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

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Abstract

Despite the general consensus among stakeholders on how useful the life cycle assessment (LCA) methodology can be in helping to reduce the environmental burdens of a road pavement, very few pavement LCA models have considered the entire pavement life cycle. This paper presents the development of a highly customizable LCA tool that provides an integrated, project-level approach that includes all six pavement life cycle phases. The developed tool encompasses six main modules, including extraction of raw materials and production; construction, maintenance and rehabilitation; transportation of materials; work-zone traffic management; usage; and end-of-life. Data regarding the Portuguese practice of pavement construction and management has been collected on site with certified Portuguese construction companies and complemented using published literature and databases.

The research described in this paper 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 project analysis period for road pavement. The use of the proposed tool for benchmarking current practices in pavement construction and management enhances the scientific basis for understanding where further efforts can be undertaken to promote sustainable pavement investment decisions.

Keywords: *asphalt pavements; life cycle assessment; road pavement life cycle; sustainable road pavements; pavement management; rolling resistance; vehicle emissions*

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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 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 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, “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 fuel consumption 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 (International Standard Organization (ISO) 2006a).

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 environmental-friendly solutions have a high initial cost even though they might be cost-effective when assessed under the project analysis period (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 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 end-of-life [EOL]) concerning LCA and the footprint evaluation of road pavements. Santero *et al.* (2011a, 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 maintenance and rehabilitation (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 (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 life cycle inventories (LCIs) and do not provide life cycle impact assessment (LCIAs); 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 decision-makers 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 CO_2 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 paper presents the development of a fully integrated and highly customizable decision-support system (DSS) that hosts a project-level pavement LCA model intended to give decision makers a computational and systematic platform to organize and cross their “in-house” data (i.e., 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 (i.e. materials extraction and production; construction, maintenance and rehabilitation (M&R); transportation of materials; work-zone (WZ) traffic management; usage; and EOL) and user-friendly communication platforms between the user and the model.

3. Pavement life cycle assessment model description

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 (i) in managing and storing a large amount of data; (ii) in dealing with information and processes that tend to change and evolve over the PAP; and (iii) in modeling the intrinsic complexity of some processes, such as vehicle fuel consumption 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 paper 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 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) from the database, all downstream materials (e.g., Hot-mix

Asphalt [HMA]) and processes (e.g., 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.

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 suitable for use in studies carried out in the Portuguese context.

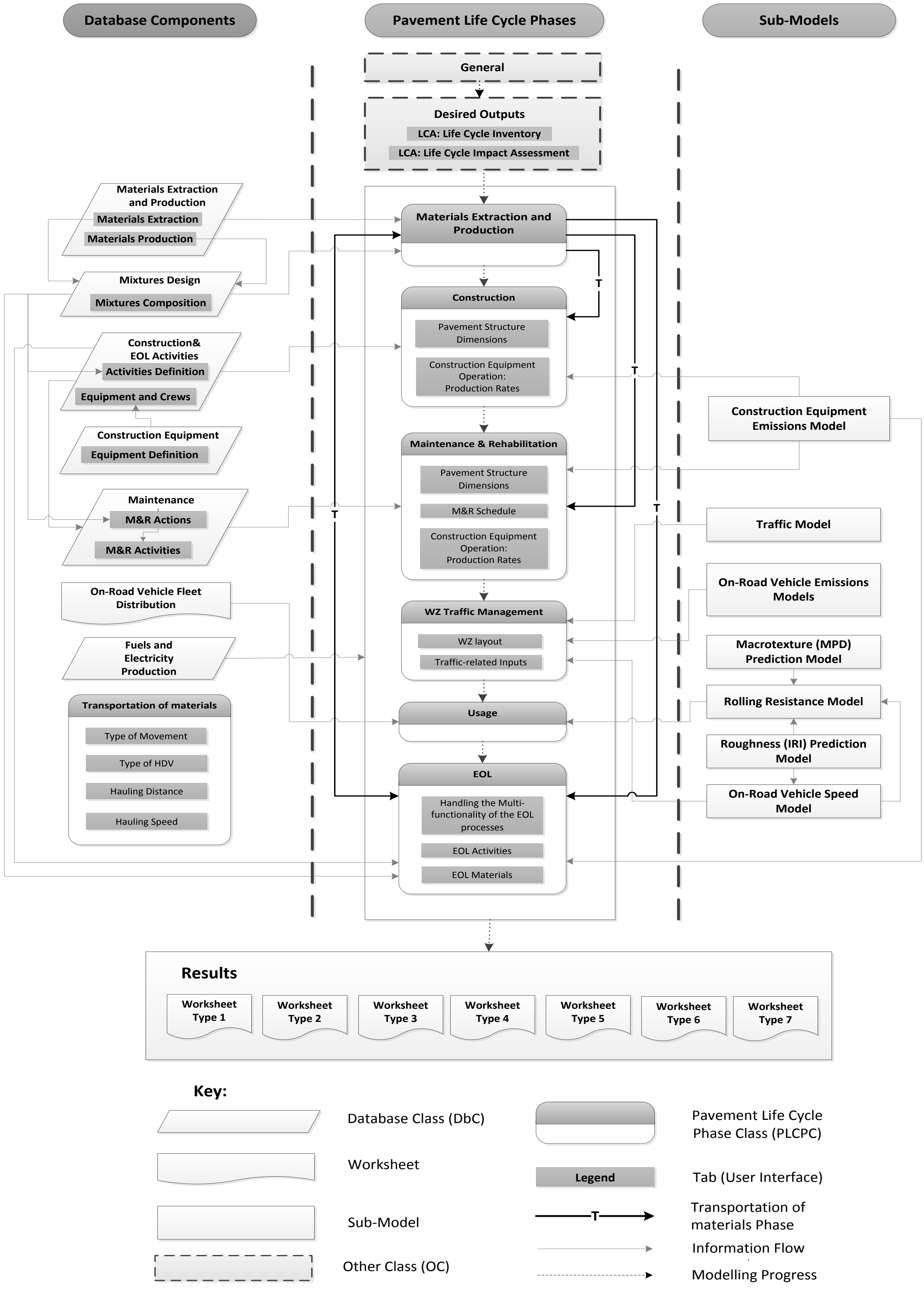

Figure 1. Pavement LCA model: computational framework.

3.2. *Goal and scope definition*

The model presented in this paper 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 resource 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.

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.

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 HMA 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 HMA mixing plants); (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 proposed model is not able to account are the following: manufacturing and maintenance of production plants and construction equipment necessary for the construction and M&R of road pavements; road related safety and signaling equipment; transportation of equipment and workers to the construction site; and capital investments attributable to the construction and maintenance phase. The exclusion of those processes was governed by one of the following reasons: the uniqueness of the condition to which it refers; the lack of reliable information; or unsuitability for the model's global scope (pavement LCA rather than a roadway LCA).

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 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. These cradle-to-gate LCIs use the European averages of 70% Middle Eastern and 30% Venezuelan origin for crude oil used in bitumen production. The bitumen produced is of grade 50/70, one of the most commonly used bitumen in Portugal.

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, 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 (UCPRC) Pavement LCA guideline* (Harvey *et al.* 2010). Following this recommendation, the feedstock energy 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 HMA are transported to an HMA mixing plant. HMA 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 HMA plant has been gathered from a Portuguese company that owns and operates a batch plant powered by natural gas. The fuel consumption 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 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. The user is also asked to enter other mixture-related data, such as density (tonne/m^3) and bulking factor.

3.2.2.2. *Transportation 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 four primary characteristics: engine technology and payload capacity of the transportation mode, transportation distance and speed, and the mass of materials being transported. As fuel consumption 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 the section of this paper on the construction and maintenance phase.

In the "*Transportation*" PLCPC, the user is asked to assign a set of data for each material and mixture being transported: 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 center facility); type of HDV (fourteen categories available) and engine technology (seven Euro legislation classes available); average distance in kilometers from the origin to the destination (only one direction), and; 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).

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 equation used for this methodology is as follows (Equation (1)):

$$E_{i,e,w}^{construction\ equipment} = HRS_{e,w} \times HP_e \times LF_e \times EF_{i,e}^{construction\ equipment} \times DF_{i,e} \tag{1}$$

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 pollutant *i* (or fuel consumption) per unit of use of construction equipment *e* (g/kWh); $DF_{i,e}$ is the degradation rate of the emission factor of pollutant *i* (or fuel consumption) 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 equation 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 emission factors and fuel consumption 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.

3.2.2.4. *Work zone traffic management phase.* In this pavement LCA model, the fuel consumption 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 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 fuel consumption 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 fuel consumption equations derived from a microscopic fuel consumption model that comprises a polynomial model of acceleration and deceleration profiles. The fuel consumption estimations based on the acceleration and deceleration models are later combined with the Tier 1 fuel consumption-dependent emission factors (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 fuel consumption and hot emissions released by on-road vehicles approaching a WZ is as follows (Equation 2):

$$E_{i,j}^{on-road} = \sum_{k}^{vehicle\ technology} EF_{i,j,k}^{on-road} \times NVeh_{j,k} \times L_j \qquad (2)$$

Where: $E_{i,k,j}^{on-road}$ is the environmental burden i resulting from the operation of the on-road vehicle of technology k at operation condition j (e.g. decelerating, accelerating, queuing, etc.); $EF_{i,k,j}^{on-road}$ is the average emission factor of pollutant i (or fuel consumption) 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 emission factors model used to estimate the fuel consumption, air pollutant emissions, and GHG produced by various vehicle categories as a function of the speed, according to technological classification and European legislation. Baseline emission factors are estimated for every major pollutant for every country and region in Europe. For fuel consumption and regularly studied pollutants, such as carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxide (NO_x), and particulate matter (PM), detailed emission factors are available, whereas for other pollutants, more simple bulk emission factors and equations 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, 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 fuel consumption. 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), 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 fuel consumption and airborne emissions due to WZ delays are calculated by subtracting fuel consumption and emissions released during a WZ period from the results of an equivalent non-WZ period (Equation 3):

$$E_{Total_i}^{on-road} = \left[E_{i,acceleration}^{on-road} + E_{i,deceleration}^{on-road} + E_{i,queuing}^{on-road} + E_{i,goingthroughWZ}^{on-road} + E_{i,detouring}^{on-road} \right] - E_{i,normaloperatingconditions}^{on-road} \quad (3)$$

Where: $E_{Total_i}^{on-road}$ is the total marginal value of the environmental burden *i*, such as fuel consumption or airborne emissions. The remaining variables have the same meaning as in Equation (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 fuel consumption for vehicle operation due to the deterioration of the pavement (increased rolling resistance), 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 rolling resistance 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 rolling resistance force describes the energy loss associated with pavement-vehicle interaction. Pavement deterioration increases rolling resistance, which in turn lowers fuel economy and increases the energy consumed by traffic. Additional fuel consumption due to the deteriorated pavement can be evaluated through the change in pavement condition over the PAP. In this pavement LCA model, the additional fuel consumption originated by rolling resistance has been estimated through the MIRIAM models (Hammarström *et al.* 2012). Derived fuel consumption function for a car (similar models exist for heavy trucks and heavy trucks with trailers) is as follows (Equation 4):

$$F_{cs} = 0.286 \times \left[\begin{pmatrix} 1.209 + 0.000481 \times IRI \times v + 0.0394 \times MPD + \\ 0.000667 \times v^2 + 0.0000807 \times ADC \times v^2 + \\ -0.00611 \times RF + 0.000297 \times RF^2 \end{pmatrix}^{1.163} \right] \times v^{0.056} \quad (4)$$

Where: F_{cs} is the fuel consumption due to rolling resistance (l/km); IRI is the pavement roughness, measured using the International Roughness Index (m/km); v is the vehicle speed (m/s); MPD is the pavement's macrotexture, represented by the parameter Mean Profile Depth (mm); ADC is the road curvature (rad/km), and; RF is the road slope (m/km).

As one can see from equation (4), the influence of pavement condition on rolling resistance comes partially from changes in the pavement's roughness and macrotexture. Therefore, the first step in estimating the influence of rolling resistance on fuel consumption 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. Fuel consumption 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 equations 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 equation whose formulation is presented below (Equation 5), users are given the option to insert their own calibration parameters.

$$IRI = a \times Ln\left(\frac{PSI}{b}\right) \tag{5}$$

Where: IRI is the International Roughness Index; PSI is the Present Serviceability Index, and; a and b are calibration parameters.

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

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 HMA. 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. HMA mixing plant) 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: (i) the cut-off; and (ii) 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 3.2.2.2) to model the transportation processes in case they are required.

3.2.3. *Other modules*

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 emission factors 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 emission factors, eight cumulative energy demand (CED) indicators (fossil, nuclear, primary forest, biomass, wind, solar, geothermal, and hydro energy), and the consumption of non-energetic resources (up to 25 pre-established categories, which include among other the elements aluminum, bauxite, cooper, iron, zinc, etc.) 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 LHV presented in Table 1. The default pavement LCA database was mostly populated with emission factors derived from the ELCD 2.0 databases (EC, JRC - IES and DGE - DG, 2008).

Table 1. Lower heating values 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	
Peat	MJ/Kg	19.5	
Soft coal	MJ/kg	8.4	
Natural gas	MJ/m^3	36.32	
LPG	MJ/kg	46.15	IEA (2005)

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): it exposes the multidimensionality of the problem of environmental assessment; it does not require additional steps for data collection, modeling, and computation, and; 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: climate change (CC), acidification (AC), terrestrial eutrophication (TE), human toxicity (HT) due to air 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.

Lastly, according to International Standard Organization (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.

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.

Table 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
Climate Change (CC)	Infrared Radiative Forcing	Global Warming Potential (GWP_{100})	CO_2-eq/kg	CO_2 CH_4 N_2O	[a]	Kendall (2012)
Acidification (AC)	Accumulated Exceedance (AE)	Acidification Potential (AP)	molc H^+-eq/kg	SO_2 NO_2 NH_3	0.6 0.2 1	Seppala *et al.* (2006); Posch *et al.* (2008)
Terrestrial Eutrophication (TE)	Accumulated Exceedance (AE)	Eutrophication Potential (EP)	molc N-eq/kg	NO_2 NH_3	2.6 9.4	Seppala *et al.* (2006); Posch *et al.* (2008)
Human Toxicity (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 SO_2 NH_3 Lead $PM_{2.5}$	1.2 0.096 0.100 29.136 0.82	Guinée *et al.* (2002)[e]
Photochemical Ozone Formation (POF)	Photochemical Ozone Creation Potential (POCP)	Ozone Formation Potential (OFP)	kg NMVOC-eq/kg	NO_x NMVOC CH_4 CO SO_x VOC	1 1 0.0101 0.0456 0.0811 0.235	van Zelm *et al.* (2008) as applied in ReCiPe 2008 (**Goedkoop *et al.* 2013)**
Abiotic Resource Depletion (ARD): mineral	Scarcity	Abiotic Depletion Potential (ADP): mineral resources	kg Antimony eq/kg (kg Sb-eq/kg)	Mineral resources	2.99E-11[b]	Guinée *et al.* (2002)[d]
Abiotic Resource Depletion (ARD): fossil fuels	Scarcity	Abiotic Depletion Potential (ADP): fossil fuels	MJ/kg or MJ/m^3	Fossil fuels	Lower heating values[c]	Guinée *et al.* (2002)[d]

[a] The value depends on time and type of GHG;
[b] Figure for Silicium;
[c] Fossil fuels are considered to be fully substitutable. Therefore, the ADP fossil fuels are given by the lower heating values of the fossil fuels;
[d] Characterization factors according to the updated version of the Center Environmental Studies of the University of Leiden´s “CML” factors (CML 2013).

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 3 summarizes the features of the worksheets hosted by the Microsoft Excel file that gathers the LCA model outputs.

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 (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.

Table 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		Precombustion 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 unit processes of several pavement life cycle phases	‘LCI_UnitProcess_MaterialsExtraction_and_Production’ ‘LCI_UnitProcess_Construction_and_Maintenance’ ‘LCI_UnitProcess_Transportation’; ‘LCI_UnitProcess _EOL’ ‘LCI_UnitProcess_WZ_Traffic_Manag.’; ‘LCI_UnitProcess_Usage’;	Lowest discretization level: pavement materials
4		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	Names are equal to those adopted in the worksheet types 2, 3, 4, and 5 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		Lowest discretization level in accordance with worksheets type 3
7		Comparative worksheets	The results displayed by worksheets type 4 and 5 are gathered and exhibited in comparative tables and charts		Lowest discretization level in accordance with worksheets types 4 and 5

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 life cycle cost analysis (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 fuel consumption 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 emission factors 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 fuel consumption. For example, the structural deflection effect, although it may be significant, was not added to the usage phase model. Concerning the marginal fuel consumption 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 fuel consumption, are difficult to predict and control during the PAP. Few MPD/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 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.

4. 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 decision-makers 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 paper 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 two of the cornerstone prerequisites of 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, both a scenario testing and a deep and detailed sensitivity analysis of the data, methodological choices, and assumptions in that case study will be performed. Third, the geographical applicability of the LCA model will be extended, in a first stage, by including sub-models tailored for other countries, namely the USA, and in a second stage by fully applying the model to a case study. Fourth, this LCA model will be accordingly coupled with a LCCA model in a multi-objective optimization framework to identify both cost-effective pavement construction solutions and pavement maintenance plans while fulfilling the environmental concerns. Fifth, the analysis level of that optimization-based LCA-LCCA 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.

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