Resources, Conservation and Recycling 116 (2017) 15–31

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

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

João Santos[a], Gerardo Flintsch (Ph.D. P.E.)[b], Adelino Ferreira (Ph.D.)[c,*]

[a] IFSTTAR, AME-EASE, Route de Bouaye, CS4, F-44341 Bouguenais, France
[b] Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute, The Charles Via, Jr. Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, 3500 Transportation Research Plaza, Blacksburg, VA 24061, USA.
[c] Road Pavements Laboratory, Research Center for Territory, Transports and Environment, Department of Civil Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal

ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form 8 July 2016
Accepted 20 August 2016

Keywords:
Life cycle costing
Life cycle assessment
In-place recycling techniques
Sustainable pavement construction and management
Multi-criteria decision analysis

ABSTRACT

Stakeholders in the pavement sector have been seeking new engineering solutions to move towards more sustainable pavement management practices. The general approaches for improving pavement sustainability include, among others, reducing virgin binder and virgin aggregate content in HMA and WMA mixtures, reducing energy consumed and emissions generated in mixtures production, applying in-place recycling techniques, and implementing preventive treatments. In this study, a comprehensive and integrated pavement life cycle costing- life cycle assessment model was developed to investigate, from a full life cycle perspective, the extent to which several pavement engineering solutions, namely hot in-plant recycling mixtures, WMA, cold central plant recycling and preventive treatments, are efficient in improving the environmental and economic dimensions of pavement infrastructure sustainability, when applied either separately or in combination, in the construction and management of a road pavement section located in Virginia, USA. Furthermore, in order to determine the preference order of alternative scenarios, a multicriteria decision analysis method was applied. The results showed that the implementation of a recycling-based maintenance and rehabilitation strategy where the asphalt mixtures are of type hot-mix asphalt containing 30% RAP, best suits the multidimensional and conflicting interests of decision-makers. This outcome was found to be robust even when different design and performance scenarios of the mixtures and type of treatments are considered.

1. Introduction

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

The activities underlying to the construction, operation and maintenance of highway infrastructures are notorious for the large amounts of natural materials and energy resources they consume, as well as for the considerable environmental impacts they generate (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 preferable way, while also using funds in the most economically responsible manner possible. This fact has motivated DOTs, and the pavement community in general, to investigate strategies that improve the environmental performance and reduce the costs of road pavement construction and maintenance practices by using sustainable engineering solutions. Some examples of solutions commonly mentioned in the literature that possess the potential to improve pavement sustainability include (but are not limited to): (1) asphalt mixes requiring lower manufacturing temperatures, such as warm mix asphalt [WMA] (Kristjánsdóttir et al., 2007; Hamzah et al., 2010; Tatari et al., 2012; Vidal et al., 2013; Mohammad et al., 2015; 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., 2015c), (3) pavement preserva-

* Corresponding author.
E-mail addresses: joao.oliveira-dos-santos@ifsttar.fr (J. Santos), flintsch@vt.edu (G. Flintsch), adelino@dec.uc.pt (A. Ferreira).

http://dx.doi.org/10.1016/j.resconrec.2016.08.025
0921-3449/© 2016 Elsevier B.V. All rights reserved.

tion 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., 2007; 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 life-cycle assessment (LCA) and life cycle costing (LCC), which enable long-term economic and environmental factors to be included in the decision- making process by providing a comprehensive and cumulative view of both the environmental and economic dimensions of a given technical solution. However, it is important to underline that life-cycle modelling approaches by themselves will not necessarily determine which solution is most suitable for a given purpose. Rather, the information that they make available should be used as one component of a more comprehensive decision making process, which among other merits, will allow the tradeoffs between the interests of the multiple stakeholders to be assessed.

2. Objectives

The main objectives of this paper are (1) to investigate from a life cycle perspective the extent to which several pavement engineering solutions, namely hot in-plant recycling mixtures, 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 and (2) to raise awareness of the importance of extending the system boundaries of environmental and economic life cycle assessments, in order to include materials and processes which, when taken into consideration, may eventually reverse the sustainability of a solution, in comparison to the situations where they are not accounted for.

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

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

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

3.1. Life cycle assessment

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

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

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

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

The 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: (i) it uses aggregate data representing the averages of several sectors of an economy, and aggregate industry sectors may make the method unable to provide information on the particular product or activity under investigation, such as specific raw materials and energy sources, and to compare similar products within an industry sector, especially if the product falls into a sector which is broadly characterized; (ii) from the I-O LCA practitioner's perspective it may look like a "black box", because comprehensively analyzing a specific process is always impossible; (iii) monetary value, the