in figures 2011 - statistical pocketbook*. European Commission, Luxembourg: Publications Office of the European Union. Available at: http://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2012_en.htm.

European Commission - Joint Research Centre - Institute for Environment and Sustainability (EC, JRC - IES), 2010. *International reference life cycle data system (ILCD) handbook: general guide for life cycle assessment - detailed guidance*. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union. Available at: http://eplca.jrc.ec.europa.eu/?page_id=86

European Commission, Joint Research Centre - Institute for Environment and Sustainability and DG Environment - Directorate G. (EC, JRC - IES and DGE - DG), 2008. *European reference life cycle database, version 2.0*. Available at: http://lca.jrc.ec.europa.eu

European Environment Agency (EEA), 2013. *EMEP/EEA air pollutant emission inventory guidebook 2009. Technical guidance to prepare national emission inventories* (European Environment Agency Technical report nº12/2013), Luxembourg: Publications Office of the European Union. Available at: http://www.eea.europa.eu/publications/emep-eea-guidebook-2013

Ferreira, A., Meneses, S. and Vicente, F., 2009a. Pavement management system for Oliveira do Hospital, Portugal. *Proceedings of the ICE - Transport*, 162(3), 157-169.

Ferreira, A., Meneses, S. and Vicente, F., 2009b. Alternative decision-aid tool for pavement management. *Proceedings of the ICE - Transport*, 162(1), 3-17.

Ferreira, A., Picado-Santos, L., Wu, Z. and Flintsch, G., 2011. Selection of pavement performance models for use in the Portuguese PMS. *International Journal of Pavement Engineering*, 12(1), 87-97.

Fox, J., Bell, D., Edmond, G., Cummings, P. and Langstraat, J., 2011. A practical tool for low-carbon road design and construction. *Proceedings of the ICE – Transport*, 164(3), 165-179.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M. and Wernet, G., 2007. Overview and Methodology. (ecoinvent report No. 1). Available at: http://www.ecoinvent.org/

Funtowicz, S., Martinez-Aler, J., Munda, G. and Ravetz, J. R., 1999. *Information tools for environmental policy under conditions of complexity* (Environmental Issues Series 9), Luxembourg: Office for Official Publications of the European Communities. Available at: http://www.eea.europa.eu/publications/ISSUE09.

Garg, A., Kazunari, K. and Pulles, T., 2006. *IPCC guidelines for national greenhouse gas inventories*. Intergovernmental Panel on Climate Change.

Gkatzoflias, D., Kouridis, C., Ntziachristos, L. and Samaras, Z., 2012. *COPERT 4-Computer programme to calculate emissions from road transport. users manual (version 9.0)*. Available at: http://www.emisia.com/copert/Copert4.html

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., Van Zelm, R., 2013. *ReCiPe 2008- a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level* (first edition, version 1.08. Report I: Characterization). Available at: http://www.lcia-recipe.net/

Guinée, J. (final ed.), Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H., de Bruijn, J., van Duin, R. and Huijbregts, M., 2002. *Handbook on life cycle assessment: operational guide to the ISO standards*. Dordrecht (The Netherlands): Kluwer Academic Publishers.

Gulen, S., Woods, R., Weaver, J. and Anderson, V., 1994. Correlation of Present Serviceability Ratings with International Roughness Index. *Transportation Research Records: Journal of the Transportation Research Board*, 1435, 27-37.

Hammarström, U., Eriksson, J., Karlsson, R. and Yahya, M.-R., 2012. *A rolling resistance model, a fuel consumption model and the traffic energy saving potential from changed road surface condition* (VTI report 748A). Available at: http://www.vti.se/en/publications/rolling-resistance-model-fuel-consumption-model-and-the-traffic-energy-saving-potential-of-changed-road-surface-conditions/

Harvey, J., Kendall, A., Lee, I.-S., Santero, N., Van Dam, T. and Wang, T., 2010. *Pavement life cycle assessment workshop: discussion summary and guidelines* (Technical Memorandum: UCPRC-TM-2010-03). Available at: http://www.ucprc.ucdavis.edu/PublicationsPage.aspx

Harvey, J., Kendall, A., Santero, N. J., Van Dam, T., Lee, I.-S. and Wang, T., 2011. Pavement Life Cycle Assessment Workshop, May 5-7, 2010 in Davis, California, USA. *International Journal of Life Cycle Assessment*, 16 (9), 944-946.

Hausberger, S., Rexeis, M., Zallinger, M. and Luz, R., 2009. *Emission factors from the model PHEM for the HBEFA version 3* (Report Nr. I-20/2009). Available at: http://www.hbefa.net/e/index.html.

Hauschild, M., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O., Margni, M., Schryver, A., Humbert, S., Laurent, A., Sala, S. and Pant, R., 2013. Identifying best existing practice for characterization modeling in life cycle impact assessment. *International Journal of Life Cycle Assessment*, 18(3), 683-697.

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M. and Nemecek, T., 2010. *Implementation of life cycle impact assessment methods* (ecoinvent report No. 3, v2.2). Available at: http://www.ecoinvent.org/

Horvath, A., Pacca, S., Masanet, E. and Canapa, R., 2007. *Palate: Pavement life-cycle assessment tool for environmental and economic effects*. Available at: www.ce.berkeley.edu/~horvath/palate.html.

Huang, Y., Bird, R. and Bell, M., 2009a. A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation. *Transportation Research Part D: Transport and Environment*, 14(3), 197-204.

Huang, Y., Bird, R. and Heidrich, O., 2009b. Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. *Journal of Cleaner Production*, 17(2), 283-296.

Huang, Y., Spray, A. and Parry, T., 2013. Sensitivity analysis of methodological choices in road pavement LCA. *International Journal of Life Cycle Assessment,* 18(1), 93-101.

International Energy Agency (IEA), 2005. *Energy Statistics Manual*. France: IED publications.

International Organization for Standardization (ISO), 2006a. *ISO 14040:2006. International Standard ISO 14040: environmental management – life cycle assessment: principles and framework, October*. Geneva (Switzerland): International Organization for Standardization.

International Organization for Standardization (ISO), 2006b. *ISO 14044:2006. International Standard ISO 14044: environmental management – life cycle assessment: requirements and guidelines, October*. Geneva (Switzerland): International Organization for Standardization.

Jullien, A., Proust, C., Martaud, T., Rayssac, E. and Ropert, C., 2012. Variability in the environmental impacts of aggregate production. *Resources, Conservation and Recycling*, 62, 1-13.

Kendall, A., 2012. Time- adjusted global warming potentials for LCA and carbon footprints. *International Journal of Life Cycle Assessment,* 17(8), 1042-1049.

Levis, J., Barlaz, M., Tayebali, A. and Ranjithan, S., 2011. Quantifying the greenhouse gas emission reductions associated with recycling hot mix asphalt. *Road Materials and Pavement Design*, 12(1), 57-77.

Loureiro, H., 2010. *Visual Basic- curso completo*. Lisboa: FCA- Editora de Informática Lda. (in Portuguese).

Melanta, S., Miller-Hooks, E. and Avetisyan, H., 2013. Carbon footprint estimation tool for transportation construction projects. *ASCE-Journal of Construction Engineering and Management*, 139(5), 547-555.

Miller, T. and Bahia, H., 2009. *Sustainable asphalt pavements: technologies, knowledge gaps and opportunities* (White Paper). Available at: http://uwmarc.wisc.edu/theses-and-white-papers.

Mizsey, P., Delgado, L. and Benko, T., 2009. Comparison of environmental impact and external cost assessment methods. *International Journal of Life Cycle Assessment,* 14(7), 665-675.

Mukherjee, A. and Cass, D., 2012. Project Emission Estimator: Implementation of a Project-Based Framework for Monitoring Pavement Greenhouse Gas Emissions. *Transportation Research Record: Journal of the Transportation Research Board,* 2282, 91-99

Paterson, W., 1987. *Road Deterioration and Maintenance Effects*. Washington, D.C.: The World Bank.

Petchers, N., 2003. *Combined heating, cooling & power handbook: technologies & applications. an integrated approach to energy resource optimization*. Liburn (Georgia): The Fairmont Press, Inc.

Picado-Santos, L. and Ferreira, A., 2008. Contributions to the development of the Portuguese road administrations pavement management system. *In: Proceedings of the 3rd European Pavement and Asset Management Conference*, Coimbra, CD edition., paper 1138.pdf, 1-10.

Posch, M., Seppälä, J., Hettelingh, J., Johansson, M., Margni, M. and Jolliet, O., 2008. The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. *International Journal of Life Cycle Assessment*, 13(6), 477-486.

Santero, N. and Horvath, A., 2009. Global warming potential of pavements. *Environmental Research Letters*, 4(3), 1-7.

Santero, N., Masanet, E. and Horvath, A., 2011a. Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation and Recycling*, 55(8-9), 801-809.

Santero, N., Masanet, E. and Horvath, A., 2011b. Life-cycle assessment of pavements. Part II: filling the gaps. *Resources, Conservation and Recycling*, 55(9-10), 810-818.

Seppälä, J., Posch, M., Johansson, M. and Hettelingh, J., 2006. Country-dependent characterization factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. *International Journal of Life Cycle Assessment*, 11(6), 403-416.

The World Bank, 2011. *ROADEO toolkit user manual. User manual: model framework and assumptions*. Available at: http://siteresources.worldbank.org/INTEAPASTAE/Resources/ROADEO_User_Manual.pdf.

Transportation Research Board (TRB), 2000. *Highway Capacity Manual 2000*. Transportation Research Board, Washington, D.C.

TRL, 2010. *CO_2 estimator tool for aggregates - user guide v2.0* (WRAP Project MRF136. Report prepared by Wayman, M., Schiavi, I., Mellor and Cordell, B., TRL Limited, Wokingham). Available at: http://aggregain.wrap.org.uk/sustainability/try_a_sustainability_tool/co2_emissions.html.

TRL, 2011. *asPECT: asphalt Pavement Embodied Carbon Tool. Software user manual*. Available at: http://www.sustainabilityofhighways.org.uk/.

United States Environmental Protection Agency (US EPA), 2004. *AP-42: compilation of air pollutant emission factors* (Volume 1: Stationary point and area sources, Chapter 11: Mineral products industry, 11.1). Available at: http://www.epa.gov/ttn/chief/ap42/ch11/index.html.

United States Environmental Protection Agency (US EPA), 2010a. *Exhaust and crankcase emission factors for nonroad engine modeling- compression- ignition* (Report No. NR-009d). Available at: http://www.epa.gov/otaq/nonrdmdl.htm#model

United States Environmental Protection Agency (US EPA), 2010b. *Motor Vehicle Emission Simulator (MOVES). user guide for MOVES2010b* (Report EPA-420-B-12-001b). Available at: http://www.epa.gov/otaq/models/moves/index.htm#user.

United States Environmental Protection Agency (US EPA), 2010c. *Median life, annual activity, and load factor values for nonroad engine emissions modeling* (Report No. NR-005d). Available at: http://www.epa.gov/otaq/nonrdmdl.htm#model

Van Zelm, R., Huijbregts, M., Den Hollander, H., Van Jaarsveld, H., Sauter, F., Struijs, J., VanWijnen, H. and Van de Meent, D., 2008. European characterization factors for human health damage of PM_{10} and ozone in life cycle impact assessment. *Atmospheric Environment*, 42(3), 441-453.

Yu, B. and Lu, Q., 2012. Life cycle assessment of pavement: methodology and case study. *Transportation Research Part D: Transport and Environment*, 17(5), 380-388.

Yu, B. and Lu, Q., 2014. Empirical model of roughness effect on vehicle speed. *International Journal of Pavement Engineering*, 15(4), 345-351.

Wang, T., Lee, I.-S., Kendall, A., Harvey, J., Lee, E.-B. and Kim, C., 2012. Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production*, 33, 86-96.

Watanatada, T., 1981. *Highway design and maintenance standards model (HDM) model description and user's manual - release II.* Transportation, Water and Telecommunications Department Report Washington, DC: The World Bank.

Zammataro, S., 2011. Assessing greenhouse gas emissions in road construction: an example of calculation tool for road projects. *In: PIARC seminar on reducing the carbon footprint in road construction*, 17-19 February 2011, New Delhi, India.

Zhang, H., Lepech, M., Keoleian, G., Qian, S. and Li, V., 2010. Dynamic life-cycle modeling of pavement overlay systems: capturing the impacts of users, construction, and roadway deterioration. *ASCE-Journal of Infrastructure Systems*, 16(4), 299-309.

Chapter 3

A Life Cycle Assessment Model for Pavement Management: Road Pavement Construction and Management in Portugal

3.1 Introduction

Worldwide, transportation authorities are setting targets and adopting policies to promote sustainable development and mitigate adverse environmental changes such as global warming, ozone depletion, and soil acidification. The European Commission (EC) has recently presented a roadmap that defines the key elements that should shape the climate actions of the EU and help the EU become a competitive, low-carbon economy by 2050 (EC, 2011). Similar objectives have been adopted by the State of California through a legislative mandate that requires statewide GHG emissions to be reduced to the 1990 level by 2020 and to 20 percent of the 1990 level by 2050 (CARB, 2008).

The transportation sector, due to its significant contribution to current emissions, has a key role to play in achieving an expressive inversion of the current trend. Within this sector, the highway infrastructure, and in particular road pavements, have a set of specificities that can be addressed accordingly to help achieve the established milestones. For instance, pavement construction requires large amounts of materials obtained through highly energy-demanding processes, which often occur far away from the construction site (Zapata and Gambetese, 2005). Additionally, the long lives of pavements make them vulnerable to deterioration, which might not be tolerated by increasingly demanding road users. Agencies must provide a service with high levels of quality, comfort, and safety. This requires regular maintenance work over the pavement's life, which often results in additional emissions and consumption of mineral and energy resources.

To improve the sustainability of road pavements, road agencies and construction companies need appropriate methodologies and tools to identify priority areas. It is necessary to know the impact of pavements on the environment to develop and implement approaches and procedures that can produce the greatest gains in all aspects and dimensions of the system, including the environmental impacts. The LCA method is a versatile tool capable of informing decisions on resource and process selection to better understand, measure, and reduce the environmental impacts of a system (Glass et al., 2013).

Since the application of LCA was extended to the pavement field in the late 1990s (Häkkinen and Mäkelä, 1996; Horvath and Hendrickson, 1998), the number of pavement LCA studies published in peer-reviewed journals has proliferated (examples include Goss et al., 2012; Kim et al., 2012; Kucubar and Tatari, 2012; Wang et al., 2012; Yu and Lu, 2012; Michael Fitch et al., 2012; Qian et al., 2013; Blankendaal et al., 2014). Those studies differ from each other in the system boundaries, functional units, analysis methodologies, processes considered, and computational structure. However, most of the examples have one feature in common: they focus on comparing alternative pavement materials based on estimated inventories and/or particular case studies to draw general conclusions.

Aside from those studies that rely on the application of LCA methodologies to particular case studies, there have been others that intend to elucidate DMs on the environmental footprint of various pavement classes. Loijos et al. (2013) quantified the GHG of twelve cement-based functional units, representing average conditions for each major roadway classification in the US. Seo and Kim (2013) estimated the overall and unit CO_2 emissions due to the consumption of materials for the construction of twelve expressway sections constructed between 2006 and 2007 in Korea. The unit emissions were utilized to predict the total emissions that might have been released from all types of roads (i.e., expressways, national highways, and local roads) up to the year 2007. In addition, average annual emissions were calculated based on road construction plans from 2009 to 2020. Gschösser et al. (2014) conducted an environmental analysis of the processes needed to construct (material production, pavement construction, transport) and maintain (pavement deconstruction, recycling, material production, pavement construction, transport) representative Swiss asphalt, concrete, and composite pavements used in highways and cantonal roads. While those studies have undeniable value in presenting LCA methodologies, documenting assumptions, and disclosing data sources (Loijos et al., 2013), their results cannot be extended to other geographical and technical contexts. By illustrating the applicability of the LCA model presented in Chapter 2 (Santos et al., 2015), this chapter provides Portuguese stakeholders with insights into the potential LCEI stemming from the construction and management of representative Portuguese road pavement structures.

3.2 Background

LCA is an emerging and systematic method to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials usage and environmental releases. Among other capabilities, LCA assesses the impacts of the emissions released to the environment as a consequence of the energy and material consumed and identifies opportunities for environmental improvements. The assessment includes the entire life cycle of the product, process, or activity and encompasses the extraction and processing of raw materials, manufacturing, transportation and distribution, use/reuse/maintenance, recycling, and final disposal (SETAC, 1993).

The LCA approach formalized by the ISO 14040 series has been internationally accepted as a set of valuable guidelines to perform a well-documented and transparent analysis. ISO divides the LCA framework into four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006). The goal and scope definition describes the functional unit used for the analysis, the life cycle system boundaries, and the target audience. The inventory analysis quantifies relevant inputs and outputs of a product or system and attributes them to processes within the life cycle system boundaries. In the LCIA phase, the inventory results are assigned to different impact categories based on the expected impact on the environment. These impact categories can be global (e.g., global warming, ozone depletion, etc.), regional (e.g., eutrophication, acidification, photo-oxidant formation, etc.), or local (e.g., nuisance, working conditions, effects of hazardous waste, effects of solid waste, etc.). The impact assessment in LCA includes two mandatory elements: classification and characterization. Classification is the process of assignment and initial aggregation of LCI data into common impact groups. Characterization is the assessment of the magnitude of potential impacts of each inventory flow into its corresponding environmental impact. Impact assessment may also include other additional steps, i.e., normalization, grouping, and weighting. The final phase of the LCIA process is aimed at interpreting the results from the inventory analysis and/or the impact assessment to point out conclusions, make suggestions, identify analysis refinements and improvements, and, in general, aid in the decision-making process.

3.3 Methodology

3.3.1 Goal and scope definition

In Chapter 2 (Santos et al., 2015) it is presented the development of a project-level, customizable pavement LCA tool that includes all six pavement life cycle phases. The main objectives of this chapter are (1) to demonstrate the potentialities and usefulness of this model for conducting a comprehensive and attributional LCA and (2) to provide Portuguese DMs with knowledge on the potential life cycle environmental performance of the standard flexible pavement structures defined in the Portuguese pavement design catalogue (JAE, 1995). Secondary objectives include (1) to identify the most relevant areas, key components, and processes of a pavement’s life cycle and to assess their contribution to the overall LCEI and (2) to assess the contribution of the traffic and pavement foundation classes to the total environmental impacts.

The procedures, techniques, and assumptions used in this analysis represent typical Portuguese practices with regard to pavement construction and management. However, given the multiplicity of solutions and processes available to perform the same functions, the results presented in this chapter are just illustrative and should not be considered fully representative of the pavement systems assessed. Rather, they should be seen as a guide and an incentive to road agencies and stakeholders to take advantage of comprehensive pavement LCA methodologies and tools, for conducting well-informed and tailored project-based LCA.

3.3.1.1 Functional unit

The functional unit is the central core of any LCA and forms the basis for comparisons between different systems. This study considers different functional units in order to cover the multiple combinations resulting from the various pavement structures, pavement foundations, and traffic classes. Each functional unit includes the construction, M&R, usage, and EOL phases of a flexible pavement structure for a straight and flat, interurban motorway segment, with two lanes per direction and two separate carriageways, which would provide safe, comfortable, economical, and durable driving conditions over a 40-year PAP.

In the Portuguese pavement design catalogue (JAE, 1995), called MACOPAV, a pavement structure is recommended depending on traffic class, which varies between T1 and T6, and pavement foundation class, which varies between F1 and F4. The traffic class is defined by the number of 80 kN equivalent single axle load (ESAL) applications for a design life. The ESALs are calculated using the annual average daily heavy-traffic ($AADT_h$), the annual average growth rate of heavy-traffic (g_h), and the average heavy-traffic damage factor or, simply, truck factor (α). On the other hand, the pavement foundation class is defined by the California Bearing Ratio (CBR) value and the design stiffness modulus (E) of the subgrade. The Portuguese manual considers 16 different flexible pavement structures for different combinations of traffic levels and pavement foundation classes. These pavement structures were defined using the Shell pavement design method (Shell, 1978), with verification by using the University of Nottingham (Brunton et al., 1987) and Asphalt Institute (Asphalt Institute, 2001) pavement design methods.

The results presented in the next sections were obtained for the following data and conditions: two traffic classes (T1 and T5) characterized in Table 3.1, three types of pavement foundations, and sixteen different pavement structures with the characteristics presented in Table 3.2. The properties of the materials in each pavement layer were provided by a certified Portuguese construction company and are within the range of values established by the Portuguese Road Administration.

For traffic composition, HDVs are assumed to represent 10% of the total AADT, of which 7.5% are rigid HDVs and the remaining percentage (2.5%) articulated HDVs. The outer lanes of each direction are assumed to carry 45% of the total HDV traffic. The remaining percentage of the total AADT (90%) is passenger cars (PCs).

The two main vehicles types (PC and HDV) are broken down into several engine capacity categories, and each of these engine capacity categories is further split into several levels of Euro stages compliance. This desegregation of the traffic categories was done for each year of the PAP, proportionally to the Portuguese traffic fleet distribution defined in the "*On-Road Vehicle Fleet Distribution*" Database Class (see Figure 2.1 in Chapter 2).

Table 3.1- Traffic classes and corresponding values.

Traffic class	$AADT_h$	g (%)	α
T5	300	3	3
T1	2000	3	5.5

Legend: $AADT_h$- annual average daily heavy-traffic; g- annual average growth rate of traffic; α- average heavy-traffic damage factor.

Table 3.2- Characteristics of the pavement structures.

Pavement structure	Surface layer			Binder layer			Base layer			Sub-base layer			SN_0	W (m)	L (km)
	Mat.	Mixture name	t_S (cm)	Mat.	Mixture name	t_{Bi} (cm)	Mat	Mixture name	t_B (cm)	Mat.	Mixture name	t_{Sb} (cm)			
P1	HMA	AC 14 Surf	4	HMA	-	-	HMA	AC 20 Base	6	CA	*Tout-Venant*	20	2.36	24[a]	1
P2	HMA	AC 14 Surf	4	HMA	-	-	HMA	AC 20 Base	8	CA	*Tout-Venant*	20	2.63		
P3	HMA	AC 14 Surf	4	HMA	AC 14 Bin	5	HMA	AC 20 Base	7	CA	*Tout-Venant*	20	3.17		
P4	HMA	AC 14 Surf	4	HMA	AC 14 Bin	6	HMA	AC 20 Base	8	CA	*Tout-Venant*	20	3.43		
P5	HMA	AC 14 Surf	5	HMA	AC 14 Bin	6	HMA	AC 20 Base	8	CA	*Tout-Venant*	20	3.61		
P6	HMA	AC 14 Surf	5	HMA	AC 20 Bin	6	HMA	AC 32 Base	10	CA	*Tout-Venant*	20	3.87		
P7	HMA	AC 14 Surf	4	HMA	AC 20 Bin	7	HMA	AC 32 Base	11	CA	*Tout-Venant*	20	3.97		
P8	HMA	AC 14 Surf	5	HMA	AC 20 Bin	6	HMA	AC 32 Base	11	CA	*Tout-Venant*	20	4.01		
P9	HMA	AC 14 Surf	5	HMA	AC 20 Bin	7	HMA	AC 32 Base	12	CA	*Tout-Venant*	20	4.28		
P10	HMA	AC 14 Surf	6	HMA	AC 20 Bin	6	HMA	AC 32 Base	12	CA	*Tout-Venant*	20	4.32		
P11	HMA	AC 14 Surf	5	HMA	AC 20 Bin	8	HMA	AC 32 Base	12	CA	*Tout-Venant*	20	4.41		
P12	HMA	AC 14 Surf	6	HMA	AC 20 Bin	8	HMA	AC 32 Base	12	CA	*Tout-Venant*	20	4.56		
P13	HMA	AC 14 Surf	5	HMA	AC 20 Bin	8	HMA	AC 32 Base	15	CA	*Tout-Venant*	20	4.81		
P14	HMA	AC 14 Surf	6	HMA	AC 20 Bin	7	HMA	AC 32 Base	15	CA	*Tout-Venant*	20	4.85		
P15	HMA	AC 14 Surf	6	HMA	AC 20 Bin	9	HMA	AC 32 Base	15	CA	*Tout-Venant*	20	5.12		
P16	HMA	AC 14 Surf	6	HMA	AC 20 Bin	11	HMA	AC 32 Base	15	CA	*Tout-Venant*	20	5.39		

Legend: Mat.- material; HMA- hot-mix asphalt; AC- asphalt concrete; CA- crushed aggregates; t_S- thickness of surface layer; t_{Bi}- thickness of binder layer; t_B- thickness of base layer; t_{Sb}- thickness of sub-base layer; SN_0- structural number of a pavement structure immediately after construction (year 0); W- width; L- length.

Notes: [a]This value corresponds to a cross-section with four main lanes, two outer shoulders, and two inner shoulders. The lanes are 3.75 m wide, whereas the outer and the inner shoulders are 3 m and 1.50 m wide, respectively.

3.3.1.2 System boundaries and system processes

The functional units were assessed throughout the total pavement life cycle phases covered by the pavement LCA model: materials extraction and production; transportation of materials; construction, M&R; WZ traffic management; usage; and

EOL (Chapter 2). However, further and more detailed insights on this topic are worthy of consideration here.

The analysis boundaries for the road pavement were set at the sub-base and at the finished road surface. They include (1) the construction of all layers contained by the limits stated above and subsequent M&R activities; (2) the extraction of the materials needed to produce the mixtures used in those layers; and (3) the movement involved in hauling materials between facilities, between facilities and work site, and vice-versa. The characteristics of the trucks used during the materials/mixtures transportation of materials phase, as well as transportation distances, are shown in Table 3.3. The upstream emissions and resources consumption associated with the production of the energy sources used to power the different processes, construction equipment, and on-road vehicles were also included in the system boundaries.

On the other hand, construction equipment and facilities production processes, road-related safety and signaling equipment (including road marking), road accessories (fences, road lighting software, etc.), and the earthworks required to build the pavement foundation were not included in the system boundaries. The earthworks were excluded because the environmental impacts related to those works are specific to a particular project. This fact makes it unsuitable for the general application of the pavement LCA model that is the objective of this case study.

Table 3.3- Description of the parameters referring to the materials/mixtures transportation of materials phase.

Type of transportation movement	Payload capacity (tonnes)	Material/ mixture	Distance (km)	Transport mode and vehicle technology	Average speed (km/h)
From extraction/ production facility to mixing plant	15	Bitumen	130	Rigid 26 - 28 t; HD Euro IV - 2005 Standards	60
	25	Aggregate: 0/31.5 mm	40	Articulated 34 - 40 t; HD Euro IV - 2005 Standards	60
	25	Aggregate: 0/4 mm	40	Articulated 34 - 40 t; HD Euro IV - 2005 Standards	60
	25	Aggregate: 4/8 mm	40	Articulated 34 - 40 t; HD Euro IV - 2005 Standards	60
	25	Aggregate: 4/14 mm	40	Articulated 34 - 40 t; HD Euro IV - 2005 Standards	60
	25	Aggregate: 4/15 mm	40	Articulated 34 - 40 t; HD Euro IV - 2005 Standards	60
	25	Aggregate: 8/15 mm	40	Articulated 34 - 40 t; HD Euro IV - 2005 Standards	60
	25	Aggregate: 15/25 mm	40	Articulated 34 - 40 t; HD Euro IV - 2005 Standards	60
	25	Tout-Venant[a]	40	Articulated 34 - 40 t; HD Euro IV - 2005 Standards	60
From mixing/ production plant to work site	21	CA	30	Rigid >32 t; HD Euro IV - 2005 Standards	60
		AC 4 reg	30	Rigid >32 t; HD Euro IV - 2005 Standards	60
	21	AC 14 surf	30	Rigid >32 t; HD Euro IV - 2005 Standards	60
	21	AC 14 bin	30	Rigid >32 t; HD Euro IV - 2005 Standards	60
	21	AC 20 bin	30	Rigid >32 t; HD Euro IV - 2005 Standards	60
	21	AC 20 base	30	Rigid >32 t; HD Euro IV - 2005 Standards	60
	21	AC 32 base	30	Rigid >32 t; HD Euro IV - 2005 Standards	60
	15	Bitumen Emulsion	40	Rigid 26 - 28 t; HD Euro IV - 2005 Standards	60
From work site to mixing plant	21	Milled HMA layers	30	Rigid >32 t; HD Euro IV - 2005 Standards	60
	21	Milled HMA layers	30	Rigid >32 t; HD Euro IV - 2005 Standards	60
	21	Removed CA	40	Rigid >32 t; HD Euro IV - 2005 Standards	60

Legend: AC- asphalt concrete; CA- crushed aggregates; HMA- hot-mix asphalt.

[a] Although labeled as "*Tout-Venant*" this material was modeled as "Aggregate: 0/31.5 mm."

The PMS of the Portuguese Road Administration uses the pavement performance model of the flexible pavement design method developed by the American Association of State Highways and Transportation Officials (AASHTO, 1993) to compute the overall quality of pavements defined by the present serviceability index in each year t (PSI_t) of the PAP. The system triggers a corrective intervention when this value drops below a determined value (warning value). The corrective M&R intervention is performed in order to restore the functional and structural capacities of the pavement. The OPTPAV system developed by Santos and Ferreira (2013) was used to determine the timing, materials type, and respective quantities for the M&R interventions applied to each functional unit. The model applies a rehabilitation activity when the PSI value is lower than 2.0 such that the PSI is restored to its initial value (4.5). The evolution of the PSI over the PAP for each functional unit is displayed in Figure 3.1. The M&R actions included in the rehabilitation activity are shown in Table 3.4. Table 3.5 presents the M&R plans applied throughout the PAP. The duration estimated for each M&R action relies on the productivity data collected from several contractors based on the Portuguese experience.

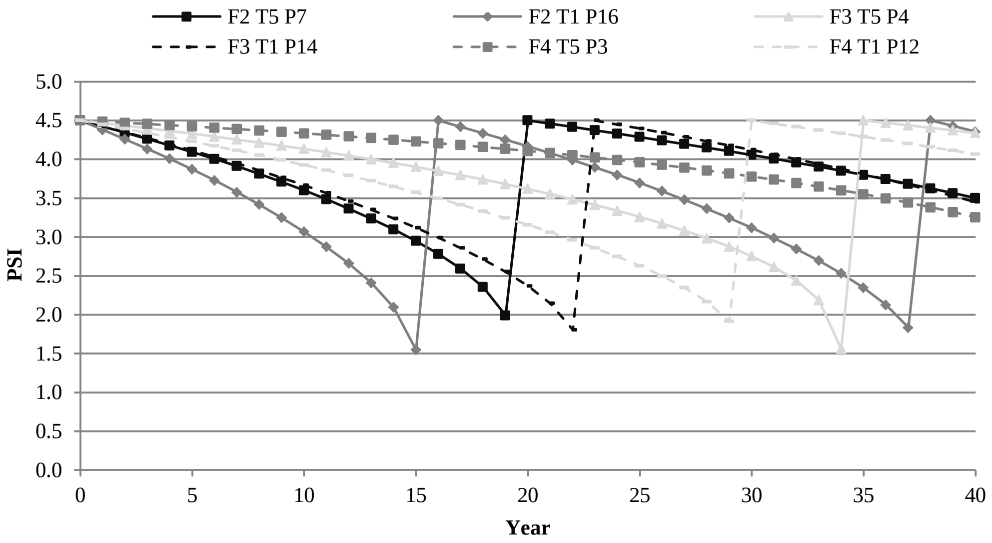

Figure 3.1- Evolution of PSI over the PAP for the six functional units.

Table 3.4- M&R activity description.

M&R activity	M&R actions involved	Mixtures applied	Thickness (cm) or area (m^2)		Duration per direction (days)
			Value	Unit	
Structural Rehabilitation	Wearing layer	AC 14 surf	5	cm	8
	Tack coat application	Bitumen Emulsion	3750[a]	m^2	
	Base layer	AC 20 base	10	cm	
	Tack coat application	Bitumen Emulsion	3750[a]	m^2	
	Surface leveling	AC 4 reg	2	cm	
	Prime coat application	Bitumen Emulsion	3750[a]	m^2	
	Milling HMA layers	-	17	cm	

Notes:[a] Value per lane.

Table 3.5- M&R plans.

Pavement foundation				Traffic class	Pavement structure	M&R schedule (year)		PSI_f
Class	CBR (%)	*E* (MPa)	υ					
F2	10	60	0.35	T5	P7	20	-	3.50
				T1	P16	16	38	4.36
F3	20	100	0.35	T5	P4	35	-	4.34
				T1	P14	23	-	3.45
F4	30	150	0.35	T5	P3	-	-	3.25
				T1	P12	30	-	4.07

Legend: CBR- Californian Bearing Ratio; E- stiffness modulus; υ- Poisson's ratio; M&R- maintenance and rehabilitation; PSI- present serviceability index; PSI_f - present serviceability index at the end of the project analysis period.

Prior to the paving operations described in Table 3.4, the initial layers are milled at the thickness required for the new layers, and the debris are transported to an asphalt mixing plant (recycling center). This procedure ensures (1) the required clearance for vertical obstacles; (2) compatibility with the existing drainage system; and (3) the protection of the new layers from the propagation of the distresses existing in the previous layers.

Another assumption is that the WZ is maintained in place during all M&R interventions because of the type of actions that are required to be performed during M&R interventions. This implies that the constraints imposed on the traffic exist whether work is being carried out or not. Regarding the WZ layout, the original lanes were narrowed and shifted laterally, taking advantage of the existing shoulders. The operation speed of the PCs and HDVs was reduced from 120 km/h and 90 km/h, respectively, to 80 km/h. Moreover, it was assumed that 10% of drivers self-detoured 10 km on a road with no limited access at an average speed of 60 km/h. The way in which the M&R activities impact the normal traffic flow depends, among other factors, on the hourly traffic distribution. In this case study, the Federal Highway Administration's (FHWA's) default weekday hourly traffic distribution was adopted (FHWA, 2004). Summaries of all relevant M&R traffic-related inputs are presented in Table 3.6.

Table 3.6- M&R traffic-related inputs.

Parameter	Value
Non-WZ Conditions	
Passenger car as % of AADT	90
$AADT_h$ (%)	10
Maximum legal speed (km/h): PCs	120
Maximum legal speed (km/h): HDVs	90
Number of lanes	2
Free flow capacity (veh./lane/hour)	2190
Rural/urban capacity	rural
Queue dissipation capacity (veh./lane/hour)	1714
Maximum AADT (total for both directions)	210286
Maximum queue length (km)	8
WZ Conditions	
Number lanes open in each direction	2
WZ length (km)	1
WZ speed limit (km/h)	80
WZ capacity (veh./lane/hour)	1500
Detour Conditions	
Detour rate (%)	10
Detour length (km)	10
Detour speed (km/h)	60

Legend: WZ- work-zone; AADT- annual average daily traffic; $AADT_h$- annual average daily heavy-traffic; PC- passenger car; HDV- heavy duty vehicle.

Regarding the calculation of the marginal environmental burdens incurred during the usage phase, the expression proposed by Al-Omari and Darter (1994) was used to convert the PSI to the IRI. The IRI degradation effect on vehicle operation speed has been taken into account by means of the model proposed by Yu and Lu (2014), according to which every 1 m/km increase of the IRI leads to a 0.84 km/h decrease of the free flow average speed.

Finally, when accounting for the EOL phase, a methodology based on the concept of "avoided burden approach," or "crediting," was developed and applied. Given the high hierarchy level of the road segments analyzed, it is expected that the most likely EOL scenario is that the pavement structures will remain in place after reaching the end of the PAP, serving as foundation for new pavement structures. From the LCA modeling perspective, such an assumption represents a situation where the current system interacts with the subsequent system by avoiding or displacing the environmental burdens that would have been generated during the pavement life cycle phases associated with the pavement construction/reconstruction of the subsequent system (i.e., raw materials extraction and mixtures production, materials and mixtures transportation, and construction equipment operation).

The extent to which the existing pavement structure may offset the environmental burdens that would occur within the next pavement system depends on its structural capacity at the end of the PAP, which in the case of flexible pavements is represented by the structural number (*SN*). To determine the value of this property when the pavement reaches the EOL (SN_f), the pavement remaining life (*RL*) was first computed; see Expression (3.1). It relies on the assumption that a pavement would fail when the PSI is equal to 1.5 (AASHTO, 1993).

$$RL = \frac{PSI_f - 1.5}{4.5 - 1.5} \times 100\% \tag{3.1}$$

Where *RL* is the remaining life of a pavement structure at the end of its PAP, and PSI_f is the *PSI* value of a pavement structure at the end of its PAP.

With the *RL* determined, the corresponding condition factor (*CF*) was calculated; see Expression (3.2). This factor represents the ratio between the pavement structural capacity at a given point in time of the PAP and the initial structural capacity. In order to determine the *RL* as a function of *CF*, several points of this relationship presented by AASHTO (1993) were plotted and a function in the form of Expression (3.2) was fitted to the data.

$$CF = a \times RL^3 + b \times RL^2 + c \times RL + d \tag{3.2}$$

Where CF is the correction factor; RL is remaining life of a pavement structure at the end of its PAP; and *a*, *b*, *c* and *d* are parameters that were found by minimizing the sum of square errors between the fitted function and the measured data. The values of the parameters *a*, *b*, *c*, and *d* were found to be 9×10^{-7}, -2×10^{-4}, 1.51×10^{-2}, and 5.2×10^{-1}, respectively. The value for R^2 in Expression (3.2) is 0.99.

Finally, the terminal structural capacity, as measured by SN_f, was estimated by multiplying the initial *SN* (SN_0), calculated from the material thickness and structural coefficients, by *CF*; see Expression (3.3). Once the SN_f was known, the thickness of an equivalent pavement structure with equal *SN* was determined according to layer structural coefficients representing the relative strength of the layer materials. Analogous to the pavement structures recommended by the Portuguese pavement design catalogue, the subsequent pavement structure was assumed to be constituted by asphalt-bound layer(s) placed on top of a previously prime coated granular sub-base layer with a maximum thickness of 20 cm. The drainage system was assumed to perform well, and the drainage coefficients were considered equal to 1.0. Moreover, as neither the PAP of the subsequent pavement system nor the project traffic are known, no further considerations were made regarding the number of bound layers, their thickness, or their mixture compositions.

$$SN_f = CF \times SN_0 \tag{3.3}$$

Where SN_f is the SN_f value of a pavement structure at the end of its PAP, *CF* is the correction factor, and; SN_0 is the *SN* value of a pavement structure immediately after construction (year 0).

The potential avoided impacts accounted for during the EOL phase of the current pavement system are those that would be potentially generated during the construction of the equivalent pavement structure and were calculated according to the Expression (3.4).

$$E_{A_i}^{EOL} = -\sum_{j}^{J} \alpha \times E_{B_{ij}}^{p} \tag{3.4}$$

Where $E_{A_i}^{EOL}$ is the environmental burden *i*, accounted for in the EOL phase of the current pavement system (A); $E_{B_{ij}}^{p}$ is the contribution of the process *j* to the environmental burden *i,* accounted for in the pavement life cycle phase *p* of the subsequent pavement system (B); and α is a weighting factor between 0 and 1.

The calculation method relies on the assumption that both the construction activities and respective preceding processes will be performed according to the same procedures, techniques, and assumptions as those considered in the equivalent pavement life cycle phases of the current pavement system. Moreover, it was also considered that the *SN* of a pavement structure is restored to its initial value when an M&R activity is applied. The rationale for making this assumption lies in the fact that the initial layers were previously milled at the thickness required for the new layers and that the structural capacity provided by the new materials is identical to that of the replaced ones.

As can be seen from Expression (3.4), the potential avoided environmental burdens were multiplied by a weighting factor, which in this case study was considered to be equal to 0.5. Therefore, only a fraction of the total potential benefits of the avoided environmental burdens were accounted for. This assumption was performed to avoid overestimating the benefits of considering the remaining structural capacity of the current pavement system as a reason to displace the need for new materials that otherwise would be applied in the subsequent system. The main reason to not fully credit the current pavement system the total avoided impacts is related to the several degrees of uncertainty inherent in the assumptions performed during the application of the "avoided burden approach." Examples of uncertainties are those related to (1) the computation of the remaining life of a pavement and its relationship with the structural capacity and (2) the prediction of which materials, construction processes, and equipment will actually be adopted in a distant future (over 40 years), and how much different the environmental efficiency of those elements may be compared with the present state-of-practice. The main data and results referring to the EOL phase modeling are displayed in Table 3.7.

Table 3.7- Data and results referring to EOL phase modelling.

Pavement foundation class	Traffic class	Pavement structure	SN_0	PSI_f	RL (%)	CF	SN_f	Granular sub-base layer		Asphalt-bound layer	
								Mixture	t_{Sb} (cm)	Mixture	$t_{A\text{-}b}$ (cm)
F2	T5	P7	3.96860	3.50	66.70	0.90426	3.58864	CA	20	AC 32	20
	T1	P16	5.38594	4.36	95.17	0.92118	4.96144	CA	20	AC 32	30
F3	T5	P4	3.43316	4.34	94.70	0.92050	3.16023	CA	20	AC 32	17
	T1	P14	4.85050	3.45	65.03	0.90348	4.38233	CA	20	AC 32	26
F4	T5	P3	3.16544	3.25	58.43	0.89882	2.84516	CA	20	AC 32	14
	T1	P12	4.58278	4.07	85.53	0.91135	4.17649	CA	20	AC 32	24

Legend: SN_0- structural number of a pavement structure immediately after construction (year 0); PSI_f - present serviceability index of a pavement structure at the end of its PAP; RL- remaining life of a pavement structure at the end of its PAP; CF- correction factor; SN_f - SN value of a pavement structure at the end of its PAP; t_{Sb}- thickness of equivalent granular sub-base layer; $t_{A\text{-}b}$- thickness of equivalent asphalt-bound layer; CA- crushed aggregates; AC- asphalt concrete.

3.4 Life cycle inventory

An LCI was determined for each pavement life cycle phase for each functional unit by using the default database of the pavement LCA model presented in Chapter 2. Table 3.8 summarizes the references for the data sources considered in the present study. The processes addressed in the materials and construction phases were modeled with help from Portuguese construction companies. Detailed information with regard to the processes addressed during both the materials phase (e.g., HMA compositions, batch plant production rate, energy consumption, etc.) and the construction and maintenance phases (e.g., construction equipment required and respective production rates, etc.) has been gathered and accounted for in the LCI.

Table 3.8- Summary of data sources considered in the case study.

Element	Data source
Bitumen	Eurobitumen (2011)
Bituminous Emulsion	Eurobitumen (2011)
Aggregates	Jullien et al. (2012)
Tap water	Althaus et al. (2007)
HMA production	US EPA (2004)
Transportation of materials	EEA (2013)
Construction equipment operation	
On-road vehicles operation	
Electricity	Dones et al. (2007); EC, JRC - IES and DGE - DG (2008)
Coal	
Crude oil	
Diesel	
Gasoline	
Natural gas	
LPG	

Legend: HMA- hot-mix asphalt; LPG- liquid petroleum gas.

The inventory analysis was used to determine, both qualitatively and quantitatively, the materials, the energy flows, and the atmospheric emissions associated with each individual process in the systems under analysis. The outputs from those unit processes were posteriorly combined in order to derive the total environmental burden of the systems. Table 3.9 provides the overall LCI per pavement life cycle phase of each functional unit, expressed in terms of atmospheric emissions.

Table 3.9- LCI per pavement life cycle phase of each functional unit.

Foundation class	Traffic class	Pavement structure	Life cycle phase	Primary energy sub-component	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	SO_2 (kg)	NO_x (kg)	NH_3 (kg)	CO (kg)	VOC (kg)	NMVOC (kg)	$PM_{2.5}$ (kg)	Pb (kg)
F2	T5	P7	Materials	P.E.	5.75E+05	6.20E+02	2.63E+02	9.31E+02	3.19E+03	1.94E-01	5.89E+03	1.20E+03	5.72E+02	2.26E+02	5.34E+01
				P.C.E.	9.06E+04	1.08E+03	0.00E+00	6.15E+02	3.23E+02	3.83E-01	3.28E+01	8.02E+02	1.34E+02	1.99E+01	1.53E-02
			Construction and M&R	P.E.	8.40E+04	8.53E+00	3.51E+00	2.13E+00	4.77E+02	2.01E-01	4.25E+02	1.08E+02	9.99E+01	5.45E+01	0.00E+00
				P.C.E.	5.45E+03	4.80E+01	0.00E+00	8.64E+01	3.46E+01	1.04E-01	1.05E+01	7.84E+01	3.03E+01	2.89E+00	8.94E-04
			Transportation of materials	P.E.	1.65E+05	1.69E+01	4.51E+00	4.21E+00	1.04E+03	6.36E-01	7.56E+01	9.52E+00	0.00E+00	7.33E+00	0.00E+00
				P.C.E.	1.08E+04	9.50E+01	0.00E+00	1.71E+02	6.85E+01	2.06E-01	2.08E+01	1.55E+02	6.00E+01	5.72E+00	1.77E-03
			WZ traffic management	P.E.	3.94E+04	2.06E+00	1.16E+00	5.22E-01	1.57E+02	2.71E-01	1.47E+03	3.12E+00	1.84E+01	1.22E+03	0.00E+00
				P.C.E.	4.52E+03	3.16E+01	0.00E+00	3.89E+01	1.59E+01	7.70E-02	6.17E+00	4.34E+01	1.18E+01	8.79E-01	9.86E-04
			Usage	P.E.	1.39E+05	5.31E+00	2.56E+00	1.27E+00	8.26E+02	4.33E+00	7.60E+02	0.00E+00	1.05E+02	2.28E+01	0.00E+00
				P.C.E.	1.47E+04	1.05E+02	0.00E+00	1.36E+02	5.56E+01	2.54E-01	2.09E+01	1.48E+02	4.23E+01	3.31E+00	3.14E-03
			EOL	P.E.	-2.26E+05	-1.76E+02	-1.03E+02	-2.58E+02	-1.39E+03	-2.72E-01	-1.83E+03	-3.66E+02	-1.91E+02	-8.34E+01	-2.05E+01
				P.C.E.	-2.68E+04	-3.32E+02	0.00E+00	-2.23E+02	-1.08E+02	-1.77E-01	-1.67E+01	-2.81E+02	-6.05E+01	-7.30E+00	-4.46E-03
			Total net		8.75E+05	1.50E+03	1.72E+02	1.51E+03	4.70E+03	6.21E+00	6.87E+03	1.90E+03	8.22E+02	1.47E+03	3.29E+01
	T1	P16	Materials	P.E.	9.28E+05	1.00E+03	3.74E+02	1.49E+03	4.61E+03	3.09E-01	9.25E+03	1.87E+03	8.63E+02	3.35E+02	5.34E+01
				P.C.E.	1.41E+05	1.74E+03	0.00E+00	9.57E+02	5.03E+02	5.88E-01	5.11E+01	1.31E+03	2.14E+02	3.10E+01	2.37E-02
			Construction and M&R	P.E.	1.27E+05	1.40E+01	5.18E+00	3.21E+00	6.82E+02	2.96E-01	6.42E+02	1.61E+02	1.47E+02	8.18E+01	0.00E+00
				P.C.E.	8.23E+03	7.24E+01	0.00E+00	1.30E+02	5.22E+01	1.57E-01	1.59E+01	1.18E+02	4.57E+01	4.36E+00	1.35E-03
			Transportation of materials	P.E.	2.50E+05	2.56E+01	6.83E+00	6.37E+00	1.58E+03	9.62E-01	1.11E+02	1.44E+01	0.00E+00	1.11E+01	0.00E+00
				P.C.E.	1.63E+04	1.44E+02	0.00E+00	2.59E+02	1.04E+02	3.12E-01	3.15E+01	2.35E+02	9.08E+01	8.65E+00	2.68E-03
			WZ traffic management	P.E.	4.17E+05	2.30E+01	1.22E+01	5.36E+00	1.81E+03	-4.53E-01	1.30E+04	1.25E+03	2.07E+03	2.91E+04	0.00E+00
				P.C.E.	4.68E+04	3.30E+02	0.00E+00	4.13E+02	1.68E+02	8.01E-01	6.47E+01	4.56E+02	1.26E+02	9.56E+00	1.01E-02
			Usage	P.E.	1.60E+06	6.20E+01	3.01E+01	1.50E+01	9.45E+03	5.15E+01	8.98E+03	0.00E+00	1.23E+03	2.61E+02	0.00E+00
				P.C.E.	1.72E+05	1.23E+03	0.00E+00	1.58E+03	6.42E+02	2.96E+00	2.43E+02	1.72E+03	4.87E+02	3.78E+01	3.69E-02
			EOL	P.E.	-3.23E+05	-2.59E+02	-1.47E+02	-3.75E+02	-1.81E+03	-3.62E-01	-2.60E+03	-5.15E+02	-2.57E+02	-1.09E+02	-2.05E+01
				P.C.E.	-3.66E+04	-4.83E+02	0.00E+00	-3.02E+02	-1.47E+02	-2.35E-01	-2.25E+01	-4.09E+02	-8.42E+01	-9.93E+00	-6.06E-03
			Total net		3.35E+06	3.90E+03	2.82E+02	4.18E+03	1.76E+04	5.68E+01	2.98E+04	6.22E+03	4.93E+03	2.98E+04	3.29E+01

Legend: LCI- life cycle inventory; WZ- work-zone; EOL- end-of-life; P.E.- process energy; P.C.E.- pre-combustion energy.

(continued)

Foundation class	Traffic class	Pavement structure	Life cycle phase	Primary energy sub-component	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	SO_2 (kg)	NO_x (kg)	NH_3 (kg)	CO (kg)	VOC (kg)	NMVOC (kg)	$PM_{2.5}$ (kg)	Pb (kg)
F3	T5	P4	Materials	P.E.	5.10E+05	5.51E+02	2.27E+02	8.32E+02	2.93E+03	1.75E-01	5.26E+03	1.07E+03	5.19E+02	2.06E+02	5.34E+01
				P.C.E.	8.92E+04	9.71E+02	0.00E+00	6.02E+02	3.16E+02	3.80E-01	3.14E+01	7.08E+02	1.21E+02	1.93E+01	1.51E-02
			Construction and M&R	P.E.	8.19E+04	8.23E+00	3.38E+00	2.07E+00	4.59E+02	1.93E-01	4.16E+02	1.07E+02	9.85E+01	5.44E+01	0.00E+00
				P.C.E.	5.32E+03	4.68E+01	0.00E+00	8.42E+01	3.38E+01	1.02E-01	1.03E+01	7.64E+01	2.96E+01	2.82E+00	8.71E-04
			Transportation of materials	P.E.	1.52E+05	1.56E+01	4.16E+00	3.88E+00	9.62E+02	5.86E-01	7.10E+01	8.80E+00	0.00E+00	6.77E+00	0.00E+00
				P.C.E.	9.96E+03	8.77E+01	0.00E+00	1.58E+02	6.33E+01	1.90E-01	1.92E+01	1.43E+02	5.54E+01	5.28E+00	1.63E-03
			WZ traffic management	P.E.	6.15E+04	3.21E+00	1.83E+00	8.19E-01	2.48E+02	6.67E-01	2.31E+03	5.15E+00	2.57E+01	1.89E+03	0.00E+00
				P.C.E.	7.07E+03	4.94E+01	0.00E+00	6.08E+01	2.48E+01	1.21E-01	9.65E+00	6.78E+01	1.83E+01	1.37E+00	1.55E-03
			Usage	P.E.	1.81E+05	7.09E+00	3.44E+00	1.72E+00	1.07E+03	5.93E+00	1.03E+03	0.00E+00	1.41E+02	2.91E+01	0.00E+00
				P.C.E.	1.96E+04	1.39E+02	0.00E+00	1.78E+02	7.26E+01	3.37E-01	2.75E+01	1.94E+02	5.50E+01	4.25E+00	4.20E-03
			EOL	P.E.	-1.98E+05	-1.51E+02	-9.01E+01	-2.22E+02	-1.26E+03	-2.45E-01	-1.60E+03	-3.21E+02	-1.72E+02	-7.55E+01	-2.05E+01
				P.C.E.	-2.38E+04	-2.87E+02	0.00E+00	-1.99E+02	-9.64E+01	-1.60E-01	-1.50E+01	-2.43E+02	-5.34E+01	-6.51E+00	-3.98E-03
			Total net		8.96E+05	1.44E+03	1.49E+02	1.50E+03	4.82E+03	8.27E+00	7.57E+03	1.82E+03	8.39E+02	2.14E+03	3.29E+01
	T1	P14	Materials	P.E.	6.79E+05	7.29E+02	3.20E+02	1.09E+03	3.60E+03	2.24E-01	6.89E+03	1.39E+03	6.56E+02	2.59E+02	5.34E+01
				P.C.E.	1.04E+05	1.27E+03	0.00E+00	7.09E+02	3.72E+02	4.38E-01	3.78E+01	9.48E+02	1.57E+02	2.29E+01	1.75E-02
			Construction and M&R	P.E.	9.01E+04	9.52E+00	3.73E+00	2.28E+00	5.04E+02	2.13E-01	4.59E+02	1.15E+02	1.06E+02	5.83E+01	0.00E+00
				P.C.E.	5.85E+03	5.15E+01	0.00E+00	9.27E+01	3.71E+01	1.12E-01	1.13E+01	8.41E+01	3.25E+01	3.10E+00	9.59E-04
			Transportation of materials	P.E.	1.85E+05	1.90E+01	5.06E+00	4.72E+00	1.17E+03	7.13E-01	8.29E+01	1.07E+01	0.00E+00	8.22E+00	0.00E+00
				P.C.E.	1.21E+04	1.07E+02	0.00E+00	1.92E+02	7.69E+01	2.31E-01	2.34E+01	1.74E+02	6.73E+01	6.42E+00	1.98E-03
			WZ traffic management	P.E.	2.22E+05	1.26E+01	6.56E+00	2.92E+00	9.32E+02	-2.78E-01	7.43E+03	1.99E+03	2.07E+03	1.45E+04	0.00E+00
				P.C.E.	2.53E+04	1.77E+02	0.00E+00	2.20E+02	8.96E+01	4.32E-01	3.47E+01	2.44E+02	6.66E+01	4.99E+00	5.51E-03
			Usage	P.E.	1.08E+06	4.16E+01	2.01E+01	1.00E+01	6.43E+03	3.41E+01	5.97E+03	0.00E+00	8.21E+02	1.77E+02	0.00E+00
				P.C.E.	1.15E+05	8.24E+02	0.00E+00	1.06E+03	4.33E+02	1.99E+00	1.63E+02	1.15E+03	3.30E+02	2.57E+01	2.46E-02
			EOL	P.E.	-2.84E+05	-2.26E+02	-1.29E+02	-3.28E+02	-1.64E+03	-3.26E-01	-2.30E+03	-4.55E+02	-2.31E+02	-9.90E+01	-2.05E+01
				P.C.E.	-3.27E+04	-4.22E+02	0.00E+00	-2.70E+02	-1.31E+02	-2.12E-01	-2.02E+01	-3.57E+02	-7.47E+01	-8.88E+00	-5.42E-03
			Total net		2.20E+06	2.59E+03	2.27E+02	2.79E+03	1.19E+04	3.76E+01	1.88E+04	5.30E+03	4.00E+03	1.49E+04	3.29E+01

Legend: LCI- life cycle inventory; WZ- work-zone; EOL- end-of-life; P.E.- process energy; P.C.E.- pre-combustion energy.

(continued)

Foundation class	Traffic class	Pavement structure	Life cycle phase	Primary energy sub-component	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	SO_2 (kg)	NO_x (kg)	NH_3 (kg)	CO (kg)	VOC (kg)	NMVOC (kg)	$PM_{2.5}$ (kg)	Pb (kg)
F4	T5	P3	Materials	P.E.	2.92E+05	3.10E+02	1.91E+02	4.82E+02	2.05E+03	9.89E-02	3.19E+03	6.50E+02	3.37E+02	1.39E+02	5.34E+01
				P.C.E.	5.65E+04	5.61E+02	0.00E+00	3.81E+02	2.00E+02	2.46E-01	1.96E+01	3.86E+02	7.13E+01	1.21E+01	9.66E-03
			Construction and M&R	P.E.	4.80E+04	4.30E+00	2.00E+00	1.21E+00	2.89E+02	1.14E-01	2.50E+02	6.38E+01	5.96E+01	3.10E+01	0.00E+00
				P.C.E.	3.12E+03	2.74E+01	0.00E+00	4.93E+01	1.98E+01	5.95E-02	6.02E+00	4.48E+01	1.73E+01	1.65E+00	5.11E-04
			Transportation of materials	P.E.	9.41E+04	9.66E+00	2.56E+00	2.40E+00	5.94E+02	3.62E-01	4.47E+01	5.42E+00	0.00E+00	4.18E+00	0.00E+00
				P.C.E.	6.15E+03	5.42E+01	0.00E+00	9.75E+01	3.91E+01	1.18E-01	1.19E+01	8.84E+01	3.42E+01	3.26E+00	1.01E-03
			WZ traffic management	P.E.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
				P.C.E.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
			Usage	P.E.	1.13E+05	4.43E+00	2.15E+00	1.08E+00	6.64E+02	3.71E+00	6.45E+02	0.00E+00	8.80E+01	1.81E+01	0.00E+00
				P.C.E.	1.22E+04	8.70E+01	0.00E+00	1.11E+02	4.52E+01	2.10E-01	1.72E+01	1.21E+02	3.42E+01	2.64E+00	2.63E-03
			EOL	P.E.	-1.69E+05	-1.25E+02	-7.71E+01	-1.87E+02	-1.13E+03	-2.18E-01	-1.37E+03	-2.77E+02	-1.52E+02	-6.77E+01	-2.05E+01
				P.C.E.	-2.09E+04	-2.42E+02	0.00E+00	-1.75E+02	-8.47E+01	-1.42E-01	-1.33E+01	-2.04E+02	-4.62E+01	-5.72E+00	-3.50E-03
			Total net		4.35E+05	6.91E+02	1.20E+02	7.63E+02	2.69E+03	4.56E+00	2.81E+03	8.79E+02	4.44E+02	1.39E+02	3.28E+01
	T1	P12	Materials	P.E.	6.44E+05	6.93E+02	3.01E+02	1.04E+03	3.47E+03	2.14E-01	6.55E+03	1.33E+03	6.28E+02	2.48E+02	5.34E+01
				P.C.E.	1.01E+05	1.21E+03	0.00E+00	6.85E+02	3.60E+02	4.25E-01	3.65E+01	8.99E+02	1.50E+02	2.21E+01	1.70E-02
			Construction and M&R	P.E.	8.70E+04	9.05E+00	3.66E+00	2.20E+00	4.95E+02	2.09E-01	4.41E+02	1.10E+02	1.01E+02	5.36E+01	0.00E+00
				P.C.E.	5.65E+03	4.97E+01	0.00E+00	8.95E+01	3.59E+01	1.08E-01	1.09E+01	8.12E+01	3.14E+01	3.00E+00	9.26E-04
			Transportation of materials	P.E.	1.78E+05	1.83E+01	4.87E+00	4.54E+00	1.13E+03	6.86E-01	8.04E+01	1.03E+01	0.00E+00	7.92E+00	0.00E+00
				P.C.E.	1.17E+04	1.03E+02	0.00E+00	1.85E+02	7.40E+01	2.23E-01	2.25E+01	1.68E+02	6.48E+01	6.18E+00	1.91E-03
			WZ traffic management	P.E.	2.21E+05	1.24E+01	6.53E+00	2.89E+00	9.32E+02	3.21E-01	7.06E+03	1.92E+03	1.99E+03	1.45E+04	0.00E+00
				P.C.E.	2.51E+04	1.76E+02	0.00E+00	2.18E+02	8.91E+01	4.29E-01	3.45E+01	2.42E+02	6.62E+01	4.97E+00	5.46E-03
			Usage	P.E.	1.09E+06	4.23E+01	2.04E+01	1.02E+01	6.48E+03	3.47E+01	6.07E+03	0.00E+00	8.33E+02	1.77E+02	0.00E+00
				P.C.E.	1.16E+05	8.32E+02	0.00E+00	1.07E+03	4.37E+02	2.01E+00	1.65E+02	1.16E+03	3.32E+02	2.59E+01	2.49E-02
			EOL	P.E.	-2.65E+05	-2.09E+02	-1.20E+02	-3.05E+02	-1.56E+03	-3.08E-01	-2.14E+03	-4.26E+02	-2.17E+02	-9.38E+01	-2.05E+01
				P.C.E.	-3.07E+04	-3.92E+02	0.00E+00	-2.54E+02	-1.24E+02	-2.00E-01	-1.90E+01	-3.32E+02	-7.00E+01	-8.35E+00	-5.10E-03
			Total net		2.18E+06	2.54E+03	2.16E+02	2.75E+03	1.18E+04	3.88E+01	1.83E+04	5.16E+03	3.91E+03	1.49E+04	3.29E+01

Legend: LCI- life cycle inventory; WZ- work-zone; EOL- end-of-life; P.E.- process energy; P.C.E.- pre-combustion energy

3.5 Life cycle impact assessment

The LCEI that are likely to stem from the different functional units were evaluated at the midpoint level, according to the potential effects on the impact categories accounted for in the pavement LCA model presented in Chapter 2. The impact categories included are CC, Ac, TE, HT due to air emissions, POF, ARD FF and ARD MR. The CED was adopted to determine and compare the energy intensity of processes and pavement life cycle phases.

The resulting LCEI allow for the identification of the phases with the highest environmental burdens and thus most worthy of major consideration by pavement engineers when designing the road pavement structures and planning for their management during the PAP. However, one should bear in mind that the processes modeled in each pavement life cycle are subjected to uncertainties even if they are framed by the same context. Therefore, the results presented in the next sections should be seen as a way to identify hot spots rather than definitive numerical results.

3.6 Results and discussion

The LCIA profile of each functional unit is presented in Table 3.10. In the context of the “avoided burdens approach”, positive values of LCIA category indicators represent environmental impacts (thus, a potential environmental burden or damage) and negative values represent avoided impacts (thus, a kind of potential environmental “benefit”). Hereafter, the expression “life cycle net environmental impact category indicator” is used to designate the quantifiable representation of an impact category corresponding to the whole life cycle of a given functional unit after deducting the avoided impacts assigned to the EOL phase. This expression differs from another one, named “life cycle environmental impact category indicator”, by subtracting the avoided impacts. In other words, the last expression only regards the impacts that are likely to be produced by the current system. In this sense, to avoid a misleading interpretation of the outcomes referring to the contribution of the several pavement life cycle phases to a determined impact category, the relative contributions are calculated in relation to the life cycle environmental impact category indicators.

According to the results shown in Table 3.10, the contribution of the several pavement life cycle phases across all the impact categories considered depends on the traffic class.

3.6.1 Influence of the traffic class in the life cycle impact assessment results

3.6.1.1 Roads with lower traffic volumes

For traffic class T5, the contribution of the materials production and extraction phase is dominant for all impact categories. Its share of the LCEI indicators ranges between 48% (impact category ARD MR corresponding to the pavement structure laid on pavement foundation F3) and 68% (impact category HT corresponding to the pavement structure laid on pavement foundation F4). When comparing the environmental performance of the materials phase referring to the materials consumed during the construction and maintenance sub-phases, the former was found to be responsible for the greatest share. Excluding the case of the pavement laid on foundation F4, which is supposed to undergo no M&R activity throughout the PAP, the construction sub-phase contributes 65-82% of the overall LCEI, while the maintenance sub-phase accounts for the remaining percentage.

The second life cycle phase that exhibits a significant contribution to the overall LCEI is the usage phase, as it contributes 10-21% of the LCEI of a given category. It is followed by the transportation of materials phase which overall was found to be responsible for 11-20% of the environmental impacts in every category. Of that share, 66-73% is incurred during the construction sub-phase, while the remaining percentage is due to the maintenance sub-phase. The importance of the transportation of materials phase to the overall environmental performance of a pavement system demonstrates that the acquisition costs cannot be the only element to take into account when selecting the materials/HMA suppliers and the depositary/recycling facilities.

Table 3.10- LCIA per pavement life cycle phase of each functional unit.

Foundation class	Traffic class	Pavement structure	Life cycle phase	CC (tonnes CO_2-eq)	Ac (molc H^+-eq)	TE (molc N-eq)	POF (kg NMVOC-eq)	HT (kg 1.4-DB-eq)	ARD MR (g Sb-eq)	ARD FF (MJ)
F2	T5	P7	Materials	752	1631	9140	5095	6122	47.54	10,595,427
			Construction and M&R	86	156	1332	713	669	9.82	1,353,497
			Transportation of materials	171	328	2896	1229	1361	19.44	2,678,731
			WZ Traffic management	38	59	452	285	1209	4.12	639,254
			Usage	128	254	2209	1102	1093	14.62	2,225,308
			EOL	-202	-587	-3888	-1960	-2664	-23.69	-3,929,064
			Total net	972	1840	12,140	6464	7790	71.84	13,563,154
	T1	P16	Materials	1153	2488	13,291	7573	8221	74.12	16,955,011
			Construction and M&R	122	227	1914	1034	965	14.81	2,041,033
			Transportation	247	496	4380	1859	2058	29.40	4,052,054
			WZ traffic management	368	1924	5144	5206	26,302	43.90	6,766,343
			Usage	1442	3020	26,646	12,680	12,520	168.64	25,737,638
			EOL	-288	-798	-5096	-2602	-3497	-27.05	-5,552,704
			Total net	3044	7358	46,278	25,749	46,569	303.82	49,999,373
F3	T5	P4	Materials	642	1513	8441	4670	5771	48.24	9,652,461
			Construction and M&R	79	151	1285	691	647	9.57	1,319,271
			Transportation of materials	150	303	2673	1135	1256	17.94	2,472,281
			WZ traffic management	50	92	716	445	1884	6.43	997,887
			Usage	161	341	3002	1435	1413	19.05	2,911,160
			EOL	-177	-524	-3527	-1768	-2414	-17.83	-3,442,345
			Total net	906	1876	12,591	6609	8558	83.40	13,910,714
	T1	P14	Materials	888	1874	10,344	5814	6731	54.91	12,423,771
			Construction and M&R	92	165	1409	756	709	10.53	1,451,810
			Transportation	191	368	3247	1378	1526	21.80	3,004,518
			WZ Traffic management	207	338	2657	4044	13,124	23.28	3,603,743
			Usage	996	1988	17,354	8591	8508	113.92	17,350,993
			EOL	-254	-714	-4613	-2345	-3164	-24.21	-4,903,017
			Total net	2121	4020	30,399	18,239	27,432	200.23	32,931,817

Legend: LCIA- life cycle impact assessment; CC- climate change; Ac- acidification; TE- terrestrial eutrophication; POF- photochemical ozone formation; HT- human toxicity; ARD FF- abiotic resource depletion: fossil fuels; ARD MR- abiotic resource depletion: mineral resources; M&R- maintenance and rehabilitation; WZ- work-zone; EOL- end-of-life.

(continued)

Foundation class	Traffic class	Pavement structure	Life cycle phase	CC (tonnes CO$_2$-eq)	Ac (molc H$^+$-eq)	TE (molc N-eq)	POF (kg NMVOC-eq)	HT (kg 1.4-DB-eq)	ARD MR (g Sb-eq)	ARD FF (MJ)
F4	T5	P3	Materials	428	969	5861	3131	4466	28.70	5,671,102
			Construction and M&R	52	92	805	427	402	5.61	773,075
			Transportation of materials	103	187	1651	701	776	11.08	1,526,822
			WZ traffic Management	-	-	-	-	-	-	-
			Usage	97	200	1712	893	879	11.86	1,814,092
			EOL	-151	-461	-3165	-1575	-2165	-15.71	-2,955,560
			Total net	528	987	6864	3577	4359	41.55	6,829,531
	T1	P12	Materials	829	1799	9951	5579	6533	52.92	11,846,885
			Construction and M&R	87	161	1382	737	692	10.17	1,402,238
			Transportation of materials	181	354	3127	1327	1469	20.99	2,892,590
			WZ traffic Management	191	338	2663	3932	13,144	23.15	3,580,938
			Usage	1003	2041	17,961	8670	8576	114.79	17,494,254
			EOL	-236	-672	-4371	-2217	-2997	-22.79	-4,578,239
			Total net	2054	4021	30,713	18,028	27,417	199.23	32,638,667

Legend: LCIA- life cycle impact assessment; CC- climate change; Ac- acidification; TE- terrestrial eutrophication; POF- photochemical ozone formation; HT- human toxicity; ARD FF- abiotic resource depletion: fossil fuels; ARD MR- abiotic resource depletion: mineral resources; M&R- maintenance and rehabilitation; WZ- work-zone; EOL- end-of-life.

Another pavement life cycle phase whose contribution deserves to be highlighted is the EOL phase. Accounting for the potential avoided impacts of the subsequent pavement system in the EOL phase of the current pavement system may reduce the LCEI of several impact categories by as much as 33% (impact category HT). A reduction in the impact category indicators of this magnitude was verified in the case of the pavement (P3) recommended for pavement foundation F4. Although seemingly counterintuitive due to the low remaining life value exhibited by pavement structure P3 at the end of its PAP, this outcome can be explained by the fact that this pavement structure is supposed to undergo no M&R activity throughout the PAP. This fact results in a strengthening of the role played by the materials phase in driving the environmental performance of the pavement structures subjected to traffic class T5. Therefore, any LCA modeling consideration affecting or related to the materials phase may result in noteworthy changes in the environmental performance of the system under analysis.

In addition, the WZ traffic management phase denotes a small contribution to the spectrum of impact categories, with percentages of the impact categories indicators ranging between 0% and 17%. This result, although seemingly counterintuitive finds support in the literature. For instance, Barth and Boriboonsomsin (2008) have shown that if moderate congestion brings average speeds down from a free flow speed of about 105 km/h to a slower speed of 73 km/h to 80 km/h, this moderate congestion can actually lower CO_2 emissions. Similar outcomes have been recently demonstrated by Avetisyan et al. (2014) in a study that quantified the effect of incidents and WZs on emissions production from on-road traffic. In our case study traffic queues are only expected to develop in limited time periods of M&R events taking place in advanced years of the PAP. Therefore, the traffic delay emissions occur mostly due to speed changes upstream and downstream of the WZ and as a consequence of additional distances that detouring vehicles are required to travel.

Another contribution of small relative magnitude is that attributable to the construction and M&R phase. This pavement LCA phase, which tracks and categorizes the emissions released by the construction equipment, was found to contribute not more than 6-10% to the overall LCEI.

3.6.1.2 Roads with higher traffic volumes

When considering traffic class T1, a different relative and absolute contribution to the overall impact categories was found for the various pavement life cycle phases. Traffic class T1 requires pavement structures to be more robust than those fulfilling the design criteria corresponding to traffic class T5. This fact entails an increase in the environmental burdens assigned to the pavement life cycle phases whose environmental performance is roughly proportional to the volume of materials consumed (i.e., materials, transportation of materials, and EOL phases). However, it does not necessarily imply that those phases keep the same preponderance in driving the life cycle environmental performance of the functional units. As revealed in Table 3.10, the usage phase relegates the materials phase to second place in the ranking of the largest contributor in the majority of the impact categories. In general, the usage phase was found to be responsible for 42-52% of the values of each impact category indicator. Overall, the relative places of the remaining phases (i.e., transportation of materials, construction, and M&R) in the ranking of the phases with the worst environmental performance remained nearly the same as those observed with regard to traffic class T5. The main exceptions to this trend were verified in the cases of the WZ traffic management phase, as a consequence of the increase of the congestion level, and EOL phase. The pavement structures recommended for carrying high traffic volumes reach their EOL with greater remaining life than the pavement structures suggested for low traffic volumes. However, given that for high traffic volumes the usage phase is the most preponderant phase, it shadows the benefits of the avoided impacts associated with the EOL phase. Consequently, the EOL phase presents lower relative savings than those observed in the case of low traffic volumes.

Another point worthy of notice when analyzing Table 3.10 is the influence of the foundation class on the environmental performance of the recommended pavement structures.

For traffic class T5, since the environmental performance is mainly driven by the materials phase, one might expect that as the bearing capacity of the pavement foundation increases, the life cycle environmental burdens of a pavement system decrease. A stronger pavement foundation requires less cross-sectional area for a pavement structure than a weaker pavement foundation. Moreover, the design process, when performed taking into account the whole pavement's life cycle, can be used to obtain environmental benefits by reducing the maintenance frequency. The fact that better pavement foundations require pavement structures to undergo rehabilitation activities later on in the PAP may also be advantageous, since more environmentally-friendly and efficient processes, materials, construction methods, and vehicle technologies are expected to be unveiled throughout the PAP. Another issue connected with the M&R schedule is the fact of whether or not the emissions timing is taken into account during the LCIA. In this case study, TAWPs (Kendall, 2012) were applied to calculate the potential global warming effects of emissions that occur over the functional units' life cycle at a particular time in the future. In doing so, emissions occurring later during the PAP have a lower global warming effect than those occurring sooner if that effect is reported with reference to the year 0.

However, the aforementioned environmental advantages may be offset by the additional impacts resulting from the higher traffic volumes experiencing the M&R events and riding on pavements in poorer condition. In a scenario where the traffic volume is expected to increase throughout the PAP, and when the functional units in comparison do not behave much differently during the materials phase, the importance of the impacts stemming from both the traffic delays associated with the M&R activities and the influence of pavement roughness on vehicle FC may play a key role in driving the functional unit's overall environmental performance. Taking the TE impact category as an example, the life cycle net environmental impact indicators of the pavement structures recommended for the foundations F2 (P7) and F3 (P4) are 12,140 and 12,591 kg 1.4-DB-eq, respectively. Despite the worse environmental performance demonstrated by the materials phase corresponding to pavement structure P7 and the greater impact potentially avoided in the EOL phase, pavement structure P4 presents an inferior life cycle environmental performance, mostly as a consequence of an increase in the emissions released during the usage and WZ traffic management phases (respectively plus 793 and 264 kg 1.4-DB-eq relative to those released by pavement structure P7). As stated previously, a rehabilitation operation is applied when the PSI value reaches its minimum quality value of 2.0. Analyzing Figure 3.1, one can see that for pavement structure P7 the first and only rehabilitation operation will be applied in year 20 when the PSI value is 1.99. For pavement structure P4, the first and only rehabilitation will be applied in year 35 when the PSI value is only 1.56. The application of the rehabilitation operation when the PSI value is higher permits the PSI degradation rate to remain lower for pavement structure P7 than for pavement structure P4 during a time frame of the PAP in which the traffic volume is greater than that carried in the early stages of the PAP. This outcome exemplifies why a general conclusion relating the bearing capacity of the pavement foundation and the pavement system's life cycle environmental performance for traffic classes representing low traffic volumes cannot be drawn.

However, for traffic classes representing high traffic volumes (i.e., traffic class T1) the results presented in Table 3.10 show that overall environmental benefits may be obtained by adopting better pavement foundations. The environmental advantages are essentially a consequence of improvements in the environmental performance of the materials and usage phases. Such improvements are achieved through the implementation of pavement structure that is less demanding in terms of consumption of raw materials and that simultaneously does not excessively degrade its structural and functional behavior.

To illustrate the potential effect of improved pavement foundations on the overall pavement system's life cycle net environmental impacts, Figure 3.2 illustrates the carbon and raw materials consumption intensity per unit of the pavement foundation's bearing capacity as measured by the average stiffness modulus. As can be seen in Figure 3.2, moving from pavement foundation F2 to pavement foundation F4 would allow savings of approximately 37 tonnes CO_2-eq (73%) and 3.74 g Sb-eq (74%) per unit of bearing capacity added to the pavement foundation. This figure also highlights the importance of the material phase in driving the overall life cycle performance (second most important, just behind the usage phase), as both curves depicted in the chart behave similarly.

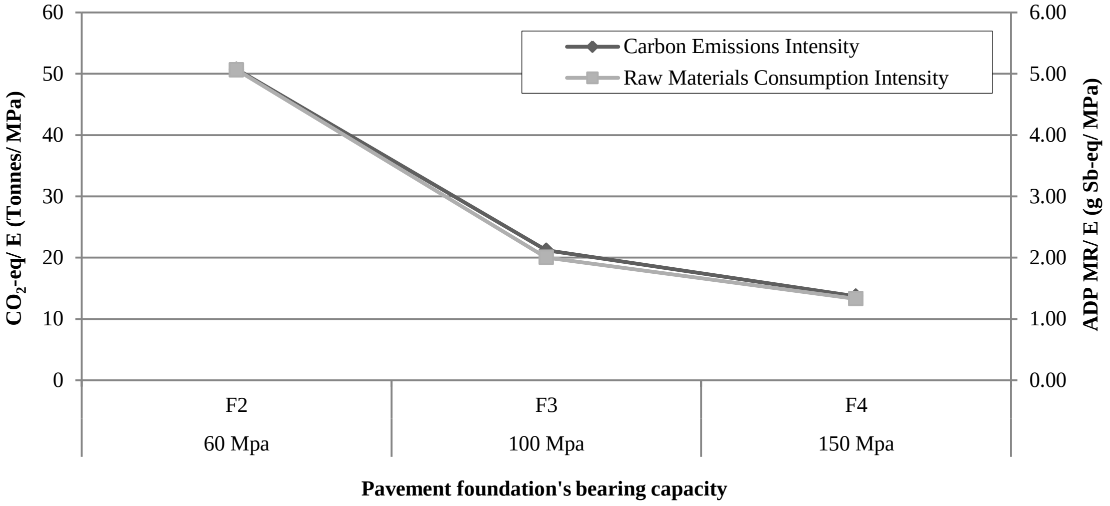

Figure 3.2- Carbon and raw material consumption intensity per unit of pavement foundation's bearing capacity.

3.6.2 Energy consumption of the analysed functional units

Table 3.11 presents the feedstock, process, and primary energy along with the CED computed for each functional unit, split up into the following categories: fossil (CED F), nuclear (CED Nuc.), primary forest (CED PF), and renewable resources (CED RR). Similar to the procedure adopted when analyzing the LCIA results referring to the remaining impact categories (e.g., CC, TE, etc.), the relative contributions (percentages) are calculated in relation to the life cycle environmental impact category indicators (i.e., they do not account for the avoided environmental burdens). By definition, CED should account for the usage of any sort of energy, including direct and indirect energy, throughout the life cycle. That means that the FsE of bitumen should also be included when accounting for CED. However, since the FsE inherent in bitumen remains unexploited while used as a binder in a pavement, it was presented separately from the primary energy as recommended by the UCPRC's Pavement LCA Guideline (Harvey et al., 2010).

For all functional units whose environmental performance was analyzed in detail, Table 3.11 shows an identical relationship between the values of the different CED indicators and the CC indicator. An analogous connection is also observed in the case of the CED Total and the Primary Energy indicators. Although both indicators refer to the sum of upstream energy requirements and process energy, the fact that the former is calculated with upper heating values (UHVs) while the latter is calculated with LHVs (Hischier et al., 2010) explains the difference of 6-16% between the values of the two energy indicators.

For traffic class T5, the materials phase was the most energy-consuming phase in terms of CED F, comprising 61%, 56%, and 59% of the 18.91 TJ, 18.73 TJ and 10.55 TJ corresponding to the life cycle of the pavement structures recommended for foundation classes F2, F3, and F4, respectively. An identical relationship has already been acknowledged with regard to CC, for which the aforementioned pavement structures were found to contribute to 64%, 59%, and 63% of the 1,174, 1,083 and 679 tonnes of CO_2-eq, respectively.

In the case of the pavement structures recommended for traffic class T1, the usage phase overtakes the materials phase as the highest energy intensive phase in all the foundation classes. Taking the CED F category as an example, it was found to be responsible for 46%, 45%, and 47% of the 59.57, 40.59, and 39.92 TJ consumed during the life cycle of the pavement structures recommended for the foundation classes F2, F3, and F4, respectively.

Table 3.11- Energy consumption analysis per pavement life cycle phase of each functional unit.

Foundation class	Traffic class	Pavement structure	Life cycle phase	FsE (MJ)	Process energy (MJ)	Primary energy (MJ)	CED F (MJ)	CED Nuc. (MJ)	CED PF (MJ)	CED RR (MJ)	CED Total (MJ)
F2	T5	P7	Materials	42,190,576	8,451,495	11,065,226	11,577,926	87,684	8	383,713	12,049,331
			Construction and M&R		1,137,456	1,375,654	1,438,201	18,834	2	3301	1,460,337
			Transportation of materials		2,251,160	2,722,583	2,846,371	37,249	4	6533	2,890,157
			WZ traffic management		532,517	647,628	679,713	10,573	0.540	1338	691,625
			Usage		1,669,454	2,068,620	2,365,942	25,396	2	4767	2,396,107
			EOL		-3,211,931	-4,061,754	-4,263,566	-37,076	-4	-95,610	-4,396,107
			Total net	42,190,576	10,830,151	13,817,958	14,644,587	142,661	12	304,041	15,091,301
	T1	P16	Materials	68,104,113	13,595,875	17,684,246	18,534,715	137,151	12	593,678	19,265,556
			Construction and M&R		1,715,249	2,074,445	2,168,764	28,408	3	4977	2,202,152
			Transportation of materials		3,405,277	4,118,388	4,305,639	56,346	6	9882	4,371,872
			WZ traffic management		5,638,983	6,856,059	7,194,354	86,755	6	14,276	7,295,392
			Usage		19,310,416	23,929,536	27,364,614	291,988	24	54,927	27,711,552
			EOL		-4,565,871	-5,733,194	-6,032,249	-78,062	-5	-129,983	-6,240,299
			Total net	68,104,113	39,099,929	48,929,481	53,535,836	522,585	45	547,758	54,606,225
F3	T5	P4	Materials	37,647,106	7,584,148	10,117,011	10,540,583	81,632	7	384,517	11,006,739
			Construction and M&R		1,108,693	1,340,868	1,401,833	18,358	2	3217	1,423,410
			Transportation of materials		2,077,663	2,512,753	2,627,000	34,379	4	6029	2,667,412
			WZ traffic management		831,206	1,010,931	1,061,049	16,463	0.838	2086	1,079,599
			Usage		2,193,114	2,715,729	3,095,209	32,926	3	6201	3,134,338
			EOL		-2,806,063	-3,560,700	-3,733,358	-33,053	-3	-85,299	-3,851,713
			Total net	37,647,106	10,988,761	14,136,592	14,992,317	150,705	13	316,751	15,459,786
	T1	P14	Materials	49,697,834	9,942,866	12,962,527	13,579,304	100,627	9	439,726	14,119,666
			Construction and M&R		1,220,076	1,475,577	1,542,667	20,201	2	3540	1,566,410
			Transportation of materials		2,524,946	3,053,703	3,192,546	41,780	4	7327	3,241,657
			WZ Traffic management		3,002,387	3,651,114	3,831,790	51,276	3	7560	3,890,630
			Usage		13,036,835	16,149,660	18,447,610	197,681	16	37,128	18,682,435
			EOL		-4,024,101	-5,064,383	-5,324,530	-45,128	-4	-116,233	-5,485,896
			Total net	49,697,834	25,703,008	32,228,199	35,269,387	366,436	30	379,049	36,014,902

Legend: FsE-feedstock energy; CED F- cumulative energy demand: fossil; CED Nuc.- cumulative energy demand: nuclear; CED PF.- cumulative energy demand: primary forest; CED RR.- cumulative energy demand: renewable resources; CED Total- cumulative energy demand: total; M&R- maintenance and rehabilitation; WZ- work-zone; EOL- end-of-life.

(continued)

Foundation class	Traffic class	Pavement structure	Life cycle phase	FsE (MJ)	Process energy (MJ)	Primary energy (MJ)	CED F (MJ)	CED Nuc. (MJ)	CED PF (MJ)	CED RR (MJ)	CED Total (MJ)
F4	T5	P3	Materials	21,488,923	4,381,224	5,965,386	6,187,215	48,975	4	246,912	6,483,106
			Construction and M&R		649,679	785,730	821,455	10,750	1	1885	834,092
			Transportation of materials		1,283,115	1,551,817	1,622,373	21,231	2	3723	1,647,330
			WZ traffic management		-	-	-	-	-	-	-
			Usage		1,366,277	1,691,989	1,928,789	20,489	2	3861	1,953,140
			EOL		-2,400,139	-3,059,580	-3,203,079	-29,029	-3	-74,988	-3,307,099
			Total net	21,488,923	5,280,156	6,935,342	7,356,754	72,416	6	181,393	7,610,569
	T1	P12	Materials	47,232,128	9,455,935	12,368,971	12,946,926	96,661	8	427,023	13,470,618
			Construction and M&R		1,178,417	1,425,193	1,489,992	19,511	2	3420	1,512,925
			Transportation of materials		2,430,884	2,939,944	3,073,614	40,223	4	7054	3,120,895
			WZ traffic management		2,983,495	3,628,057	3,807,532	50,978	3	7517	3,866,030
			Usage		13,190,487	16,329,351	18,599,982	199,082	16	37,408	18,836,487
			EOL		-3,753,271	-4,730,044	-4,970,740	-42,442	-4	-109,358	-5,122,545
			Total net	47,232,128	25,485,947	31,961,472	34,947,305	364,013	30	373,063	35,684,411

Legend: FsE-feedstock energy; CED F- cumulative energy demand: fossil; CED Nuc.- cumulative energy demand: nuclear; CED PF.- cumulative energy demand: primary forest; CED RR.- cumulative energy demand: renewable resources; CED Total- cumulative energy demand: total; M&R- maintenance and rehabilitation; WZ- work-zone; EOL- end-of-life.

The results described above can be seen as representative of a road transportation mode, and particularly the road sector, which is still excessively dependent on the combustion of fossil fuels. A similar conclusion can be drawn by interpreting the very small contributions of approximately 1.0%, 1.2%, and 0.000083% of the CED Nuc., CED RR, and CED PF, respectively, to the CED Total category. In all the functional units analyzed, the main purpose of the latter three types of energy is the production and delivery of other energy sources, mainly electricity, to their point of consumption, as opposed to the fossil energy (e.g., diesel, gasoline, etc.) that is used, amongst other functions, to power the processes directly linked to the construction, maintenance, and usage phases of the pavement systems.

Moreover, the majority of the airborne emissions released during the diverse pavement life cycle phases stem from the combustion of fossil fuels, as the production of the materials consumed to construct and maintain the pavement structures does not include the chemical reactions that would contribute to additional airborne emissions (e.g., limestone's calcination during cement production, etc.).

Comparing FsE and CED F, Table 3.11 shows the FsE of the bituminous materials to be, on average, approximately 3.7 times the CED F corresponding to the materials phase of the various functional units.

3.6.3 Influence of the pavement surface properties and vehicle types in the life cycle impact assessment results of the usage phase

In the usage phase of the pavement LCA model applied in this case study, only the RR effect was accounted for. RR is a result of a complex interaction between tires and road surface properties, of which the macrotexture, as measured by MPD, is one indicator. The macrotexture is difficult to control and predict, since it strongly depends on the quality of materials and processes used during the construction and maintenance phases of the pavement life cycle, as well as the sort of distresses that develop on the pavement throughout the PAP. Therefore, the environmental performance of all pavement structures was analyzed by assuming that the MPD remains constant (equal to 1 mm) during the whole PAP.

In addition to the baseline scenario, four alternative scenarios were analyzed to enhance the understanding of how the environmental impacts of the usage phase are influenced by the macrotexture and the effect of the various vehicle types. Those scenarios consisted of ranging, in a stepwise way, the MPD from 0.6 mm (nearly the lowest value allowed by the Portuguese road administration) to 1.4 mm (close to the highest value achieved by typical Portuguese HMA wearing courses).

Figure 3.3 depicts, for each scenario, the usage phase's total CO_2-eq emissions corresponding to the pavement structure (P16) recommended for traffic class T1 and foundation class F2, broken down by vehicle type. This figure shows that the relative contributions of the several vehicle types to the total CO_2-eq emissions are considerably different from the traffic composition. The traffic was assumed to be composed of 90% PCs, 7.5% rigid HDVs, and 2.5% articulated HDVs. However, when analyzing Figure 3.3 one can see that for all five scenarios, the single HDVs and articulated HDVs contribute between 14% and 36% of the total CO_2-eq emissions, whereas the PCs are responsible for only 50%. Those results agree well with the findings of Hammarström et al. (2012), who noticed that the FC of PCs is less affected by road surface characteristics than heavier vehicles.

Figure 3.4 depicts the marginal CO_2-eq emissions corresponding to each scenario relative to the baseline scenario. As shown in this figure, changes in the CO_2-eq emissions of the usage phase resulting from considering different macrotexture values are small, following an almost linear trend. By increasing the macrotexture by 0.4 mm the total CO_2-eq emissions of the usage phase would rise 2,206 kg. This increment represents a difference of 0.077% and 0.067% relative to the emissions released during the usage phase and total life cycle of the baseline scenario, respectively. Reductions with an analogous consequence in terms of the amount of emissions of CO_2-eq are expected if the macrotexture value is set at 0.6 mm.

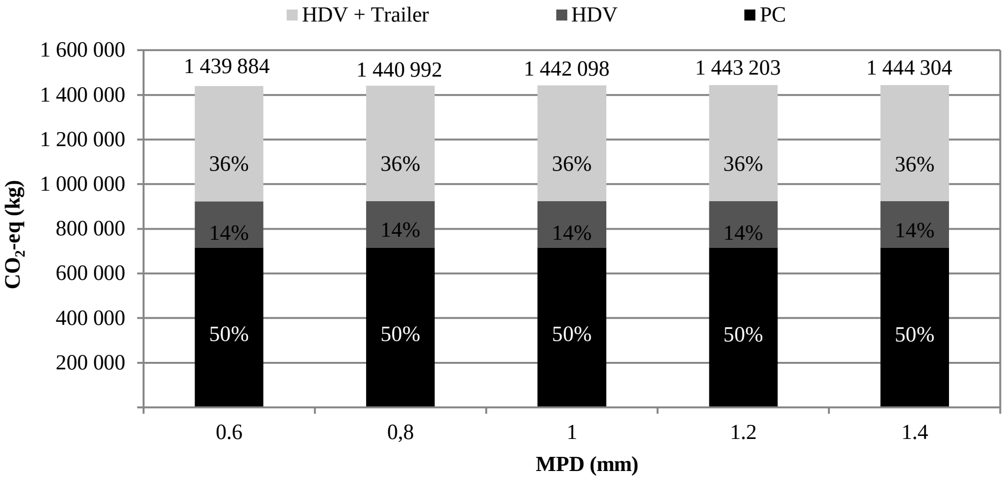

Figure 3.3- Usage phase's total CO2-eq emissions corresponding to pavement structure recommended for traffic class T1 and foundation class F2, broken down by vehicle type.

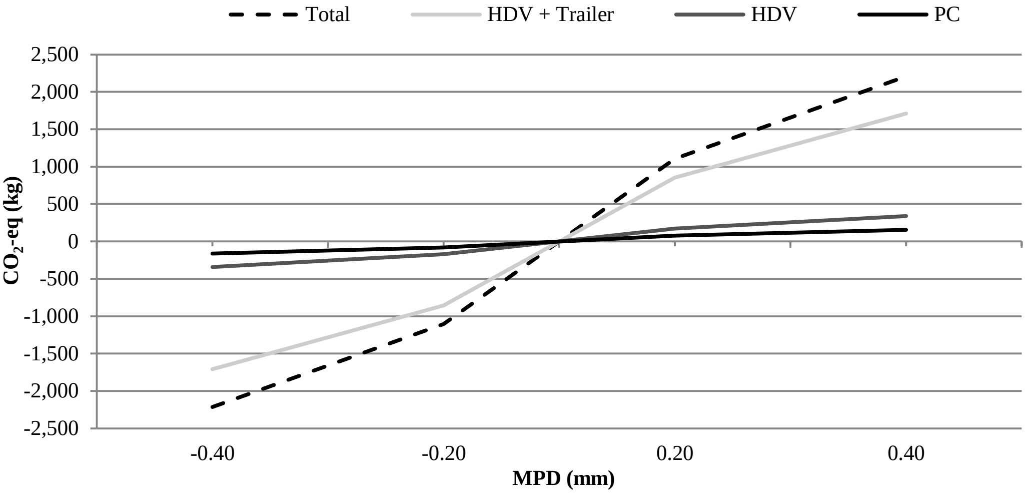

Figure 3.4- Usage phase's marginal CO2-eq emissions corresponding to each scenario in relation to the base scenario.

3.7 Summary and conclusions

This chapter presents the results of a comprehensive LCA of the standard flexible pavement structures defined in the Portuguese pavement design manual. The potentialities and usefulness of a pavement LCA model were demonstrated by estimating the potential environmental impacts of the six life cycle phases of the functional units at midpoint level. Complementarily, an energy consumption indicator (CED) was used to identify the most energy-demanding processes and the type of energy consumed.

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

- The level of traffic has a significant impact on the dominant life cycle phase. For lower volume traffic classes, the materials phase is the main contributor to the road pavement's overall life cycle environmental impacts (LCEI). On the other hand, if the road pavement is expected to carry a significant volume of traffic throughout its PAP, the usage phase becomes more prevalent;
- The bearing capacity of the pavement foundation is also an important factor in driving the life cycle environmental performance of pavements, especially for roads with heavy traffic. In this case, a high bearing capacity would result in lower overall LCEI than a foundation with lower bearing capacity. However, this pattern was not observed in pavements with low traffic volumes;
- During the usage phase, the contributions of HDVs to the environmental performance of a pavement system exceed several times their percentage of the traffic. In addition, these vehicle types were also found to be more sensitive to macrotexture variations than other types.

Given the success achieved at the project level, the authors believe that the pavement LCA model can be expanded to support pavement management decisions at the strategic and network levels. However, the particularity of each project would always require tools to deal with project-specific features while implementing the higher decision level's orientations.

In the near future, the development of this model will proceed in four main directions. First, the geographical applicability of the LCA model will be extended, in a first stage, by including sub-models tailored for other countries, namely the US, and in a second stage by fully applying the model to a case study. Second, the methodologic approach of this LCA model will be upgraded from the process-based approach to the hybrid approach. This improvement in the model's approach will be performed by integrating it with a comprehensive pavement LCC model that allows the several sub-models to connect with one another by monetary flows associated with exchanges of the pavement system that are directly covered by the LCC model but for which specific P- LCI data are either completely or partially unavailable. Third, the comprehensive pavement LCC-LCA model will be incorporated, along with a decision-support module, within a MOO framework to identify optimal pavement M&R strategies that yield the best tradeoff between conflicting objectives. Fourth, the analysis level of that optimization-based LCC-LCA model will be updated from the project to the network level to ensure that the decisions taken at project level end up in optimal sustainable solutions for the whole road pavement network.

3.8 References

Al-Omari, B. and Darter, M., 1994. Relationships between international roughness index and present serviceability rating. *Transportation Research Record: Journal of the Transportation Research Board*, 1435, 130-136.

Althaus, H., Chudacoff, M., Hischier, R., Jungbluth, N., Osses, M. and Primas, A., 2007. *Life cycle inventories of chemicals* (ecoinvent report No. 8, v2.0 EMPA). Available at: http://www.ecoinvent.org/

American Association of State Highway and Transportation Officials (AASTO), 1993. *Guide for design of pavement structures*. 4th ed. Washington, DC: American Association of State Highway and Transportation Officials.

Asphalt Institute, 2001. *Thickness design: asphalt pavements for highways and streets*. Lexington, KY: Asphalt Institute.

Avetisyan, H., Miller-Hooks, E., Melanta, S. and Qi, B., 2014. Effects of vehicle technologies, traffic volume changes, incidents and work-zones on greenhouse gas emissions production. *Transportation Research Part D: Transport and Environment*, 26, 10-19.

Barth, M. and Boriboonsomsin, K., 2008. Real world CO_2 impacts of traffic congestion. *Transportation Research Record: Journal of the Transportation Research Board*, 2058, 163-171.

Blankerdaal, T., Schuur, P. and Voordijk, H., 2014. Reducing the environmental impact of concrete and asphalt: a scenario approach. *Journal of Cleaner Production*, 66(1), 27-36.

Brunton, J., Brown, S. and Pell, P., 1987. *Developments to the Nottingham analytical design method for asphalt pavements*. *In:* Proceedings of the 6th International Conference on the Design of Asphalt Pavements. Ann Arbor, MI: University of Michigan.

California Air Resources Board (CARB), 2008. *Climate change scoping plan: a framework for change*. Available at: http://www.arb.ca.gov/cc/scopingplan/document/scopingplandocument.htm

Dones, R., Bauer, C., Bolliger, R., Burger, B., Emmenegger, F., Frischknecht, R., Heck, T., Jungbluth, N., Röder, A. and Tuchschmid, M., 2007. *Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries* (ecoinvent report No. 5). Available at: http://www.ecoinvent.org/.

Eurobitume, 2011. *Life cycle inventory: bitumen*. Available at: http://www.eurobitume.eu/hse/sustainability

European Commission (EC), 2011. *White paper. Roadmap to a single European transport area - towards a competitive and resource efficient transport system*. COM(2011) 144 final, Brussels: European Commission, Brussels. Available at: http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0144:EN:NOT.

European Commission, Joint Research Centre - Institute for Environment and Sustainability and DG Environment - Directorate G. (EC, JRC - IES and DGE – DG), 2008. *European reference life cycle database, version 2.0*. Available at: http://lca.jrc.ec.europa.eu

European Environment Agency (EEA), 2013. *EMEP/EEA air pollutant emission inventory guidebook 2009. Technical guidance to prepare national emission inventories* (European Environment Agency Technical report nº12/2013), Luxembourg: Publications Office of the European Union. Available at: http://www.eea.europa.eu/publications/emep-eea-guidebook-2013

Federal Highway Agency (FHWA), 2004. *Life-cycle cost analysis. Realcost user manual*. Available at: http://www.fhwa.dot.gov/infrastructure/asstmgmt/rc2100.cfm

Glass, J., Dyer, T., Georgopoulos, C., Goodier, C., Paine, K., Parry, T., Baumann, H. and Gluch, P., 2013. Future use of life-cycle assessment in civil engineering. *Proceeding of the ICE: Construction Materials*, 106(4), 204-2012.

Gschösser, F., Wallbaum, H. and Adey, B., 2014. Environmental analysis of new construction and maintenance processes of road pavements in Switzerland. *Structure and Infrastructure Engineering*, 10(1), 1-24.

Häkkinen, T. and Mäkelä, K., 1996. *Environmental impact of concrete and asphalt pavements* (Technical Research Center of Finland, VTT, Research Notes 1752). Available at: http://www.vtt.fi/inf/pdf/tiedotteet/1996/T1752.pdf.

Hammarström, U., Eriksson, J., Karlsson, R. and Yahya, M.-R., 2012. *A rolling resistance model, a fuel consumption model and the traffic energy saving potential from changed road surface condition* (VTI report 748A). Available at: http://www.vti.se/en/publications/rolling-resistance-model-fuel-consumption-model-and-the-traffic-energy-saving-potential-of-changed-road-surface-conditions/

Harvey, J., Kendall, A., Lee, I.-S., Santero, N., Van Dam, T. and Wang, T., 2010. *Pavement life cycle assessment workshop: discussion summary and guidelines* (Technical Memorandum: UCPRC-TM-2010-03). Available at: http://www.ucprc.ucdavis.edu/PublicationsPage.aspx

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., …Nemecek, T., 2010. *Implementation of life cycle impact assessment methods* (ecoinvent report No. 3, v2.2). Available at:

http://db.ecoinvent.org/files.php?area=463ee7e58cbf8&action=list

Horvath, A. and Hendrickson, C., 1998. Comparison of environmental implications of asphalt and steel-reinforced concrete pavements. *Transportation Research Record: Journal of the Transportation Research Board,* 1626, 105-113.

International Organization for Standardization (ISO), 2006. *ISO 14040:2006. International Standard ISO 14040: environmental management – life cycle assessment: principles and framework, October*. Geneva (Switzerland): International Organization for Standardization.

JAE, 1995. *Manual of pavement structures for the Portuguese road network*, Junta Autónoma de Estradas, Lisboa, Portugal, 1-54 (in Portuguese).

Jullien, A., Proust, C., Martaud, T., Rayssac, E. and Ropert, C., 2012. Variability in the environmental impacts of aggregate production. *Resources, Conservation and Recycling*, 62, 1-13.

Kendall, A., 2012. Time-adjusted global warming potentials for LCA and carbon footprints. *International Journal of Life Cycle Assessment*, 17(8), 1042-1049.

Kim, B., Lee, H., Park, H. and Kim, H., 2012. Framework for estimating greenhouse gas emissions due to asphalt pavement construction. *ASCE-Journal of Construction Engineering and Management*, 138 (11), 1312-1321.

Kucukvar, M. and Tatari, O., 2012. Ecologically based hybrid life cycle analysis of continuously reinforced concrete and hot-mix asphalt pavements. *Transportation Research Part D: Transport and Environment*, 17(1), 86-90.

Loijos, A., Santero, N. and Ochsendorf, J., 2013. Life cycle climate impacts of the US concrete pavement network. *Resources, Conservation and Recycling*, 72, 76-83.

Michael Fitch, G., Smith, J. and Clarens, A., 2013. Environmental life-cycle assessment of winter maintenance treatments for roadways. *ASCE-Journal of Transportation Engineering*, 139(2), 138-146.

Qian, S., Li, V., Zhang, H. and Keoleian, G., 2013. Life cycle analysis of pavement overlays made with Engineered Cementitious Composites. *Cement and, Concrete Composites*, 35(1), 78-88.

Santos, J. and Ferreira, A., 2013. Life-cycle cost analysis system for pavement management at project level. *International Journal of Pavement Engineering*, 14(1), 71-84.

Santos, J., Ferreira, A. and Flintsch, G., 2015. A life cycle assessment model for pavement management: methodology and computational framework. *International Journal of Pavement Engineering*, 16(3), 268-286.

Seo, Y. and Kim, S.-M., 2013. Estimation of materials-induced CO_2 emission from road construction in Korea. *Renewable and Sustainable Energy Reviews*, 26, 625-631.

Society of Environmental Toxicology and Chemistry (SETAC), 1993. *Guidelines for life-cycle assessment: a 'code of practice'*. Brussels (Belgium): SETAC publications.

Shell, 1978. *Shell pavement design manual - asphalt pavements and overlays for road traffic*. London: Shell International Petroleum Company Ltd.

United States Environmental Protection Agency (US EPA), 2004. *AP-42: compilation of air pollutant emission factors* (Volume 1: Stationary point and area sources, Chapter 11: Mineral products industry, 11.1). Available at: http://www.epa.gov/ttn/chief/ap42/ch11/index.html.

Wang, T., Lee, I.-S., Kendall, A., Harvey, J., Lee, E.-B. and Kim, C., 2012. Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production*, 33, 86-96.

Yu, B. and Lu, Q., 2012. Life cycle assessment of pavement: methodology and case study. *Transportation Research Part D: Transport and Environment*, 17(5), 380-388.

Yu, B. and Lu, Q., 2014. Empirical model of roughness effect on vehicle speed. *International Journal of Pavement Engineering*, 15(4), 345-351.

Zapata, P. and Gambatese, J. A., 2005. Energy consumption of asphalt and reinforced concrete pavement materials and construction. *ASCE-Journal of Infrastructure Systems*, 11, 9-20.

Chapter 4

A Life Cycle Assessment of In-Place Recycling and Conventional Pavement Construction and Maintenance Practices

4.1 Introduction

The US' National Highway System (NHS) includes over 264000 km of highways (FHWA, 2011). With the majority of highway construction complete since the 1980's, a large part of the national highway system is reaching the end of its design life. Recently, the ASCE report card (ASCE, 2013) evaluated the US' roads, and assigned it a grade of D, partly as a result of the fact that 32% of the major roads are in poor or mediocre conditions. The report card estimates that traveling on deficient pavements cost US motorists approximately $67 billion a year, or $324 per motorist.

In an effort to address poor pavements condition, agencies have adopted different M&R approaches. However, M&R of such an extensive road network consumes a significant amount of natural resources, mainly aggregates and bitumen. For example, the United States Geological Survey (USGS) reported that 460 million tonnes of crushed aggregate were used in 2011, mostly in the construction, maintenance, and rehabilitation of the US pavement network (USGS, 2013). Furthermore, approximately 23.4 million tonnes of paving bitumen was produced in 2008, according to Freedonia Group (2009). This pattern of consumption of natural resources does not appear to be sustainable and there has been growing societal concern about the environmental effects of constructing, operating, and maintaining the highway infrastructure network. In an attempt to mitigate the adverse environmental impacts, transportation authorities are seeking more sustainable pavement technologies and strategies.

Some common practices highlighted by the literature to increase the environmental performance of the road projects include the usage of asphalt mixes requiring lower manufacturing temperatures (Rubio et al., 2013), and the incorporation of recycled materials and byproducts (Jullien et al., 2006; Chiu et al., 2008; Huang et al., 2007; Huang et al., 2009; Sayagha et al., 2010). In particular, in-place pavement recycling reduces the need for virgin materials and reuses materials that would be otherwise hauled away and stockpiled or landfilled. While the true environmental benefit resulting from applying some of the aforementioned measures appears to be dependent on the system boundaries considered in the analysis (Tatari et al., 2012; Vidal et al., 2013), some recycling practices have been proven to enhance the life cycle environmental performance of pavements. One example is the application of in-place pavement recycling techniques to rehabilitate distressed pavements (Thenoux et al., 2007).

A LCA is the tool that is generally used to account for a systems' environmental performance. The results of an LCA can provide beneficial information to an agency that is in charge of managing infrastructure; for example, it can help determine which processes and maintenance techniques produce the highest and lowest environmental burdens. An important consideration for LCA is the boundaries chosen for the analysis. Ideally, an LCA is a cradle to grave analysis that accounts for the entire life cycle of the materials, including all the processes involved with the system, as well as other processes impacted by the system. However, a lack of information and an inability to accurately predict certain parameters, such as material life and the impact of the system condition on the user, sometimes lead to a constraint on the system boundaries for a pavement LCA. Thus, in the case of pavements, most LCA have excluded the use phase of the project (Park et al., 2003; Zapata and Gambatese, 2005; Huang et al., 2009).

Recently, research has produced more reliable models to quantify the impact of the pavement condition on vehicle FC and emissions (Karlsson et al., 2012; Chatti and Zaabar, 2012), which facilitates the inclusion of the use phase into a pavement LCA. By including the usage phase in the pavement LCA, the environmental footprint associated with the application of in-place pavement recycling techniques can be analyzed more thoroughly than in the previous LCA studies analyzing the environmental performance of this pavement M&R alternative (Thenoux et al., 2007; Miliutenko et al., 2013).

4.2 Objectives

This chapter presents the results of a pavement LCA conducted for an in-place pavement recycling rehabilitation project in the state of Virginia. It also illustrates the development of a comprehensive pavement LCA model that includes the usage phase into the system boundaries and accounts for the upstream impacts in the production and delivery of the energy sources. The project under consideration incorporated several in-place pavement recycling techniques and a unique traffic management approach. The results for the recycling-based project are compared to two other pavement management alternatives: (1) a traditional pavement reconstruction, and (2) a corrective maintenance approach. The three alternatives are summarized in Table 4.1. The reason for including more future actions in the corrective maintenance strategy will be discussed more thoroughly in a later section of this chapter.

4.3 Methodology

A comprehensive pavement LCA model was developed to calculate and compare the LCEI and energy consumption of multiple M&R activities applied in a road pavement section. The LCA was performed taking into account the guidelines provided by ISO

(ISO, 2006a; ISO, 2006b) and the UCPRC's Pavement LCA Guideline (Harvey et al., 2010). Field data for the case study were provided by the Virginia Department of Transportation (VDOT) (Diefenderfer et al., 2012). In the cases where no field data were available from VDOT, data were gathered from LCA inventories and relevant literature.

In order to automatically compute the environmental burdens assigned to the case study, the framework of the LCA model was implemented in a software written in VB.NET (Loureiro, 2010) and SQL programming languages (Damas, 2005), the latter being used for managing the data introduced and held in the system.

Table 4.1- Summary of the M&R Strategies.

M&R Strategy	Initial M&R Activity	Future M&R Activities
Recycling-Based	Left lane: Cold in place recycling (CIR) method to mill, refine and replace the top 13 cm (5 inches) of pavement. Right lane: A combination of full depth reclamation (FDR) and CCPR to treat 45 cm (18 inches) in depth. Both lanes: Apply an AC riding surface.	Maintenance actions performed in years 12, 22, 32 and 44 (Table 4.2)
Traditional Reconstruction	Left lane: Mill and replace the top 5 cm (2 inches) of pavement. Right lane: Mill and replace full depth of existing pavement and apply a cement treatment to the base/subgrade. Both lanes: Apply an AC riding surface.	Maintenance actions performed in years 12, 22, 32 and 44 (Table 4.3)
Corrective Maintenance	Both Lanes: 5% full depth patching followed by a 10 cm (4 inch) mill and overlay.	Maintenance actions performed in years 4, 10, 14, 18, 24, 28, 34, 38, 44 and 48 (Table 4.4)

Legend: AC- asphalt concrete; CIR- cold in-place recycling; FDR- full depth reclamation.
Note: Throughout this document the pavement M&R strategies are named "M&R Strategies", whereas the individual activities that integrate each M&R strategy are named "M&R Activities".

4.3.1 Goal and scope definition

This chapter presents the results from an extensive LCA conducted for three M&R strategies applied on a pavement segment. The first step consisted of developing a comprehensive pavement LCA model to estimate the environmental burdens related to the entire life cycle of the pavement section. The application of the pavement LCA model to the case study presented in this chapter allowed us to:

(1) Estimate the potential environmental advantages resulting from applying in-place pavement recycling techniques against two traditional M&R methods;
(2) Demonstrate a methodology that facilitates the inclusion of environmental loads assigned to the processes and pavement LCA phases typically excluded from the system boundaries of a pavement LCA;
(3) Identify the most important processes, and consequently pavement life cycle phases, in driving the environmental load of a road pavement section throughout its life cycle.

These results will provide state and local agencies with quantitative evidence to support the adoption of sustainable pavement management processes.

4.3.1.1 Functional unit

The specific project chosen for achieving the aforementioned objectives is a 5.9-km long, 2-lane (in one direction) asphalt section of Interstate 81 near Staunton, Virginia. The PAP is 50 years, beginning in 2011 with the in-place pavement recycling project that rehabilitated the existing pavement structure. The AADT for the first year was obtained from the VDOT traffic website[1] and consisted of approximately 25,000 vehicles with 28% trucks (85% of the truck traffic consisted of five- and six-axle tractor trailer combination vehicles). The traffic growth rate was assumed as 3%.

4.3.1.1.1 Pre-maintenance and rehabilitation conditions

Prior to the initial rehabilitation, the distresses along the pavement included cracking that extended through the full pavement depth in the right lane, and extensive rutting and patching throughout both lanes. The left lane was determined to be in better condition than the right lane, such that it was decided to design separate treatments for each lane. The overall structure of the pavement was evaluated, and deflection testing

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[1] http://www.virginiadot.org/info/ct-trafficcounts.asp

was used to determine that the structure of the pavement was in poor condition to the depth of the subgrade in the right lane. Thus, it was determined that a full reconstruction was needed for the right lane, and a heavy rehabilitation for the left lane. The project included two different construction methods, and further details about the project can be found in Diefenderfer et al. (2012). The left lane used a cold in-place recycling (CIR) method to mill, refine, and replace the top layers of the pavement. The CIR was performed using one machine on the site. The reconstruction of the right lane consisted of a combination of CCPR and FDR to extend to the subgrade.

4.3.1.1.2 Maintenance and rehabilitation scenarios

This study compared the three maintenance alternatives presented in Table 4.1. Details on the actions performed in each M&R strategy, as well as the respective schedule for future M&R actions are presented in Tables 4.2, 4.3 and 4.4.

For the recycling-based and traditional reconstruction M&R strategies, the expected M&R activities and respective M&R actions outlined by VDOT were followed (VDOT, 2011). For the corrective M&R scenario, past performance and construction history indicates that a 5-cm mill and overlay would be required every 4-6 years, along with partial depth patching. This was verified by using deflection data obtained prior to the rehabilitation of the road to calculate the Modified Structural Index (MSI) of the pavement, and using it as a predictor of future performance as outlined in Bryce et al. (2013).

The MSI is a modified version of the structural capacity index (SCI) initially developed by the Texas DOT to describe the in-situ structural state of the pavement. It is calculated by dividing the effective structural number over the required structural number, which means that it is an unbounded index. According to the definition of its general form, if the ratio is greater than one, no structural rehabilitation is expected to be required as the effective structural number is greater than the required structural number. For further details on the MSI development and applications the reader is referred to Bryce et al. (2012).

Table 4.2- Features of the M&R actions included in the recycling-based M&R strategy.

M&R activity	M&R actions	Mixture name	Thickness (cm)	Schedule (year)
Recycling-based reconstruction	Right lane: mill bound layers	-	25	0
	Right lane: FDR using calciment as the stabilizing agent	FDR- stabilized layer	30	
	Right lane: CCPR using hydraulic cement and foamed asphalt as the stabilizing agents	CCRP- material produced	15	
	Right lane: tack coat application	Bituminous emulsion	-	
	Right lane: lay AC IM layer	IM 19.0D	10	
	Right lane: tack coat application	Bituminous emulsion	-	
	Right lane: overlay SMA wearing course	SMA 12.5E	5	
	Left lane: mill bound layers	-	5	
	Left lane: CIR using hydraulic cement and foamed asphalt as the stabilizing agents	CIR- stabilized layer	13	
	Left lane: tack coat application	-	-	
	Left lane: lay AC IM layer	IM 19.0D	5	
	Left lane: tack coat application	Bituminous emulsion	-	
	Left lane: overlay SMA wearing course	SMA 12.5E	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	IM 19.0D	36	12
	Right and left lanes: mill bound layers	-	5	
	Right and left lanes: tack coat application	Bituminous emulsion	-	
	Right and left lanes: replace AC wearing course	SM 12.5A	5	
Structural mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	IM 19.0D	36	22
	Right and left lanes: mill bound layers	-	5	
	Right and left lanes: tack coat application	Bituminous emulsion	-	
	Right and left lanes: replace AC IM layer	IM 19.0D	5	
	Right and left lanes and shoulders: tack coat application	Bituminous emulsion	-	
	Right and left lanes and shoulders: overlay AC wearing course	SM 12.5A	5	
Major rehabilitation	Right and left lanes: pre-overlay full-depth patching 5%	IM 19.0D	41	32
	Right and left lanes: mill SM and IM layers	-	10	
	Right and left lanes: tack coat application	Bituminous emulsion	-	
	Right and left lanes: replace AC IM layer	IM 19.0D	5	
	Right and left lanes and shoulders: tack coat application	Bituminous emulsion	-	
	Right and left lanes and shoulders: overlay AC wearing course	SM 12.5A	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	IM 19.0D	41	44
	Right and left lanes: mill bound layers	-	5	
	Right and left lanes: tack coat application	Bituminous emulsion	-	
	Right and left lanes: replace AC wearing course	SM 12.5A	5	

Legend: AC- asphalt concrete; CCPR- cold central plant recycling; CIR- cold in-place recycling; FDR- full depth reclamation; IM- intermediate mixture; SM- surface mixture; SMA- stone mastic asphalt.

Table 4.3- Features of the M&R actions included in the traditional reconstruction M&R strategy.

M&R activity	M&R actions	Mixture name	Thickness (cm)	Schedule (year)
Reconstruction	Right lane and outside shoulder: mill bound layers	-	32	0
	Right lane and outside shoulder: undercut the existing base/subgrade	-	46	
	Right lane and outside shoulder: lay geotextile fabric	-	-	
	Right lane and outside shoulder: lay open graded base (OGB)	OGB 25.0	30	
	Right lane and outside shoulder: lay 21B aggregate base material	DGAB 21B	15	
	Right lane and outside shoulder: lay bound base layer	BM 25.0D	25	
	Left lane and inside shoulder: mill bound layers	-	5	
	Right and left lanes, and shoulders: tack coat application	Bituminous emulsion	-	
	Right and left lanes, and shoulders: lay AC IM layer	IM 19.0D	5	
	Right and left lanes, and inside shoulder: tack coat application	Bituminous emulsion	-	
	Right and left lanes, and inside shoulder: overlay SMA wearing course	SMA 12.5E	5	
	Outside shoulder: tack coat application	Bituminous emulsion	-	
	Outside shoulder: overlay AC wearing course	SM 12.5A	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	IM 19.0D	36	12
	Right and left lanes: mill bound layers	-	5	
	Right and left lanes: tack coat application	Bituminous emulsion	-	
	Right and left lanes: replace AC wearing course	SM 12.5A	5	
Structural mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	IM 19.0D	36	22
	Right and left lanes: mill bound layers	-	5	
	Right and left lanes: tack coat application	Bituminous emulsion	-	
	Right and left lanes: replace AC IM layer	IM 19.0D	5	
	Right and left lanes and shoulders: tack coat application	Bituminous emulsion	-	
	Right and left lanes and shoulders: overlay AC wearing course	SM 12.5A	5	
Major rehabilitation	Right and left lanes: pre-overlay full-depth patching 5%	IM 19.0D	41	32
	Right and left lanes: mill SM and IM layers	-	10	
	Right and left lanes: tack coat application	Bituminous emulsion	-	
	Right and left lanes: replace AC IM layer	IM 19.0D	5	
	Right and left lanes and shoulders: tack coat application	Bituminous emulsion	-	
	Right and left lanes and shoulders: overlay AC wearing course	SM 12.5A	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	IM 19.0D	41	44
	Right and left lanes: mill bound layers	-	5	
	Right and left lanes: tack coat application	Bituminous emulsion	-	
	Right and left lanes: replace AC wearing course	SM 12.5A	5	

Legend: AC- asphalt concrete; BM- base mixture; DGAB- dense graded aggregate base; IM- intermediate mixture; OGB- open graded base; SM- surface mixture; SMA- stone mastic asphalt.

Table 4.4- Features of the M&R actions included in the corrective M&R strategy.

M&R activity	M&R actions	Mixture name	Thickness (cm)	Schedule (year)
Major rehabilitation	Right and left lanes: pre-overlay full-depth patching 5%	IM 19.0D	31	0
	Right and left lanes: mill SM and IM layers	-	10	
	Right and left lanes: replace AC IM layer	IM 19.0D	5	
	Right and left lanes, and shoulders: tack coat application	Bituminous emulsion	-	
	Right and left lanes, and shoulders: overlay AC wearing course	SM 12.5A	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	IM 19.0D	36[a]	4, 18, 34, 38, 48
	Right and left lanes: mill bound layers	-	5	
	Right and left lanes: tack coat application	Bituminous emulsion	-	
	Right and left lanes: replace AC wearing course	SM 12.5A	5	
Structural mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	IM 19.0D	36	10, 24
	Right and left lanes: mill bound layers	-	10	
	Right and left lanes: tack coat application	Bituminous emulsion	-	
	Right and left lanes: replace AC IM layer	IM 19.0D	5	
	Right and left lanes, and shoulders: tack coat application	Bituminous emulsion	-	
	Right and left lanes, and shoulders: overlay AC wearing course	SM 12.5A	5	
Major rehabilitation	Right and left lanes: pre-overlay full-depth patching 5%	IM 19.0D	41[b]	14, 28, 44
	Right and left lanes: mill SM and IM layers	-	10	
	Right and left lanes: tack coat application	Bituminous emulsion	-	
	Right and left lanes: replace AC IM layer	IM 19.0D	5	
	Right and left lanes, and shoulders: tack coat application	Bituminous emulsion	-	
	Right and left lanes, and shoulders: overlay AC wearing course	SM 12.5A	5	

Legend: AC- asphalt concrete; BM- base mixture; IM- intermediate mixture; SM- surface mixture.

Notes: [a] Whenever the “pre-overlay full-depth patching 1%” M&R action is applied, its thickness increases 5 cm relatively to the previous application. An exception to this rule occurs in the case of the first type of “Functional mill and replace” M&R activity. The “Right and left lines: pre-overlay full-depth patching 1%” M&R action scheduled at years 34 and 38 have the same thickness (46 cm).

[b] Whenever the “pre-overlay full-depth patching 5%” M&R action is applied, its thickness increases 5 cm relatively to the previous application.

For the pavement section under assessment the MSI value was found to be 0.78, which indicates a considerably weak structural condition and that the deterioration of the condition should occur much more rapidly than a pavement with adequate structure (i.e., a pavement with an MSI of 1) (Bryce et al., 2013). The predicted deterioration curve along with past condition data (in terms of the Critical Condition Index [CCI]), is shown in Figure 4.1a.

In order to determine the roughness of the pavement as a function of time for the corrective M&R strategy, past IRI data for the pavement section was plotted and a function in the form of the Expression (4.1) was fitted to the data.

$$IRI(t) = at^2 + bt + c \tag{4.1}$$

Where *IRI(t)* is the IRI value (m/km) in year *t; c* is the IRI value (m/km) after M&R is performed; *a* and *b* are parameters that were found by minimizing the sum of square errors between the fitted function and the measured data. The values the parameters *a*, *b* and *c* are presented in Table 4.5.

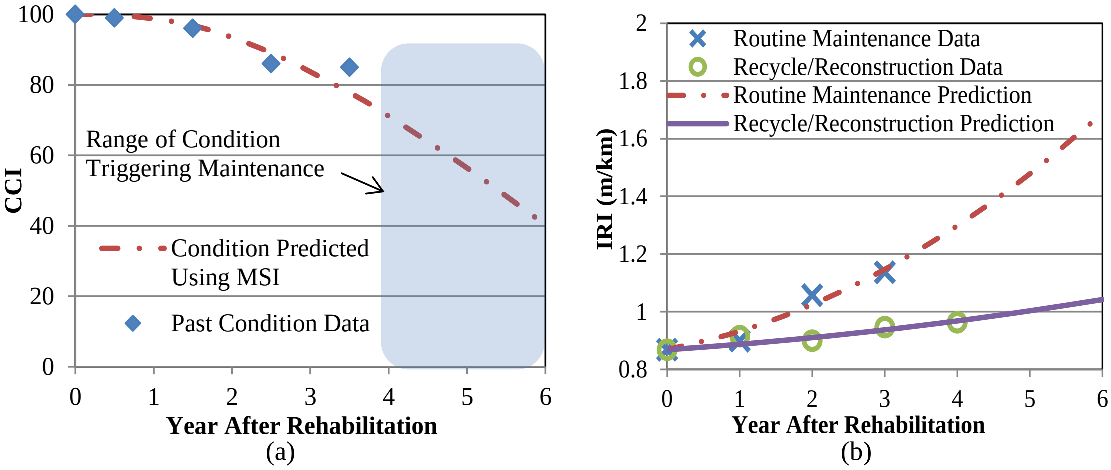

Figure 4.1- (a) Predicted deterioration for the rehabilitation M&R strategy, and (b) predicted roughness for each M&R strategy.

Table 4.5- Parameters values of the Expression (4.1).

M&R strategy	Parameters		
	a	b	c
Recycling-based	0.002	0.017	0.868
Traditional Reconstruction	0.002	0.017	0.868
Corrective Maintenance	0.015	0.05	0.868

A similar procedure was conducted for the cases of the recycling-based and traditional reconstruction M&R strategies; however, in those M&R strategies data from an adjacent pavement section that was rehabilitated in 2005 was used. The reason for using data from the adjacent pavement section was the lack of long term IRI measurements for the pavement section under investigation. Furthermore, the adjacent pavement section had an MSI value of 1.3 (structurally adequate) and was expected to be subjected to similar environmental and traffic loading as the pavement section under investigation. The values of the parameters are presented in Table 4.5. The functions and measured data are shown in Figure 4.1b.

4.3.1.2 System boundaries, system processes and life cycle inventory data

The life cycle of a road pavement is generally divided into five phases (Harvey et al., 2010): (1) materials extraction and production; (2) construction; (3) M&R; (4) usage; and (5) EOL. However, in the proposed model, the environmental impacts associated with the on-road vehicles when subject to a WZ traffic management plan (implemented during the reconstruction and M&R activities) are treated as an individual phase and designated as WZ traffic management phase. The WZ traffic management phase was separated out in order to highlight the influence of the WZ on the environmental performance when compared to normal traffic flow. Transportation of materials and asphalt mixtures between facilities and work site, and vice-versa, was also analyzed separately. Therefore, the proposed pavement 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. The various models evoked while modeling each pavement LCA phase, as well as the data required to run those models, are introduced and discussed in the following sections.

4.3.1.2.1 Materials extraction and production phase

Pavement-related environmental burdens assigned to this phase are due to material acquisition and processing. This includes all materials manufacturing processes, from extraction of raw materials to their transformation into a pavement input material (material extraction sub-phase), and ending up 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 mixing plant (e.g., dryer, hot screen, mixers, etc.), as well as the operation of the wheel loader during the movement of aggregates from the stockpiles to the feed bins. The manufacturing of the facilities, such as the construction of the mixture production plants, is excluded from the system boundaries. All environmental burdens stemming from transportation between facilities (i.e., transporting aggregates from the quarry to the mixture production plant) are assigned to the transportation of materials phase. The LCI data of the materials and mixtures used in this case study was collected from several published LCI and LCA reports.

Inventory data for both fine and coarse natural aggregate was taken from Stripple (2001). The LCI data for the bitumen, which in this case study was used either as binder in asphalt mixtures or as stabilizing agent, were obtained from Eurobitumen (2011). The LCI data for the hydraulic cement used as an active filler was obtained by adapting Marceau et al. (2006) LCI data corresponding to the hydraulic cement production through the precalciner process. The LCI data of calciment (the stabilizing agent used during the FDR portion), a combination of hydraulic cement (70%) and lime kiln dust (30%), was determined by multiplying by a factor of 0.7 the hydraulic cement's LCI data. No environmental load was assigned to the lime kiln dust given that it is an existing by-product of another manufacturing process.

The LCI data associated with the operation of natural gas fired dryers, hot screens and mixers at a drum mix plant were obtained by combining the emissions factors published by the AP-42 study of HMA plants (US EPA, 2004) corresponding to a fabric filter-controlled drum-mix plant with the energy consumption presented by Sathaye et al. (2009) for the same type of plant. The electricity consumption referring to the operation of the conveyor system was obtained from Stripple (2001). Emissions and energy consumption due to the operation of the wheel loader were estimated based on the rate at which the wheel loader can move aggregates (Expression (4.2)) and the methodology adopted by the US EPA's NONROAD 2008 model (US EPA, 2010b). Further information on this methodology is given in section 4.3.1.2.3. The environmental burdens from CCPR process are accounted by the construction and M&R phase, since they are produced by a mobile plant which is classified as construction equipment.

$$r_{WL} = \frac{WL_{cap} \times \rho_{aggregates}}{t_{trip}} \tag{4.2}$$

Where r_{WL} is the rate at which the wheel loader can move aggregates (Kg/hr); WL_{cap} is the volumetric capacity of the bucket's wheel loader (3.3 m^3); $\rho_{aggregates}$ is the average density of the aggregates in the bucket of the wheel loader (1700 Kg/m^3), and; t_{trip} is the time required to complete a round trip from the stockpile to the feed bins (min). The value assumed was 2 min.

4.3.1.2.2 Transportation of materials phase

The environmental impacts resulting from the transportation of materials are due to the combustion process emissions released by the transportation vehicles. All materials and mixtures were assumed to be hauled by HDVs, and the United States Environmental Protection Agency (US EPA) Motor Vehicle Emissions Simulator (MOVES) (US EPA, 2010a) was used to determine the average FC and airborne emissions factors for operating diesel powered, single unit short-haul trucks and long-haul combination trucks. These factors were computed for the typical climate conditions during the month of April for Augusta County in Virginia.The transportation distances considered for each material and mixture used in this case study, as well as the payload capacity of the hauling trucks are shown in Table 4.6. Outside of the system boundaries of this model are the air emissions associated with the production and maintenance of the hauling HDVs, as well as the transportation of the construction equipment from the construction company's facilities to the work-site.

Table 4.6- Features of the movements of transportation of materials.

Material/ mixture	One-way trip distance (km)	Hauling trucks payload capacities (tonnes)
Milled asphalt material (prior to FDR)	1.9	20
Milled asphalt material (prior to CIR)	25	20
Removed granular material (subgrade)	25	20
CCRP material produced	1.9	20
Hydraulic cement and calciment	346	27
Tap water	20	15
Crushed and fine aggregates	0.6	20
Binder and bitumen emulsion	125	15
Open graded base- 25.0 granular material	25	20
21B aggregate material	25	20
Asphalt mixtures (to site)	25	20

Legend: CCRP- cold central plant recycling; CIR- cold in-place recycling; FDR- full depth reclamation.

4.3.1.2.3 Construction, maintenance and rehabilitation phase

The construction and M&R related environmental burdens were obtained by applying the methodology adopted by the US EPA’s NONROAD 2008 model (US EPA, 2010b). Pollutants covered by this methodology include HC, CO, NO_x, PM, CO_2, and SO_2. FC is accounted for on the basis of the brake specific FC (BSFC) indicator. The calculation of N_2O and CH_4 emissions used the US EPA’s guide on calculating GHG emissions from mobile sources (US EPA, 2008). Information regarding the type and features (e.g., brand, model, engine horsepower, etc.) of each equipment used to perform the several M&R activities, as well as their respective production rates were taken from Diefenderfer et al. (2012) and complemented with technical specifications from the equipment’s manufacturers. Future M&R activities are assumed to take place during the month of April, as was the reconstruction and rehabilitation performed in the beginning of the PAP of each M&R scenario. The same production rates of construction equipment were assumed for the remaining M&R activities.

4.3.1.2.4 Work-zone traffic management phase

The WZ traffic management includes aspects for two routes: the single lane of I-81 to remain open during the work, and the detour road. As discussed in Diefenderfer et al. (2012), this project included an innovative traffic management technique that consisted of detouring cars from the road onto a parallel route, while trucks were allowed to remain on I-81 during construction. In this pavement LCA model, the FC and airborne emissions assigned to on-road vehicles during the WZ traffic management plan have been determined by adopting a two-step method. First, the US EPA's MOVES model was run multiple times to compute a set of FC and emissions factors representing the national scale vehicle fleet characteristics per type of vehicle, and Augusta county's average climatic conditions during the month of April in three distinct years of the PAP (2011, 2035 and 2050). For years between 2011 and 2050, the emissions factors were interpolated according to a Lagrangian interpolation function. The EFs for the year 2050 were applied to analysis years beyond 2050. Each model run generated an output file displaying the emissions factors on an hourly basis as a function of sixteen speed ranges, called speed bins, and two types of road categorized as rural restricted access and rural unrestricted access. The former category is assumed to represent the operating conditions existing in I-81, whereas the latter fits the features of the detour road (Virginia Route 11).

Secondly, changes in driving patterns were modelled using the capacity and delay models proposed by the HCM 2000 (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. Each section where there is a change in driving pattern was considered to be a new road "link". The characteristics of each link (length, number of vehicles and average speed) was combined with the MOVES FC and emissions factors previously computed and stored in look up tables to derive the environmental load of a WZ day. Finally, the marginal FC and airborne emissions due to the WZ traffic management plan were calculated by subtracting FC and airborne emissions released during a WZ period from the results of an equivalent non-WZ period.

4.3.1.2.5 Usage phase

The usage phase addresses the pavement's environmental burdens resulting from the interaction of the pavement with the vehicles and environment throughout its PAP. The following are factors that have been identified in past research as pertinent to consider during the usage phase of the pavement (Santero et al., 2011; Sandberg et al., 2011; Chatti and Zaabar, 2012); Tire-Pavement Interaction, Traffic Flow, Albedo, Leachate and Runoff, Carbonation, and Lighting. However, many of these factors (i.e., Albedo, Carbonation and Lighting) do not directly apply to the project currently under evaluation. Thus, the main contribution that was considered from the usage phase in this analysis is the tire-pavement interaction. Tire-pavement interaction influences vehicle RR, and is impacted by several variables such as: macro-texture, pavement stiffness, roughness and the transversal slope of the pavement. Given that this study compared several maintenance plans using the same surface materials, the only factor that was considered in the usage phase is the impact of the pavement roughness on the pavements overall environmental burden.

In order to determine the impact of the pavement roughness on vehicle FC and emissions, the HDM 4 FC model (Bennett and Greenwood, 2003), calibrated and validated for US conditions by Chatti and Zaabar (2012), was combined with data from the EPA's MOVES model. The approach proposed in this chapter differs from other proposed approaches (i.e., Wang et al., 2012) in that the impact of increasing RR can be combined with the MOVES emissions rates models without the need to modify the vehicle specific power model within the MOVES program (which calculates emissions rates from vehicles travelling along a smooth surface). The first step in the proposed approach is to use the model given in Chatti and Zaabar (2012) 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, instead of using the actual AADT in the MOVES emissions rate model, an effective AADT was used to relate the increase in roughness to the increase in FC and emissions. The effective AADT ($AADT_E$) for a given roughness at time t, in terms of the IRI, was calculated using Expression (4.3).

$$AADT_E(t) = AADT(t) \times \frac{FC_{IRI(t)}}{FC_{Smooth}} \tag{4.3}$$

Where $FC_{IRI(t)}$ is the FC for the vehicle fleet travelling on a pavement with a specified IRI at time *t*, and FC_{Smooth} is the FC of the same vehicle fleet travelling along a typical smooth pavement.

4.3.1.2.6 End-of-life phase

When a road pavement reaches its service life, it can be given two main fates: (1) remain in place serving as support for a new pavement structure, and (2) be removed. Removed pavements materials are: (1) disposed in a landfill (generally a very small percentage in the US), or (2) recycled and re-used either as a replacement for virgin aggregate in a base layer or as a replacement for virgin asphalt and aggregate in new asphalt mixtures. It is expected that the most likely EOL scenario for the pavement sections in this analysis is that they remain in place after reaching the end of the PAP, serving as foundation for the new pavement structure. Thus, by adopting a “cut-off” allocation method no environmental impacts were assigned to the EOL phase of all M&R scenarios in comparison in the current pavement system.

4.3.1.3 Energy sources production

Energy source production refers to the impact of producing and delivering the energy that is used to power the various equipment and processes that are required for the project (e.g., the production of the fuel to power the transportation of the materials, etc.). Although it is not considered a pavement life cycle phase, as those previously introduced, the energy sources production and transportation is an unavoidable process that is common to all pavement life cycle phases. For this reason their life cycle impacts should be considered and displayed separately from the impacts due to the process energy consumption. Presenting the impacts from the energy sources production facilitates the understanding of where in the pavement life cycle the use of less environmentally burdensome energy sources may help reduce the environmental load of a road pavement. Therefore, before inclusion in the database, the LCI data of each material and mixture was disaggregated to the processes level in order to distinguish the

LCI due to the pre-combustion energy, from that due to the process energy combustion in the final destination. In this case study, the GREET model (Argonne National Laboratory, 2013) was used as the source of the LCI data 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 the electricity, a default electricity mix was modified to reflect the electricity production in the state of Virginia (US EIA, 2012).

4.3.2 Life cycle inventory

The LCI corresponding to the case study was performed for each life cycle phase of each pavement M&R strategy using the models and data sources presented in the previous sections. The inventory analysis was used to determine, both qualitatively and quantitatively, the materials, the energy flows, and the atmospheric emissions associated with each individual process within the system under analysis. The outputs arisen from those unit processes were posteriorly combined in order to derive the total environmental burden of the system. Table 4.7 provides the overall LCI per pavement life cycle phase of each pavement M&R strategy, expressed in terms of atmospheric emissions.

Table 4.7- LCI per pavement life cycle phase of each M&R strategy.

M&R strategy	Life cycle phase	Sub component	CO_2 (Kg)	CH_4 (Kg)	N_2O (Kg)	SO_2 (Kg)	NO_x (Kg)	NH_3 (Kg)	CO (Kg)	VOC (Kg)	NMVOC (Kg)	$PM_{2.5}$ (Kg)	Pb (Kg)
Recycling-based	Materials	P.E.	1.11E+06	5.04E+02	4.35E+00	5.88E+02	2.08E+03	2.94E-01	3.78E+03	1.18E+03	6.16E+01	1.58E+02	1.70E-02
		P.C.E.	5.96E+05	1.22E+04	7.80E+02	1.54E+03	1.29E+03	0.00E+00	3.10E+02	1.52E+02	0.00E+00	2.01E+02	0.00E+00
	Construction and M&R	P.E.	1.38E+05	7.80E+00	3.47E+00	1.62E+02	8.16E+02	0.00E+00	5.55E+02	0.00E+00	0.00E+00	3.28E+01	0.00E+00
		P.C.E.	2.87E+04	2.50E+02	3.87E-01	4.48E+01	8.11E+01	0.00E+00	2.07E+01	1.43E+01	0.00E+00	0.00E+00	0.00E+00
	Transportation of materials	P.E.	2.38E+05	8.85E+00	4.37E-01	1.62E+00	5.59E+02	4.55E+00	1.75E+02	3.57E+01	2.89E+01	1.99E+01	0.00E+00
		P.C.E.	5.02E+04	4.38E+02	6.78E-01	7.85E+01	1.42E+02	0.00E+00	3.64E+01	2.50E+01	0.00E+00	0.00E+00	0.00E+00
	WZ traffic management	P.E.	3.48E+06	2.29E+02	3.60E+01	4.69E+01	3.15E+03	2.11E+02	1.51E+04	7.69E+02	5.40E+02	1.82E+02	0.00E+00
		P.C.E.	7.45E+05	6.50E+03	1.01E+01	1.17E+03	2.12E+03	0.00E+00	5.38E+02	9.81E+02	0.00E+00	1.27E+02	0.00E+00
	Usage	P.E.	1.12E+08	2.33E+03	2.46E+02	1.54E+03	1.39E+05	2.91E+04	1.09E+05	0.00E+00	6.39E+03	7.12E+05	0.00E+00
		P.C.E.	3.00E+07	2.61E+05	4.04E+02	4.71E+04	8.50E+04	0.00E+00	2.17E+04	3.11E+04	0.00E+00	3.36E+03	0.00E+00
	Total		1.48E+08	2.84E+05	1.49E+03	5.23E+04	2.35E+05	2.93E+04	1.51E+05	3.43E+04	7.02E+03	7.16E+05	1.70E-02
Traditional Reconstruction	Materials	P.E.	2.14E+06	7.91E+02	1.55E+01	1.51E+03	5.31E+03	4.03E-01	6.24E+03	1.89E+03	4.85E+01	2.57E+02	2.76E-02
		P.C.E.	1.12E+06	1.97E+04	1.40E+03	2.86E+03	2.34E+03	0.00E+00	5.50E+02	2.67E+02	0.00E+00	2.91E+02	0.00E+00
	Construction and M&R	P.E.	2.22E+05	1.25E+01	5.56E+00	3.29E+02	1.28E+03	0.00E+00	8.96E+02	0.00E+00	0.00E+00	3.36E+01	0.00E+00
		P.C.E.	4.60E+04	4.01E+02	6.20E-01	7.19E+01	1.30E+02	0.00E+00	3.33E+01	2.29E+01	0.00E+00	0.00E+00	0.00E+00
	Transportation of material	P.E.	5.38E+05	1.74E+01	1.04E+00	3.65E+00	2.01E+03	1.07E+01	6.60E+02	1.67E+02	1.52E+02	7.75E+01	0.00E+00
		P.C.E.	1.13E+05	9.88E+02	1.53E+00	1.77E+02	3.21E+02	0.00E+00	8.20E+01	5.64E+01	0.00E+00	0.00E+00	0.00E+00
	WZ traffic management	P.E.	3.76E+06	2.41E+02	4.08E+01	5.31E+01	3.43E+03	2.45E+02	1.85E+04	9.84E+02	7.43E+02	2.21E+02	0.00E+00
		P.C.E.	8.04E+05	7.02E+03	1.09E+01	1.27E+03	2.28E+03	0.00E+00	5.81E+02	1.10E+03	0.00E+00	1.44E+02	0.00E+00
	Usage	P.E.	1.12E+08	2.33E+03	2.46E+02	1.54E+03	1.39E+05	2.91E+04	1.09E+05	0.00E+00	6.39E+03	7.12E+05	0.00E+00
		P.C.E.	3.00E+07	2.61E+05	4.04E+02	4.71E+04	8.50E+04	0.00E+00	2.17E+04	3.11E+04	0.00E+00	3.36E+03	0.00E+00
	Total		1.51E+08	2.93E+05	2.12E+03	5.49E+04	2.41E+05	2.94E+04	1.58E+05	3.56E+04	7.34E+03	7.16E+05	2.76E-02

Legend: : LCI- life cycle inventory; M&R- maintenance and rehabilitation; WZ- work-zone; EOL- end-of-life; P.E.- process energy; P.C.E.- pre-combustion energy.

(continued)

M&R strategy	Life cycle phase	Sub component	CO_2 (Kg)	CH_4 (Kg)	N_2O (Kg)	SO_2 (Kg)	NO_x (Kg)	NH_3 (Kg)	CO (Kg)	VOC (Kg)	NMVOC (Kg)	$PM_{2.5}$ (Kg)	Pb (Kg)
Corrective Maintenance	Materials	P.E.	2.36E+06	1.07E+03	6.94E+00	9.97E+02	4.05E+03	5.91E-01	8.37E+03	2.56E+03	5.68E+01	3.41E+02	3.79E-02
		P.C.E.	1.22E+06	2.52E+04	1.62E+03	3.18E+03	2.61E+03	0.00E+00	6.26E+02	3.13E+02	0.00E+00	3.31E+02	0.00E+00
	Construction and M&R	P.E.	2.30E+05	1.30E+01	5.77E+00	1.92E+02	1.39E+03	0.00E+00	1.03E+03	0.00E+00	0.00E+00	7.68E+01	0.00E+00
		P.C.E.	4.77E+04	4.16E+02	6.44E-01	7.46E+01	1.35E+02	0.00E+00	3.45E+01	2.37E+01	0.00E+00	0.00E+00	0.00E+00
	Transportation of material	P.E.	4.95E+05	1.97E+01	9.49E-01	3.36E+00	9.77E+02	9.83E+00	3.27E+02	7.00E+01	5.35E+01	3.19E+01	0.00E+00
		P.C.E.	1.04E+05	9.09E+02	1.41E+00	1.63E+02	2.95E+02	0.00E+00	7.55E+01	5.18E+01	0.00E+00	0.00E+00	0.00E+00
	WZ traffic management	P.E.	7.26E+06	4.83E+02	7.18E+01	9.10E+01	7.48E+03	3.91E+02	2.59E+04	1.36E+03	8.74E+02	3.67E+02	0.00E+00
		P.C.E.	1.55E+06	1.35E+04	2.09E+01	2.44E+03	4.40E+03	0.00E+00	1.12E+03	1.93E+03	0.00E+00	2.41E+02	0.00E+00
	Usage	P.E.	1.54E+08	3.29E+03	3.42E+02	2.16E+03	1.89E+05	4.04E+04	1.47E+05	0.00E+00	9.01E+03	1.00E+06	0.00E+00
		P.C.E.	4.22E+07	3.68E+05	5.69E+02	6.63E+04	1.20E+05	0.00E+00	3.05E+04	4.40E+04	0.00E+00	4.77E+03	0.00E+00
	Total		2.10E+08	4.13E+05	2.64E+03	7.56E+04	3.30E+05	4.08E+04	2.15E+05	5.03E+04	9.99E+03	1.01E+06	3.79E-02

Legend: : LCI- life cycle inventory; M&R- maintenance and rehabilitation; WZ- work-zone; EOL- end-of-life; P.E.- process energy; P.C.E.- pre-combustion energy.

4.3.3 Life cycle impact assessment

The purpose of the LCIA is to assign the LCI results to different impact categories based on the expected types of impacts on the environment. According to the type of substances released and resources consumed and the impact categories commonly recognized as the most representative of the three protection areas (human health, natural environment, and natural resources), the following categories were selected: CC, Ac due to air emissions, EU due to air emissions, human health criteria pollutants (HH), photochemical smog formation (PSF) and ARD. The US-based impact assessment tool, the Tool for the Reduction and Assessment of Chemical and other environmental Impacts 2.0 (TRACI 2.0), was chosen as the main methodology to conduct the impact assessment step of the LCA. The reader is referred to Bare (2011) for a more detailed discussion of TRACI. The characterization models and associated characterization factors from TRACI 2.0 were applied to quantify the contribution of each LCI element to the Ac air, EU air, HH and PSF impact categories. The time-adjusted characterization model for the CC impact category that was proposed by Kendall (2012) was used in this approach as opposed to the traditional time-steady IPCC model. The characterisation factors present in the April 2013 updated version of the LCIA methodology developed by the Center of Environmental Science (CML) of Leiden University in Netherlands (Guinée, 2002) were used to determine the impact assessment for ARD of mineral resources (ARD MR) and fossil fuels (ARD FF). Furthermore, an energy analysis was carried out based on the CED indicators, expressed as CED F, CED Nuc. and CED RR. This indicator was computed according to Hischier et al. (2010) but adopting the UHVs defined in the GREET model.

Lastly, according to ISO 14044, normalization, grouping, and weighting steps in LCA are optional. While they might be useful in translating the impact scores of different impact categories into a more understandable and somehow digestible form (Dahlbo et al., 2013), they also entail a risk of oversimplifying the results. Therefore, in the pavement LCA model application reported in this chapter the normalization, grouping, and weighting steps were not included.

4.4 Results and discussion

4.4.1 Life cycle impact assessment results

The potential life cycle impacts for each pavement M&R strategy are shown in Table 4.8. Figure 4.2 shows the relative contribution of each life cycle phase for each impact category. As can be seen from Figure 4.2, the usage phase possesses greatest impact in almost all the impact categories. Its contribution ranges between 89% (HH in traditional reconstruction M&R strategy) and 97% (EU in recycling-based M&R strategy) depending on the impact category and the M&R strategy under analysis. Those results agree well with the literature that have accounted for the effects of this phase on the environmental performance of a pavement structure (Wang et al., 2012; Yu and Lu, 2012; Loijos et al., 2013). The exception to the usage phase' dominance is for the ARD MR where the materials phase is the main contributor. This outcome can be explained by the fact the mineral resources consumed during the pre-combustion energy-related processes are not tracked by the GREET model. Consequently, all the mineral resources accounted for the ARD MR are exclusively those existing in the aggregates and cement-based materials consumed during the M&R activities.

Due to the relatively high influence of the usage phase on the overall environmental performance of the M&R strategies in comparison, it can be inferred that the M&R strategy with the worst environmental performance during the usage phase is simultaneously the least environmentally-friendly overall. Therefore, it seems plausible to expect that the adoption of an M&R strategy able to slow down the deterioration rate of the pavement roughness would lead to valuables improvements in the life cycle environmental performance of a pavement system.

Table 4.8- Total LCEI per pavement life cycle phase of each M&R strategy.

M&R Strategy	Life cycle phase	CC (tonnes CO$_2$-eq.)	Ac (Kg SO$_2$ eq.)	EU (Kg N eq.)	HH (Kg PM$_{2.5}$ eq.)	PSF (Kg O$_3$ eq.)	ARD MR (g Sb- eq.)	ARD FF (MJ- eq.)
Recycling-based	Materials	(-51%) 1,937	(-42%) 4,349	(-49%) 150	(-47%) 515	(-50%) 88,944	(-40%) 2.273	(-49%) 30,630,859
	Construction and M&R	(-37%) 152	(-37%) 835	(-41%) 40	(-50%) 52	(-41%) 22,315	0	(41%) 9,870,565
	Transportation of materials	(-50%) 260	(-46%) 579	(-45%) 32	(-42%) 30	(-45%) 17,607	0	(-42%) 2,796,061
	WZ traffic management	(-51%) 3,593	(-56%) 7,776	(-57%) 417	(-50%) 441	(-55%) 137,776	0	(-53%) 119,846,834
	Usage	(-28%) 112,926	(-27%) 334,441	(-27%) 18,178	(-28%) 13,614	(-27%) 5,753,783	0	(-29%) 2,021,713,679
	Total	(-30%) 118,868	(-28%) 348,023	(-28%) 18,816	(-30%) 14,652	(-29%) 6,020,425	(-40%) 2.273	(-31%) 2,184,857,998
Traditional Reconstruction	Materials	(-5%) 3,788	(25%) 9,361	(15%) 339	(6%) 1,036	(12%) 198,092	(12%) 4.272	(-10%) 54,490,152
	Construction and M&R	(6%) 258	(4%) 1,390	(-7%) 63	(-34%) 69	(-7%) 35,155	0	(-15%) 5,910,886
	Transportation of materials	(33%) 694	(70%) 1,834	(82%) 105	(104%) 106	(83%) 58,688	0	(61%) 7,757,770
	WZ traffic management	(-46%) 3,942	(-72%) 4,956	(-53%) 456	(-42%) 510	(-51%) 150,306	0	(-49%) 127,594,511
	Usage	(-28%) 112,926	(-27%) 334,441	(-27%) 18,178	(-28%) 13,614	(-27%) 5,753,783	0	(-29%) 2,021,713,679
	Total	(-28%) 121,607	(-28%) 351,981	(-27%) 19,140	(-27%) 15,335	(-27%) 6,196,024	(12%) 4.272	(-30%) 2,217,466,998
Corrective Maintenance	Materials	3,980	7,517	295	979	176,562	3.810	60,530,715
	Construction and M&R	242	1,334	68	104	37,952	0	6,989,318
	Transportation of materials	524	1,076	58	52	32,020	0	4,823,867
	WZ traffic management	7,335	17,862	975	885	308,212	0	252,602,364
	Usage	156,859	458,264	24,790	18,961	7,914,396	0	2,847,020,941
	Total	168,940	486,053	26,185	20,981	8,469,142	3.810	3,171,967,206

Legend: LCEI- life cycle environmental impacts; CC- climate change; Ac- acidification; EU- eutrophication; HH- human health criteria pollutant; PSF- photochemical ozone formation; ARD FF- abiotic resources depletion: fossil fuels; ARD MR- abiotic resources depletion: mineral resources; Sb- antimony; M&R- maintenance and rehabilitation; WZ- work-zone.

Note 1: The potential environmental impacts in terms of CC were estimated for a 100-year time horizon.

Note 2: The numbers in brackets represent the reduction (negative values) or the increase (positive values) of the impact category scores with respect to the homologous phase of the corrective M&R strategy.

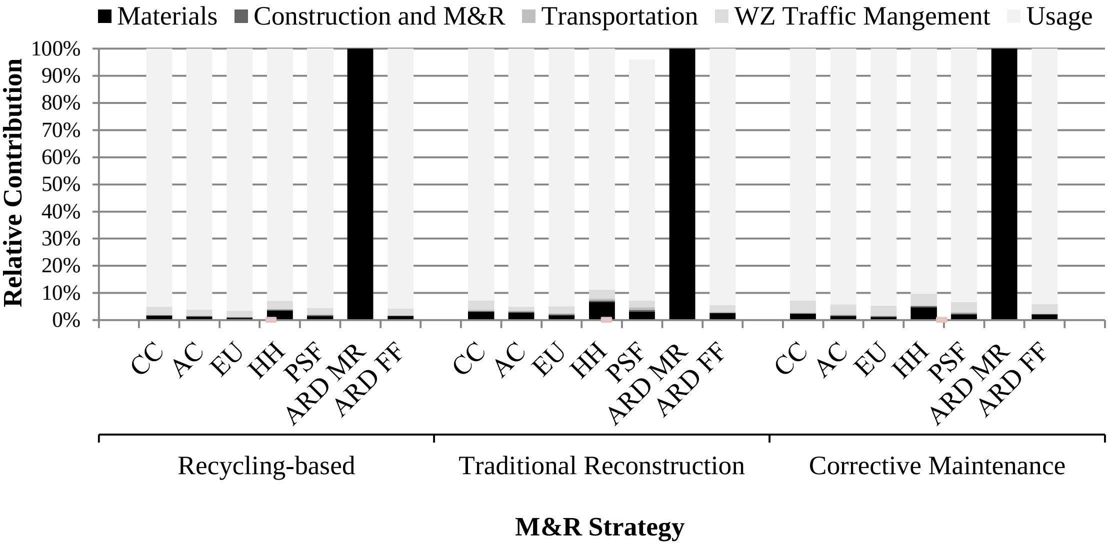

Figure 4.2- Relative contributions to each impact category (in percentage) per pavement life cycle phase of each M&R strategy. Impact category acronyms: CC- climate change; Ac- acidification due to airborne emissions; EU- eutrophication due to airborne emissions; HH- human health criteria pollutants; PSF- photochemical smog formation; ARD MR- abiotic resources depletion of mineral resources; ARD FF- abiotic resources depletion of fossil fuels.

In response to the issues raised in the previous paragraph, this study demonstrated that by implementing a recycled-based M&R strategy, a reduction of approximately 28%-30% in the overall life cycle impacts can be achieved relatively to those of a corrective M&R strategy. Moreover, in the case that only the materials and construction and M&R phases are considered in the LCA system boundaries, the recycling-based M&R strategy was still found to outperform the remaining M&R strategies in comparison.

Table 4.9 presents the feedstock, process and primary energy along with the CED Total corresponding to each M&R strategy, split up in fossil, nuclear and renewable resources. By definition, CED should account for the usage of any sort of energy, including direct and indirect energy, throughout the life cycle. That means that the FsE of bitumen should also be included when accounting for CED. However, since the FsE inherent to bitumen remains unexploited while used as a binder in a pavement, it was presented separately from the process and pre-combustion energy as recommended by the UCPRC's Pavement LCA Guideline (Harvey et al., 2010).

Table 4.9- Feedstock, process and primary energy and CED indicators per pavement life cycle phase of each M&R strategy.

M&R strategy	Life cycle Phase	FsE (MJ)	Process energy (MJ)	Primary energy (MJ)	CED F (MJ)	CED Nuc (MJ)	CED R (MJ)	CED Total (MJ)
Recycling-based	Materials	(-51%) 150 020 350	(-49%) 32,407,121	(-49%) 38,416,682	(-50%) 40,498,823	(-52%) 478,720	(-52%) 235,497	(-50%) 41,213,490
	Construction and M&R	0	(-40%) 1,854,509	(-40%) 2,226,086	(-40%) 2,374,473	(-40%) 3,974	(-40%) 2,487	(-40%) 2,380,933
	Transportation of materials	0	(-52%) 2,250,145	(-52%) 3,901,356	(-52%) 4,161,414	(-52%) 6,965	(-52%) 4,358	(-52%) 4,172,736
	WZ traffic management	0	(-52%) 48,210,242	(-52%) 57,897,901	(-50%) 61,818,525	(-50%) 198,809	(-54%) 99,796	(-50%) 62,117,129
	Usage	0	(-29%) 1,938,650,938	(-29%) 2,327,831,483	(-29%) 2,484,626,525	(-29%) 4,157,553	(-29%) 2,601,593	(-29%) 2,491,385,490
	Total	(-51%) 150 020 350	(-30%) 2,024,372,955	(-30%) 2,430,273,508	(-30%) 2,593,479,578	(-33%) 4,846,020	(-33%) 2,944,180	(-30%) 2,601,269,779
Traditional Reconstruction	Materials	(-32%) 208 041 104	(-16%) 53,285,763	(-15%) 64,375,381	(-16 %) 67,635,921	(-10%) 901,930	(-10%) 444,755	(-16%) 68,982,606
	Construction and M&R	0	(-4%) 2,976,271	(-4%) 3,572,608	(-4%) 3,810,752	(-4%) 6,378	(-4%) 3,991	(-4%) 3,821,121
	Transportation of materials	0	(9%) 7,335,245	(9%) 8,804,963	(9%) 9,391,886	(9%) 15,718	(9%) 9,835	(9%) 9,417,440
	WZ traffic management	0	(-48%) 52,045,077	(-48%) 62,505,020	(-46%) 66,741,303	(-45%) 217,508	(-52%) 104,541	(-46%) 67,063,351
	Usage	0	(-29%) 1,938,650,938	(-29%) 2,327,831,483	(-29%) 2,484,626,344	(-29%) 4,157,553	(-29%) 2,601,593	(-29%) 2,491,385,490
	Total	(-32%) 208 041 104	(-29%) 2,054,293,295	(-29%) 2,467,089,456	(-29%) 2,632,206,207	(-27%) 5,299,087	(-28%) 3,165,714	(-29%) 2,640,670,008
Corrective Maintenance	Materials	306 134 253	63,788,792	75,765,936	80,231,939	1,004,434	494,185	81,730,559
	Construction and M&R	0	3,088,334	3,707,125	3,954,235	6,618	4,141	3,964,994
	Transportation of materials	0	6,746,643	8,098,426	8,638,253	14,457	9,046	8,661,756
	WZ traffic management	0	100,376,784	120,542,044	123,082,069	397,567	217,687	123,697,322
	Usage	0	2,729,510,520	3,277,462,866	3,498,239,621	5,853,635	3,662,918	3,507,756,174
	Total	306 134 253	2,903,511,072	3,485,576,396	3,714,146,117	7,276,711	4,387,978	3,725,810,805

Legend: FsE- feedstock energy; CED F- cumulative fossil energy demand; CED Nuc- cumulative nuclear energy demand; CED R- cumulative renewable energy demand; CED Total- cumulative total energy demand; M&R- maintenance and rehabilitation; WZ- work-zone.

Note 1: The feedstock energy, process energy and primary energy were computed through the GREET model's LHVs. The CED indicators values were computed through the GREET model's UHVs.

Note 2: The numbers in brackets represent the reduction (negative values) or the increase (positive values) of the impact category scores with respect to the homologous phase of the corrective M&R strategy.

Following the trend noticed for the remaining impact categories, the results presented in Table 4.9 show that the recycling-based M&R strategy is also the least harmful to the environment from the point of view of energy consumption. Overall, a reduction of about 30%-33% in all the types of energy can be achieved as a result of implementing the recycling-based M&R strategy over the corrective maintenance one. Similar overall reductions might be obtained through the reconstruction M&R strategy, even though it denotes the most energy demanding transportation phase among the various strategies under assessment. This is because the reconstruction M&R activity requires the removal, and consequent transportation, of all the materials applied in the existing subgrade/base. The poor performance of the corrective M&R activity with respect to the CED indicator can be explained by the higher rate of change of IRI and pavement condition over the PAP, which requires vehicles to spend additional amounts of fuel to overcome the rolling resistance. Although less energy demanding than the usage phase, the WZ traffic management phase exhibit the second worst behavior, as considerable amount of fuel is burned by the light vehicles while detouring the WZ.

When analyzing the relevance of each type of energy (fossil energy, nuclear energy and renewable energy) in the energy consumption, it can be seen that the nuclear and renewable energy sources are only consumed to power the pre-combustion energy-related processes. This fact explains the residual contributions of approximately 0.20% and 0.12% given by the CED Nuc. and CED RR to the CED Total. The negligible role played by the nuclear and renewable energy sources can be seen as a mirror of a road transport mode, and particularly a road pavement construction and management sector, still excessively depending on the consumption of fossil fuels for energy sources. It is expected that the results would differ slightly if the introduction of alternative automotive fuels was taken into account in modeling the usage phase. However, there are both considerable uncertainties on how the rolling resistance effect would change the FC pattern of the vehicles propelled by alternative fuels, and the assumptions on the proliferation of alternative fuels in the long-term market.

Another notable result from Table 4.9 is that approximately 17% of the primary energy attributable to each pavement life cycle phase is due to the pre-combustion energy for all M&R strategies. However, in the case of the remaining impact categories, the environmental impacts due to the upstream processes might be of such dimension that they turn out to be the main contributor to the global value of a determined impact category result. Thus, it is clear that the pre-combustion energy has a significant indirect impact on the environmental burdens of the several competing M&R strategies. Therefore, adopting narrowly defined system boundaries by neglecting supply-chain related impacts can result in underestimates of life cycle environmental footprint of pavement systems.

When comparing FsE and CED F, Table 4.9 shows the FsE of the bitumen to be almost three to four times the energy spent during the materials phase corresponding to the traditional reconstruction, recycling-based and corrective M&R strategies. This result is roughly 6%-8% of the CED Total for each of the strategies. If the energy spent during the usage phase were excluded from the CED indicator, the values would rise to be 137%-140% of the CED Total in all the strategies in comparison.

To further elaborate on the potential environmental differences arising from implementing the recycling-based activity as opposed to the traditional reconstruction activity, the results were separated into the materials, construction and M&R, transportation of materials and WZ traffic management phases. In doing so, the environmental impacts assigned to the M&R activities that are expected to take place in the remaining years of the PAP were disregarded. The difference between the environmental impacts stemmed from the recycling-based activity and those arisen from the traditional reconstruction activity can be interpreted as “potential environmental impact savings”, since the pavement is assumed to behave similarly after the initial recycling-based/traditional reconstruction. Figure 4.3 presents the impact of the two M&R activities on CC, with regard to materials, construction and M&R, transportation of materials and WZ traffic management phases, respectively. Table 4.10 shows the changes in environmental impacts of each phase of the recycling-based M&R activity relative to the traditional reconstruction M&R activity, presented in absolute value and percentage. Those results are to be understood as follows: negative relative numbers mean that the recycling-based M&R activity improves the LCIA results in relation to those associated with the traditional reconstruction M&R activity, while positive numbers represent a deterioration of the environmental profile. The CC impact category has been chosen to be analysed in more detail due to three main reasons: (1) it is the impact category with which most of the stakeholders tend to be more familiar with; (2) the majority of the measures aiming at reducing the environmental footprint of a process or an activity focus on attenuating the GHG emissions; (3) for both intervention strategies the relative contribution of each phase to the remaining impact categories is analogous to that observed in the case of the CC. Furthermore, the results were discretized in terms of the contributions given by the process energy and pre-combustion energy related processes.

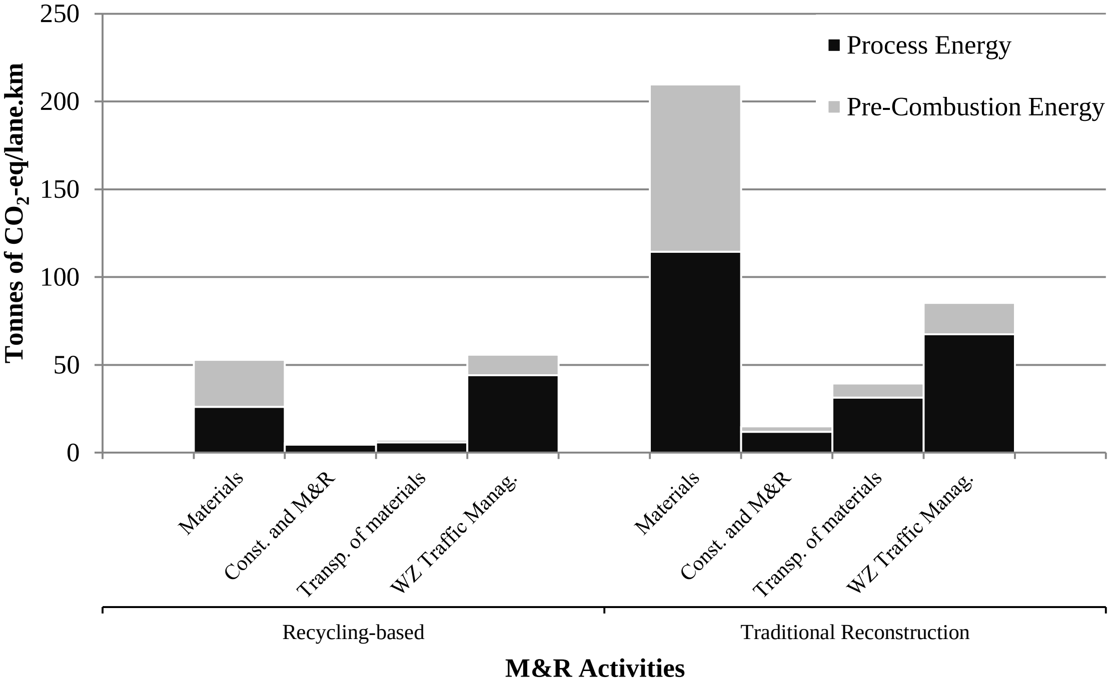

Figure 4.3- Comparison of the global warming score associated with the application of the recycling-based and traditional reconstruction M&R activities. Legend: Const. and M&R- construction, maintenance and rehabilitation; Transp. of materials- transportation of materials; WZ Traffic Manag.- work-zone traffic management.

Table 4.10- Changes in global warming score of the recycling-based M&R activity relative to the traditional reconstruction M&R activity (absolute values in tonnes CO_2-eq./km.lane).

Pavement life cycle phase				Total
Materials	Construction and M&R	Transportation of materials	WZ traffic management	
-157 (-75%)	-9 (-62%)	-32 (-81%)	-30 (-35%)	-228 (-65%)

Legend: M&R- maintenance and rehabilitation; WZ- work-zone.

As can be seen from the Figure 4.3, the most meaningful environmental advantage, in absolute value, resulting from applying the recycling-based M&R activity comes from the materials phase. A reduction of 157 tonnes of CO_2-eq/lane-km, i.e. 75% of the emissions occurred during homologous phase of the traditional reconstruction M&R activity, is expected to be achieved if the recycling-based M&R activity is undertaken. Although the reduction of the virgin materials consumption is mainly responsible for this achievement, it also benefits from the fact that the in-place production of the recycling-based mixtures (FDR, CCPR and CIR) are included in the construction and M&R phase, whereas the production of the asphalt mixtures applied in the traditional reconstruction activity are accounted for the materials extraction and production phase.

However, if the analysis is carried out on a relative basis, then the transportation of materials phase would be the greatest benefited from the application of the recycling-based M&R activity. The resulting reduction in the CO_2-eq/lane-km emissions from 39 tonnes to 7 tonnes translates to an improvement in the environmental performance as measured by the CC impact category of 81%. Such an outcome is a consequence of a reduction in the total hauling movements from 10.875 mega tonne-km to 1.771 mega tonne-km. However, it should be noted that the transportation of materials phase-related environmental benefits associated with the recycling-based M&R activity would be greater if the quarry that supplied the aggregates consumed during the project was not inside the boundary of the asphalt drum plant facility.

4.4.2 Key findings

From the results presented and thoroughly discussed in the previous section, the following findings are worth highlighting:

- The usage phase accounts for the majority of the overall LCEI of the studied pavement system;
- A significant decrease in environmental pollutants is realized by increasing the strength of the pavement, and thus decreasing the frequency of needed maintenance;
- The recycling-based M&R strategy significantly enhance the environmental performance of the pavements over the life cycle by lowering the environmental impacts of the initial activity;
- The recycling-based M&R strategy reduces the overall LCEI and energy consumption by as much as 30%, when compared to the corrective M&R strategy;
- The pre-combustion energy represents approximately 17% of the primary energy consumed over the life cycle of a pavement system. Furthermore, this value might be of such magnitude that it turns out to be the main contributor to the global value of a given impact category result;
- A reduction of 75% in the environmental impacts occurred during the raw materials extraction and mixtures production can be achieved by undertaking the recycling-based M&R activity as an alternative to traditional reconstruction M&R activity;
- The recycling-based M&R activity allows savings of about 84% in the hauling movements, as measured by tonnes-kilometer, what represents a reduction of approximately 81% in the GHG emissions.

4.5 Summary and conclusions

This chapter presents the results of a comprehensive LCA of three M&R strategies for a pavement segment, and compares the relative environmental impacts of each strategy. A comprehensive pavement LCA model was developed that allows accounting for the environmental impacts resulting from the entire life cycle of a pavement system, including the upstream processes underlying to the production and transportation of the energy sources. The pavement LCA model comprises 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. In addition, an original methodology is implemented that easily combines the vehicle emissions model MOVES with the HDM-4 rolling resistance model calibrated to North American conditions, to estimate the additional FC, and consequently the environmental impacts, resulting from the deterioration of the pavement over the life cycle.

The results from this case study show that for the conditions considered the usage phase is the phase of the life cycle with the greatest contribution across the majority of the impact categories. It was also found that the corrective M&R strategy entails an additional total energy consumption, as measured by the CED Total, of 44% and 42% relatively to the total energy consumed in the case that the recycling-based and traditional reconstruction M&R strategies are alternatively adopted.

When analyzing the relevance of each type of energy (fossil energy, nuclear energy and renewable energy) in the energy consumption, it was displayed that the nuclear and renewable energy sources have residual contributions of 0.20% and 0.12% to the CED Total. Concerning the contribution given by the upstream processes in the production and transportation of the energy sources, it was shown that approximately 17% of the primary energy consumed during each pavement life cycle phase is due to the energy sources production. The magnitude of this value clearly suggests that the consumption of more sustainable energy sources may play an important role in lowering the life cycle environmental burdens of a road pavement.

By comparing the in-place recycling-based activity against the traditional reconstruction activity, a reduction of 157 tonnes of CO_2-eq/lane.km is expected to be achieved exclusively due to the materials phase if the recycling-based activity is undertaken. This value represents a reduction of 75% relatively to the CO_2-eq emissions accounted for equal phase of the rehabilitation activity. Despite the lower impact when compared to the materials phase, the environmental benefits arisen from the WZ traffic management and transportation phases should also not be disregarded. However, it is important to note that the results may be strongly dependent on the traffic management and material location decisions made within this particular project.

Moreover, because the highway rehabilitation project analyzed in this chapter was innovative in incorporating several in-place pavement recycling techniques, in the future, it would be desirable to assess the reliability of the proposed methodology based on the analysis of multiple sites with the same characteristics and rehabilitated with the same techniques, and thus arriving to a prediction model based on statistical analysis. Consequently, the generalization of the results presented in this chapter must be made carefully.

Despite the exclusivity of each project, by implementing in-place recycling strategies, the highway agencies are moving in the right direction towards reducing the overall LCEI related to the pavement construction and management practices. However, while the LCA is useful to increase the environmental consciousness of the highway agencies, the environmental aspect is only one of the three elements that compose the triple bottom line that schematically represent the concept of sustainability.

To guide highway agencies towards complete life cycle thinking, future work on this specific topic should compare the various M&R strategies according to their performance in terms of the criteria addressed by the remaining branches of the sustainability concept.

4.6 References

American Society of Civil Engineering (ASCE), 2013. *2013 Report card for America's infrastructure.* Available at: http://www.infrastructurereportcard.org/a/#p/roads/overview

Argonne National Laboratory, 2013. *GREET life-cycle model. user guide.* Center for Transportation Research, Energy Systems Division, Argonne National Laboratory. Available at: http://greet.es.anl.gov/

Bare, J., 2011. TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technologies and Environmental Policy*, 13, 687-696. doi 10.1007/s10098-010-0338-9

Bennett, C. and Greenwood, I., 2003. *Volume 7: Modeling road user and environmental effects in HDM-4, Version 3.0, International Study of Highway Development and Management Tools (ISOHDM).* World Road Association (PIARC), ISBN 2-84060-103-6, Paris.

Bryce, J., 2012. *A pavement structural capacity index for use in network level evaluation of asphalt pavements.* Master's thesis, Virginia Tech, Blacksburg, VA.

Bryce, J., Flintsch, G., Katicha, S. and Diefenderfer, B., 2013. Developing a network-level structural capacity index for asphalt pavements. *ASCE-Journal of Transportation Engineering*, 139(2), 123-129.

Chatti, K. and Zaabar, I., 2012. *Estimating the effects of pavement condition on vehicle operating costs* (National Cooperative Highway Research Program Report No. 720). Available at: http://www.trb.org/Main/Blurbs/166904.aspx

Chiu, C.-T., Hsu, T.-H. and Yang, W.-F., 2008. Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. *Resources, Conservation and Recycling*, 52(3), 545-556.

Dahlbo, H., Koskela, S., Pihkola, H., Nors, M., Federley, M. and Seppälä, J., 2013. Comparison of different normalised LCIA results and their feasibility in communication. *The International Journal of Life Cycle Assessment*, 18(4), 850-860.

Damas, L., 2005. *SQL- Structured Query Language.* Lisboa: FCA- Editora de Informática Lda. (in Portuguese).

Diefenderfer, B., Apeagyei, A., Gallo, A., Dougald, L. and Weaver, C., 2012. In-place pavement recycling on I-81 in Virginia. *Transportation Research Record: Journal of the Transportation Research Board*, 2306, 21-27.

Eurobitume, 2011. *Life cycle inventory: bitumen*. Available at: http://www.eurobitume.eu/hse/sustainability

Federal Highway Agency (FHWA), 2011. *Our nation's highway 2011* (Publication No. FHWA-PL-11-028). Available at: https://www.fhwa.dot.gov/policyinformation/pubs/hf/pl11028/

Guinée, J. (Ed.), 2002. *Handbook on life cycle assessment: operational guide to the ISO standards. Series: eco-efficiency in industry and science*. Kluwer Academic Publishers: Dordrecht.

Harvey, J., Kendall, A., Lee, I.-S., Santero, N., Van Dam, T. and Wang, T., 2010. *Pavement life cycle assessment workshop: discussion summary and guidelines* (Technical Memorandum: UCPRC-TM-2010-03). Available at: http://www.ucprc.ucdavis.edu/PublicationsPage.aspx

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., …Nemecek, T., 2010. *Implementation of life cycle impact assessment methods* (ecoinvent report No. 3, v2.2). Available at: http://db.ecoinvent.org/files.php?area=463ee7e58cbf8&action=list

Huang, Y., Bird, R. and Heidrich, O., 2007. A review of the use of recycled solid waste materials in asphalt pavements. *Resources, Conservation and Recycling,* 52(1), 58-73.

Huang, Y., Bird, R. and Heidrich, O., 2009. Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. *Journal of Cleaner Production*, 17(2), 283-296.

International Organization for Standardization (ISO), 2006a. *ISO 14040:2006. International Standard ISO 14040: environmental management - life cycle assessment: principles and framework, October*. Geneva (Switzerland): International Organization for Standardization.

International Organization for Standardization (ISO), 2006b. *ISO 14044:2006. International Standard ISO 14044: environmental management - life cycle assessment: requirements and guidelines, October*. Geneva (Switzerland): International Organization for Standardization.

Jullien, A., Monéron, P., Quaranta, G. and Gaillard, D., 2006. Air emissions from pavement layers composed of varying rates of reclaimed asphalt. *Resources, Conservation and Recycling*, 47(4), 356-374.

Karlsson, R., Carlson, A. and Dolk, E., 2012. *Energy use generated by traffic and pavement maintenance. Decision support for optimization of low rolling resistance maintenance* (VTI Report 36A–2012). Available at: http://www.vti.se/en/publications/energy-use-generated-by-traffic-and-pavement-maintenance--decision-support-for-optimization-of-low-rolling-resistance-maintenance-treatments/

Kendall, A., 2012. Time-adjusted global warming potentials for LCA and carbon footprints. *The International Journal of Life Cycle Assessment*, 17(8), 1042-1049.

Loijos, A., Santero, N. and Ochsendorf, J., 2013. Life cycle climate impacts of the US concrete pavement network. *Resources, Conservation and Recycling*, 72, 76-83.

Loureiro, H., 2010. *Visual Basic- curso completo*. Lisboa: FCA- Editora de Informática Lda. (in Portuguese).

Marceau, M., Nisbet, M. and VanGeem, M., 2006. *Life cycle inventory of portland cement manufacture* (PCA R&D Serial No. 2095b). Available at: http://www.cement.org/bookstore/profile.asp?store=&pagenum=1&pos=0&catID=&id=11004

Miliutenko, S., Björklund, A. and Carlsson, A., 2013. Opportunities for environmentally improved asphalt recycling: the example of Sweden. *Journal of Cleaner Production*, 43, 156-165.

Park, K., Hwang, Y., Seo, S., nad Seo, H., 2003. Quantitative assessment of environmental impacts on life cycle of highways. *ASCE-Journal of Construction Engineering and Management*, 129(1), 25-31.

Rubio, M., Moreno, F., Martínez-Echevarría, M., Martínez, G. and Vázquez, J., 2013. Comparative analysis of emissions from the manufacture and use of hot and half-warm mix asphalt. *Journal of Cleaner Production*, 41, 1-6.

Sandberg, U., Haider, M., Conter, M., Goubert, L., Bergiers, A., Glaeser, K.-P., … Harvey, J., 2011. *Rolling resistance - basic information and state-of-the-art on measurement methods* (Report MIRIAM SP1 01). Available at: http://www.miriam-co2.net/Publications/Publications.htm

Santero, N., Masanet, E., and Horvath, A., 2011. Life-cycle assessment of pavements. part I: critical review. *Resources, Conservation and Recycling*, 55(9-10), 801-809.

Sathaye, N., Horvath, A., Madanat, S., 2009. *Unintended Impacts of Increased Truck Loads on Pavement Supply-chain Emissions*. Working Paper UCB-ITSVWP-2009-7. U.C. Berkeley, CA: Berkeley Center for Future Urban Transport, A Volvo Center of Excellence. Available at: http://www.its.berkeley.edu/publications/UCB/2009/VWP/UCB-ITS-VWP-2009-1.pdf.

Sayagh, S., Ventura, A., Hoang, T., François, D. and Jullien, A., 2010. Sensitivity of the LCA allocation procedure for BFS recycled into pavement structures. *Resources, Conservation and Recycling,* 54(6), 348-358.

Stripple, H., 2001. *Life cycle assessment of road: a pilot study for inventory analysis* (Swedish Environmental Research Institute (IVL) report B 1210 E, 2nd revised ed.). Available at: http://www.ivl.se/publikationer/importeradebrapporterrorej/lifecycleassessmentofroadapilotstudyforinventoryanalysissecondrevisededition.5.7df4c4e812d2da6a416800040296.html

Tatari, O., Nazzal, M. and Kucukvar, M., 2012. Comparative sustainability assessment of warm-mix asphalts: a thermodynamic based hybrid life cycle analysis. *Resources, Conservation and Recycling,* 58, 18-24.

The Freedonia Group, 2009. *Asphalt: US Industry Study with Forecasts for 2013 & 2018.* (Study number No. 2544). Available at: http://www.freedoniagroup.com/industry-study/2544/asphalt.htm

Thenoux, G., González, A. and Dowling, R., 2007. Energy consumption comparison for different asphalt pavements rehabilitation techniques used in Chile. *Resources, Conservation and Recycling*, 49(4), 325-339.

Transportation Research Board (TRB), 2000. *Highway Capacity Manual 2000.* Transportation Research Board, Washington, D.C.

United States Energy Information Administration (US EIA), 2012. *State electricity profiles 2010* (Report DOE/EIA-0348(01)/2). Available at: http://www.eia.gov/electricity/state/

United States Environmental Protection Agency (US EPA), 2004. *AP-42: compilation of air pollutant emission factors* (Volume 1: Stationary point and area sources, Chapter 11: Mineral products industry, 11.1). Available at: http://www.epa.gov/ttn/chief/ap42/ch11/index.html

United States Environmental Protection Agency (US EPA), 2008. *Direct emissions from mobile combustion sources. climate leaders GHG Inventory protocol core module guidance* (Report EPA430-K-08-004). Available at: http://www.epa.gov/climateleadership/index.html

United States Environmental Protection Agency (US EPA), 2010a. *Motor Vehicle Emission Simulator (MOVES). user guide for MOVES2010b* (Report EPA-420-B-12-001b). Available at: http://www.epa.gov/otaq/models/moves/index.htm#user.

United States Environmental Protection Agency (US EPA), 2010b. *Exhaust and crankcase emission factors for nonroad engine modeling- compression- ignition* (Report No. NR-009d). Available at: http://www.epa.gov/otaq/nonrdmdl.htm#model

United States Geological Services (USGS), 2013. *2011 minerals yearbook: stone, crushed*. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/

Vidal, R., Moliner, E., Martínez, G. and Rubio, M., 2013. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. *Resources, Conservation and Recycling*, 74, 101-114.

Virginia Department of Transportation (VDOT), 2011. *Life cycle costs analysis*. Materials Division, Virginia Department of Transportation. Available at: http://www.virginiadot.org/business/materials-download-docs.asp

Wang, T., Lee, I.-S., Kendall, A., Harvey, J., Lee, E.-B. and Kim, C., 2012. Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production*, 33, 86-96.

Yu, B. and Lu, Q., 2012. Life cycle assessment of pavement: methodology and case study. *Transportation Research Part D: Transportation and Environment*, 17(5), 380-388.

Zapata, P., and Gambatese, J., 2005. Energy consumption of asphalt and reinforced concrete pavement materials and construction. *ASCE-Journal of Infrastructure Systems*, 11(1), 9-20.

Chapter 5

A Comprehensive Life Cycle Costs Analysis of In-Place Recycling and Conventional Pavement Construction and Maintenance Practices

5.1 Introduction

Transport infrastructure is one of the main backbones of all commodity and passenger flows in the US, and the availability of transport is an essential condition for trade and economic growth. Despite its undeniable contribution to the national economy, the current road network requires significant investments in M&R to maintain its quality at an acceptable level. For example, the most recent American Society of Civil Engineers' report card (ASCE, 2013) estimates that maintaining all of the nation's highways in their current condition would cost $101 billion in annual capital investment between 2008 and 2028, whereas improving the nation's highways would require an annual capital investment of $170 billion, or an additional $79 billion annually from current investments, during that same time period. Therefore, it is important to use long-term scope-based decision support methodologies to help DMs determine the costs of providing road infrastructures services beyond the construction phase, and to allocate road investment funds to competing projects is of the utmost importance.

LCCA is an analytical methodology that uses economic principles to evaluate long-term alternative investment options in infrastructure management processes and to select optimum strategies. By comparing the resulting LCC of two or more alternatives an optimal investment alternative can be found that should minimize the total long-term cost by finding a suitable tradeoff between spending today and future savings (Walls and Smith, 1998). Thus, LCC involves the evaluation of all future costs related to design, construction and/or production, distribution, operation, maintenance and support, retirement, and material disposal; that means every phase in the system life cycle (Fabrycky and Blanchard, 1991).

During the last decade, many state departments of transportation (DOTs) and researchers have dedicated their efforts to four main key areas:

(1) improving LCCA concepts and methodologies (Salem et al., 2003; Li and Madanu, 2009; Swei et al., 2013; Salem et al., 2013; Mirzadeh et al., 2014) and computer tools (Chen and Flintsch, 2007; Santos and Ferreira, 2012; Santos and Ferreira, 2013);

(2) providing guidance on how to apply and handle the LCCA methodology and their key issues (Walls and Smith, 1998; FHWA, 2002; FHWA, 2003; Hall et al., 2003; Ozbay et al., 2003);

(3) documenting how LCCA has been applied by DOTs (Rangaraju et al., 2008; Chan et al., 2008), and;

(4) applying the LCCA concept for making comparative assessments of the cost effectiveness of pavement design, materials and M&R alternatives (Tighe et al., 2007; Amini et al., 2012; Sakhaeifar et al., 2013).

Recently, as society has become more aware of the effects of human activity on the environment, sustainability has started to play a more significant role in the decision-making and planning processes, including pavement management. To embrace the concept of sustainability, pavement managers need to deliver infrastructures that are both economically competitive and less environmentally damaging.

An important part of these sustainable pavement practices can be achieved by constructing new pavement structures that incorporate recycled materials in the sub-base and base layers and by implementing in-place pavement recycling techniques to rehabilitate distressed pavements (Thenoux et al., 2007; Lee et al., 2010; Miliutenko et al., 2013; Santos et al., 2015). However, a solution which is found to be environmentally advantageous might not be preferred over another which is technically equivalent, if it is not economically competitive. Although rehabilitation using in-place recycling is commonly presented as advantageous from an economic point of view, there are still some questions about the extent to which such techniques are cost effective throughout their life cycle. It is also important to quantify which factors are the key drivers of economic performance, and which stakeholders benefit the most with the application of in-place pavement recycling.

Answering those questions requires a change in the way LCCA has been conducted in the pavement management field. Instead of merely using a cash flow analysis, it would be better to use a process-oriented accounting method, to allow us to understand the interaction of the contributing costs that accumulate among the relevant stakeholders during the different phases of the asset (Lindholm and Suomala, 2005).

To implement the LCC methodology this way it is necessary to comprehensively track the consumption of resources in their multiple categories (e.g., raw materials, energy sources, labour, equipment, etc.). Moreover, the operations chain preceding the pavement life cycle phase in which a construction and M&R activity is delivered should not be merely summarised by its bid price, and viewed as a "black box" (Settanni and Emblemsvåg, 2010). A detailed characterization of all the costs incurred by highway agencies when performing road construction and maintenance activities and imposed on other affected stakeholders over the entire life cycle of those activities is important to gain in-depth insights into the extent to which new technical solutions, such as in-place recycling, provide cost reductions, and thereby allow more transparent and informed decisions to be made at an early stage of project development.

In summary, when conducting a LCCA of in-place recycling techniques there is a growing and significant need for a general LCCA model that includes a long-term scope-based and explicit cost-tracking mechanism, bringing together information from various sources, which would result in the basis for the calculation of the delivery cost of new pavement construction and M&R practices. Such a model is essential to account for the connection between technical changes and production and downstream costs, and to provide the DM with a complete understanding of construction and M&R activity costs over time. This detailed analysis can also be used to update or clarify the understanding of assumptions in the pavement management decision-making process.

5.2 Objectives

This chapter presents the results from an extensive (cradle-to-grave) LCCA of an in-place pavement recycling rehabilitation project in the state of Virginia. It also illustrates the development of a comprehensive pavement LCC model intended to give DMs a systematic framework that provides an in-depth perspective of the costs incurred by highway agencies and road users during pavement construction and maintenance activities. The results for the recycling-based project are compared to two other pavement management alternatives: (1) a traditional pavement reconstruction and (2) a corrective maintenance approach. The features of the three M&R strategies are summarised in Table 5.1.

5.3 Methodology

A comprehensive pavement LCC model was developed to calculate and compare several categories of costs borne by highway agencies and road users during the M&R, usage, and EOL pavement phases. This model builds on the LCA model presented in Chapter 4 (Santos et al., 2015) to calculate and compare the environmental impacts of in-place recycling and conventional pavement construction and M&R practices. Therefore, besides the main references on how to conduct LCCA of pavements (Walls and Smith, 1998; FHWA, 2002; FHWA, 2003; Hall et al., 2003), the methodology adopted to develop this model took into account, as far as possible and suitable, the UCPRC's Pavement LCA Guideline (Harvey et al., 2010).

The pavement LCC model described in this chapter is intended to give highway agencies a systematic framework that allows them to get an in-depth perspective of the costs incurred by the various stakeholders when performing highway construction and maintenance activities. This required the adoption of more data- and time-intensive sub-models than had traditionally been used for pavement LCCA. The "traditional" less data-intensive models do not allow analysis to be performed with the same level of detail and customization when applied to specific projects.

The data required to carry out the case study were provided by the VDOT (Diefenderfer et al., 2012) and gathered from relevant literature as it will be seen in the next sections. The strategies compared are summarised in Table 5.1.

Table 5.1- Summary of the M&R strategies.

M&R Strategy	Initial M&R Activity	Future M&R Activities
Recycling-Based	Left lane: CIR method to mill, refine and replace the top 13 cm (5 inches) of pavement. Right lane: A combination of FDR and CCPR to treat 45 cm (18 inches) in depth. Both lanes: Apply an AC riding surface.	Maintenance actions performed in years 12, 22, 32 and 44 (Table 4.2)
Traditional Reconstruction	Left lane: Mill and replace the top 5 cm (2 inches) of pavement. Right lane: Mill and replace full depth of existing pavement and apply a cement treatment to the base/subgrade. Both lanes: Apply an AC riding surface.	Maintenance actions performed in years 12, 22, 32 and 44 (Table 4.3)
Corrective Maintenance	Both Lanes: 5% full depth patching followed by a 10 cm (4 inch) mill and overlay.	Maintenance actions performed in years 4, 10, 14, 18, 24, 28, 34, 38, 44 and 48 (Table 4.4)

Legend: M&R- maintenance and rehabilitation; AC- asphalt concrete; CIR- cold in-place recycling; FDR- full depth reclamation; CCPR- cold central plant recycling.

Note: Throughout this document the pavement M&R strategies are named "M&R Strategies", whereas the individual activities that integrate each M&R strategy are named "M&R Activities".

In order to automatically cross the data between the multiple sub-models and compute the costs inherent to the successive pavement life cycle phases, the framework of the LCC model was implemented in a software written in VB.NET (Loureiro, 2010) and SQL (Damas, 2005) programming languages, the latter used for managing the data introduced and held in the system.

5.3.1 Goal and scope definition

This chapter presents the results from a comprehensive LCCA conducted for three M&R strategies applied to a pavement segment. The first step consisted of developing a comprehensive pavement LCC model to thoroughly estimate the costs incurred by the highway agency and road users throughout the entire life cycle of the pavement section. However, we should keep in mind that this study was not intended to be strictly the counterpart of the LCA performed according to the life cycle sustainability assessment (LCSA) scheme defined in Klöpffer (2008), since it imposes several methodological requirements (e.g., the share of the same system boundaries, etc.) that have not been intentionally adopted. Rather, it used the LCI of resources flows, operating parameters and other exchanges reported in Chapter 4 (Santos et al., 2015) as a starting basis for modelling the relationships between pavement life cycle phases and the costs incurred by highway agencies and road users.

However, the concern with gathering cost information from different entities to implement the LCC methodology is constrained to some extent by supply chain relationships. In this case, it may be impossible to gain insight into the costs structure of other supply chain actors with different and competing interests, and with whom the highway agencies interact (e.g., raw materials, energy sources and construction equipment suppliers, etc.). Unless an unlikely joint effort to achieve cost savings beyond the influence of a highway agency is undertaken, there is no way of truly managing the drivers that control cost propagation through the supply chain upstream from the highway agency. Therefore, this part of the whole pavement supply chain is left out of the scope of this model. The total value of the costs within the boundaries of those organizations or actors is viewed by the highway agency as a cradle-to-factory gate cost that reflects the complete upstream process. In this case, the market price for a given process input is used as a measure for the aggregated upstream costs, thus not requiring any differentiation and knowledge of the detailed costs and added values of those upstream processes. The same assumption is made with regard to the expenses incurred by the road users due to pavement deterioration and WZ traffic management plans (e.g., FC, oil consumption tyre wear, vehicles maintenance and repair, etc.).

Additionally, planning, engineering, design, administrative overhead costs (e.g., office and management, etc.) and profit were not accounted for and added to the total HAC because they do not depend on the scope and nature of the work being performed, or in other words, they are not a direct consequence of the pavement management decision-making process. Rather, they are determined by the overall agency and/or contractor structure, scope, size and geographic location, and are allocated according to the organization-specific cost allocation.

Another important clarification which should be made is regarding whether or not, the asphalt mixtures production and delivery should be seen as a product acquired by the highway agency in which only the final cost is important (it falls into the case mentioned above), or as an in-house product, thus requiring a detailed process costs analysis that includes accounting for raw materials cost, energy sources costs, transportation of materials costs, etc. Given the core importance of this activity for the pavement management decision-making process, the proposed model sees it as a product manufacturer, meaning that the process costs inherent to it are thoroughly analysed.

The application of the pavement LCC model to the case study presented in this chapter aims to:

1. estimate the potential economic advantages resulting from applying in-place pavement recycling techniques compared to two traditional M&R methods;
2. demonstrate a methodology that explicitly tracks the costs resulting from the use of various materials, energy sources, equipment and technological

processes, allowing the connection between technical aspects, production (agency) costs, and costs imposed on other affected stakeholders (i.e., road users), to be accounted for, and;

(3) identify the most important processes, and consequently pavement life cycle phases, in driving the economic performance of a road pavement section throughout its life cycle, from the perspective of different stakeholders.

These results provide state and local agencies with quantitative evidence to support the adoption of cost effective pavement management processes.

5.3.1.1 Functional unit

The specific project chosen for achieving these objectives is a 5.9-km long, 2-lane (in one direction) section of Interstate 81 near Staunton, Virginia. The PAP is 50 years, beginning in 2011 (date of completion of the in-place pavement recycling project that rehabilitated the existing pavement structure). The AADT for the first year was obtained from the VDOT traffic website[2] and consisted of approximately 25,000 vehicles with 28% trucks (85% of the truck traffic consisted of five- and six-axle tractor trailer combination vehicles). The traffic growth rate was assumed as 3%.

5.3.1.2 System boundaries, system processes and life cycle inventory data

The life cycle of a road pavement is generally divided into five main phases (Harvey et al., 2010). They are the following: (1) materials extraction and production; (2) construction; (3) M&R; (4) usage; and (5) EOL. However, in the proposed model, the costs incurred by road users when facing a WZ traffic management plan (implemented during the reconstruction and M&R activities) are accounted for in an individual phase designated as WZ traffic management phase. The WZ traffic management phase was

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[2] http://www.virginiadot.org/info/ct-trafficcounts.asp

separated out from the construction and M&R phase in order to facilitate the identification, computation and report of the costs borne by different actors (highway agency and road users) who may have conflicting goals. The costs associated with the transportation of materials and asphalt mixtures between facilities and work site, and vice-versa, were also analysed separately. Therefore, the proposed pavement LCC 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. The various models evoked while computing the costs incurred during each pavement life cycle phase, as well as the data required to run those models, are introduced and discussed in the following sections.

5.3.1.2.1 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. The typical total bid cost provided by DOTs comprises manufacturing and transportation of raw materials, manufacturing of mixtures, labour, overheads, profit margins and other costs as one number. This practice makes it difficult: (1) to differentiate the relative contribution of the fixed and variable costs; (2) to investigate the impact of variability in pricing, types of mixtures, mixture compositions and mixture process technologies on the total bid price; and (3) to identify the main cost drivers of the life cycle, and then point out improvements that can be advantageous for all or some of the stakeholders involved in the system. Therefore, for a detailed LCCA, the calculation procedure of the materials extraction and production phase costs cannot rely on bid prices.

To address this issue, the materials extraction and production phase costs were divided into three main categories: (1) raw materials costs, corresponding to the materials that make up the asphalt mixtures, as well as those that are directly applied at the work site (e.g., lime, hydraulic cement, etc.); (2) energy sources costs, meaning specifically the cost of the energy required to produce the asphalt mixtures; and (3) asphalt plant operating costs, which are the costs incurred due to the operation of the asphalt plant.

This last category was further divided into fixed and variable costs sub-categories. The fixed costs sub-category are those costs that remain fairly much the same regardless of the volume of the mixtures produced, and were calculated by allocating an annual cost. Typically, they include: (1) the asphalt plant depreciation cost; (2) the auxiliary equipment depreciation costs; (3) insurance; (4) taxes, licensing and permits; (5) utilities; and (6) the labour costs (e.g., asphalt plant operator, auxiliary equipment operator, maintenance technician, etc.). Other fixed costs incurred prior to asphalt plant installation, such as engineering design/planning and real estate purchase were disregarded.

The variable costs sub-category includes the costs which depend on production volume. Apart from the raw materials costs and asphalt mixture production-related energy costs that were accounted for as individual categories, the variable asphalt plant operating costs include costs resulting from the operation of the asphalt plant (e.g., filters, oils and grease applied in the asphalt plant setup and auxiliary equipment, diesel consumed by the wheel loader, etc.). The unit costs adopted to calculate the several categories and sub-categories of costs incurred during this pavement life cycle phase are presented in Table 5.2, Table 5.3 and Table 5.4.

Table 5.2- Unit costs of the raw materials items (in 2011 US dollars).

Raw material item	Unit cost		Data source
	Unit	Value[a]	
Asphalt binder	$/tonne	653.94	VDOT (http://www.virginiadot.org/business/const/indices-previous.asp)
Calciment	$/tonne	76.98[b]	US ACE (2011a)
Hydraulic cement	$/tonne	76.81	USGS (2013a)
Asphalt emulsion	$/tonne	792.52	Virginia Paving Company (www.virginiapaving.com)
Crushed aggregates	$/tonne	10.73[c]	USGS (2013b)
Fine aggregates	$/tonne	10.96[c]	USGS (2013b)

Notes: [a]Free on board costs.
[b]Value bid adopted by the material supplier: Mintek.
[c]Data referring to aggregates sold or used by producers in the US, by use, in 2011.

Table 5.3- Unit costs of the energy sources items (in 2011 US dollars).

Energy source item	Unit cost		Data source
	Unit	Value	
Diesel	$/litre	1.00	US EIA(2014a)
Electricity	$/kWh	0.065[a]	US EIA (2014b)
Natural gas	\$/m^3	0.227[a]	US EIA (2014c)
Gasoline	$/litre	0.93	US EIA (2014a)

Notes: [a]Industrial sector price.

Table 5.4- Unit values of the asphalt plant operating costs items (in 2011 US dollars).

Sub-category	Item	Unit cost[a]		Data source
		Unit	Value	
Fixed	Asphalt plant depreciation costs	$/tonne of asphalt mixture	0.75[b]	Morgan (2005)[c]
	Auxiliary equipment depreciation costs		0.32[d]	Morgan (2005)[c]
	Utilities (water and electricity)		0.66[e]	Morgan (2005)[c]
	Licensing, taxes and general operation permits		0.09[f]	Estimated
	Insurance		0.18[g]	Estimated
	Labour: asphalt plant operator		0.63[h]	US DL (2011a)
	Labour: wheel loader operator		0.46[i]	US DL (2011a)
	Labour: maintenance technician		0.48[j]	US DL (2011a)
Variable	Asphalt plant maintenance and repair		1.00	Morgan (2005)[c]
	Diesel consumed by the wheel loader		0.24[k]	US EIA (2014a)
	Anti-strip additive		0.50[l]	Epps at al. (2003)

Notes: [a]The calculation procedure relies on the average annual asphalt mixtures production per plant (114,000 tonnes) during the year of 2011 in Virginia (Hansen and Copeland, 2013).

[b]Value obtained by considering an acquisition cost of $1,500,000.00 depreciated over 15 years and a residual value equal to 15% of the acquisition cost ($225,000.00).

[c]Since these unit costs depend on a large number of factors, the values reported by this source were used as reference in setting representative values.

[d]Includes the acquisition costs of the following auxiliary equipment: quality control laboratory ($100,000.00; 15 years; 15%), anti-strip system ($20 000.00; 8 years; 15%), platform scales ($45,000.00; 15 years; 15%) and wheel loader ($246,000.00; 8 years; 15%). Where ($; years; %) stands for (acquisition cost; depreciation period; residual value as percentage of the acquisition cost).

[e]Although the utilities cost comprises a fixed and a variable component, the total cost was assigned to the fixed sub-category due to the absence of more detailed information that would allow for a further division of this item.

[f]Based on an annual value of $10,000.00.

[g]Based on 1% of the value of all assets existing in the facility.

[h]Value obtained by considering the annual 90th percentile total compensation for the "Paving, Surfacing, and Tamping Equipment Operators" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (US DL, 2011b).

[i]Value obtained by considering the annual 50th percentile total compensation for the "Paving, Surfacing, and Tamping Equipment Operators" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (US DL, 2011b).

[j]Value obtained by considering the annual 50th percentile total compensation for the "Maintenance and Repair Workers, General" occupational group in Virginia. It results from considering the wages and salaries equal to 68% of the total compensation (US DL, 2011b).

[k]Energy consumption corresponding to the operation of a wheel loader Caterpillar 950K estimated according to the rate at which the wheel loader can move aggregates and the methodology adopted by the US EPA's NONROAD 2008 model (US EPA, 2010a). See Chapter 4 (Santos et al., 2015) for further details.

[l]Based on an additive usage rate of 0.5% by weight of the binder (Diefenderfer and Hearon, 2010). The 2003 price was scaled up to the 2010 price by using the Producer price index (PPI) for "material and supply inputs to highway and street construction sector". 2010 is the last year for which the annual index is known.

5.3.1.2.2 Construction, maintenance and rehabilitation phase

The construction and M&R phase costs include 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 comprise: (1) the owning costs of construction equipment (i.e., depreciation, interest, insurance, taxes and licenses); (2) construction equipment operation costs (i.e., FC, equipment planned maintenance, equipment repairs, tyre wear, special wear items, mobilization and demobilization); and (3) labour costs corresponding to the wages and benefits paid to the crew members. The materials costs, as well as the costs associated with the hauling movements required to deliver the materials from the production to the destination places are accounted for in individual phases. A detailed description of the LCC model formulation referring to this pavement life cycle phase can be found in Appendix A.1.

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 ACE, 2011b; Caterpillar Inc., 2012). Table A.1 in Appendix A.1. shows the costs of the variables corresponding to each piece of equipment required to perform the M&R actions that constitute the M&R activities considered in the case study analysed in this chapter.

Finally, the labour costs were calculated according to the data displayed in Table A.2 presented in Appendix A.1. The number of workers needed for carrying out the various M&R actions that comprise 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 (EAPA and NAPA, 2011).

5.3.1.2.3 Transportation of materials phase

The 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 make up the total delivery price.

Similar to construction and M&R phase costs, three main cost categories are considered: (1) hauling trucks owning costs; (2) hauling trucks operation costs; and (3) labour costs. The two first categories were further divided into several subcategories as shown in Appendix A.2. The meaning of each cost category and subcategory, its respective formulation and the values of the variables required to calculate them are presented in Appendix A.2.

5.3.1.2.4 Work-zone traffic management phase

When an M&R activity takes place on a highway segment, it is likely that the drivers using those highways segments will experience changes to their normal travelling patterns, such as delays, which force vehicles to be operated at less than-optimal speeds, and detours (either externally or self-imposed) that require drivers to increase the distance travelled.

Operating a vehicle in those WZ conditions commonly results in additional costs to road users, which are commonly referred to road user costs (RUC). Therefore, the WZ traffic management costs comprise the additional costs borne by the road users 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 are considered: (1) time delay costs (TDC), and (2) vehicle operating costs (VehOperC). The accidents 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). The methodologies adopted to calculate these costs are described in the following sections.

5.3.1.2.4.1 Time delay costs

The TDC are calculated as the difference between the cost of the time spent by the vehicle's occupants and goods while travelling at detour speed, or WZ reduced speed and normal operating speed during a non-WZ period. Four types of WZ delays were considered to contribute to the total TDC: (1) the time necessary to decelerate from the upstream approaching speed to the WZ speed and then to accelerate back to the initial approaching speed after traversing the work-zone under unrestricted traffic flow; (2) the time required to go through the WZ section at the WZ speed; (3) the idling time corresponding to stop-and-go driving conditions in the upstream queue; and (4) the time required to travel the additional distance resulting from detouring around the WZ section.

The capacity and delay models proposed by the HCM 2000 (TRB, 2000) were used to determine, in each hour of a WZ period, the number of vehicles that undergo a variation in their normal operation speed and the distance during which it is experienced. Finally, to calculate the TDC, the estimated delays to personal travel, business travel, and freight inventory caused by the WZ is multiplied by the unit cost ($/hr) of travel time. The monetary value of the time for users and goods was estimated according to the US DOT Office of the Secretary of Transportation (OST)'s guidelines and procedures for calculating the value of travel time saved or lost by road users (US DOT, 2003). It relies on the concept that time spent traveling would otherwise have been spent productively, whether for remunerative work or recreation (Mallela and Sadasivam, 2011). The unit cost of travel time adopted for the various categories of vehicles is presented in Table 5.5. The values of the main parameters used in the calculation of the unit costs of travel time are presented in Appendix A.3.

Table 5.5- Unit cost of travel time for the several categories of vehicles (in 2011 US dollars).

Vehicle category	Unit cost	
	Unit	Value
Hourly time value of passenger cars (PCs)	$/hr	28.70
Hourly time value of single-unit trucks (SUTs)		22.42
Hourly time value of combination-unit trucks (CUTs)		29.27
Hourly freight inventory costs for SUTs		0.21
Hourly freight inventory costs for CUTs		0.31

Legend: PC- passenger car; SUT- single-unit truck; CUT- combination unit truck.

5.3.1.2.4.2 Vehicle operation costs

The WZ-related VehOperC represent the costs incurred by the vehicle drivers due to the vehicle owning, operating and maintenance, and are computed as the difference between the costs incurred while travelling at detour speed or WZ reduced speed, and those corresponding to transverse the highway WZ section at the normal operating speed during a non-WZ period. Five types of VehOperC subcategories were considered to contribute to the total VehOperC: (1) FC; (2) oil consumption; (3) tyre wear; (4) vehicle maintenance and repair; and (5) vehicle depreciation. The costs of operating a vehicle on a given road section are obtained by multiplying the "consumption" of the aforementioned subcategories with the corresponding unit cost.

The methodology adopted for quantifying the additional VehOperC resulting from changes in traffic flow conditions consisted of initially modelling each cost subcategory separately, and then adding them to obtain the total VehOperC value. This modelling procedure was adopted in order to ensure coherence with the work performed in Chapter 4 (Santos et al., 2015) and to allow for a better integration with subsequent research work. The FC was determined using the US EPA's MOVES (US EPA, 2010b) as detailed in Chapter 4 (Santos et al., 2015). The speed-constant and speed-change cycles Highway Economic Requirements System- State Version (HERS-ST) sub-models (FHWA, 2005) were considered in calculating the rates of oil consumption, tyre wear and maintenance and repair. Finally, the vehicle depreciation costs were equally estimated according to the methodology outlined in the HERS-ST Technical Report (FHWA, 2005). This relies on the assumption that vehicles depreciate both as a result of their usage and their aging, which is independent of the vehicle use. Thus, the time lost by the occupants of the different vehicle categories while traversing or detouring a WZ was considered to contribute to the time-related depreciation costs, whereas the additional distance travelled to detour the WZ was assumed to contribute to the mileage-related depreciation costs.

The unit costs expressed in 2011 US dollars, and respective data sources, required to compute the additional VehOperC incurred during the WZ period are shown in Table 5.6. To estimate the costs for the beginning of the PAP (year 2011), the unit costs were multiplied by standard prices indices, such as Consumer Prices Index (CPI) and Producer Prices Index (PPI).

Table 5.6- Economic unit costs of the WZ-related VOC subcategories (in 2011 US dollars).

WZ-related VehOperC subcategory	Cost unit	Unit cost per vehicle category			Data source
		PC	SUT	CUT	
Fuel: gasoline	$/litre	0.93	-	-	US EIA (2014a)
Fuel: diesel	$/litre	-	1.00	1.00	US EIA (2014a)
Oil	$/ litre	9.58	3.83	3.83	FHWA (2005)
Tyres	$/tyre	93.11	613.32	613.32	FHWA (2005)
Maintenance and repair	$/1000 miles	158.79	553.23	553.23	FHWA (2005)
Time-related depreciation	$/hr	1.23	3.16	9.57	FHWA (2005)
Mileage-related depreciation	$/hr	0.58	0.49	2.20	FHWA (2005)

Legend: WZ- work-zone; VehOperC- vehicle operation costs; PC- passenger car; SUT- single-unit truck; CUT- combination unit truck.

5.3.1.2.5 Usage phase

The usage phase costs, frequently named non-WZ RUC, account for the marginal VehOperC incurred by the vehicle drivers throughout the PAP as a consequence of the deterioration of the pavement condition. In the proposed LCC model, the pavement roughness, as measured by the IRI, was used to estimate the RUC associated with the overall pavement surface condition. The following cost categories were considered to be contributors to the total usage phase costs: (1) FC; (2) tyre wear; (3) vehicle maintenance and repair; and (4) mileage-related vehicle depreciation.

The first three costs categories were estimated by adopting the VehOperC model developed by Chatti and Zaabar (2012) as result of the calibration of the HDM-4 VehOperC model to consider US conditions.

In order to allow for an automatic calculation of the usage phase costs categories and an easy integration with the remaining LCC sub-models, the Chatti and Zaabar's model was run multiple times to compute a set of unit cost factors representing the usage phase costs originated by the full range of IRI values that are likely to be measured over the PAP in the three M&R strategies in comparison. The model runs were conducted in a step wise way, keeping the surface texture, pavement grade and unit traffic composition constant, but changing the temperature according to Stauton's monthly average air temperature in the months of February, April and June. The generated unit cost factors referring to each usage phase cost category were plotted and trend lines following a linear equation were fitted to the data. The unit cost factors obtained by using those equations were then combined accordingly to derive, for each cost category, the unit cost factors representing both Stauton's annual average climatic conditions and the road segments' pavement condition.

With regard to the mileage-related depreciable value, the study carried out by Barnes and Langworthy (2003) was used to estimate the effect of the pavement roughness on vehicle depreciation costs. It relies on the assumption that a vehicle driven almost exclusively on smooth highways will be able to travel more kilometres than one that is driven mostly on rough pavement. Therefore, since mileage-related depreciation reflects the loss in "life expectancy" of the vehicle as it is driven more, factors that reduce the ultimate number of kilometres that the car can be driven must be taken into account by increasing the rate at which the car depreciates.

Expression (5.1) was incorporated into the LCC model to estimate the marginal effects of pavement roughness on the mileage-related depreciable value. It was developed by fitting a function in the form of Expression (5.1) to the adjustment factors reported by Barnes and Langworthy (2003) to estimate VehOperC as a function of pavement condition taking as baseline an IRI value of 1.2 m/km.

$$AF_{Mileage-related\ depreciation} = a \times IRI^2 + b \times IRI + c \tag{5.1}$$

where $AF_{Mileage-related\ depreciation}$ is the adjustment factor that represents the effect of pavement roughness on VehOperC, and IRI is the International Roughness Index (m/km). The values of the parameters *a*, *b* and *c* were found to be 0.0125, 0.0225 and 0.9625, respectively. The value for R^2 in Expression (5.1) is 0.9966.

5.3.1.2.6 End-of-life phase

When a road pavement reaches its service life, it can be given two main destinations: (1) remain in place serving as support for a new pavement structure, and (2) be removed. Removed pavement materials are: (1) disposed of in a landfill (increasingly less adopted in the US), or (2) recycled and re-used either as a replacement for virgin aggregate base or as a replacement for virgin asphalt and aggregate in new HMA.

From the LCCA perspective, these two alternatives can be considered mutually exclusive and entail different costs (or benefits) for the highway agencies that reflect the remaining worth of a pavement at the end of the PAP, or in other words, the salvage value. If the pavement is expected to remain in place after reaching the end of the PAP, the salvage value is designated as remaining service life value and refers to the value (positive cash flow) of the structural and functional life remaining in the pavement at the end of the PAP. On the other hand, if the pavement is expected to be demolished once the end of the PAP is reached, then the salvage value is designated as residual value and refers to either: (1) the net value of the recycled materials (the monetary value of the recycled materials minus the costs of removal, transportation and recycling) if the pavement debris is to be recycled, or (2) the sum of the costs resulting from the removal, transportation and landfilling of the pavement debris if the pavement is supposed to be landfilled.

In the case study the most likely EOL scenario for the analysed 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 as the value of its remaining service life. The service life of the pavement was assumed to end when the IRI exceeds 3.16 m/km (200 in/mile), which according to the VDOT's Highway System Performance Dashboard (VDOT, 2012) corresponds to the threshold ($IRI_{Terminal}$) 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 the end of the PAP, Expression (5.2) was adopted. It quantifies the residual value of the pavement as the proportion of the total HAC 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).

$$C_{EOL\,phase} = C_{Last\,M\&R\,activity} \times \frac{IRI_{Terminal} - IRI_{EOL}}{IRI_{Terminal} - IRI_{Initial}} \tag{5.2}$$

where $C_{Last\,M\&R\,activity}$ is the total HAC resulting from the application of the last M&R activity. This is obtained by adding 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; $IRI_{Initial}$ is the IRI value of a new pavement (0.87 m/km); IRI_{EOL} is the IRI of the pavement at the end of the PAP, and $IRI_{Terminal}$ is the IRI value beyond which a ride is classified as "very poor" (3.16 m/km).

5.3.2 Life cycle costs computation

Once all the cost categories associated with each M&R strategy under assessment were identified and calculated, the net present value (NPV) was computed to compare the M&R strategies according to their life cycle economic performance (Expression (5.3)). It allows expenses occurring at different points in time to be added up on a yearly basis by using a discount rate in the calculations to reflect the "time value of money".

In this case study a real discount rate of 2.3% was used. It follows the Office of Management and Budget (OMB)'s guidelines for conducting benefit-cost of federal programs with durations longer than 30 years for the calendar year of 2011 (OMB, 2013).

$$NPV = \sum_{i=0}^{all\ life\ cycle\ phases} \sum_{t=0}^{T+1} \left[\begin{array}{l} X_i \times X_j \times \displaystyle\sum_{j=0}^{NCostCateg_i} \sum_{k=0}^{NCostSubCateg_{ij}} \frac{C_{ijk}(t)}{(1+d)^t} + \\ (1-X_i) \times (1-X_j) \times \displaystyle\sum_{j=0}^{NCostCateg_{EOL}} \sum_{k=0}^{NCostSubCateg_{EOLj}} \frac{C_{EOLjk}(T+1)}{(1+d)^{T+1}} \end{array} \right] \tag{5.3}$$

where NPV is the net present value of the total LCC of a given M&R strategy; i is the pavement life cycle phase; T is the number of years of the PAP; X_i is a factor equal to one if i is not equal to the EOL phase, otherwise it is equal to zero; X_j is a factor equal to one if t is lower or equal to T, otherwise it is equal to zero; $C_{ijk}(t)$ is the value in the year t of the costs subcategory k belonging to the costs category j, accounted for during the pavement life cycle phase i; $NCostCateg_i$ is the number of cost categories considered in the pavement life cycle phase i; $NCostSubCateg_{ij}$ is the number of costs subcategories belonging to the cost category j accounted for during the pavement life cycle phase i, and; $C_{EOLjk}(t)$ is the value in the year $T+1$ of the costs subcategory k belonging to the costs category j accounted for during the EOL phase; $NCostCateg_{EOL}$ is the number of cost categories considered in the EOL phase; $NCostSubCateg_{EOLj}$ is the number of costs subcategories belonging to the cost category j accounted for during the EOL phase, and d is the discount rate.

5.4 Results and discussion

The following sections provide an overview and discussion of the outcomes obtained by applying the pavement LCC model to the case study. Firstly, the costs incurred by the several pavement stakeholders in each pavement life cycle phase are introduced. Secondly, the total LCC corresponding to each M&R strategy are presented and compared. Thirdly, a sensitivity analysis is performed to enhance the understanding of the sensitivity of the results to variation of the input parameters.

5.4.1 Costs per pavement life cycle phase

5.4.1.1 Materials extraction and production phase

Table 5.7 shows the present value (PV) of the LCC incurred by the highway agency during the materials extraction and production phase corresponding to each M&R strategy. They are estimated at approximately $2,438,588 for the recycling-based M&R strategy, $4,538,675 for the traditional reconstruction M&R strategy, and $4,737,806 for the corrective maintenance M&R strategy. According to these values, the recycled-based M&R strategy would allow highway agency savings throughout the pavement life cycle of about $2,299,217 (49%) and $2,100,086 (46%) with regards to the expenses incurred during the homologous phase of the corrective maintenance and traditional reconstruction strategies, respectively.

Regarding the contributions of the various categories to the total cost, the raw materials were found to be by far the main costs driver of this pavement life cycle phase. Its contribution ranges between 87% (traditional reconstruction and corrective maintenance strategies) and 88% (recycling-based strategy), whereas the costs incurred with the remaining categories do not exceed 6% of the total share in all M&R strategies.

To give insights into which elements are behind this high contribution and to what extent they dominate the costs incurred by highway agencies during this life cycle phase, Figure 5.1 shows the breakdown of the PV of the total life cycle raw materials costs. As can be seen, the majority of the costs assigned to this category are due to the consumption of the asphalt binder. It represents 76%, 65% and 76% of the PV of the total life cycle raw materials costs corresponding to the recycling-based, traditional reconstruction and corrective maintenance M&R strategies, respectively. On the other hand, the consumption of aggregates although being 16, 28 and 17 times greater (in mass) than the consumption of asphalt binder represents merely 19%, 33% and 21% of the PV of the total life cycle raw materials costs. Therefore, the adoption of construction and M&R solutions that do not rely exclusively on the application of virgin bituminous-related materials, such as in-situ recycling techniques, has been demonstrated to be an effective way of lowering highway agency expenditures.

Table 5.7- Materials extraction and production phase costs per cost category for each M&R strategy.

M&R strategy	Asphalt plant operation costs ($)		Raw materials ($)	Energy ($)	Total ($)
	Fixed	Variable			
Recycling-based	140,995 (6%)	68,837 (3%)	2,143,750 (88%)	85,006 (3%)	2,438,588
Traditional reconstruction	274,610 (6%)	134,072 (3%)	3,964,745 (87%)	165,247 (4%)	4,538,675
Corrective maintenance	305,642 (6%)	149,222 (3%)	4,098,819 (87%)	184,122 (4%)	4,737,801

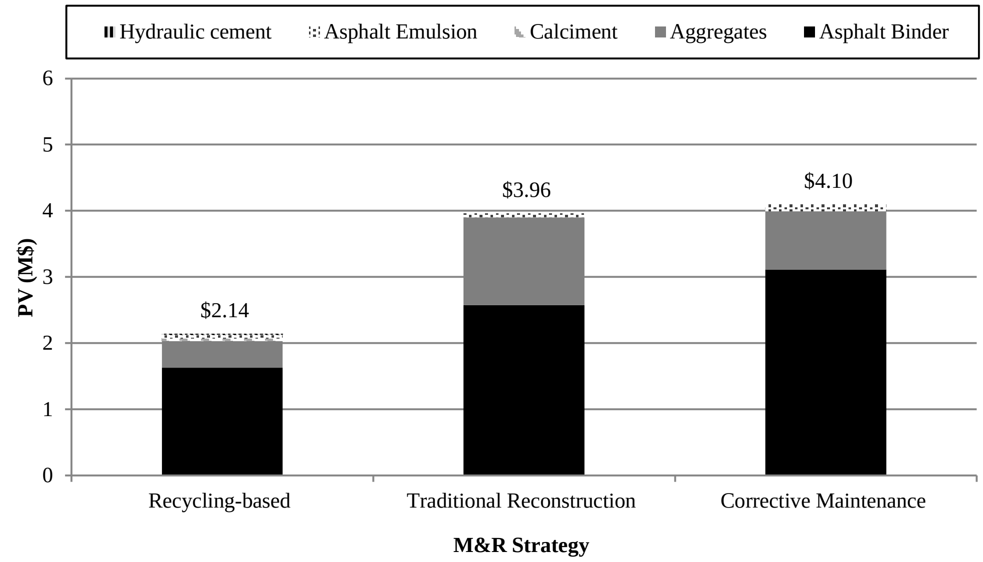


Figure 5.1- Breakdown of the raw material cost category for each M&R strategy. Legend: PV-present value.

5.4.1.2 Construction, maintenance and rehabilitation phase

Table 5.8 displays the PV of the LCC incurred by the highway agency during the construction and M&R phase corresponding to each M&R strategy. The total costs associated with the ownership and operation of the construction equipment over the pavement life cycle ranges from $358,230, for the recycling-based strategy, to $726,126 for the traditional reconstruction strategy. The majority of the costs incurred by the highway agency during this phase are labour costs (38%-42%), followed by fuel consumed (17%-18%), construction equipment repairs (15%) and the construction equipment depreciation costs (12%-13%), respectively. The costs associated with the allocation of the construction equipment to the work site represent a small share of the total costs (6%-7%), whereas the contribution of the remaining subcategories is almost negligible (less than 2%).

Looking at the life cycle construction and M&R costs associated with the application of the various competing M&R strategies, the recycling-based strategy reveals a remarkable economic advantage over the traditional reconstruction and corrective maintenance strategies. It would allow life cycle highway agency savings of about 51% and 31%, respectively.

Table 5.8- PV of the LCC incurred by the highway agency during the construction and M&R phase per cost subcategory for each M&R strategy.

M&R strategy	Owning costs ($)			
	Depreciation	Interest	Insurance	Taxes
Recycling-based	44,100 (12%)	1,744 (0%)	8,158 (2%)	5,439 (6%)
Traditional Reconstruction	92,741 (13%)	3,755 (1%)	17,857 (2%)	11,904 (2%)
Corrective Maintenance	60,641 (12%)	2,387 (0%)	10,990 (2%)	7,327 (1%)

(continued)

M&R strategy	Operating costs ($)						Labour ($)	Total[a] ($)
	FC	PlM and FOG	Repair	Tyre wear	Special wear items	Mobilization		
Recycling-based	65,422 (18%)	7,742 (2%)	54,175 (15%)	4,724 (1%)	1,943 (1%)	21,428 (6%)	143,355 (40%)	358,230 (100%)
Traditional Reconstruction	131,415 (18%)	16,129 (2%)	109,764 (15%)	9,024 (1%)	13,313 (2%)	42,373 (6%)	277,852 (38%)	726,126 (100%)
Corrective Maintenance	87,596 (17%)	10,423 (2%)	75,996 (15%)	9,273 (2%)	859 (0%)	34,727 (7%)	221,890 (42%)	522,108 (100%)

Legend: PV- present value; FC- fuel consumption; LCC- life cycle costs; M&R- maintenance and rehabilitation; PlM and FOG- planned maintenance and filters, oil and greases.

Notes: [a]It corresponds to the sum of the costs associated with the ownership and operation of the construction equipment, including the labour costs.

5.4.1.3 Transportation of materials phase

Table 5.9 summarises the PV of the LCC incurred by highway agency during the transportation of materials phase corresponding to each M&R strategy. The results presented in Table 5.9 show that the bulk of the materials transportation costs comes from the labour costs category, which was found to be 53%-55% of the total life cycle transportation of materials costs. The two remaining costs categories (i.e., owning and operating costs) represent nearly 9 % and 37% of the total LCC incurred during this phase. The main contributors to these outcomes are hauling trucks depreciation costs (5%-6%) and the cost of the fuel consumed (25%-26%), respectively. The plausibility of such results is sustained by the American Transportation Research Institute (ATRI) that reports, on an annual basis, the operational costs of trucking. According to the 2013 updated version of this report (Fender and Pierce, 2013), driver wages and fuel costs were also found to be the main costs incurred by motor carriers in 2011.

When comparing the various M&R strategies according to their economic performance during this pavement life cycle phase, the recycling-based strategy evidences an outstanding performance in comparison to that of the competing alternatives. For the conditions considered in this study a reduction of approximately 66% and 51% in the total life cycle materials transportation costs can be achieved compared to those of traditional reconstruction and corrective strategies, respectively.

Table 5.9- PV of the LCC incurred by the highway agency during the transportation of materials phase per cost subcategory for each M&R strategy.

M&R strategy	Owning costs ($)			
	Depreciation	Interest	Insurance	Taxes
Recycling-based	13,353 (6%)	854 (0%)	4,415 (2%)	2,944 (1%)
Traditional Reconstruction	35,061 (5%)	2,442 (0%)	13,046 (2%)	8,697 (1%)
Corrective Maintenance	25,902 (5%)	1,727 (0%)	9,070 (2%)	6,047 (1%)

(continued)

M&R strategy	Operating costs ($)				Labour ($)	Total[a] ($)
	FC	PlM and FOG	Repair	Tyre wear		
Recycling-based	61,786 (26%)	7,353 (3%)	14,581 (6%)	3,234 (1%)	124,704 (53%)	233,224 (100%)
Traditional Reconstruction	176,404 (26%)	20,992 (3%)	40,182 (6%)	9,262 (1%)	379,527 (55%)	685,612 (100%)
Corrective Maintenance	119,971 (25%)	14,277 (3%)	29,357 (6%)	6,627 (1%)	258,988 (55%)	471,965 (100%)

Legend: PV- present value; FC- fuel consumption; LCC- life cycle costs; M&R- maintenance and rehabilitation; PlM and FOG- planned maintenance and filters, oil and greases.

Notes: [a]It corresponds to the sum of the costs associated with the ownership and operation of the construction equipment, including the labour costs.

5.4.1.4 Work-zone traffic management phase

Table 5.10 illustrates the PV of the additional life cycle WZ traffic management costs associated with the application of M&R activities. As can be seen in this Table, the TDC are the main contributors to the life cycle WZ traffic management costs. This result is strongly attributable to the cost of the additional time required to creep through the queues under forced flow conditions and to transverse both the WZ and the detour at the lower posted speed. They represent 62%-68% and 11%-17%, respectively, of the total life cycle RUC incurred during this pavement life cycle phase. Less expressive than the previous subcategories but equally worthy of mention is the relative importance of the cost of the fuel consumed within the set of costs that constitute the WZ traffic management phase costs. With a LCC ranging between $855,968 (recycling-based M&R strategy) and $1,678,343 (traditional reconstruction M&R strategy), it was found to be responsible for 9%-10% of the life cycle RUC accounted for this phase. In contrast, several cost subcategories, such as vehicle maintenance and repair costs and mileage-related vehicle depreciation costs had a negligible share of the total costs (slightly greater than 0%).

Table 5.10- PV of the marginal life cycle RUC incurred during the WZ traffic management phase per cost subcategory for each M&R strategy.

M&R strategy	VehOperC ($)						TDC ($)	Total ($)
	FC	Oil consump.	Tyre wear	Vehicles maintenance & repair	Vehicles time-related depreciation	Vehicles mileage-related depreciation		
Recycling-based	855,968 (9%)	86,414 (1%)	43,084 (0%)	152 (0.0017%)	851,363 (9%)	19,460 (0%)	7,265,082 (80%)	9,121,523 (100%)
Traditional Reconstruction	967,485 (10%)	96,855 (1%)	50,777 (1%)	182 (0.0018%)	935,501 (9%)	24,388 (0%)	8,033,503 (79%)	10,108,692 (100%)
Corrective Maintenance	1,678,343 (9%)	268,001 (1%)	117,693 (1%)	392 (0.0021%)	1,736,790 (9%)	30,020 (0%)	14,663,049 (79%)	18,494,287 (100%)

Legend: PV- present value; RUC- road user costs; WZ- work-zone; M&R- maintenance and rehabilitation; VehOperC- vehicle operation costs; FC- fuel consumption; Oil consump.- oil consumption; TDC- time delay costs.

Regarding the economic performance of the competing M&R strategies, the recycling-based strategy was found to outperform the remaining ones, giving road user savings of $987,168 (10%) and $9,372,764 (51%) compared to the expenses incurred during the homologous phase of the traditional reconstruction and corrective maintenance strategies, respectively. When compared with the traditional reconstruction strategy, its advantage results from the lower time required to complete the recycling-based M&R activity compared to that of the traditional reconstruction. On the other hand, the corrective maintenance strategy exhibited the poorest economic performance. From the broader point of view of the life cycle, this M&R strategy is particularly penalizing for the road users due to the greater number of M&R activities that need to be performed during this M&R strategy compared to that for the other M&R strategies.

5.4.1.5 Usage phase

Table 5.11 illustrates the PV of the marginal life cycle usage phase costs per cost category for each M&R strategy. From the results in Table 5.11, the corrective maintenance M&R strategy was found to be the least suitable for the road users, as it requires vehicle owners to spend $1,061,820 (43%) more throughout the pavement life cycle than predicted in the same time period for either a recycling-based or a traditional reconstruction M&R strategy. The fact that the recycling-based and traditional reconstruction M&R strategies entail the same life cycle roughness-related RUC is related to the schedule and features of the M&R actions included in the M&R strategies, and respective consequences on pavement performance. As thoroughly discussed in Chapter 4 (Santos et al., 2015) both M&R strategies are expected to have the same pavement deterioration pattern.

Table 5.11- PV of the marginal life cycle RUC due to pavement roughness per cost category for each M&R strategy.

M&R strategy	FC ($)	Tyre wear ($)	Vehicles maintenance & repair ($)	Vehicles mileage-related depreciation ($)	Total ($)
Recycling-based	1,465,882 (30%)	96,674 (2%)	0 (0%)	902,588 (18%)	2,465,145 (100%)
Traditional Reconstruction	1,465,882 (59%)	96,674 (4%)	0 (0%)	902,588 (37%)	2,465,145 (100%)
Corrective Maintenance	2,067,987 (59%)	136,383 (4%)	0 (0%)	1,322,595 (37%)	3,526,964 (100%)

Legend: PV- present value; RUC- road user costs; M&R- maintenance and rehabilitation; FC- fuel consumption.

An interesting result from Table 5.11 is the fact that no additional vehicle maintenance and repair costs are expected to be incurred throughout the 50-year PAP. Although this seems unlikely, it can be explained because: (1) Chatti and Zaabar (2012) showed that there is no effect of roughness on vehicle maintenance and repair costs up to an IRI of 3 m/km and (2) according to the roughness prediction models developed in Chapter 4 (Santos et al., 2015) and applied in this case study, the pavement roughness, as measured by IRI, is never expected to reach that threshold value throughout the life cycle of any M&R strategy.

In contrast to the vehicle maintenance and repair costs category, the greatest share of the life cycle usage phase costs is attributable to FC, which amounts to 59%. On the other hand, tyre wear costs show a reduced relative contribution (4%), whereas the vehicle mileage-related depreciation costs category exhibits an intermediate relevance by accounting for 37% of the PV of the total LCC.

5.4.1.6 End-of-life phase

Table 5.12 presents the PV of the EOL phase costs for each M&R strategy. In this case study, the EOL phase costs represent the salvage value of the pavement structures and are given as the value of the remaining service life. Thus, they are better designated as a credit given to the highway agency rather than a cost incurred by this authority. This explains the negative values of the cost displayed in Table 5.12. As can be seen in this table, regardless of which M&R strategy is adopted, the IRI value at the end of the PAP is approximately the same and the EOL costs are practically negligible when compared with the most relevant costs components. However, as the discounted total cost incurred by the highway agency with the application of the last M&R activity is lower for the corrective maintenance strategy than for the remaining competing strategies, the former M&R strategy entails a credit to the highway agency that is approximately 11% lower than that associated with the recycled-based and traditional reconstruction strategies.

Table 5.12- PV of the EOL cost incurred by the highway agency for each M&R strategy.

M&R strategy	Total HAC corresponding to the last M&R Activity ($)	IRI at EOL (m/km)	EOL cost [Remaining service life value] ($)
Recycling-based	163,363	1.03	- 151,932
Traditional reconstruction	163,363	1.03	- 151,932
Corrective maintenance	145,394	1.02	- 135,856

Legend: PV- present value; EOL- end-of-life; M&R- maintenance and rehabilitation; HAC- highway agency costs; IRI- international roughness index.

5.4.2 Total life cycle costs

Figure 5.2 compares the NPV of the LCC for the three M&R strategies and the distribution per pavement life cycle phase. Table 5.13 shows the difference in the PV of the LCC associated with each phase of the recycled-based strategy in relation to those of the traditional reconstruction and corrective maintenance strategies. Those results are to be understood as follows: negative relative numbers mean that the recycling-based M&R strategy allows for cost savings in relation to the expenditures associated with the traditional reconstruction and corrective maintenance strategies, while positive numbers represent additional costs.

With a life cycle PV of about $14.465 million, the recycling-based strategy is the least costly M&R strategy, with life cycle net savings of $3.908 million (21%) and $13.152 million (48%) compared to the expenses incurred with the adoption of traditional reconstruction and corrective maintenance strategies, respectively. In absolute value, the majority of the economic advantage the recycling-based strategy's life cycle has over the traditional reconstruction strategy is obtained during the materials phase (less $2.100 million), mostly as a consequence of a reduction in the consumption of bituminous-related materials. In relative terms, the largest cost saving happens during the transportation of materials phase (66%). With respect to the decrease in the expenditures that are expected to be achieved by implementing the recycling-based strategy in detriment of a corrective maintenance M&R strategy, the reduction of the WZ traffic management phase costs (less $9.373 million) is the main factor behind this result in absolute value, whereas in relative terms, the transportation of materials and

WZ traffic management phases are both responsible for the most meaningful LCC reduction (51%).

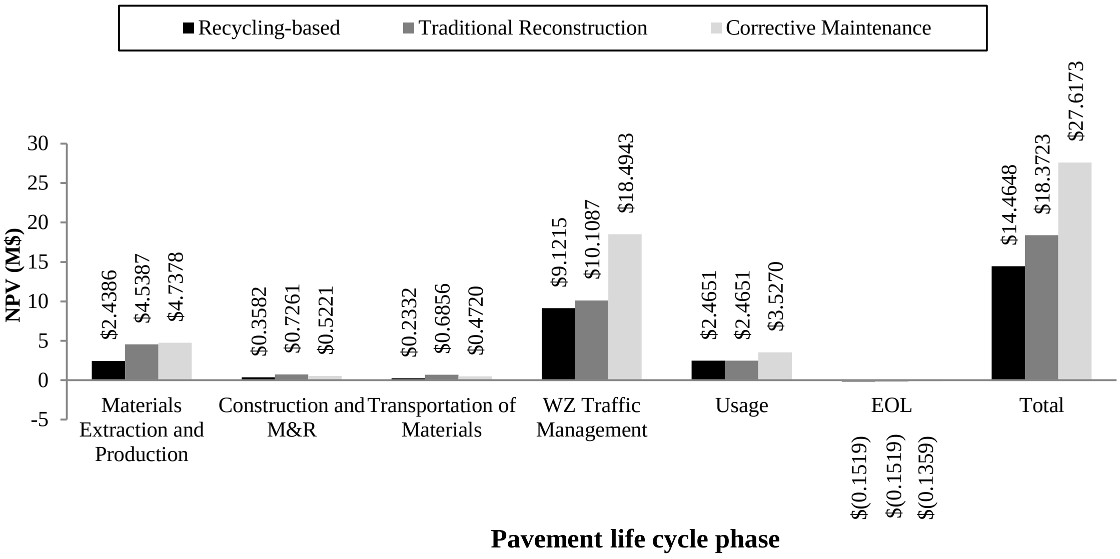


Figure 5.2- Breakdown of the NPV of LCCs of each M&R alternative per pavement life cycle phase.

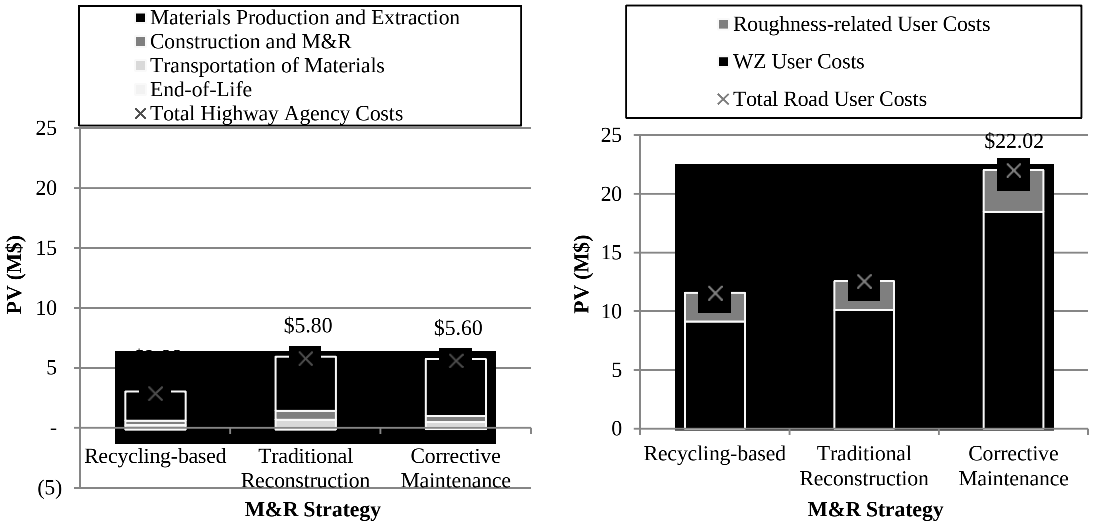
Table 5.13- Difference between the PV of the LCC associated with each phase of the recycled-based strategy and those of the traditional reconstruction and corrective maintenance strategies.

M&R strategy	Pavement life cycle phase						Total
	Materials extraction and production	Construction and M&R	Transportation of materials	WZ Traffic management	Usage	EOL	
Traditional reconstruction	-2.100 (-46%)	-0.368 (-51%)	-0.452 (-66%)	-0.987 (-10%)	0 (0%)	0 (0%)	-3.908 (-21%)
Corrective maintenance	-2.299 (-49%)	0.164 (31%)	-0.239 (-51%)	-9.331 (-51%)	-1.062 (-30%)	-0.016 (-12%)	-13.152 (-48%)

Legend: PV- present value; LCC- life cycle costs; M&R- maintenance and rehabilitation; WZ- work-zone; EOL- end-of-life.

To give pavement stakeholders a better perception of the costs borne by highway agencies and road users when one M&R strategy is preferred over another, Figure 5.3 depicts the PV of the total LCC split into HAC and RUC. Two interesting facts are: (1) the traditional reconstruction strategy is more costly to the highway agencies than the corrective maintenance strategy, and (2) the lower preponderance of the usage phase (16%-21%) in driving the total RUC in comparison to that of the WZ traffic management phase (79%-84%).

With respect to the former, despite the greater number of M&R activities that need to be implemented throughout the PAP in the case of the corrective maintenance strategy, such a result can be explained by the fact that the reconstruction activity requires the removal, and consequent transportation, of all the materials applied in the existing subgrade/base. Therefore, the economic benefit resulting from the materials phase as a consequence of the reduction of the number of required M&R activities is offset by the greater operation time associated with the material removal.



(a) (b)

Figure 5.3- PV of the life cycle highway agency costs (a), and RUC (b). Legend: PV- present value.

To explain the second outcome, two main reasons can be pointed out. First, the WZ traffic management plan implemented during all the M&R activities of any M&R strategy was exclusively designed to be efficient in dealing with the traffic demand existing in the year 0 of the PAP. In other words, it is unable to prevent road users and freight from experiencing substantial delays when facing the M&R events scheduled for the next years. Second, either M&R strategy allows the pavement condition throughout the PAP to be kept at an IRI level lower than 3 m/km. As mentioned previously this IRI value is the threshold after which the vehicle maintenance and repair costs will start to be incurred by vehicle owners (Chatti and Zaabar, 2012). This fact is particularly important given that Islam and Buttlar (2012) have shown that for IRI values greater than 3 m/km this cost category may amount to about 58% to 62% of the total usage phase costs. Consequently, its inexistence strongly contributes for the reduction of the total RUC incurred during the usage phase.

To further elaborate on the potential cost differences arising from implementing the recycling-based activity as opposed to the traditional reconstruction activity, the results were separated into the materials extraction and production, transportation of materials, construction and M&R, and WZ traffic management phases. In doing so, the costs incurred by highway agencies and road users due to the M&R activities that are expected to take place in the remaining years of the PAP were disregarded. Figure 5.4 presents the costs of the two M&R activities broken down by pavement life cycle phases. Table 5.14 presents the difference in the costs associated with the recycling-based M&R activity compared to the traditional reconstruction M&R activity, presented in absolute values and as a percentage. These results should be interpreted in the same way as those displayed in Table 5.13.

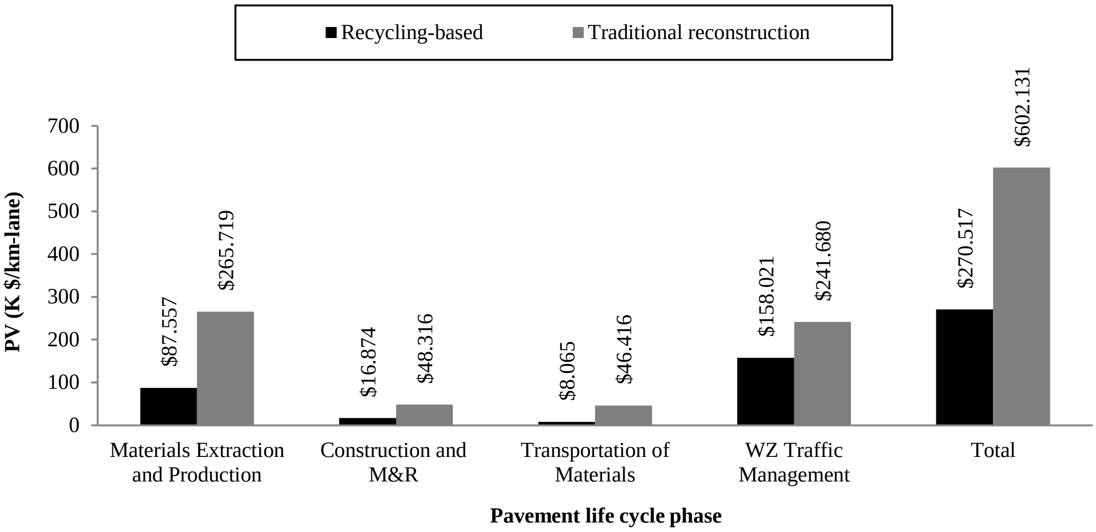


Figure 5.4- Costs of the recycling-based and traditional reconstruction M&R activities broken down per pavement life cycle phase. Legend: PV- present value; M&R- maintenance and rehabilitation; WZ- work-zone.

Table 5.14- Difference between the costs corresponding to recycling-based M&R activity and those of the traditional reconstruction M&R activity (K $/lane-km).

Pavement life cycle phase				
Materials extraction and production	Construction and M&R	Transportation of materials	WZ Traffic management	Total
-178.162 (-67%)	-31.442 (-65%)	-38.352 (-83%)	-83.658 (-35%)	-331.614 (-55%)

Legend: M&R- maintenance and rehabilitation; WZ- work-zone.

Looking at the results presented in Figure 5.4 and Table 5.14 from the perspective of the highway agency, it can be seen that the most meaningful cost savings, in absolute values, from applying the recycling-based M&R activity comes in the materials phase. It shows a reduction of $178.162 thousands/lane-km, or 67% of the costs incurred during the homologous phase of the traditional reconstruction M&R activity. However, if the analysis is carried out on a relative basis, then the transportation of materials phase would lead highway agencies to the greatest cost savings, as the transportation costs are expected to decrease by 83%, which in absolute value corresponds to a reduction from $46.416 thousands/lane-km to $8.065 thousands/lane-km.

As for the road users, Figure 5.4 and Table 5.14 unsurprisingly reveal that the adoption of the recycling-based M&R activity in lieu of the traditional reconstruction can also be beneficial. Although less expressive than the savings for highway agencies, road users are likely to benefit from a costs reduction that amounts to $83.658 thousands/lane-km (35%).

5.4.3 Sensitivity analysis

A sensitivity analysis was conducted to examine how variations across a set of parameters and assumptions affect the robustness of the reported outcomes, and thereby, the relative merits of the alternatives being considered and compared.

Based on the costs drivers identified in the previous sections and the critical assumptions common to any LCCA, the potential effects on the LCC due to the variation in the value of the following parameters were analysed: (1) discount rate; (2) bituminous materials costs (BMC); (3) TDC; and (4) hauling distance of the virgin aggregates. Each single parameter was varied uniformly on a unit-by-unit basis from the established baseline value in the positive and negative direction, while holding all others at their average values. An exception to this methodological procedure was considered in the case of the hauling distances of the virgin aggregates. The influence of this parameter on the results was assessed by considering three distinct values (20 km, 50 km and 80 km) in addition to the baseline value (0.6 km).

Figure 5.5 presents the impacts of varying the discount rate and BMC, ± 60%, on the HAC. It can be seen that the recycling-based strategy's LCC advantage over the remaining M&R strategies is robust even when considerable relative changes in the parameter values were tested against the baseline values. Unless a very high discount rate is considered, the recycling-based strategy is always preferable for the highway agency. In contrast, the relative differences in the economic performance of the remaining M&R strategies denote some volatility as the discount rate and BMC are changed. If the increase in the costs of the BMC exceeds approximately 35% of the baseline value, the corrective maintenance strategy would become more attractive than the traditional reconstruction strategy. A similar consequence is observed when the discount rate varies more than approximately -15% (in absolute value) in relation to the baseline value. Finally, Figure 5.5 also shows that the HAC are more sensitive to changes in the BMC than in the discount rate, as can be seen from the steeper slope of the curves representing the impacts of varying the first input on the HAC.

Figure 5.6 depicts the sensitivity of changes in discount rate and TDC on RUC. The analysis indicates that overall neither the TDC nor the discount rate are critical parameters when evaluating the relative differences between the RUC over the ± 60% sensitivity range. However, a more careful analysis of the behaviour of the curves shows that the disadvantage of the corrective maintenance strategy over the remaining alternatives is attenuated as the discount rate and the TDC increase and decrease, respectively. The corrective maintenance strategy requires more M&R events throughout the PAP but its first M&R event is less time consuming than the homologous event in the competing alternatives. This fact explains why at higher discount rates the economic performance of all M&R strategies tends to become closer. With regard to the influence of the TDC on the RUC, the results suggest that for the conditions considered in this case study, at higher TDC the effect of the number of M&R events prevails over the effect of their duration.

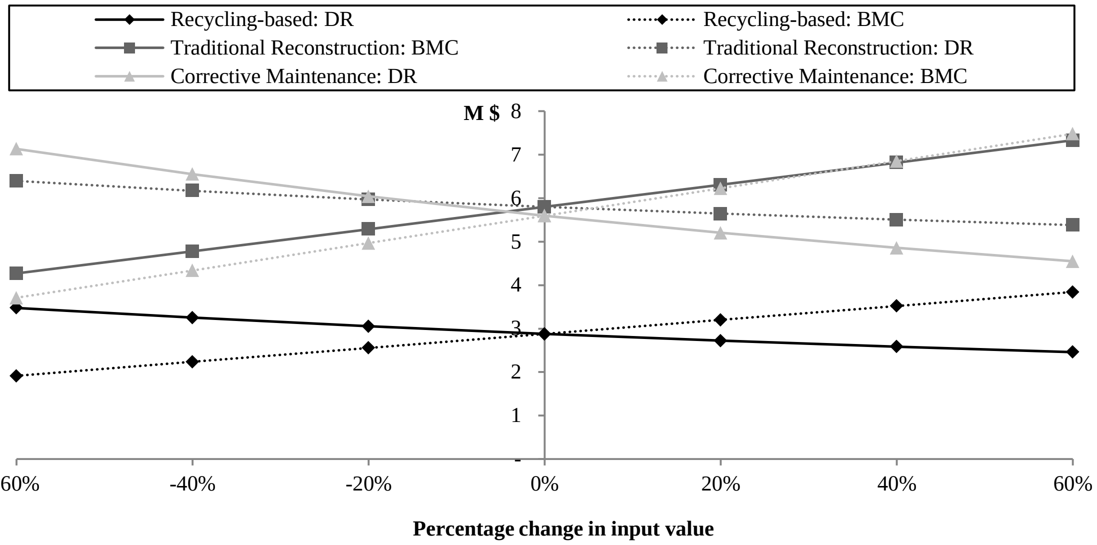


Figure 5.5- Sensitivity analysis of total HAC. Legend: HAC- highway agency costs; DR- discount rate; BMC- bituminous materials costs.

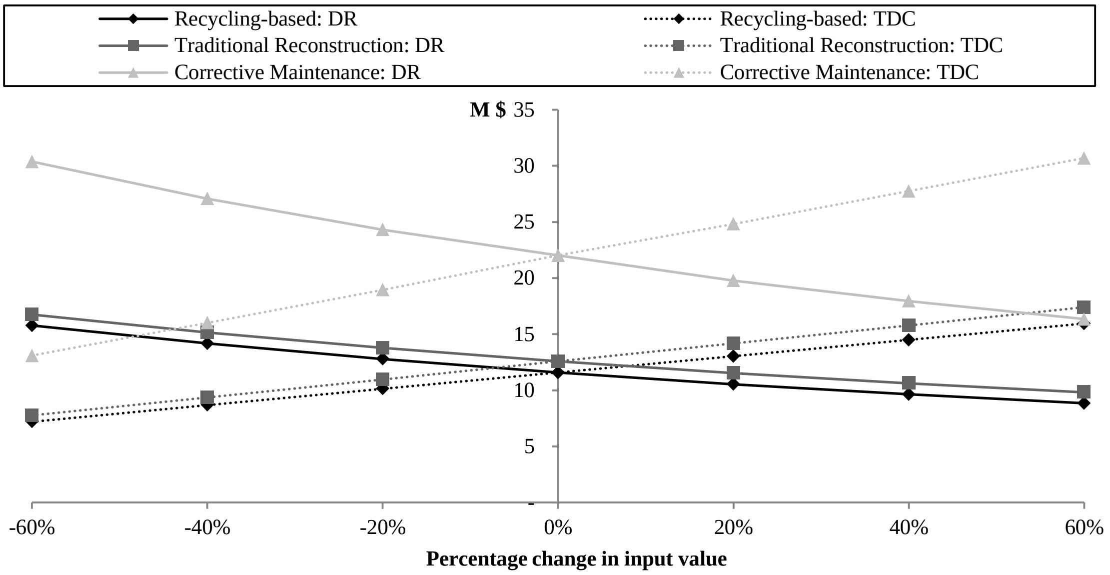
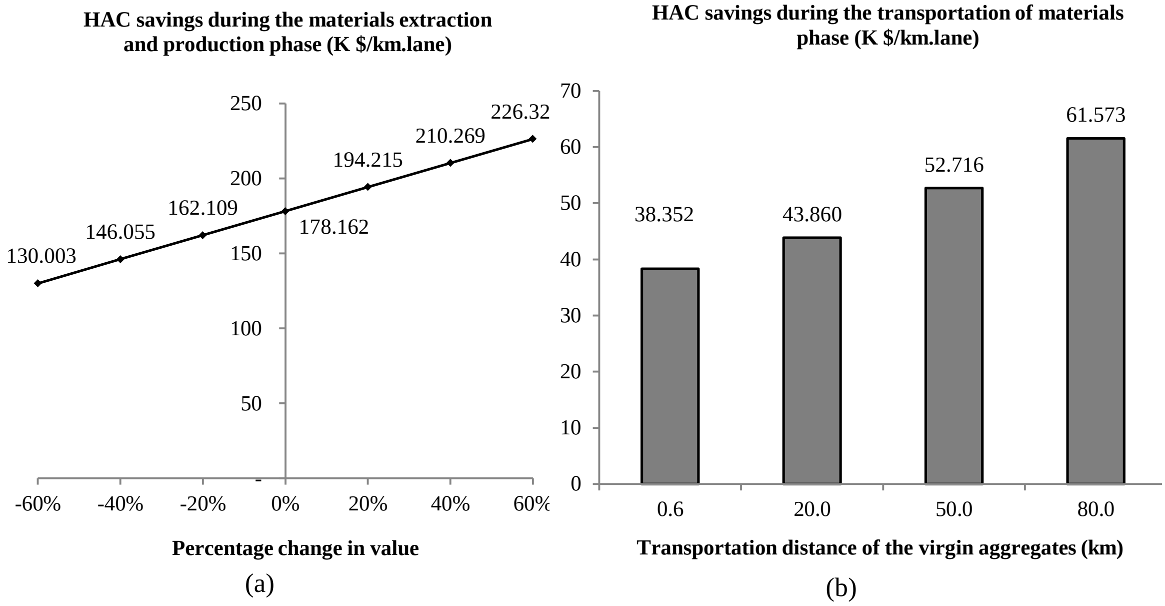
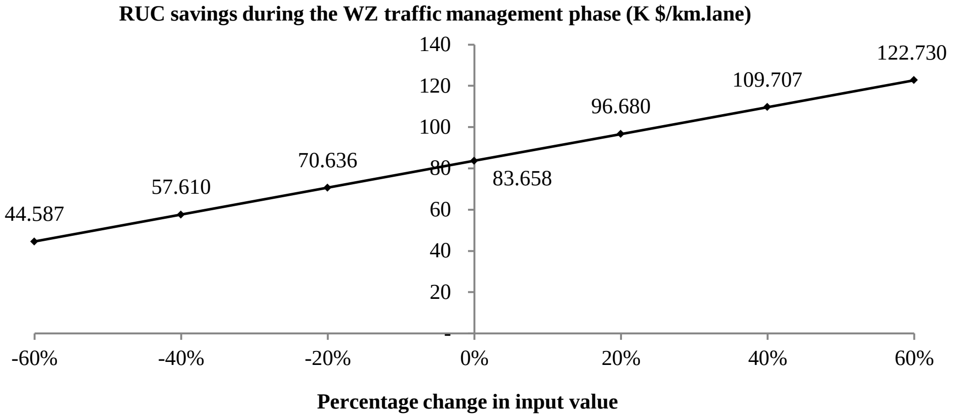


Figure 5.6- Sensitivity analysis of RUC. Legend: RUC- road user costs; DR- discount rate; TDC- time delay costs.

A similar study was conducted which aims to evaluate how the economic benefits resulting from implementing the recycling-based M&R activity in lieu of the traditional reconstruction M&R activity (see Table 5.14) varies as a function of changes in the value of (1) BMC, (2) transportation distance of the virgin aggregates, and (3) TDC. Unlike the previous analyses, the influence of the discount rate on the outcomes was not assessed because the two alternative M&R activities are undertaken in year 0 of the PAP. On the other hand, the analysis includes the assessment of the impacts on the highway agency costs resulting from considering different values of the transportation distance of virgin aggregates. Although it is not as important as the BMC, the economic competitiveness of in-place pavement recycling techniques is also affected by material transportation costs and how such costs compare to the cost of new virgin material delivered to the construction site. The recycling project analysed in this case study did not take full advantage of this common feature of in-place recycling techniques given that quarry that supplied the aggregates consumed during the project was inside the boundary of the asphalt plant facility. To provide insights into the magnitude of the influence of this parameter on the highway agency costs, three distinct transportation distance values of virgin aggregates were considered (20 km, 50 km and 80 km) in addition to the baseline value (0.6 km).





(c)

Figure 5.7- Sensitivity analysis of the economic benefits resulting from applying the recycling-based M&R activity in lieu of the traditional reconstruction M&R activity, due to variability in: (a) BMC; (b) transportation distance of the virgin aggregates, and (c) TDC. Legend: HAC- highway agency costs; RUC- road user costs; WZ- work-zone; BMC- bituminous materials costs; TDC- time delay costs.

Unsurprisingly, the results presented in Figure 5.7(a) underline the importance of the BMC in driving the superior economic performance demonstrated by the recycling-based M&R activity. In a theoretical scenario where the costs of the binder and bituminous emulsions rise up to 60% of the baseline values, the option for the recycling-based M&R activity would bring HAC savings of approximately $226 thousands/km-lane, representing an increment of 27% compared to those corresponding to the baseline scenario. Disregarding the fact that an increase in the BMC would not be disassociated from a likely increase in the costs of other petroleum-derived products (e.g., fuels, oils, lube, etc.), the savings reported above are of such a magnitude that they are just slightly lower than the total savings (roughly 248 thousands/km-lane, see Table 5.14) that highway agency are likely to benefit during the materials, construction and M&R, and transportation of materials phases for the conditions considered in the baseline scenario.

With respect to the influence of the transportation distance of virgin aggregates on the costs incurred by highway agency during the corresponding pavement life cycle phase, Figure 5.7(b) shows that in a plausible scenario where the transportation distance of virgin aggregates is equal to 50 km, the HAC savings increase by 37%. This percentage would increase to 61% if a longer distance (80 km) was considered. Although the importance of the transportation distance of virgin aggregates to the economic advantage associated with the transportation of materials phase is not as expressive as the BMC to the total economic benefit of the recycling-based M&R activity, we should bear in mind that this analysis only addresses the influence of the transportation distance of virgin aggregates. Additional costs savings are expected to be incurred during this pavement life cycle phase if the transportation distances of the asphalt mixtures were greater than those considered in this case study.

Finally, from Figure 5.7(c) it can be concluded that changes in the TDC lead to similar relative costs savings experienced by the road users during the WZ traffic management phase. For example, when the TDC increase by 60%, the RUC savings increase by 47%. This value is greater than the relative savings (27%) made by the highway agency during the materials phase when the BMC increases accordingly.

5.4.4 Key findings

From the results presented and thoroughly discussed in the previous sections, the following findings were identified:

- the recycling-based M&R strategy is the least costly M&R strategy, allowing life cycle net savings of 21% and 48% compared to the expenses incurred with the adoption of the traditional reconstruction and corrective maintenance strategies;
- the recycling-based M&R strategy significantly enhances the overall economic performance of the pavements over the life cycle by lowering the costs incurred during the materials transportation and materials extraction and production phases, independently of whether the analysis is carried out from the perspective of relative or absolute values;
- although the corrective maintenance strategy costs road users more 9 % than the traditional reconstruction, it was found to be 4% less costly to the highway agencies than the traditional reconstruction strategy;

- regardless of the type of M&R strategy adopted, the main LCC incurred by highway agencies and road users are due to materials extraction and production and WZ traffic management phases, respectively;
- the cost of the bituminous-related materials was found to be the main cost driver of the materials phase costs, whereas the TDC have the greatest impact on the WZ traffic management phase's economic performance;
- the life cycle RUC can be as much as 4 times greater than the LCHAC;
- a reduction of 67% in the costs incurred by highway agencies during the materials extraction and production phase can be achieved by undertaking the recycling-based M&R activity in lieu of the traditional reconstruction M&R activity;
- the recycling-based strategy's LCC advantage over the remaining M&R strategies is robust even when considerable relative changes in the discount rate, TDC and BMC values were tested against the baseline values;
- if the transportation distance of the virgin aggregates increases to 50 km and 80Km, the HAC savings will increase by 37% and 61%, respectively, when the recycling-based M&R activity is adopted in lieu of the traditional reconstruction M&R activity.

5.5 Summary and conclusions

This chapter presents the development of a cradle-to-grave and comprehensive LCC-based decision support tool that can assist DMs in determining whether current interest in the adoption of more environmentally-friendly construction and M&R practices leads to an increase in the expenditures incurred by the different pavement stakeholders. Rather than relying on aggregated inputs, the proposed model allows for the disaggregation of the costs of new construction and M&R techniques and materials, not only in terms of the pavement life cycle phases where they are incurred, but also from the perspective of the delivery cost's upstream supply chain.

The chapter showed that through a step-wise and thorough analysis, the proposed LCC model can be applied to calculate and compare several categories of costs incurred by the highway agencies and road users arising from assumptions and parameters considered across a wider range of the processes modelled throughout 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.

The proposed LCC model was applied to quantify the economic benefits of an in-place pavement recycling rehabilitation project. The results of the LCCA of three competing M&R strategies for a pavement segment show that, for a rehabilitation project with features similar to those of the case study introduced in this chapter, the implementation of recycling-based M&R strategies has the potential to be simultaneously advantageous from the environmental and economic perspectives. In addition to the environmental benefits previously acknowledged in Chapter 4 (Santos et al., 2015), those rehabilitation solutions proved to be also efficient in lowering the total LCC incurred both by highway agencies and road users.

From the perspective of the highway agencies, the majority of the economic advantage the recycling-based strategy’s life cycle has over the competing alternatives is expected to be obtained during the materials phase, essentially due to the reduction in the consumption of bituminous-related materials. From the road users’ perspective, the WZ traffic management phase has a more significant impact than the usage phase, as it provides the greatest source of RUC savings thanks to the reduction of the TDC.

A sensitivity analysis was undertaken to assess the robustness of the outcomes in response to variations in some of the most relevant input values. The analysis has shown that variances to the key assumptions applied within LCC analysis do not alter the cost advantage of the recycling-based M&R strategy’s life cycle over the remaining M&R strategies.

To guide highway agencies towards an optimised allocation of resources while meeting the environmental concerns, future work on this topic should focus on the development of a MOO-based framework that integrates this LCC model in a systematic and parallel way with an upgraded version of the pavement LCA model presented in Chapter 4 (Santos et al., 2015).

5.6 References

American Society of Civil Engineering (ASCE), 2013. *2013 Report card for America's infrastructure.* Available at: http://www.infrastructurereportcard.org/a/#p/roads/overview

Amini, A., Mashayekhi, M., Ziari, H. and Nobakht, S., 2012. Life cycle cost comparison of highways with perpetual and conventional pavements. *International Journal of Pavement Engineering*, 13(6), 553-568.

Barnes, G. and Langworthy, P., 2003. *The per-mile costs of operating automobiles and trucks* (Report No. MN/RC 2003-19). Available at: www.lrrb.org/pdf/200319.pdf

Caterpillar, Inc., 2012. Caterpillar performance handbook, 42nd Ed., Caterpillar, Peoria, IL.

Chan, A., Keoleian, G. and Gabler, E., 2008. Evaluation of life-cycle cost analysis practices used by the Michigan Department of Transportation. *ASCE-Journal of Transportation Engineering*, 134(6), 236-245.

Chatti, K. and Zaabar, I., 2012. *Estimating the effects of pavement condition on vehicle operating costs* (National Cooperative Highway Research Program Report No. 720). Available at: http://www.trb.org/Main/Blurbs/166904.aspx

Chen, C. and Flintsch, G., 2007. Fuzzy logic pavement maintenance and rehabilitation triggering approach for probabilistic life-cycle cost analysis, *Transportation Research Record: Journal of the Transportation Research Board*, 1990(1), 80-91.

Damas, L., 2005. *SQL- Structured Query Language*. Lisboa: FCA- Editora de Informática Lda. (in Portuguese).

Diefenderfer, S. and Hearon, A., 2010. *Performance of Virginia's warm-mix asphalt trial sections.* Virginia Transportation Research Council (Report VTRC 10-R17). Available at: http:/www.virginiadot.org/vtrc/main/online_reports/pdf/10-r17.pdf

Diefenderfer, B., Apeagyei, A., Gallo, A., Dougald, L. and Weaver, C., 2012. In-place pavement recycling on I-81 in Virginia. *Transportation Research Record: Journal of the Transportation Research Board*, 2306(1), 21-27.

Epps, J., Berger, E. and Anagnos, J., 2003. *Treatments. Moisture sensitivity of asphalt pavements- a national seminar, San Diego, California*. Transportation Research Board, Washington, D.C. Available at: http://www.trb.org/Publications/Blurbs/153655.aspx

European Asphalt Pavement Association and National Asphalt Pavement Association (EAPA and NAPA), 2011. *The asphalt paving industry: a global perspective (2nd edition).* Available at: http://www.eapa.org/userfiles/2/Publications/GL101-2nd-Edition.pdf

Fabrycky, W. and Blanchard, B., 1991. *Life-cycle cost and economic analysis*. New Jersey: Prentice Hall.

Federal Highway Administration (FHWA), 2002. *Life-cycle cost analysis primer* (Report No FHWA-IF-02-047). Available at: http://www.fhwa.dot.gov/infrastructure/asstmgmt/lcca.cfm

Federal Highway Administration (FHWA), 2003. *Economic analysis primer* (Report No FHWA-IF-03-032). Available at: http://www.fhwa.dot.gov/infrastructure/asstmgmt/primer00.cfm

Federal Highway Administration (FHWA), 2005. *Highway economic requirements system- state version (HERS-ST). Technical report*. Available at: http://www.fhwa.dot.gov/asset/hersst/pubs/tech/tech00.cfm

Fender, K. and Pierce, D., 2013. *An analysis of the operational costs of trucking: 2013 update.* Available at: http://atri-online.org/2013/09/04/an-analysis-of-the-operational-costs-of-trucking-2013-update/

Hall, K., Correa, C., Carpenter, S. and Elliott, R., 2003. *Guidelines for life-cycle cost analysis of pavement rehabilitation strategies*. Proceeding of the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C.

Hansen, K. and Copeland, A., 2013. *2nd annual asphalt pavement industry survey on reclaimed asphalt pavement, reclaimed asphalt shingles, and warm-mix asphalt usage: 2009-2011*. Information series 138, National Asphalt Pavement Association, MD. Available at: http://www.asphaltpavement.org/index.php?option=com_content&view=article&id=946:napa-fhwa-seek-asphalt-mix-producers-input-for-survey&catid=24:napa-news4&Itemid=1308

Harvey, J., Kendall, A., Lee, I.-S., Santero, N., Van Dam, T. and Wang, T., 2010. *Pavement life cycle assessment workshop: discussion summary and guidelines* (Technical Memorandum: UCPRC-TM-2010-03). Available at: http://www.ucprc.ucdavis.edu/PublicationsPage.aspx

Islam, S. and Buttlar, W., 2012. Effect of pavement roughness on user costs. *Transportation Research Record: Journal of the Transportation Research Board,* 2285, 47-55.

Klöpffer, W., 2008. Life cycle sustainability assessment of products. *International Journal of Life Cycle Assessment*, 13(2), 89-94.

Lee, J., Edil, T., Tinjum, J. and Benson, C., 2010. Quantitative assessment of environmental and economic benefits of recycled materials in highway construction. *Transportation Research Record: Journal of the Transportation Research Board,* 2158, 138-142.

Li, Z. and Madanu, S., 2009. Highway project level life-cycle benefit/cost analysis under certainty, risk, and uncertainty: methodology with case study. *ASCE-Journal of Transportation Engineering*, 135(8), 516-526.

Lindholm, A. and Suomala, P., 2005. Present and future of life cycle costing: reflections from Finnish companies. *The Finnish Journal of Business Administration*, 2, 282-292.

Loureiro, H., 2010. *Visual Basic- curso complete*. Lisboa: FCA- Editora de Informática Lda. (in Portuguese)

Miliutenko, S., Björklund, A. and Carlsson, A., 2013. Opportunities for environmentally improved asphalt recycling: the example of Sweden. *Journal of Cleaner Production*, 43, 156-165.

Mirzadeh, I., Butt, A., Toller, S. and Birgisson, B., 2014. Life cycle cost analysis based on the fundamental cost contributors for asphalt pavements. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance,* 10(12), 1638-1647.

Morgan, J., 2005. *Hot mix asphalt for county roads: private providers or public plants?* Comptroller of the Treasury, Offices of Research and Education Accountability, State of Tennessee. Available at: http://www.comptroller.tn.gov/AuditsAndReportsSearch/CategorySearchResults.aspx

Office of Management and Budget (OMB), 2013. *Discount rates for cost-effectiveness, lease purchase, and related analyses*. Table of past years discount rates from Appendix C of OMB Circular No. A-94. Available at: http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c

Ozbay, K., Parker, N., Jawad, D. and Hussain, S., 2003. *Guidelines for life cycle cost analysis* (Report No FHWA-NJ-2003-012). Available at: http://cait.rutgers.edu/research-reports/guidelines-life-cycle-cost-analysis

Rangaraju, P., Amirkhanian, S. and Guven, Z., 2008. *Life cycle cost analysis for pavement type selection* (Report No FHWA-SC-08-01). Available at: http://www.clemson.edu/t3s/scdot/pdf/projects/SPR656Final.pdf.

Sakhaeifar, M., Brown, E, Tran, N. and Dean, J., 2013. Evaluation of long-lasting perpetual asphalt pavement with life-cycle cost analysis. *Transportation Research Record: Journal of the Transportation Research Board*, 2368(3), 3-11.

Salem, O., Abourizk, S. and Ariaratnam, S., 2003. Risk-based life-cycle costing of infrastructure rehabilitation and construction alternatives. *ASCE-Journal of Infrastructure Systems*, 9(1), 6-15.

Salem, O., Deshpande, A., Genaidy, A. and Geara, T., 2013. User costs in pavement construction and rehabilitation alternative evaluation. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance,* 9(3), 285-294.

Santos, J. and Ferreira, A., 2012. Pavement design optimization considering costs and preventive interventions. *ASCE-Journal of Transportation Engineering,* 138(7), 911-923.

Santos, J. and Ferreira, A., 2013. Life-cycle cost analysis system for pavement management at project level. *International Journal of Pavement Engineering,* 14(1), 71-84.

Santos, J., Bryce, J., Flintsch, G., Ferreira, A. and Diefenderfer, B., 2015. A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance,* 11(9), 1199-1217.

Settanni, E. and Emblemsvåg, J., 2010. Applying a non-deterministic conceptual life cycle costing model to manufacturing processes. *Journal of Modelling in Management*, 5(3), 220-262.

Swei, O., Gregory, J. and Kirchain, R., 2013. Probabilistic characterization of uncertain inputs in the life-cycle cost analysis of pavements. *Transportation Research Record: Journal of the Transportation Research Board*, 2366, 71-77.

Thenoux, G., González, A. and Dowling, R., 2007. Energy consumption comparison for different asphalt pavements rehabilitation techniques used in Chile. *Resources, Conservation and Recycling*, 49(4), 325-339.

Tighe, S., Haas, R. and Ponniah, J., 2007. Life-cycle cost analysis of mitigating reflective cracking. *Transportation Research Record: Journal of the Transportation Research Board*, 1823, 73-79.

Transportation Research Board (TRB), 2000. *Highway Capacity Manual 2000.* Transportation Research Board, Washington, D.C.

United States Army Corps of Engineers (US ACE), 2011a. *Sheboygan harbor strategic navigation dredging, WI. Appendix A- Cost appendix for design project report for Sheboygan harbor Dredged Material Management Plan (DMMP).* US Army Corps of Engineers, Detroit District. Available at: http://www.lre.usace.army.mil/Portals/69/docs/PPPM/PlanningandStudies/DraftPlanningStudies/oneSheboyganHrbWIInterimDMMPmainDec2011.pdf.

United States Army Corps of Engineers (US ACE), 2011b. *Construction equipment ownership and operating expense schedule, Region II.* Document EP 1110-1-8, Vol. 2. Washington D.C.: US Army Corps of Engineers.

United States Department of Labor (US DL), 2011a. *Occupational employment statistics May 2011.* Bureau of Labor Statistics, Department of Labor. Available at: http://www.bls.gov/oes/2011/may/oes_stru.htm

United States Department of Labor (US DL), 2011b. *Employer costs for employee compensation – June 2011.* Bureau of Labor Statistics, Department of Labor. Available at: http://www.bls.gov/schedule/archives/ecec_nr.htm#2011

United States Department of Transportation (US DOT), 2003. *Valuation of Travel Time in Economic Analysis, Revised Departmental Guidance, Memorandum*. Office of the Secretary of Transportation, U.S. Department of Transportation, Washington, DC. Available at: http://www.dot.gov/office-policy/transportation-policy/revised-departmental-guidance-valuation-travel-time-economic

United States Energy Information Administration (US EIA), 2014a. *Lower Atlantic (PADD 1C) gasoline and diesel retail prices*. Available at: http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_r1z_a.htm

United States Energy Information Administration (US EIA), 2014b. *Average retail price of electricity to ultimate customers: by state, by provider, annual back to 1990 (Form EIA-861)*. Available at: http://www.eia.gov/electricity/data.cfm#sales

United States Energy Information Administration (US EIA), 2014c. *Virginia Natural Gas Prices.* Available at: http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_sva_a.htm

United States Environmental Protection Agency (US EPA), 2010a. *Exhaust and crankcase emission factors for nonroad engine modeling- compression- ignition* (Report No. NR-009d). Available at: http://www.epa.gov/otaq/nonrdmdl.htm#model

United States Environmental Protection Agency (US EPA), 2010b. *Motor Vehicle Emission Simulator (MOVES). user guide for MOVES2010b* (Report EPA-420-B-12-001b). Available at: http://www.epa.gov/otaq/models/moves/index.htm#user.

United States Geologic Services (US GS), 2013a. *2011 minerals yearbook: cement [Advance Release]*. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/cement/

United States Geologic Services (US GS), 2013b. *2011 minerals yearbook: stone, crushed [Advance Release]*. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/

Virginia Department of Transportation (VDOT), 2012. *Business Rules and User's Information, Dashboard 3.0*. Available at: http://dashboard.virginiadot.org/Help/DB%20User%20Guide.PDF.

Walls, J. and Smith, M., 1998. *Life-cycle cost analysis in pavement design - in search of better investment decisions* (Report No. FHWA-SA-98-079). Available at: http://isddc.dot.gov/OLPFiles/FHWA/013017.pdf

Chapter 6

Environmental and Economic Assessment of Pavement Construction and Management Practices for Enhancing Pavement Sustainability

6.1 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 US as well as to promote economic growth, many 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 (BCRB and HCA, 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 WMA (Kristjánsdóttir 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., 2015b); (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; Mladenovič 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 LCA and life cycle costing, 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.

6.2 Objectives

The main objective of this chapter is to investigate from a life cycle perspective the extent to which several pavement engineering solutions, namely hot in-plant recycling mixtures, WMA, 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 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 chapter were further analyzed by employing a multi-criteria decision-making (MCDM) method.

6.3 Background to the life cycle modelling approaches adopted in the proposed framework

6.3.1 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 iteractive stages (ISO, 2006a; ISO, 2006b): (1) goal and scope definition; (2) LCI; (3) LCIA; and (4) 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: (1) process-based LCA (P-LCA); (2) input-output LCA (I-O LCA); and (3) 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 I-O 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 I-O LCA method eliminates the truncation error by tracking all upstream processes, there are several drawbacks: (1) 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; (2) from the I-O LCA practitioner's perspective it may look like a "black box", because comprehensively analyzing a specific process is always impossible; (3) monetary value, the most commonly used representation of inter-industry transactions, can distort physical flow relations between industries due to price inhomogeneity; (4) 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; (5) available I-O 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 I-O data; and (6) data used in the I-O 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 I-O 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 I-O LCA models while mitigating their respective limitations, four main hybrid LCA models have been developed, namely tiered, I-O-based, integrated hybrid (Suh et al., 2004) and augmented process-based approach (Bilec et al., 2006; Bilec et al., 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 I-O 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).

6.3.2 Life cycle costing

Life cycle costing 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 life cycle costing into conventional, environmental or societal. Conventional life cycle costing 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 life cycle costing, 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 life cycle costing based on physical LCA, there is no conversion from environmental measures to monetary measures in order to avoid double counting of externalities in life cycle costing and the complementary LCA. Finally, in the Societal life cycle costing 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.

6.4 Methodology

6.4.1 Principles of the integrated pavement life cycle costs- life cycle assessment model

The research work presented in this chapter builds on the P-LCA and LCC models introduced in Chapters 2 and 4 (Santos et al., 2015a; Santos et al., 2015b) and Chapter 5 (Santos et al., 2015c), 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 P-LCA models (Chapters 2, 3 and 4). These are combined with the I-O methodology for deriving the underpinning environmental burdens. Thus, by interactively integrating the strengths of P-LCI and I-O 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 Carnegie Mellon University's Economic Input-Output Life Cycle Assessment tool (EIO-LCA) (Carnegie Mellon University Green Design Institute, 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 DL, 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.

6.4.2 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, 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, CCPR and preventive treatments.

The application of the pavement LCC-LCA model to the case study presented in this chapter 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.

6.4.3 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 ISO (ISO, 2006a; ISO, 2006b) and the UCPRC's Pavement LCA Guideline (Harvey et al., 2010) and the life cycle costing methodology based on the Swarr et al. (2011).

6.4.3.1 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 PAP was 50 years, beginning in 2011 with the construction of the pavement structure. The AADT for the first year was 20,000 vehicles of which 25% were trucks (5% of the truck traffic consisted of SUT and the remaining percentage of CUT). The traffic growth rate was set equal to 3% per year.

6.4.3.2 Product system: the pavement structure

6.4.3.2.1 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 VDOT's Manual of Instructions for the Materials Division (VDOT, 2014). The assumptions considered during the design process are presented in Table 6.1. Based on the assumptions listed in the Table a pavement structure was designed with a SN of 6.72. The details of the interstate flexible pavement structure and HMA mixtures properties are described in Table 6.2.

Table 6.1- Pavement design inputs.

Pavement design variable	Value
Initial construction design (years)	30
Lanes in design direction	2
Lane distribution factor (%)	90
PCs ESAL factor (ESALs/vehicle)	0.0002
SUT ESAL factor (ESALs/vehicle)	0.46
CUT 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
SN	6.72

Legend: PC- passenger car; SUT- single unit truck; CUT- combination unit truck; ESAL- equivalent single axle load; PSI- present serviceability index; Z_R- standard normal deviate; S_0- combined standard error of the traffic prediction and performance prediction; SN- structural number; W_{18}- number of 80 kN ESAL.

Table 6.2- Interstate flexible pavement structure and mixes properties.

Layer ID	Material	Thickness (cm)	Asphalt binder PG	Binder content (%)	Fine aggregates (%)	Coarse aggregates (%)
1	SM 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
3	BM 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	-	-	-	-

Legend: PG- performance grade; SM- surface mixture; IM- intermediate mixture; BM- base mixture.

Notes: 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 antistrip agent at a dosage rate of 1% by total weight of bitumen in mixture.

6.4.3.2.2Maintenance 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 major rehabilitation was carried out through the combination of an in-place recycling technique, namely CCPR, and conventional asphalt layers. The recycling-based M&R activity was designed in such a way that it provides equivalent structural capacity to non-recycling-based one and takes 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 (PrM) 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 6.3. Details on the M&R activities and M&R actions considered in the several M&R scenarios are presented in Table 6.4. Table 6.5 presents the M&R activities considered in each M&R scenario, and respective application years.

Regarding the typologies of M&R activities, VDOT classifies them into five categories: (1) Do Nothing (DN); (2) Preventative Maintenance (PrM); (3) Corrective Maintenance (CM); (4) Restorative Maintenance (RM); and (5) Reconstruction/Rehabilitation (RC). Using the base form corresponding to Expression (6.1), 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 Expression (6.1) for asphalt pavements of Interstate highways are presented in Table 6.6 (Stantec Consulting Services and Lochner, 2007).

$$CCI(t) = CCI_0 - e^{a+b\times c^{ln\left(\frac{1}{t}\right)}} \tag{6.1}$$

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 6.6).

Contrary to the remaining categories, VDOT did not develop individual PPPM for preventive treatments. Thus, in this case study the considered preventive treatments, i.e. microsurfacing and THMACO, were respectively modelled as a 8-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, without reduction of the effective age. 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.

Table 6.3- 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]

Legend: VDOT- Virginia Department of Transportation; HMA- hot-mix asphalt; RAP- reclaimed asphalt pavement; WMA- warm-mix asphalt; THMACO- thin hot mix asphalt concrete overlay.

Notes: The types of bound mixes used in the construction of the initial pavement structure are coherent with the scenario name.

[a] According to VDOT (2012a), RAP cannot be incorporated into the THMACO formulation.

Table 6.4- Types of M&R activities and M&R actions.

M&R activity		M&R actions	Thickness (cm)	Mixture name
ID	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
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC surface layer	3.81 (1.5 in.)	SM 12.5

Legend: M&R- maintenance and rehabilitation; BM- base mixture; IM- intermediate mixture; SM- surface mixture; AC- asphalt concrete.

(continued)

M&R activity		M&R actions	Thickness (cm)	Mixture name
ID	Name			
3	Major rehabilitation	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
		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
4	Recycling-based major rehabilitation	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[a,b]
		Tack coat application	-	Bituminous emulsion
		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
5	Microsurfacing	Surface preparation: brushing	-	
		Surface preparation: tack coat application	-	Diluted bituminous emulsion
		Microsurfacing spreading	-	Microsurfacing - Type C[c]
6	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[d]

Legend: M&R- maintenance and rehabilitation; BM- base mixture; IM- intermediate mixture; SM- surface mixture; AC- asphalt concrete; CCPR- cold central plant recycling; THMACO- thin hot mix asphalt concrete overlay.

Notes: [a] A layer coefficient value of 0.40 was used for design purpose based on Diefenderfer (2014).

[b] A 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).

[c] Based on Ducasse et al. (2004), a mix formulation consisting of 180 liters of emulsion per m^3 aggregates, 3% of Styrene-Butadiene Rubber (SBR) by weight of asphalt binder, 2% of Portland cement by weight of aggregate and 140 liters of water by m^3 of aggregate was used.

[d] Mix 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 6.5- M&R activities considered in each M&R scenario, and respective application years.

M&R scenario ID	M&R activity ID					
	1	2	3	4	5	6
1 to 6	12, 44	22	32	-	-	-
7 to 12	12, 44	22	-	32	-	-
13	9, 17, 25, 41, 49	-	32	-	7, 15, 23, 39, 47	
14	10, 18, 27, 41, 50	-	32	-	-	7, 16, 24, 39, 47

Legend: M&R- maintenance and rehabilitation.

Table 6.6- Coefficients of VDOT's load-related PPPM expressed by the Expression (6.1) 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

Legend: VDOT- Virginia Department of Transportation; PPPM- pavement performance prediction models; M&R- maintenance and rehabilitation; CCI_0 - critical condition index immediately after a treatment; *a*, *b*, and *c* are load-related PPPM coefficients; CM- corrective maintenance; RM- restorative maintenance; RC- reconstruction/Rehabilitation.

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 linear roughness prediction model, expressed in terms of IRI, was considered (Expression (6.2)).

$$IRI(t) = IRI_0 + IRI_{grw} \times t \tag{6.2}$$

where $IRI(t)$ is the IRI value (m/km) in year t, IRI_0 is the IRI immediately after the application of a given M&R activity and IRI_{grw} is the IRI growth rate over time, which was set at 0.08 m/km (Bryce et al., 2014). It was assumed that the application of an M&R activity other than preventive treatment restore the IRI to the value of a brand new pavement (IRI equal to 0.87 km/h). The IRI reduction due to the application of a preventive treatment was determined based on the expected treatment life and assuming that there is no change in the IRI_{grw} value after the preventive treatment application (the same assumption was also made in the case of the remaining M&R activities). Thus, by assuming treatment life periods of 3 and 5 years (Chowdhury, 2011), respectively for microsurfacing and THMACO preventive treatments, reductions in the IRI value of 0.24 and 0.40 m/km were obtained.

Figure 6.1 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.

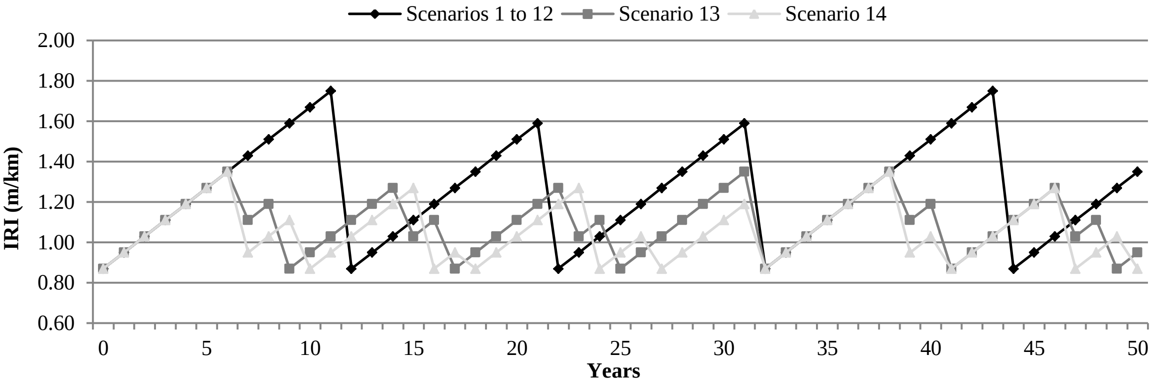


Figure 6.1- IRI over the PAP resulting from the implementation of the alternatives M&R scenarios.

6.4.3.3 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 P-LCA modelling considerations can be found in Chapter 4 (Santos et al., 2015b). Detailed inventory data and complementary assumptions performed throughout the model application are shown in Appendix B

6.4.3.3.1 Environmental dimension

6.4.3.3.1.1 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.

6.4.3.3.1.1.1 Materials extraction sub-phase

P-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 I-O LCI approach: hydrated lime, SBR, WMA additive (Sasobit®).

Information about the economic sectors responsible for manufacturing the previously mentioned materials are presented in Table 6.7.

Table 6.7- I-O LCI data sources (Carnegie Mellon University Green Design Institute, 2008).

Pavement life cycle phase(s)		Element name	Sector ID and name	Notes
Materials		Hydrated lime manufacturing	327410 Lime and gypsum product manufacturing^a	-
		SBR manufacturing	325110 Petrochemical Manufacturing^a	-
		Sasobit® manufacturing	325110 Petrochemical Manufacturing^a	-
	Asphalt plant	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
Construction and M&R	Construction 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	-
		Tyres manufacturing	326210 Tire Manufacturing^b	-
		special wear item manufacturing	333120 Construction Machinery Manufacturing^b	proxy
		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	Hauling trucks	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	PCs	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	-
	HDV	Manufacturing	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	-

Legend: FOG- filters, oil and greases; WZ- work-zone; PC- passenger car; HDV- heavy duty vehicle.

Notes: ^{a}US 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.

^{b}US 2002 (428 sector) Consumer Price Model.

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 or removing the pavement and hauling the recycled materials from the work site to the recycling unit were not included into the system boundaries on the basis of a 'cut-off' allocation criterion. Thus, only the post-processing of these materials is considered.

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 tonnes 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 US EPA's NONROAD 2008 model (US EPA, 2010a). However, the crusher units also emit fugitive 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 US EPA's AP-42: Compilation of Air Pollutant Emission Factors (US EPA, 2004).

6.4.3.3.1.1.2 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 Expression (6.3).

$$Q = \frac{\sum_{i=0}^{M} m_i \times \int_{T_{oi}}^{T_{fi}} c_i(T)\,dT \quad + \quad L_v \times \left(m_{wv_f} - m_{wv_o}\right)}{HeatingEffF} \tag{6.3}$$

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 (ºC); T_{oi} is the initial temperature of material i (ºC); $c_i(T)$ is the specific heat capacity coefficient, as a function of temperature, of material i [J/(kg/ºC)]; L_v is the latent heat required to evaporate water (2256 J/kg); m_{wv_o} is the initial mass of water vapor (kg); m_{wv_f} 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 Waples and Waples (2004b) were adopted, taking the temperature of 20ºC 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/ºC)]. In the case of the surface layers, the value for quartzite [1013 J/(kg/ºC)] and diabase [860 J/(kg/ºC)] 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 3% and

1% (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 160ºC (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 15ºC. In the case of the latter, it was considered that it remains stored at 160ºC 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 (Table B.1, Table B.2 and Table B.3 in Appendix B). 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 25ºC in relation to the reference temperature of 160ºC. This assumption was based on the range values of reduction of temperature of 20-30ºC 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 EFs published by the AP-42 study of 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 CO_2 emissions primarily result from FC, the average emission of this GHG was combined with the fuel emission coefficient (53.1 Kg/MMBtu) reported by United Sates Energy Information Agency (US EIA) to determine the quantity of natural gas whose combustion would release the same amount of CO_2 (US EIA, 2013). Thirdly, for each mix an EF multiplier was determined through the ratio between the thermal energy computed with Expression (6.3) 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 6.8. 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 6.8- 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 mixture	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

Legend: EF- Emission factor; HMA- hot-mix asphalt; WMA- warm-mix asphalt; BM- base mixture; IM- intermediate mixture; SM- surface mixture; RAP- reclaimed asphalt pavement; THMACO- thin hot-mix asphalt overlay;

Notes: [a]It does not include the requirements for heating the insulated bitumen storage tanks.

[b]It 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 (Chapter 4) 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 I-O 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 6.7). 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) × 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.

6.4.3.3.1.2 Construction, maintenance and rehabilitation 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 ACE, 2011; Caterpillar Inc., 2012).

In addition to the process-based components presented previously, the I-O LCI approach was adopted to estimate the environmental burdens associated with the equipment manufacturing, repair, maintenance, 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 6.7).

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.

6.4.3.3.1.3 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 HDVs. The US EPA’s 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 I-O LCI components considered in this pavement life cycle phase can be found in Table 6.7.

6.4.3.3.1.4 Work-zone 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 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 HCM 2000 (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 I-O LCI components shown in Table 6.7.

6.4.3.3.1.5 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 in Chapter 4 (Santos et al., 2015b). As far as the I-O 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 6.7).

6.4.3.3.1.6 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.

6.4.3.3.1.7 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).

6.4.3.3.2Economic dimension

6.4.3.3.2.1 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).

6.4.3.3.2.2 Construction, maintenance and rehabilitation 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 ACE, 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 (EAPA and NAPA, 2011).

6.4.3.3.2.3 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).

6.4.3.3.2.4 Work-zone traffic management phase

The WZ traffic management costs consist of the additional costs borne by the road users, which are commonly referred to 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) TDC and (2) VehOperC. 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).

6.4.3.3.2.5 Usage phase

The usage phase costs, frequently named non-WZ RUC, account for the marginal VehOperC 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 VehOperC 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).

6.4.3.3.2.6 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 salvage 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 salvage value of the pavement at end of the PAP, Expression (6.4) was adopted. It quantifies the salvage value of the pavement as the proportion of the total HAC 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).

$$C_{EOL\,phase} = C_{LastM\&R\,activity} \times \frac{CCI_{EOL} - CCI_{Terminal}}{100 - CCI_{Terminal}} \tag{6.4}$$

where $C_{LastM\&R\,activity}$ 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".

6.4.4 Life cycle impact 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: Ac due to air emissions, EU due to air emissions, HH and PSF. The time-adjusted characterization model for the CC impact category that was proposed by Kendall (2012) was used, as opposed to the traditional time-steady IPCC model. Furthermore, three energy-based indicators were also included in the assessment: (1) primary energy obtained from fossil resources (FoPE); (2) primary energy obtained from non-fossil resources (NFoPE); and (3) FsE. The FsE was fully allocated to the virgin binder, with none attributed to RAP. This assumption aims to avoid double counting since it would be expected to be accounted for in the previous pavement system.

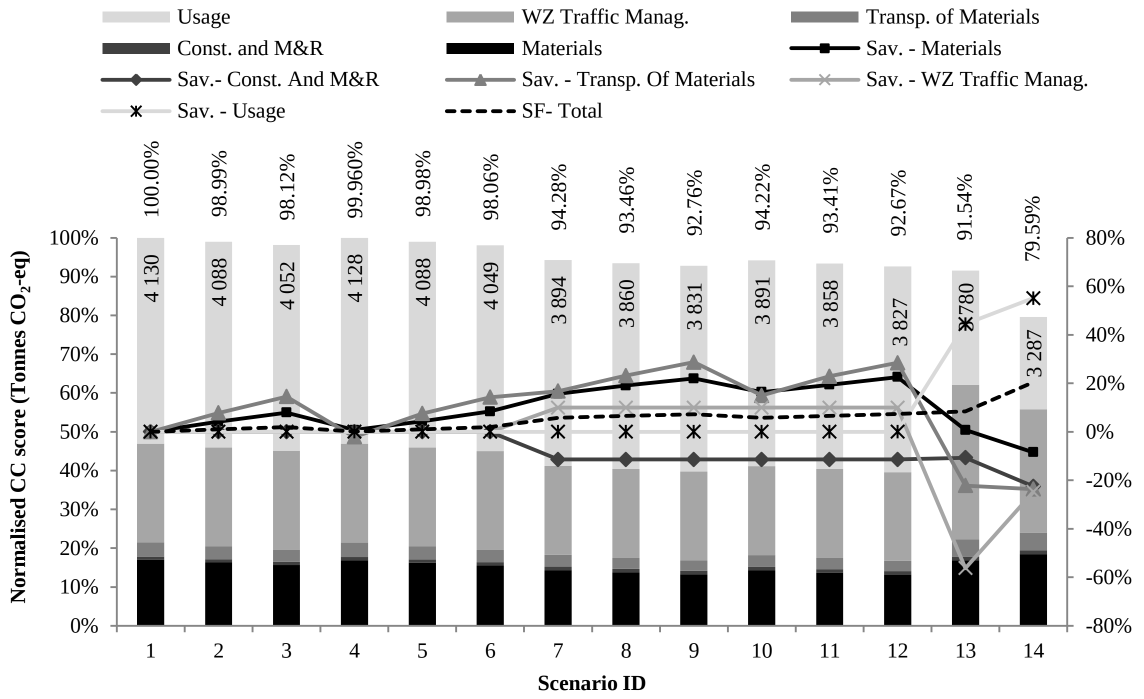
6.4.1 Life cycle costs computation

Once all the cost categories associated with each scenario under assessment are identified and calculated, the concept of NPV was applied. This allows expenses occurring at different points in time to be summed up on a yearly basis by using a discount rate in the calculations to reflect the "time value of money". In this case study, a real discount rate of 2.3% was used. It follows the OMB's guidelines for conducting benefit-cost of federal programs with durations of longer than 30 years for the calendar year of 2011 (OMB, 2013).

6.5 Results and discussion

6.5.1 Life cycle impact assessment

Figure 6.2(a)-6.2(h) display the normalized life cycle impacts of the alternative scenarios across the eight impact and energy demand categories. Each scenario is normalized by the impact category score observed in the first scenario, where all conventional materials and M&R activities were applied. 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 impact category scores are illustrated with labels placed right below the top of the bars.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Transp. of Materials
Const. and M&R
Materials
Sav. - Materials
Sav.- Const. And M&R
Sav. - Transp. Of Materials
Sav. - WZ Traffic Manag.
Sav. - Usage
SF- Total
100.00%
98.99%
98.12%
99.960%
98.98%
98.06%
94.28%
93.46%
92.76%
94.22%
93.41%
92.67%
91.54%
79.59%
4 130
4 088
4 052
4 128
4 088
4 049
3 894
3 860
3 831
3 891
3 858
3 827
3780
3 287
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
Normalised CC score (Tonnes CO_2-eq)
1
2
3
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5
6
7
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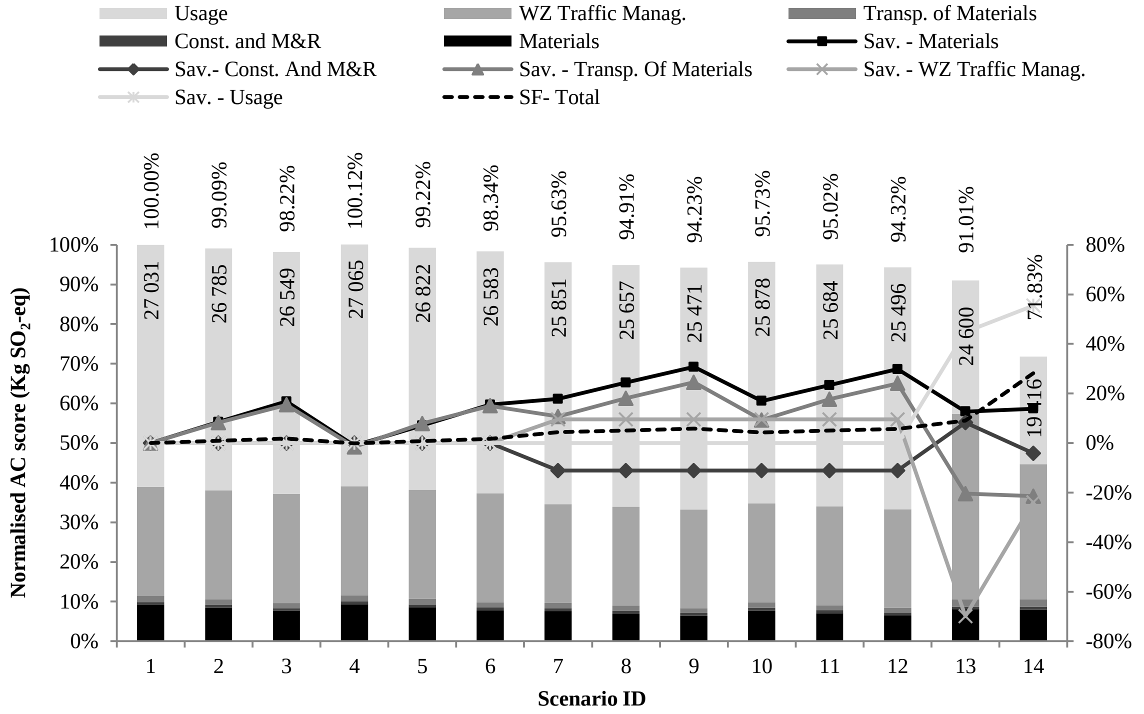
9
10
11
12
13
14
Scenario ID

(a)


Usage
WZ Traffic Manag.
Transp. of Materials
Const. and M&R
Materials
Sav. - Materials
Sav.- Const. And M&R
Sav. - Transp. Of Materials
Sav. - WZ Traffic Manag.
Sav. - Usage
SF- Total
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99.09%
98.22%
100.12%
99.22%
98.34%
95.63%
94.91%
94.23%
95.73%
95.02%
94.32%
91.01%
71.83%
27 031
26 785
26 549
27 065
26 822
26 583
25 851
25 657
25 471
25 878
25 684
25 496
24 600
19 416
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
Normalised AC score (Kg SO_2-eq)
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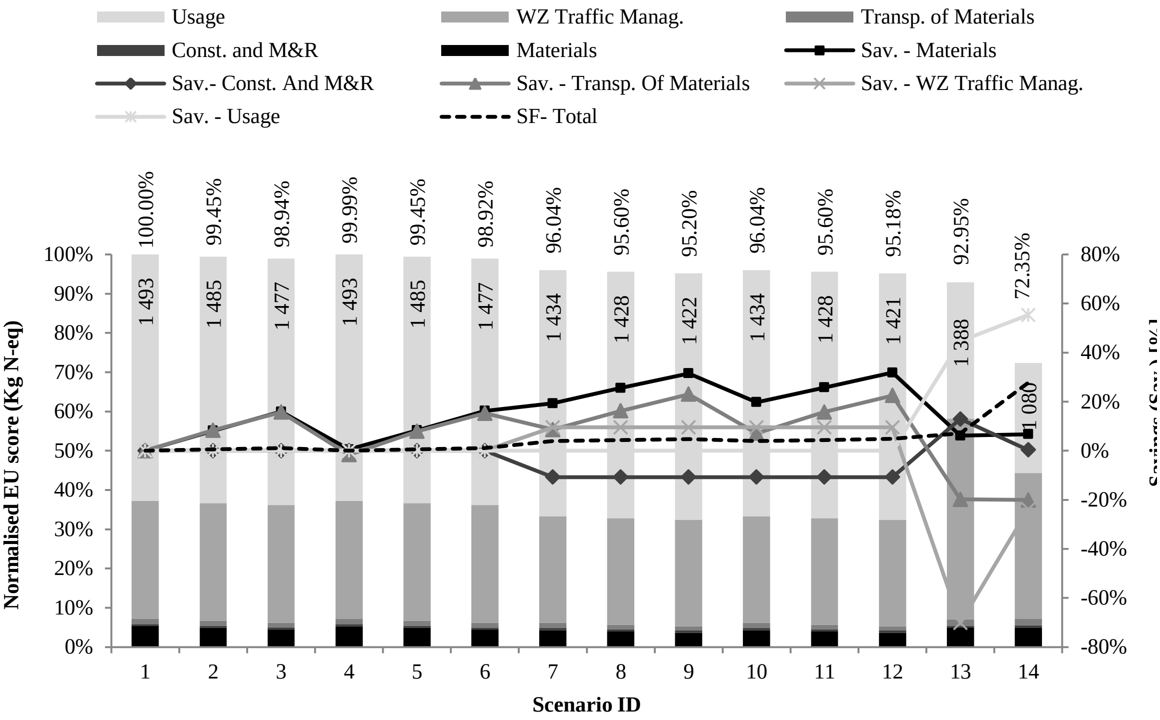
12
13
14
Scenario ID

(b)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Sav.- Const. And M&R
Sav. - Transp. Of Materials
Sav. - WZ Traffic Manag.
Sav. - Usage
SF- Total
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99.99%
99.45%
98.92%
96.04%
95.60%
95.20%
96.04%
95.60%
95.18%
92.95%
72.35%
1 493
1 485
1 477
1 493
1 485
1 477
1 434
1 428
1 422
1 434
1 428
1 421
1 388
1 080
Normalised EU score (Kg N-eq)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
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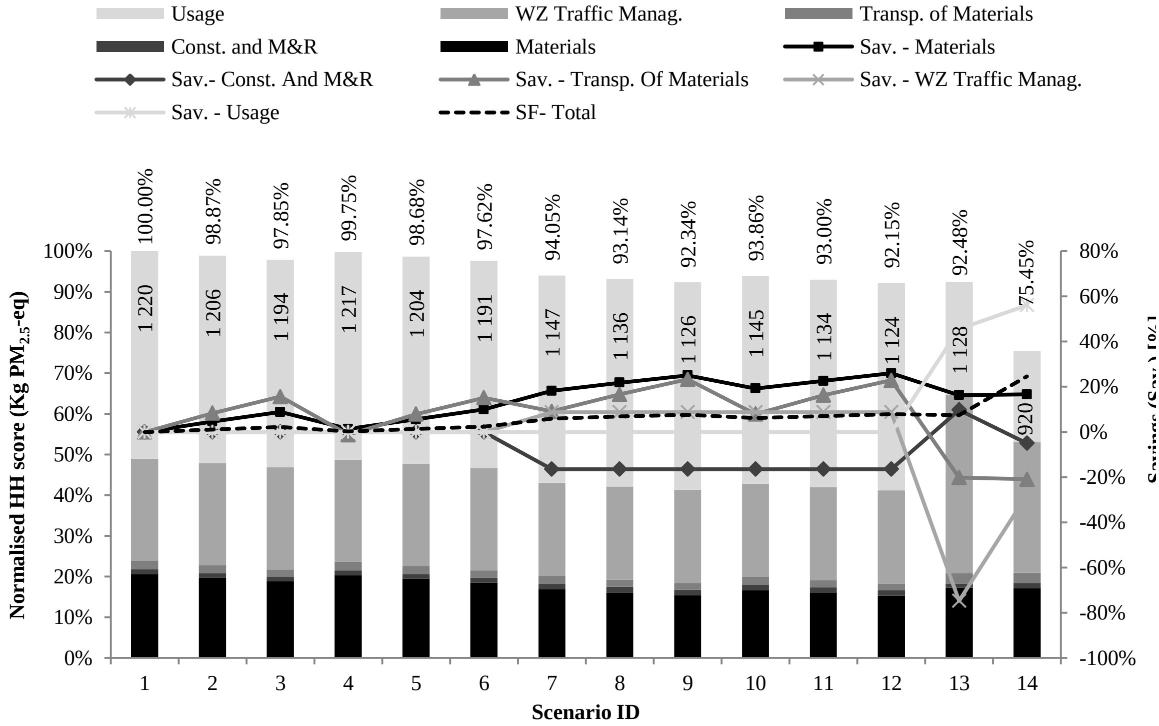
Scenario ID

(c)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Materials
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Sav.- Const. And M&R
Sav. - Transp. Of Materials
Sav. - WZ Traffic Manag.
Sav. - Usage
SF- Total
100.00%
98.87%
97.85%
99.75%
98.68%
97.62%
94.05%
93.14%
92.34%
93.86%
93.00%
92.15%
92.48%
75.45%
1 220
1 206
1 194
1 217
1 204
1 191
1 147
1 136
1 126
1 145
1 134
1 124
1 128
920
Normalised HH score (Kg PM$_{2.5}$-eq)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
-100%
1
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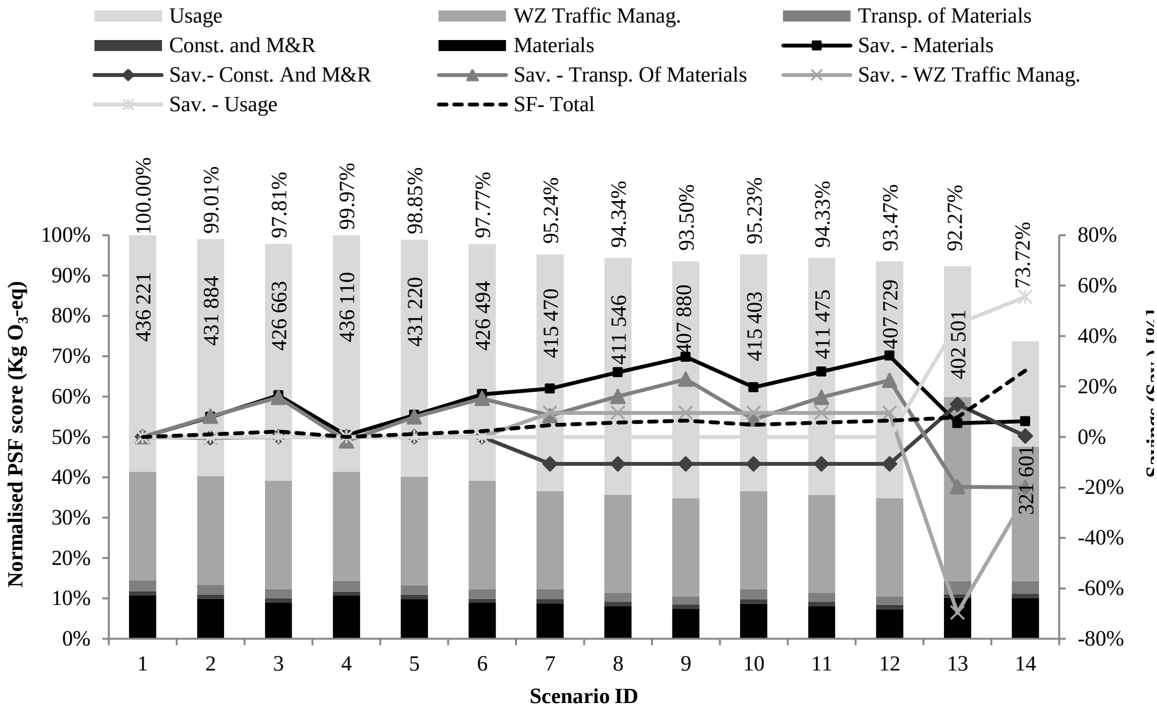
12
13
14
Scenario ID

(d)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Transp. of Materials
Const. and M&R
Materials
Sav. - Materials
Sav.- Const. And M&R
Sav. - Transp. Of Materials
Sav. - WZ Traffic Manag.
Sav. - Usage
SF- Total
Normalised PSF score (Kg O_3-eq)
Scenario ID
100.00%
99.01%
97.81%
99.97%
98.85%
97.77%
95.24%
94.34%
93.50%
95.23%
94.33%
93.47%
92.27%
73.72%
436 221
431 884
426 663
436 110
431 220
426 494
415 470
411 546
407 880
415 403
411 475
407 729
402 501
321 601
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
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0%
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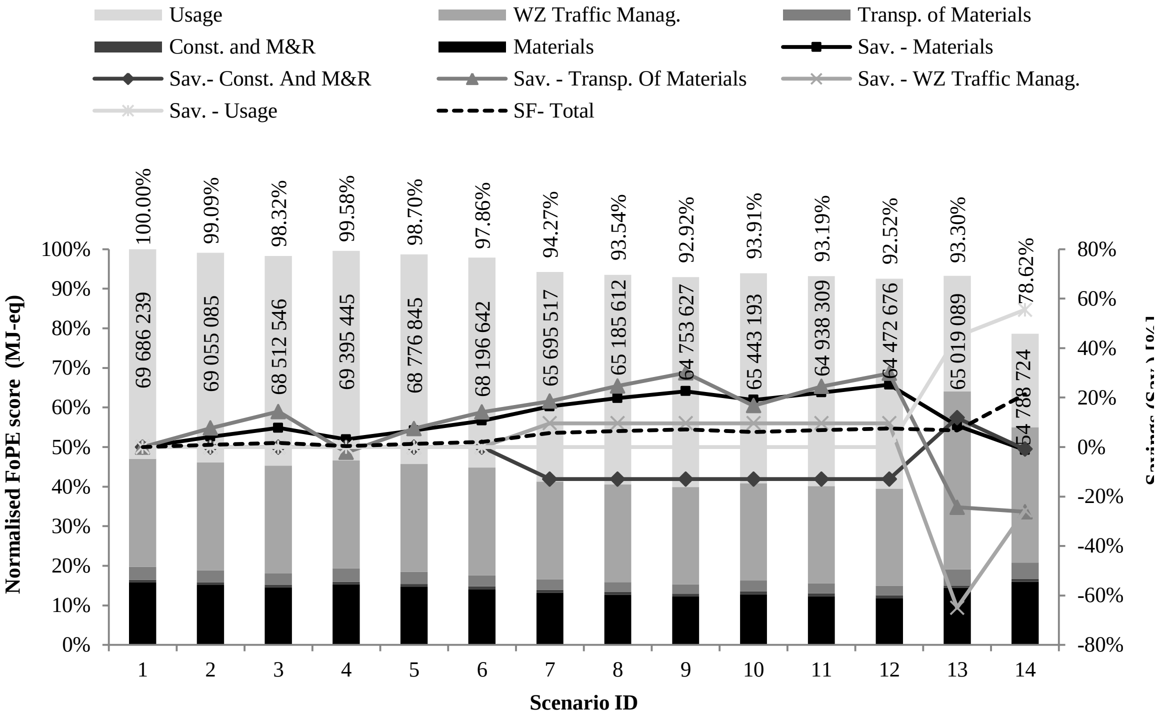
(e)


Usage
WZ Traffic Manag.
Transp. of Materials
Const. and M&R
Materials
Sav. - Materials
Sav.- Const. And M&R
Sav. - Transp. Of Materials
Sav. - WZ Traffic Manag.
Sav. - Usage
SF- Total
Normalised FoPE score (MJ-eq)
Scenario ID
100.00%
99.09%
98.32%
99.58%
98.70%
97.86%
94.27%
93.54%
92.92%
93.91%
93.19%
92.52%
93.30%
78.62%
69 686 239
69 055 085
68 512 546
69 395 445
68 776 845
68 196 642
65 695 517
65 185 612
64 753 627
65 443 193
64 938 309
64 472 676
65 019 089
54 788 724
0%
10%
20%
30%
40%
50%
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(f)

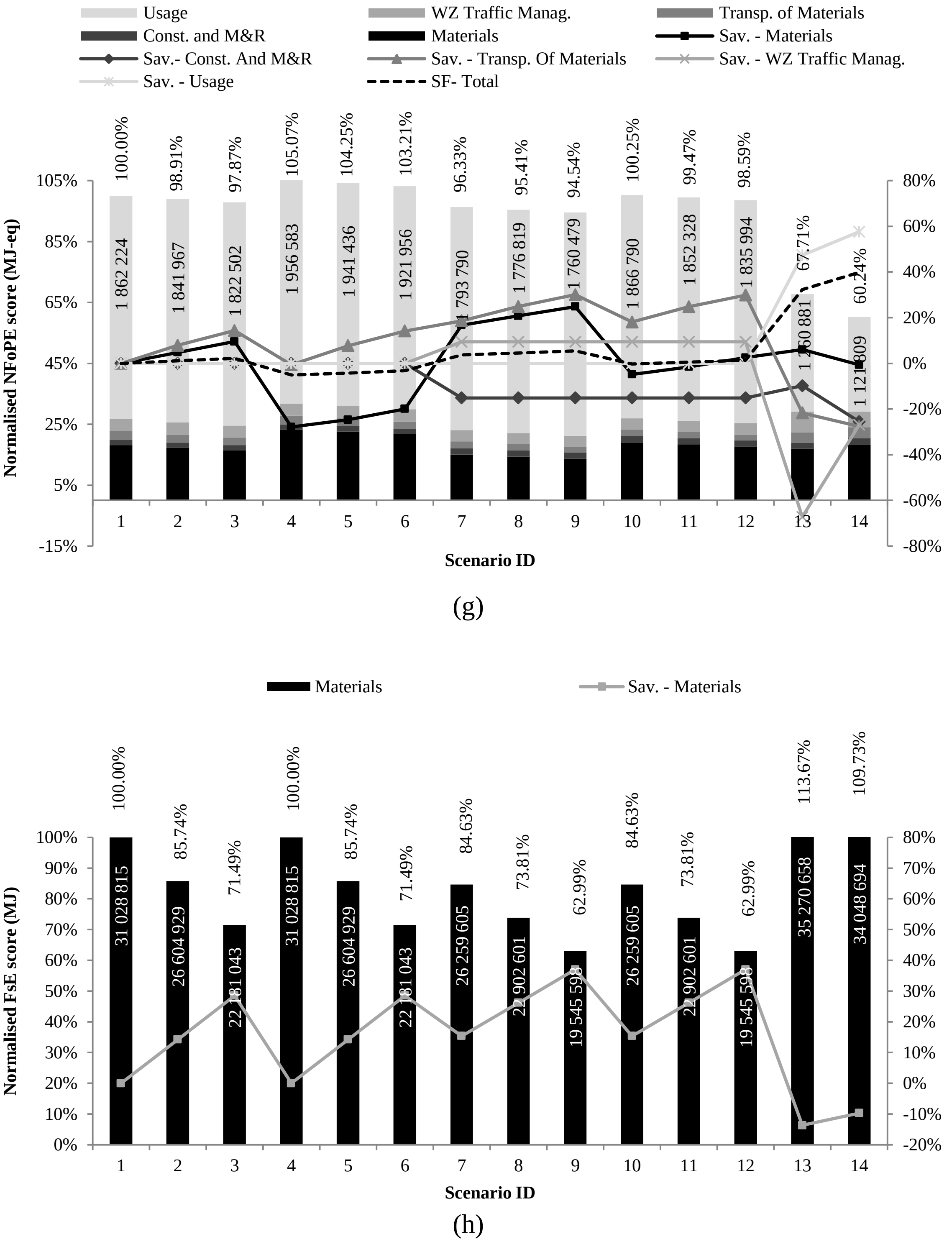


Figure 6.2- Life cycle impact assessment results: (a) CC, (b) Ac, (c) EU, (d) HH, (e) PSF, (f) FoPE, (g) NFoPE and (h) FsE.

These results clearly indicate that scenario 14 (PrM: THMACO) is the least harmful to the environment, as it was found to cause the lowest impact in seven out of eight impact and energy demand categories. Compared to scenario 1, a reduction in all impacts ranging from 20% (CC) to 40% (NFoPE), can be achieved as a result of implementing the THMACO-based preventive M&R strategy. The second best environmental performance is denoted by the microsurfacing-based preventive M&R scenario. Although this PrM scenario presents the poorest performances in three out of five pavement life cycle phases, the fact that the implementation of preventive M&R strategies results in a better pavement condition throughout the PAP along with the key role played by the usage phase in driving the environmental performance of a pavement system, explains the greater reduction in the environmental impact associated with the implementation of scenarios 13 and 14.

Contrary to the merits exhibited by the PrM scenarios, the scenarios consisting of implementing the VDOT M&R strategy present the highest environmental impact. In particular, scenario 1 (VDOT M&R strategy: HMA - 0% RAP) entails the highest environmental impact for five 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 disadvantages of conventional mixtures over WMA, since the environmental burdens that scenario1 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 6.2(a), which display the savings of emissions of CO_2-eq incurred during the materials phases, one can see that the difference between the aforementioned scenarios is just 0.69%. Residual savings are also observed in the remaining impact and energy demand categories. The exception is the NFoPE energy demand, where a decay of the environmental performance was observed, which can be as high as 27.86%. Such residual and contradictory values mean that for the conditions considered in this case study, the overall impacts of WMA are not substantially different from 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 into 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% (EU and PSF due to transportation of 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, Figure 6.2(a)-6.2(h) show considerable environmental impact reductions across all categories. The maximum reduction in environmental burden can be as high as 19% and was observed in the EU, PSF and NFoPE energy demand and impact categories of the materials phase and in the FoPE and NFoPE energy demand categories of the transportation of materials phase. In absolute terms, the majority of the environmental benefits spring from materials and WZ traffic management phases, depending on the impact category being considered. Despite the overall benefits associated with the implementation of the recycling-based VDOT M&R 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.

6.5.2 Life cycle costs analysis

Figures 3(a) shows the normalized LCHAC corresponding to the alternative scenarios. Each scenario is normalized by the net life cycle highway agency 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 LCHAC are illustrated with 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 M&R 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 28% of the net LCHAC can be achieved if this scenario is implemented instead of the first one. The contributions to the reduction of the net LCHAC for the scenario 9 come from the materials (32%) and transportation of materials (26%) phases. Despite the overall benefits resulting from implementing recycling-based VDOT scenarios, their construction and M&R phases exhibit worse economic performances than the non-recycling-based counterparts. 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, the PrM scenarios are the least beneficial for the highway agency's interests, as they imply an increase in the life cycle costs of about 9 and 7% in relation to scenario 1. These outcomes are explained by the greater number of interventions that are required to be implemented in order to comply with the M&R triggering policy.

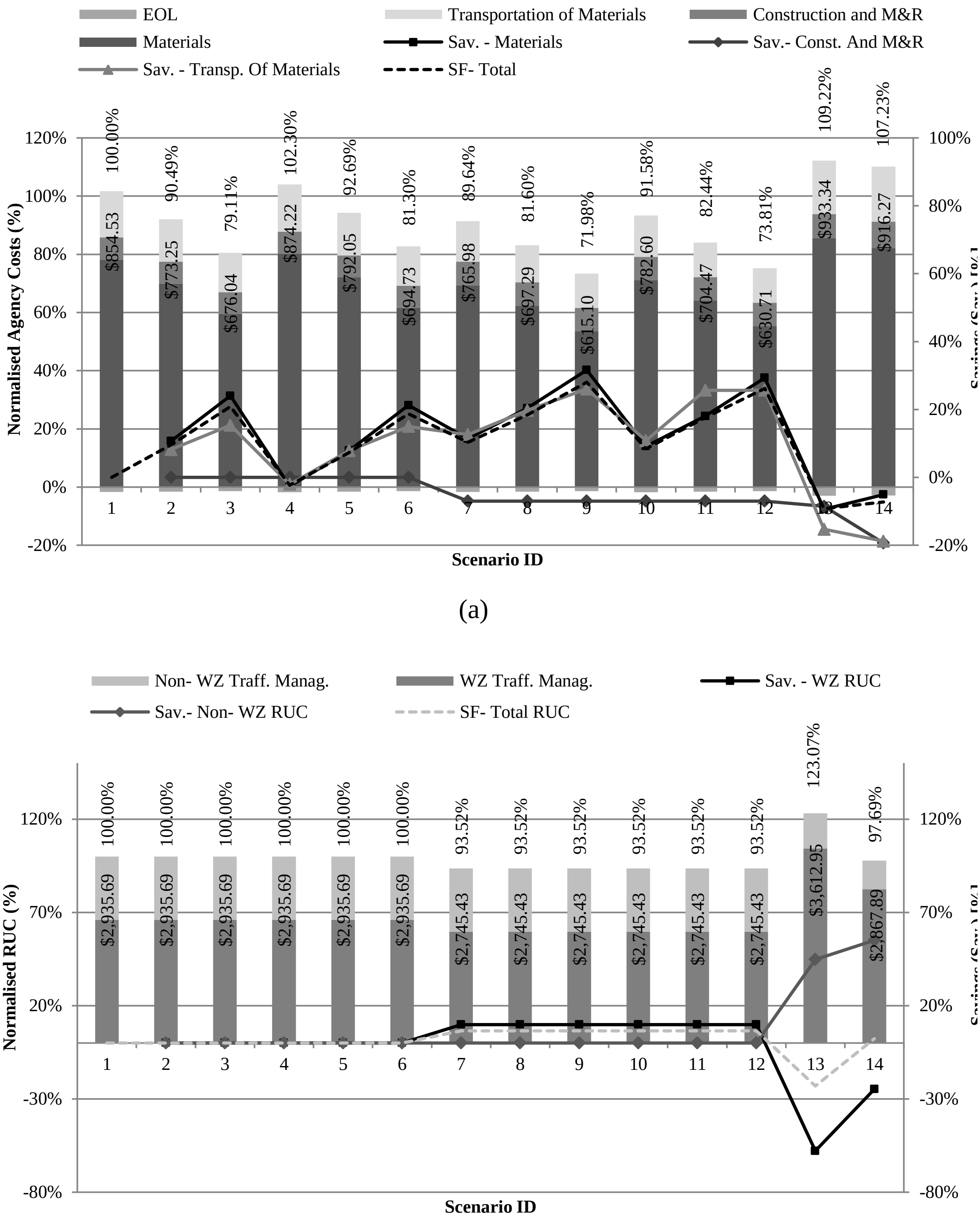


Figure 6.3- Life cycle costing results: (a) highway agency costs (HAC) and (b) road user costs (RUC).

Another outcome worth highlighting in Figure 6.3(a) concerns the third poorest performance, among all the competing alternatives, as seen in scenario 4 (VDOT M&R strategy: Sasobit$^{®}$ WMA - 0% RAP), as it implies a slight increase in the HAC of about 2.3% 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$^{®}$.

As for the costs incurred by road users, Figure 6.3(b) shows the normalized life cycle RUC. Analogously to Figure 6.3(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 life cycle RUC, expressed in thousands of US dollars, are also presented in the same figure. Scenarios 7 to 12 (recycling-based VDOT M&R scenarios), exhibit the lowest life cycle RUC among alternatives, with a value of approximately $2,745,434. These scenarios are followed by the THMACO-based scenario, which imposes on road users a life cycle cost of about $2,867,890. On the other hand, the microsurfacing-based scenario implies the highest costs for road users, with a life cycle value of approximately $3,612,945. 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 15 to 33%, with an average value of 32%.

6.5.3 Overall performance

In order to determine the preference order of alternative scenarios, a MCDM 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 DMs with different agendas and biases towards their interests. To elucidate DMs 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 by 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 MCDM, 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 6.4 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 two dominance areas separated by a straight equilibrium line. This line comprises a set of points in the triangle where the scenarios being compared have the same ranking position. From the analysis of Figure 6.4 one can conclude that of the competing scenarios, only two (scenarios 9 and 14) have the potential to rank best. Of those, scenario 9 is clearly the one that presents the largest area of superiority. If the decision is exclusively based on either HAC or RUC, scenario

9 ranks best. In turn, if the environmental performance is the only criterion taken into account, then scenario 14 outperforms the remaining ones.

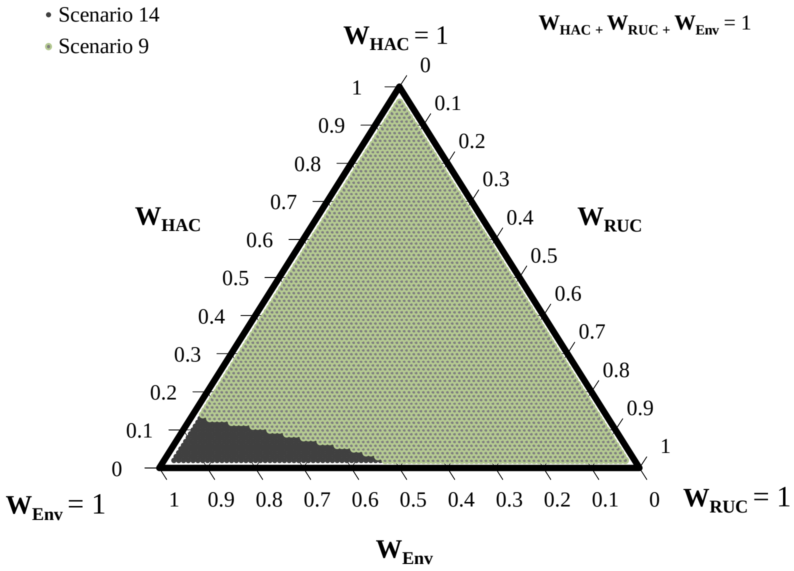


Figure 6.4- Best scenarios for all possible weighting combinations of the main criteria. Legend: W_{HAC}- weight assigned to highway agency costs; W_{RUC}- weight assigned to road user costs; W_{Env}- weight assigned to environmental impacts.

6.5.4 Key findings

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

- THMACO-based PrM 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 20% (CC) to 40% (NFoPE) can be achieved as a result of implementing the THMACO-based preventive M&R strategy;
- The LCEI 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 29% (FsE impact category). 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 impacts;
- Applying a recycling-based VDOT M&R strategy where the structural treatments is carried out through a CCPR technique leads to reduction in the environmental burdens of some pavement life cycle phases that can be as high as 19% in relation to those generated by an equivalent and conventional M&R strategy;
- Applying the microsurfacing-based preventive M&R strategy is the most costly strategy for both highway agency and road users. On the other hand, implementing a recycling-based VDOT M&R scenarios where the asphalt mixtures are of type HMA containing 30% of RAP (scenario 9), yields the greatest life cycle highway agency and RUC savings;
- The recycling-based VDOT M&R strategy: HMA - 30 % RAP is prominently the scenario that best suits the majority of the interests of the stakeholders as a whole.

6.6 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 wide-scoped 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, CIR and preventive treatments throughout the life cycle of a pavement structure. For the conditions considered in this case study, the recycling-based VDOT M&R strategy, where the asphalt mixtures are of type HMA containing 30% of RAP has been shown to be more compliant with the highway agency and road users' demands for affordable road maintenance and 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 MCDM. On the other hand, from the exclusive environmental performance's point of view, implementing a THMACO-based PrM strategy has proven to be the most environmentally-friendly solution.

Providing life cycle perspectives of the environmental and economic implications of implementing new pavement engineering solutions and management practices is without doubt 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 (MOO) framework.

6.7 References

American Association of State Highway and Transportation Officials (AASTO), 1993. Guide for design of pavement structures. 4th ed. Washington, DC: American Association of State Highway and Transportation Officials.

Anupam, K., Lal, P., Bist, V., Sharma, A. and Swaroop, V., 2014. Raw material selection for pulping and papermaking using TOPSIS multiple criteria decision making design. *Environmental Progress & Sustainable Energy*, 33(3), 1034-1041.

Argonne National Laboratory, 2013. *GREET life-cycle model. user guide*. Center for Transportation Research, Energy Systems Division, Argonne National Laboratory. Available at: http://greet.es.anl.gov/

Asphalt Pavement Environmental Council, 2000. *Best management practices to minimize emissions during HMA construction.* EC 101, National Asphalt Pavement Association, the Asphalt Institute, and the State Asphalt Pavement Associations.

Aurangzeb, Q., Al-Qadi, I., Ozer, H. and Yang, R., 2014. Hybrid life cycle assessment for asphalt mixtures with high RAP content. *Resources, Conservation and Recycling*, 83, 77-86.

Bare, J., 2011. TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technologies and Environmental Policy*, 13(5), 687-696.

Barnes, G. and Langworthy, P., 2003. *The per-mile costs of operating automobiles and trucks* (Report No. MN/RC 2003-19). Available at: www.lrrb.org/pdf/200319.pdf

Bennett, C., and Greenwood, I., 2003. *Modeling road user and environmental effects in HDM-4*, version 3.0, International Study of Highway Development and Management Tools (ISOHDM) (Vol. 7). Paris: World Road Association (PIARC). ISBN 2-84060-103-6.

Bilec, M., Ries, R., and Matthews, S., 2010. Life-cycle assessment modeling of construction processes for buildings. *ASCE-Journal of Infrastructure Systems*, 16(3), 199-205.

Bilec, M., Ries, R., Mattews, S. and Sharrard, A., 2006. Examples of a hybrid life-cycle assessment of construction processes. *ASCE-Journal of Infrastructure Systems*, 12(4), 207-215.

Birgisdóttir, H., Pihl, K., Bhander, G., Hauschild, M. and Christensen, T., 2006. Environmental assessment of roads constructed with and without bottom ash from municipal solid waste incineration. *Transportation Research Part D: Transport and Environment*, 11 (5), 358-368.

British Columbia Road Builders and Heavy Construction Association (BCRB and HCA), 2011. *Reducing greenhouse gas emissions in the B.C. road building and maintenance industry*, Road building and highway maintenance best practice guidelines, British Columbia Ministry of Transportation and Infrastructure. Available at: http://www.th.gov.bc.ca/publications/eng_publications/geotech/3348_Roadbuilding_BP-V13-232ppi.pdf

Bryce, J., Flintsch, G. and Hall, R., 2014. A multi criteria decision analysis technique for including environmental impacts in sustainable infrastructure management business practices. *Transportation Research Part D: Transport and Environment*, 32, 435-445.

Carnegie Mellon University Green Design Institute CMUGDI, 2010. *Economic input-output life cycle assessment (EIO-LCA)*, U.S. 2002 Industry Benchmark model. Available at: http://www.eiolca.net

Carpenter, A. and Gardner, K., 2009. Use of industrial by-products in urban roadway infrastructure. Argument for increased industrial ecology. *Journal of Industrial Ecology,* 13(6), 965-977.

Carpenter, A., Gardner, K., Fopiano, J., Benson, C. and Edil, T., 2007. Life cycle based risk assessment of recycled materials in roadway construction. *Waste Management*, 27(10), 1458-1464.

Caterpillar, Inc.,2012. *Caterpillar performance handbook*, 42nd Ed., Caterpillar, Peoria, IL.

Chatti, K., and Zaabar, I., 2012. *Estimating the effects of pavement condition on vehicle operating costs* (National Cooperative Highway Research Program Report No. 720). Available at: http://www.trb.org/Main/Blurbs/166904.aspx

Chowdhury, T., 2011. *Supporting document for the development and enhancement of the pavement maintenance decision matrices used in the needs-based analysis*. Virginia Department of Transportation, Maintenance Division, Richmond, VA.

D'Angelo, J., Harm, E., Bartoszek, J., Baumgardner, G., Corrigan, M., Cowsert, J., et al., 2008. *Warm-mix asphalt: European practice* (Report No. FHWA-PL-08-007). Available at: http://international.fhwa.dot.gov/pubs/pl08007/pl08007.pdf.

Diefenderfer, B. and Apeagyei, A., 2014. *I-81 In-place pavement recycling project* (Report No. FHWA/VCTIR 15-R1). Virginia Center for Transportation Innovation and Research. Available at: http://www.virginiadot.org/vtrc/main/online_reports/pdf/15-r1.pdf

Ducasse, K., Distin, T. and Osborne, L., 2004. *The use of microsurfacing as a cost effective remedial action for surface rutting*. In: Proceedings of the 8th Conference on Asphalt Pavements for Southern Africa, Sun City, South Africa.

Eurobitume, 2011. *Life cycle inventory: Bitumen*. Available at: http://www.eurobitume.eu/hse/sustainability

European Asphalt Pavement Association and National Asphalt Pavement Association (EAPA and NAPA), 2011. *The asphalt paving industry: a global perspective (2nd edition).* Available at: http://www.eapa.org/userfiles/2/Publications/GL101-2nd-Edition.pdf

Ferrão, P. and Nhambiu, J., 2009. A comparison between conventional LCA and hybrid EIO-LCA: analyzing crystal giftware contribution to global warming potential. *In*: Suh, S., editor. *Handbook of input–output economics in industrial ecology*. The Netherlands: Springer, 219-30.

Finnveden, G., Hauschild, M., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. and Suh, S., 2009. Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, 91(1), 1-21.

Gambill, W., 1957. You can predict heat capacities. *Chemical Engineering*, 64, 243-248.

Giustozzi, F., Crispino, M. and Flintsch, G., 2012. Multi-attribute life cycle assessment of preventive maintenance treatments on road pavements for achieving environmental sustainability. *International Journal of Life Assessment*, 17(4), 409-419.

Gluch, P. and Baumann, H., 2004. The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. *Building and Environment,* 39(5), 571-580.

Graham, D. and Midgley, N., 2000. Graphical representation of particle shape using triangular diagrams: an Excel spreadsheet method. *Earth Surface Processes and Landforms*, 25(13), 1473-1477.

Hamzah, M., Jamshidi, A. and Shahada, Z., 2010. Evaluation of the potential of Sasobit® to reduce required heat energy and CO_2 emission in the asphalt industry. *Journal of Cleaner Production*, 18(18), 1859-1865.

Hansen, K. and Copeland, A., 2014. *Annual asphalt pavement industry survey on recycled materials and warm-mix asphalt usage: 2009-2013*. 4th Annual Asphalt Pavement Industry Survey, Information series 138, National Asphalt Pavement Association. Available at: http://www.asphaltpavement.org/PDFs/IS138/IS138-2013_RAP-RAS-WMA_Survey_Final.pdf.

Harder, G., Le Goff, Y., Loustau, A., Martineau, Y., Heritier, B. and Romier, A., 2008. Energy and environmental gains of warm and half- warm asphalt mix: quantitative approach. Paper #08-2456. Presented at 87th Annual Meeting of the Transportation Research Board, Washington, D.C.

Harvey, J., Kendall, A., Lee, I.-S., Santero, N., Van Dam, T. and Wang, T., 2010. *Pavement life cycle assessment workshop: discussion summary and guidelines* (Technical Memorandum: UCPRC-TM-2010-03). Available at: http://www.ucprc.ucdavis.edu/PublicationsPage.aspx

Hofstetter, P., Braunschweig, A., Mettier, T., Müller-Wenk, R. and Tietje, O., 1999. The mixing triangle: correlation and graphical decision support for LCA-based comparisons. *Journal of Industrial Ecology,* 3(4), 97-115.

Huang, Y., Bird, R. and Heidrich, O., 2009. Development of life cycle assessment tool for construction and maintenance of asphalt pavements. *Journal of Cleaner Production,* 17(2), 283-296.

Hunkeler, D., Lichtenvort, K. and Rebitzer, G., 2008. *Environmental life cycle costing*. Pensacola (FL): SETAC Pr in collaboration with CRC Pr, Boca Raton (FL).

Hwang, C. and Yoon, K., 1981. *Multiple attribute decision making-methods and application: a state-of-the-art survey*. New York, USA: Springer-Verlag.

Illinois Interchange, 2012. *Recycling/reclaiming a savings spree.* Illinois Technology Transfer Center, Illinois Department of Transportation, Vol. 2012-02. Available at: http://idot.illinois.gov/Assets/uploads/files/Transportation-System/Newsletters/T2/Vol2012-02.pdf.

International Organization for Standardization (ISO), 2006a. *ISO 14040:2006. International Standard ISO 14040: environmental management - life cycle assessment: principles and framework, October*. Geneva (Switzerland): International Organization for Standardization.

International Organization for Standardization (ISO), 2006b. *ISO 14044:2006. International Standard ISO 14044: environmental management - life cycle assessment: requirements and guidelines, October*. Geneva (Switzerland): International Organization for Standardization.

International Organization for Standardization (ISO), 2008. *ISO 15686-5: 2008. Buildings and constructed assets - Service-life planning - Part 5: Life-cycle costing.* Geneva (Switzerland): International Organization for Standardization.

Jato-Espino, D., Castillo-Lopez, E., Rodriguez-Hernandez,J. and Canteras-Jordana, J., 2014. A review of application of multi-criteria decision making methods in construction. *Automation in Construction*, 45, 151-162.

Junnila, S., 2006. Empirical comparison of process and economic input–output life cycle assessment in service industries. *Environmental Science & Technology*, 40(22), 7070-7076.

Kendall, A., 2012. Time-adjusted global warming potentials for LCA and carbon footprints. *The International Journal of Life Cycle Assessment*, 17(8), 1042-1049.

Kristjánsdóttir, Ó., Muench, S., Michael, L. and Burke, G., 2007. Assessing potential for warm-mix asphalt technology adoption. *Transportation Research Record: Journal of the Transportation Research Board,* 2040, 91-99.

Lee, J., Edil, T., Tinjum, J. and Benson, C., 2010. Quantitative assessment of environmental and economic benefits of recycled materials in highway construction. *Transportation Research Record: Journal of the Transportation Research Board,* 2158, 138-142.

Lee, E.-B., Kim, C. and Harvey, J., 2011. Selection of pavement for highway rehabilitation based on life.cycle cost analysis. Validation of California interstate 710 project, phase 1. *Transportation Research Record: Journal of the Transportation Research Board*, 2227, 23-32.

Leontief, W., 1970. Environmental repercussions and the economic structure: an input–output approach. *Review of Economics and Statistics*, 52, 262-271.

Lippiat, B., 2007. *BEESRG 4.0: building for environmental and economic sustainability technical manual and user guide* (The National Institute of Standards and Technology Report No. 7423). Available at: http://fire.nist.gov/bfrlpubs/build07/art018.html

Majeau-Bettez, G., Strømman, A. and Hertwich, E., 2011. Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues. *Environmental Science & Technology,* 45(23), 10170-10177.

Mattila, T., Pakarinen, S. and Sokka, L., 2010. Quantifying the total environmental impacts of anindustrial symbiosis - a comparison of process-, hybrid and input-output lifecycle assessment. *Environmental Science & Technology,* 44(11), 4309-4314.

Mladenovič, A., Turk, J., Kovač, J., Mauko, A. and Cotič, Z., 2015. Environmental evaluation of two scenarios for the selection of materials for asphalt wearing courses. *Journal of Cleaner Production,* 87, 683-691.

Mohammad, L., Hassan, M., Vallabhu, B., and Kabir, M., 2015. Louisiana's experience with WMA technologies: mechanistic, environmental, and economic analysis. *ASCE-Journal of Materials in Civil Engineering*, 27(6), 04014185.

Nicholson, A., Olivetti, E., Gregory, J. and Field, F., Kirchain, R., 2009. End-of-life LCA allocation methods: open loop recycling impacts on robustness of material selection decisions. In: *Sustainable systems and technology*, ISSST'09, IEEE international symposium, 1-6.

Office of Management and Budget, 2013. *Discount rates for cost-effectiveness, lease purchase, and related analyses*. Table of past years discount rates from Appendix C of OMB Circular No. A-94. Available at: http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c

Robinette, C. and Epps, J., 2010. Energy, emissions, material conservation, and prices associated with construction, rehabilitation, and material alternatives for flexible pavement. *Transportation Research Record: Journal of the Transportation Research Board,* 2179, 10-22.

Rodríguez-Alloza, A., Malik, A., Lenzen, M. and Gallego, J., 2015. Hybrid input-output life cycle assessment of warm mix asphalt mixtures. *Journal of Cleaner Production,* 90, 171-182.

Rubio, M., Martínez, G., Baena, L. and Moreno, F., 2012. Warm mix asphalt: an overview. *Journal of Cleaner Production,* 24, 76-84.

Rubio, M., Moreno, F., Martínez-Echevarría, M., Martínez, G. and Vázquez, J., 2013. Comparative analysis of emissions from the manufacture and use of hot and half-warm mix asphalt. *Journal of Cleaner Production,* 41, 1-6.

Sakhaeifar, M., Brown, E., Tran, N. and Dean, J., 2013. Evaluation of long-lasting perpetual asphalt pavement with life-cycle cost analysis. *Transportation Research Record: Journal of the Transportation Research Board,* 2368, 3-11.

Santos, J., Ferreira, A. and Flintsch, G., 2015a. A life cycle assessment model for pavement management: methodology and computational framework. *International Journal of Pavement Engineering*, 16(3), 268-286.

Santos, J., Bryce, J., Flintsch, G., Ferreira, A. and Diefenderfer, B., 2015b. A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, 11(9), 119-1217.

Santos, J., Bryce, J., Flintsch, G. and Ferreira, A., 2015c. A comprehensive life cycle costs analysis of in-place recycling and conventional pavement construction and maintenance practices. *International Journal of Pavement Engineering* (in press). http://dx.doi.org/10.1080/10298436.2015.1122190

Sayagh, S., Ventura, A., Hoang, T., Francois, D. and Jullien, A., 2010. Sensitivity of the LCA allocation procedure for BFS recycled into pavement structures. *Resources, Conservation and Recycling,* 54(6), 348-358.

Sheriff, Y. and Kolarik, W., 1981. Life cycle costing: concept and practice. *Omega- The International Journal of Management Science*, 9(3), 287-296.

Somerton, W., 1992. *Thermal properties and temperature-related behavior of rock/fluid systems*. Developments in Petroleum Science, 37, Amsterdam: Elsevier.

Stantec Consulting Services and Lochner, H., 2007. *Development of performance prediction models for Virginia department of transportation pavement management system*. Virginia Department of Transportation, Richmond, VA.

Stripple, H., 2001. *Life cycle assessment of road: A pilot study for inventory analysis* (2nd rev. ed., Swedish Environmental Research Institute (IVL) Report B 1210 E). Available at: http://www.ivl.se/publikationer/importeradebrapporterrorej/lifecycleassessmentofroadapilotstudyforinventoryanalysissecondrevisededition.5.7df4c4e812d2da6a416800040296.html

Suh, S. and Huppes, G., 2005. Methods for life cycle inventory of a product. *Journal of Cleaner Production*, 13(7), 687-697.

Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J. and Norris, G., 2004. System boundary selection in life-cycle inventories using hybrid approaches. *Environmental Science & Technology*, 38(3), 657-664.

Swarr, T., Hunkeler, D., Klöpffer, W., Pesonen, H.-L., Ciroth, A., Brent, A. and Pagan, R., 2011. *Environmental life cycle costing: a code of practice*. Pensacola (FL): Society of Environmental Chemistry and Toxicology (SETAC).

Tatari, O., Nazzal, M. and Kucukvar, M., 2012. Comparative sustainability assessment of warm-mix asphalts: a thermodynamic based hybrid life cycle analysis. *Resources, Conservation and Recycling,* 58, 18-24.

The White House, 2014. *FACT SHEET: Building a 21st century infrastructure: increasing public and private collaboration with the Build America investment initiative*, Office of the Press Secretary. Available at: http://www.whitehouse.gov/the-press-office/2014/07/17/fact-sheet-building-21st-century-infrastructure-increasing-public-and-pr

Thenoux, G., González, A. and Dowling, R., 2007. Energy consumption comparison for different asphalt pavements rehabilitation techniques used in Chile. *Resources, Conservation and Recycling,* 49(4), 325-339.

Transportation Research Board TRB, 2000. *Highway capacity manual 2000*. Washington, DC: Transportation Research Board.

United States Army Corps of Engineers (US ACE), 2011. *Construction equipment ownership and operating expense schedule, Region II*. Document EP 1110-1-8, Vol. 2. Washington D.C.: US Army Corps of Engineers. Available at:

http://www.publications.usace.army.mil/USACEPublications/EngineerPamphlets.aspx?udt_43545_param_page=12

United States Energy Information Administration (US EIA), 2012. *State electricity profiles 2010* (Report DOE/EIA-0348(01)/2). Available at: http://www.eia.gov/electricity/state/

United Sates Energy Information Administration (US EIA), 2013. *Carbon dioxide emissions coefficients.* Available at:

http://www.eia.gov/environment/emissions/co2_vol_mass.cfm

United States Environmental Protection Agency (US EPA), 2004. *AP-42: Compilation of air pollutant emission factors* (Vol. 1: Stationary point and area sources, Chap. 11: Mineral products industry 11.1). Available at: http://www.epa.gov/ttn/chief/ap42/ch11/index.html

United States Environmental Protection Agency (US EPA), 2010a. *Exhaust and crankcase emission factors for nonroad engine modelling - compression-ignition* (Report No. NR-009d). Available at: http://www.epa.gov/otaq/nonrdmdl.htm#model

United States Environmental Protection Agency (US EPA), 2010b. *Motor Vehicle Emission Simulator (MOVES). user guide for MOVES2010b* (Report EPA-420-B-12-001b). Available at: http://www.epa.gov/otaq/models/moves/index.htm#user.

Vidal, R., Moliner, E., Martínez, G. and Rubio, M., 2013. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. *Resources, Conservation and Recycling,* 74, 101-114.

Virginia Department of Transportation (VDOT), 2011. *State of the pavement - 2011*. Virginia Department of Transportation Maintenance Division. Available at: http://www.virginiadot.org/info/resources/State_of_the_Pavement_2011.pdf.

Virginia Department of Transportation (VDOT), 2012a. *2012 Construction resources guidebook, Division II- Materials, Special provision copied notes (SPCNs), special provision (SPs) and Supplemental specifications (ss), updated July 8, 2014,* Virginia Department of Transportation Construction Division, Central Office, Richmond. Available at: http://www.virginiadot.org/business/resources/const/07ImpRev.zip

Virginia Department of Transportation (VDOT), 2012b. *Business rules and user's information, dashboard 3.0*. Available at: http://dashboard.virginiadot.org/Help/DB%20User%20Guide.PDF.

Virginia Department of Transportation (VDOT), 2013. *Project selection guidelines for cold pavement recycling*. Virginia Department of Transportation Materials Division. Available at: http://www.virginiadot.org/VDOT/Business/asset_upload_file526_3638.docx

Virginia Department of Transportation (VDOT), 2014. *Manual of instructions for the materials division*. Virginia Department of Transportation Materials Division. Available at: http://www.virginiadot.org/business/materials-download-docs.asp

Walls, J. and Smith, M., 1998. *Life-cycle cost analysis in pavement design - in search of better investment decisions* (Report No. FHWA-SA-98-079). Available at: http://isddc.dot.gov/OLPFiles/FHWA/013017.pdf

Waples, D. and Waples, J., 2004a. A review and evaluation of specific heat capacities of rocks, minerals, and surface fluids, part 1: mineral and non porous rocks. *Natural Resources Researches*, 13(2), 97-122.

Waples, D. and Waples, J., 2004b. A review and evaluation of specific heat capacities of rocks, minerals, and surface fluids, part 2: fluids and porous rocks. *Natural Resources Researches*, 13(2), 123-130.

Weidema, B., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. and Wernet, G., 2013. The ecoinvent database: overview and methodology, Data quality guideline for the ecoinvent database version 3, www.ecoinvent.org.

West, R., Rodezno, C., Julian, G., Prowell, B., Frank, B., Osborn, L. and Kriech, T., 2014. *Field performance of warm mix asphalt technologies* (National Cooperative Highway Research Program Report No. 779). Available at: http://www.trb.org/Main/Blurbs/171480.aspx

Zaumanis, M., 2014. *Warm mix asphalt*, K. Gopalakrishnan et al. (eds.), Climate Change, Energy, Sustainability and Pavements, Green Energy and Technology, Springer-Verlag.

Zhao, G.-J. and Guo, P., 2012. Workability of Sasobit warm mixture asphalt. *Energy Procedia*, 16, 1230-1236.

Chapter 7

An Adaptive Hybrid Genetic Algorithm for Pavement Management

7.1 Introduction

In the current economic paradigm, the need to maintain and preserve existing highway infrastructure assets has been at the forefront of the transportation infrastructure decision-makers' concerns. This is reflected by highway agency budgets shifting funding from new construction and/or reconstruction to maintenance. For instance, in the US the FHWA reported that throughout the 10-year period from 2000 to 2010, highway and bridge systems rehabilitation expenditures grew at an average annual rate of 6.4 percent. In turn, systems expansion expenditures have increased at a slower average annual rate of 1.8 percent, resulting in a decline in share of total capital outlays from 37.4 percent in 2000 to 27.4 percent in 2010 (FHWA, 2014). This shift in priorities is not likely to change over the coming decades, underlining the importance of establishing consistent procedures and developing innovative and optimization-based engineering management systems to achieve effectiveness in: (1) managing huge investments in M&R of pavement systems; (2) identifying and implementing proven maintenance, rehabilitation and preservation practices and techniques; and (3) ensuring proper timing and intensity of application of those treatments.

Optimization is a broad concept that can be applied at different levels of evaluation and for different categories of infrastructure assets. Pavement M&R is one of the most critical and costly forms of infrastructure asset management that has benefited from the potentialities of the optimization techniques. The first widely recognized PMS that took advantage of the mathematical optimization dates back to 1982, when the state of Arizona developed and implemented a PMS to optimize maintenance policies for its highway network (Golabi et al., 1982). Savings of $14 million were reported in the first year of implementation, and $101 million was predicted for the following 4 years. Since then, due to computational capabilities enhancements, many systems have been developed, using integrated techniques of performance prediction and optimization methods, such as linear programming, non-linear programming, integer programming, dynamic programming, etc. (Zimmerman, 1995), with the intention of helping the highway agencies to design optimal pavement structures and to plan optimal M&R activities that should be implemented in new pavement segments or in existing pavement segments.

The growing complexity of large-scale problems required to be solved optimally, such as those that the PMS have to deal with, has imposed great obstacles to the efficiency and effectiveness of the traditional optimization techniques. For instance, the problem of identifying adequate M&R activities for individual pavement segments is usually formulated using integer variables to represent M&R activities selected for individual pavement segments. This problem is a combinatorial one which, due to a huge solution space, is very difficult to solve optimally using the traditional optimization techniques.

Evolutionary algorithms (EA), which is a subfield of artificial intelligence, have demonstrated their effectiveness over the last few decades as powerful optimizers for difficult, nonlinear, multimodal optimization problems (Eiben and Smith, 2010). EA are generally, but not always, based on some natural process. Some popular EA include particle swarm optimization (PSO) (Kennedy and Eberhart, 1995), differential evolution

(DE) (Storn and Price, 1995), ant colony optimization (ACO) (Dorigo et al., 1999), genetic programming (GP) (Banzhaf et al., 2000), evolutionary programming (EP) (Fogel, 1999) and GA (Mitchell, 1996; Goldberg, 1989). From the above mentioned EA, GA have had one of the most successful applications on occasions in which there is a need to deal with complex engineering optimization problems. Like any other heuristic method, GA do not guarantee global optimum solutions. However, if properly designed, they will often provide either optimum or near-optimum solutions to the optimization problems.

In the field of infrastructure management, the GA has been object of considerable attention. For instance, Fwa et al. (1996) applied GA to develop a road maintenance strategy based on different agency costs. Ferreira et al. (2002a) and Ferreira et al. (2002b) formulated a mixed integer optimization model for network level PMS. They used GA heuristics to solve the optimization problem that aimed to minimize the expected total discounted costs of pavement M&R actions over a planning period. Jawad and Ozbay (2006) paired GA as a search toll with Monte Carlo simulations as a risk analysis technique in a lifecycle cost optimization model for pavement management at project-level. Santos and Ferreira (2012) presented a GA-based road pavement design optimization model, called OPTIPAV, which considers pavement performance, construction costs, M&R costs, user costs, the residual value of the pavement at the end of the PAP, and preventive M&R interventions. The model was developed and programmed to help pavement designers to choose the best pavement structure for a road or highway. Mathew and Isaac (2014) developed a deterministic optimization model with the objectives of maximizing the performance of the road network and minimizing the maintenance cost using GA as the optimization tool. The applicability of the model was illustrated using a case study for the rural road network of Kerala state in India.

The examples of applications of GA in the pavement management sector presented below are merely illustrative, since many others could have been given. The same is also true with respect to the particular allusion to PMS, since its versatility has been proven through its application to other infrastructure management systems, such as bridges (Frangopol and Liu, 2007; Almeida et al., 2015), water pipes (Maier et al., 2014; Bi et al., 2015; Stokes et al., 2015), and railways (Jha et al., 2007; Caetano and Teixeira, 2013).

In view of such an extensive usage for solving a wide variety of combinatorial optimization problems, in which traditional approaches may not work adequately, it is worth looking at the specific attributes of GA that give them an edge over other traditional optimization techniques. These are (TRB, 2007): (1) GA do not require the objective function to be continuous or differentiable; (2) GA have good robustness for many applications; (3) GA have outstanding global search capabilities for convex and non-convex problems; (4) GA have inherent parallel processing capabilities; and (5) GA are relatively easy to implement.

Notwithstanding the advantages recognized above due to the stochastic search mechanisms behind the GA and the remaining bio-inspired and space-based EA, there may also be drawbacks with algorithms as follows: (1) long computing time; (2) premature convergence; and (3) limited capacity to fine-tune solutions. To alleviate, and in some cases overcome integrally many of the shortcomings, several advances have been made in the evolutionary computation field. Abu-Lebdeh et al. (2014) pointed out six courses of action that can make the application of GA more efficient, rapid and productive. They are: (1) selection of appropriate operators and parameter values; (2) appropriate problem-specific representations of candidate solutions; (3) faster or better evaluation of solutions (or individuals); (4) structuring of individuals into subpopulations or various other classes that are treated separately with respect to, e.g., application of various operators; (5) division of workload among multiple loosely-coupled processors (as in a cluster or network, for example); and (6) hybridizing GA with other none evolutionary search methods.

While it is intuitive that the first three areas need to be done right in order to get the most from the GA, and that the fifth action can be done regardless of the structure of GA employed or any of the other actions, the fourth and sixth points represent promising research domains that are still in their early days. In particular, research studies have found that a skilled combination of EA with LS heuristics, named "memetic algorithms" (MA) (Moscato, 1989), can improve the performance of EA in terms of efficiency (i.e., requiring orders of magnitude fewer evaluations to find optimal solutions) and effectiveness (i.e., identifying higher quality solutions), especially when dealing with real-world and large scale problems (Ting and Liao, 2010; Souza et al., 2011; Vidal et al., 2013).

Several GA-based MA have been developed in the past few years in various engineering fields (Espinoza and Minsker, 2006; Singh and Bhukya, 2011; Arivudainambi and Rekha, 2013; Zong and Dhanasekar, 2014). However, to the best of our knowledge no study exists in the literature that has applied this concept to the pavement management sector.

In this chapter, an AHGA combing GA with an LS mechanism is presented for solving the pavement M&R strategy selection problem. The AHGA framework is provided with a pool of LS operators and an Adaptive Local Search Operator Selection (ALSOS) method to decide dynamically and on-the-fly on the relevance of conducting an LS according to a given search strategy. Online learning probabilities are then used to select both the LS operator from the pool and the LS intensity that leads to the best gains of search efficiency and effectiveness.

7.2 Problem statement: the pavement maintenance and rehabilitation strategy selection problem

From the highway agency's standpoint, the pavement M&R strategy selection problem is traditionally formulated as an optimization problem where the objective consists in minimizing the present value (PV) of the total M&R costs over the PAP, while satisfying several technical, quality standards and budgetary requirements. Notwithstanding the particular pavement management policies and practices of each highway agency, the optimization model introduced above can be formulated generically, as follows:

$$\text{Min} \sum_{r=1}^{R} \sum_{s=1}^{S} \sum_{t=1}^{T} \frac{1}{\left(1+d\right)^{t}} \times MC_{rst} \times X_{rst} \tag{7.1}$$

Subject to:

$$Z_{st} = \Phi(Z_{s0}, X_{1s1}, ..., X_{1st}, ..., X_{rs1}, ..., X_{rst}), \qquad r = 1,..., R; s = 1,..., S; t = 1,..., T \tag{7.2}$$

$$Z_{st} \begin{Bmatrix} \leq \\ \geq \end{Bmatrix} \overline{Z}, \qquad s = 1,...,S;\ t = 1,...,T \tag{7.3}$$

$$X_{rst} \in \Omega\left(Z_{st}\right), \qquad r = 1,..., R; \quad s = 1,..., S; \quad t = 1,..., T \tag{7.4}$$

$$\sum_{r=1}^{R} X_{rst} = 1, \qquad s = 1,...,S; t = 1,...,T \tag{7.5}$$

$$MC_{rst} = \Psi a \left(Z_{st}, X_{rst}\right), \quad r = 1,..., R; \quad s = 1,..., S; \quad t = 1,..., T \tag{7.6}$$

$$\sum_{r=1}^{R} \sum_{s=1}^{S} MC_{rst} X_{rst} \leq B_t, \qquad t = 1,..., T \tag{7.7}$$

$$\sum_{r=2}^{R} \sum_{t=1}^{T} X_{rst} \leq N\,max_s, \quad s = 1,...,S \tag{7.8}$$

$$\Delta t_r \leq \Delta t_r^{max}, \qquad r = 1,...,R \tag{7.9}$$

Where *R* is the number of alternative M&R activities; *S* is the number of pavement sections considered for analysis; *T* is the number of years of the PAP; MC_{rst} is the maintenance cost for applying M&R activity *r* to pavement section *s* in year *t*; X_{rst} is equal to one if M&R activity *r* is applied to pavement structure *s* in year *t*, otherwise it is equal to zero; *d* is the discount rate; Z_{st} are the condition variables for pavement section *s* in year *t*; $\overline{Z}$ are the warning levels for the condition variables of pavement structures; B_t is the highway agency budget for pavement maintenance in year *t*; $N\text{max}_s$

is the maximum number of M&R activities that may occur in pavement section *s* over the PAP; Φ are the pavement condition functions; Ψa are the highway agency cost functions; Ω are the feasible operations sets; Δt_r is the time interval between the application of two consecutives M&R activities of type *r*; Δt_r^{max} is the maximum time interval between the application of two consecutives M&R activities of type *r*.

Equation (7.1), the objective function of this quite complex, highly non-linear discrete optimization model, expresses the minimisation of the PV of the total M&R costs over the PAP, while keeping the pavement sections condition above specified quality standards. Constraints (7.2) correspond to the pavement condition functions, expressing pavement condition in each section and year as a set of functions of the initial pavement state and the M&R activities previously applied to the pavement section. These functions can describe the pavement condition with regard to variables such as cracking, rutting, longitudinal roughness, surface disintegration (potholing and ravelling) and overall quality of pavements, etc. Constraints (7.3) are the warning level constraints which define the minimum level (or the maximum, depending on the type of indicator) for the pavement condition variables. Constraints (7.4) represent the feasible operation sets, i.e. the M&R activities that can be applied to maintain or rehabilitate the pavement structure in relation to its condition. Constraints (7.5) indicate that only one M&R activity should be performed per pavement structure in each year. Constraints (7.6) represent the M&R costs, which express the costs for the highway agency involved in the application of a given M&R activity to a pavement section in a given year as a function of the pavement condition in that section and year. Constraints (7.7) are the annual budget constraints. They specify the maximum amount of money to be spent on M&R activities during each year. Constraints (7.8) were included in the model to avoid the frequent execution of M&R activities on the same pavement section. Constraints (7.9) represent technical limitations which may impose limits to the life of a given M&R activity.

7.3 Adaptive Hybrid Genetic Algorithm framework

7.3.1Components of the Adaptive Hybrid Genetic Algorithm

The framework of the proposed AHGA is illustrated in simple terms in Figure 7.1. It features the following main components: (1) the encoding of solutions; (2) the initial population generation; (3) the solutions' fitness evaluation; (4) the parents selection; (5) the reproduction process; (6) the population replacement process; (7) the stagnation prevention methodology; (8) the iterations stopping criteria; and (9) the adaptive LS mechanism.

Below, each of the aforementioned components is thoroughly described.

7.3.1.1 Encoding of solutions

After identifying the parameters that characterize the problem at hand and defining the objective function and constraints (problem formulation), the problem solutions are encoded into genetic representation. The use of an appropriate encoding representation is of great importance for the efficiency of a GA when applied to real-world problems. In the developed AHGA an integer coding is adopted to represent the M&R alternatives. Each individual represents a potential solution (M&R strategy) and consists of a sequence of $S \times T$ genes, where S is the number of pavement sections considered for analysis, T represents the PAP defined by the decision-maker, and the allele values for each of these genes represent a possible M&R activity.

7.3.1.2 Initial population generation

The first step in applying a GA to solve an optimization problem is to generate an initial population. In the proposed AHGA the initial population with size N is randomly generated, and the best $N \times Elite\_rate$ individuals are copied and stored in an archive pool according to a user-defined rate ($Elite\_rate$). This scheme prevents solutions of the highest relative fitness from being excluded from the next generation through the nondeterministic selection process.

Additionally, the AHGA's user is given the change of seeding the initial population with pre-defined solutions.

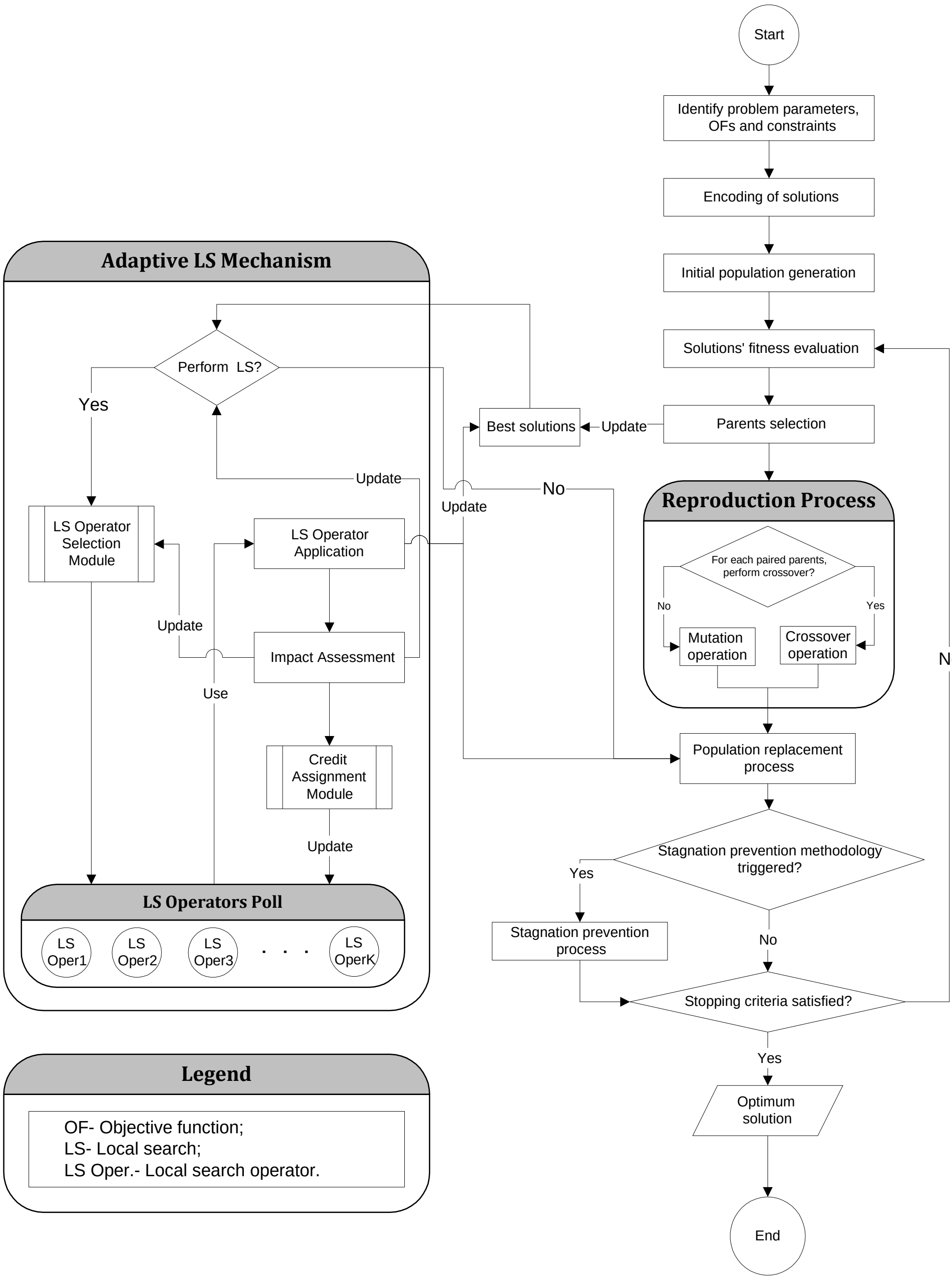


Figure 7.1- Adaptive Hybrid Genetic Algorithm framework.

7.3.1.3 Fitness evaluation

Once the population has been created at each generation, the individual's fitness has to be evaluated according to the objective function and constraints corresponding to the features of the problem being tackled.

GA were initially developed to tackle unconstrained optimization problems. The challenges in solving constrained optimization problems arise from the various limits on the decision variables, the constraints involved, the interference among constraints, and the interrelationship between the constraints and the objective functions (Tessema and Yen, 2006). Because GA do not have any explicit constraint-handling mechanism, the application of the traditional genetic search operators (i.e., crossover and mutation), which are ''blind'' with respect to constraints, may produce infeasible solutions. Therefore, an important issue that needs to be taken into account when designing GA to solve constrained optimization problems is how to handle the constraints.

In the literature, many constraint handling techniques have been proposed for single-objective evolutionary algorithms (Mezura-Montes and Coello Coello, 2011). Due to its simplicity and satisfactory performance, the penalty function method has become very popular and is one of the most common approaches to handling constraints. The main idea behind this method is to transform a constrained optimization problem into an unconstrained one by adding a constraint violation measure to the objective function as a penalty term, based on the amount of constraint violation.

In this research work a dynamic and parameter-free penalty approach based on the concept of superiority of feasible solutions was developed and incorporated into the AHGA.

Without loss of generality, let the formulation represented by Expressions (7.10)-(7.12) be the formulation of a minimization-type constrained optimization problem. It is transformed into an unconstrained one, by defining a new modified objective function (Expression (7.13)).

$$minimize\ f(\vec{X}) \tag{7.10}$$

Subject to:

$$g_j(\vec{X}) \le 0, \quad j = 1,...,q \tag{7.11}$$

$$h_j(\vec{X}) = 0, \quad j = q+1,...,c \tag{7.12}$$

$$minimize\ F(\vec{X}) = f(\vec{X}) + CV(\vec{X}) \times P \tag{7.13}$$

Where $\vec{X}$ is a *T*-dimensional vector of design variables; $g_j(\vec{X})(j = 1,...,q)$ are the q inequality constraints; $h_j(\vec{X})(j = q+1,...,c)$ are the $c - q$ equality constraints. $F(\vec{X})$ is the penalized objective function of individual $\vec{X}$; $CV(\vec{X})$ is the scalar constraint violation of individual $\vec{X}$; *P* is a single penalty factor. The scalar constraint violation, $CV(\vec{X})$, of individual $\vec{X}$ is calculated as the summation of the normalized constraint violations divided by the number of constraints (Expression (7.14)):

$$CV(\vec{X}) = \frac{1}{C} \times \sum_{j=1}^{C} \frac{CV_j(\vec{X})}{CV_{max}^{j}} \tag{7.14}$$

Where $CV_j(\vec{X})$ is the constraint violation of an individual $\vec{X}$ on the *j*th constraint, which is calculated according to Expression (7.15); CV_{max}^{j} is the maximum violation of the *j*th constraint in the population (Expression (7.16)); *C* is the total number of constraints.

$$CV_j(\vec{X}) = \begin{cases} max(0, g_j(\vec{X})), & j = 1,...,q \\ max\left(0, \left|h_j(\vec{X})\right| - \varepsilon\right), & j = p+1,...,c \end{cases} \tag{7.15}$$

$$CV_{max}^{j} = \max_{\vec{X}} CV_j(\vec{X}) \tag{7.16}$$

In Expression (7.15), ε is a tolerance parameter (0.0001) that transforms equality constraints into inequality ones, allowing all constraints to be treated by the same constraint-handling approach.

Finally, the penalty parameter *P*, which varies from one generation to another, is determined according to Expression (7.17).

$$P = \frac{f(\vec{X}^{F}_{worst}) - f(\vec{X}^{UF}_{Best})}{CV(\vec{X}^{UF}_{Lowest})} \tag{7.17}$$

Where $f(\vec{X}^{F}_{worst})$ and $f(\vec{X}^{UF}_{Best})$ are, respectively, the objective function values of the worst and best feasible and unfeasible individuals currently available in the population, whilst $CV(\vec{X}^{UF}_{Lowest})$ is the lowest value of the constraint violation of an unfeasible individual. Thus, the fitness of an infeasible individual not only depends on the amount of constraint violation, but also on the population of individuals of each generation.

7.3.1.4 Parents selection method

The parent selection process is used to determine which solutions of the population will be used by the crossover operator to generate new solutions, called offspring solutions. In the developed AHGA a Ranking-based Selection (RS) method (Chuang et al., 2015) was implemented after preliminary experiments revealed the superiority of this method over the traditional tournament selection method. In the RS method the chromosomes in the population are firstly ranked based on their fitness. Then, the $N \times Discard\_rate$ chromosomes that have relatively lower rankings (i.e., worse fitness) are rejected while at the same time an equal amount of chromosomes that present higher ranking are reproduced, thus ensuring the constancy of the number of chromosomes in the population. The above mentioned parameter $Discard\_rate$ is a user-defined value representing the percentage of individuals from the population of a given generation that will be rejected.

7.3.1.5 Reproduction process

7.3.1.5.1 Crossover operator

Crossover is the process by which one or more new individuals are created through the combination of genetic material selected from two or more parents of the source population, to form the members (offspring chromosomes) of a successor population. In the proposed AHGA a Direction-based Crossover (DBX) operator was implemented (Chuang et al., 2015). This crossover operator work as follows. Once the RS is performed, the N population members are sorted in ascending order according to their fitness, after which the chromosomes are divided into two groups: the leading group (group A: $\chi^A = \{\vec{X}_1, \vec{X}_2, ..., \vec{X}_{\frac{N}{2}}\} \equiv \{\vec{X}_1^A, \vec{X}_2^A, ..., \vec{X}_M^A\}$), which contains the fitter solutions, and the inferior group (group B: $\chi^B = \{\vec{X}_{\frac{N}{2}+1}, \vec{X}_{\frac{N}{2}+2}, ..., \vec{X}_N\} \equiv \{\vec{X}_1^B, \vec{X}_2^B, ..., \vec{X}_M^B\}$), which as the name suggests comprises the worst chromosomes in the current population. The $M = \frac{N}{2}$ chromosomes belonging to the leading group are then paired with the individual having the homologue ranking position in the inferior group. Next, for each pair of parents a random number in the interval [0,1] is generated with uniform probability and compared to a pre-determined crossover rate (p_c). If the random number is greater than the crossover rate, no crossover is performed and the pair members will undergo mutation. In turn, if the random number is lower than or equal to the crossover rate, they are guided to generate two new candidate offspring according to the following rules:

$$\vec{X}_i^{A*} = \vec{X}^A + S_{c,i} \times \vec{D}_i, \qquad i = 1,2,...,M \tag{7.18}$$

$$\vec{X}_i^{B*} = \vec{X}_i^B + S_{c,i} \times \vec{D}_i, \qquad i = 1,2,...,M \tag{7.19}$$

Where X_i^{A*} and X_i^{B*} are, respectively, the offspring individuals obtained from the parents X_i^A and X_i^B; $S_{c,i}$ is the crossover step-size given by Expression (7.20); $\vec{D}_i = [D_{i,1}, D_{i,2}, ..., D_{i,T}]$ is the crossover direction vector, in which their components are generated according to Expression (7.21).

$$S_{c,i} = \frac{\left| f(X_i^A) - f(X_i^B) \right|}{f(X_{Worst}) - f(X_{Best})}, \qquad i = 1,\ldots,M \tag{7.20}$$

$$\vec{D}_i = \begin{cases} 0, & if\ rand_j < 0.5 \\ X_{i,j}^A - X_{i,j}^B & if\ rand_j \geq 0.5 \end{cases} \qquad i = 1,\ldots,M; \quad j = 1,\ldots,T \tag{7.21}$$

In Expression (7.20), $f(\vec{X}_i^A)$ and $f(\vec{X}_i^B)$ represent the objective function value of the i^{th} individual belonging to the groups A and B, respectively; $f(\vec{X}_{Worst})$ and $f(\vec{X}_{Best})$ symbolize the objective function value of the worst and best individuals in the current population, respectively. Finally, in Expression (7.21) $rand_j$ represents a number randomly chosen from the interval [0,1] for the j^{th} gene of a given individual.

From the expressions presented above, it is perceptible that two specific situations may occur in which no crossover would be performed. One situation happens when the paired parents' chromosome has the same fitness value originating a null step size $S_{c,i}$. The second is a consequence of a random number $rand_j$ lower than 0.5, which generates a direction vector $\vec{D}_i$ with null elements. In the event of the first situation, the crossover process is replaced by mutation according to the procedure that will be described in the next section. In turn, the second situation is dealt with by randomly selecting a non-zero crossover direction $D_{i,j}$ from $\vec{D}_i$.

7.3.1.5.2 Mutation operator

The mutation operator aims to introduce new genetic material into an existing individual, ensuring that the full range of allele is accessible for each gene. Thereby, it allows the exploration of different areas of the search space by potentially generating solutions that have never been analysed while it prevents the search from being trapped in a local optima.

As previously stated, in the proposed AHGA each pair of parents which do not meet the crossover criterion will automatically undergo mutation according to the Dynamic

Random Mutation (DRM) operator (Chuang et al., 2015). The way this operator works is described by Expressions (7.22) and (7.23).

$$\vec{X}_i^{A*} = \vec{X}_i^{A} + S_m \times \Phi_o \times (\vec{X}^U - \vec{X}^L) \tag{7.22}$$

$$\vec{X}_i^{B*} = \vec{X}_i^{B} + S_m \times \Phi_o \times (\vec{X}^U - \vec{X}^L) \tag{7.23}$$

Where Φ_o is a random perturbation vector in the n-dimensional cube $[-\phi_o, +\phi_o]^n$; ϕ_o is a user-defined number chosen from the interval [0,1]; $\vec{X}^U$ and $\vec{X}^L$ represent individuals in which all genes are equal to the greatest and lowest value of the decision variables, respectively ($\vec{X}^U = [X_{1,max}, X_{2,max} ..., X_{T,max}]$; $\vec{X}^L = [X_{1,min}, X_{2,min} ..., X_{T,min}]$); S_m is the mutation step size defined according to Expression (7.24).

$$S_m = \left(1 - \frac{k}{K_{max}}\right)^b \tag{7.24}$$

Where b is a parameter used to control the decay rate of S_m; k and k_{max} denote, respectively, the current generation number and the maximum number of generations.

7.3.1.6 Truncation procedure for integer restrictions

After reproduction has been performed (or LS operations as will be shown later on in this chapter), in order to ensure that the integer restrictions are satisfied, the following truncation procedure is applied (Expressions (7.25) and (7.26)):

$$\Delta X_j = X_j - X_j^{int} \tag{7.25}$$

$$\begin{cases} X_j^{int*} = X_j^{int}, & for\ X_{min} \le X_j \le X_{max} \quad if\ \Delta X_j < 0.5 \\ X_j^{int*} = X_j^{int} + 1, & for\ X_{min} < X_j < X_{max} \quad if\ \Delta X_j \ge 0.5 \\ X_j^{int*} = X_{min}, & if\ X_j < X_{min} \\ X_j^{int*} = X_{max}, & if\ X_j > X_{max} \end{cases} \tag{7.26}$$

where X_j is the continuous value of the variable to be integerized; X_j^{int} is the integer portion of X_j; X_j^{int*} is the integerized value of the variable X_j; X_{min} and X_{max} are, respectively, the minimum and maximum values of the set of decision variables (M&R activities) considered for the problem being tackled.

7.3.1.7 Replacement process

The replacement process aims to determine which solutions among parents, offspring and elite members (if applicable) of the current population, are selected to compose the successor population. There are several evolutionary schemes that can be used, depending on the extent to which chromosomes from the source population are allowed to pass unchanged into the successor population. These range from complete replacement, where all members of the successor population are generated through selection and recombination, to steady state, where the successor population is created by generating one new chromosome at each generation and using it to replace a less-fit member of the source population (McCall, 2005).

In the developed AHGA a *replacement-with-elitism* methodology was adopted. By this process, each offspring chromosome is directly compared with its parent and the better (fitter) chromosome moves to the next generation. The survivor chromosomes are posteriorly joined by the elite chromosomes initially preserved. In this way, the performance of the algorithm is enhanced by ensuring that the good individuals survive to the next generation.

7.3.1.8 Stagnation prevention methodology

Due to the evolutionary nature of the GA, it may happen that at some given time the population achieves a low diversity level such that the search process stalls around a local optimum. To avoid this situation, a stagnation prevention methodology was implemented in the proposed AHGA. It consists of refreshing all chromosomes of the population, excepting the current best one, whenever a stagnation index (*SI*), expressed by the standard deviation of the population's fitness, falls below a pre-defined convergence threshold value (τ). Once the stagnation prevention methodology is triggered, the population is regenerated according to two mechanisms, a random regeneration and a biased regeneration, aiming to strike a balance between the exploration of the search space and the exploitation of the best solution. In the random regeneration, 25% of N individuals are randomly generated in order to introduce some diversity into the genetic material available for generating new offspring chromosomes in the upcoming recombination processes. With respect to the biased regeneration, the best individual is used to construct the remaining individuals by using two especially designed operators. These operators, which are meant to promote the exploitation, work as follows. Considering each real M&R activity of the best individual as reference (i.e., an M&R activity different from DN), the first operator acts on that individual by moving those M&R activities back and forward on a yearly basis and within a 3-year time window. In relation to the second operator, it simply replaces each real M&R activity by a DN M&R activity. For instance, if the best individual involves the execution of a given real M&R activity in year 12, 7 new solutions are created by applying the first operator, which consist in moving this M&R activity to years 9, 10, 11, 13, 14 and 15. In turn, the second operator generates one only solution in which the DN M&R activity is performed in year 12. These procedures are repeated for all years (genes) where it is supposed that a real M&R activity is to be implemented. If the total number of new chromosomes exceeds the spots available to complete the population of size N, the recently created chromosomes are ranked based on the fitness value and the fittest ones are selected.

7.3.1.9 Iteration stopping criteria

The implementation of an efficient stopping criterion is an important aspect for any iterative method. If properly designed it may lead to substantial savings in computational times. The proposed AHGA incorporates the following termination criteria: (1) the number of generations attains the user-specified maximum number (*Max_gen*) and (2) the number of continuous generations without improvement of the best solution attains the user-specified maximum number (*Max_gen_NoImprov*). A generation is considered to be a no improvement with regard to its predecessor if the difference of the fitness values of their best individuals is inferior to 0.01%.

7.3.1.10 Local search mechanism

In the proposed algorithm a GA with a classic framework without any kind of LS is hybridized with an adaptive LS mechanism that aims to either accelerate the discovery of good solutions, for which evolution alone would take too long to discover, or to reach solutions that would otherwise be unreachable by evolution or a local method alone (Krasnogor et al., 2006).

Two of the most important aspects that need to be taken into account when designing a hybrid algorithm are concerned with the computational budget and the need to maintain a suitable level of diversity in the population. Performing LS until a solution converges to a local optimum, which is referred to as complete LS, or, in the case of partial LS, if the search space under consideration has wide basins of attraction from which crossover and mutation could not easily escape, may lead to the loss of population diversity (Whitley et al., 1994) and may also be computationally expensive. This can be even more significant when the LS is applied on all individuals of the population on costly function evaluations (El-Mihoub et al., 2006).

With these points in mind, in the developed AHGA a partial LS is applied, instead of performing a complete LS in every solution generated by the evolutionary operators. Specifically, the LS is carried out on the current best solutions of a generation based on a best first improvement strategy. That means that the LS stops when the first better neighbor solution is found, up to a user-specified maximum number of attempts (*MaxNumLS_iter*). If the LS succeeds, the improved solution replaces the starting solution. In turn, if no better solution has been found by the time the LS process is halted, the solution that underwent LS is kept in the archive of best solutions.

Another issue worthy of note when setting the features of LS regards the connection between the features of the search space, the type of LS operators, the LS intensity (i.e., the number of LS iterations) and the LS frequency (i.e., the number of continuous uninterrupted generations that a GA performs before applying LS (El-Mihoub et al., 2006)). Depending on the type of problem and the LS operator being applied, an improving move may be achieved after a great number of attempts, or, contrarily, a few or even one single attempt may be enough for the LS to succeed (Hsiao et al., 2012).

To avoid a waste of algorithm resources due to an improper use of eventually expensive LS, the AHGA incorporate a dynamic approach that controls both the LS frequency and the LS intensity, or, in other words, the maximum number of LS iterations allowed for the LS algorithm to get a successful move (*MaxNumLS_iter*).

In the proposed AHGA the LS frequency is initially set to 1. However, after a given number of unsuccessful LS executions, the decision on whether or not to perform LS is made probabilistically according to a user-defined probability (*p_minLS*). For that purpose, a sliding time window with a user-defined size *W_LS* is adopted to record the performance of the last *W_LS* LS operations. When none of the last *W_LS* LS operations were successful, the execution of the LS at a given time point *t* is triggered probabilistically.

With respect to the LS intensity, the value of *MaxNumLS_iter* at time point *t* is initially set to $MaxNumLS\_iter_{max}$ and will be linearly reduced according to the consecutive number of unsuccessful LS operations (*UnsucLS_iter*) up to a user-defined limit value ($MaxNumLS\_iter_{min}$) (Expression (7.27)). The *MaxNumLS_iter* is restored to the initial value whenever a LS operation is successful.

$$MaxNumLS\_iter = MaxNumLS\_iter_{max} - \frac{MaxNumLS\_iter_{max} - MaxNumLS\_iter_{min}}{W\_LS} \times UnsucLS\_iter \qquad (7.27)$$

Given the underlying idea in the previous paragraph, a sensible LS design approach would not be based on a priori choice of one single LS operator that may prove to be unproductive for the problem at hand. Rather, a more efficient design would consider the incorporation of multiple LS operators and the decision of which LS operator to apply on a given search moment would be more rational if made dynamically. This system of adaptive LS process promotes both cooperation and competition among various problem-specific LS operators and favors neighborhood structures containing high quality solutions that may be arrived at by low computational efforts (Ong et al., 2006). To this aim, the AHGA framework is provided with a pool of LS operators and an Adaptive Local Search Operator Selection (ALSOS) method in order to decide dynamically and on-the-fly, based on their recent performances, if it is worthy to perform an LS, and if so, to select the LS operator, from the several available options, that leads to the best gains in search efficiency.

Next, the components of the LS mechanism will be described in detail.

7.3.1.10.1 Adaptive local search operator selection method

The ALSOS method is divided into two main modules: (1) a credit assignment module, which assigns a reward to each LS operator based on their impacts on the progress of the search and (2) an operator selection module, which selects the operator to apply to the next LS step, based on the credits previously assigned. The details of the previously mentioned modules are provided in the next sections.

7.3.1.10.1.1 Credit assignment module

In the proposed AHGA, the assessment of the performance of each LS operator, based on the impact of its application on the progress of the search, is carried out by applying the fitness improvement rate (FIR) method. This method was chosen over the commonly applied raw values of the fitness improvements because they not only vary from problem to problem but also change depending on the stage of the optimization process. Typically, the raw fitness improvement value is much greater at early stages than at later ones (Li et al., 2014). The FIR achieved by an LS operator *k* at the time point *t* is computed as follows (Expression (7.28)):

$$FIR_{i,t} = \frac{f(X^{Neighbor}) - f(X^{Initial})}{f(X^{Initial})} \tag{7.28}$$

where $f(\vec{X}^{Neighbor})$ is the fitness value of the neighbor solution; $f(\vec{X}^{Initial})$ is the fitness value of the initial solution.

Once the performance is assessed, the reward of each operator is determined according to the *Extreme Value* approach (Fialho et al., 2008). Relying on the principle that rare but possibly large improvements in the performance criterion are likely to be more effective than frequent but small ones, it advocates that LS operators should be rewarded based on the maximal FIR values recently achieved. For that purpose, a sliding window with fixed size *W_CredAssig* was adopted for each LS operator to store the FIR values resulting from the last *W_CredAssig* applications of the LS operators. The sliding windows work as a first-in, first-out (FIFO) queue, to the extent that the most recent FIR values are added at the tail of the sliding window, while the oldest ones are removed to preserve the window size. The reward of each LS operator at the point time *t* is then calculated as the greatest FIR value among the current values stored in the sliding window. Formally, if *t* is the current time point and $FIR_k(t)$ the fitness improvement rate observed at that moment of the search, then the expected reward for LS operator *k* at time *t* ($rew_k(t)$) is calculated as follows (Expression (7.29)):

$$rew_k(t) = max\{FIR_{k,1}, FIR_{k,2}, ..., FIR_{k,W\_CredAssig}\} \tag{7.29}$$

The sliding window is mean to represent the time scale of the process and can be thought of as a memory. Small *W_CredAssig* values disregard the performance of the LS operators at early stages of the search, meaning that LS operators originating large but infrequent performance improvements will be missed. On the other hand, big *W_CredAssig* values lead to extended learning periods, which may delay the switch from the previous best operator to the next best one.

7.3.1.10.1.2 Local search operator selection module

The LS operator selection is performed by adapting the application rates of the LS operators according to a proportional probability scheme. The proposed AHGA was equipped with two selection methods, namely the Probability Matching (ProMat) method (Goldberg, 1990) and the Adaptive Pursuit (AP) method (Thierens, 2005).

Let *K* be the set of LS operators available in a pool $K = \{ LSOper_1, LSOper_2, ..., LSOper_k \}$, the selection probability of each LS operator at time point *t* be $P(t) = \{ p_1(t), ..., p_k(t) \}$, such that $\forall t: p_{min} \leq p_k(t) \leq 1; \sum_{k=1}^{K} p_k(t) = 1$, and the estimated quality of LS operator *k* be $\hat{q}_k(t)$. At each time point *t*, these methods: (1) randomly select a LS operator *k* with a probability $p_k(t)$, and assign it a reward $rew_k(t)$, calculated according to the *Extreme Value*-based credit assignment mechanism and (2) update the quality of the selected LS operator *k* ($\hat{q}_k(t+1)$) according to the reward $rew_k(t)$, based on the quality empirical estimate presented by Expression (7.30).

$$\hat{q}_k(t+1) = (1-\alpha) \times \hat{q}_k(t) + \alpha \times rew_k(t) \tag{7.30}$$

where $\alpha \in [0, 1]$ is a user-defined parameter that represents the adaptation rate.

After having performed preliminary experiments considering the two abovementioned methods, the second one was selected to adaptively update the probability $p_k(t)$ of LS operator *k* when applied to the computational experiments described in sections 7.4.1 and 7.5.1.

The AP method, originally proposed for learning automata, adopts a winner-takes-all strategy to increase the chance of selecting the best LS operator k^* up to p_{max} while the remaining probabilities are decreased to p_{min}. According to this method, the probability of each LS operator is updated as follows:

$$p_{k^*}(t+1) = p_{k^*}(t) + \beta \times [\, p_{max} - p_{k^*}(t)], \quad if \;\; k = k^* \tag{7.31}$$

$$p_k(t+1) = p_k(t) + \beta \times [\, p_{min} - p_k(t)], \quad \forall k \neq k^* \tag{7.32}$$

Where:

$$k^* = arg\,max_k\,[\,\hat{q}_k(t+1)],\quad k = 1,\ldots,K \tag{7.33}$$

Under the constraints:

$$p_{max} = p_{min} + 1 - K \times p_{min} \quad and \quad p_{min} < \frac{1}{K} \tag{7.34}$$

This constraint ensures that if $\sum_{k=1}^{K} p_k(t) = 1$, then the sum of the updated probabilities remains equal to 1, i.e., $\sum_{i=1}^{K} p_k(t+1) = 1$ (Thierens, 2005).

In addition to the adaptation rate α used to update the empirical quality estimates (Expression (7.30)), the AP contemplates another parameter, the learning rate $\beta \in [0, 1]$, which controls the greediness of the winner-takes-all strategy.

7.3.1.10.1.2.1 Pool of local search operators

In the proposed AHGA, a set of LS operators were considered to generate several neighbors' structures, and consequently neighborhood solutions, for the problem being tackled. It should be mentioned that the choice of LS operators for the pool is to some extent subjective, as there is no conventional procedure in the literature for guiding the selection of the best set of LS operators for a given problem. Thus, the choice of the LS operators presented in the list below was based on the authors' knowledge of the problem and on empirical evidence, and resulted from narrowing down an initial extended list. The LS operators are the following:

1) Swap mutation (SWM), which consists of randomly selecting two genes and swapping their positions in the chromosome;
2) Forward shift mutation (FSM), which consists of randomly selecting two genes and moving the first gene into the position immediately preceding the second gene;
3) Backward shift mutation (BSM), which consists of randomly selecting two genes and moving the second gene into the position immediately succeeding the first gene;

4) Cauchy Distribution-based Mutation (CaDM), which consists of randomly performing a Cauchy-based mutation on a randomly selected gene (X_j) according to Expression (7.35).

$$X_j^{new} = X_j + cauchy() \times \left|\left(X_a - X_b\right)\right| \tag{7.35}$$

Where $cauchy()$ is a random number generated by the Cauchy distribution function (Expression (7.36)); X_a and X_b are two randomly selected genes different from X_j .

$$F(x) = \frac{1}{2} + \left(\frac{1}{\pi}\right) \times arctan(x) \tag{7.36}$$

5) Chaotic Dynamic-based Mutation (ChDM), which consists of randomly performing a Chaotic dynamic-based mutation on a randomly selected gene (X_j) according to Expression (7.37).

$$\begin{cases} X_j^{new} = X_j + ch_k \times (X_{max} - X_{min}), & if \ rand_j \geq 0.5 \\ X_j^{new} = X_j - ch_k \times (X_{max} - X_{min}), & if \ rand_j < 0.5 \end{cases} \tag{7.37}$$

Where ch_k is the chaotic variable after *k* iterations; $rand_j$ is a number randomly chosen from the interval [0,1]; X_{min} and X_{max} represent, respectively, the minimum and maximum values of the set of decision variables (M&R activities) considered for the problem being tackled. The sinusoidal iterator, represented by Expression (7.38), was selected to perform the chaotic local search after *k*=300 iterations. The first chaotic variable, ch_0, was generated randomly in the range [0,1].

$$ch_k = sin(\pi \times ch_{k-1}), \quad ch_k \in [0,1] \tag{7.38}$$

6) Delete Mutation (DelMut), which consists of randomly selecting one gene of the chromosome among those representing a real M&R action and replacing it with another one where a DN M&R action is supposed to be performed.

7.4 Parameters setting for the proposed Adaptive Hybrid Genetic Algorithm

Before measuring and comparing the performances of the AHGA and traditional GA when applied to different case studies, a parameter tuning campaign was undertaken to determine the set of parameter values that yields the best algorithm performance.

For a reduced number of parameters with a few alternative levels, the usage of calibration approaches relying on a full factorial design, where all possible combinations for a given set of parameters are identified and examined, would be a costly and time consuming process due to the huge number of experiments required. An alternative approach consists of using orthogonal arrays (OAs) to reduce the number of experiments required, while maximizing the test coverage (Wang et al., 2014).

A commonly used orthogonal method, which was applied in this study to carry out the parameter tuning, is the Taguchi approach (Roy, 2010). Extensively used for engineering process optimization, it aims to produce high quality products at low cost to the manufacturer, following the philosophy that quality is best achieved by minimizing the deviation from a target. To reduce errors in the product, Taguchi designs experiments using OAs to systematically vary and test the different levels of the control factors (i.e., parameter settings). The appropriate levels for those factors are those that make the system more “robust”, or in other words, less sensitive to variations in uncontrollable (noise) factors. To conclude on the robustness of a given process or system, a criterion entitled Signal-to-Noise (S/N) ratio (η_{dB}) is adopted, where factor levels that maximize the appropriate S/N ratio are optimal. The usage of this criterion is suggested when multiple runs are conducted for the same experiment and the results are measured in quantitative terms.

The S/N ratio is derived from the quality loss function and depending on the desired performance response can be of three standard types:

1) The “smaller-the-better” (Expression (7.39)):

$$S / N = -10 \times Log\left(\frac{1}{N}\sum_{i=1}^{N} {y_i}^2\right) \tag{7.39}$$

2) The nominal is the best (Expression (7.40)):

$$S / N = -10 \times Log\left(\frac{\overline{y}^2}{S^2}\right) \tag{7.40}$$

3) The “larger-the-better” (Expression (7.41)):

$$S / N = -10 \times Log\left(\sum_{i=1}^{N} \frac{1}{y_i^2}\right) \tag{7.41}$$

Where *S/N* is the Signal-to-Noise ratio in dB; *N* is the total number of trials for a given experiment; y_i is the value of the performance characteristic for trial *i*; $\overline{y}$ is the mean value of the performance characteristic for a given experiment; s^2 is the variance of the performance characteristic for a given experiment.

Once all of the S/N ratios have been computed for each run of an experiment, the Taguchi method suggests a graphical approach to analyze the data. According to this approach, the S/N ratios and average responses are plotted for each factor against each of its levels. The graphs are then examined to determine the optimal factor level, i.e., to select the factor level which (1) best maximizes the mean of the S/N rations and (2) minimizes the mean of the average responses.

7.4.1Experimental design

To concretize the parameter tuning process, the AHGA was applied to a case study consisting of determining the best M&R strategy that minimizes the total discounted

M&R costs of a one-way road pavement section of an Interstate highway in Virginia, USA, with the features displayed in Table 7.1.

Table 7.1- Features of the case study.

Name	Value	Unit
PAP	50	year
Beginning year	2011	year
$AADT_0$	20000	vehicle
Percentage of PCs in the AADT	75	%
Percentage of HDVs in the AADT	25	%
Traffic growth rate	3	%/year
CCI_0	85	-
Age	5	year
Number of lanes	2	-
Lanes length	1	km
Lane width	3.66	m

Legend: PAP- project analysis period; $AADT_0$- initial annual average daily traffic; AADT- annual average daily traffic; PC- passenger car; HDV- heavy duty vehicle; CCI_0- Initial Critical Condition Index.

The M&R activities considered were based on Chowdhury (2011), and defined as DN, PrM, CM, RM and RC. Details on the M&R actions comprising each M&R activity can be found in Chapter 6 (Santos et al., 2015a).The M&R costs were determined according to the methodology presented in Chapter 5 (Santos et al., 2015b) and are presented in Table 7.2.

In order to determine the pavement performance over time, the VDOT's 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. Using the base form corresponding to Expression (7.42), VDOT defines PPPM for the last three categories (Stantec Consulting Services and Lochner, 2007). The coefficients of VDOT's load-related PPPM expressed by Expression (7.42) for asphalt pavements of Interstate highways are presented in Table 7.3 (Stantec Consulting Services and Lochner, 2007).

$$CCI(t) = CCI_0 - e^{a + b \times c^{\ln\left(\frac{1}{t}\right)}} \tag{7.42}$$

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; *a*, *b*, and *c* are the load-related PPPM coefficients (Table 7.3).

Table 7.2- Unit costs of the M&R activities.

ID	Name	Total MC ($/Km.lane)
1	DN	0
2	PrM: microsurfacing	6,621
3	PrM: THMACO	17,593
4	CM	35,696
5	RM	58,969
6	RC	169,594

Note: MC- maintenance and rehabilitation costs; DN- do nothing; PrM- preventive maintenance; THMACO- thin hot-mix asphalt concrete overlay; CM- corrective maintenance; RM- restorative maintenance; RC- reconstruction/rehabilitation.

Table 7.3- Coefficients of VDOT's load-related PPPM expressed by Expression (7.42) 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

Legend: VDOT- Virginia Department of Transportation; PPPM- pavement performance prediction models; M&R- maintenance and rehabilitation; CCI_0 - critical condition index immediately after treatment; *a, b,* and *c* are load-related PPPM coefficients; CM- corrective maintenance; RM- restorative maintenance; RC- reconstruction/Rehabilitation.

Unlike the other categories, VDOT did not develop individual PPPM for PrM treatments. Thus, in this case study the considered PrM treatments, i.e. microsurfacing and THMACO, were respectively modelled as an 8-point and 15-point improvement in the CCI of a road segment (Chowdhury, 2011). Once the treatment is applied, it is assumed that the pavement deteriorates according to the PPPM of a CM, without reduction of the effective age. 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.

Based on the generic formulation presented in section 7.2 and on the considerations introduced above, the optimization problem was formulated as follows:

$$Minimize \sum_{t=1}^{6} \sum_{t=1}^{50} \frac{1}{(1+d)^{t}} \times MC_{rt} \times X_{rt} \tag{7.43}$$

Subject to:

$$CCI_{t} \geq CCI_{min}, \qquad t = 1,...,50 \tag{7.44}$$

$$\sum_{r=1}^{6} X_{rt} = 1, \quad t = 1,...,50 \tag{7.45}$$

$$\Delta t_{r} \leq \Delta t_{RC}^{max}, \qquad r = 6 \tag{7.46}$$

Where X_{rt} is equal to one if M&R activity r is applied in year t, otherwise it is equal to zero; d is the discount rate and was set to 2.3% according to OMB (2013); CCI_t is the CCI value in year t; CCI_{min} is the minimum CCI value allowed for a pavement structure and was set to 40; Δt_r is the time interval between the application of two consecutives M&R activities of type r; Δt_{RC}^{max} is the maximum time interval between the application of two consecutives M&R activities of type RC and was considered to be equal to 30 years according to VDOT (2014). The values of the index r identifying the M&R activities are coherent with the ID values presented in Table 7.2.

For simplicity, the presentation of the constraints represented by Expressions (7.2), (7.4) and (7.6) in section 7.2 was omitted from the formulation listed above.

7.4.2 Parameter tuning using the Taguchi method

The parameter tuning process described in this section focus exclusively on the parameters specifically related to the hybrid version of the GA (i.e., AHGA). The value of the parameters common to both algorithms are presented in Table 7.4. This parameter setting was chosen based on the guidelines provided by Chuang et al. (2015) and on the best and most stable results obtained from preliminary and exploratory tests on parameter sensitivity conducted with the non-hybridized version of the proposed GA.

Table 7.4- Parameters setting.

Parameter	Value
N	100
$Elite\_rate$	1%
$Discard\_rate$	$\frac{1}{N}$
C	2
p_c	90%
ϕ_o	0.35
b	1
ε	10^{-4}
Max_gen	300
$Max\_gen\_NoImprov$	100

As stated in the previous section, the application of the Taguchi method requires the determination of a suitable quality loss function as the objective function. Preliminary AHGA runs revealed that the algorithm was always able to converge to the best known solution regardless of the selected parameter setting. Thus, the objective considered in calibrating the AGHA was to ensure it converges to the best known solution at the lowest computational running time. In other words, the quality loss will be smaller if the required computational running time of the algorithm to find the best known solution is smaller. Thus, the objective function for the calibration of the AHGA was defined by choosing a quality loss function with the characteristics of "smaller-the-better" (Expression (7.39)).

In the process of parameter tuning, the control factors are referred to as parameters and the levels as parameters values. The parameters (control factors) that were calibrated through the Taguchi method are the following: (1) maximum number of LS iterations ($MaxNumLS\_iter_{max}$); (2) minimum number of LS iterations ($MaxNumLS\_iter_{min}$); (3) probability of performing LS (*p_minLS*); (4) size of the sliding time window used to store the status of the LS operations (*W_LS*); (5) size of the sliding time window used to store the performance of the LS operators, expressed in terms of FIR (*W_CredAssig*);

(6) adaptation rate (α) considered by the credit assignment module of the ALSOS method; (7) minimum probability of selecting a given operator (p_{min}) considered by the AP method; and (8) learning rate (β) considered by the AP method. Overall, for each parameter three alternative values (levels) were considered based on preliminary tests (Table 7.5).

Table 7.5- Parameters levels.

ID	Name	L1	L2	L3
1	$MaxNumLS\_iter_{max}$	50	150	-
2	$MaxNumLS\_iter_{min}$	5	25	45
3	*p_minLS*	5%	20%	50%
4	*W_LS*	5	15	25
5	*W_CredAssig*	10	50	100
6	α	0.1	0.5	0.9
7	p_{min}	5%	10%	15%
8	β	0.2	0.5	0.8

According to the Taguchi method, for a calibration process with such features, i.e., eight parameters with three alternative values, the L18 OA is recommended for the matrix experiment. The OA comprises eight columns of parameters and eighteen rows of experiments representing a specific design alternative with a defined set of design parameter values. When compared to factorial design, the time savings are evident, as the same number of parameters and alternative values examined with factorial design would require 6561 (3^8) experiments, whereas with the Taguchi method only eighteen are needed.

After implementing the AHGA in MATLAB® programming software (MATLAB, 2015), each experiment defined by the OA was run 10 times on a computational platform Intel Core 2 Duo 2.4 GHz processor with 4.00 GB of RAM, on the Windows 7 professional operating system.

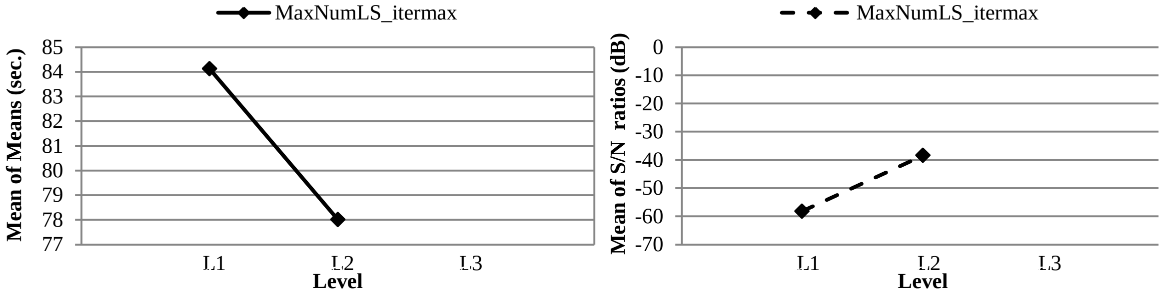
The results obtained for the Taguchi experiment are summarized in Table 7.6 along with the layout of the L18 OA. Figure 7.2 depicts the mean of S/N ratios along with the averaged responses for each parameter, expressed in terms of computational running time (seconds).

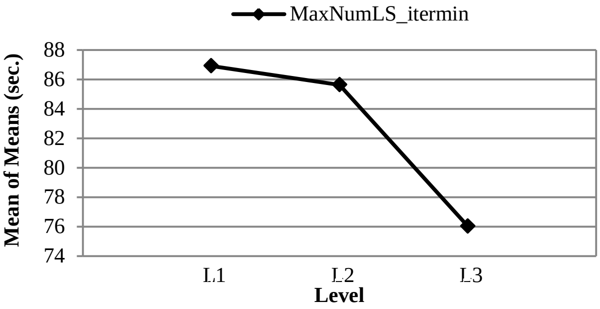
Table 7.6- Taguchi experiment results and L18 OA layout.

Experiment	Parameter ID								Averaged computational	S/N (dB)
ID	1	2	3	4	5	6	7	8	running time (sec.)	
1	50	0.1	0.05	5	10	0.1	0.05	0.2	111.0091	-42.2906
2	50	0.1	0.2	15	50	0.5	0.1	0.5	80.69418	-38.9327
3	50	0.1	0.5	25	100	0.9	0.15	0.8	56.39403	-36.4397
4	50	0.5	0.05	5	50	0.5	0.15	0.8	116.901	-42.3645
5	50	0.5	0.2	15	100	0.9	0.05	0.2	99.92245	-41.2259
6	50	0.5	0.5	25	10	0.1	0.1	0.5	71.27712	-37.3086
7	50	0.9	0.05	15	10	0.9	0.1	0.8	76.39255	-38.0864
8	50	0.9	0.2	25	50	0.1	0.15	0.2	57.11317	-35.6053
9	50	0.9	0.5	5	100	0.5	0.05	0.5	64.76956	-36.8037
10	150	0.1	0.05	25	100	0.5	0.1	0.2	78.68935	-38.688
11	150	0.1	0.2	5	10	0.9	0.15	0.5	109.3454	-41.5612
12	150	0.1	0.5	15	50	0.1	0.05	0.8	85.39461	-39.8269
13	150	0.5	0.05	15	100	0.1	0.15	0.5	52.89346	-34.8525
14	150	0.5	0.2	25	10	0.5	0.05	0.8	80.92878	-38.517
15	150	0.5	0.5	5	50	0.9	0.1	0.2	91.88262	-39.9784
16	150	0.9	0.05	25	50	0.9	0.05	0.5	68.04786	-37.1613
17	150	0.9	0.2	5	100	0.1	0.1	0.8	109.6858	-42.2859
18	150	0.9	0.5	15	10	0.5	0.15	0.2	80.27925	-39.6368

Legend: S/N - Signal-to-Noise ratio.

The optimal parameter values were then identified by applying the Taguchi's parameter design approach, according to which the optimal parameter values are the ones that best maximize the mean of S/N ratios and minimize the mean of the average responses. Table 7.7 summarizes the optimal value of the parameters. These parameter values will be used by the AHGA when comparing its performance against that of the non-hybridized version of the GA.




MaxNumLS_itermin
Mean of Means (sec.)
88
86
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82
80
78
76
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L1
L2
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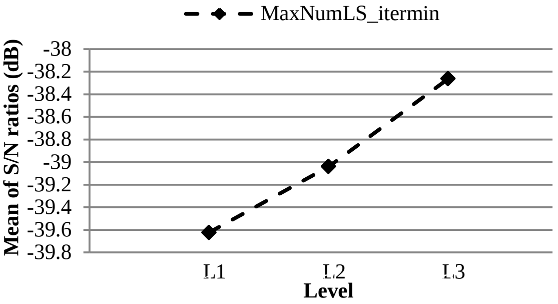
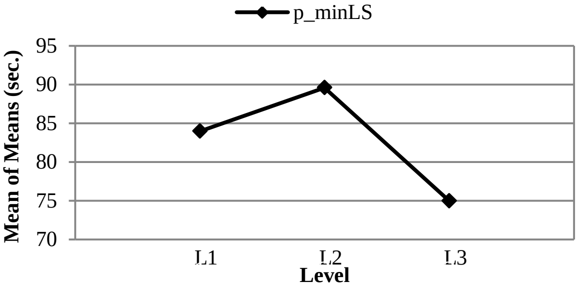
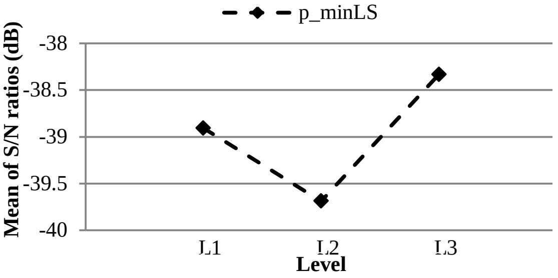
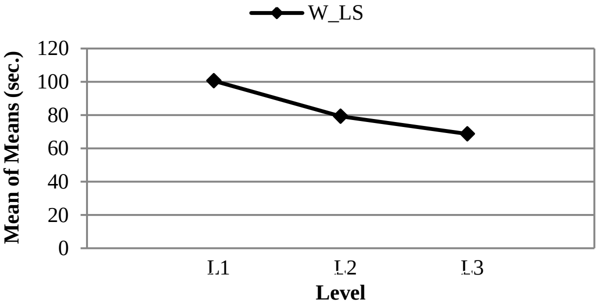
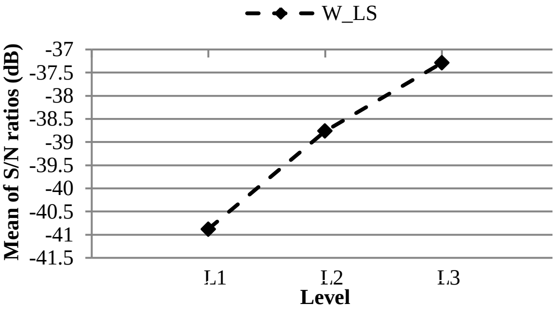
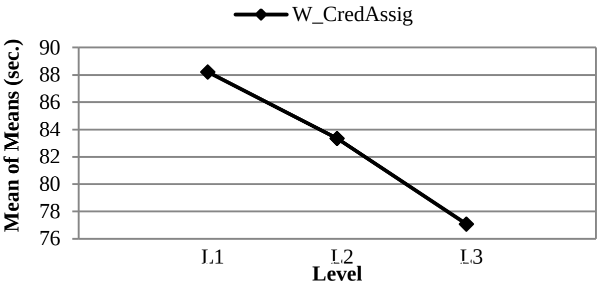

MaxNumLS_itermin
Mean of S/N ratios (dB)
-38
-38.2
-38.4
-38.6
-38.8
-39
-39.2
-39.4
-39.6
-39.8
L1
L2
L3
Level

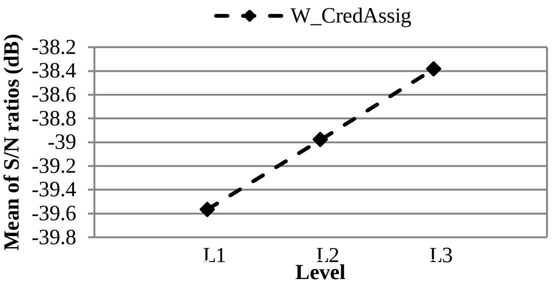

p_minLS
Mean of Means (sec.)
95
90
85
80
75
70
L1
L2
L3
Level

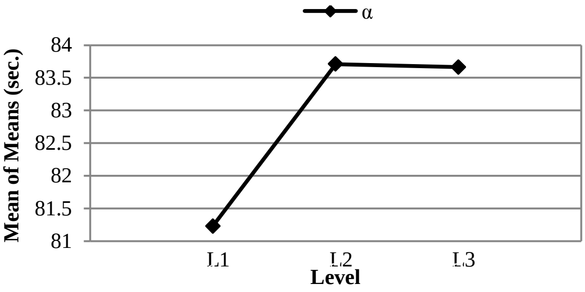

p_minLS
Mean of S/N ratios (dB)
-38
-38.5
-39
-39.5
-40
L1
L2
L3
Level

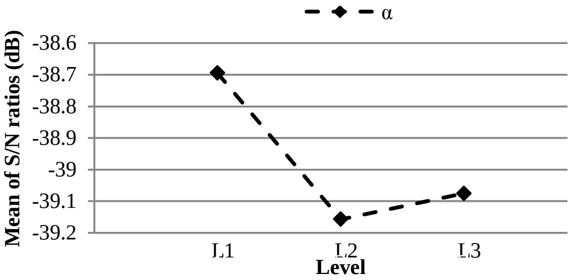

W_LS
Mean of Means (sec.)
120
100
80
60
40
20
0
L1
L2
L3
Level


W_LS
Mean of S/N ratios (dB)
-37
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
-41
-41.5
L1
L2
L3
Level


W_CredAssig
Mean of Means (sec.)
90
88
86
84
82
80
78
76
L1
L2
L3
Level


W_CredAssig
Mean of S/N ratios (dB)
-38.2
-38.4
-38.6
-38.8
-39
-39.2
-39.4
-39.6
-39.8
L1
L2
L3
Level


α
Mean of Means (sec.)
84
83.5
83
82.5
82
81.5
81
L1
L2
L3
Level


α
Mean of S/N ratios (dB)
-38.6
-38.7
-38.8
-38.9
-39
-39.1
-39.2
L1
L2
L3
Level

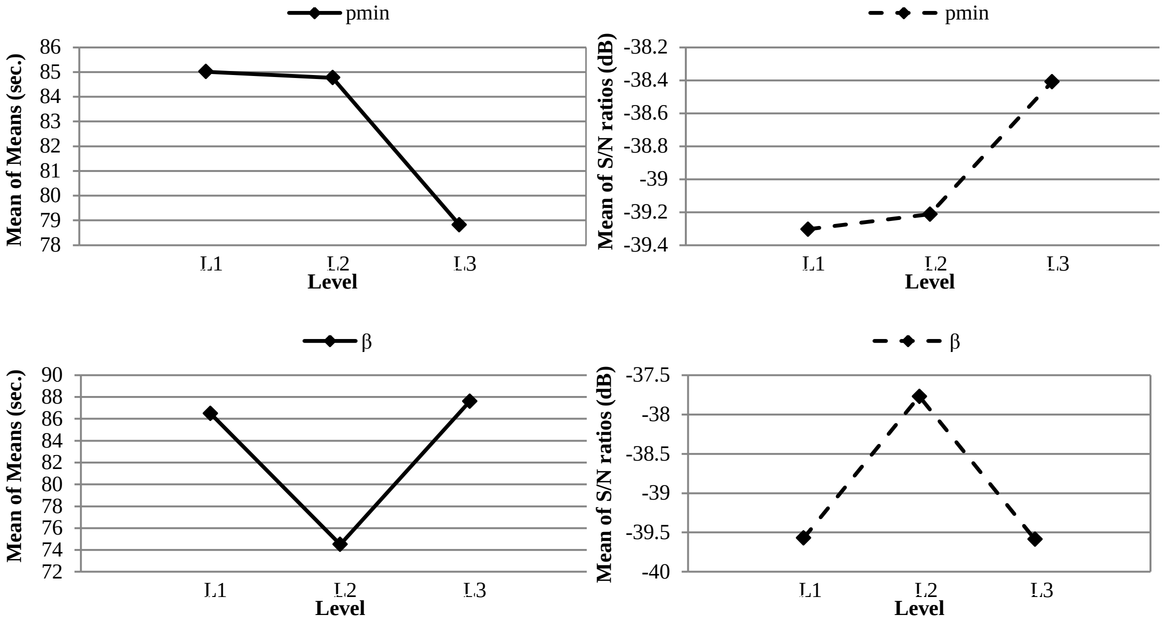


Figure 7.2- Mean of means and S/N ratios for each parameter.

Table 7.7- Optimal parameters values.

Name	Level	Value
$MaxNumLS\_iter_{max}$	L2	150
$MaxNumLS\_iter_{min}$	L3	45
p_minLS	L3	50%
W_LS	L3	25
W_CredAssig	L3	100
α	L1	0.1
p_{min}	L3	15%
β	L2	0.5

7.5 Comparison of the algorithms performance

7.5.1Experimental setup

In this section, the proposed AHGA is compared with the non-hybrid version of the GA with respect to (1) its ability to consistently reach the fittest solution achieved ($\omega_{Optimum}^{Min.M\&R\,Costs.}$) by employing the two algorithms and (2) the convergence behavior during the search process. The fittest solution obtained from the usage of both algorithms is considered the point of comparison of the effectiveness of the algorithms because the problem size (i.e., number of M&R considered and PAP length), the complexity of the

PPPM and the way they relate to each other (see section 7.4.1) mean the use of analytical or exhaustive optimization approaches would not reach the global optimum solution within the span of a human lifetime.

Both algorithms were applied to several case studies with the objective of determining the best pavement M&R strategy that minimizes the total discounted M&R costs of a one-way road pavement section of an Interstate highway in Virginia, USA, with the geometric and traffic characteristics formerly displayed in Table 7.1 of section 7.4.1, and complying with the types of M&R activities and PPPM described in the same section. With respect to pavement conditions, 16 different scenarios with the features presented in Table 7.8 were considered, and for each scenario ten independent computational runs were performed. To provide a fair basis for the comparison of the performance of both algorithms, they were run considering the same values for the parameters common to both algorithms as listed in Table 7.4 of section 7.4.2. In turn, the parameter setting displayed in Table 7.7 of section 7.4.2 was adopted when specifically applying the AHGA.

In order to examine the statistical difference between the algorithms, two non-parametric tests were carried out: the Wilcoxon signed-rank test (Hollander et al., 2014) and Page's trend test (Page, 1963). Non-parametric tests were preferred over parametric ones because the latter require the assumptions of normality, independence and homoscedasticity of the data for the sake of reliability (Derrac et al., 2011), which either may not be easy to guarantee or may be impossible to ensure at all when considering stochastic search algorithms such as those introduced in this chapter.

Specifically, the non-parametric Wilcoxon signed-rank test was conducted to compare the algorithms' final results with the significance level (α) of 5%. According to this test, the optimum objective function value found by the AHGA on each of the ten independent computational runs is compared to the optimum objective function value found by the GA on that same run. The difference between these two optimum objective function values, d_i, was stored in a vector of differences, D, of length 10 ($n_{runs} = 10$). The Wilcoxon signed-rank test was then performed to test the null hypothesis that the data in the vector D is a random sample with a mean value of 0 against the two-sided alternative hypothesis that the mean difference is different from 0. The computation of the p-value for this test was done by using the function "*signrank*" existing in MATLAB®.

Table 7.8- Features of the case studies.

Case study ID	PAP (years)	Initial pavement age (years)	Initial pavement CCI	CCI warning level
1	50	30	40	40
2	50	0	100	40
3	50	10	68	40
4	50	5	85	40
5	50	30	50	50
6	50	0	100	50
7	50	10	68	50
8	50	5	85	50
9	30	30	40	40
10	30	0	100	40
11	30	10	68	40
12	30	5	85	40
13	30	30	50	50
14	30	0	100	50
15	30	10	68	50
16	30	5	85	50

Legend: PAP- project analysis period; CCI- critical condition index.

Page's trend test was adopted to assess the algorithms' convergence performance, considering intermediate results instead of just the final results in each case study. This test is applied under the assumption that an algorithm with a good convergence performance will advance towards the optimum faster than another algorithm with a worse performance (Derrac et al., 2014). According to this test, the averages of the optimum objective function values found by the AHGA over the ten independents computational runs at c different steps of the search (cut-points) are subtracted by the homologous values resulting from employing the traditional GA. Next, for each case study the c cut-points are ranked from 1 to c, where the cut-point with the greatest absolute difference is given the ranking 1 and the cut-point with the lowest absolute difference is given the ranking c. Once this procedure is performed, the value of the ranks obtained by each cut-point in the several case studies are summed up and numbered from 1 to c, where the cut-point with the smallest sum of ranks is given the number 1 and the cut-point with the largest sum is given the number *c*. Page's *L* statistic is then calculated to test the null hypothesis that the equality between the *c* cut-points analyzed can be rejected in favor of a predefined ordered alternative with a significance level of α=0.05.

7.5.2 Analysis of the results

7.5.2.1 Optimum objective function values

Table 7.9 presents the performance of each algorithm with respect to their ability to consistently reach the fittest solution obtained ($\omega_{Optimum}^{Min.M\&R\,Costs.}$) by employing the two algorithms. For each scenario, the best (Min.), the worst (Max.), the median (Avg.) and the standard deviation (σ) of the results over ten computational runs are reported. In addition, the average relative percentage deviation ($\overline{ARPD}$) from the best known objective function value obtained through the application of both algorithms is also calculated for each scenario according to the Expression (7.47).

$$\overline{ARPD} = \frac{\displaystyle\sum_{i=1}^{n_{runs}} \frac{\omega_i^{Min.M\&R\,Costs} - \omega_{Optimum}^{Min.M\&R\,Costs}}{\omega_{Optimum}^{Min.M\&R\,Costs.}}}{n_{runs}} \times 100\,\% \tag{7.47}$$

where $\omega_{Optimum}^{Min.M\&R\,Costs.}$ is the best known solution produced over ten computational runs by the two algorithms; $\omega_i^{Min.M\&R\,Costs.}$ is the solution given by the computational run *i*; n_{runs} is the maximum number of independent computational runs considered.

From Table 7.9 it can be seen that the AHGA was always able to reach the best known solution regardless of the case study considered, whereas the GA did not present this general capacity by failing to converge to the best solution in case study 5. With respect to the ability of the algorithms to more consistently achieve the best know solutions, the AHGA was found to almost always converge to the best known solution in 10 out of the 10 computational runs, with the exception of case studies 7 and 8. In the case of the first exception, it was found to converge to within 10% of the best known solution on 9 out of 10 computational runs, representing a $\overline{ARPD}$ of 2%. This results is slightly worse than that observed in the second exception, as the AHGA was found to converge to the best known solution within 1% of this value on 9 of the 10 computational runs, leading to an $\overline{ARPD}$ equal to 0.34%, whereas for higher deviations, i.e. 5% and 10% of the best known solution, it always converged on all of the ten computational runs.

Table 7.9- Statistics of the objective function values and number of runs (of 10) converged within δ (%) of lowest achieved objective function values.

Case study ID	Algorithm	Min. ($)	Avg. ($)	Max. ($)	σ	$\overline{ARPD}$	δ (%)		
							≤ 1	≤ 5	≤ 10
1	AHGA	522,470.00	522,470.00	522,470.00	0	0.00	10	10	10
	GA	522,470.00	599,355.00	672,920.00	56385	14.72	2	2	4
2	AHGA	198,950.00	198,950.00	198,950.00	0	0.00	10	10	10
	GA	198,950.00	198,950.00	198,950.00	0	0.00	10	10	10
3	AHGA	270,400.00	270,400.00	270,400.00	0	0.00	10	10	10
	GA	270,400.00	288,557.00	355,090.00	22470	6.71	1	9	9
4	AHGA	230,640.00	230,640.00	230,640.00	0	0.00	10	10	10
	GA	230,640.00	231,186.00	236,100.00	1638	0.24	9	10	10
5	AHGA	537,670.00	539,947.00	540,200.00	759	0.42	10	10	10
	GA	558,110.00	615,805.00	702,350.00	40889	14.53	0	2	2
6	AHGA	217,220.00	217,220.00	217,220.00	0	0.00	10	10	10
	GA	217,220.00	223,321.00	241,060.00	9308	2.81	7	7	9
7	AHGA	333,210.00	338,320.00	384,310.00	15330	1.53	9	9	9
	GA	333,210.00	349,247.00	396,600.00	21488	4.81	5	7	8
8	AHGA	266,950.00	267,976.00	272,080.00	2052	0.38	8	10	10
	GA	266,950.00	270,031.00	275,530.00	3410	1.15	5	10	10
9	AHGA	370,020.00	370,020.00	370,020.00	0	0.00	10	10	10
	GA	370,020.00	378,522.00	422,260.00	17552	2.30	8	8	9
10	AHGA	47,390.00	47,390.00	47,390.00	0	0.00	10	10	10
	GA	47,390.00	49,578.60	69,276.00	6566	4.62	9	9	9
11	AHGA	244,160.00	244,160.00	244,160.00	0	0.00	10	10	10
	GA	244,160.00	244,160.00	244,160.00	0	0.00	10	10	10
12	AHGA	210,610.00	210,610.00	210,610.00	0	0.00	10	10	10
	GA	210,610.00	210,610.00	210,610.00	0	0.00	10	10	10
13	AHGA	403,700.00	403,700.00	403,700.00	0	0.00%	10	10	10
	GA	403,700.00	409,250.00	421,000.00	6774	1.37	6	10	10
14	AHGA	76,629.00	76,629.00	76,629.00	0	0.00	10	10	10
	GA	76,629.00	76,629.00	76,629.00	0	0.00	10	10	10
15	AHGA	265,000.00	265,000.00	265,000.00	0	0.00	10	10	10
	GA	265,000.00	265,000.00	265,000.00	0	0.00	10	10	10
16	AHGA	228,590.00	228,590.00	228,590.00	0	0.00	10	10	10
	GA	228,590.00	228,590.00	228,590.00	0	0.00	10	10	10

Legend: AHGA- adaptive hybrid genetic algorithm; GA- genetic algorithm; Min.- minimum; Max.- maximum; Avg.- median; σ- standard deviation; $\overline{ARPD}$- average relative percentage deviation; δ- tolerance of the best known solution.

Note: For each case study the $\omega^{Min.M\&RCosts.}_{Optimum}$ corresponds to the lowest value of the best solutions (Min.) obtained by employing the two algorithms.

By contrast, GA was only able to converge to the best known solution in all of the ten computational runs when it was applied to case studies 2, 11, 12, 14, 15 and 16. The poorest performances were observed in case studies 1 and 5, where it was found to converge to within 10% of the best know solution on 4 and 2 out of the 10 computational runs, respectively. This inconsistency translates, in both cases, to an

$\overline{ARPD}$ equal to 15%. Moreover, excluding the case studies where it revealed full ability to converge to the best known solution regardless of the relative deviation considered (i.e., 1%, 5% and 10%), only in case studies 4 and 8 did the GA converge to within 10% of the best know solution in all of the ten computational runs. However, it should be noted that, overall, for this relative deviation it was found to fail the “10 in 10” by only one computational run.

Finally, Table 7.10 shows the difference between the objective function values, d_i, of the best solutions obtained by the two algorithms as well as the *p*-values computed by the Wilcoxon signed-rank test. From this Table it can be concluded that the AGHA does not present an overwhelming superiority over the GA with respect to its capacity to consistently achieve fitter solutions. Indeed, the null hypothesis can be rejected in only 4 of the 10 case studies in which differences were observed in the fitness of the best solutions obtained by the algorithms in at least 1 of the 10 computational runs. From those four case studies, three feature a PAP of 50 years, which may suggest that the AHGA should be preferred over the GA with respect to the performance’s criterion under analysis when the case study being tackled possesses a long PAP.

Therefore, the overall conclusion that can be extracted from the Wilcoxon signed-rank test results, if only the fitness of the best solutions produced by the algorithms were to be analyzed, would be that the two algorithms exhibit a similar behavior. However, this conclusion should not be overemphasized since it strongly depends on the stopping criterion adopted. In fact, if enough time is given to the GA (it seems to be what happened in the case studies analyzed) it will reach a comparable solution to the AHGA, but the point of using the AHGA is not only to obtain high-quality solutions but also to do it in a shorter time. In the next section, the issue of how quick the algorithms are in achieving the best know solutions will be addressed.

Table 7.10- Difference between the objective function values ($), di, of the best solutions obtained by the two algorithms and Wilcoxon signed-rank test results.

Case study ID	$\omega_{Optimum}^{Min.M\&R\,Costs.}$	Computational run ID										*p*-value
		1	2	3	4	5	6	7	8	9	10	
1	522,470.00	117,100.00	-	102,040.00	26,720.00	29,800.00	-	138,390.00	137,620.00	150,450.00	66,730.00	0.01172
2	198,950.00	-	-	-	-	-	-	-	-	-	-	-
3	270,400.00	12,110.00	12,110.00	12,110.00	12,110.00	-	12,110.00	12,110.00	12,110.00	84,690.00	12,110.00	0.00389
4	230,640.00	-	-	-	-	-	5,460.00	-	-	-	-	0.31731
5	537,670.00	17,910.00	65,590.00	98,150.00	60,810.00	17,910.00	65,590.00	65,480.00	106,840.00	98,150.00	162,150.00	0.00498
6	217,220.00	-	-	17,480.00	-	-	23,840.00	-	-	19,090.00	600.00	0.06789
7	333,210.00	-	3,120.00	8,410.00	17,340.00	1,080.00	63,390.00	-38,120.00	51,100.00	-	2,950.00	0.09289
8	266,950.00	8,010.00	8,580.00	-	-2,290.00	-	-	-	1,120.00	5,130.00	-	0.13801
9	370,020.00	-	-	-	-	-	-	52,240.00	-	-	32,780.00	0.17971
10	47,390.00	21,886.00	-	-	-	-	-	-	-	-	-	0.31731
11	244,160.00	-	-	-	-	-	-	-	-	-	-	-
12	210,610.00	-	-	-	-	-	-	-	-	-	-	-
13	403,700.00	-	-	16,300.00	17,300.00	6,300.00	-	-	-	12,300.00	3,300.00	0.04311
14	76,629.00	-	-	-	-	-	-	-	-	-	-	-
15	265,000.00	-	-	-	-	-	-	-	-	-	-	-
16	228,590.00	-	-	-	-	-	-	-	-	-	-	-

Legend: $\omega_{Optimum}^{Min.M\&R\,Costs.}$ - best known solution produced over ten computational runs by the two algorithms.

7.5.2.2 Computational running time

As mentioned previously, the computational speed of an algorithm is also an important performance criterion that shouldn't be neglected when assessing its applicability. Table 7.11 reports the computational running times, per algorithm and case study, corresponding to two different instants of the search process: the discovery of the best know solution and the completion of the iteration process. From this Table it can be observed that the AHGA not only requires less time to converge to the best known solution but also denotes greater precision, as substantiated by the lower standard deviation values associated to this algorithm in comparison to those of the GA for the same case study.

Additionally, Table 7.11 is also useful in validating the results of the AHGA's calibration process. By comparing the average computational running time of case study 4, which corresponds to the discovery of the optimum solution (43.1 seconds), with the values presented in Table 7.6, one can see that none of the experiments required an inferior averaged computational running time to converge to the best know solution. The best performance was attained by experiment 13, which required, on average, approximately 10 more seconds than case study 4. A confirmation test would have been conducted if the case study considered for the calibration purpose was not among those used to compare the performances of the algorithms.

In order to assess the statistical significance of the difference of the algorithm's convergence performance throughout the search process, Page's trend test was conducted. Table 7.12 displays the cut-point rankings (r_j) computed for the absolute difference in the objective function value of the best solutions produced by the two algorithms and the summation of all r_j per cut-point (R_j).

Table 7.11- Statistics of the computational running time.

Case study ID	Type of computational running time (sec.)	GA				AHGA			
		Min.	Avg.	Max.	σ.	Min.	Avg.	Max.	σ
1	1	326.62	425.06	472.25	46.13	52.14	93.46	124.49	23.05
	2	435.08	469.81	501.25	21.23	243.73	316.11	371.08	31.06
2	1	194.53	289.24	423.56	66.98	31.04	83.97	168.87	40.02
	2	369.67	431.70	479.34	30.35	248.48	319.45	397.11	49.81
3	1	137.77	323.15	448.26	90.32	61.00	131.87	172.04	33.61
	2	321.87	483.96	656.20	90.98	241.21	321.67	361.69	34.50
4	1	160.03	302.85	518.88	102.24	30.71	43.10	55.13	7.86
	2	351.72	479.39	555.77	57.47	206.92	248.74	313.69	31.16
5	1	464.08	550.32	780.65	98.62	31.97	92.64	166.36	51.85
	2	494.21	579.93	825.10	101.80	254.46	310.49	377.26	43.61
6	1	145.37	343.93	519.09	124.14	40.74	60.53	95.90	17.57
	2	325.27	467.25	625.18	82.46	249.20	281.04	316.55	23.30
7	1	281.59	391.11	429.03	46.38	66.66	170.24	337.76	101.79
	2	438.05	457.96	484.49	15.13	293.31	434.41	647.03	106.63
8	1	122.35	306.83	444.73	91.12	35.96	131.16	217.96	67.14
	2	296.63	421.31	454.25	45.67	248.71	349.04	441.53	73.87
9	1	69.83	174.02	286.32	82.44	12.61	32.52	82.15	18.12
	2	186.21	254.45	298.79	47.27	151.45	192.64	223.89	24.62
10	1	14.68	80.06	156.64	46.13	19.42	75.40	274.36	67.72
	2	129.26	196.19	269.06	46.66	142.96	232.88	446.69	93.28
11	1	38.62	115.76	196.33	57.74	12.58	26.25	42.48	9.68
	2	162.51	268.23	411.06	86.72	133.04	178.66	237.75	37.19
12	1	58.03	89.55	144.62	25.00	12.90	20.03	38.99	7.32
	2	183.26	217.96	277.99	27.07	137.61	158.79	195.79	17.99
13	1	90.09	205.23	315.30	91.72	11.08	34.51	84.20	19.51
	2	217.69	284.45	337.43	42.63	138.00	162.10	208.00	18.94
14	1	23.06	48.26	76.27	17.11	10.12	19.82	31.42	7.48
	2	150.64	176.49	209.13	18.23	139.52	155.93	191.29	15.06
15	1	12.14	98.28	204.46	59.44	9.59	44.29	134.29	44.92
	2	147.44	227.48	327.36	57.83	133.91	171.49	250.04	39.70
16	1	17.28	111.10	252.76	64.69	11.24	66.45	150.46	42.72
	2	152.60	238.90	333.35	54.39	156.12	217.66	309.63	48.00

Legend: AHGA- adaptive hybrid genetic algorithm; GA- genetic algorithm; Min.- minimum; Max.- maximum; Avg.- median; σ- standard deviation.

Notes: 1- computational running time when the optimum solutions is found; 2- computational running time when the stopping criteria is triggered.

Table 7.12- Computation of ranks for Page’s trend test.

Case study ID	Cutting-point ID (generation ID)							
	1 (12)	2 (24)	3 (36)	4 (48)	5 (60)	6 (72)	7 (84)	8 (96)
1	1	2	3	4	5	6	7	8
2	1	2	3	4	5	6	7	8
3	1	5	3	2	4	6	7	8
4	1	2	3	4	5	6	7	8
5	1	2	3	4	5	6	7	8
6	1	2	3	4	5	6	7	8
7	1	2	3	5	8	7	6	4
8	1	2	3	4	6	5	7	8
9	1	2	3	4	5	6	7	8
10	8	7	2	1	3.5	3.5	5.5	5.5
11	1	2	3	4	5	6	7	8
12	1	2	3	4	5	6	7	8
13	1	2	3	4	5	6	7	8
14	1	2	3	4	5	6	7	8
15	1	2	3	4	5	6	7	8
16	1	2	4	7	3	6	5	8
R_j	23	40	48	63	79.5	93.5	107.5	121.5
j	1	2	3	4	5	6	7	8
$R_j \times j$	23	80	144	252	397.5	561	752.5	972

From the results presented in Table 7.12, a Page’s *L* statistic value of 3182 was computed, which corresponds to a *p*-value inferior to 0.0001 at a significance level of α=0.05. Thus, given the low *p*-value the hull hypothesis can be strongly rejected. This fact allows us to conclude that the increasing trends in the rankings observed in the last row of the Table 7.12 are backed up statistically, or, in other words, that the AHGA converges faster than the GA.

Therefore, the overall conclusion that can be extracted from the Page’s trend test results is that if the computational running time is a limiting factor, the AHGA may achieve better results in less time through the definition of stopping criteria that terminates the optimization process either when a determined amount of improvement is not achieved after a given number of iterations or when a predefined number of iterations is reached.

7.5.2.3 Analysis of learned local search operators selection probabilities and frequency of usage

This section provides insights on the role played by the several LS operators and the dynamic behavior of the ALSOS method throughout the optimization process. For that purpose, one computational run of case studies 4 and 12 was taken as an example. Figure 7.3 displays the values of the learned LS operator selection probabilities throughout the computational run of case study 4, whereas Figure 7.4 presents the identity of the LS operator applied in each LS call and the FIR resulting from its employment. In turn, Figure 7.5 and Figure 7.6 introduce the same type of information as Figure 7.3 and Figure 7.4 do, but for case study 12. From these Figures it can be seen that the outline of the applied LS operators seems to vary depending on the features of the case study being tackled as well as the stage of the optimization process at the time LS is performed. Such a result cannot be obviously disassociated from the relationship between the frequency of usage of a given LS operator and the FIR produced, although there is some randomness inherent to the stochastic nature of the AP rule employed. Although in case study 4 the largest FIR were achieved with the usage of LS operator 5, in case study 12 the most prominent FIR were obtained thanks to LS operator 4. Therefore, one can say that there is not a single best LS operator. Instead, all of them seem to play different but cooperating roles in the process of effectively solving a given problem.

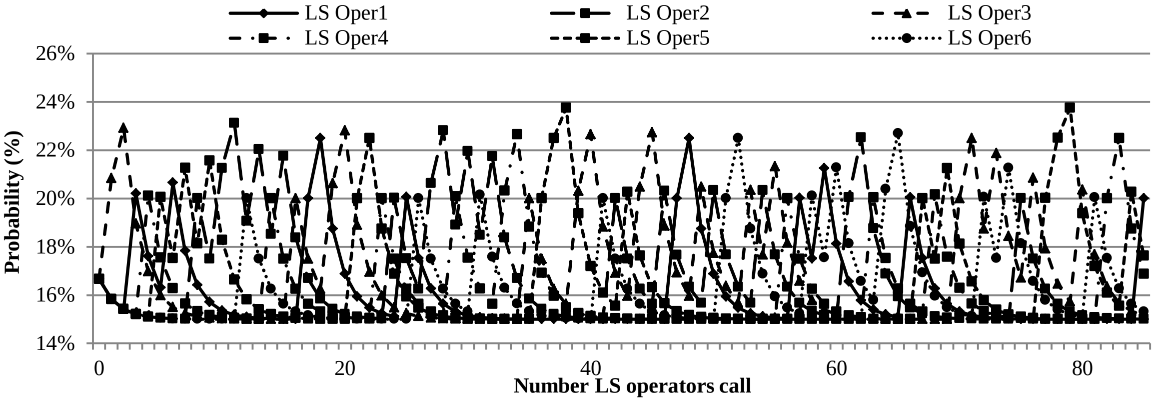


Figure 7.3- Online LS operator learned probabilities throughout the computation run for case study 4.

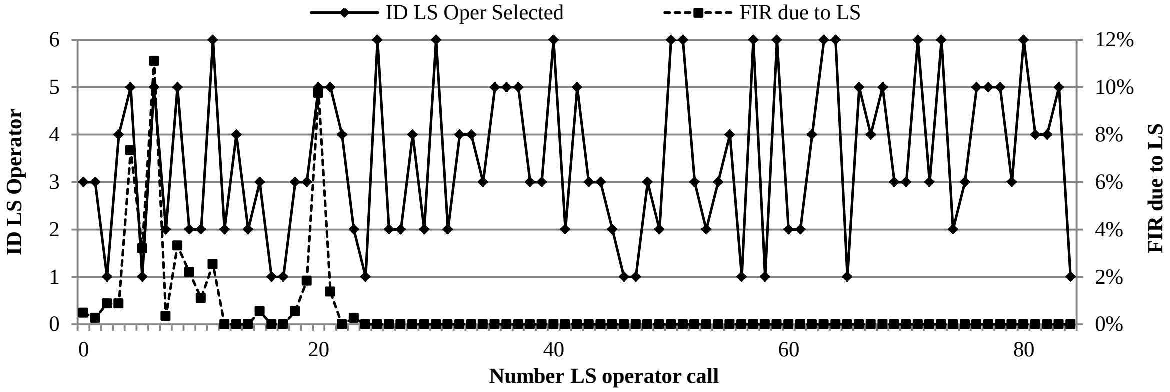


Figure 7.4- Identity of the LS operator applied in each LS call and FIR resulting from its employment for case study 4.

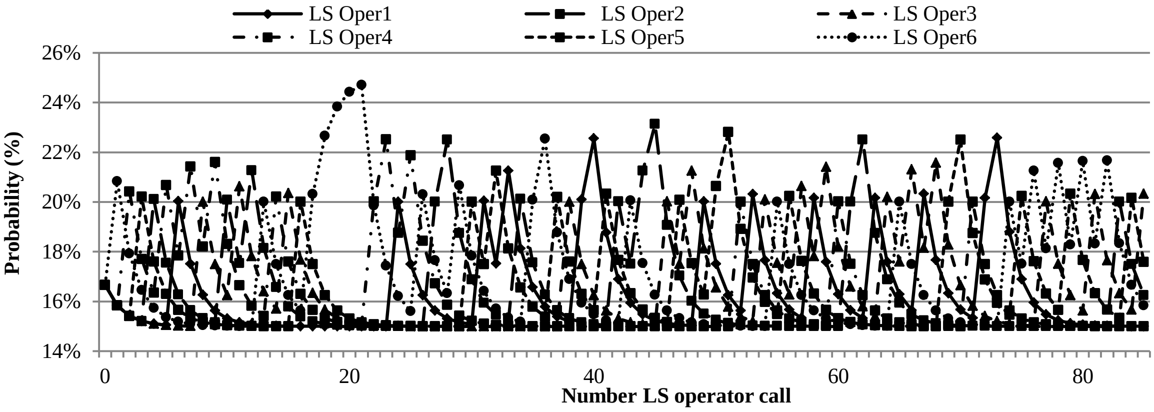


Figure 7.5- Online LS operator learned probabilities throughout the computation run for case study 12.

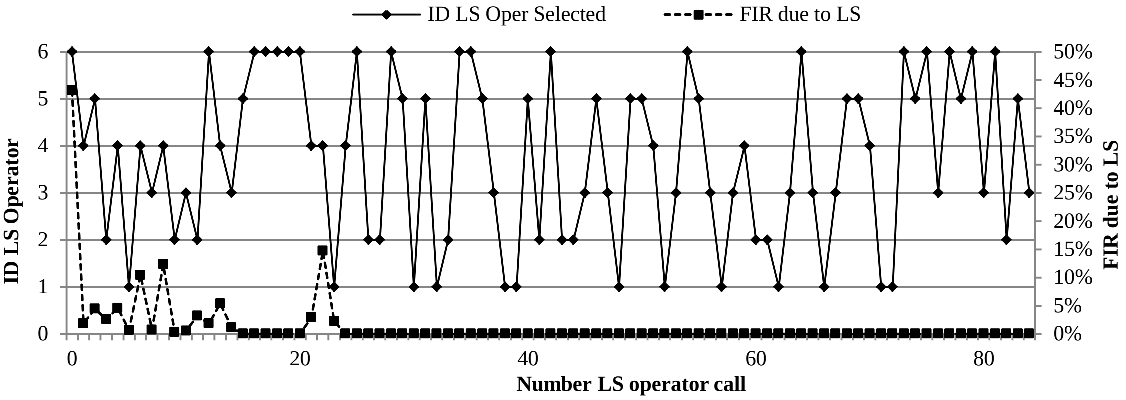


Figure 7.6- Identity of the LS operator applied in each LS call and FIR resulting from its employment for case study 12.

7.6 Summary and conclusions

This chapter presents the development of an AHGA intended to help decision makers in the field of pavement management tackle the optimization problem consisting in minimizing the life cycle M&R costs of a given pavement section throughout its PAP, while keeping the pavement condition above a predefined threshold value, meeting technical constraints and considering deterministic and non-linear PPPM.

The proposed algorithm maintains the exploring ability of a traditional GA and improves its exploiting aptitude through the execution of LS operations. Its main novelty lies on the inclusion of a pool of LS operators and the use of an adaptive LS operator selection approach within the framework of a traditional GA. Specifically, a dynamic-based learning mechanism was developed to decide on the worthiness of performing an LS and to automatically select which LS operator should be applied at each instant of the search, while solving the problem, according to how well each of the LS operators included in the pool have recently performed in the same optimization process.

After the algorithm parameters had been calibrated using the Taguchi method, its efficiency and effectiveness were compared with those of a traditional GA through its application to several case studies designed to replicate VDOT’s real-pavement management problems for a pavement section. The outcomes of the comparative experiments undertaken and accordingly supported by statistical tests proved the superiority of the proposed algorithm in consistently converging to the optimum solution while requiring a lower computational running time.

The analysis of the learned probabilities and selection frequency of the LS operators in the pool revealed that different case studies possess different patterns of LS operator usage. Furthermore, it was clearly observed that there is not a single best LS operator common to the whole search process. Rather, different search moments require distinct LS operators, advocating the usefulness of using dynamic-based adaptive mechanisms to select the most suitable LS operator while solving the problem.

Further work on this topic will follow different directions:

1) Assess the impact on the efficiency and effectiveness of the search process due to the consideration of other (i) LS operators, (ii) credit assignment mechanisms and (iii) LS operator selection techniques;
2) Investigate the benefits resulting from extending the dynamic nature of the AHGA by considering: (i) multiple selection strategies for choosing individuals in the population that will create offspring for the next generation and how many offspring each will create; (ii) multiple evolutionary operators (i.e., crossover and mutation operators); and (iii) multiple replacement strategies to determine which of the current members of the population, if any, should be replaced by the new solutions. Furthermore, work should also be carried out to study the impact of allowing automatic selection not only of which parameter and/or evolutionary operator to apply at a given moment of the search process but also the rate at which the chosen parameter and/or operator should be applied;
3) Extend the applicability of the proposed algorithm to other objective functions and problems on a larger scale.

7.7 References

Abu-Lebdeh, G., Chen, H. and Ghanim, M., 2014. Improving performance of genetic algorithms for transportation systems: case of parallel genetic algorithms. *ASCE-Journal of Infrastructure Systems*, A4014002.

Almeida, J., Teixeira, P. and Delgado, R., 2015. Life cycle cost optimisation in highway concrete bridges management. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, 11(10), 1263-1276.

Arivudainambi, D. and Rekha, D., 2013. Memetic algorithm for minimum energy broadcast problem in wireless ad hoc networks. *Swarm and Evolutionary Computation*, 12, 57-64.

Banzhaf, W., Koza, J., Ryan, C., Spector, L. and Jacob, C., 2000. Genetic programming. *IEEE Intelligent Systems and their Applications*, 15(3), 74-84.

Bi, W., Dandy, G. and Maier, H., 2015. Improved genetic algorithm optimization of water distribution system design by incorporating domain knowledge. *Environmental Modelling & Software*, 69, 370-381.

Caetano, L. and Teixeira, P., 2013. Availability approach to optimizing railway track renewal operations. *ASCE-Journal of Transportation Engineering*, 139(9), 941-948.

Chuang, Y.-C., Chen, C.-T. and Hwang, C., 2015. A real-coded genetic algorithm with a direction-based crossover operator. *Information Sciences*, 305(1), 320-348.

Derrac, J., Garcia, S., Molina, D. and Herrera, F., 2011. A practical tutorial on the use of nonparametric statistical tests as a methodology for comparing evolutionary and swarm intelligence algorithms. *Swarm and Evolutionary Computation*, 1, 3-18.

Dorigo, M., Di Caro, G. and Gambardella, L., 1999. Ant algorithms for discrete optimization. *Artificial Life*, 5(2), 137-172.

Eiben, A. and Smith, J., 2003. *Introduction to evolutionary computing*. Springer-Verlag Berlin Heidelberg.

El- Mihoub, T., Hopgood, L. Nolle, L. and Battersby, A., 2006. Hybrid genetic algorithms: a review. *Engineering Letters*, 13(2), 1- 14.

Espinoza, F. and Minsker, B., 2007. Development of the enhanced self-adaptive hybrid genetic algorithm (e-SAHGA). *Water Resources Research*, 42(8), 1-6.

Federal Highway Agency (FHWA), 2014. *2013 status of the nation's highways, bridges, and transit: conditions & performance*. Available at: http://www.fhwa.dot.gov/policy/2013cpr/pdfs.cfm

Ferreira, A., Antunes, A. and Picado-Santos, L., 2002a. Probabilistic segment-linked pavement management optimization model. *ASCE-Journal of Transportation Engineering*, 128(6), 568-577.

Ferreira, A., Picado-Santos, L. and Antunes, A., 2002b. A segment-linked optimization model for deterministic pavement management systems. *International Journal of Pavement Engineering*, 3(2), 95-105.

Fialho, A., Costa, L., Schoenauer, M. and Sebag, M., 2008. Extreme value based adaptive operator selection. 1*0th International Conference on Parallel Problem Solving From Nature (PPSN X)*, Sep 2008, Dortmund, Germany. 5199/2008, pp.175-184, 2008, Lecture Notes in Computer Science; Parallel Problem Solving from Nature- PPSN X.

Fogel, D., 1999. An overview of evolutionary programming. *In*: Davis, L.D., De Jong, K.A., Vose, M.D., Whitley, L.D. (eds.) Evolutionary Algorithms: IMA Volumes in Mathematics and its Applications, Vol. 111, Springer, New York, pp. 89-109.

Frangopol, D. and Liu, M., 2007. Maintenance and management of civil infrastructure based on condition, safety, optimization, and life-cycle cost. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, 3(1), 29-41.

Fwa, T., Chan, W., and Tan, C., 1996. Genetic-algorithm programming of road maintenance and rehabilitation. *ASCE-Journal of Transportation Engineering*, 122(3), 246-253.

Golabi, K., Kulkarni, R. and Way, G., 1982. A state-wide pavement management system. *Interfaces*, 12(6), 5-21.

Goldberg, D.,1990. Probability matching, the magnitude of reinforcement, and classifier system bidding. *Machine Learning*, 5(4), 407-425.

Goldberg, D., 1989. *Genetic algorithm in search, optimization, and machine learning*. Reading, MA: Addison-Wesley.

Hollander, M., A. Wolfe, D. and Chicken, E., 2014. *Nonparametric Statistical Methods*. 3rd Edition, John Wiley & Sons, Inc., Hoboken, NJ, USA.

Hsiao, P.-C., Chiang, T.-C. and Fu, C.-L., 2012. *A VNS-based hyper-heuristic with adaptive computational budget of local search.* In: Proceedings of the 2012 IEEE World Congress on Computational Intelligence, Brisbane, Australia, 1-8.

Jawad, D. and Ozbay, K., 2006. Probabilistic life-cycle cost optimization for pavement management at the project-level. *Transportation Research Board 85th Annual Meeting Compendium of Papers CD-ROM*, 06-1591, Washington DC, United States.

Jha, M., Schonfeld, P. and Samanta, S., 2007. Optimizing rail transit routes with genetic algorithms and geographic information system. *ASCE-Journal of Urban Planning Development*, 133(3), 161-171.

Kennedy, J. and Eberhart, R., 1995. *Particle swarm optimization*. In: IEEE International Joint Conference on Neural Networks, Perth, Western Australia, pp. 1942-1948.

Krasnogor, N., Aragon, A. and Pacheco, J., 2006. *Memetic algorithms*. In: Metaheuristics Procedures for Training Neural Networks, volume 35 of Operations Research/Computer Science Interfaces Series, Alba, E. and Martí, R. Eds. Springer US, pp. 225-247.

Li, K., Fialho, A., Kwong, S. and Zhang, Q., 2014. Adaptive operator selection with bandits for a multiobjective evolutionary algorithm based on decomposition. *IEEE Transitions on Evolutionary Computation*, 18(1), 114-130.

Maier, H., Kapelan, Z., Kasprzyk, J., Kollat, J., Matott, L., Cunha, M., Dandy, G., Gibbs, M., Keedwell, E., Marchi, A., Ostfeld, A., Savic, D., Solomatine, D., Vrugt, J., Zecchin, A., Minsker, B., Barbour, E., Kuczera, G., Pasha, F., Castelletti, A., Giuliani, M. and Reed, P., 2014. Evolutionary algorithms and other metaheuristics in water resources: current status, research challenges and future directions. *Environmental Modelling & Software*, 62, 271-299.

MATLAB, 2015. *MATLAB primer, version 8.5*. The MathWorks Inc., Natick, MA.

Mathew, B. and Isaac, K., 2014. Optimisation of maintenance strategy for rural road network using genetic algorithm. *International Journal of Pavement Engineering,* 15(4), 352-360.

McCall, J., 2005. Genetic algorithms for modelling and optimization. *Journal of Computational and Applied Mathematics,* 184(1), 205-222.

Mezura-Montes, E. and Coello Coello, C., 2011. Constraint-handling in nature-inspired numerical optimization- past, present and future. *Swarm and Evolutionary Computation*, 1(4), 173-194.

Mitchell, M., 1996. *An introduction to genetic algorithms*. Cambridge, MA: MIT Press.

Moscato, P., 1989. *On evolution, search, optimization, genetic algorithms and martial arts: Towards memetic algorithms* (Technical Report C3P 826), Caltech Concurrent Computation Program, California Institute of Technology, Pasadena, CA.

Office of Management and Budget (OMB), 2013. *Discount rates for cost-effectiveness, lease purchase, and related analyses*. Table of past years discount rates from Appendix C of OMB Circular No. A-94. Available at: http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c

Ong, Y.-S., Lim, M.-H., Zhu, N. and Wong, K.-W., 2006. Classification of adaptive memetic algorithms: a comparative study. *IEEE Transactions on Systems, Man, and Cybernetics- Part B: Cybernetics*, 36(1), 141-152.

Page, E., 1963. Ordered hypotheses for multiple treatments: a significance test for linear ranks. *Journal American Statistics Association*, 58(301), 216-230.

Roy, R., 2010. *A primer on the Taguchi method*. Michigan: Society of Manufacturing Engineers.

Santos, J. and Ferreira, A., 2013. Life-cycle cost analysis system for pavement management at project level. *International Journal of Pavement Engineering*, 14(1), 71-84.

Santos, J., Flintsch, G. and Ferreira, A., 2015a. Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability. *Resources, Conservation and Recycling* (Submitted for publication).

Santos, J., Bryce, J., Flintsch, G. and Ferreira, A., 2015b. A comprehensive life cycle costs analysis of in-place recycling and conventional pavement construction and maintenance practices. *International Journal of Pavement Engineering* (in press). http://dx.doi.org/10.1080/10298436.2015.1122190

Singh, A. and Bhukya, W., 2011. A hybrid genetic algorithm for the minimum energy broadcast problem in wireless ad hoc networks. *Applied Soft Computing*, 11(1), 667-674.

Souza, B., Carrano, E., Neto, O. and Takahashi, R., 2011. Immune system memetic algorithm for power distribution network design with load evolution uncertainty. *Electric Power Systems Research*, 81(2), 527-537.

Stantec Consulting Services and Lochner, H., 2007. *Development of performance prediction models for Virginia department of transportation pavement management system*. Virginia Department of Transportation, Richmond, VA.

Stokes, C., Simpson, A. and Maier, H., 2015. A computational software tool for the minimization of costs and greenhouse gas emissions associated with water distribution systems. *Environmental Modelling & Software*, 69, 452-467.

Storn, R. and Price, K., 1995. *Differential evolution - a simple and efficient adaptive scheme for global optimization over continuous spaces* (Technical Report TR-95-012), International Computer Science Institute, Berkeley, California.

Tessema, B. and Yen, G., 2006. *A self-adaptive constrained evolutionary algorithm*. In: Proceedings IEEE Cong. Evol. Comput., Vancouver, Canada, 246-253.

Thierens, D., 2005. An adaptive pursuit strategy for allocating operator probabilities. In: Beyer, H.G., ed.: Proc. GECCO'05, ACM Press (2005), 1539-1546.

Ting, C.-K. and Liao, C.-C., 2010. A memetic algorithm for extending wireless sensor network lifetime. *Information Sciences*, 180(24), 4818-4833.

Transportation Research Board (TRB), 2007. *Artificial intelligence in transportation-information for application*. Transportation Research Circular E-C113.

Vidal, T., Crainic, T., Gendreau, M., Lahrichi, N. and Rei, W., 2012. A hybrid genetic algorithm for multi-depot and periodic vehicle routing problems. *Operations Research,* 60(3), 611-624.

Vidal, T., Crainic, T., Gendreau, M. and Prins, C., 2013. A hybrid genetic algorithm with adaptive diversity management for a large class of vehicle routing problems with time-windows. *Computers & Operations Research*, 40(1), 475-489.

Virginia Department of Transportation (VDOT), 2014. *Manual of instructions for the materials division*. Virginia Department of Transportation Materials Division. Available at: http://www.virginiadot.org/business/materials-download-docs.asp

Wang, H., Geng, Q. and Qiao, Z., 2014. Parameter tuning of particle swarm optimization by using Taguchi method and its application to motor design. *2014 4th IEEE International Conference on Information Science and Technology (ICIST),* 722-726.

Whitley, D., Gordon, S. and Mathias, K., 1994. *Lamarckian Evolution, the Baldwin effect and function optimization*. In: Parallel Problem Solving from Nature - PPSN III vol. 866, Lecture Notes in Computer Science, Y. Davidor, H.-P. Schwefel, and R. Manner, Eds. Berlim Heidelberg: Springer-Verlag, 6-15.

Zimmerman, K., 1995. *Pavement management methodologies to select projects and recommend preservation treatments*. National Cooperative Highway Research Program Synthesis of the Highway Practice 222, Transportation Research Board, Washington, DC., 1-102.

Zong, N. and Dhanasekar, M., 2014. Hybrid genetic algorithm for elimination of severe stress concentration in railhead ends. *ASCE-Journal of Computing in Civil Engineering*, 29(5), 04014075.

Chapter 8

A Multi-Objective Optimization-based Pavement Management Decision-Support System for Enhancing Pavement Sustainability

8.1 Introduction

Road infrastructure provides a fundamental foundation to the performance of all national economies, delivering a wide range of economic and social benefits. Adequately maintaining road infrastructure is therefore essential to preserve and enhance those benefits. In order to efficiently manage their networks of this physical asset, many private and governmental agencies around the world have relied on the core principles and processes of Asset Management (AM) (World Road Association, 2014).

AM is a business process and a decision-making framework that covers an extended time horizon, drawing from economics and engineering theory and practice, to tradeoff between alternative investment options at multiple levels of decision-making, and uses this information to help agencies make cost-effective investment decisions (FHWA, 2007). Most of the current AM practices adopted by transportation agencies consist of applying economic analysis techniques, such as the LCCA, to select from among various infrastructures designs and/or M&R intervention alternatives those that are most economically appealing, according to their interests and existing constraints. However, recent recognition that transportation infrastructure management decisions and practices also have substantial impacts on the environment (Santero and Horvath, 2009), along with the increasing awareness of sustainability and climate change, have motivated governmental agencies to promote a shift in focus in the management of transportation infrastructures towards achieving sustainable transportation systems. For instance, the US DOT's Strategic Plan for the fiscal years 2014-2018 includes a separate strategic goal to "*Advance environmentally sustainable policies and investments that reduce carbon and other harmful emissions from transportation sources."* (US DOT, 2014).

In the particular case of the road pavement sector, the implementation of effective sustainable pavement management systems requires the development of approaches that enable the prediction of (1) the pavement performance, (2) the construction and maintenance-related budget requirements, (3) the costs incurred by road users and (4) the environmental impacts related to the pavement life cycle, using appropriate performance measures.

While LCCA provides an effective evaluation to pinpoint cost effective solutions for the design and maintenance of pavement systems (Walls and Smith, 1998), the environmental impacts associated with their life cycle are best characterized using a LCA approach (Santero et al., 2011). LCA is a method for determining the environmental sustainability of a product or system by calculating the resources and energy flows consumed and the consequent environmental effects from a "cradle to grave" perspective (Harvey et al., 2015). LCA provides metrics that can be used to measure progress towards sustainability (Keoleian and Spitzley, 2006), and, thus, anticipate unintended consequences of a policy or practice.

Despite the recognized merits of LCCA and LCA methods in evaluating the economic and environmental dimensions of sustainability, these methods applied individually are inefficient to optimally address the common tradeoff of relationships and interactions between life cycle sustainability indicators. Rather, they are better employed when integrated into an optimization-based pavement life cycle management framework accounting for various objectives and constraints, and allowing LCCA and LCA to be carried out in parallel. However, the traditional practice in optimized decision-making in pavement management has been based on the optimization of a single objective, mostly the minimization of LCC, which can be either the total HAC or, less often, the summation of the total HAC and RUC. It is therefore evident that a steady and effective implementation of a SPMS, through the addition of the environmental dimension to the traditional cost-based optimization framework, requires the mathematic formulation of the decision problems to migrate from the SSO to the MOO domain, in which the DMs, are provided not with one single preferred solution, but with a set of potentially preferred solutions.

Currently, the literature addressing the concomitant consideration of (1) LCC incurred by highway agencies and road users, (2) environmental metrics covering the whole pavement life cycle phases and (3) life cycle optimization models aiming to identify optimal pavement designs and/or M&R strategies based on specific objectives and constraint(s) is still in its infancy.

To the best authors' knowledge, the Zhang et al. (2010) study was the first time that environmental criteria, namely the minimization of the life cycle energy consumption and GHG emissions, were combined with costs (HAC and RUC) in a life cycle optimization model. The developed dynamic programing-based SOO model was applied at project-level to help DMs to select optimal overlay preservation strategies for three pavement overlay systems in Michigan: concrete, HMA and engineered cementitious composites (ECC), according to three different objective functions.

Since then, a few other studies have been undertaken. Zhang et al. (2012) extended the model introduced above to the network-level and applied it to compare the optimal preservation strategies with the Michigan DOT's current preservation practice. However, they did not analyze the tradeoffs between the costs and environmental indicators, since the former were converted into marginal damage costs. Yu et al. (2013)

applied a dynamic programming-based life cycle optimization model to determine an optimal preservation strategy for pavement overlay systems of a road segment that minimized LCC and energy consumption/GHG emissions. Nevertheless, the study only considered the major maintenance activities while ignoring minor ones and, similarly as the previous study, the tradeoffs between the costs and environmental indicators were not performed. Lidicker et al. (2013) used a bi-objective multi-criteria optimization model to account for the tradeoffs between environmental impacts and agency and RUC in the resurfacing problem of two pavement segments already built in California, while Reger et al. (2014) extended the previous model to tackle the multi-facility problem. However, in both cases only one type of pavement treatment, “mill-and-fill” rehabilitation activity, was accounted for and the WZ traffic management phase, which is one of the most environmentally damaging and costly for road users, was disregarded. Gosse et al. (2013) presented an expanded PMS framework with respect to the Virginia highway system, to incorporate GHG emissions and pavement performance by utilizing a multi-objective genetic algorithm (MOGA). Despite addressing the tradeoff problem between costs and environmental indicators and considering multiple treatments with different levels of robustness, the system boundaries of the LCA model did not include the two most harmful pavement life cycle phases, i.e. the usage and WZ traffic management phases, and the RUC were not accounted for. Faghih-Imani and Amador-Jimenez (2013) proposed a three-step integer linear programming method to identify the optimal set of treatments for a planning horizon, which minimize highway agency and RUC (i.e., VehOperC) energy use and GHG emissions, while trying to achieve as high a level of service as possible. Nevertheless, the environmental burdens associated with the usage and the WZ traffic management phases were once again left out of the system boundaries. Bryce et al. (2014) presents a practical optimization-based MCDM technique that relates highway agency costs, pavement condition and energy consumption resulting from implementing pavement maintenance plans at network-level. However, the environmental burdens associated with the WZ traffic management phase and the RUC were not taken into accounted.

Despite the unneglectable merits and achievements of the above mentioned studies, all of them suffer from at least one or a combination of drawbacks such as: (1) the inability to estimate the environmental and economic burdens associated with the usage and/or WZ traffic management phases; (2) the consideration of a reduced number of M&R treatment alternatives, which in some studies means that promising treatments for improving the sustainability of pavement systems, such as preventive and in-place recycling-based treatments, were not considered; (3) the consideration of short PAPs, which do not allow for the assessment of the long-term and cumulative economic and environmental impacts resulting from the decision-making process; (4) the tradeoff analysis between the costs incurred by the several pavement management stakeholders (i.e., highway agencies and road users) and environmental indicators were not carried out or if they were, they were limited to a bi-objective perspective encompassing HAC and environmental indicators, and (5) the HAC, RUC are environmental impacts are presented in an excessively aggregated manner, making it difficult for the DM to acquire insights into (i) the relative contribution of the subcomponents to the total figures, and (ii) the economic and environmental implications resulting from implementing new pavement management policies and practices, due to the lack of understanding of the relationship between parameters/processes and outcomes.

8.2 Objectives

The objective of this chapter is to present a comprehensive and modular MOO-based pavement management DSS for enhancing pavement sustainability. The main novelty of the DSS lies in the incorporation of a comprehensive and integrated pavement LCC-LCA model, along with a decision-support module, within a MOO framework applicable to pavement management. The aims of the DSS are twofold: (1) to enhance the sustainability of the pavement management policies and practices by identifying the most economically and environmentally promising pavement M&R strategies, given a set of constraints, and (2) to help DMs to select a final optimum pavement M&R strategy among the set of Pareto optimal pavement M&R strategies.

8.3 Multi-objective optimization and Pareto optimality concept

Many real-world problems commonly require optimizing more than one objective. In general, these objectives are conflicting and compete with each other, meaning that finding a solution that is optimal for all objectives at the same time is an impossible task. Therefore, the goal becomes a search for a set of solutions that are optimal according to the *Pareto optimum concept*.

Without loss of generality, let us consider a MOO problem defined as (Expression (8.1)):

$$\min F(\vec{X}) = [\, f_1(\vec{X}),\ldots,f_{N_{obj}}(\vec{X})]^T \text{ subject to } \vec{X} \in \Omega \tag{8.1}$$

Where $F(\vec{X}) = [\, f_1(\vec{X}),\ldots,f_{N_{obj}}(\vec{X})]^T$ is the vector of objective functions, N_{obj} ($N_{obj} \geq 2$) is the number of objectives, $\vec{X} = [x_1, x_2, \ldots, x_n]^T$ is the vector representing the decision variables, $\Omega \subseteq \Re^n$ represents the set of feasible solutions associated with equality and inequality constraints and bounds, $Z = F(\Omega)$ represents the set of feasible solutions in the objective space and $z = F(\vec{X}) = (y_1, y_2, \ldots, y_{N_{obj}})$, where $y_i = f_i(\vec{X})$, is a point of the objective space.

In light of the *Pareto dominance concept* extended to solutions, a solution $\vec{X} \in \Omega$ is called *dominated* by a solution $\vec{X}^* \in \Omega$ ($\vec{X}^* \prec \vec{X}$) if and only if (Expression (8.2)):

$$\forall\, i \in \{1,\ldots,N_{obj}\}: f_i(\vec{X}^*) \leq f_i(\vec{X}) \wedge \exists\, i \in \{1,\ldots,N_{obj}\}: f_i(\vec{X}^*) < f_i(\vec{X}) \tag{8.2}$$

If strict inequality holds for all N_{obj} objective functions, then $\vec{X}^*$ is said to *strictly dominate* $\vec{X}$. The non-dominance relationship determines the concept of *Pareto optimality*. A solution $\vec{X}^* \in \Omega$ is then called *Pareto optimal* if for every $\vec{X} \in \Omega$, $\vec{X}$ does not dominate $\vec{X}^*$. In other words, a Pareto-optimal solution cannot be improved in one objective without losing quality in another one. The set of all these non-dominated solutions is called the *Pareto optimal set* and represents the solutions of the MOO problem. The objective values of the *Pareto optimal set* in the objective space is named *Pareto front*. Finding the *Pareto optimal set* is then the main goal when tackling a MOO problem in the Pareto sense. Given that this goal is in many circumstances computationally intractable, heuristic algorithms are commonly employed to find as good an approximation as possible to the *Pareto front* (Ehrgott and Gandibleux, 2004).

8.4 Decision-support system methodology

The methodological framework of the DSS comprises three main modules (Figure 8.1): (1) a MOO module; (2) a comprehensive and integrated pavement LCC-LCA module; and (3) a decision-support module. The MOO module is further divided into three sub-components: (i) the formulation of the MOO model, which consists of defining the decision variables, the objective functions and constraints; (ii) the solution approach, which hosts the method to be employed to solve the MOO model and find the Pareto optimal set of solutions; and (iii) the optimization algorithm developed to solve the MOO model.

In addition to the aforementioned main modules, the architecture of the DSS includes (1) a data management module, which is responsible for gathering data, storing it in several libraries and ensuring the integrity and readiness of the data required by the multiple models incorporated into the DSS, and (2) a results report module, which provides a detailed description of the optimization results. In the following sections, each main component will be introduced in detail.

8.4.1 Multi-objective optimization model module

8.4.1.1 Multi-objective optimization model formulation

The formulation of the MOO model encompasses three main steps: (1) identification of the decision variables of the problem to be tackled; (2) definition of the objective functions; and (3) set the constraints.

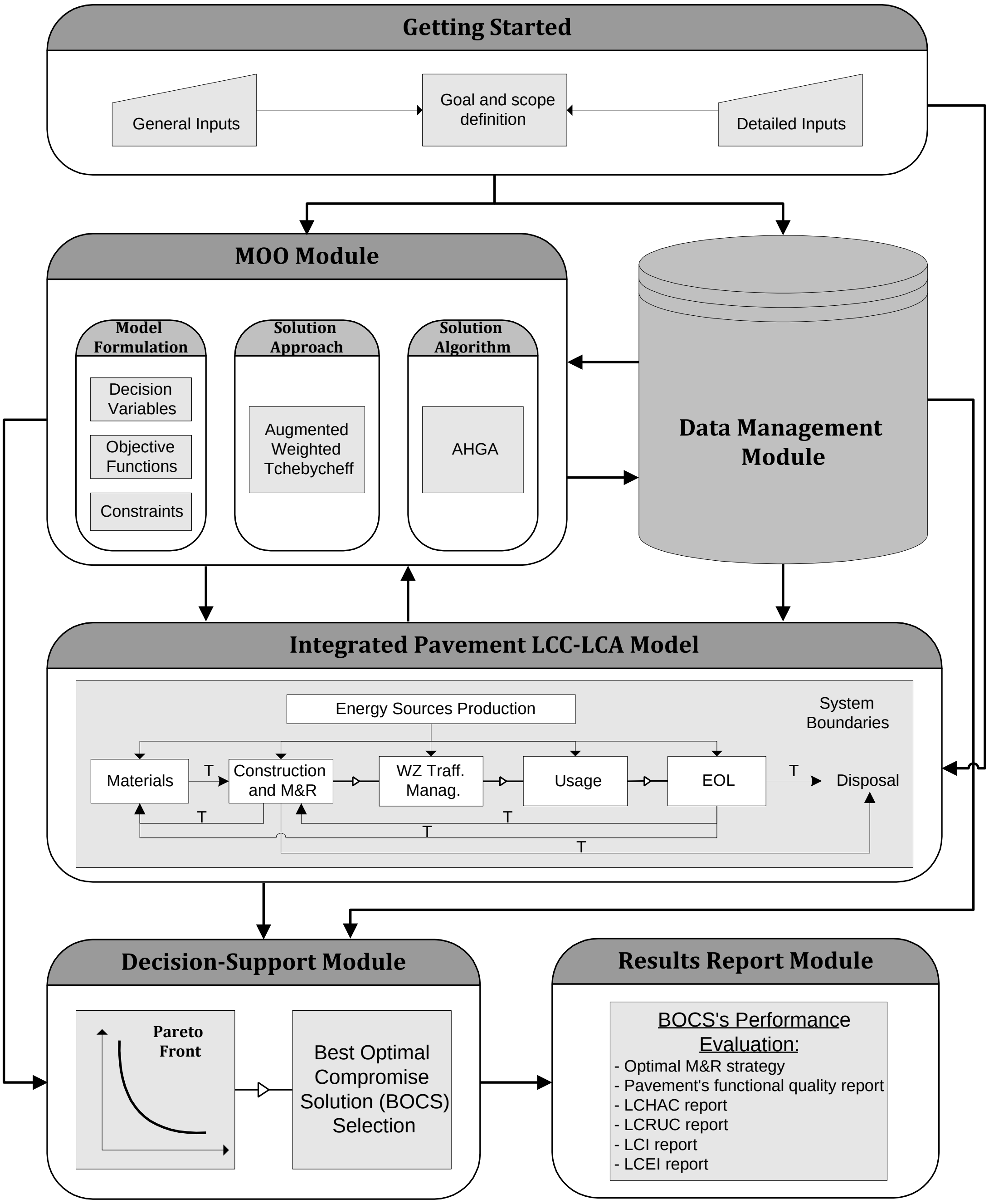


Figure 8.1- Flowchart outlining the DSS framework. Legend: MOO- multi-objective optimization; AHGA- adaptive hybrid genetic algorithm; T- transportation of materials phase; M&R- maintenance and rehabilitation; WZ Traff. Manag.- work-zone traffic management; EOL- end-of-life; BOCS- best optimal compromise solution; LCHAC- life cycle highway agency costs; LCRUC- life cycle road user costs; LCI- life cycle inventory; LCEI- life cycle environmental impacts.

The main set of decision variables of the pavement M&R strategy selection problem, which are defined by an integer figure, is designed to represent all feasible M&R activities to be performed in each pavement section and in each year of the PAP. Examples of other sets of variables include those describing the pavement performance in each year of the PAP.

As far the definition of the objective functions is concerned, the main goal underlying the development of this DSS suggests the definition of objective functions representing the commonly conflicting perspectives and interests of the three main pavement management stakeholders: highway agency, road users, and environment. Given this, the following objectives were inserted by default into the DSS: (1) minimization of the PV of the total costs incurred by highway agencies with the construction, M&R and EOL of a road pavement section throughout its life cycle; (2) maximization of the pavement performance over the PAP; (3) the minimization of the PV of the total LCRUC incurred during both the execution of a M&R activity and the normal operation of the infrastructure; and (4) the minimization of the life cycle environmental burdens arising from all pavement life cycle phases. Metrics of environmental impact are obtained by employing 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. The TRACI impact categories available for analysis include: CC; Ac due to airborne emissions; EU due to airborne emissions; HH and PSF. Furthermore, three energy-based indicators are also made available: (1) FoPE; (2) NFoPE; and (3) FsE.

Finally, the main set of constraints to be considered in the MOO model is meant to ensure that the problem solutions comply with: (1) pavement performance quality requirements; (2) annual budget limitations; and (3) technical and policy requirements.

8.4.1.2 Solution approach

Several approaches have been developed to solve MOO problems, which include, among others, aggregation methods (e.g., weighted sum method), weighted metric methods (e.g., compromise programming methods), goal programming method, achievement functions method, goal attainment method, ε-constrained method, dominance-based approaches (e.g., NSGA-II, SPEA2, PESA-II, etc.). (Miettinen, 1999; Marler and Arora, 2004; Talbi, 2009). For a thorough review of the application of MOO techniques to the highway AM problems the reader is referred to Wu et al. (2012).

In the proposed DSS, the augmented weighted Tchebycheff method is adopted to solve the MOO model. This is a modified version of the compromise programming method in which the value of the parameter p is equal to ∞. Unlike the widely applied weighted sum method, it can be applied to generate solutions on the non-convex portions of the Pareto front and overcomes the drawback of its unmodified version by alleviating the potential for solutions that are only weakly Pareto optimal (Marler and Arora, 2004).

8.4.1.3 Solution algorithm

The optimization model described in the previous sections is extremely difficult to solve to an exact optimum given its marked combinatorial nature and the difficulties in verifying, when they exist, the required mathematical properties of continuity, convexity and derivability. In fact, previous experience with a segment-linked optimization model (Ferreira et al., 2002), has shown that we cannot rely on exact methods to find guaranteed optimal solutions within an acceptable time period when applying this type of models to a real-world road network. Even for small-size instances, those algorithms may require impractically high computational times to solve them to the exact optimum when the pavement performance in the years following the application of a given treatment is modelled through a non-linear equation, which varies depending on the type of the last treatment, and in some circumstances, on the type of treatments preceding the last one, as in case study introduced later on in this chapter. Therefore, to solve the transformed SOO model, and thus generate the Pareto front, the GA-based search heuristic developed in Chapter 7 (Santos et al., 2015e) was employed. Although the GA has been thoroughly presented in the aforementioned reference, a brief overview of the method is provided in this section because it is a core component of the optimization-based DSS introduced in this chapter.

This GA possesses a hybrid nature in that LS techniques have been incorporated into the traditional GA framework to improve the overall efficiency of the search. Specifically, it contains two dynamic learning mechanisms to adaptively guide and combine the exploration and exploitation search processes. The first learning mechanism aims to reactively assess the worthiness of conducting an LS and to efficiently control the computational resources allocated to the application of this search technique. The second learning mechanism uses instantaneously learned probabilities to select which one, from a set of pre-defined LS operators which compete against each other for selection, is the most appropriate for a particular stage of the search to take over from the evolutionary-based search process.

Compared to its initial version, a change was made in the set of LS operators available for on-line selection. In particular, the “delete” LS operator originally defined in Chapter 7 (Santos et al., 2015e) was replaced by another one, named “displacement” LS operator, which can be described by the following steps: (1) randomly select a subchromosome corresponding to the time period between the application of two of the most structurally robust M&R activities; (2) randomly select one gene of the subchromosome which encodes a real M&R activity; (3) displace backwards all genes between the first gene of the subchromosome and the gene picked in the previous step; (4) in the position of the gene picked in step (1) encode a DN M&R activity. The remainders components and parameters of the algorithm remained unchanged.

8.4.2 Integrated pavement life cycle costs-life cycle assessment module

The integrated pavement LCC-LCA model follows a cradle-to-grave approach, and consists of a parallel application of the LCA methodology taking into account, as far as possible and suitable, the guidelines provided by the ISO (ISO, 2006a; ISO, 2006b) and the UCPRC’s Pavement LCA Guideline (Harvey et al., 2010) and the life cycle costing methodology based on the Swarr et al. (2011).

The pavement life cycle model covers six 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 which connect to each other by data flows computed through a hybrid life cycle inventory (LCI) approach. 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 are combined with an I-O methodology for deriving the underpinning environmental burdens. By interactively integrating the strengths of P-LCI and I-O LCI, the resources which are readily available are 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 builds on the P-LCA and LCC models introduced in Chapters 2 and 4 (Santos et al., 2015a; Santos et al., 2015b) and Chapter 5 (Santos et al., 2015c), respectively, and complement them with the Carnegie Mellon University's EIO-LCA (Carnegie Mellon University Green Design Institute, 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 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 are 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 DL, by the respective sectorial environmental multipliers obtained from the EIO-LCA model.

8.4.3 Decision-support module

Once a set of non-dominated solutions is generated representing the optimums for the problem being tackled, the DM faces a MCDM problem should he desire to choose a single Pareto optimal solution out of the Pareto optimal set. A natural idea would be to choose the solution in the Pareto front furthest from the most inferior solution, in which the most inferior solution is the one with the maximum value for all objectives, assuming that all the objective functions are meant to be minimized. In order to assist the DM with this task, a decision-support model is implemented in the proposed DSS, where the calculation of distances from the most inferior solution relies on the membership function concept in the fuzzy set theory (Zimmormann, 1996).

According to the adopted methodology the accomplishment level of each non-dominated solution j in satisfying the objective i is given by the membership function represented by Expression (8.3). The sum of the accomplishment levels of each non-dominated solution j is posteriorly rated with respect to all the M non-dominated solutions by normalizing its accomplishment over the sum of the accomplishments of the M non-dominated solutions (Expression (8.4)). The normalized membership function β_j provides de fuzzy cardinal priority ranking of each non-dominated solution j. The solution with the maximum value of β_j is considered as the best optimal compromise solution (BOCS).

$$u_i^j = \frac{f_i^{max} - f_i^j}{f_i^{max} - f_i^{min}} \tag{8.3}$$

$$\beta_j = \frac{\sum_{i=1}^{N_{obj}} u_i^j}{\sum_{i=1}^{N_{obj}} \sum_{j=1}^{M} u_i^j} \tag{8.4}$$

Where u_i^j is the membership function value for the *j*th non-dominated solution with respect to the *i*th objective; f_i^{max} and f_i^{min} are the maximum and minimum values of the *i*th objective, respectively; f_i^j is *i*th objective value for the *j*th non-dominated solution; β_j is the normalized membership function value for the *j*th non-dominated solution; N_{obj} is the number of objectives for the MOO problem; and M is the number of non-dominated solutions.

8.5 Case study

8.5.1 General description

In order to illustrate the capabilities of the proposed DSS, it is applied to two case studies consisting of determining the optimal M&R strategy for a one-way flexible pavement section of a typical Interstate highway in Virginia, USA, that yields the best tradeoff between the following three, often conflicting, objectives: (1) minimization of the PV of the total LCHAC; (2) minimization of the PV of the LCRUC; and (3) minimization of the LCEI, which in this case study is limited to one impact category for the sake of brevity. In that sense, the CC was selected because it is increasingly regulated and discussed by both governmental and non-governmental institutions.

Furthermore, for each case study two scenarios were considered depending on whether or not the most structurally robust M&R activity available for employment throughout the PAP includes recycling-based layers. The features of the case studies are shown in Table 8.1.

The road pavement sections previously described were assessed according to their economic and environmental performances in the following pavement life cycle phases: (1) materials extraction and production; (2) construction and M&R; (3) transportation of materials; (4) WZ traffic management; and (5) usage. The EOL phase was excluded from the system boundaries because the road pavement sections are expected to remain in place after reaching the end of the PAP, serving as a support for the new pavement structures. In view of this scenario, the salvage values of the pavement structures are given as the value of their remaining service life, which was proven to be negligible when compared to the costs incurred during the remaining pavement life cycle phases (Santos et al., 2015c). With regard to the environmental impacts assigned to this phase, they were disregarded on the basis of the 'cut-off' allocation method, which is the most-widely used technique to handle the EOL phase in pavements LCAs (Aurangzeb et al., 2014). According to this technique, all benefits are given to the pavement taking advantage of the reduction in the use of virgin materials due to the structural capacity provided by the existing pavement structure.

For detailed information on the processes within the system boundaries of each life cycle phase, applied modelling methodologies, assumptions and relevant data sources, the reader is referred to (Santos et al., 2015d).

Table 8.1- Features of the case study.

Name	Parameter value		Parameter unit
	Case study I	Case study II	
PAP	50	50	year
Beginning year	2011	2011	year
$AADT_0$	5000	20000	vehicle
Percentage of PCs in the AADT	75	75	%
Percentage of HDVs in the AADT	25	25	%
Traffic growth rate	3	3	%/year
Initial CCI	87	87	-
Initial IRI	1.27	1.27	m/km
Age	5	5	year
Number of lanes	2	2	-
Lanes length	1	1	km
Lanes width	3.66	3.66	m

Legend: PAP- project analysis period; $AADT_0$- Initial annual average daily traffic; AADT- annual average daily traffic; PC-passenger car; HDV- heavy duty vehicle; CCI- critical condition index; IRI- international roughness index.

8.5.2 Maintenance and rehabilitation activities

The M&R activities considered for application over the PAP were based on Chowdhury (2011), and defined as DN, PrM, CM, RM and RC. In the case of the PrM treatments, two types of treatments were considered: microsurfacing and THMACO. As for the RC treatment, two alternatives were also considered. They were named conventional RC and recycling-based RC and differ from each other in that the former comprises exclusively conventional asphalt layers, whereas the latter consists of a combination of conventional asphalt layers with in-place recycling layers. The recycling-based RC activity was designed in such a way that it provides equivalent structural capacity to its non-recycling-based counterpart and takes into account the VDOT's surface layers requirements for layers placed over recycling-based layers (VDOT, 2013). Details on the M&R actions comprising each M&R activity are shown in Table 8.2.

In order to provide insights into the economic and environmental advantages resulting from applying recycling-based M&R activities as opposed to conventional ones, M&R activities 6 and 7 were considered mutually exclusive. Therefore, in the first analysis scenario the set of feasible M&R activities comprises M&R activities numbers 1, 2, 3, 4, 5 and 6, whereas in the second analysis scenario M&R activity number 6 is replaced by its recycling-based counterpart (i.e., M&R activity number 7).

Table 8.2- Types of M&R activities and M&R actions.

M&R activity		M&R actions	Thickness (cm)	Mixture name
ID	Name			
1	DN	-	-	-
2	Microsurfacing	Surface preparation: brushing	-	-
		Surface preparation: tack coat application	-	Diluted bituminous emulsion
		Microsurfacing spreading	-	Microsurf.-Type C[a]
3	THMACO	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[b]
4	CM	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[c]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of AC surface layer	5.08 (2 in.)	SM 12.5[c]

(continued)

M&R activity		M&R actions	Thickness (cm)	Mixture name
ID	Name			
5	RM	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[c]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC intermediate layer	5.08 (2 in.)	IM 19.0[c]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC surface layer	3.81 (1.5 in.)	SM 12.5[c]
6	Conventional RC	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[c]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC intermediate layer	10.16 (4 in.)	IM 19.0[c]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC surface layer	5.08 (2 in.)	SM 12.5[c]
7	Recycling-based RC	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[d,e]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC intermediate layer	7.62 (3 in.)	IM 19.0[c]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC surface layer	5.08 (2 in.)	SM 12.5[c]

Legend: BM- base mixture; IM- intermediate mixture; SM- surface mixture; AC- asphalt concrete; CCPR- cold central plant recycling; THMACO- thin hot mix asphalt concrete overlay; DN- do nothing; CM- corrective maintenance; RM- restorative maintenance; RC- reconstruction.

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

[b] Mix 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, 2012).

[c] All mixes have a reclaimed asphalt pavement (RAP) content equal to 15%. For details on mixes properties the reader is referred to Chapter 6 (Santos et al., 2015d).

[d] A layer coefficient value of 0.40 was used for design purpose based on Diefenderfer (2014).

[e] A 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).

8.5.3 Pavement performance modelling

In order to determine the pavement performance over time, the VDOT's 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.

Using the base form corresponding to Expression (8.5), VDOT defines PPPM for the following types of M&R activities (Stantec Consulting Services and Lochner, 2007): CM, RM and CM. The coefficients of VDOT's load-related PPPM represented by Expression (8.5) for asphalt pavements of Interstate highways are presented in Table 8.3 (Stantec Consulting Services and Lochner, 2007).

$$CCI(t) = CCI_0 - e^{a + b \times c^{\ln\left(\frac{1}{t}\right)}} \tag{8.5}$$

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 8.3).

Table 8.3- Coefficients of VDOT's load-related PPPM expressed by Expression (8.5) 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

Legend: VDOT- Virginia Department of Transportation; PPPM- pavement performance prediction models; M&R- maintenance and rehabilitation; CCI_0 - critical condition index immediately after a treatment; *a, b,* and *c* are load-related PPPM coefficients; CM- corrective maintenance; RM- restorative maintenance; RC- reconstruction/Rehabilitation.

Unlike the previous M&R activity categories, VDOT did not develop individual PPPM for PrM treatments. Thus, in this case study the considered PrM treatments, i.e. microsurfacing and THMACO, were respectively modelled as an 8-point and 15-point improvement in the CCI of the road segment. Once the treatment is applied, it is assumed that the pavement deteriorates according to the PPPM of a CM, but without reduction of the effective age. 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 linear roughness prediction model, expressed in terms of International Roughness Index (IRI), was considered (Expression (8.6)).

$$IRI(t) = IRI_0 + IRI_{grw} \times t\,, \tag{8.6}$$

where $IRI(t)$ is the IRI value (m/km) in year *t*; IRI_0 is the IRI immediately after the application of a given M&R activity; and IRI_{grw} is the IRI growth rate over time, which was set at 0.08 m/km (Bryce et al., 2014). It was assumed that the application of an M&R activity other than PrM restore the IRI to the value of a brand new pavement (IRI equal to 0.87 km/h). The IRI reduction due to the application of a PrM treatment was determined based on the expected treatment life and assuming that there is no change in the value after the PrM application (the same assumption was also made in the case of the remaining M&R activities). Thus, by assuming treatment life periods of 3 and 5 years (Chowdhury, 2011), respectively for microsurfacing and THMACO treatments, reductions in the IRI value of 0.24 and 0.40 m/km were obtained.

8.5.4 Model formulation

The MOO problems introduced above can be mathematically expressed as follows:

$$Minimize\ \ OF_1 = \sum_{t=1}^{50} \frac{1}{(1+d)^t} \times \sum_{r=1}^{6} \left(C_{rt}^{MatExt\ Prod} + C_{rt}^{C.M\&R} + C_{rt}^{TM} \right) \times X_{rt} \tag{8.7}$$

$$Minimize\ \ OF_2 = \sum_{t=1}^{50} \frac{1}{\left(1+d\right)^{t}} \times \left\{ \left[\sum_{r=1}^{6} \left(VehOperC_{rt}^{WZTM} + TDC_{rt}^{WZTM} \right) \times X_{rt} \right] + VehOperC_{t}^{Usage} \right\} \quad (8.8)$$

$$Minimize\ \ OF_3 = \sum_{i=1}^{3} CF_i^{CC} \times \left\{ \begin{array}{l} \displaystyle\sum_{t=1}^{50} \left[\sum_{r=1}^{6} \left(LCI_{irt}^{MatExt\,Prod} + LCI_{irt}^{C.M\&R} + LCI_{irt}^{TM} + LCI_{irt}^{WZTM} \right) \times X_{rt} \right] + \\ LCI_{it}^{Usage} \end{array} \right\} \quad (8.9)$$

Subject to:

$$CCI_t = \Phi(CCI_0 , X_{11} ,..., X_{1t} ,..., X_{r1} ,..., X_{rt}), \qquad r = 1,...,6; \quad t = 1,...,50 \qquad (8.10)$$

$$X_{rs} \in \Omega\left(CCI_t\right), \qquad r = 1,...,6; \quad t = 1,...,50 \qquad (8.11)$$

$$CCI_t \geq CCI_{min}, \qquad t = 1,...,50 \qquad (8.12)$$

$$\sum_{r=1}^{6} X_{rt} = 1, \quad t = 1,...,50 \qquad (8.13)$$

$$\Delta t_{RC} \leq \Delta t_{RC}^{max} \qquad (8.14)$$

$$\left\{ C_{rt}^{MatExt\,Prod} ; C_{rt}^{C.M\&R} ; C_{rt}^{TM} \right\} = \Psi a \ \left(CCI_t , X_{rt} \right), \quad r = 1,...,6; \quad t = 1,...,50 \qquad (8.15)$$

$$\left\{ VehOperC_{rt}^{WZTM} ; TDC_{rt}^{WZTM} \right\} = \Psi u \ \left(CCI_t , X_{rt} \right), \quad r = 1,...,6; \quad t = 1,...,50 \qquad (8.16)$$

$$VehOperC_{t}^{Usage} = \Psi u \ \left(CCI_t \right), \quad t = 1,...,50 \qquad (8.17)$$

$$\begin{array}{l} \left\{ LCI_{irt}^{MatExt\,Prod} ; LCI_{irt}^{C.M\&R} ; LCI_{irt}^{TM} ; LCI_{irt}^{WZTM} \right\} = \Psi LCI_i \ \left(CCI_t , X_{rt} \right), \quad i = 1,...,3; \\ r = 1,...,6; \quad t = 1,...,50 \end{array} \qquad (8.18)$$

$$\left\{ LCI_{it}^{Usage} \right\} = \Psi LCI_i \ \left(CCI_t \right), \quad i = 1,...,3; \quad t = 1,...,50 \qquad (8.19)$$

Where d is the discount rate and was set to 2.3% according to OMB (2013); $C_{rt}^{MatExt\,Prod}$ is the materials extraction and production phase costs incurred by the highway agency for applying M&R activity *r* in year *t*; $C_{rt}^{C.M\&R}$ is the M&R phase costs incurred by the highway agency for applying M&R activity *r* in year *t*; C_{rt}^{TM} are the transportation of the materials phase costs incurred by the highway agencies for applying M&R activity *r* in year *t*; X_{rt} is equal to one if M&R activity *r* is applied in year *t*, otherwise it is equal to zero; $VehOperC_{rt}^{WZTM}$ are the VehOperC incurred by the road users during the WZ traffic management phase due to the application of the M&R activity *r* in year *t*. It includes five types of VehOperC subcategories: (1) FC; (2) oil consumption; (3) tyre wear; (4) vehicle maintenance and repair; and (5) vehicle depreciation. TDC_{rt}^{WZTM} are the TDC incurred by the road users during the WZ traffic management phase due to the application of the M&R activity *r* in year *t*; $VehOperC_{t}^{Usage}$ are the marginal VehOperC incurred by the road users in year *t* of the PAP as a consequence of the deterioration of the pavement condition. It includes four types of VehOperC subcategories: (1) FC; (2) tyre wear; (4) vehicle maintenance and repair; and (5) mileage-related vehicle depreciation. CF_{i}^{CC} is the CC characterization factor for inventory flow *i*, given by the IPCC's characterization model for a horizon period of 100 years (IPCC, 2007). The following GHG were considered to contribute to CC impact category: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). $LCI_{irt}^{MatExt\,Prod}$ is the quantity of the inventory flow *i*, released during the materials extraction and production phase associated with the execution of the M&R activity *r* in year *t*; $LCI_{irt}^{C.M\&R}$ is the quantity of the inventory flow *i*, released during the M&R phase associated with the execution of the M&R activity *r* in year *t*; LCI_{irt}^{TM} is the quantity of the inventory flow *i*, released during the transportation of materials phase associated with the execution of the M&R activity *r* in year *t*; LCI_{irt}^{WZTM} is the quantity of the inventory flow *i*, released during the WZ traffic management phase associated with the execution of the M&R activity *r* in year *t;* LCI_{it}^{Usage} is the quantity of the inventory flow *i*, released in year *t* of the usage phase of the road pavement section; CCI_t is the CCI value in year *t*; CCI_{min} is the minimum CCI value allowed for a pavement structure and was set to 40; Δt_{RC} is the time interval between the application of two consecutives M&R activities of type RC; Δt_{RC}^{max} is the maximum time interval between the application of two consecutives M&R activities of type RC; Φ are the pavement condition functions; Ω are the feasible M&R activities sets; Ψa are the HAC; Ψu are the RUC functions; ΨLCI_i are the LCI functions.

Expression (8.7), the first objective function of this quite complex, highly non-linear discrete optimization model, expresses the minimization of the PV of the total LCHAC. Expression (8.8) expresses the minimization of the PV of the total LCRUC. Expression (8.9) expresses the minimization of total life cycle CC score (LCCCsc).

Constraints (8.10) correspond to the pavement condition functions given by Expression (8.5) and Table 8.3. They express the CCI of the pavement section in each year *t* as a set of functions of the initial condition (CCI_0) and the M&R activities previously applied to the pavement. Constraints (8.11) represent the feasible operation sets, i.e. the M&R activities that can be applied to maintain or rehabilitate the pavement structure in relation to its quality condition. In this case study, two sets were considered. The first one, adopted in scenario analysis I, comprises M&R activities 1, 2, 3, 4, 5 and 6 (Table 8.2). The second, adopted in scenario analysis II, includes M&R activities 1, 2, 3, 4, 5 and 7 (Table 8.2). Constraints (8.12) are the warning level constraints which define the minimum CCI value allowed for a pavement structure. Constraints (8.13) indicate that only one M&R activity should be performed in each year. Constraint (8.14) represents technical limitations which impose limits to the life of the initial pavement design and RC treatment. Its inclusion in the model is based on the VDOT criteria according to which the initial pavement design is equal to 30 years (VDOT, 2014). Constraints (8.15) represent the LCHAC which are computed in relation to the pavement condition and the M&R activity applied to the pavement in a given year. The total unitary M&R costs are presented in Table 8.4 and were computed according to the methodology presented in Chapter 5 (Santos et al., 2015c). Constraints (8.16) represent the LCRUC which are computed in relation to the M&R activity applied to the pavement in a given year. Constraints (8.17) represent the LCRUC which are computed in relation to the pavement condition observed in each year *t* of the PAP. The values of the unit costs of travel time are given in Table 8.5. Constraints (8.18) correspond to the LCI functions which are computed in relation to the M&R activity applied to the pavement in a given year. Constraints (8.19) correspond to the LCI functions which are computed in relation to the pavement condition observed in each year *t* of the PAP. For a deep understanding on the methodologies and formulations adopted to calculate the multiple subcategories of HAC and RUC as well as the LCI associated with the several pavement life cycle phases, the reader is referred to the Chapters 4, 5 and 6 (Santos et al., 2015b; Santos et al., 2015c; Santos et al., 2015d).

Table 8.4- Unit costs of the M&R activities.

ID	Name	Total MC ($/Km.lane)
1	DN	0
2	PrM: microsurfacing	6,621
3	PrM: THMACO	17,593
4	CM	35,696
5	RM	58,969
6	Conventional RC	199,594
7	RC	120,960

Legend: MC- maintenance and rehabilitation costs; DN- do nothing; PrM- preventive maintenance; THMACO- thin hot-mix asphalt concrete overlay; CM- corrective maintenance; RM- restorative maintenance; RC- reconstruction/rehabilitation.

Table 8.5- Unit cost of travel time for the several categories of vehicles.

Item	Unit cost of travel time ($/hr)
Hourly time value of PCs	28.70
Hourly time value of SUTs	22.42
Hourly time value of CUTs	29.27
Hourly freight inventory costs for SUTs	0.21
Hourly freight inventory costs for CUTs	0.31

Legend: PC- passenger car; SUT- single-unit truck; CUT- combination unit truck.

8.5.5 Solution approach

In order to solve the MOO model and find the Pareto optimal set of solutions the augmented weighted Tchebycheff method was employed (Dächert et al., 2012). To that end, the MOO problems were converted into a SOO one, by combining the three aforementioned objectives into a single objective, which is expressed as follow (Expression (8.20) and Expression (8.21)):

$$\max_{i=1,\ldots,3}\left[w_i \times \frac{f_i(\vec{x}) - f_i^{min}}{f_i^{max} - f_i^{min}}\right] + \rho \times \sum_{i=1}^{N_{obj}} \frac{f_i(\vec{x}) - f_i^{min}}{f_i^{max} - f_i^{min}}\ , \tag{8.20}$$

Subject to:

$$\begin{gathered} w_i \geq 0, \quad i = 1,\ldots,N_{obj}, \quad \sum_{i=1}^{Nobj} w_i = 1, \quad \rho \in \Re \\ w_i + \rho > 0, \quad i = 1,\ldots,N_{obj} \end{gathered} \tag{8.21}$$

Where w_i is the weight assigned to the objective *i*; $f_i(\vec{x})$ is the value of the objective function *i* for the solution $\vec{x}$; f_i^{min} is the minimum allowed value of the i^{th} objective function; f_i^{max} is the maximum allowed value of the i^{th} objective function; N_{obj} is the number of objectives for the MOO problem being considered (i.e., 3) and ρ is a non-negative scalar, which was set at 10^{-3} based on Steuer (1986).

8.5.6 Results and discussion

The aforementioned non-linear optimization model was solved with the AHGA developed in Chapter 7 (Santos et al., 2015e), by varying the weights through a grid of values from 0 to 1 in an increment step of 0.01. The AHGA was written in MATLAB® programming software (MATLAB, 2015), and run on a computational platform Intel Core 2 Duo 2.4 GHz processor with 4.00 GB of RAM, on the Windows 7 professional operating system. AHGA parameters utilized for this case study are the same as those determined in Chapter 7 (Santos et al., 2015e).

8.5.6.1 Non-recycling-based maintenance and rehabilitation strategies

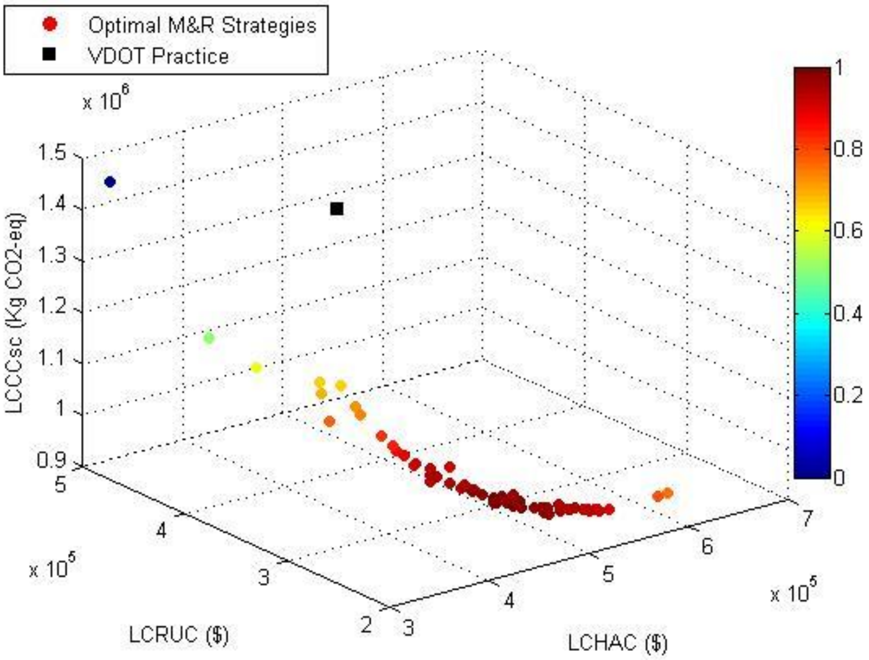
Figure 8.2 displays the Pareto optimal set of solutions in the objective space, outlining the optimal pavement M&R strategies for the non-recycling-base case study, along with the M&R strategy defined by VDOT. Complementarily, to determine the strength of the relationship between the objectives considered in the MOO analysis, and thus help to interpret the behavior of the Pareto front, a Spearman's correlation analysis was performed. It uses a correlation coefficient, named Spearman rank correlation coefficient (r_s) to measure the monotonic relationship between two variables (i.e., whether one variable tends to take either a larger or smaller value, though not necessarily linearly) by increasing the value of the other variable (Expression (8.22)) (Machin et al., 2007). The value of the correlation coefficient defines two properties of the correlation: (1) the sign of r_s (i.e., negative or positive) defines the direction of the relationship and (2) the absolute value of r_s, which varies between -1 and 1, indicates the strength of the correlation. In turn, the square of r_s, named coefficient of determination, gives the proportion of the variation of one variable explained by the other (Zou et al., 2003).

The Spearman rank correlation method was employed in detriment of the well-known Pearson correlation method because the first does not require the assumptions of normality and linearity. Furthermore, to test whether a calculated r_s value is significantly different from a hypothesized population correlation coefficient (ρ) of zero, a significant test was used. The statistical test of the null hypothesis $\rho = 0$ is given by Expression (8.23) and follows a Students' t-distribution with $df = n - 2$ (Machin et al., 2007).

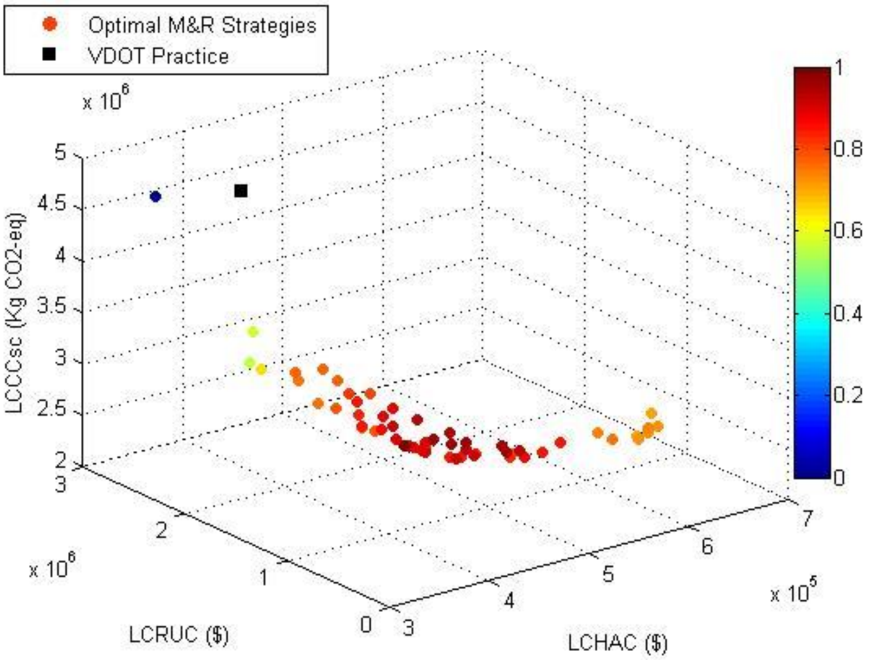
$$r_s = 1 - \frac{6 \times \sum_{i=1}^{n} d_i^2}{n^3 - n} , \tag{8.22}$$

$$t = r_s \times \frac{\sqrt{n-2}}{\sqrt{1 - r_s^2}} \tag{8.23}$$

Where r_s is the Spearman rank correlation coefficient; d_i is the difference in paired ranks i; n is the number of paired ranks; and t is the two tailed t-test value calculated for a significance level (α) of 0.05. The r_s and r_s^2 values along with the statistical tests results are presented in Table 8.6.



(a)



(b)

Figure 8.2- M&R strategy defined by VDOT and non-recycling-based Pareto optimal fronts: (a) case study I and (b) case study II. Legend: LCHAC- life cycle highway agency costs; LCRUC- life cycle road user costs; LCCCsc- life cycle climate change score. Note: The fuzzy cardinal priority ranking of each non-dominated solution was normalized so that it falls into the range [0;1].

Table 8.6- Spearman rank correlation coefficient values, determination coefficient values and statistical tests results (r_s; r_s^2; $t(calc.)$; $t(\alpha=0.05)$).

Case study		LCHAC	LCRUC	LCCCsc
I	LCHAC	-	-0.90; 0.81; -79.834; 2.002	-0.86; 0.74; -47.399; 2.002
	LCRUC	-0.90; 0.81; -79.834; 2.002	-	0.98; 0.96; 35.080; 2.002
	LCCCsc	-0.86; 0.74; -47.399; 2.002	0.98; 0.96; 35.080; 2.002	-
II	LCHAC	-	-0.70; 0.49; -8.575; 2.001	-0.81; 0.65; -21.229; 2.001
	LCRUC	-0.70; 0.49; -8.575; 2.001	-	0.74; 0.55; 4.931; 2.001
	LCCCsc	-0.81; 0.65; -21.229; 2.001	0.74; 0.55; 4.931; 2.001	-

Legend: LCHAC- life cycle highway agency costs; LCRUC- life cycle road users costs; LCCCsc- life cycle climate change score; r_s- Spearman rank correlation coefficient; r_s^2- coefficient of determination; $t(calc.)$- two tailed t-test value calculated for a significance level (α) of 0.05; t(α=0.05)- critical value of the t-distribution for α equal to 0.05.

Key (http://www.statstutor.ac.uk/): $r_s = 0$- no correlation; $r_s \in\ ]0; 0.2[$- very weak correlation; $r_s \in [0.2; 0.4[$- weak correlation; $r_s \in [0.4; 0.6[$- moderate correlation; $r_s \in [0.6; 0.8[$- strong correlation; $r_s \in [0.8; 1[$- very strong correlation; $r_s = 1$- perfect correlation.

For a low-volume traffic roadway the results in Table 8.6 show a very strong correlation between the objective functions. In other words, an increase in the LCHAC not only leads to a reduction in the LCRUC but it is also beneficial in reducing the LCCCsc. Moreover, over 96% of the variance of one objective function can be explained by the other. On the other hand, for a high-volume traffic roadway the results in Table 8.6 show a degradation of the strength of the association between the objective functions. Specifically, while a ‘very strong’ correlation between the LCHAC and LCCCsc is still observed, the correlations between LCHAC and LCRUC and between LCRUC and LCCCsc are only ‘strong’. That explains why for the low-volume traffic roadway the Pareto front is nearly two-dimensional, whereas for the heavier traffic class its shape is better described as a cloud of points, meaning that highway agencies are presented with a greater variety of potential solutions within a narrow range of LCHAC values.

As far the statistical significance of the relationships between the objective functions described above is concerned, the results presented in Table 8.6 provide evidence in support of the rejection of the null hypothesis ($|t(calc)|>t(0.05)$) in all statistical hypothesis tests undertaken.

Despite the overall reduction in LCRUC and LCCCsc that can be achieved by increasing highway agency expenditures, a carefully analysis of Figure 8.2 reveals that there exists an investment level after which the Pareto fronts denote a flat trend, though it is more evident in the case of the least trafficked roadway. That trend means that any increase in pavement M&R expenditures has a greatly reduced reflex in reducing both the LCRUC and LCCCsc. Moreover, when a rough comparison is made, for low-volume traffic roadways, the majority of the non-dominated M&R strategies seems to be located in the flatter section of the Pareto front (which corresponds to the higher LCHAC), whereas for high-volume traffic roadways, the majority of the non-dominated M&R strategies seems to be located in the steeper section of the Pareto front. The practical implication of this change in the tradeoff relationships is that for pavement sections carrying high traffic volumes the money is likely to have a better marginal value than that for pavement sections carrying low traffic volumes. However, due to the deterioration of the strength of the relationships between the objectives observed for the heavier traffic class, the validity of the relationships previously described cannot be fully taken as guaranteed.

Table 8.7 and Table 8.8 detail the features of the BOCSs chosen according to the methodology described in section 8.4.3 as well as the M&R strategy defined by VDOT. Table 8.9 and Table 8.10 present the variation of the LCHAC, LCRUC and LCCCsc for the BOCSs when compared to the current VDOT practice. These results are to be understood as follows: positive numbers mean that the BOCSs improve on VDOT practice, while negative numbers represent a deterioration of the metrics considered. According to the results presented in these tables, the selected optimal M&R strategies always improve on VDOT practice with regard to LCRUC and LCEI for both traffic classes. However, if for the heavier traffic class this result is accompanied by a reduction in the LCHAC (16%), in the case of the least demanding traffic class it comes at the cost of an increase in the expenditures incurred by the highway agency (8%). This result is explained by the type and frequency of M&R activities belonging to the respective optimal M&R strategies. While the optimal M&R strategy for case study II comprises six M&R activities, five of which are scheduled to take place in the second half of the PAP when the traffic volume is more intense and the discounting factors present lower values, the optimal M&R strategy for case study I features ten evenly distributed M&R activities. Although half of the ten M&R activities are PrM treatments (i.e., microsurfacing or THMACO), which incur the lowest costs among those available for selection, the fact that the total number of required M&R activities is double that of the VDOT practice (i.e., 5) explains the increase in the LCHAC.

Table 8.7- M&R strategies of the best non-recycling-based optimal compromise solutions and current VDOT practice.

Case study	Type of M&R strategy	M&R activity ID (application year)										Avg. CCI	Avg. IRI
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		
I	Current VDOT practice	4 (7)	5 (17)	6 (27)	4 (39)	5 (49)	-	-	-	-	-	82.74	1.27
II		4 (7)	5 (17)	6 (27)	4 (39)	5 (49)	-	-	-	-	-	82.74	1.27
I	Optimal	2 (2)	4 (6)	4 (14)	2 (20)	6 (24)	2 (30)	4 (33)	3 (38)	4 (43)	3 (47)	82.88	1.08
II		4 (13)	6 (25)	2 (32)	4 (36)	4 (41)	3 (46)	-	-	-	-	77.18	1.30

Legend: M&R- maintenance and rehabilitation; VDOT- Virginia Department of Transportation; Avg.- average; CCI- critical condition index; IRI- international roughness index.

Table 8.8- Objective function values of the best non-recycling-based optimal compromise solutions and current VDOT practice.

Case study	Type of M&R strategy	LCHAC ($)	LCRUC ($)	LCCCsc (Kg CO_2-eq)	W_{HAC}	W_{RUC}	W_{Env}
I	Current VDOT practice	425,163.98	373,159.66	1,451,953	-	-	-
II		425,163.98	2,665,172.68	4,512,113	-	-	-
I	Optimal	460,727.78	255,321.72	968,758	0.4	0.4	0.2
II		357,559.71	1,925,908.77	3,356,906	0.8	0.1	0.1

Legend: M&R- maintenance and rehabilitation; VDOT- Virginia Department of Transportation; LCHAC- life cycle highway agency costs; LCRUC- life cycle road users costs; LCCCsc- life cycle climate change score; W_{HAC}- weight assigned to the highway agency costs objective function; W_{RUC}- weight assigned to the road users costs objective function; W_{Env}- weight assigned to the environmental impacts objective function.

Another result of interest shown in Table 8.7-Table 8.10 is the fact that the reduction in the LCRUC and LCEI for the heavier traffic class is achieved even though the optimal M&R strategy leads to a slight reduction in the average pavement condition throughout the pavement life cycle. This is because in the optimal M&R strategy five out of six M&R activities are scheduled to take place in the second half of the PAP, whereas the VDOT practice consists of applying only three M&R activities in the same time period, thereby ensuring that the pavement is kept in good overall condition when the traffic is particularly intense.

Table 8.9- Variation of the LCHAC and LCRUC for the non-recycling-based BOCSs when compared to the current VDOT practice.

Stakeholder	Life cycle phase	Case study			
		I		II	
		Absolute ($)	Relative (%)	Absolute ($)	Relative (%)
Highway agency	Materials	-24,315.82	-5.72	49,497.71	11.64
	M&R	-1,194.01	-0.28	7,564.73	1.78
	Transp. of materials	-10,053.97	-2.36	10,541.82	2.48
	Total	-35,563.80	-8.36	67,604.27	15.90
Road users	WZ traffic management	-11,364.37	-3.05	768,696.39	28.84
	Usage	129,202.31	34.62	-29,432.48	-1.10
	Total	117,837.94	31.58	739,263.91	27.74
	Total global	82,274.14	23.21	806,868.18	43.64

Legend: LCHAC- life cycle highway agency costs; LCRUC- life cycle road users costs; BOCS- best optimal compromise solution; VDOT- Virginia Department of Transportation; M&R- maintenance and rehabilitation; Transp. of Materials- transportation of materials; WZ- work-zone.

Table 8.10- Variation of the LCCCsc for the best non-recycling-based optimal compromise solutions when compared to the current VDOT practice.

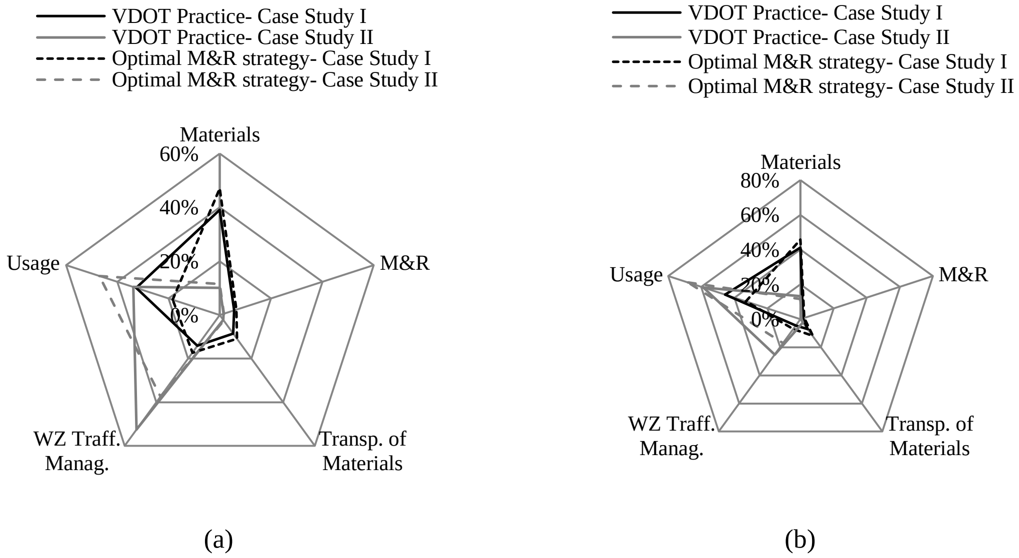
Stakeholder	Life cycle phase	Case study			
		I		II	
		Absolute (Kg CO_2-eq)	Relative (%)	Absolute (Kg CO_2-eq)	Relative (%)
Highway agency	Materials	153,878	10.60	210,375	4.66
	M&R	425	0.03	3,661	0.08
	Transp. of materials	-12,006	-0.83	12,988	0.29
Road users	WZ traffic management	-2,307	-0.16	562,000	12.46
	Usage	343,204	23.64	366,184	8.12
	Total global	483,195	33.28	1,155,207	25.60

Legend: LCCCsc- life cycle climate change score; VDOT- Virginia Department of Transportation; M&R- maintenance and rehabilitation; Transp. of Materials- transportation of materials; WZ- work-zone.

When analyzing the relevance of each pavement life cycle phase in the relative variation of the three metrics as a consequence of implementing the optimal M&R plans, Table 8.9 and Table 8.10 show that the materials phase, among those directly related to the highway agencies' responsibilities (i.e., materials extraction and production, M&R and transportation of materials), always has the greatest influence in either the increase or decrease of the LCHAC. With regard to LCRUC, it can be seen that the traffic volume does not play a uniform role. In other words, for low-volume traffic roadways implementing the best optimal compromise M&R strategy results in a reduction of the non-WZ RUC (approximately 35%) and in a slight increase of the WZ RUC (approximately 3%). In turn, for high-volume traffic roadways there is a reduction in the WZ RUC (approximately 29%) and a small increase in the non-WZ RUC (approximately 1%) when the best optimal compromise M&R strategy is implemented in lieu of the current VDOT's M&R strategy. However, regardless of the traffic volume, the reductions in the LCRUC achieved through the implementation of the optimal M&R strategies always outperform the increase in the costs occurred during either the WZ traffic management phase or the usage phase. Finally, the analysis of the variations of the LCCCsc allows us to come to a conclusion on the GHG emissions reductions that are expected to be obtained across all pavement life cycle phases when the optimal M&R strategy is implemented in a high-volume traffic roadway. Such reductions are more substantial during the WZ traffic management (12%) and materials (5%) phases. Different relative results are reported in the case of low-volume traffic roadways, where the most meaningful reductions are attained during the usage phase (24%), while transportation of materials and WZ traffic management were found to contribute negatively to a small percentage increase in the environmental burdens.

To provide an overall understanding of the relative importance of the traffic volume in the distribution of the costs and environmental impacts, the breakdown of the LCC and LCCCsc per pavement life cycle phase is provided in Figure 8.3a and Figure 8.3b, respectively. Figure 8.3a depicts that for low-volume traffic roadways the LCHAC are slightly greater than the LCRUC. Behind this result are the materials and usage phases that were found to be the biggest contributors to the total LCC in contrast to the M&R phase that is only a minor contributor. This is true for both M&R strategies, i.e. current VDOT practice and optimal M&R strategy, although the latter implies, respectively, an increase and a decrease in the contributions the materials and usage phases and a rise in the importance of the WZ traffic management. For high-volume traffic roadways, the LCRUC overwhelm the LCHAC, although the pavement life cycle phase that is responsible for the greatest share varies depending on the M&R strategy considered. Specifically, in a maintenance scenario where the current VDOT practice is adopted, the majority of the LCRUC are incurred during the WZ traffic management phase, whereas the usage phase is more costly to road users when the optimal M&R strategy is implemented. Regardless of the maintenance scenario adopted, the M&R and transportation of materials remain the least costly life cycle phases.

In terms of the LCCCsc, analysis of Figure 8.3b reveals the existence of two dominant phases. For heavily trafficked pavements, the cumulative effects of rolling resistance on fuel economy and vehicle emissions become much greater than the environmental burdens arising from the joint effect of the remaining phases. On the other hand, for pavements carrying low volumes of traffic, the materials phase takes the leader in the raking of the least environmentally-friendly pavement life cycle phases, although in percentage terms this is not as marked as the usage phase in the case of the high-volume traffic roadways.

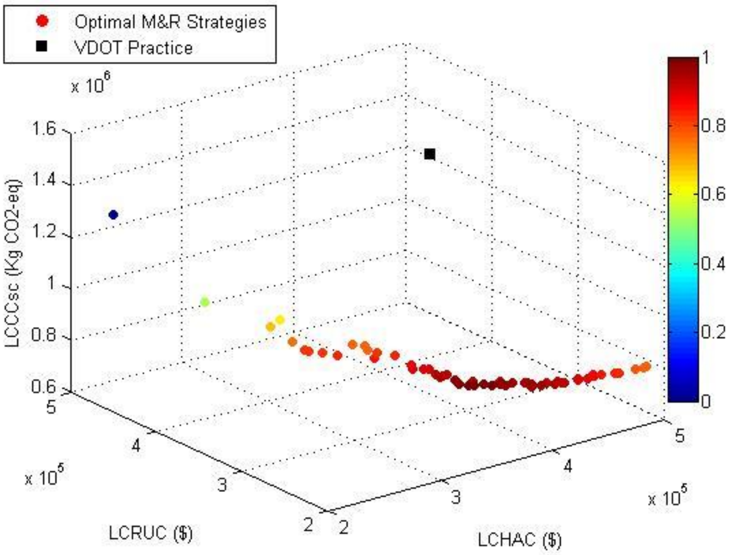


(a) (b)

Figure 8.3- Breakdown of the (a) LCC and (b) LCCCsc per pavement life- cycle phase. Legend: M&R- maintenance and rehabilitation; Transp. of Materials- transportation of materials; WZ- work-zone.

8.5.6.1 Recycling-based maintenance and rehabilitation strategies

Figure 8.4 depicts the Pareto optimal set of solutions for the maintenance scenario where the M&R activity of type RC combines conventional asphalt layers with in-place recycling layers. From this figure one can see that the Pareto front exhibits the same overall trend as that observed when the RC treatment consists of exclusively non-recycling-based asphalt layers (Figure 8.2). More interestingly, this figure, when analyzed in conjunction with Figure 8.2, also shows that the entire Pareto front shifts down and towards the intersection of the LCHAC and LCRUC axis, resulting in significant costs and emissions savings across the pavement life cycle. This change will benefit both the highway agency and road users, with each seeing a decrease in the limits of the range of costs corresponding to the set of non-dominated solutions. Taking the high-volume traffic roadway section as an example, the lower and upper bounds of the LCHAC will respectively decrease by 29% and 14%, whereas the road users are expected to experience more modest reductions in the incurred costs, which amount to 2% and 1%, respectively, for the lower and upper boundaries. With regard to the range of GHG emissions, the lower and upper boundaries are likely to be reduced by 8% and 3%, respectively.



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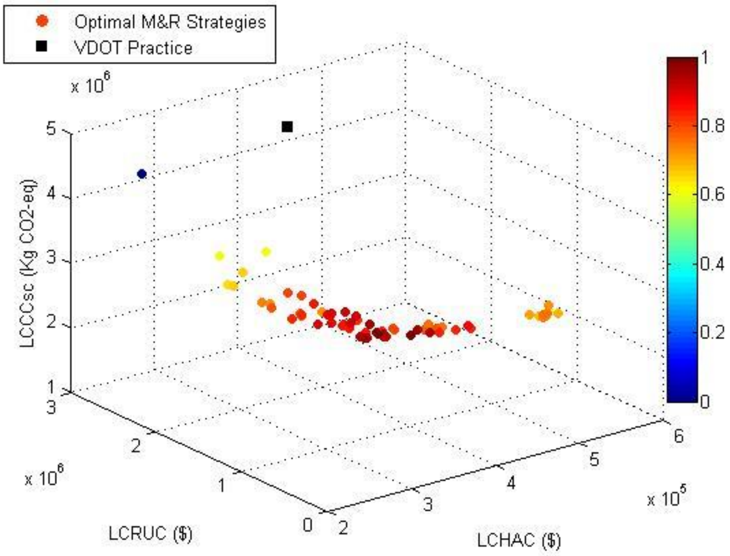

(b)

Figure 8.4- M&R strategy defined by VDOT and recycling-based Pareto optimal fronts: (a) case study I and (b) case study II. Legend: LCHAC- life cycle highway agency costs; LCRUC- life cycle road user costs; LCCCsc- life cycle climate change score. Note: The fuzzy cardinal priority ranking of each non-dominated solution was normalized so that it falls into the range [0;1].

Table 8.11 and Table 8.12 detail the features of the best recycling-based optimal compromise M&R strategies chosen according to the methodology described in section 8.4.3 as well as the M&R strategy defined by VDOT, but in which no recycling-based M&R activities are considered. Table 8.13 and Table 8.14 present the variation of the LCHAC, LCRUC and LCCCsc for the BOCSs when compared to the current VDOT practice. As stated in the previous paragraph, Table 8.12-Table 8.14 show that, compared to the M&R plan in current VDOT practice, both costs and GHG emissions are considerably lower for the best optimal compromise M&R strategies in both traffic scenarios. For instance, GHG emissions could be reduced by 45% and LCHAC and LCRUC by 13% and 59%, respectively, if the highway agency switched the adopted M&R strategy to the BOCS among those lying on the Pareto front for a high-volume traffic roadway.

Table 8.11- M&R strategies of the best recycling-based optimal compromise solutions and current VDOT practice.

Case study	Type of M&R strategy	M&R activity ID (application year)										Avg. CCI	Avg. IRI
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		
I	Current VDOT practice	4 (7)	5 (17)	6 (27)	4 (39)	5 (49)	-	-	-	-	-	82.74	1.27
II		4 (7)	5 (17)	6 (27)	4 (39)	5 (49)	-	-	-	-	-	82.74	1.27
I	Recycling-based optimal	2 (1)	4 (8)	3 (14)	4 (20)	7 (25)	3 (31)	4 (37)	3 (42)	4 (47)	-	81.24	1.08
II		2 (2)	4 (4)	3 (12)	4 (18)	7 (24)	4 (30)	3 (36)	4 (41)	-	-	80.76	1.11

Legend: M&R- maintenance and rehabilitation; VDOT- Virginia Department of Transportation; Avg.- average; CCI- critical condition index; IRI- international roughness index.

Table 8.12- Objective functions values of the best recycling-based optimal compromise solutions and current VDOT practice.

Case study	Type of M&R strategy	LCHAC ($)	LCRUC ($)	LCCCsc (Kg CO_2-eq)	W_{HAC}	W_{RUC}	W_{Env}
I	Current VDOT practice	425,163.98	373,159.66	1,451,953	-	-	-
II		425,163.98	2,665,172.68	4,512,113	-	-	-
I	Recycling-based optimal	366,597.22	247,082.78	814,726	0.3	0.4	0.3
II		369,013.26	1,083,439.83	2,499,971	0.2	0.8	0

Legend: VDOT- Virginia Department of Transportation; M&R- maintenance and rehabilitation; LCHAC- life cycle highway agency costs; LCRUC- life cycle road users costs; LCCCsc- life cycle climate change score; W_{HAC}- weight assigned to the highway agency costs objective function; W_{RUC}- weight assigned to the road users costs objective function; W_{Env}- weight assigned to the environmental impacts objective function.

Table 8.13- Variation of the LCHAC and LCRUC for the best recycling-based optimal compromise solutions when compared to the current VDOT practice.

Stakeholder	Life cycle phase	Case study			
		I		II	
		Absolute ($)	Relative (%)	Absolute ($)	Relative (%)
Highway agency	Materials	53,930.18	12.68	52,440.58	12.33
	M&R	-6,489.01	-1.53	-7,137.23	-1.68
	Transportation of materials	11,125.59	2.62	10,847.37	2.55
	Total	58,566.76	13.78	56,150.72	13.21
Road users	WZ traffic management	-4,819.44	-1.29	1,160,552.62	43.55
	Usage	130,896.32	35.08	421,180.23	15.80
	Total	126,076.87	33.79	1,581,732.85	59.35
	Total global	184,643.63	47.56	1,637,883.57	72.56

Legend: LCHAC- life cycle highway agency costs; LCRUC- life cycle road users costs; VDOT- Virginia Department of Transportation; M&R- maintenance and rehabilitation; Transp. of materials- transportation of materials; WZ- work-zone.

Table 8.14- Variation of the LCCCsc for the best recycling-based optimal compromise solutions when compared to the current VDOT practice.

Stakeholder	Life cycle phase	Case study			
		I		II	
		Absolute (Kg CO_2-eq)	Relative (%)	Absolute (Kg CO_2-eq)	Relative (%)
Highway agency	Materials	276,930	19.07	288,159	6.39
	M&R	-3,183	-0.22	-2,304	-0.05
	Transportation of materials	19,209	1.32	24,286	0.54
Road users	WZ traffic management	122	0.01	804,717	17.83
	Usage	344,149	23.70	897,283	19.89
	Total global	637,227	43.89	2,012,142	44.59

Legend: LCCCsc- life cycle climate change score; VDOT- Virginia Department of Transportation; M&R- maintenance and rehabilitation; Transp. of Materials- transportation of materials; WZ- work-zone.

An interesting analysis is to understand how the use of a recycling-based RC treatment changes the frequency and type of treatments integrating the optimal M&R strategies, and how that translates into savings in both costs and GHG emissions. The results in Table 8.11-Table 8.14 show that for a low-volume traffic roadway, the savings across all considered metrics are achieved by reducing by one the number of M&R activities performed throughout the PAP in relation to that of the optimal non-recycling-based M&R strategy. While the reduction in the LCHAC and in the GHG emissions released during the materials phase are not necessarily surprising, the same cannot be said about the savings in both the LCRUC and GHG emissions released during the remaining phases. With regard to the metrics previously mentioned, the optimal recycling-based M&R strategy would not only mean a reduction in the increase of the WZ RUC in relation to those arising from the VDOT's M&R strategy, but, surprisingly, would also lead to a reduction in the roughness-related environmental and economic burdens, despite the slight deterioration of the average pavement condition over the PAP when compared to that associated with implementation of either the current VDOT practice or the optimal non-recycling-based M&R strategy. This stems from a combination of M&R activities, and respective timing of application, that turns out to be more cost-effective and environmentally-friendly over the PAP.

As for the high-volume traffic roadways, the benefits are obtained by increasing the number of M&R activities applied over the PAP (majority PrM treatments), which translates into a smoother pavement surface over the PAP, thus reducing both the RUC and GHG emissions associated with the most important phase for a high-volume traffic roadway, i.e. the usage phase. Obviously, the increase in the frequency of M&R activities, without raising the expenditures incurred by the highway agency, was only possible because the recycling-based RC is cheaper than its non-recycling-based counterpart. Thereby, highway agencies are allowed to get more done with lower consumption of resources.

8.5.7 Key findings

From the results presented and thoroughly discussed in the previous section, the following findings are worth highlighting:

- In a tri-objective optimization analysis, minimizing LCHAC and LCCCsc are conflicting objectives, while LCRUC and LCCCsc denote the same trend;
- For low-volume traffic roadways:
    i) the Pareto front is nearly two-dimensional;
    ii) the best optimal compromise M&R strategy implies an increase in the LCHAC and a reduction in the remaining metrics when compared to the non-optimized pavement M&R strategy;
    iii) the LCHAC are greater than the LCRUC, regardless of the type of M&R strategy adopted;
    iv) the materials phase plays the most important role in driving the road pavement section’s environmental performance;
- For high-volume traffic roadways:
    i) The Pareto front is better described as a cloud of points, meaning that highway agencies are presented with a greater variety of potential solutions within a narrow range of LCHAC values;

ii) the money has potentially a better marginal value than that for roadways carrying low traffic volumes;
iii) the best compromise optimal M&R strategy always improves on VDOT practice with regard to the three considered metrics;
iv) the LCRUC are considerably greater than the LCHAC, regardless of the type of M&R strategy adopted;
v) the usage phase is by far the most meaningful driver of the environmental performance of a road pavement section;

- The best recycling-based optimal compromise M&R strategies always improve on VDOT practice with regard to the three considered metrics. Relatively speaking, the greatest reductions are achieved in the LCCCsc for a low-volume traffic roadway (44%), whereas, in the case of a high-volume traffic roadway, there is an outstanding reduction of the LCRUC, which can be up to approximately 60%.

8.6 Summary and conclusions

This chapter presents the development of a DSS framework for pavement management that has the ability to involve road users and environmental concerns, in addition to the highway agencies, in the road pavement maintenance decision-making process, by comprehensively identifying and quantifying from a cradle-to-grave perspective the HAC, RUC and environmental impacts arisen throughout the pavement life cycle. Moreover, beyond the traditional economic objective (i.e., minimization of HAC), it enables environmental and road user-related objectives to be jointly optimized by employing a tri-objective optimization procedure to generate a set of potentially optimal pavement M&R strategies for a road pavement section while satisfying multiple constraints. Finally, the capabilities of the presented framework are enhanced by including a decision-support module that provides the DM with the BOCS among those lying on the Pareto front.

The capabilities of the proposed DSS were demonstrated by mean of two case studies consisting of determining, respectively, the optimal M&R strategy for a low-volume and a high-volume traffic road flexible pavement section of a typical Interstate highway in Virginia, USA. The MOO results revealed the existence of conflict between the LCHAC and LCRUC and between LCHAC and LCCCsc, whereby an increase in one of the objectives leads to a decrease in the other. In turn, LCRUC and LCCCsc were found to follow the same trend since an increase in one metric is accompanied by an increase in the other. Furthermore, to assess the strength of relationships between the objective functions previously described, Spearman's correlation analysis was performed along with significant tests of correlation coefficients. The results of the analysis not only demonstrate that the relationships are at least strong but also that they are backed up statistically.

The results of this case study also indicate that for a low-volume traffic roadway the best optimal compromise M&R strategy allows LCRUC and LCCCsc metrics to be reduced in relation to those associated with the current VDOT's pavement M&R practice, although it comes at the cost of an increase in the pavement M&R expenditures (i.e., LCHAC). On the other hand, for a high-volume traffic roadway the best optimal compromise M&R plan has the potential to improve on current VDOT's pavement M&R practice with regard to the three considered metrics.

Furthermore, in order to assess the extent to which new pavement engineering solutions can potentially enhance pavement sustainability, a complementary analysis scenario was performed in which the most structurally robust M&R activity initially considered was replaced by an equivalent recycling-based M&R activity. The results of this analysis showed that reductions in all three considered metrics can be achieved by moving from the current pavement M&R practice to the best recycling-based optimal compromise M&R strategy, regardless of the traffic volume the road pavement section is expected to carry throughout the PAP.

In the future, the development of this DSS will proceed in two main directions. First, the decision level for which the current version is intended for will be upgraded from the project level to the network level to ensure that the road pavement maintenance decisions taken at project level end up in optimal sustainable solutions for the whole road pavement network. Second, the number of LCA-based metrics allowed to be simultaneously optimized with highway agencies and road user-related objectives will be extended. In an effort to overcome the computational limitations associated with solving many-objective optimization (MaOO) problems, the use of dimensionality reduction techniques in improving the efficiency and efficacy of the current DSS's solution algorithm when applied to solve MaOO problems will be assessed. If the applicability of those techniques to the pavement management problems is found to be successful, they will become the MaOO problems computationally tractable by identifying redundant objectives that can be omitted while still preserving the problem structure as far as possible.

8.7 References

Aurangzeb, Q., Al-Qadi, I., Ozer, H. and Yang, R., 2014. Hybrid life cycle assessment for asphalt mixtures with high RAP content. *Resources, Conservation and Recycling*, 83, 77-86.

Bare, J., 2011. TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technologies and Environmental Policy*, 13(5), 687-696.

Bryce, J., Flintsch, G. and Hall, R., 2014. A multi criteria decision analysis technique for including environmental impacts in sustainable infrastructure management business practices. *Transportation Research Part D: Transport and Environment*, 32, 435-445.

Carnegie Mellon University Green Design Institute, 2010. *Economic input-output life cycle assessment (EIO-LCA)*, U.S. 2002 Industry Benchmark model. Available at: http://www.eiolca.net.

Chowdhury, T., 2011. *Supporting document for the development and enhancement of the pavement maintenance decision matrices used in the needs-based analysis*. Virginia Department of Transportation, Maintenance Division, Richmond, VA.

Därcher, K., Gorski, J. and Klamroth, K., 2012. An augmented weighted Tchebycheff method with adaptively chosen parameters for discrete bicriteria optimization problems. *Computers & Operation Research*, 39(12), 2929-2943.

Diefenderfer, B. and Apeagyei, A., 2014. *I-81 In-place pavement recycling project* (Report No. FHWA/VCTIR 15-R1), Virginia Center for Transportation Innovation and Research. Available at: http://www.virginiadot.org/vtrc/main/online_reports/pdf/15-r1.pdf

Ducasse, K., Distin, T. and Osborne, L., 2004. *The use of microsurfacing as a cost effective remedial action for surface rutting*. In: Proceedings of the 8th Conference on Asphalt Pavements for Southern Africa, Sun City, South Africa.

Ehrgott, M. and Gandibleux, X., 2004. Approximative solution methods for combinatorial multicriteria optimization. *TOP*, 12(1), 1-88.

Faghih-Imani, A. and Amador-Jimenez, L., 2013. Toward sustainable pavement management. *Transportation Research Record: Journal of the Transportation Research Board*, 2366, 13-21.

Federal Highway Administration (FHWA), 2007. *Asset management overview*. Available at: https://www.fhwa.dot.gov/asset/if08008/amo_00.cfm

Ferreira, A., Picado-Santos, L. and Antunes, A., 2002. A segment-linked optimization model for deterministic pavement management systems. *International Journal of Pavement Engineering*, 3(2), 95-105.

Gosse, C., Smith, B. and Clarens, A., 2013. Environmentally preferable pavement management systems. *ASCE-Journal of Infrastructure Systems*, 19(3), 315-325.

Harvey, J., Kendall, A., Lee, I.-S., Santero, N., Van Dam, T. and Wang, T., 2010. *Pavement life cycle assessment workshop: discussion summary and guidelines* (Technical Memorandum: UCPRC-TM-2010-03). Available at: http://www.ucprc.ucdavis.edu/PublicationsPage.aspx

Harvey, J., Kendall, A. and Saboori, A., 2015. *The Role of LCA in reducing GHG emissions form Road Construction and Maintenance*. *A White Paper from the National Center for Sustainable Transportation.* National Center for Sustainable Transportation and Institute of Transportation Studies of University of California, Davis. Available at: http://ncst.ucdavis.edu/research/white-papers/

International Panel on Climate Change (IPCC), 2007. *Climate change 2007: the physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

International Standard Organization (ISO), 2006a. *ISO 14040: 2006. International Standard ISO 14040: environmental management - life cycle assessment: principles and framework*, *October*. Geneva (Switzerland): International Organization for Standardization.

International Standard Organization (ISO), 2006b. *ISO 14044:2006. International Standard ISO 14044: environmental management - life cycle assessment: requirements and guidelines, October*. Geneva (Switzerland): International Organization for Standardization.

Keoleian, G. and Spitzley, D., 2006. Life cycle based sustainability metrics. Chapter 7 in *Sustainability Science and Engineering: Defining Principles (Sustainability Science and Engineering, Volume 1),* M.A. Abraham, Ed. Elsevier, 127-159.

Lidicker, J., Sathaye, N., Madanat, S. and Horvath, A., 2013. Pavement resurfacing policy for minimization of life-cycle costs and greenhouse gas emissions. *ASCE-Journal of Infrastructure Systems*, 19(2), 129-137.

Machin, D., Cambpell, M. and Walters, S., 2007. *Medical statistics: a textbook for health sciences*. 4th ed. U.K.: Wiley.

Marler, R. and Arora, J., 2004. Survey of multi-objective optimization methods for engineering. *Structural and Multidisciplinary Optimization*, 26(6), 369-395.

MATLAB, 2015. *MATLAB primer, version 8.5*. The MathWorks Inc., Natick, MA.

Miettinen, K. 1999. *Nonlinear multiobjective optimization*. Boston: Kluwer Academic Publishers.

Office of Management and Budget (OMB), 2013. *Discount rates for cost-effectiveness, lease purchase, and related analyses*. Table of past years discount rates from Appendix C of OMB Circular No. A-94. Available at: http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c

Reger, D., Madanat, S. and Horvath, A., 2014. Economically and environmentally informed policy for road resurfacing: tradeoffs between costs and greenhouse gas emissions. *Environmental Research Letters*, 9(10), 104020.

Santero, N. and Horvath, A., 2009. Global warming potential of pavements. *Environmental Research Letters*, 4(3), 1-7.

Santero, N., Masanet, E., and Horvath, A., 2011. Life-cycle assessment of pavements. Part I: critical review. *Resources, Conservation and Recycling*, 55(8-9), 801-809.

Santos, J., Ferreira, A. and Flintsch, G., 2015a. A life cycle assessment model for pavement management: methodology and computational framework. *International Journal of Pavement Engineering*, 16(3), 268-286.

Santos, J., Bryce, J., Flintsch, G., Ferreira, A. and Diefenderfer, B., 2015b. A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, 11(9), 119-1217.

Santos, J., Bryce, J., Flintsch, G. and Ferreira, A., 2015c. A comprehensive life cycle costs analysis of in-place recycling and conventional pavement construction and maintenance practices. *International Journal of Pavement Engineering* (in press). http://dx.doi.org/10.1080/10298436.2015.1122190

Santos, J., Bryce, J., Flintsch, G. and Ferreira, A., 2015d. Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability. *Resources, Conservation and Recycling* (submitted for publication).

Santos, J., Ferreira, A., and Flintsch, G., 2015e. An adaptive hybrid genetic algorithm for pavement management. *Engineering Optimization* (working paper).

Stantec Consulting Services and Lochner, H., 2007. *Development of performance prediction models for Virginia department of transportation pavement management system*. Virginia Department of Transportation, Richmond, VA.

Steuer, R., 1986. *Multiple criteria optimization: theory, computation and application*. NewYork: JohnWiley and Sons.

Swarr, T., Hunkeler, D., Klöpffer, W., Pesonen, H.-L., Ciroth, A., Brent, A. and Pagan, R., 2011. *Environmental life cycle costing: a code of practice*. Pensacola (FL): Society of Environmental Chemistry and Toxicology (SETAC).

Talbi, E.-G., 2009. *Metaheuristics: from design to implementation.* New Jersey: John Wiley & Sons, Inc.

United States Department of Transportation (US DOT), 2014. *Transportation for a new generation. Strategic plan for fiscal years 2014-2018.* Available at: https://www.transportation.gov/administrations/office-policy/fy-2014-2018-strategic-plan

Virginia Department of Transportation (VDOT), 2012. *2012 Construction resources guidebook, Division II- Materials, Special provision copied notes (SPCNs), special provision (SPs) and Supplemental specifications (ss), updated July 8, 2014,* Virginia Department of Transportation Construction Division, Central Office, Richmond. Available at: http://www.virginiadot.org/business/resources/const/07ImpRev.zip

Virginia Department of Transportation (VDOT), 2013. *Project selection guidelines for cold pavement recycling*. Virginia Department of Transportation Materials Division. Available at: http://www.virginiadot.org/VDOT/Business/asset_upload_file526_3638.docx

Virginia Department of Transportation (VDOT), 2014. *Manual of instructions for the materials division*. Virginia Department of Transportation Materials Division. Available at: http://www.virginiadot.org/business/materials-download-docs.asp

Walls, J. and Smith, M., 1998. *Life-cycle cost analysis in pavement design - in search of better investment decisions* (Report No. FHWA-SA-98-079). Available at: http://isddc.dot.gov/OLPFiles/FHWA/013017.pdf

World Road Association, 2014. *The importance of road maintenance* (Report 2014R02). World Road Association. Available at:

http://www.piarc.org/en/search.htm?q=The+importance+of+road+maintenance.+World+Road+Association

Wu, Z., Flintsch, G., Ferreira, A., and Picado-Santos, L., 2012. Framework for multiobjective optimization of physical highway assets investments. *ASCE-Journal of Transportation Engineering*, 138(12), 1411-1421.

Yu, B., Lu, Q. and Xu, J., 2013. An improved pavement maintenance optimization methodology: integrating LCA and LCCA. *Transportation Research Part A: Policy and Practice*, 55, 1-11.

Zhang, H., Keoleian, G., and Lepech, M., 2012. Network-level pavement asset anagement system integrated with life-cycle analysis and life-cycle optimization. *ASCE-Journal of Infrastructure Systems*, 19(1), 99-107.

Zhang, H., Keoleian, G., Lepech, M. and Kendall, A., 2010. Life-cycle optimization of pavement overlay systems. *ASCE-Journal of Infrastructure Systems*, 16(4), 310-322.

Zimmormann, H., 1996. *Fuzzy set theory- and its application.* 3rd ed. Norwell: Kluwer Academic Publishers.

Zou, K., Tuncall, K. and Silverman, S., 2003. Correlation and simple linear regression. *Radiology*, 227(3), 617-628.

Chapter 9

Summary, Conclusions and Future Work

9.1 Summary and conclusions

With finite natural resources, sensitive environmental conditions and limited economic resources, transportation agencies are increasingly recognizing that enhancing pavement sustainability must be a priority. A key aspect in the process of moving towards more sustainable pavement systems lies in the ability of the transportation agencies, owners, operators and DMs in general to assess the current state of road pavement infrastructures, report on their technical, economic, environmental and social performances, predict future conditions and performances from a cradle-to-grave perspective, and, based on the indicators and metrics obtained, make decisions that, hopefully, are effective in enhancing pavement sustainability. In view of this, the decision-making process involved in sustainable pavement management, requires practical tools and techniques, which relying on comprehensive and life cycle-based appraisal methods, allow users to assess sustainability from a multi-dimensional perspective and in all of the life cycle phases of road pavement infrastructures. Current approaches for road pavement infrastructure appraisal are to some extent, and from an overall standpoint, valuable for helping DMs meet some of their sustainability targets within their specific scope. However, as economic considerations have until now been the main focus of DMs in pavement management, their manner of analysis is biased towards a merely economic assessment, failing to effectively account for the environmental impact, and thus preventing the pavement community to move towards building and maintaining the road pavement infrastructures in a more environmentally friendly fashion. Furthermore, they are overly focused both on certain phases of the pavement life cycle and on the particular transportation agency's interests.

Recognizing the limitations of state-of-practice life cycle-based analytical models and tools in highway asset management, this thesis developed a highly customizable optimization-based pavement management DSS, which includes several comprehensive stand-alone but logically interconnected pavement life cycle approaches that aim ultimately to foster pavement sustainability. By integrating and combining LCA, LCCA, life cycle optimization, MCDM methods (i.e., Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM) methods) into the same computational platform, this DSS provides a basis for establishing benchmark values and setting future performance goals, tracking trends and monitoring progresses towards or regression from desired sustainability targets, and comparing the performance between different pavement design and M&R strategy alternatives.

The development of the proposed DSS started with the design of a conceptual framework for a project-level pavement LCA. In Chapter 2, in addition to the conceptual framework, a methodology incorporated into a software environment for a pavement LCA tool was presented. In comparison with the traditional approaches described in the literature it has five main distinctive features. Firstly, it is comprehensive in that it incorporates all six pavement life cycle phases, i.e., materials extraction and production, construction and M&R, transportation of materials, WZ traffic management, usage and EOL, and considers several processes within the boundaries of each phase. Secondly, all phases and models are logically connected but differentially recognized so that the user can both understand the overall environmental impacts and the specific contributions from individual phases, models, processes and components. Therefore, the more relevant areas and related key points of the pavement life cycle can be measured and benchmarked against other solutions and projects. Thirdly, by accounting for as many variables in a pavement project as possible, it is flexible enough to add, delete, combine and divide component units to adapt to a particular project, with minimum repetitive work. It is also flexible as will allow users to update models and revise formulas in the future. Fourthly, all phases and models are fed by an open and customizable database. This customization property promotes the accuracy of all estimates by allowing the user either to add project-specific data or to edit pre-existing data so that it fits the characteristics and particularities of the analysis being performed. It is also beneficial for evaluating the results of different decision-making scenarios, as well as for performing sensitivity analysis on the results due to variations of design and operational parameters, assumptions, and methodological choices. Fifthly and lastly, it expands the LCIA to categories other than CC and upgrades the impact assessment techniques typically incorporated in the majority of pavement LCA tools through the inclusion of dynamic characterization factors. Still in Chapter 2, several data sources were suggested with potential relevance for an LCA conducted in the Portuguese context.

On the basis on the features summarized previously, the research described in the abovementioned chapter provides a widely applicable pavement LCA model that will enable highway agencies, private companies and the construction industry to estimate emissions and environmental impacts during the PAP of a road pavement. The use of the proposed tool for benchmarking current practices in pavement construction and management will enhance the scientific basis for understanding where further efforts can be undertaken to promote sustainable pavement investment decisions.

To illustrate the potential and usefulness of the pavement LCA model introduced in the Chapter 2 for conducting a comprehensive and attributional LCA, in Chapter 3, we presented the results of a study aimed to estimate and compare the LCEI of the flexible pavement structures defined in the Portuguese pavement design catalogue. The analysis assessed the functional units over a 40-year PAP, considering all pavement life cycle phases: (1) extraction of raw materials and production; (2) transportation of materials; (3) construction and M&R; (4) WZ traffic management; (5) usage; and (6) end-of-life. The results of the case study showed that for the least demanding traffic classes the materials phase is the main contributor to the road pavement's overall LCEI. However, if the road pavement is expected to carry significant volumes of traffic over its PAP, then the usage phase dominates the road pavement's overall environmental performance.

An important element in improving the environmental sustainability of road pavement projects that is commonly mentioned by the literature is the use of new technologies, processes, and products that possess the potential to enhance the projects' environmental sustainability through reduced consumption of fossil energy and virgin materials. A good example is the use of recycled materials or more environmentally-friendly pavement M&R practices. The likely environmental benefits, however, need to be quantified and compared against the burdens they impose if they require additional processing and implementation efforts. Therefore, comparative studies are needed to investigate the many impacts that arise from implementing alternative practices to ensure that the pavement project is carried out with the smallest environmental impact in terms of energy use, emissions released and natural resources consumed. On the other hand, an essential feature to enhance the credibility of the results produced by life cycle approaches is related to their ability to properly address the context- and geographical-sensitive nature of the models, processes, practices and concerns of the society where the project under assessment is located. In view of those two main aspects, Chapter 4 described the development of a comprehensive pavement LCA model tailored for US conditions, which rely on the conceptual framework introduced in Chapter 2. One of its main novelties lies in the development and implementation of a methodology that easily combines the vehicle emissions model MOVES with the HDM-4 RR model calibrated to North American conditions, to estimate the additional FC, and consequently the environmental impacts, resulting from the deterioration of the pavement over the life cycle. The model was applied to conduct an LCA study of an in-place pavement recycling rehabilitation project in the state of Virginia, USA. The project under consideration incorporated several in-place pavement recycling techniques, namely CIR, CCPR and FDR, and a unique traffic management approach. The results for the recycling-based project were compared to two other pavement management alternatives: (1) a traditional pavement reconstruction and (2) a corrective maintenance approach. The results obtained for the conditions considered in that case study showed that the usage phase is the part in the pavement life cycle that contributes most across the majority of the impact categories. It was also found that the corrective M&R strategy entails additional energy consumption, as measured by the CED Total, of 44% and 42% of the total energy consumed in the case where the recycling-based and traditional reconstruction M&R strategies are adopted as an alternative. Moreover, when comparing the in-place recycling-based activity to the traditional reconstruction activity, a reduction of 157 tonnes of CO_2-eq/lane.km is expected to be achieved, exclusively due to the materials phase if the recycling-based activity was undertaken. This value represents a reduction of 75% in comparison to the CO_2-eq emissions accounted for in the same phase of the rehabilitation activity. Despite the lower impact compared to the materials phase, the environmental benefits arising from the WZ traffic management and transportation phases should also not be disregarded.

The potential of in-place recycling techniques to enhance the environmental sustainability of highway agencies' pavement management decisions for asphalt pavements has been demonstrated in Chapter 4. However, a solution which an LCA finds environmentally advantageous might not be preferred over another which is technically equivalent, if it is not economically competitive. Indeed, it may seem intuitive to think that there is a direct relationship between a reduction in costs and a reduction in environmental impact when adopting pavement recycling techniques. However, the potential existence of such a connection can only be confirmed when the complete life cycle of the pavement is taken into account. In this vein, Chapter 5 presented the development of a comprehensive pavement LCC model intended to give DMs a systematic framework that provides an in-depth perspective of the costs incurred by highway agencies and road users during the materials, construction and M&R, WZ traffic management, usage and EOL pavement life cycle phases. When compared with the existing LCCA tools, the proposed model, by not relying on “black-box” and aggregated process costs, depicts more accurately the new outlook of costs resulting from changes in construction and maintenance techniques, productivity rates, crew sizes and composition, equipment fleets, etc. The proposed model was applied to perform a comprehensive, cradle-to-grave LCCA of the in-place pavement recycling rehabilitation project introduced in Chapter 4. The results showed that for a rehabilitation project with features similar to those of the case study introduced in the chapter previously mentioned, the implementation of recycling-based M&R strategies has the potential to be simultaneously advantageous from both the environmental and economic perspectives. From the highway agencies’ standpoint, the reduction in the consumption of bituminous-related materials was found to be the main source of the economic advantage exhibited by the recycling-based strategy’s life cycle over the competing alternatives. From the road users’ perspective, the RUC savings incurred during the WZ traffic management phase due to the reduction of the TDC was shown to be more expressive than those arising from the usage phase. Furthermore, the sensitivity analysis performed to assess the robustness of the outcomes in response to variations in some of the most relevant input values showed that the key assumptions considered within LCCA do not alter the cost advantage of the recycling-based M&R strategy over the competing M&R strategies.

Chapters 2, 3 4 and 5 addressed the development and individual application of comprehensive LCA and LCC tools. Although these appraisal tools can be used alone or in tandem to measure sustainability, using them together allows for a better assessment of the total impacts of a proposed project, practice or policy, making it easier to arrive at balanced conclusions regarding the economic and environmental goals. With this in mind, in Chapter 6 the development of a new pavement life cycle approach was presented. In particular, a comprehensive and integrated LCC-LCA model was developed which builds on the P-LCA and LCC models introduced in

Chapters 2, 4 and 5. Compared to the previous P-LCA framework, the LCA methodology adopted by the tool proposed in Chapter 6 relies on a hybrid LCI approach that allows the sub-models assessing the economic and environmental dimensions of sustainability to connect with one another by 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 this way, it allows the "cutoff" errors to be reduced and the consistency between the system boundaries of the pavement life cycle, when analyzed concomitantly from the economic and environmental viewpoint, to be improved by determining the underpinning environmental burdens associated with several processes, such as the manufacturing and maintenance of construction equipment, manufacturing of on- and off-road vehicle tires, lubricant oil production, etc., that had been disregarded in the previous P-LCA models. Furthermore, to strengthen the proposed pavement LCC-LCA model as a tool and to improve its usefulness for sustainability decision-making, and thus, enabling the DM to choose between multiple alternatives when they have conflicting performances in the considered criteria, a MCDM, the TOPSIS method, was added to the tool's framework. Its usefulness was illustrated with a case study that consisted of investigating, from a full life cycle perspective, the extent to which several pavement engineering solutions, namely hot in-plant recycling mixtures, WMA, 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 section located in Virginia, USA. For the conditions considered in the case study, the results showed that a recycling-based VDOT M&R strategy, where the asphalt mixtures are of type HMA, containing 30% of RAP are more compliant with the highway agency and road users' demands for affordable road maintenance and usage over its life cycle than the other 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 multi-criteria decision analysis. On the other hand, from the viewpoint of pure environmental performance, implementing a THMACO-based PrM strategy has proven to be the most environmentally-friendly solution.

With the objective of endowing the DSS with life cycle approaches with increasing complexity of analysis, in Chapter 7, an optimization model was presented to tackle the pavement M&R strategy selection problem. The objective of the model was to minimize the PV of the life cycle M&R costs of a given pavement section throughout its PAP, while keeping the pavement condition above a predefined threshold value, meeting technical constraints and considering deterministic and non-linear PPPM. Due to the nature of this problem, it is very difficult to solve to an exact optimum using traditional optimization techniques. Therefore, a new AHGA combing GA with an LS mechanism was developed for tackling the pavement life cycle optimization problem. The main novelty of this algorithm lies on the incorporation of dynamic LS techniques into a GA framework to improve the overall efficiency of the search, either by accelerating the discovery of good solutions, for which evolution alone would take too long to find, or by reaching solutions that would otherwise be unreachable by evolution or a local method alone. The proposed AHGA framework contains two dynamic learning mechanisms to adaptively guide and combine the exploration and exploitation search processes. The first learning mechanism aims to reactively assess the worthiness of conducting an LS, and to efficiently control the computational resources allocated to the application of this search technique. The second learning mechanism uses instantaneously learned probabilities to select which one, from a set of pre-defined LS operators which compete against each other for selection, is the most appropriate for a particular stage of the search to take over from the evolutionary-based search process. After the algorithm parameters had been calibrated using the Taguchi method, its efficiency and effectiveness were compared with those of a traditional GA by applying it to several case studies designed to replicate VDOT’s real pavement management problems for a flexible pavement section. The outcomes of the comparative experiments undertaken and accordingly supported by statistical tests proved the superiority of the proposed algorithm in consistently converging to the optimum solution while requiring a lower computational running time, in spite of the very simple calibration process used.

Despite the fact that multi-attribute decision analysis can deal explicitly with different components of sustainability as shown in Chapter 6, the applicability of that category of MCDM methods is constrained to the situation in which the DM has to select an alternative among a set of pre-defined alternatives. Thus, it may well be the case that none of the pre-defined alternatives available for selection make the best possible use of the resources available and leads to best possible performance in all the considered metrics. In that sense, a better incorporation of the sustainability concept into the decision-making process is obtained when the sustainability concerns, expressed through metrics, are considered as the criteria for designing the alternatives by using a MOO method. In view of that, Chapter 8 described the last enhancements performed in the DSS, which aimed to improve its life cycle optimization capabilities. In particular, the single-objective-based life cycle optimization model developed in Chapter 7 was extended to a multi-objective formulation and combined with the comprehensive and integrated pavement LCC-LCA model introduced in Chapter 6. Finally, as MOO problems give rise to a set of optimal solutions, a decision-support module was added to the DSS methodology to help the DM to conveniently select a final optimal solution. The enhanced capabilities of the proposed DSS were illustrated with two case studies consisting of determining the optimal M&R strategy for a one-way flexible pavement section of a typical Interstate highway in Virginia, USA, which yields the best tradeoff between the following three, often conflicting, objectives: (1) minimization of the PV of the total LCHAC; (2) minimization of the PV of the LCRUC; and (3) minimization of the LCCCsc. The MOO results demonstrated the existence of conflict between the LCHAC and LCRUC and between LCHAC and LCCCsc, whereas LCRUC and LCCCsc were found to follow the same trend. The strength of relationships between the considered sustainability criteria was assessed through a Spearman’s correlation analysis and the statistical significance of the correlation coefficients was successfully ascertained by mean of hypothesis tests. The results of these case studies also indicate that for a low-volume traffic roadway the best optimal compromise M&R strategy allows LCRUC and LCCCsc metrics to be reduced in relation to those associated with the current VDOT's pavement M&R practice, although it comes at the expense of an increase in the LCHAC. On the other hand, for a high-volume traffic roadway the best optimal compromise M&R plan was found to improve on current VDOT pavement M&R practice in the three considered metrics. Finally, in order to assess the extent to which new pavement engineering solutions can potentially enhance pavement sustainability, a complementary analysis scenario was performed in which the most structurally robust M&R activity initially considered was replaced by an equivalent recycling-based M&R activity. The results of this analysis showed that reductions in all three considered metrics can be achieved by moving from the current VDOT pavement M&R practice to the best recycling-based optimal compromise M&R strategy, regardless of the traffic volume the road pavement section is expected to carry throughout the PAP.

9.2 Future work

A software environment was developed to incorporate the DSS and the different pavement life cycle approaches described in this thesis. Since it is a prototype software, not all the user interfaces exhibit the same level of user-friendliness. A few improvements are required to make it easily usable for third party users. There are also several pavement life cycle approaches that can benefit from either further research or improvements. In addition, some of the findings could be expanded to consider scenarios beyond those considered in the case studies analyzed in this thesis. In this sense, at the end of each chapter several topics were mentioned that deserve further research and/or developments. Some of those topics have been addressed in the following chapters, but others were left for future research.

For instance, the pavement LCA framework proposed in Chapter 2 can be enhanced mainly in the three first steps that characterize an LCA study. Starting with the scope, two main lines for future development are suggested. The first regards the number of processes and phenomena considered in each phase, whereas the second one deals with the accuracy of the methodologies and models adopted to model the processes underlying each phase. The best example to illustrate this first line has to do with the usage phase. In the proposed framework, only the environmental burdens arising from the RR, and in particular those arising from the pavement surface properties (i.e., roughness and macrotexture), were taken into account. For that purpose, it was considered that the former surface property varies equally in all lanes, whereas the latter was assumed to not vary either over time or across pavement section. Therefore, future enhancements on this topic can be undertaken on two levels. Firstly, the roughness evolution over time should be considered in distinct ways across the pavement section by considering lane distribution factors. As far as the macrotexture is concerned, the first step to be taken lies in the inclusion of macrotexture prediction models into the LCA framework as soon as they are available, whereas a second step aims to account for the lane effect on the macrotexture evolution by means of lane distribution factors. Secondly, the number of considered physical mechanisms affecting the RR should be extended by considering the pavement structural responsiveness to loading. Pavement structural responsiveness to loading is determined by layer thicknesses, stiffness and material types that determine viscoelastic and elastic pavement response under different conditions of wheel loading, vehicle speed, temperature and moisture conditions. This mechanism of RR affects the on-road vehicle's FC based on the premise that pavements are deflected as vehicles pass overhead, thus absorbing energy that would otherwise be used for accelerating the vehicle (Zaniewski, 1989). This topic has been subject to recent and ongoing research, but the influence of structural responsiveness on fuel economy and associated environmental impacts has not been comprehensively validated with an experiment that accounts for the broad range of environmental conditions or the various types of pavement structures and respective properties. As a result, the available models have not been calibrated with the type of data that allows the general application of the models to evaluate in-service pavements under the range of traffic and climatic conditions that occur daily, seasonally, and from location to location (Van Dam et al., 2015). Research is thus needed that uses field measurements of fuel economy for a range of vehicles, climates, and pavement structural responses, controlling roughness and macrotexture, to complete calibration and validation of models. After those studies have been completed and the developed models properly validated and matured, they should be included into the pavement LCA framework.

Due to different reasons several other usage phase effects were not accounted for. They include tire-pavement noise, storm water runoff through permeable pavement surfaces, thermal pavement performance and its contribution to urban and global climate, lighting, pavement friction and safety. Thus, future developments of the pavement LCA framework should address these aspects.

With regard to the second line for future developments previously mentioned, it may focus on the improvement of the methodology employed to capture the impact of traffic disruptions caused by the execution of M&R activities on environmental and economic WZ-related burdens. The current methodology relies on the HCM methodology which utilizes hourly traffic demand data and capacity analyses to estimate WZ mobility impacts such as traffic delays, queuing, and associated WZ RUC and environmental impacts. While it is good for analyzing the performance of isolated WZ sections with relatively moderate congestion problems by quickly predicting capacity, density, speed, delay, and queuing, it is limited in its ability to analyze both network or system effects (e.g., detours) and lane closure strategies, such as the WZ layout in which one lane is often closed down at a time, while flagman at either end of the WZ alternate the traffic flow in both directions through the remaining open lane. For instance, the limitations associated with the consideration of a constant detour rate during a WZ period may be overcome by using a traffic assignment mechanism. In this context, road users will adapt their behavior, i.e. go through the WZ or detour, in such a way that they reduce travel costs. A better solution, which would mean surpassing not only the limitations related to the detour modelling, but also those associated with the static nature of the HCM's approach in predicting traffic performance, consists of using traffic simulation tools. By dividing the analysis period into short time slices, a simulation model can evaluate the buildup, dissipation, and duration of traffic congestion in short time periods. Also, it can evaluate the interference that occurs when congestion builds up at one location and impacts the capacity of another location (Alexiadis et al., 2004). However, one should bear in mind that those simulation tools, particularly the micro-simulation tools, require a plethora of input data and manipulation of a large amount of potential calibration parameters. Moreover, they imply the loss of the unity of the LCA framework because they need to be run in an individual software platform, after which the simulation outputs produced are fed into the pavement LCA model.

Another relevant issue is the ability to acquire and employ high quality input data to carry out the LCI step of a LCA study. Although an effort has been made to employ, as far as possible, the best data available for the technical, geographical and social contexts associated with the case studies, the quality of the data used was not always as high as it could have been due to several reasons, such as data scarcity, reliability and lack of tailored data. In fact, data quality and availability are key issues that have received attention from the pavement LCA community, which has underlined the need for a centralized database of non-proprietary LCIs for materials, equipment, vehicles, and other items that can be used as a reference database for pavement LCA.

In the majority of the pavement LCA models available in the literature, if not all, the point in time at which a substance is released is usually not accounted for in the LCIA step, whereby the distribution of emissions over time is lost. The LCA models developed in this thesis took a step further by allowing the models' users to choose between the IPCC's GWPs and the TAWPs proposed by Kendall (2012). However, the lack of either consistent or geographically suitable sets of other time-adjusted characterization factors across multiple impact categories did not allow for the accounting of time effects in impact categories other than CC. Therefore, a future field for improving the pavement LCA models integrating the DSS should focus on extending the dynamic nature of the LCA to other impact categories.

In Chapter 5 a comprehensive pavement LCC model was developed which was particularly suited to determining the costs incurred by highway agencies and road users when new pavement practices are implemented. Despite the considerable comprehensiveness of the developed model, it can be further enhanced with regard to this attribute. In particular, other cost categories may be added to the current framework. For example, the costs of accidents associated with WZ and WZ-related detours, which were left out of the system boundaries due to the high level of subjectivity associated with their occurrence. However, for the sake of confidence in the results, the inclusion of this cost category into the LCCA should be constrained to the situations in which there is historical accident rate data covering a large time period for the road pavement section under analysis. This would allow the implementation of the accident costs calculation methodologies, which rely on the knowledge of the pre-existing accident rate and crash modification factors. Other categories and sub-categories of highway agency costs, such as (1) indirect costs, i.e. overhead expenses related to a specific project but not directly linked to any specific work item (e.g., staffing for project management and supervision, office trailers and vehicles assigned to the project team, etc.), (2) general overhead costs, i.e. company level general and administrative overhead expenses incurred by the contractor/highway agency in support of the overall construction program and shared by all projects in proportion to their cost and duration (e.g., office maintenance, office personnel, office equipment and services, etc.) and (3) markup costs, i.e. project contingency costs and contractor profit, which are likely to vary from project to project, from contractor/highway agency to contractor/highway agency and from one geographic location to another, could easily be added to the LCC framework as well.

In order to improve the consistency between the system boundaries of the pavement life cycle when analyzed concomitantly from the economic and environmental viewpoints, a comprehensive and integrated pavement LCC-LCA model was developed and presented in Chapter 6. In the proposed model, the P-LCA model presented in Chapter 4 was combined with an I-O methodology for deriving the underpinning environmental burdens of processes commonly disregarded by the pavement LCA models available in the literature. However, I-O LCA has a limitation, which lies in the fact that the same output is generated when producing one monetary unit of goods in each productive sector because it uses the national average data for each productive sector of the economy (Lenzen, 2000; Suh et al., 2004). Therefore, the level of aggregation inherent in I-O data makes it impossible to obtain the same level of detail for individual items as can be achieved by P-LCA. In this context, the accuracy of the results provided by the LCA sub-model could be enhanced through the disaggregation of the existing I-O models by combining top-down economic information with bottom-up emissions data to better represent the underlying economic transactions, supply chains, and emissions for the specific sub-sector that best describes the process for which we want to calculate the environmental burdens.

An important component of the research developed in this thesis addressed the economic and environmental assessment of new pavement engineering solutions, of which the recycling-based materials and WMA are examples. The assessments were carried out on the basis that those new paving solutions perform in the same way as their conventional counterparts. Although this assumption finds support in several studies (Mohammad et al., 2015), there are also other studies suggesting that some of those solutions may not perform as well as the conventional solutions (Modarres et al., 2014). Given the lack of results obtained from comprehensive field studies about the long term performance of road pavements incorporating new pavement engineering solutions, it would be pertinent to consider that new paving materials/solutions may not be as durable as the conventional materials and, thus result in more frequent M&R, which may compromise their economic and environmental advantages, as found in Chapters 4, 5 and 6 of this thesis. In view of this, a pertinent line for future research would be the application of the pavement life cycle approaches described in the aforementioned chapters to homologous case studies, but considering that pavement structures incorporating alternative materials present a greater degradation rate, and thereby need to undergo M&R activities more often.

Another additional line for future research relates to the pavement life cycle optimization model introduced in Chapter 7. In particular, the further research direction can be explored on four main fronts: (1) to extend the calibration efforts to other objective functions, such as (i) the maximization of the pavement performance over time, (ii) the minimization of the LCRUC, (iii) the minimization of a given life cycle environmental metric, etc.; (2) to calibrate the algorithm by employing a better calibration method (see Eiben and Smit (2011) for an overview on tuning methods and a discussion on related methodological issues); (3) to assess the impact on the efficiency and effectiveness of the search process due to the consideration of other (i) LS operators, (ii) credit assignment mechanisms and (iii) LS operator selection techniques; (4) to investigate the benefits resulting from extending the dynamic nature of the AHGA by considering (i) multiple selection strategies for choosing individuals in the population that will create offspring for the next generation and how many offspring each will create, (ii) multiple evolutionary operators (i.e., crossover and mutation operators) and (iii) multiple replacement strategies to determine which of the current members of the population, if any, should be replaced by the new solutions; and (4) to study the impact of allowing automatic selection not only of which parameter and/or evolutionary operator to apply at a given moment of the search process, but also the rate at which the chosen parameter and/or operator should be applied.

The penultimate chapter of this thesis formulated the pavement M&R strategy selection problem as a tri-objective optimization problem in which only one environmental metric was considered as an objective function to be minimized. However, a more comprehensive analysis should be performed that considers a wider set of aspects of the natural environment, human health and resources. With this in mind, the current approach could be improved by extending the number of LCA-based metrics allowed to be simultaneously optimized with highway agencies and road user-related objectives. This enhancement in the analysis capability of the proposed life cycle optimization model can be introduced, for instance, by employing dimensionality reduction techniques to overcome the computational limitations associated with solving MaOO problems.

Still within the optimization domain, an interesting analysis that could also be performed would be to analyze whether or not the introduction of emissions pricing, for instance, under an emissions trading scheme or as a methodology to account for environmental damages, would make the use of a MOO approach unnecessary when the life cycle emissions costs, LCHAC and LCRUC are all added and tackled from a SOO problem perspective, or whether such an approach can provide additional insights that are useful in a decision-making context.

Life cycle-based studies are generally subject to assumptions and simplifications regarding their scope, system boundaries and data, leading unavoidably to uncertainties in the assessments. Taking the LCA approach as an example, Huijbregts et al. (2001) discuss the existence of three sources of uncertainty: parameter uncertainty (due to data variability), uncertainty due to choices (due to scenario assumptions), and model uncertainty (due to different impact assessment methods). Thus, given the deterministic nature of the pavement life cycle approaches proposed in this thesis, another interesting line for future developments would be to add probabilistic capabilities to the developed approaches to propagate the uncertainty into the comparative analysis and characterize the difference from a statistical standpoint.

Throughout this thesis, the sustainability concept has been addressed from the economic and environmental perspectives. However, from a broader perspective, it should also consider the social aspects related to pavement systems. In this context, an additional line for future enhancements should address the development of life cycle approaches to assess the social performance of pavement management practices. The development of social LCA is still in its infancy, and up to now a standardized framework for assessing the social dimension of sustainability has not been developed yet. Possible social impacts to be measured may include the impacts on workers, infrastructure users, the local community, the general public (including non-users), and supply-chain actors (Benoît et al., 2010), and indicators may assess fair salaries, working hours, discrimination, health and safety, consumer privacy, EOL responsibility, cultural heritage, community engagement, local employment, technology development, corruption, and fair competition (Parrish and Chester, 2014). However, no agreed method is available for the selection of impact categories and the measurement of indicators.

The last line suggested for future development relates to the decision level for which the life cycle approach is intended. Current approaches can be extended from the project level to the network level to ensure that the road pavement maintenance decisions taken at project level end up in optimal sustainable solutions for the whole road pavement network.

To sum up, the total or partial accomplishment of the research lines suggested above will certainly provide the proposed DSS with valuable enhancements in its capability to advance the state-of-the-practice as it relates to improving pavement sustainability. Nevertheless, the author believes that the life cycle approaches developed in this thesis can already be seen as useful tools for helping DMs striving for more sustainable pavement systems.

9.3 References

Alexiadis, V., Jeannotte, K. and Chandra, A., 2004. *Traffic analysis toolbox volume I: traffic analysis tools primer* (Report No. FHWA-HRT-04-038). Cambridge Systematics, Inc. Available at: http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol1/vol1_primer.pdf

Benoît, C., Norris, G., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., Prakash, A., Ugaya, C. and Beck, T., 2010. The guidelines for social life cycle assessment of products: Just in time! *International Journal Life Cycle Assessment*, 15(2), 156-163.

Eiben, A. and Smit, S., 2011. Parameter tuning for configuring and analyzing evolutionary algorithms. *Swarm and Evolutionary Computation*, 1(1), 19-31.

Huijbregts, M., Norris, G., Bretz, R., Ciroth, A., Maurice, B., Von Bahr, B., Weidema, B. and De Beaufort, A., 2001. Framework for modeling data uncertainty in life cycle inventories. *International Journal Life Cycle Assessment*, 6(3), 127-132.

Kendall, A., 2012. Time-adjusted global warming potentials for LCA and carbon footprints. *International Journal of Life Cycle Assessment*, 17 (8), 1042-1049.

Lenzen, M., 2000. Errors in conventional and input-output-based life-cycle inventories. *Journal of Industrial Ecology,* 4(2), 127-148.

Modarres, A., Rahimzadeh, M. and Zarrabi, M., 2014. Field investigation of pavement rehabilitation utilizing cold in-place recycling. *Resources, Conservation and Recycling*, 83, 112-120.

Mohammad, L., Hassan, M., Vallabhu, B., and Kabir, M., 2015. Louisiana's experience with WMA technologies: mechanistic, environmental, and economic analysis. *ASCE-Journal of Materials in Civil Engineering*, 27(6), 04014185.

Parrish, K. and Chester, M., 2014. Life-cycle assessment for construction of sustainable infrastructure. *Practice Periodical Structural Design Construction,* 19, SPECIAL ISSUE: Construction Engineering: Leveraging Project and Career Success, 89-94.

Suh, S., Lenzen, M., Treloar, G., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard and Norris, G., 2004. System boundary selection in life-cycle inventories using hybrid approaches. *Environmental Science & Technology*, 38(3), 657-664.

Van Dam, T., Harvey, J., Muench, S., Smith, K., Snyder, M., Al-Qadi, I., Ozer, H., Meijer, J., Ram, P., Roesler, J. and Kendall, A., 2015. *Towards sustainable pavement systems- a reference document* (Report No. FHWA-HIF-15-002). Available at: www.fhwa.dot.gov/pavement/sustainability/hif15002/hif15002.pdf

Zaniewski, J., Butler, B., Cunningham, G., Elkins, G., Paggi, M. and Machemehl, R., 1982. *Vehicle operating costs, fuel consumption, and pavement type and condition factors* (Report No. FHWA/PL/82/001). Available at: http://ntl.bts.gov/lib/42...0/42239/FHWA-PL-82-001.pdf

Appendix A

A.1. Construction and M&R phases

(i) Model formulation:

$$C_{C.M\&R} = C_{EOw} + C_{EOp} + C_{Labor} \tag{A.1.1}$$

$$C_{EOw} = C_{EOw:C} + C_{EOw:Int} + C_{EOw:Tx} + C_{EOw:Ins} \tag{A.1.2}$$

$$C_{EOp} = C_{EOp:FC} + C_{EOp:PM\,\&FOG} + C_{EOp:R} + C_{EOp:Tw} + C_{EOp:SWI} + C_{EOp:Mob} \tag{A.1.3}$$

$$C_{EOw:C} = \frac{AC - TC - SV}{AOP \times AYU} \tag{A.1.4}$$

$$C_{EOw:C} = \frac{LCV}{LCD} \tag{A.1.5}$$

$$C_{EOw:Int} = \frac{\dfrac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times IntR}{AYU} \tag{A.1.6}$$

$$C_{EOw:Tx} = \frac{\dfrac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times TxR}{AYU} \tag{A.1.7}$$

$$C_{EOw:Ins} = \frac{\dfrac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times InsR}{AYU} \tag{A.1.8}$$

$$C_{EOp:FC} = FC \times FCost \tag{A.1.9}$$

$$C_{EOp:PM\,\&FOG} = C_{EOp:FC} \times F_{PM\,\&FOG} \tag{A.1.10}$$

$$C_{EOp:R} = \frac{(AC - TC) \times F_R}{AOP \times AYU} \tag{A.1.11}$$

$$C_{EOp:TW} = \frac{TCF \times TC}{TLF \times TWF \times TL} \tag{A.1.12}$$

$$C_{EOp.SWI} = SWIC \tag{A.1.13}$$

$$C_{EOp:Mob} = MC \tag{A.1.14}$$

$$C_{Labor} = \sum_{WCat=0}^{N_{WCat}} n_{Wcat} \times \frac{WB_{WCat}}{WD_{Eff} \times WD \times WH} \times V_{act} \times AF_{WCat,act} \tag{A.1.15}$$

(ii) Notation:

$C_{C.M\&R}$	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;
C_{EOw}	construction equipment owning costs. They are the same regardless of whether the construction equipment are parked in the constructor's yard, or operating (or idling) at a given work site;
C_{EOp}	construction equipment operating costs. They vary in proportion to hours of actual operation;
C_{Labor}	hourly costs fully incurred by the employer with the human resources required at work site to actually perform a given construction and M&R action (i.e. including wages and benefits);
$C_{EOw.C}$	hourly cost to protect the asset's value. If the equipment is owned by the constructor this subcategory is named depreciation cost (Expression (A.1.4)). On the other hand, when the equipment is not owned by the constructor, the most likely scenario is that the equipment is leased. In this case the $C_{EOw.C}$ is named leasing cost (Expression (A.1.5)), and depending on the clauses set out in the leasing contract, some of the remaining C_{EOw} subcategories may be exempted from direct and individual accounting;
$C_{EOw.Int}$	costs incurred due to the capital invested in an equipment, regardless of whether the equipment is purchased with constructor assets' or financed;
$C_{EOw.Tx}$	costs of property tax and license for the equipment;
$C_{EOw.Ins}$	costs incurred due to fire, theft, accident, and liability insurance for the equipment;
AC	cost of acquisition of the construction equipment;
TC	cost of a new set of tyres ($);
AOP	average ownership period (years);
SV	salvage or resale value ($) of the construction equipment at the end of the AOP;
AYU	average yearly usage (hr);
LCV	leasing contract value ($);
LCD	leasing contract duration (hr);
$IntR$	interest rate expressed in decimal value;
$AInsC$	annual insurance cost ($);
TxR	tax rate expressed in decimal value;
$InsR$	insurance rate expressed in decimal value;
$C_{EOp.FC}$	cost of the fuel consumed per each equipment piece at a work site;
$C_{EOp.PM\&FOG}$	cost for routine servicing of the construction equipment, as typically specified in the operation and maintenance manuals provided for each construction equipment, including

	filters, oils and greases;
$C_{EOp:R}$	cost for equipment repairs, maintenance, and major overhauls performed either in the work site or in the shop;
$C_{EOp:TW}$	tyre wear costs;
$C_{EOp:SWI}$	costs incurred with high-wear items, such as cutting edges and bucket teeth;
$C_{EOp:Mob}$	costs of construction equipment mobilization and demobilization;
FC	hourly fuel consumption during the operation period (litres/hr) estimated according to the methodology adopted by the US EPA’s NONROAD2008 model (US EPA, 2010a);
$FCost$	unit fuel cost ($/litre);
$F_{PM\&FOG}$	factor that represent the $C_{EOp:PM\&FOG}$ as a percentage of the hourly fuel cost;
F_{R}	factor that represent the $C_{EOp:R}$ as a percentage of the cost of a new equipment after subtracting the tyres cost (TC);
TCF	factor that accounts for the cost of recapping tyres. It represents the purchase of the original tyre plus one recap. According to US ACE (2011) it is estimated at 1.5, which means that a recap costs approximately 50 % of the cost of new tyres ;
TL	estimated tyre life (hr);
TLF	factor that represents the original tyre life plus one recap. According to US ACE (2011) it is estimated that a recap lasts approximately 80 percent of the life of a new tyre;
TWF	factor that represents the intensity of the tyre wear as a function of their position, type and condition of use. It is estimated according to the methodology proposed by the US ACE (2011);
$SWIC$	hourly cost of special wear items ($/hr);
Mob	hourly cost of equipment mobilization/demobilization ($/hr);
C_{Labor}	hourly cost fully incurred by the employer with the human resources required at work site to actually perform a given construction and M&R action (i.e. including wages and benefits);
N_{WCat}	total number of work categories required to perform the construction and M&R action act ;
n_{Wcat}	number of workers of the category $WCat$ that integrate the crew in charge of performing the construction and M&R action act ;
WB_{WCat}	total annual employer cost ($) for employee compensation of the category $WCat$, which includes wages, salaries and total benefits;
WD	total number of paid working days per year;
WD_{Eff}	coefficient representing the ratio between the number of days per year that a worker of a given category is actually available for working and the total number of paid working days per year (WD). The numerator of this ratio is obtained from the denominator by deducting the vacations, holidays, sick days, breaks, training and meeting days, and other;
WH	number of working hours per day;
V_{act}	total duration in hours of a construction and M&R action act ;
$AF_{WCat,act}$	assignment factor ranging between 0 and 1 that represents the time during one hour of a construction and M&R action act that a worker of the category $WCat$ is allocated to that construction and M&R action;

Appendix A

Table A.1- Values of the variables corresponding to each piece of construction equipment needed to compute the construction equipment owning and operating costs.

Lane	Activity	Process	Name	Brand	Model	AYU (hr)	AOP (years)	AC ($)	SV ($)	$F_{PM\&FOG}$	F_R	$IntR$ (%)	$InsR$ (%)	TxR (%)
Right	FDR	Milling	Milling Machine	Wirtgen	W 2100	606	8	700,000	140,000	0.119	1	3.25	3	2
		Reclaiming	Reclaimer	Wirtgen	WR 2400	606	8	523 000	104,600	0.119	1	3.25	3	2
			Water tank truck (skid-mounted, 4000 gallons)	Mack	Granite GU713	1,641	8	175,000	35,000	0.119	0.65	3.25	3	2
			Cement spreader truck (truck mounted spreader-27 tonnes)	Truck: Mack Cement spreader: Stoltz	Granite GU713	1,641	8	190,000	38,000	0.119	0.65	3.25	3	2
		Compacting	6-ton vibratory soil compactor	Caterpillar	CP44	760	8	124,000	24,800	0.102	0.8	3.25	3	2
		Grading	Motor Grader	Caterpillar	120H	962	8	280,000	70,000	0.144	0.75	3.25	3	2
	CCPR	CCPR	CCPR mobile plant	Wirtgen	KMA 220	606	8	517,000	103,400	0.119	0.9	3.25	3	2
			Wheel loader	Caterpillar	950K	761	8	246,000	61,500	0.111	0.7	3.25	3	2
		Paving and compacting	Paver	Dynapac	SD2550 C	821	8	340,000	51,000	0.119	1.00	3.25	3	2
			12-ton Double steel-drum vibratory roller	Hamm	HD+ 120 VO	760	8	150,000	22,500	0.102	1.20	3.25	3	2
			14-ton Double steel-drum vibratory roller	Hamm	HD +120 VV	760	8	213,000	31,950	0.102	1.20	3.25	3	2
			10-ton vibratory rubber tyre roller	Hamm	GWR10	760	8	109,000	16,350	0.102	1.20	3.25	3	2

Legend: FDR- full-depth reclamation; CCPR- cold central plant recycling.

(continued)

Lane	Activity	Process	Name	Brand	Model	TCF	TC ($)	TLF	TWF	TL (hr)	$SWIC$ ($/hr)	Mob ($/hr)
Right	FDR	Milling	Milling Machine	Wirtgen	W 2100	-	-	-	-	-	35	10.5
		Reclaiming	Reclaimer	Wirtgen	WR 2400	1.5	13,662	1.8	0.9	3,000	35	10.5
			Water tank truck (skid-mounted, 4000 gallons)	Mack	Granite GU713	1.5	4,976	1.8	0.9	5,000	-	10.5
			Cement spreader truck (truck mounted spreader- 27 tonnes)	Truck: Mack Cement spreader: Stoltz	Granite GU713	1.5	4,976	1.8	0.9	5,000	-	10.5
		Compacting	6-ton vibratory soil compactor	Caterpillar	CP44	1.5	4,082	1.8	0.9	5,000	-	10.5
		Grading	Motor Grader	Caterpillar	120H	1.5	2,031	1.8	0.9	5,000	-	10.5
	CCPR	CCPR	CCPR mobile plant	Wirtgen	KMA 220	-	-	-	-	-	-	10.5
			Wheel loader	Caterpillar	950K	1.5	9,810	1.8	0.9	5,000	-	10.5
		Paving and compacting	Paver	Dynapac	SD2550C	-	-	-	-	-	-	10.5
			12-ton Double steel-drum vibratory roller	Hamm	HD+ 120 VO	-	-	-	-	-	-	10.5
			14-ton Double steel-drum vibratory roller	Hamm	HD +120 VV	-	-	-	-	-	-	10.5
			10-ton vibratory rubber tyre roller	Hamm	GWR10	1.5	4,339	1.8	0.9	5,000	-	10.5

Legend: FDR- full-depth reclamation; CCPR- cold central plant recycling.

(continued)

Lane	Activity	Process	Name	Brand	Model	AYU (hr)	AOP (years)	AC ($)	SV ($)	$F_{PM\,\&\,FOG}$	F_R	$IntR$ (%)	$InsR$ (%)	TxR (%)
Left	CIR	Milling	Milling Machine	Wirtgen	W 2100	606	8	700,000	140,000	0.119	1	3.25	3	2
		Recycling	Cement spreader truck (truck mounted spreader- 27 tonnes)	Truck: Mack Cement spreader: Stoltz	Granite GU713	1,641	8	190,000	38,000	0.119	0.65	3.25	3	2
			Asphalt heated tank truck (trailer, 4000 gallons)	Truck: Mack Asphalt tank: Etnyre	CHU613	1,641	8	205,000	41,000	0.119	0.85	3.25	3	2
			Cold recycler	Wirtgen	3800 CR	606	8	900,000	180,000	0.119	1	3.25	3	2
		Compacting	16- ton double steel-drum vibratory roller	Hamm	HD 120	760	8	104,000	15,600	0.102	1.20	3.25	3	2
			16- ton double steel-drum vibratory roller	Hamm	HD 120	760	8	104,000	15,600	0.102	1.20	3.25	3	2
			25-ton vibratory rubber-tyre roller	Hamm	GWR 280	760	8	148,000	22,200	0.102	1.20	3.25	3	2
Both Lanes	Asphalt Paving	HMA and SMA paving and compacting	Paver	Dynapac	SD2550C	821	8	340,000	51,000	0.119	1.00	3.25	3	2
			Breakdown roller	Dynapac	CP 142	760	8	120,000	18,000	0.102	1.20	3.25	3	2
			Breakdown roller	Dynapac	CP 142	760	8	120,000	18,000	0.102	1.20	3.25	3	2
			Finishing roller	Dynapac	CC324HF	760	8	122,000	18,300	0.102	1.20	3.25	3	2
		Tack coat application	Diesel Engine	Perkins	1100 Series	815	8	10,000	1,000	0.102	0.6		-	2
			Skid steer (sweeper)	Bobcat	S630	818	8	38,000	7,600	0.111	0.8	3.25	3	2
			Asphalt distributor truck (skid mounted, 3000 gallons)	Truck: Mack Asphalt tank: Etnyre	Granite GU713	1,641	8	195,000	39,000	0.119	0.85	3.25	3	2
	Unbound Layers Removal	Excavation	Excavator	Hitachi	Zaxis 350LC-5	1,092	8	410,000	102,500	0.149	0.8	3.25	3	2

Legend: CIR- cold in-place recycling; HMA- hot-mix asphalt; SMA- stone mastic asphalt.

(continued)

Lane	Activity	Process	Name	Brand	Model	*TCF*	*TC* ($)	*TLF*	*TWF*	*TL* (hr)	*SWIC* ($/hr)	*Mob* ($/hr)
Left	CIR	Milling	Milling Machine	Wirtgen	W 2100	-	-	-	-	-	35	10.5
		Recycling	Cement spreader truck (truck mounted spreader- 27 tonnes)	Truck: Mack Cement spreader: Stoltz	Granite GU713	1.5	4,976	1.8	0.9	5,000	-	10.5
			Asphalt heated tank truck (trailer, 4000 gallons)	Truck: Mack Asphalt tank: Etnyre	CHU613	1.5	9,358	1.8	0.8	5,000	-	10.5
			Cold recycler	Wirtgen	3800 CR	-	-	-	-	-	35	10.5
		Compacting	16- ton double steel-drum vibratory roller	Hamm	HD 120	-	-	-	-	--	-	10.5
			16- ton double steel-drum vibratory roller	Hamm	HD 120	-	-	-	-	-	-	10.5
			25-ton vibratory rubber-tyre roller	Hamm	GWR 280	1.5	4,016	1.8	0.9	1,500	-	10.5
Both Lanes	Asphalt Paving	HMA and SMA paving and compacting	Paver	Dynapac	SD2550C	-	-	-	-	-	-	10.5
			Breakdown roller	Dynapac	CP 142	1.5	1,523	1.8	0.9	1,500	-	10.5
			Breakdown roller	Dynapac	CP 142	1.5	1,523	1.8	0.9	1,500	-	10.5
			Finishing roller	Dynapac	CC324HF	-	-	-	-	-	-	10.5
		Tack coat application	Diesel Engine	Perkins	1100 Series	-	-	-	-	-	-	10.5
			Skid steer (sweeper)	Bobcat	S630	1.5	1,188	1.8	0.9	5,000	-	10.5
			Asphalt distributor truck (skid mounted, 3000 gallons)	Truck: Mack Asphalt tank: Etnyre	Granite GU713	1.5	5,720	1.8	0.9	5,000	-	10.5
	Unbound Layers Removal	Excavation	Excavator	Hitachi	Zaxis 350LC-5	-	-	-	-	-	25	10.5

Table A.2- Values of the variables corresponding to each worker category needed to compute the respective hourly labor cost.

$WCat$	WB_{WCat} (\$/year)[a]	WD (days)[e]	WD_{eff} [e]	WH (hr)
Foremen	71,853.51[a]	260	0.77	8
Paving equipment operator	52,212.26[b]	260	0.77	8
Laborers	41,061.29[c]	260	0.77	8
Screed man	52,212.26[b]	260	0.77	8
Hauling truck driver	55,798.19[d]	260	0.77	8

[a] Value obtained by considering the annual 90th percentile total compensation for the "Paving, Surfacing, and Tamping Equipment Operators" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (US DL, 2011).

[b] Value obtained by considering the annual 50th percentile total compensation for the "Paving, Surfacing, and Tamping Equipment Operators" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (US DL, 2011).

[c] Value obtained by considering the annual 50th percentile total compensation for the "Construction laborers" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (US DL, 2011).

[d] Value obtained by considering the annual 50th percentile total compensation for the "Heavy and Tractor-Trailer Truck Drivers" occupational group in Virginia. It results from considering the wages and salaries equal to 66.4% of the total compensation (US DL, 2011).

[e] Data source: Wiegmann et al. (2011). It corresponds to a "year-round, full-time" hours figure of 2,080 hours.

A.2. Transportation of materials phase

(i) Model formulation:

$$C_{TP} = C_{HTOw} + C_{HTOp} + C_{Labour} \tag{A.2.16}$$

$$C_{HTOw} = C_{HTOw:C} + C_{HTOw:Int} + C_{HTOw:Tx} + C_{HTOw:Ins} \tag{A.2.17}$$

$$C_{HTOp} = C_{HTOp:FC} + C_{HTOp:PM\,\&\,FOG} + C_{HTOp:R} + C_{HTOp:T} \tag{A.2.18}$$

$$C_{HTOw:C} = \frac{AC - TC - SV}{AOP \times AYU} \tag{A.2.19}$$

$$C_{HTOw:C} = \frac{LCV}{LCD} \tag{A.2.20}$$

$$C_{HTOw:Int} = \frac{\dfrac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times IntR}{AYU} \tag{A.2.21}$$

$$C_{HTOw:Tx} = \frac{\dfrac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times TxR}{AYU} \tag{A.2.22}$$

$$C_{HTOwIns} = \frac{\frac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times InsR}{AYU} \tag{A.2.23}$$

$$C_{HTOpFC} = FC \times FCost \tag{A.2.24}$$

$$C_{HTOpPM\,\&\,FOG} = C_{HTOpFC} \times F_{PM\,\&\,FOG} \tag{A.2.25}$$

$$C_{HTOp:R} = \frac{(AC - TC) \times F_R}{AOP \times AYU} \tag{A.2.26}$$

$$C_{HTOpTW} = \frac{TCF \times TC}{TLF \times TWF \times TL} \tag{A.2.27}$$

$$C_{Labor} = \frac{WB_{HTD}}{WD_{Eff} \times WD \times WH} \times \frac{L_{HM}}{S_{HM}} \times 2 \tag{A.2.28}$$

(ii) Notation:

C_{TP}	costs incurred by the highway agency due to the transportation of the materials;
C_{HTOw}	hauling truck owning costs. They are the same regardless of whether the hauling truck is parked in the hauling truck owner's yard, or operating;
C_{HTOp}	hauling truck operating costs. They vary in proportion to hours of actual operation;
C_{Labour}	hourly costs fully incurred by the employer with the hauling truck driver (i.e. including wages and benefits);
C_{HTOwC}	hourly cost to protect the value of assets. If the hauling truck is owned by the constructor this subcategory is named depreciation cost (Expression (A.2.19)). On the other hand, when the hauling truck is not owned by the constructor, the most likely scenario is that it is leased. In this case the C_{HTOwC} is named leasing cost (Expression (A.2.20)), and depending on the clauses set out in the leasing contract, some of the remaining C_{HTOw} subcategories may be exempted from a direct and individual accounting;
$C_{HTOwInt}$	costs incurred due to the capital invested in the hauling truck, regardless of whether it is purchased with constructor assets' or financed;
C_{HTOwTx}	costs of property tax and license for the hauling truck;
$C_{HTOwIns}$	costs incurred due to fire, theft, accident, and liability insurance for the hauling truck;
C_{HTOpFC}	cost of the fuel consumed by the hauling trucks;
$C_{HTOpPM\,\&\,FOG}$	cost for routine servicing of the hauling truck, as typically specified in the operation and maintenance manuals provided for each hauling truck;
C_{HTOpR}	cost for hauling trucks repairs, maintenance, and major overhauls;
C_{HTOpTW}	tyre wear costs;
FC	fuel consumption (litres/km) estimated according to the US EPA's MOVES (US EPA, 2010b) as detailed by Santos et al. (2015);
L_{HM}	distance of the hauling movement [km] (1 way);
S_{HM}	average speed of the hauling movement (km/hr);

The meaning of the remaining variables is the same as that presented in "Appendix A.1. Construction and M&R phase".

Table A.3- Values of the variables corresponding to each hauling truck needed to compute the materials transportation costs.

Name	Brand	Model	AYU (km)	AOP (years)	AC ($)	SV ($)	$F_{PM\&FOG}$	F_{Repair}	$InsR$ (%)	$IntR$ (%)	TxR (%)	TCF	TC ($)	TLF	TWF	TL (km)
Dump truck	Mack	Granite GU 713	166,000	10	140,000	60,000	0.119	0.65	3	3.25	2	1.5	4,976	1.8	0.77	322,000
Water tank truck	Mack	Granite GU 713	166,000	10	175,000	35,000	0.119	0.65	3	3.25	2	1.5	4,976	1.8	0.77	322,000
Cement tank truck	Mack	Granite GU 713	166,000	10	190,000	38,000	0.119	0.65	3	3.25	2	1.5	4,976	1.8	0.77	322,000
Asphalt distributor tank truck	Mack	Granite CHU 613	166,000	10	205,000	41,000	0.119	0.65	3	3.25	2	1.5	9,358	1.8	0.77	322,000
Bituminous emulsions distributor tank truck	Mack	Granite GU 713	166,000	10	195,000	39,000	0.119	0.65	3	3.25	2	1.5	4,976	1.8	0.77	322,000

Acronyms: as specified in the formulation presented in section “Appendix A.1. Construction and M&R phase”.

A.3. Work-zone traffic management phase

Table A.4- Values of the main parameters used in the computation of the unit cost of travel time for PC.

Parameter			Data Source
Name	Unit	Value	
Proportion of PC on personal travel	%	93.7	National Household Transportation Survey [NHTS] (http://nhts.ornl.gov/tools.shtml)
Average vehicle occupancy of PC for personal travel	person/veh	1.67	NHTS (http://nhts.ornl.gov/tools.shtml)
Hourly value of personal travel time as a percentage of wage rate for an intercity travel type	%	70	US DOT (2003)
Median annual household income of all US households	$	50 054	DeNavas-Walt et al. (2012)
Hourly time value of a person on personal time	$/person.hr	16.85	-
Hourly time value of a vehicle on personal travel	$/veh.hr	28.13	-
Proportion of PC on business travel	%	6.3	NHTS (http://nhts.ornl.gov/tools.shtml)
AVO of PC for business travel	person/veh	1.24	NHTS (http://nhts.ornl.gov/tools.shtml)
Hourly value of personal travel time as a percentage of wage rate for an intercity travel type	%	100	US DOT (2003)
Total hourly wages and benefits of all civilian workers	$	29.98	US DL(2011)
Hourly time value of a person on business time	$/person.hr	29.98	-
Hourly time value of a vehicle on business travel	$/veh.hr	37.18	-
Weighted average of hourly time value of PC	**$/hr**	**28.70**	**-**

Legend: PC- passenger car; AVO- Average vehicle occupancy.

Table A.5- Values of the main parameters used in the computation of the unit cost of travel time for trucks.

Parameter			Data Source
Name	Unit	Value	
AVO of SUT	person/veh	1.025	FHWA (2005)
AVO of CUT	person/veh	1.12	FHWA (2005)
Average wages and benefits for SUT drivers	$	21.87	US DL (2011)
Average wages and benefits for CUT drivers	$	26.13	US DL (2011)
Hourly time value of SUT	**$/hr**	**22.42**	**-**
Hourly time value of CUT	**$/hr**	**29.27**	**-**

Legend: AVO- Average vehicle occupancy; SUT- single-unit truck; CUT- combination unit truck.

Table A.6- Values of the main parameters used in the computation of the cost of freight inventory delay.

Parameter			Data Source
Name	Unit	Value	
Percentage of empty loaded SUT	%	29	Alam at al. (2007)
Percentage of empty loaded CUT	%	24	Alam at al. (2007)
Average payload of SUT	lb	27,859	Alam and Rajamanickam (2007)
Average payload of CUT	lb	42,527	Alam and Rajamanickam (2007)
Average prime bank lending rate	%	3.25	Board of Governors of the Federal Reserve System (http://www.federalreserve.gov/releases/H15/data.htm#fn2)
Average value of commodities shipped by truck	$/lb	1.52	FHWA (2005)
Hourly value of freight shipped by truck	$/lb.hr	7.36×10^{-06}	-
Hourly freight inventory costs for SUT	**$/hr**	**0.21**	**-**
Hourly freight inventory costs for CUT	**$/hr**	**0.31**	**-**

Legend: SUT- single-unit truck; CUT- combination unit truck.

A.4. References

Alam, M., Fekpe, E. and Majed, M., 2007. *FAF^2 Freight traffic analysis*. Office of Freight Management and Operations (HFMO), Federal Highway Administration (FHWA), Washington, D.C. Available at: http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf2_reports/reports7/index.htm

Alam, M., and Rajamanickam, G., 2007. *Development of truck payload equivalent factor*. Office of Freight Management and Operations (HFMO), Federal Highway Administration (FHWA), Washington, D.C. Available at: http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf2_reports/reports9/index.htm

DeNavas-Walt, C., Proctor, B. and Smith, J., 2012. *Income, poverty, and health Insurance coverage in the United States: 2011* (Report No. P60-243), US Census Bureau, September 2012. Available at: http://www.census.gov/library/publications/2012/demo/p60-243.html

Federal Highway Administration (FHWA), 2005. *Highway economic requirements system- state version (HERST-ST). Technical report*. Available at: http://www.fhwa.dot.gov/asset/hersst/pubs/tech/tech00.cfm

Santos, J., Bryce, J., Flintsch, G., Ferreira, A., and Diefenderfer, B., 2015. A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, 11(9), 119-1217.

United States Department of Labor (US DL), 2011. *Employer costs for employee compensation – June 2011*. Bureau of Labor Statistics, Department of Labor. Available at: http://www.bls.gov/schedule/archives/ecec_nr.htm#2011

United States Department of Transportation (US DOT), 2003. *Valuation of Travel Time in Economic Analysis*, *Revised Departmental Guidance, Memorandum*. Office of the Secretary of Transportation, U.S. Department of Transportation, Washington, DC. Available at: http://www.dot.gov/office-policy/transportation-policy/revised-departmental-guidance-valuation-travel-time-economic

United States Environmental Protection Agency (US EPA), 2010a. *Exhaust and crankcase emission factors for nonroad engine modeling- compression- ignition* (Report No. NR-009d). Available at: http://www.epa.gov/otaq/nonrdmdl.htm#model

United States Environmental Protection Agency (US EPA), 2010b. *Motor Vehicle Emission Simulator (MOVES). user guide for MOVES2010b* (Report EPA-420-B-12-001b). Available at: http://www.epa.gov/otaq/models/moves/index.htm#user.

Wiegmann, J., Sundararajan, A. and Tao, Z., 2011. *Decision making for outsourcing and privatization of vehicle and equipment fleet maintenance* (National Cooperative Highway Research Program Report No. 692). Transportation Research Board, Washington, D.C. Available at: http://www.trb.org/Main/Blurbs/165623.aspx

Appendix B

B.1.Materials extraction and production phase

Table B.1- Time that a volume of asphalt binder is heated at an asphalt plant.

Data item	Value	Unit
Total annual HMA production per asphalt mixing plant	114000	tonnes
Number of tanks at a typical asphalt mixing plant	2	-
Percentage of aggregates in HMA (average value)	95	%
Density of asphalt binder	1.03	tonnes/m^3
Annual throughput of asphalt binder per storage tank	2767	m^3
Time that a typical mixing plant is in operation annually	8	months
Time that a volume of asphalt binder is heated	**2.08**	**hr/m^3**

Table B.2- Tanks features.

Data item	Value	Unit
Tank type	Vertical	-
Insulation thickness	7.62 (3)	cm (in)
Diameter	9.18	m
Length	3.38	m
Surface area	229.85	m^2

Table B.3- Heating requirements for maintaining tanks temperature against heat losses.

Data item	Value	Unit
Storage temperature (ºC)	160	ºC
Ambient temperature (ºC)	15	ºC
Heat loss rate	42.59	W/m^2/hr
Insulation adjustment factor (fiberglass)	1	-
Heat loss through the insulated tank body	9.79	kWhr
Heat loss through the accessories: 100 feet of asphalt piping, 4-in. diameter	2.91	kWhr
Heat loss through the accessories: 230 feet of hot oil piping, 2-1/2 in. diameter	4.37	kWhr
Heat loss due to heater inefficiency (for an heating efficiency of 85%)	1.47	kWhr
Total heat losses	18.54	kWhr
Design safety factor	25	%
Total Heat Loss (including safety factor)	23.18	kWhr
Energy required to heat asphalt binder at an asphalt mixing plant	138.97	MJ/m^3

Notes: Based on http://www.pentairthermal.com/literature/literature-types.aspx#dg1

Table B.4- Unit costs of the raw materials items (in 2011 US dollars).

Raw material item	Unit cost		Data source
	Unit	Value[a]	
Asphalt binder PG 64-22	$/tonne	653.94	VDOT (www.virginiadot.org/business/const/indices-previous.asp)
Asphalt binder PG 70-22	$/tonne	703.94[b]	VDOT (www.virginiadot.org/business/const/indices-previous.asp)
Asphalt binder PG 70-28	$/tonne	703.94[b]	VDOT (http://www.virginiadot.org/business/const/indices-previous.asp)
Hydrated lime	$/tonne	130.90	USGS (2013a)
Bitumen emulsion	$/tonne	792.52	Virginia Paving Company (www.virginiapaving.com)
Limestone: coarse aggregates, graded- bituminous aggregate, coarse	$/tonne	10.30	USGS (2013b)
Limestone: fine aggregates- Stone sand, bituminous mix or seal	$/tonne	10.62	USGS (2013b)
Crushed stone: coarse aggregates, graded- bituminous surface treatment aggregate	$/tonne	12.61	USGS (2013b)
Quartzite: coarse aggregates, graded- bituminous aggregate, coarse	$/tonne	11.96	USGS (2013b)
Quartzite: fine aggregates- Stone sand, bituminous mix or seal	$/tonne	7.56	USGS (2013b)
Crushed stone: coarse and fines aggregates- graded road base or subbase	$/tonne	7.63	USGS (2013b)
Traprock: coarse aggregates, bituminous aggregate, coarse	$/tonne	10.68	USGS (2013b)
Traprock: fine aggregates- Stone sand, bituminous mix or seal	$/tonne	12.65	USGS (2013b)
Tap water	$/tonne	1.05[c]	City of Richmond www.richmondgov.com/publicutilities/UtilityRates.aspx#ResidentialWater
RAP (processed at asphalt plant)	$/tonne	1.22[d]	-
SBR	$/tonne	1,547.06[e]	www.argusmedia.com/Petrochemicals/Argus-DeWitt-Butadiene-Services
Sasobit®	$/tonne	2,502.83[f]	Kristjánsdóttir et al. (2007)

[a] Free On Board costs.

[b] PG 64-22 unit cost plus $50 to account for the higher quality of the crude required to produce this grade, based on Willis et al. (2012).

[c] Charge for industrial water usage in Richmond after adjusting the US 2014 Dollar value to US 2011 Dollar.

[d] Value corresponding to the ownership and operating costs of the RAP processing unit (which comprises a diesel-powered crusher, a diesel-powered mobile screening plant, an electrically-powered stackable conveyor and a wheel loader) plus the wheel loader operator wage and benefits.

[e] Butadiene cost as a proxy for SBR.

[f] The 2006 value was scaled up to the 2011 value by using the Producer price index (PPI) for "Petrochemical manufacturing" sector.

Table B.5- Unit values of the asphalt plant operating costs items (in 2011 US dollars).

Sub-category	Item	Unit cost ($/ tonne of asphalt mixture) [a]	Data source
Fixed	Asphalt and pugmill plant depreciation costs	1.47[b]	Morgan (2005)[c] and US ACE (2011)[c]
	Auxiliary equipment depreciation costs	0.28[d] or 0.32[e]	Morgan (2005)[c], US ACE (2011)[c], Kristjánsdóttir et al. (2007)[f] and http://www.con-crete.com/silos.htm[f]
	Utilities (water and electricity)	0.66[g]	Morgan (2005)[c]
	Licensing, taxes and general operation permits	0.37[h] or 0.38[i]	Estimated
	Insurance	0.35[j]	Estimated
	Interest	0.57[k]	
	Labour: plant supervisor	1.08 [l]	US DL (2011a)
	Labour: asphalt plant operator	0.63[m]	US DL (2011a)
	Labour: wheel loader operator	0.46[n]	US DL (2011a)
	Labour: maintenance technician	0.48[o]	US DL (2011a)
Variable	Filters, oils and greases (FOG): asphalt plant , pugmill plant and wheel loader	0.30[p]	US ACE (2011)
	Repair: asphalt plant , pugmill plant and wheel loader	1.64[q]	US ACE (2011)
	Diesel consumed by the wheel loader	0.078[r]	US EIA (2014)

[a] The calculation procedure relies on the average annual asphalt mixtures production per plant (114,000 tonnes) during the year of 2011 in Virginia (Hansen and Copeland, 2013).

[b] Value obtained by considering acquisition costs of $2,638,802.00 and $194,815.00 for asphalt and pugmill plants, respectively, depreciated over 15 and 7 years, respectively, and a residual value equal to 20% and 10% of the acquisition costs.

[c] Since these unit costs depend on a large number of factors, the values reported by these sources were used as reference in setting representative values.

[d] Includes the acquisition costs of the following auxiliary equipment: quality control laboratory ($100,000.00; 15 years; 15%), anti-strip system ($20 000.00; 8 years; 15%), platform scales ($45,000.00; 15 years; 15%) and wheel loader ($155,104.00; 6 years; 25%). Where ($; years; %) stands for (acquisition cost; depreciation period; residual value as percentage of the acquisition cost).

[e] In addition to the items referred in [d] it also includes the acquisition cost of the Sasobit® feeder ($25,000.00; 7 years; 15%).

[f] Reference sources used in particular to estimate the equipment modification and/or installation costs required to produce WMA mixtures.

[g] Although the utilities cost comprises a fixed and a variable component, the total cost was assigned to the fixed sub-category due to the absence of more detailed information that would allow for a further division of this item.

[h] Obtained by applying a rate of 2.15% to the total annual assets value of $42,611.56.

[i] It differs from the value in [h] because the total annual assets value also includes the annualised value of the modifications required to produce WMA mixtures ($341.70).

[j] Obtained by applying a rate of 2% to the total annual assets value. The value is approximately the same regardless of whether or not the asphalt plant modification required to produce WMA mixtures are accounted for.

[k] Obtained by applying a rate of 3.25% to the total annual assets value. The value is approximately the same regardless of whether or not the asphalt plant modification required to produce WMA mixtures are accounted for.

[l] Value obtained by considering the annual 50th percentile total compensation for the "Civil Engineers" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (US DL, 2011b).

[m] Value obtained by considering the annual 90th percentile total compensation for the "Paving, Surfacing, and Tamping Equipment Operators" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (US DL, 2011b).

[n] Value obtained by considering the annual 50th percentile total compensation for the "Paving, Surfacing, and Tamping Equipment Operators" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (US DL, 2011b).

[o] Value obtained by considering the annual 50th percentile total compensation for the "Maintenance and Repair Workers, General" occupational group in Virginia. It results from considering the wages and salaries equal to 68% of the total compensation (US DL, 2011b).

[p] Total value resulting from considering the factors (0.88;0.135), (0.88;0.45) and (0.88;0.11) for the asphalt plant, pugmill plant and wheel loader, respectively. Where (X;Y) stands for (labour adjustment factor; FOG factor).

[q] Total value resulting from considering the factors (1.00;0.88), (0.70;0.62) and (0.65;0.57) for the asphalt plant, pugmill plant and wheel loader, respectively. Where (X;Y) stands for (repair cost factor; repair factor).

[r] Energy consumption corresponding to the operation of a wheel loader Caterpillar 924Hz estimated according to the rate at which the wheel loader can move aggregates and the methodology adopted by the US EPA's NONROAD 2008 model (US EPA, 2010a). See Santos et al. (2015) for further details.

B.2.Construction and M&R phase

(i) Model formulation:

$$C_{C.M\&R} = C_{EOw} + C_{EOp} + C_{Labor} \tag{B.2.1}$$

$$C_{EOw} = C_{EOw:C} + C_{EOw:Int} + C_{EOw:Tx} + C_{EOw:Ins} \tag{B.2.2}$$

$$C_{EOp} = C_{EOp:FC} + C_{EOp:PM\&FOG} + C_{EOp:R} + C_{EOp:Tw} + C_{EOp:SWI} + C_{EOp:Mob} \tag{B.2.3}$$

$$C_{EOw:C} = \frac{AC - TC - SV}{AOP \times AYU} \tag{B.2.4}$$

$$C_{EOw:C} = \frac{LCV}{LCD} \tag{B.2.5}$$

$$C_{EOw:Int} = \frac{\frac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times IntR}{AYU} \tag{B.2.6}$$

$$C_{EOw:Tx} = \frac{\frac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times TxR}{AYU} \tag{B.2.7}$$

$$C_{EOw:Ins} = \frac{\frac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times InsR}{AYU} \tag{B.2.8}$$

$$C_{EOp:FC} = FC \times FCost \tag{B.2.9}$$

$$C_{EOp:PM\&FOG} = C_{EOp:FC} \times F_{PM\&FOG} \tag{B.2.10}$$

$$C_{EOp:R} = \frac{(AC - TC) \times F_R}{AOP \times AYU} \tag{B.2.11}$$

$$C_{EOp:TW} = \frac{TCF \times TC}{TLF \times TWF \times TL} \tag{B.2.12}$$

$$C_{EOp:SWI} = SWIC \tag{B.2.13}$$

$$C_{EOp:Mob} = MC \tag{B.2.14}$$

$$C_{Labor} = \sum_{WCat=0}^{N_{WCat}} n_{Wcat} \times \frac{WB_{WCat}}{WD_{Eff} \times WD \times WH} \times V_{act} \times AF_{WCat,act} \tag{B.2.15}$$

(ii) Notation:

$C_{C.M\&R}$	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;
C_{EOw}	construction equipment owning costs. They are the same regardless of whether the construction equipment are parked in the constructor's yard, or operating (or idling) at a given work site;
C_{EOp}	construction equipment operating costs. They vary in proportion to hours of actual operation;
C_{Labor}	hourly costs fully incurred by the employer with the human resources required at work site to actually perform a given construction and M&R action (i.e. including wages and benefits);
$C_{EOw.C}$	hourly cost to protect the asset's value. If the equipment is owned by the constructor this subcategory is named depreciation cost (Expression (B.2.4)). On the other hand, when the equipment is not owned by the constructor, the most likely scenario is that the equipment is leased. In this case the $C_{EOw.C}$ is named leasing cost (Expression (B.2.5), and depending on the clauses set out in the leasing contract, some of the remaining C_{EOw} subcategories may be exempted from direct and individual accounting;
$C_{EOw.Int}$	costs incurred due to the capital invested in an equipment, regardless of whether the equipment is purchased with constructor assets' or financed;
$C_{EOw.Tx}$	costs of property tax and license for the equipment;
$C_{EOw.Ins}$	costs incurred due to fire, theft, accident, and liability insurance for the equipment;
AC	cost of acquisition of the construction equipment;
TC	cost of a new set of tyres ($);
AOP	average ownership period (years);
SV	salvage or resale value ($) of the construction equipment at the end of the AOP;
AYU	average yearly usage (hr);
LCV	leasing contract value ($);
LCD	leasing contract duration (hr);
$IntR$	interest rate expressed in decimal value;
$AInsC$	annual insurance cost ($);
TxR	tax rate expressed in decimal value;
$InsR$	insurance rate expressed in decimal value;
$C_{EOp.FC}$	cost of the fuel consumed per each equipment piece at a work site;
$C_{EOp.PM\&FOG}$	cost for routine servicing of the construction equipment, as typically specified in the operation and maintenance manuals provided for each construction equipment, including filters, oils and greases;
$C_{EOp.R}$	cost for equipment repairs, maintenance, and major overhauls performed either in the work site or in the shop;
$C_{EOp.TW}$	tyre wear costs;
$C_{EOp.SWI}$	costs incurred with high-wear items, such as cutting edges and bucket teeth;
$C_{EOp:Mob}$	costs of construction equipment mobilization and demobilization;
FC	hourly fuel consumption during the operation period (litres/hr) estimated according to the methodology adopted by the US EPA's NONROAD2008 model (US EPA, 2010a) ;
$FCost$	unit fuel cost ($/litre);
$F_{PM\&FOG}$	factor that represent the $C_{EOp.PM\&FOG}$ as a percentage of the hourly fuel cost;

F_R	factor that represent the $C_{EOp:R}$ as a percentage of the cost of a new equipment after subtracting the tyres cost (TC);
TCF	factor that accounts for the cost of recapping tyres. It represents the purchase of the original tyre plus one recap. According to US ACE (2011) it is estimated at 1.5, which means that a recap costs approximately 50 % of the cost of new tyres ;
TL	estimated tyre life (hr);
TLF	factor that represents the original tyre life plus one recap. According to US ACE (2011) it is estimated that a recap lasts approximately 80 percent of the life of a new tyre;
TWF	factor that represents the intensity of the tyre wear as a function of their position, type and condition of use. It is estimated according to the methodology proposed by the US ACE (2011);
$SWIC$	hourly cost of special wear items ($/hr);
Mob	hourly cost of equipment mobilization/demobilization ($/hr);
C_{Labor}	hourly cost fully incurred by the employer with the human resources required at work site to actually perform a given construction and M&R action (i.e. including wages and benefits);
N_{WCat}	total number of work categories required to perform the construction and M&R action act;
n_{Wcat}	number of workers of the category $WCat$ that integrate the crew in charge of performing the construction and M&R action act;
WB_{WCat}	total annual employer cost ($) for employee compensation of the category $WCat$, which includes wages, salaries and total benefits;
WD	total number of paid working days per year;
WD_{Eff}	coefficient representing the ratio between the number of days per year that a worker of a given category is actually available for working and the total number of paid working days per year (WD). The numerator of this ratio is obtained from the denominator by deducting the vacations, holidays, sick days, breaks, training and meeting days, and other;
WH	number of working hours per day;
V_{act}	total duration in hours of a construction and M&R action act;
$AF_{WCat,act}$	assignment factor ranging between 0 and 1 that represents the time during one hour of a construction and M&R action act that a worker of the category $WCat$ is allocated to that construction and M&R action;

Table B.6- Values of the variables corresponding to each piece of construction equipment needed to compute the construction equipment owning and operating costs.

Activity	Process	Name	Brand	Model	AYU (hr)	AOP (years)	AC ($)	SV ($)	$F_{PM\&FOG}$	F_R	$IntR$ (%)	$InsR$ (%)	TxR (%)
FDR	Milling	Milling Machine	Wirtgen	W 2100	606	8	700,000	140,000	0.119	1	3.25	3	2
	Reclaiming	Reclaimer	Wirtgen	WR 2400	606	8	523 000	104,600	0.119	1	3.25	3	2
		Water tank truck (skid-mounted, 4000 gallons)	Mack	Granite GU713	1,641	8	175,000	35,000	0.119	0.65	3.25	3	2
		Cement spreader truck (truck mounted spreader-27 tonnes)	Truck: Mack Cement spreader: Stoltz	Granite GU713	1,641	8	190,000	38,000	0.119	0.65	3.25	3	2
	Compacting	6-ton vibratory soil compactor	Caterpillar	CP44	760	8	124,000	24,800	0.102	0.8	3.25	3	2
	Grading	Motor Grader	Caterpillar	120H	962	8	280,000	70,000	0.144	0.75	3.25	3	2
CCPR	CCPR	CCPR mobile plant	Wirtgen	KMA 220	606	8	517,000	103,400	0.119	0.9	3.25	3	2
		Wheel loader	Caterpillar	950K	761	8	246,000	61,500	0.111	0.7	3.25	3	2
	Paving and compacting	Paver	Dynapac	SD2550 C	821	8	340,000	51,000	0.119	1.00	3.25	3	2
		12-ton Double steel-drum vibratory roller	Hamm	HD+ 120 VO	760	8	150,000	22,500	0.102	1.20	3.25	3	2
		14-ton Double steel-drum vibratory roller	Hamm	HD +120 VV	760	8	213,000	31,950	0.102	1.20	3.25	3	2
		10-ton vibratory rubber tyre roller	Hamm	GWR10	760	8	109,000	16,350	0.102	1.20	3.25	3	2

Legend: FDR- full-depth reclamation; CCPR- cold central plant recycling.

(continued)

Activity	Process	Name	Brand	Model	TCF	TC ($)	TLF	TWF	TL (hr)	$SWIC$ ($/hr)	Mob ($/hr)
FDR	Milling	Milling Machine	Wirtgen	W 2100	-	-	-	-	-	35	10.5
	Reclaiming	Reclaimer	Wirtgen	WR 2400	1.5	13,662	1.8	0.9	3,000	35	10.5
		Water tank truck (skid-mounted, 4000 gallons)	Mack	Granite GU713	1.5	4,976	1.8	0.9	5,000	-	10.5
		Cement spreader truck (truck mounted spreader- 27 tonnes)	Truck: Mack Cement spreader: Stoltz	Granite GU713	1.5	4,976	1.8	0.9	5,000	-	10.5
	Compacting	6-ton vibratory soil compactor	Caterpillar	CP44	1.5	4,082	1.8	0.9	5,000	-	10.5
	Grading	Motor Grader	Caterpillar	120H	1.5	2,031	1.8	0.9	5,000	-	10.5
CCPR	CCPR	CCPR mobile plant	Wirtgen	KMA 220	-	-	-	-	-	-	10.5
		Wheel loader	Caterpillar	950K	1.5	9,810	1.8	0.9	5,000	-	10.5
	Paving and compacting	Paver	Dynapac	SD2550C	-	-	-	-	-	-	10.5
		12-ton Double steel-drum vibratory roller	Hamm	HD+ 120 VO	-	-	-	-	-	-	10.5
		14-ton Double steel-drum vibratory roller	Hamm	HD +120 VV	-	-	-	-	-	-	10.5
		10-ton vibratory rubber tyre roller	Hamm	GWR10	1.5	4,339	1.8	0.9	5,000	-	10.5

Legend: FDR- full-depth reclamation; CCPR- cold central plant recycling.

(continued)

Activity	Process	Name	Brand	Model	AYU (hr)	AOP (years)	AC ($)	SV ($)	$F_{PM\,\&\,FOG}$	F_R	$IntR$ (%)	$InsR$ (%)	TxR (%)
CIR	Milling	Milling Machine	Wirtgen	W 2100	606	8	700,000	140,000	0.119	1	3.25	3	2
	Recycling	Cement spreader truck (truck mounted spreader- 27 tonnes)	Truck: Mack; Cement spreader: Stoltz	Granite GU713	1,641	8	190,000	38,000	0.119	0.65	3.25	3	2
		Asphalt heated tank truck (trailer, 4000 gallons)	Truck: Mack; Asphalt tank: Etnyre	CHU613	1,641	8	205,000	41,000	0.119	0.85	3.25	3	2
		Cold recycler	Wirtgen	3800 CR	606	8	900,000	180,000	0.119	1	3.25	3	2
		Water tank truck (skid-mounted, 4000 gallons)	Mack	Granite GU713	1,641	8	175,000	35,000	0.119	0.65	3.25	3	2
	Compacting	16- ton double steel-drum vibratory roller	Hamm	HD 120	760	8	104,000	15,600	0.102	1.20	3.25	3	2
		16- ton double steel-drum vibratory roller	Hamm	HD 120	760	8	104,000	15,600	0.102	1.20	3.25	3	2
		25-ton vibratory rubber-tyre roller	Hamm	GWR 280	760	8	148,000	22,200	0.102	1.20	3.25	3	2

Notes: CIR- cold in-place recycling.

(continued)

Activity	Process	Name	Brand	Model	TCF	TC ($)	TLF	TWF	TL (hr)	$SWIC$ ($/hr)	Mob ($/hr)
CIR	Milling	Milling Machine	Wirtgen	W 2100	-	-	-	-	-	35	10.5
	Recycling	Cement spreader truck (truck mounted spreader- 27 tonnes)	Truck: Mack Cement spreader: Stoltz	Granite GU713	1.5	4,976	1.8	0.9	5,000	-	10.5
		Asphalt heated tank truck (trailer, 4000 gallons)	Truck: Mack Asphalt tank: Etnyre	CHU613	1.5	9,358	1.8	0.8	5,000	-	10.5
		Cold recycler	Wirtgen	3800 CR	-	-	-	-	-	35	10.5
		Water tank truck (skid-mounted, 4000 gallons)	Mack	Granite GU713	1.5	4,976	1.8	0.9	5,000	-	10.5
	Compacting	16- ton double steel-drum vibratory roller	Hamm	HD 120	-	-	-	-	--	-	10.5
		16- ton double steel-drum vibratory roller	Hamm	HD 120	-	-	-	-	-	-	10.5
		25-ton vibratory rubber-tyre roller	Hamm	GWR 280	1.5	4,016	1.8	0.9	1,500	-	10.5

Legend: CIR- cold in-place recycling.

(continued)

Activity	Process	Name	Brand	Model	AYU (hr)	AOP (years)	AC ($)	SV ($)	$F_{PM\&FOG}$	F_R	$IntR$ (%)	$InsR$ (%)	TxR (%)
Asphalt Paving	HMA paving and compacting	Paver	Dynapac	SD2550C	821	8	340,000	51,000	0.119	1.00	3.25	3	2
		Breakdown roller	Dynapac	CP 142	760	8	120,000	18,000	0.102	1.20	3.25	3	2
		Breakdown roller	Dynapac	CP 142	760	8	120,000	18,000	0.102	1.20	3.25	3	2
		Finishing roller	Dynapac	CC324HF	760	8	122,000	18,300	0.102	1.20	3.25	3	2
	Tack coat application	Diesel Engine	Perkins	1100 Series	815	8	10,000	1,000	0.102	0.6		-	2
		Skid steer (sweeper)	Bobcat	S630	818	8	38,000	7,600	0.111	0.8	3.25	3	2
		Asphalt distributor truck (skid mounted, 3000 gallons)	Truck: Mack; Asphalt tank: Etnyre	Granite GU713	1,641	8	195,000	39,000	0.119	0.85	3.25	3	2
Unbound Layers Removal	Excavation	Excavator	Hitachi	Zaxis 350LC-5	1,092	8	410,000	102,500	0.149	0.8	3.25	3	2
Unbound Layers Laying and Compacting	Grading	Motor grader	Caterpillar	120H	962	8	280,000	70,000	0.144	0.75	3.25	3	2
	Compacting	Finishing roller	Dynapac	CC324HF	760	8	122,000	18,300	0.102	1.20	3.25	3	2
Subgrade Preparation	Compacting	Finishing roller	Dynapac	CC324HF	760	8	122,000	18,300	0.102	1.20	3.25	3	2
Microsurfacing	Materials spreading	Materials spreader truck	Truck: Mack; Materials spreader: Bergkamp M210	Granite GU713	1,641	8	175,000	35,000	0.119	0.65	3.25	3	2
Asphalt Paving	THMACO paving and compacting	Paver	Dynapac	SD2550C	821	8	340,000	51,000	0.119	1.00	3.25	3	2
		Breakdown roller	Dynapac	CP 142	760	8	120,000	18,000	0.102	1.20	3.25	3	2
		Breakdown roller	Dynapac	CP 142	760	8	120,000	18,000	0.102	1.20	3.25	3	2
		Finishing roller	Dynapac	CC324HF	760	8	122,000	18,300	0.102	1.20	3.25	3	2

Legend: HMA- hot-mix asphalt; THMACO- thin hot mix asphalt overlay concrete.

(continued)

Activity	Process	Name	Brand	Model	*TCF*	*TC* ($)	*TLF*	*TWF*	*TL* (hr)	*SWIC* ($/hr)	*Mob* ($/hr)
Asphalt Paving	HMA paving and compacting	Paver	Dynapac	SD2550C	-	-	-	-	-	-	10.5
		Breakdown roller	Dynapac	CP 142	1.5	1,523	1.8	0.9	1,500	-	10.5
		Breakdown roller	Dynapac	CP 142	1.5	1,523	1.8	0.9	1,500	-	10.5
		Finishing roller	Dynapac	CC324HF	-	-	-	-	-	-	10.5
	Tack coat application	Diesel Engine	Perkins	1100 Series	-	-	-	-	-	-	10.5
		Skid steer (sweeper)	Bobcat	S630	1.5	1,188	1.8	0.9	5,000	-	10.5
		Asphalt distributor truck (skid mounted, 3000 gallons)	Truck: Mack Asphalt tank: Etnyre	Granite GU713	1.5	5,720	1.8	0.9	5,000	-	10.5
Unbound Layers Removal	Excavation	Excavator	Hitachi	Zaxis 350LC-5	-	-	-	-	-	25	10.5
Unbound Layers Laying and Compacting	Grading	Motor grader	Caterpillar	120H	1.5	2,031	1.8	0.9	5,000	-	10.5
	Compacting	Finishing roller	Dynapac	CC324HF	-	-	-	-	-	-	10.5
Subgrade Preparation	Compacting	Finishing roller	Dynapac	CC324HF	-	-	-	-	-	-	10.5
Microsurfacing	Materials Spreading	Materials spreader truck	Truck: Mack; Materials spreader: Bergkamp M210	Granite GU713	1.5	4,976	1.8	0.9	5,000	-	10.5
Asphalt Paving	THMACO paving and compacting	Paver	Dynapac	SD2550C	-	-	-	-	-	-	10.5
		Breakdown roller	Dynapac	CP 142	1.5	1,523	1.8	0.9	1,500	-	10.5
		Breakdown roller	Dynapac	CP 142	1.5	1,523	1.8	0.9	1,500	-	10.5
		Finishing roller	Dynapac	CC324HF	-	-	-	-	-	-	10.5

Legend: HMA- hot-mix asphalt; THMACO- thin hot mix asphalt overlay concrete.

Table B.7- Values of the variables corresponding to each worker category needed to compute the respective hourly labor cost.

$WCat$	WB_{WCat} (\$/year)[a]	WD (days)[e]	WD_{eff} [e]	WH (hr)
Foremen	71,853.51[a]	260	0.77	8
Paving equipment operator	52,212.26[b]	260	0.77	8
Labourers	41,061.29[c]	260	0.77	8
Screed man	52,212.26[b]	260	0.77	8
Hauling truck driver	55,798.19[d]	260	0.77	8

[a] Value obtained by considering the annual 90th percentile total compensation for the “Paving, Surfacing, and Tamping Equipment Operators” occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (US DL, 2011b).

[b] Value obtained by considering the annual 50th percentile total compensation for the “Paving, Surfacing, and Tamping Equipment Operators” occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (US DL, 2011b).

[c] Value obtained by considering the annual 50th percentile total compensation for the “Construction laborers” occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (US DL, 2011b).

[d] Value obtained by considering the annual 50th percentile total compensation for the “Heavy and Tractor-Trailer Truck Drivers” occupational group in Virginia. It results from considering the wages and salaries equal to 66.4% of the total compensation (US DL, 2011b).

[e] Data source: Wiegmann et al. (2011). It corresponds to a “year-round, full-time” hours figure of 2,080 hours.

B.3.Transportation of materials phase

The model formulation and notation are equal to those presented in section “Appendix A.1. Construction and M&R phase”.

Table B.8- Values of the variables corresponding to each hauling truck needed to compute the materials transportation costs.

Name	Brand	Model	AYU (km)	AOP (years)	AC ($)	SV ($)	$F_{PM\&FOG}$	F_{Repair}	$InsR$ (%)	$IntR$ (%)	TxR (%)	TCF	TC ($)	TLF	TWF	TL (km)
Dump truck	Mack	Granite GU 713	166,000	10	140,000	60,000	0.119	0.65	3	3.25	2	1.5	4,976	1.8	0.77	322,000
Water tank truck	Mack	Granite GU 713	166,000	10	175,000	35,000	0.119	0.65	3	3.25	2	1.5	4,976	1.8	0.77	322,000
Cement tank truck	Mack	Granite GU 713	166,000	10	190,000	38,000	0.119	0.65	3	3.25	2	1.5	4,976	1.8	0.77	322,000
Asphalt distributor tank truck	Mack	Granite CHU 613	166,000	10	205,000	41,000	0.119	0.65	3	3.25	2	1.5	9,358	1.8	0.77	322,000
Bituminous emulsion distributor tank truck	Mack	Granite GU 713	166,000	10	195,000	39,000	0.119	0.65	3	3.25	2	1.5	4,976	1.8	0.77	322,000

Acronyms: as specified in the formulation presented in section "Appendix A.1. Construction and M&R phase".

Table B.9- Features of the movements of transportation of materials.

Material	Truck name	Distance (one way trip)	Hauling trucks payload capacity (tonnes)
PG 70-22 binder	Asphalt distributor tank truck	125	15
Limestone: coarse aggregates	Dump truck	40	20
Hydraulic cement	Cement tank truck	346	27
Limestone: fine aggregates	Dump truck	40	20
Tap water	Water tank truck	25	15
IM19.0D: HMA- 0% RAP	Dump truck	25	20
SM12.5D: HMA- 0% RAP	Dump truck	25	20
Quartzite: coarse aggregates	Dump truck	40	20
Bitumen emulsion	Bituminous emulsion distributor tank truck	125	11
BM25.0D: HMA- 0% RAP	Dump truck	25	20
Quartzite: fine aggregates	Dump truck	40	20
Crushed stone: surface treatment Aggregates	Dump truck	40	20
Hydrated lime	Cement tank truck	346	27
SBR	Dump truck	125	20
SM9.5D: HMA- 0% RAP	Dump truck	25	20
Removed materials	Dump truck	25	20
Removed materials	Dump truck	0.6	20
CCPR: mixtures produced	Dump truck	0.6	20
Unbound sub-base mix- 0% RAP	Dump truck	25	20
Sasobit®	Dump truck	125	20
PG 70-28 (PMB)	Asphalt distributor tank truck	125	15
IM19.0D: HMA- 15% RAP	Dump truck	25	20
SM12.5D: HMA- 15% RAP	Dump truck	25	20
BM25.0D: HMA- 15% RAP	Dump truck	25	20
SM9.5D: HMA- 15% RAP	Dump truck	25	20
Unbound sub-base mix- 15% RAP	Dump truck	25	20
Unbound sub-base mix- 30% RAP	Dump truck	25	20
IM19.0D: HMA- 30% RAP	Dump truck	25	20
SM12.5D: HMA- 30% RAP	Dump truck	25	20
BM25.0D: HMA- 30% RAP	Dump truck	25	20
SM9.5D: HMA- 30% RAP	Dump truck	25	20
IM19.0D: WMA Sasobit® - 0% RAP	Dump truck	25	20
SM12.5D: WMA Sasobit® - 0% RAP	Dump truck	25	20
BM25.0D: WMA Sasobit® - 0% RAP	Dump truck	25	20
SM9.5D: WMA Sasobit® - 0% RAP	Dump truck	25	20
SM9.5D: WMA Sasobit® - 15% RAP	Dump truck	25	20

(continued)

Material	Truck name	Distance (one way trip)	Hauling trucks payload capacity (tonnes)
M19.0D: WMA Sasobit® - 15% RAP	Dump truck	25	20
SM12.5D: WMA Sasobit® - 15% RAP	Dump truck	25	20
BM25.0D: WMA Sasobit® - 15% RAP	Dump truck	25	20
SM9.5D: WMA Sasobit® - 30% RAP	Dump truck	25	20
IM19.0D: WMA Sasobit® - 30% RAP	Dump truck	25	20
SM12.5D: WMA Sasobit® - 30% RAP	Dump truck	25	20
BM25.0D: WMA Sasobit® - 30% RAP	Dump truck	25	20
PG 64-22 binder	Asphalt distributor tank truck	125	15
Crushed stone: coarse and fine aggregates	Dump truck	40	20
Traprock: coarse aggregates	Dump truck	40	20
Traprock: fine aggregates	Dump truck	40	20
THMACO 9.5: 0% RAP	Dump truck	25	20

B.4. Work-zone traffic management phase

i) Time delay costs

Table B.10- Unit cost of travel time for the several categories of vehicles.

Vehicle category	Unit cost of travel time ($/hr)
Hourly time value of passenger cars (PCs)	28.70
Hourly time value of single-unit trucks (SUTs)	22.42
Hourly time value of combination-unit trucks (CUTs)	29.27
Hourly freight inventory costs for SUT	0.21
Hourly freight inventory costs for CUT	0.31

Legend: PC- passenger car; SUT- single-unit truck; CUT- combination unit truck.

Table B.11- Values of the main parameters used in the computation of the unit cost of travel time for PC.

Parameter Name	 Unit	 Value	Data Source
Proportion of PCs on personal travel	%	93.7	NHTS (http://nhts.ornl.gov/tools.shtml)
Average vehicle occupancy of PCs for personal travel	person/veh	1.67	NHTS (http://nhts.ornl.gov/tools.shtml)
Hourly value of personal travel time as a percentage of wage rate for an intercity travel type	%	70	US DOT (2003)
Median annual household income of all US households	$	50 054	DeNavas-Walt et al. (2012)
Hourly time value of a person on personal time	$/person.hr	16.85	-
Hourly time value of a vehicle on personal travel	$/veh.hr	28.13	-
Proportion of PC on business travel	%	6.3	NHTS (http://nhts.ornl.gov/tools.shtml)
AVO of PCs for business travel	person/veh	1.24	NHTS (http://nhts.ornl.gov/tools.shtml)
Hourly value of personal travel time as a percentage of wage rate for an intercity travel type	%	100	US DOT (2003)
Total hourly wages and benefits of all civilian workers	$	29.98	US DL (2011)
Hourly time value of a person on business time	$/person.hr	29.98	-
Hourly time value of a vehicle on business travel	$/veh.hr	37.18	-
Weighted average of hourly time value of PCs	**$/hr**	**28.70**	**-**

Legend: PC- passenger car; SUT- single-unit truck; CUT- combination unit truck; AVO- Average vehicle occupancy.

Table B.12- Values of the main parameters used in the computation of the unit cost of travel time for trucks.

Parameter Name	 Unit	 Value	Data Source
AVO of SUTs	person/veh	1.025	FHWA (2005)
AVO of CUTs	person/veh	1.12	FHWA (2005)
Average wages and benefits for SUTs drivers	$/hr	21.87	US DL (2011b)
Average wages and benefits for CUTs drivers	$/hr	26.13	US DL (2011b)
Hourly time value of SUTs	**$/hr**	**22.42**	**-**
Hourly time value of CUTs	**$/hr**	**29.27**	**-**

Legend: AVO- Average vehicle occupancy; SUT- single-unit truck; CUT- combination unit truck.

Table B.13- Values of the main parameters used in the computation of the cost of freight inventory delay.

Parameter Name	 Unit	 Value	Data Source
Percentage of empty loaded SUTs	%	29	Alam at al. (2007)
Percentage of empty loaded CUTs	%	24	Alam at al. (2007)
Average payload of SUTs	lb	27 859	Alam and Rajamanickam (2007)
Average payload of CUTs	lb	42 527	Alam and Rajamanickam (2007)
Average prime bank lending rate	%	3.25	Board of Governors of the Federal Reserve System (http://www.federalreserve.gov/releases/H15/data.htm#fn2)
Average value of commodities shipped by truck	$/lb	1.52	FHWA (2005)
Hourly value of freight shipped by truck	$/lb.hr	7.36×10^{-06}	-
Hourly freight inventory costs for SUTs	**$/hr**	**0.21**	**-**
Hourly freight inventory costs for CUTs	**$/hr**	**0.31**	**-**

Legend: SUT- single-unit truck; CUT- combination unit truck.

ii) Vehicle operation costs

Table B.14- Economic unit costs of the WZ-related VehOperC subcategories (in 2011 US dollars).

WZ-related VehOperC subcategory	Cost unit	Unit costs per vehicle category PC	 SUT	 CUT	Data source
Fuel: gasoline	$/litre	0.93	-	-	US EIA (2014)
Fuel: diesel	$/litre	-	1.00	1.00	US EIA (2014)
Oil	$/ litre	9.58	3.83	3.83	FHWA (2005)
Tyres	$/tyre	93.11	613.32	613.32	FHWA (2005)
Maintenance and repair	$/1000 miles	158.79	553.23	553.23	FHWA (2005)
Time-related depreciation	$/hr	1.23	3.16	9.57	FHWA (2005)
Mileage-related depreciation	$/hr	0.58	0.49	2.20	FHWA (2005)

Legend: WZ- work-zone; VehOperC- vehicle operation costs; PC- passenger car; SUT- single-unit truck; CUT- combination unit truck.

B.5.References

Alam, M., Fekpe, E. and Majed, M., 2007. *FAF^2 Freight traffic analysis*. Office of Freight Management and Operations (HFMO), Federal Highway Administration (FHWA), Washington, D.C. Available at: http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf2_reports/reports7/index.htm

Alam, M., and Rajamanickam, G., 2007. *Development of truck payload equivalent factor*. Office of Freight Management and Operations (HFMO), Federal Highway Administration (FHWA), Washington, D.C. Available at: http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf2_reports/reports9/index.htm

DeNavas-Walt, C., Proctor, B. and Smith, J., 2012. *Income, poverty, and health Insurance coverage in the United States: 2011* (Report No. P60-243), US Census Bureau, September 2012. Available at: http://www.census.gov/library/publications/2012/demo/p60-243.html

Federal Highway Administration (FHWA), 2005. *Highway economic requirements system- state version (HERST-ST). Technical report.* Available at: http://www.fhwa.dot.gov/asset/hersst/pubs/tech/tech00.cfm

Hansen, K. and Copeland, A., 2013. *2nd annual asphalt pavement industry survey on reclaimed asphalt pavement, reclaimed asphalt shingles, and warm-mix asphalt usage: 2009-2011*. Information series 138, National Asphalt Pavement Association, MD. Available at: http://www.asphaltpavement.org/index.php?option=com_content&view=article&id=946:napa-fhwa-seek-asphalt-mix-producers-input-for-survey&catid=24:napa-news4&Itemid=1308

Kristjánsdóttir, Ó., Muench, S., Michael, L. and Burke, G., 2007. Assessing potential for warm-mix asphalt technology adoption. *Transportation Research Record: Journal of the Transportation Research Board,* 2040, 91-99. doi: 10.3141/2040-10

Mallela, J. and Sadasivam, S., 2011. *Work zone road user costs - concepts and applications* (Report No FHWA-HOP-12-005). Office of Operations (OPS), Federal Highway Administration (FHWA), Washington, D.C. Available at: http://www.ops.fhwa.dot.gov/wz/resources/publications/fhwahop12005/index.htm

Morgan, J., 2005. *Hot mix asphalt for county roads: private providers or public plants?*, Comptroller of the Treasury, Offices of Research and Education Accountability, State of Tennessee. Available at: http://www.comptroller.tn.gov/AuditsAndReportsSearch/CategorySearchResults.aspx

Santos, J., Bryce, J., Flintsch, G., Ferreira, A. and Diefenderfer, B., 2015. A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, 11(9), 1199-1217. doi:10.1080/15732479.2014.945095

United States Army Corps of Engineers (US ACE), 2011. *Construction equipment ownership and operating expense schedule, Region II* (Document EP 1110-1-8, Vol. 2), Washington D.C.: US Army Corps of Engineers. Available at: http://www.publications.usace.army.mil/USACEPublications/EngineerPamphlets.aspx?udt_43545_param_page=12

United States Department of Labor (US DL), 2011a. *Occupational employment statistics May 2011*. Bureau of Labor Statistics, Department of Labor. Available at: http://www.bls.gov/oes/2011/may/oes_stru.htm

United States Department of Labor (US DL), 2011b. *Employer costs for employee compensation - June 2011*. Bureau of Labor Statistics, Department of Labor. Available at: http://www.bls.gov/schedule/archives/ecec_nr.htm#2011

United States Department of Transportation (US DOT), 2003. *Valuation of Travel Time in Economic Analysis, Revised Departmental Guidance, Memorandum.* Office of the Secretary of Transportation, U.S. Department of Transportation, Washington, DC. Available at: http://www.dot.gov/office-policy/transportation-policy/revised-departmental-guidance-valuation-travel-time-economic

United States Energy Information Administration (US EIA), 2014. *Lower Atlantic (PADD 1C) gasoline and diesel retail prices*. Available at: http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_r1z_a.htm

United States Environmental Protection Agency (US EPA), 2010a. *Exhaust and crankcase emission factors for nonroad engine modelling - compression-ignition* (Report No. NR-009d). Available at: http://www.epa.gov/otaq/nonrdmdl.htm#model

United States Environmental Protection Agency (US EPA), 2010b. *Motor Vehicle Emission Simulator (MOVES). user guide for MOVES2010b* (Report EPA-420-B-12-001b). Available at: http://www.epa.gov/otaq/models/moves/index.htm#user.

United States Geologic Services (USGS), 2013a. *2011 minerals yearbook: cement [Advance Release]*. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/cement/

United States Geologic Services (USGS), 2013b. *2011 minerals yearbook: stone, crushed [Advance Release]*. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/

Wiegmann, J., Sundararajan, A. and Tao, Z., 2011. *Decision making for outsourcing and privatization of vehicle and equipment fleet maintenance* (National Cooperative Highway Research Program Report No. 692). Transportation Research Board, Washington, D.C. Available at: http://www.trb.org/Main/Blurbs/165623.aspx

Willis, J., Turner, P., Julian, G., Taylor, A., Tran, N. and Padula, F., 2012. *Effects of changing virgin binder grade and content on RAP mixture properties* (NCAT Report No. 12-03), National Center for Asphalt Technology (NCAT) at Auburn University. Available at: http://www.ncat.us/files/reports/2012/rep12-03.pdf.