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Life-Cycle Evaluation of Pavements: A Critical Review

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Abstract

With the spread of the notion of sustainability, evaluating alternative roadway design options in terms of economic factors solely has become insufficient, and a need has risen to incorporate environmental and social dimensions. In response to this need, life-cycle evaluation (LCE), which consists of assessing the impacts of certain product/project from cradle to grave, has gained popularity among the pavement community. In its broad sense, LCE encompasses three main evaluation methods that are discussed thoroughly in this paper: life-cycle cost analysis (LCCA), life-cycle assessment (LCA), and social life-cycle assessment (SLCA). An integration of all three LCE methods is known as life-cycle sustainability assessment (LCSA). This paper presents a review of the evolution of LCE through each of these evaluation methods with a focus on pavement methods, applications, and tools. The authors attempt to identify gaps in research and practice of pavement LCE, and to propose enhancements. Incorporating the social dimension of sustainability in pavement LCE and relying on accurate performance prediction and traffic characterization are examples of such improvements. The authors also give suggestions for LCSA scope definition and multi-objective decision making. The paper concludes with recommendations for future research and applications.

Keywords: LCA, LCCA, LCSA, Life-Cycle Evaluation, Pavement, SLCA, Sustainability

1. Introduction

The past few decades have witnessed a fast-growing public concern over the rapid deterioration of the environment. Hence, the need to limit this decline and to protect natural resources has become at the top of the agenda of policy makers, practitioners and academics and within many industries, including pavements—the focus of this paper. Evaluating alternative pavement options in terms of economic factors solely has become insufficient from a sustainability standpoint, and a need has risen to incorporate environmental and social dimensions. Moreover, with the recognition that impacts should be accounted for on a long-term basis, the idea of life-cycle evaluation (LCE) has taken the spotlight. LCE consists of evaluating the economic, environmental, or social impact of a certain product/project over its entire life-cycle, starting from material extraction and manufacturing, through production/construction, use/operation, maintenance, and end-of-life.

In its broad sense, LCE encompasses three main evaluation methods that are discussed thoroughly in this paper: life-cycle cost analysis (LCCA), life-cycle assessment (LCA), and social life-cycle assessment (SLCA). LCCA assesses the economic cost of a product/project from cradle to grave [1], LCA evaluates its environmental impact [2], and SLCA studies its social impact [3-5]. With the acknowledgement of the importance of incorporating the three dimensions of sustainability in a single LCE, an evolution of LCE methods has led to the development of the life-cycle sustainability assessment (LCSA) framework [3-5]. LCSA is an LCE framework that incorporates the three aspects of sustainability by combining LCA, LCCA and SLCA [6].

Similar to other industries, the roadway industry particularly that related to pavement materials and construction, has in turn adopted LCCA and LCA. With the significant environmental impact that the pavement industry carries, its stakeholders have invested in sustainable solutions and innovations in pavement materials, construction, maintenance and rehabilitation strategies and end-of-life salvaging alternatives. Among these solutions are the use of high percentage of reclaimed asphalt pavements (RAP), recycled asphalt shingles (RAS), and warm-mix asphalt (WMA). This has consequently led to a need to accurately quantify or assess economic and environmental impacts, and thus the adoption of LCCA and LCA. Pavement-specific frameworks and tools [7, 8] have been under development to meet this purpose.

This paper presents a thorough review of LCE methods and their evolution (Section 2), with particular interest and focus on pavement applications (Section 3) and tools (Section 4). The study identifies gaps and limitations associated with existing pavement LCE applications such as incomplete coverage of impact categories and life-cycle stages. Proposed enhancements for pavement LCE, such as incorporating the social dimension of sustainability in pavement LCE and relying on accurate performance prediction and traffic characterization, are presented in Section 5, along with a methodology for evaluating pavement alternatives. The paper concludes with recommendations for future research (Section 6).

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2. Evolution of LCE methods

Comparing several pavement alternatives, processes, and methodologies is a dynamic part of any decision-making process. It is often the case where there is a need to evaluate different alternatives for a particular life-cycle or service life. Such evaluation or assessment has for years comprised solely of economic analyses until recently when other factors such as environmental, safety, and social have also become of the essence. The following section sheds light on the evolution of various techniques for LCE, including LCCA, LCA, and SLCA.

2.1. Life-cycle cost analysis (LCCA)

LCCA is a method used to evaluate the economic cost of a product or service beyond the narrow scope of initial investment by taking a broader view of the entire product life-cycle [9]. It emerged in the US in the 1960s and was first used by the government to reduce construction costs. LCCA falls under a wider economic analysis tool, i.e. benefit-cost analysis (BCA) [9, 10]. While BCA, as its name suggests, takes into account both costs and benefits in the comparison of project alternatives, LCCA focuses merely on the cost aspect of the products or projects under study [10].

The definition of LCCA as an 'economic cost' evaluation tool might be misguiding, as almost all LCCA's focus on a single aspect of economics, which is monetary cost, not taking into account any other economic parameter.

LCCA consists of five main steps: (1) establishing design alternatives, (2) determining activity timing, (3) estimating costs, (4) computing life-cycle costs, and (5) analysing the results [10]. Typically, costs of all phases are projected to a present value using a certain discount rate [9].

2.1.1. Deterministic versus probabilistic LCCA

There are two computational approaches in LCCA: deterministic and probabilistic. Deterministic LCCA consists of assigning a fixed discrete value to each input variable based on historical evidence or professional judgment, yielding a fixed result that is easy to compute and interpret [10]. To solve the problem of uncertainty that deterministic LCCA fails to capture, probabilistic LCCA defines inputs based on probabilistic distributions and uses simulation programming to randomly draw variables for the computation of the results [10].

2.1.2. Limitations of LCCA

A major drawback of LCCA is that it is data-intensive, depends greatly on data quality, and presents a challenge when calculating costs associated with the use/operation phase of a product/project [1, 10].

LCCA typically requires that only costs that present differences between alternatives be calculated [10]. Although this simplifies calculations, the authors believe that this could lead to misguided results, since it prevents benchmarking costs of different phases with respect to the total cost of the project and, therefore, deters proper comparison. Moreover, LCCA accommodates biased analysis; chosen inputs, such as interest rate can skew the analysis in favour of a particular alternative. Another major downside of LCCA as a stand-alone evaluation method is its failure to incorporate the environmental and social impacts of the alternatives under evaluation.

2.2. Life-cycle assessment (LCA)

LCA was first developed in the early 1970s at the Midwest Research Institute in the United States [11], and was first used to evaluate the environmental impacts of different bottling options for the Coca-Cola Company [12]. Between 1990 and 1993, the Society of Environmental Toxicology and Chemistry (SETAC and SETAC-Europe) held a series of workshops aiming to develop the framework of LCA [11]. These workshops led to the 'Code of Practice' of 1993 [11], based on which the LCA framework was standardized by ISO in the 14040 series in 1997 [13] and was later updated in 2006 [2].

According to ISO, LCA is a technique used to assess the environmental aspects and potential impacts associated with a product over its entire life-cycle. Impact categories considered include: resource use, human health, and ecological consequences [2]. The added-value of LCA compared to other environmental evaluation methods lies in looking at the entire life-cycle of the product which avoids problem-shifting from one life-cycle phase to another, or from one environmental problem to another [14].

LCA consists of four major steps [2]: (1) goal and scope definition, (2) life-cycle inventory (LCI), (3) life-cycle impact assessment (LCIA), and (4) interpretation of results.

There are three types of LCA: process LCA, economic input-output LCA and hybrid LCA.

2.2.1.1. *Process LCA:* Process LCA comprises of dividing the product or project under study to unit processes or flows, and analysing the input and output of each flow. The drawback of process LCA is that dissecting the system into flows can become too overwhelming, and it is practically infeasible to include all unit processes. Often, processes which have significant contribution to the overall evaluation are not considered, leading to inaccurate interpretations and analyses. Similar to LCCA, process LCA is resource intensive [15].

2.2.1.2. *Economic input-output LCA:* Economic input-output LCA uses the concept and framework of 'input-output analysis (IOA)' and applies it to environmental analysis. IOA is a field of economics that studies the connections between different industry sectors on a supply-chain basis. It is often used to estimate the environmental impacts generated throughout the upstream supply-chain to deliver a certain amount of different goods and services [14]. The drawback of EIO-LCA lies in the fact that the data is based on average values for the sector; and thus, the results are subject to fluctuation or inaccuracy, depending on how close or far the object is under study is to the average [14, 15].

2.2.1.3. *Hybrid LCA:* Recognizing the drawbacks of both process LCA and input-output LCA, a technique called Hybrid LCA was developed to combine both types of LCA, taking advantage of their strengths and mitigating the difficulties and uncertainties they present individually. As such, hybrid LCA applies an economic input-output technique for upstream processes and a process LCA for downstream processes [14, 16].

2.3. Social life-cycle assessment (SLCA)

SLCA consists of evaluating the social impact of a product/project over its life-cycle. SLCA indicators are divided into four main impact categories: (1) human rights, (2) labour practices and decent work conditions, (3) society, and (4) product responsibility. SLCA impact categories can be either quantitative or qualitative A detailed survey of the SLCA impact categories and indicators that had been developed up until 2008 date was performed by Jorgensen et al. (2008) [6].

It has been debated that SLCA is rooted in the enterprise's Corporate Social Responsibility, and is thus function of the company and not the product [6]. Others, however, believe that common data can be derived for a certain product leading to somewhat unified social impact assessment [6]. Even so, SLCA presents numerous challenges, mainly related to challenges in the collection of data and the creation of common impact categories, as some parameters are qualitative while others may be quantitative or semi-quantitative [6].

Further discussion of SLCA is presented in Section 6.1.

2.4. Life-cycle sustainability assessment (LCSA)

LCCA, LCA and SLCA typically address economic, environmental, and social impacts, respectively and independently. Sustainability, however, involves an integration of the three dimensions. Therefore, a holistic life-cycle analysis that involves all three aspects is essential to avoid problem shifting from one dimension to the other [3-5, 14]. Moreover, debatably, eliminating social impacts from LCA is inconsistent with the definition of LCA, since they affect impact categories within the scope of LCA, the most prominent being human health [6, 14].

Therefore, LCE evolved over time to expand from a scope limited to a single dimension to one that adopts a broad sustainability perspective. The feasibility of incorporating the three dimensions of sustainability in each phase of the LCE was first studied by Andersson et al. [3]. Eventually, the need for a perspective that was wider than LCA led to the concept of Life-Cycle Sustainability Assessment (LCSA) [3-5].

LCSA, first formalized by Klopffer in 2008, comprises of three major components: LCA (life-cycle analysis), LCCA (life-cycle cost analysis), and SLCA (social life-cycle assessment) [3]. The term LCSA has been used to indicate two evaluation methodologies: life-cycle sustainability *assessment*, and life-cycle sustainability *analysis*. Life-cycle sustainability *assessment* involves analysing each dimension of sustainability individually, and then combining the results in the final analysis [4]. Zamagni et al. and others [3-5] suggest, that the limitation of life-cycle sustainability assessment lies in the fact that it fails to consider mutual integrated relations among the three dimensions of sustainability. Zamagni et al. discuss the concept of life-cycle sustainability *analysis* which consists of an integrated framework that relates the different sustainability parameters together [4]. Life-cycle sustainability analysis, however, is much more complex, and is still conceptual. LCSA from here on in this paper refers to life-cycle sustainability assessment.

LCSA is still relatively new, and has not yet been widely adopted. Most analyses consist of integrating LCCA and LCA, and overlook the social dimension. Moreover, even LCA and LCCA do not fully cover all impact categories or all the life-cycle stages of the product or project under study. Both LCSA and SLCA are still under development conceptually and practically [3-5].

3. LCE methods and tools for pavements

This section presents an overview of pavement LCE methods and applications.

3.1. *Overview of pavement LCE methods*

3.1.1. LCCA for pavements

Over the past few decades, the use of LCCA in the infrastructure industry, particularly for pavement projects, has shown a lot of growth on both the conceptual and the practical levels.

LCCA for pavements incorporates both agency costs and user costs. Agency costs cover the entire life-cycle of the pavement, from initial cost, to maintenance and rehabilitation, restoration and reconstruction, and terminal value, where all future costs are discounted to present value. Terminal value could be interpreted as the salvage value, i.e. net value from the recycling of the materials at the project's end-of-life, or residual service life, i.e. the value of the remaining years in the project's life if its service life extends beyond the analysis period [10]. User costs account for the vehicle operating costs, travel time costs (user delay), and crash costs during both the initial construction and maintenance phases.

One of the most widely used LCCA tools for pavements is RealCost. RealCost is a Microsoft Excel-based software developed by the Federal Highway Administration (FHWA) to calculate agency and user costs. It can perform both deterministic and probabilistic LCCAs. Further information on RealCost is provided in the section on LCE tools and in Table 2. The main shortcoming of LCCA is that it is highly influenced by variables such as interest rate and hourly user cost. Varying these inputs can greatly affect the outcome of an LCCA and give unreliable favouritism for one alternative over the over.

3.1.2. LCA for pavements

As environmental concerns became more pressing and as LCA came into the picture, several attempts were made in the pavement industry to quantify the environmental impact of pavements [7, 16-18]. Still, to date, the environmental effect of pavements is not well understood; conducted LCAs generally study only parts of the life-cycle, tackle only a few impact categories, and omit components of the pavement life-cycle that could highly impact the final results such as rolling resistance, concrete carbonation, albedo and roadway lighting [19, 20]. The reason behind this is the complexity of the nature of the relation of pavements with the environment and the lack of full understanding and documentation of it in literature [19, 21].

The components of the pavement life-cycle assessment process are represented in the flow chart in Figure 1.

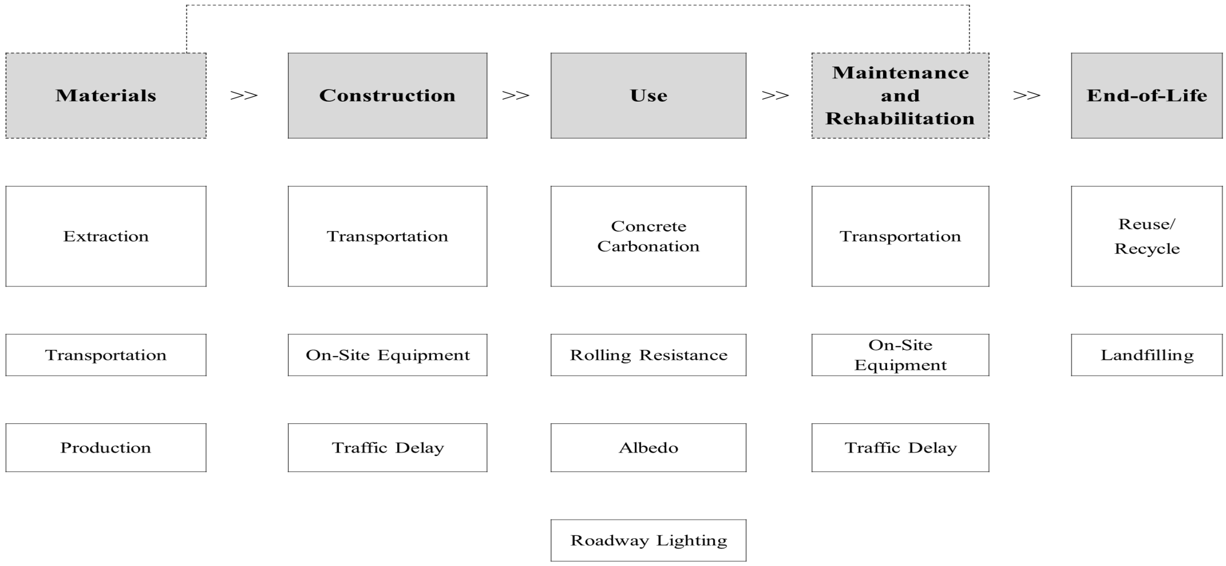

Fig. 1. Components of the pavement life-cycle assessment process [7, 19].

The most studied environmental indicator in pavement LCA is the global warming potential (GWP) as measured by units of carbon dioxide equivalent (CO_2e), followed by energy consumption typically measured in mega-joules (MJ) [9, 22]. In an attempt to get a clearer picture of the magnitude of the impact of each phase of the life-cycle, Santero and Horvath conducted a relatively comprehensive study on the GWP (in terms of carbon dioxide equivalent) of different life-cycle stages, taking into account stages that are typically cut off, such as albedo, carbonation and roadway lighting [19]. The results presented possible ranges of carbon dioxide equivalent for each life-cycle component and showed that rolling resistance typically corresponds to the highest impact [19]. The study also concluded that it is difficult to accurately categorize the life-cycle phases in terms of increasing or decreasing impact since some parameters, such as traffic volume and maintenance schedules, are project-specific, and thus results may vary from one pavement to another [19].

Challenges in pavement LCA: Despite the fact that LCA is relatively well-developed as a concept and framework, there is lack of unanimity when it comes to its application to pavements [8]. There is a lack of consensus regarding the goal and scope, namely the system boundaries and functional units, of pavement LCA. [8, 20]. Inconsistency in functional units is mainly due to the complexity of pavement structures and hinders the comparison of results of different LCA studies [20]. For instance, while some LCA applications adopt ESALs over the design life as functional units, others consider AADT over the analysis period [20].

Pavement LCA relies on and is sensitive to input data that is often challenging to characterize or estimate accurately, such as traffic distribution. Traffic is the most influential input parameter; it affects rolling resistance and user cost directly, and materials, transportation, equipment and carbonation indirectly by affecting the structure of the pavement. Traffic also has an indirect effect on lighting since it affects the functional classification of a roadway [19].

Quantifying the environmental impacts of the use phase of the pavement life-cycle is intricate as a concept [19]. A challenge presented by user cost analysis is that it is project and site specific [21].

The maintenance schedule is typically portrayed very simplistically in pavement LCAs and fails to properly convey the phase's wide-ranging impact [20]. The importance of using the MEPDG software (Mechanistic Empirical Pavement Design Guide) along with any LCE lies in accurately predicting the performance of the pavement over its service life and building a comprehensive maintenance schedule accordingly, as discussed in more detail in Section 5.3.

3.1.3. LCSA for pavements

The notion of applying LCSA for pavements has been set forth [23]; however, no clear framework for pavement LCSA has been established yet, and very few LCEs have ventured into the social dimension. One such study is [24] which focuses on the sustainable benefits of concrete pavements, taking into account hydroplaning and night-time visibility as social parameters. More on pavement SLCA is discussed in Section 5.1 under suggested enhancements for pavement LCE.

3.2. Overview of applications of LCE for pavements

A review of literature reveals a set of studies that address various aspects of pavement LCE's with a majority focusing on LCCA or LCA. Table 1 presents a thorough compilation of pavement LCE applications. Evaluations of pavement life-cycles have targeted three main aspects: economic (LCCA), environmental (LCA), and integrated economic and environmental. The scopes of LCEs presented in the table vary from evaluation of particular paving materials to the assessment of full project alternatives. The applications are therefore grouped in the table in terms of pavement types, materials and additives, maintenance and rehabilitation strategies, and innovative pavement solutions. The goals and scopes, boundaries, geographical and time contexts, and impact categories of the studies presented in the table vary, and the stakeholders are mainly researchers or highway agencies. It is important to note that this compilation, though thorough, is not comprehensive.

Separate LCA and LCCA studies have been commonly conducted on several aspects of pavements, mostly targeting comparison of HMA and PCC pavements or evaluating each individually. Integrated LCA and LCCA studies are less prevalent, but common nonetheless.

LCSA for pavements, as previously mentioned, has not been thoroughly investigated yet, and very few attempts at implementing it have been made. An example of LCSA targeting concrete pavements is provided in [24].

Table 1. Thorough compilation of pavement LCE applications.

		LCA	LCCA	Integrated LCA and LCCA
FLEXIBLE PAVEMENTS	**Asphalt Mix Type**			
	Cold Mix Asphalt (CMA)	[25]		
	Hot Mix Asphalt (HMA)	[26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [25], [37], [38], [39], [40], [54], [112],	[16], [41], [42], [43], [44], [45], [46]	[47]
	Stone Mastic/Matrix Asphalt (SMA)	[9], [48], [49], [50]		
	Warm Mix Asphalt (WMA)	[22], [51], [48], [34], [112], [113]	[41]	
	Materials and Additives			
	Ash	[52], [53], [112]		
	Binder/Bitumen	[55], [56]	[57]	
	Foundry	[53]		
	High Reclaimed Asphalt Pavement (RAP)	[58]		[59]
	Mastic			[56]
	Polymer Additives		[60]	
	Reclaimed Asphalt Pavement (RAP)	[22],[7], [17], [52], [112], [113]	[61]	
	Recycled Asphalt Shingles (RAS)	[113]		[62]
	Rubber	[113]	[43], [46]	
	Slag	[9]		
	Waste Glass	[52]		
	Wax	[55]		
	Pavement Maintenance and Rehabilitation			
	Chip Seal	[63], [110]	[60], [46]	
	Crack Seal	[63], [110]	[111]	
	Full Depth Reclamation (FDR)	[54], [110], [112]	[64]	
	HMA Overlay	[112]	[111]	[65], [66]
	Thick HMA Overlay		[67]	
	Ultrathin HMA Overlay	[63]	[67]	
	Hot In-Place Recycling		[67]	
	Maintenance of Porous Asphalt (PA) Using Rejuvenation Technology	[68]		
	Microsurfacing	[110]	[67]	[65]
	Slurry Seal	[110]		[65]
	Innovative Solutions and Other			
	Double-Layer Pavement (Guss Asphalt + SMA)		[69]	
	Foam Stabilized Base (FSB)	[58]		
	Life Long Asphalt Pavement (Perpetual Pavement)		[70], [71], [44], [45]	
	Low Asphalt Binder Content	[72]		
	Porous Pavement		[73]	
	Quiet Pavement		[74]	
RIGID PAVEMENTS	**PCC Pavement Type**			
	Continuous Reinforced Concrete Pavement (CRCP)	[35], [39], [40]	[75]	[76], [77]
	Jointed Plain Concrete Pavement (JPCP)	[28], [49], [50], [36], [25], [37], [38], [39], [114]		[76], [77]
	Jointed Reinforced Concrete Pavement (JRCP)			[76]
	Materials and Additives			
	Air-Cooled Blast Furnace Slag Coarse Aggregate (ACBFS)		[78]	
	Crushed Concrete Aggregate (CCA)		[78]	
	Fly Ash	[22], [79], [112]		
	High Volume Fly Ash (HVFA)	[80]		
	Portland Cement Concrete (PCC)	[81], [29], [30], [31], [32], [33], [82]		
	Supplementary Cementitious Materials (SCM)		[78]	[65]
	Pavement Maintenance and Rehabilitation			
	Crack, Seat and Overlay (CSOL)	[83]		[66]
	Dowel Bar Retrofitting (DBR)		[84]	
	PCC Overlay/Whitetopping			[66]
	Reflective Cracking Mitigation		[85], [86]	
	Removal and Replacement with New HMA	[83]		
	Removal and Replacement with New PCC	[83], [110]		
	Shotblasting			[65]
	Thin and Ultrathin Whitetopping			
	Innovative Solutions and Other			

	Life Long Portland Cement Concrete Pavement		[44]
	Photocatalytic Cement (Noise Reduction)		[87]
C*		[31], [112]	[88], [89]
	C*: COMPOSITE PAVEMENTS		

4. LCE tools for pavement applications

Ever since the wide-reaching recognition of the importance of LCE and the spread of LCA and LCCA, several LCE tools have been developed by researchers and/or software companies through private or governmental initiatives. This section discusses 12 selected LCE tools that are among the most widely-used (
The tools are listed in a chronological order based on the release date of the first version of each tool. It is noticeable that tools developed in the early 1990s were tailored for manufacturing industries. With time, tools became more customized to fit the construction industry, and their platforms became simpler, consisting of online tools or Microsoft Excel workbooks. The development of LCE tools that target pavements specifically evolved in the early 2000s.
Table 1). The aim is to pinpoint the strengths and limitations of each tool, particularly in addressing pavements, and to highlight the elements that future tools or those currently under development need to tackle for improvement. The information provided targets researchers or practitioners wanting to perform a pavement LCE or to develop a new LCE tool.

The tools are listed in a chronological order based on the release date of the first version of each tool. It is noticeable that tools developed in the early 1990s were tailored for manufacturing industries. With time, tools became more customized to fit the construction industry, and their platforms became simpler, consisting of online tools or Microsoft Excel workbooks. The development of LCE tools

Most of these tools evolved from LCCA tools such as RealCost to tools like PaLate that incorporate both LCA and LCCA.

EIO-LCA:
EIO-LCA is the only tool among those presented in Table 2 that uses pure input-output LCA, relying on the interaction between different sectors. Other tools use process-based or hybrid LCA. Apart from the fact that it is inconvenient to model the life-cycle of a pavement using EIO-LCA, its drawback is the high level of accuracy it presents due to the fact that the data is country-specific (US) and may be out-of-date [90].

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Table 1. Summary of selected LCE tools.

	Tool Name	Developer	Release Date	Latest Update	LCA	LCCA	Industry	Platform	Environmental Output Examples	Project Phases
1	SimaPro [91]	Pre Netherlands	1990 -	2014	✓		Multiple, Mainly Manufacturing	Stand-Alone Package	Carbon Footprint; Water Footprint	N/A
2	GaBi [92]	PE International, University of Stuttgart	1991 -	2014	✓	✓	Multiple, Mainly Manufacturing	Stand-Alone Package	Energy Consumption; GHG Emissions	N/A
3	EIO-LCA [90]	Carnegie Mellon	1997 -	2002	✓		Multiple, possibly construction	Web Application or Matlab Version	GHG emissions; Energy Consumption; Toxic Releases; Water Use	N/A
4	BEES [93]	NIST (National Institute of Standards and Technology)	1998 -	2010	✓	✓	Construction	Web Application	GWP; Acidification Potential; Ozone Depletion Potential; Smog Potential; Eutrophication Potential; Fossil Fuel Consumption	Building Products (Raw Materials Acquisition, Manufactur, Transportation, Installation, Use, and Recycling and Waste Management)
5	RealCost [94]	FHWA	2002 -	N/A		✓	Roadway	Microsoft Excel Workbook	N/A	Construction; Maintenance
6	PaLate [95]	University of California, Berkeley	2003 -	N/A	✓	✓	Roadway	Microsoft Excel Workbook	Energy Consumption; GHG Emissions; Leachate Information	All Except Use/Operation

7	RUCKS (HDM-4 RUC) [96]	World Bank	2006 -	2010	✓	✓	Roadway	Microsoft Excel Workbook	Resource Use; Emissions	Use/Operation
8	OpenLCA [97]	GreenDelta	2008 -	2014	✓	✓	Multiple, Mainly Manufacturing	Stand-Alone Package	Carbon Footprint; Water Footprint	N/A
9	Changer [98]	International Road Federation	2009 -	N/A	✓		Roadway	Stand-Alone Package	Carbon Footprint	Construction
10	PE-2 [99]	Michigan Technological University (MTU)	2011 -	N/A	✓		Roadway	Web Application	GHG Emissions	Construction; Maintenance; Use/Operation
11	Roadprint [100]	Pavia Systems	2012 -	N/A	✓		Roadway	Web Application	GHG Emissions; Energy Consumption	Construction; Maintenance
12	Athena Impact Estimator for Highways, recently Anthena Impact Estimator for Pavements [101]	Athena Sustainable Materials Institute	2013 -	N/A	✓	✓	Roadway	Stand-Alone Package	GWP; Acidification Potential; Ozone Depletion Potential; Smog Potential; Eutrophication Potential; Fossil Fuel Consumption	Materials; = On-Site Construction; Maintenance; Pavement Vehicle Interaction

GaBi, SimaPro and Open LCA:
Tools that target manufacturing processes such as GaBi, SimaPro, and OpenLCA may be used for the materials extraction and manufacturing stage of a pavement LCA. However, given the complexity of the pavement life-cycle, using such tools can become overwhelming when modeling the many processes that it entails. Thus, several tools were developed to cater to the need for simple customized pavement LCE.
The advatage of OpenLCA over GaBi and SimaPro lies in the fact that it is free and open-source. Open-source tools are significant since they allow the exploration of the tool architecture and understanding of how it functions. More importantly, open-source tools can be customizable to fit a certain application, in terms of geographical or time context for instance.

HDM-4:
The conceptual framework of HDM-4 was initiated in the late 1960s, and it has since been developed and expanded to become a stand-alone MS Windows application for highway development and maintenance management system [96]. HDM-4 targets highway project analysis in general, and not pavements specifically. It provides a system for an in-depth economic analysis of highway alternatives as well as an environmental impact assessment. It also offers a road-network performance prediction module that is empirical in nature, relying on stochastic and numerical models, and which falls short of the mechanistic-empirical performance prediction that the MEPDG offers. The downside of HDM-4 is that it is costly, and does not target pavements specifically. Thus, the focus in this section will be on HDM-4 RUCKS (Road User Cost Knowledge System) which is a selected part of HDM-4 that has been implemented as a Microsoft Excel tool and that is available for free.
HDM-4 RUCKS targets road user costs specifically, i.e. only the user costs associated with the use/operation phase. It provides highly detailed environmental and economic outputs about user costs without tackling other pavement life-cycle phases. It entails in-depth details regarding vehicle maintenance costs and emissions. The downside, however, is the rigorous inputs required and the need to rely on default values, which might skew the results.

PaLate:
PaLate is an Excel-based, user-friendly tool that is tailored for pavements and calculates environmental and economic costs of all life-cycle stages except the use/operation phase. PaLate can be coupled with HDM-4 RUCKS to provide a full-fledged pavement LCA and LCCA. PaLate's inventory database has been criticized for being outdated, and a new version, PaLate II, is under development [102].

RealCost:
RealCost is a pavement LCCA Excel-based tool that calculates both agency and user costs during the construction and maintenance/rehabilitation phases of the pavement's life-cycle. RealCost can also be used to account for life-cycle costs associated with the use/operation phase by providing cost calculations associated with user delay.

Athena Impact Estimator:
The Athena Impact Estimator offers a user-friendly platform designed specifically for highways. It offers comprehensive environmental outputs and life-cycle agency costs. It does not, however, account for user costs, and therefore other tools such as HDM-4 and RealCost should be used for this purpose. Its main limitation, however, is that the data is Canada-specific.

Changer, PE-2 and Roadprint:
The shortcoming of tools such as Changer, PE-2 and Roadprint is that they perform LCA only, and target specific phases of the pavement life-cycle. With the importance of integrating both economic and environmental costs to get a holistic picture of the impact of all the stages of a project or alternative, these tools should be coupled with others for a fully-integrated LCA and LCCA.

From the review of tools discussed above, it is safe to state that none is comprehensive enough to cover all impact categories and pavement life-cycle stages. To achieve a full-fledged integrated LCA and LCCA over the entire pavement life-cycle, it is thus necessary to couple two or more tools as depicted in Figure 2. Such approach, however, could prove to be tedious or impractical for some applications and conditions particularly that the tools could have different platforms, and may require different types of inputs, levels of detail, and units among other attributes. Moreover, even such integration of tools fails to cover the end-of-life phase. It is thus apparent that there is a need for a comprehensive and user-friendly tool that incorporates both LCA and LCCA for the entire pavement life-cycle.

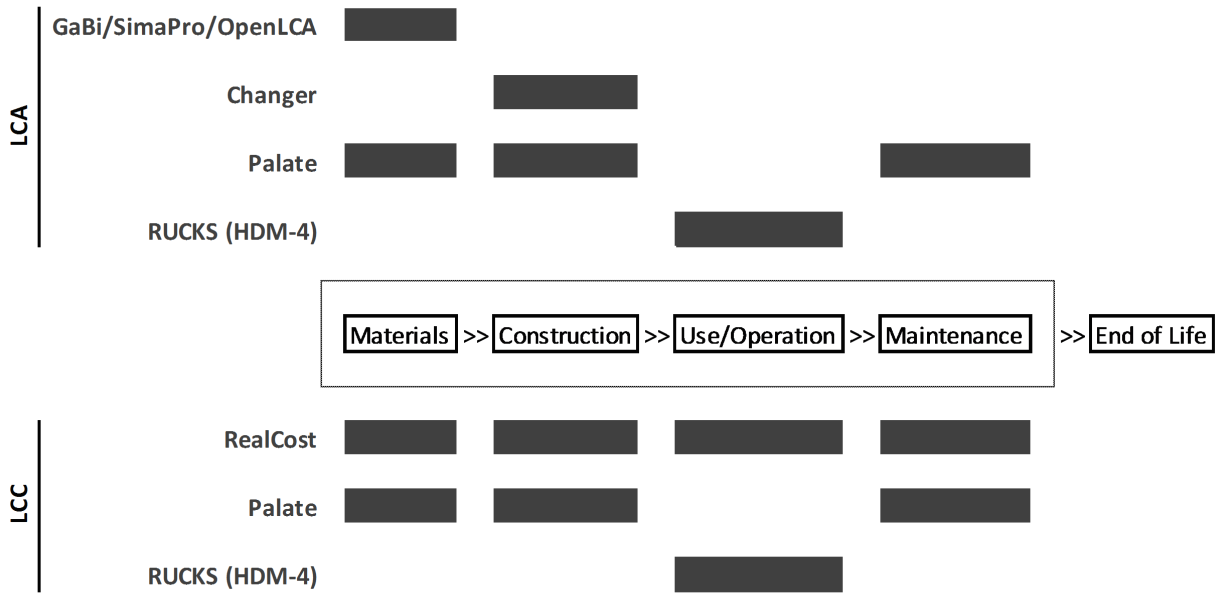

Fig. 2. Integration of various tools required for a comprehensive pavement LCE.

The reliability of the tools is highly dependent on the reliability of the data they require. Several tools, for instance, use country-specific data that may be inaccurate for application in other geographical contexts [106]. Thus, transparency is an essential feature of an LCE tool. For example, Kim et al. enhanced and customized RealCost, which could be regarded as open-source, for use in California [103].

5. Suggested enhancements for pavement LCE

In light of the aforementioned discussions, it is apparent that for a comprehensive and reliable LCE for pavements, several enhancements and modifications need to be introduced. Some of the most significant among those are discussed herein.

5.1. Importance of social life cycle assessment in pavement decision-making

The social dimension is one of the three pillars of sustainability, and several social parameters (safety, traffic delay, and health among others) lie on the border of the two other pillars: environment and economics. Absence of the social dimension from any LCE – as is the case of LCE applications and tools discussed in this paper – fails to portray a rounded view of all impacts and may consequently bias the decision-making process. Hence, any effort to conduct a comprehensive LCE of pavements should include SLCA in addition to LCCA and LCA.

SLCA, however, is intricate in terms of goal and scope definition, collection and quantification of data, and most importantly in terms of achieving an unbiased analysis of the findings. The relatively long life-span of pavements presents a challenge in terms of understanding and studying how various parameters and their consequent social impacts vary with time. Hence, to achieve a reliable SLCA, it is necessary to have a clear definition of the goal, scope, and system boundaries. It is also important to be practical when choosing the impact categories to consider, and the type of data to collect, how to collect it, and how to analyse it in order to minimize data-related complexities and possible bias.

For example, the scope of SLCA entails direct effects, such as impacts on workers or road users during construction, or indirect and broad societal consequences such as discrimination. For both direct and indirect impacts, data sources can be either generic or site-specific. Though site-specific information could be more accurate, its reliability is dependent on the quality of the data collection/auditing approach [6].

For pavement SLCA, as any other SLCA, it can be debated that some components are organization-specific, depending highly on the corporate and social policies of the company (mainly the contractor) in question. These components include labour wages and human rights among others. The authors believe that if the scope entails comparing alternatives on a research level to come up with general conclusion, such as the use of HMA versus the use of WMA, it may be irrelevant to include several social components, specifically those that are organization-specific, and thus may be excluded. Moreover, for comparison of project alternatives within a single organization, it not only biased, but also irrelevant to include such components. However, including organization-specific aspects becomes highly important when comparing bid alternatives for public decision-making.

Some SLCA parameters such as health (in terms of emissions for example) and safety (accident and fatality rates) can be easily quantified. Others, however, require semi-quantitative or descriptive allocation since no clear universal metric is available. These include parameters such as human rights, job creation, and support of local suppliers. Physical working conditions of pavement construction workers is one such example. Taking the case of comparing WMA to HMA, for instance, physical conditions can be partly quantified in terms of exposure to emissions and partly described in terms of physical comfort. (Note that 'physical conditions' of workers encompass some health parameters that affect the workers directly on the job site, whereas 'health' in general addresses impacts associated with the well-being of the population within the geographical scope of the assessment.) Human rights and community-related impacts can be simply assessed in terms of yes/no questions or through allocation of a certain weight on a suitable scale.

Some of the components of SLCA lie on the borders of LCA and LCCA. SCLA is intertwined with many levels of the pavement life-cycle, and further research needs to be made to improve the accuracy of prediction of long-term social impacts, such as how pavement albedo can affect thermal comfort of individuals etc.

Reaching an agreement on social assessment is challenging since the perception of social impact is often subjective. Further research and documentation must be made to provide a unified basis for pavement SLCA.

It should be taken into account that SLCA as both a framework and practice is still not well developed, particularly for the case of pavements. Accounting for SLCA in the final analysis of the pavement life-cycle and the decision-making process is discussed in Section 5.5.

5.2. Defining the scope of pavement LCE

The first step in any life-cycle evaluation is goal and scope definition. Determining the scope of an LCE involves defining the functional unit (e.g. lane meter or m^3 of material), the system boundaries (e.g. geographical context and time frame), the data categories, the data quality requirements, the key assumptions and limitations, among others [2]. The scope of the LCE is dependent on the goal, and can range from very narrow boundary conditions and limited time frame, to a full-fledged all-encompassing evaluation. More research must be conducted to determine the optimal scope for a pavement LCE. For instance, should the chosen time period span the pavement service life or the life-time of individuals impacted by the pavement? However, regardless of the magnitude of the scope, the authors believe that for a successful life-cycle sustainability assessment, the scope should be consistent among all three components of the evaluation: the environmental, the economic, and the social. A consistent scope among the three components ensures proper comparison of their impacts and avoids problem-shifting from one dimension to another. Nonetheless, providing a consistent scope among the three components might be challenging, particularly when it comes to social life-cycle assessment which is still under development. If this is a hindrance, an alternative would be unifying the scope of the environmental and economic evaluations. In this case, the social life-cycle assessment can be appended with a distinct limited scope that is of interest to the evaluation.

Figure 3 presents, through a fishbone diagram, selected components for a comprehensive pavement LCSA. The figure shows the parameters of each of SLCA, LCCA and LCA separately and portrays the boundary relationship among them.

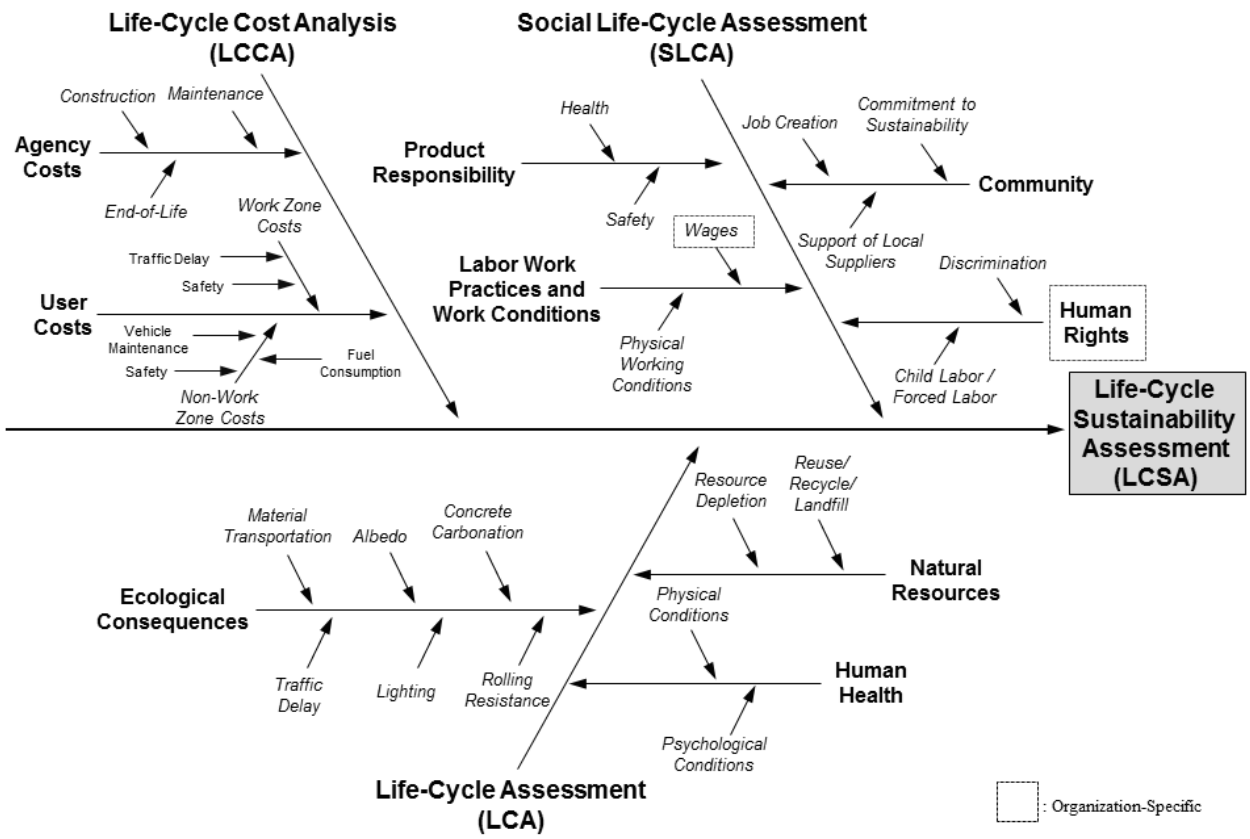

Fig. 3(a) Selected components of LCSA.

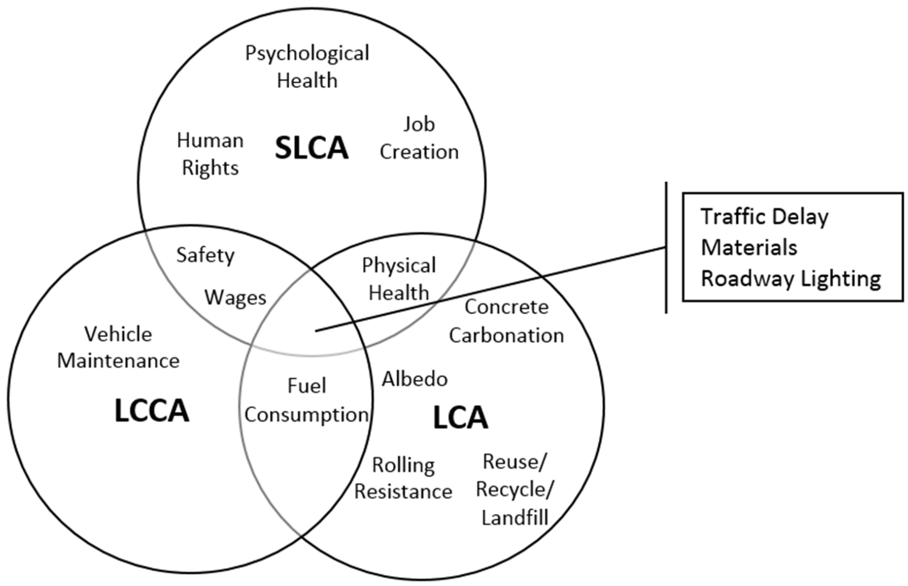

Fig. 3(b) Boundary relationship among selected LCSA components.
Fig. 3 Pavement LCSA framework.

5.3. Incorporating performance prediction in pavement LCE

Accurate pavement performance prediction over its life-cycle is essential for reliable and realistic LCE. Various components of the pavement life-cycle are either directly or indirectly related to pavement ridability (often measured through international roughness index, IRI) [104], which in turn is a function of the various distress levels (fatigue cracking, thermal cracking, rutting, and faulting, among others) and surface quality (surface friction and drainage efficiency among others). Examples of components that are highly affected by the accuracy of the predicted pavement performance include impact of traffic and safety, thus affecting characterization factors such as emissions, resource depletion, and accident and fatality rates. Additionally, accurate performance prediction is of the essence for optimizing the pavement maintenance and rehabilitation schedule allowing for more precise forecasting of economic costs and environmental impacts associated with construction materials and consequent traffic delays.

For accurate performance prediction, advanced mechanistic material models and performance prediction models need to be utilized [105], particularly when evaluating new technologies and/or alternatives, such as the use of RAP [107-109]. The recently released mechanistic-empirical pavement design guide (MEPDG) by AASHTO, also known as Pavement-ME, is one such software that is gaining popularity among the pavement community for its ability to deliver such an objective. The MEPDG offers a three-level hierarchal approach to data input, with the highest level being the most detailed and most case-specific, and the lowest level relying on default values. It should thus be noted that the reliability of the MEPDG's performance prediction is dependent on the accuracy of the input data and the level of detail used.

5.4. Incorporating traffic characterization in pavement LCE

Different components of the pavement life-cycle require different level of characterization of the traffic level. Similar to the case of performance prediction models where the accuracy is a function of the level of detail of traffic input, the accuracy and reliability of LCSA is a function of the level of detail and comprehensiveness of traffic data. Yet given that obtaining a full characterization of traffic such as distribution by type, truck axles, time of day, speed, month of year, lane distribution, speed, a life-cycle assessor would need to consider the limited availability of such comprehensive data and rely on judgment and objective of the LCE to decide on the suitability of less comprehensive traffic data. At times, default or assumed values could be sufficient. Components that are critically affected or sensitive to traffic data variation include traffic delay, rolling resistance, and overall pavement performance.

5.5. Proposed methodology for evaluating pavement alternatives based on LCE components

A practitioner deciding on pavement alternatives (PCC or AC pavements, HMA or WMA etc.) would be looking into different life-cycle evaluation components (LCA, LCCA and SLCA). However, different impact categories have different units of measurement (cost: USD, emissions: CO_2-equivalent, depletion: tons, energy consumption: MJ, human rights: yes/no etc.) Hence, when analysing the results of a comprehensive LCE, comparing different impact categories and accounting for the various units can be a complex process. It is, thus, important to simplify the analysis of the acquired results for a reliable comparison of different alternatives. To do so, it is essential to look into which categories give the clearest overall image of the impact and prioritize them for the application in question – in the case of this paper, pavements. Attempts have been made to combine economic and environmental costs in a single unit (USD or unit-less metric) for comparison [9, 65], but it is still necessary to develop further metrics that take into account more categories such as energy consumption, leachate, and social parameters. Theoretically, universalizing the metric would allow better comparison and benchmarking of different LCSA studies. Practically, however, this can be an intricate and possibly unnecessary process. In essence, the problem of combining the three LCE evaluations (economic, environmental and social) and selecting the optimal pavement design is a multi-objective decision making problem. For such problems, several methods can be adopted to analyse the alternatives at hand including combining the multiple objectives into one objective and using a multi-step decision making process where each objective serves as a filter to evaluate pavement alternatives.

5.5.1. Conversion of multi-objectives to a single objective

Converting multi-objectives to a single objective can be achieved through weighting. ‘Weighting is typically an optional step of impact assessment in which the indicator results for each impact category assessed are assigned numerical factors according to their relative importance, multiplied by these factors and possibly aggregated [2].’

Weighting methods can be derived from economics, law, or decision theory. They provide the easiest means of comparison across alternatives, given that the weighting factors are known and are reliable (example: converting CO_2 equivalent and MJ to dollar values). Ideally, weighting across the three dimensions of sustainability (i.e. combining the environmental, economic, and social factors in a single metric) provides an easy platform for alternative comparison. However, such combination is not always possible, particularly due to the complexity of some LCA units and SLCA units that are sometimes descriptive or pseudo-quantitative. Therefore, although theoretically, weighting is a simple means to compare alternatives, practically, it can be overwhelming if many parameters are involved. There is no standard baseline method for weighting. Moreover, according to ISO 14042, weighting is not recommended for comparative assertions disclosed to the public because it may be biased [2]. Therefore, even though weighting can be useful in research-related life-cycle evaluations, the authors believe that it is not the most optimal, most realistic way to analyse LCSA results.

5.5.2. Multiple-step filtering

For a simple and realistic implementation of LCSA and comparison of alternatives which reflect standard practice, the authors suggest that multi-step filtering be used. Here, it is important to identify and define four main hierarchal filtering levels (Figure 4a):

Level 1: Filtering out politically infeasible alternatives

The Level 1 filter is the highest-level filter where the decision-making is up to policy-makers who typically initiate pavement or road projects. It mainly involves a Go/No Go decision that might rely on some economic, environmental and social considerations, but mainly depends on policies, politics, and sometimes lobbying. For example, if HMA and PCC are two pavement alternatives for a certain highway, politics may favour one option over the other for reasons beyond the control of agencies and researchers. If an alternative is ruled out at this level, there is practically no point of further assessing it. A practical example is a recent case in a Middle Eastern country where HMA and PCC were two options for a major highway. At a political level, and due to a simultaneous spike in asphalt prices and deterioration of the local cement industry, concrete was favoured over asphalt in order to boost local production.

Level 2: Filtering out publically opposed alternatives

Level 2 involves a high-level filter that follows that of policy-makers and is also out of the control of agencies and researchers. It mainly involves broad social or environmental criteria, or a combination of both. The influencer of this filter is the public, which is often represented by NGOs and/or ministries, parliament, public representatives, communities and citizen groups, local opposition groups and others. For instance, any pavement renovation/reconstruction alternative that is lengthy and disrupts traffic might be objected. Here also, if an alternative is ruled out at this level, there is practically no point of further assessing it.

Levels 3: Filtering out environmentally and/or economically undesirable alternatives

The Level 3 filter involve investigating the alternatives that passed the first two filters from an economic and environmental perspective. Here comes the role of LCA and LCCA. Whether the environmental filter precedes the economic filter or vice versa is project-specific and depends on the priorities of the decision-makers. These two filters can either be separate or combined in one, if both economic and environmental impacts are of equal importance (i.e. integrated LCA and LCCA). These two levels are of interest to both agencies and researchers.

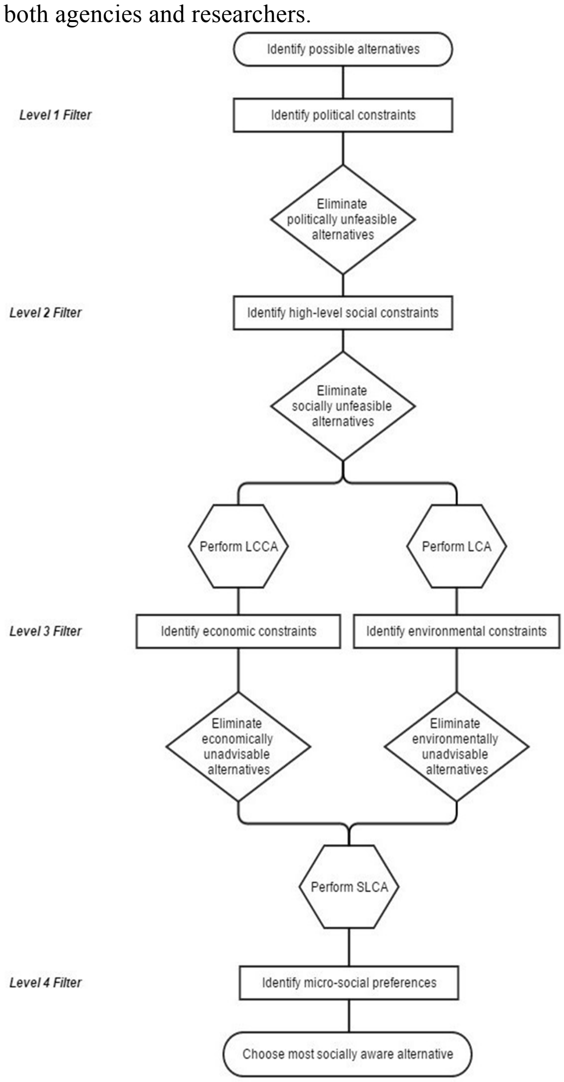

Fig. 4(a) General framework of multi-step filtering for the decision-making of pavement solutions.

Level 4: Selecting most socially-aware alternatives
The Level 4 is filter is the last step in the decision-making process. This does not mean its importance is undermined. On the contrary, this is the final checkpoint before a decision is made. It involves evaluating the alternatives that passed the level 3 filter based on specific (narrow) social criteria. The role of SLCA comes in at this level. Such an application involves the evaluation of different alternatives, products or contractors during bidding based on labour laws, safety records, health, human rights violations, and so on. An example is the use of cutbacks versus emulsions, where emulsions might be preferred for safety considerations. This filter serves to rule out any alternative, product or contractor that does not satisfy minimum social standards set forth by the decision-makers.
If several alternatives pass the Level 4 filter, these can be re-evaluated and the final alternative selected based on the priority of the decision-makers (example: most economical).

To illustrate the filtering process described above, consider the following example. A concrete highway crosses a busy commercial area. Its IRI has become lower than the acceptable range and corrective action needs to be taken. The flowchart in Figure 4b demonstrates the multi-step alternative filtering and decision-making process.

The multi-step filtering process described above is a realistic portrayal of the current state of practice. Level 1 constraints are often a function of the level of development of the country in question.

Note that multi-step filtering is most reasonably implemented in actual scenarios and projects that require decision-making. However, running LCCA, LCA and SLCA simultaneously within a single platform becomes useful when studying new pavement-related innovations on a research-level.

6.

7.

8. Conclusions and recommendations

In any LCE, considering the three dimensions of sustainability and performing an LCSA is essential to get a clear characterization of the impact of the product/project under study. It is recommended that further research be made to better understand the components of pavement SLCA and their relation to LCCA and LCA, and to eventually refine the LCSA framework and customize it for pavements and other specific applications.

Nonetheless, the ultimate aim is to minimize impacts, and therefore assessing them solely is not enough. Evaluating impacts without coupling the assessment with active decision-making to minimize them is trivial. As such, the direction of future research must head towards setting up a reliable framework for life-cycle sustainability optimization, i.e. optimizing decisions, and not just assessing alternatives, with respect to the three pillars of sustainability: the economic, the environmental and the social. This can be partly achieved by implementing some of the suggestions presented in Section 5 of this paper but further research is required in this area.

In any life-cycle evaluation or life-cycle optimization framework, the tools and methods used must not leave any room for bias that might undermine objectivity. Future research must also be directed towards draining out any subjective parameters or loopholes present in LCE methods and tools. The aim is to make LCE as objective, user-independent, realistic and reliable as possible without steering its outcome to satisfy lobbying agendas and other biased objectives.

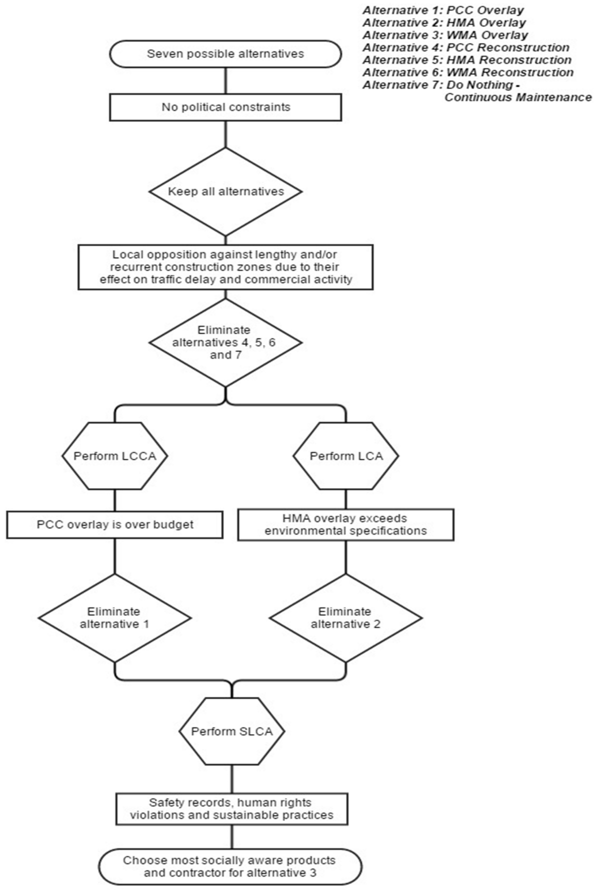

Fig. 4(b). Example of multi-step filtering for the decision-making of pavement solutions.
Fig. 4. Multi-step filtering for the decision-making of pavement solutions.

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