NATIONAL SUSTAINABLE PAVEMENT CONSORTIUM

TPF 5 (268)

Pre-Print

COMPARISON OF LIFE CYCLE ASSESSMENT TOOLS FOR ROAD PAVEMENT INFRASTRUCTURE

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Word Count: 6,249+ 3×250 + 2×250 = 7,499
Number of Tables: 3
Number of Figures: 2
Submission Date: August 1, 2016

ABSTRACT

Road pavements have considerable environmental burdens associated with their initial construction, maintenance and usage, which has led the pavement stakeholder community make congregate efforts to better understand and mitigate these negative effects. Life cycle assessment (LCA) is a versatile methodology to quantify the effect of decisions regarding the selection of resources and processes. However, there is a considerable variety of tools for conducting pavement LCAs. The objective of this paper is to provide the pavement stakeholder community with insights on the potential differences in the life cycle impact assessment results of a pavement by applying American and European LCA tools, namely PaLATE V2.2, VTTI/UC asphalt pavement LCA model, GaBi, DuboCalc and ECORCE-M, to a Spanish pavement reconstruction project. Construction and maintenance life cycle stages were considered in the comparison.

Based on the impact assessment methods adopted by the different tools, the following indicators and impact categories were analyzed: energy consumption, climate change, acidification, eutrophication and photochemical ozone creation. The results of the case study showed that it is of crucial importance to develop (1) a more standardized framework for performing a LCA of road pavement that can be adapted to various tools and (2) local databases of materials and processes, which follow national and international standards.

INTRODUCTION

Road pavements have considerable environmental burdens associated with their construction, maintenance and use. Concurrently, the environmental issues are becoming more relevant in social and political contexts. This has led the pavement stakeholder community to congregate efforts to better understand and mitigate these negative effects.

In this context, a "twining" activity was initiated in 2014 between LCE4ROADS consortium (FP7 EU funded project Grant Agreement nº 605748), led by ACCIONA, and the US National Sustainable Pavements Consortium pooled fund effort, led by Virginia Department of Transportation (DOT) and supported by the US Federal Highway Administration (FHWA) and three other State DOTs, and managed by the Virginia Tech Transportation Institute (VTTI). This initiative of cooperation resulted from an arrangement signed in Washington on February 12, 2013, by the European Commission (EC) and the US DOT that aims to foster collaboration on research, development and technology transfer activities that are of mutual benefit. In particular, the main objective of this twining activity is to foster the exchange of knowledge between both sides of the Atlantic, finding synergies in research aimed at enhancing sustainability in pavements. The agreement focuses on the following aspects:

(1)   Life cycle assessment (LCA) methodologies and their applications to roads pavement construction and maintenance practices;

(2)   Life cycle costs analysis (LCCA) for pavements and integration of use phase models. Analysis of the influence of pavement deterioration on vehicle fuel consumption and emissions and the interaction between the pavement, the environment, and humans;

(3)   Climate change (CC) adaptation measures for road infrastructures;

(4)   Product Category Rules (PCRs) and Environmental Product Declarations (EPDs); and

(5)   Implementation of strategies in terms of Green Public Procurement for road infrastructures.

To improve the sustainability of road pavement infrastructure, road agencies and construction companies are adopting appropriate methodologies and tools to identify priority areas for improvement. Thus, it is necessary to know the impact of pavements on the environment to develop and implement approaches and procedures that can produce the greatest gains in all aspects and dimensions of the system. LCA is a versatile methodology capable of informing decisions on resource and process selection to better understand, measure, and reduce the environmental impacts of a system (*1*).

However, there is a considerable variety of tools for conducting pavement LCAs and there are notable differences between them. Available tools cover different phases and processes of the pavement's life cycle, take different environmental issues into account, and model with distinct level of accuracy within chosen functional unit and system boundaries. They can be global, national or even regional or local. They are also developed for different purposes, for example, research, consulting, decision making, and its domain of applicability is tailored for different phases of a project's life cycle, for example, planning, designing, construction and maintenance. Also distinct is the level of interaction they allow with the user. While some of the tools are "black-boxes" in the sense that only the default processes and data can be used, others allow the users to use their own data, to choose the database that best match the features of the case study, or even modify the existing datasets.

OBJECTIVES

The main objective of this paper is to provide the pavement stakeholder community with insights on the potential differences in the life cycle impact assessment (LCIA) results of a pavement LCA

by applying American and European LCA tools to a Spanish case study. As a consequence of comparing the features of different tools and potential life cycle environmental impacts, the differences in datasets and life cycle inventory will be analyzed as well. In order to avoid an excessive level of complexity, the number of tools considered in the study had to be controlled. Thus, the selected tools are as follows: (1) PaLATE V2.2, (2) VTTI/UC asphalt pavement LCA model, (3) GaBi; (4) DuboCalc and, (5) ECORCE-M.

BACKGROUND
Over the last years, many LCA tools have been developed for assisting decision makers in evaluating the environmental performance of their pavement-related decisions. Among others, the set of pavement-specific LCA tools includes ROAD-RES (*2*), PaLATE V2.2 (*3*), UK asphalt pavement LCA model (*4*), ROADEO (*5*), CMS RIPT (*6*), PE-2 (*7*), CFET (*8*), ECORCE-M (*9*), DuboCalc (*10*), CO_2NSTRUCT (*11*), VTTI/UC asphalt pavement LCA model (*12*, *13*) and Athena Impact Estimator for Highways (*14*). Additionally, commercial LCA tools, such as *SimaPro* (*15*) and *Gabi* (*16*), despite being not specifically designed for pavement-specific LCAs, have been used for that purpose (*17*, 18) since they are quite complete in terms of elementary flows inventoried and unit processes taken into account, some of which with particular applicability to the pavement domain (e.g., raw materials and equipment fuel combustion).

Overview of the Tools Compared
The tools assessed in this study are briefly described and the main aspects of each one highlighted. An overview of the impact categories included in each tool are given in TABLE 1. Furthermore, despite not being considered an impact category, the eventual ability of the tools to track the energy consumption throughout the pavement life cycle is also displayed. Table 2 describes the types and number of elementary flows characterized by the LCA tools. Since PaLATE V2.2 accounts only for CO_2 it was not included in the table.

VTTI/UC Pavement LCA Tool
The VTTI/UC asphalt pavement LCA tool is a project-level pavement LCA tool conceived to estimate the environmental burdens associated with materials extraction and production, construction and M&R, transportation of materials, work-zone (WZ) traffic management, usage and phases of the life cycle of a flexible road pavement located in the US. It was developed as a collaborative effort between the University of Coimbra and Virginia Tech.

PaLATE V2.2
PaLATE V2.2 stands for Pavement Lifecycle Assessment Tool for Environmental and Economic Effects and was originally developed by Horvath et al., in 2003 (*19*). The tool used in this study was a modified version of PaLATE V2.2 developed to complete project requirement life cycle inventory (LCI) for the Greenroads® Rating System, which is a third-party, points-based system available to certify sustainable transportation infrastructure projects. The tool primarily uses the Economic Input-Output (EIO)-LCA approach, but transportation and equipment emissions are calculated according to a Process-based LCA (P-LCA) approach.

PaLATE V2.2 adopts both the Carnegie Mellon University EIO-LCA software database for U.S. 2002 NAICS Producer numbers, and the Transportation Energy Data Book Edition 29 from 2010, which contains values that are typically more recent (2006 and 2007 years were available for most data).

TABLE 1 Impact Categories Computed by the Different LCA Tools

Impact category	GaBi	PaLATE V2.2	DuboCalc	VTTI/UC	ECORCE-M
Abiotic depletion	-	-	Y	-	-
Climate change	Y	Y	Y	Y	Y
Ozone depletion	Y	-	Y	-	-
Photochemical ozone creation	Y	-	Y	Y	Y
Acidification	Y	-	Y	Y	Y
Eutrophication	Y	-	Y	Y	Y
Human toxicity	Y	-	Y	-	-
Freshwater aquatic ecotoxicity	Y	-	Y	-	-
Marine aquatic ecotoxicity	Y	-	Y	-	-
Terrestrial ecotoxicity	Y	-	Y	-	-
Energy consumption	Y	Y	-	Y	Y
Human health criteria pollutants	-	-	-	Y	-
Chronic ecotoxicity	-	-	-	-	Y[a]
Chronic toxicity	-	-	-	-	Y

Note: [a] Beyond the toxicity specific to humans, which has been treated separately in ECORCE-M (Chronic toxicity), all other toxicity indicators for the various ecosystems (i.e., freshwater aquatic, marine aquatic and terrestrial) have been aggregated into this single ecotoxicity indicator.

- means impact category not measured

GaBi
GaBi software was developed by PE international in collaboration with University of Stuttgart. It details the costs, energy and environmental impact of sourcing and refining every raw material or processed component of a manufactured item. GaBi Software combines GaBi Databases, created by PE INTERNATIONAL, with other commercial databases and regional content such as Ecoinvent, US LCI, ELCD and others. GaBi datasets include both aggregated and unit process datasets. Underlying over 4,500 aggregated datasets are thousands of pre-modeled subsystems based on real-world data which saves modeling time while ensuring reliable results. For modelling the life cycle of the road, ACCIONA has used the available database modules from GaBi to account for specific processes and materials for construction industry.

DuboCalc
DuboCalc is the abbreviation of "Duurzaam Bouwen Calculator", meaning "Sustainable Construction Calculator" in Dutch. It is a software program which was developed some years ago by the Dutch NRA Rijkswaterstaat in order to stimulate sustainability in procurement procedures. Nowadays, a calculation with DuboCalc (already version 4) is compulsory in all large procurement procedures; the participating parties can earn a fictional discount on the tendering offer when their environmental impact reaches a certain low score.

TABLE 2 Characterized Elementary Flows.

Impact category	DuboCalc			ECORCE-M			Gabi			VTTI/UC		
	#	Top 5	CF	#	Top 5	CF	#	Top 5	CF	#	Top 5	CF
CC (kg CO_2-eq/ kg)	66	air HFE-236ca12 (HG-10)	28000	20	air sulfur hexafluoride	22800	102	Sulphur hexafluoride [Inorganic emissions to air]	22800	3	air CO_2	1
		air sulfur hexafluoride	22800		air methane, trifluoro-, HFC-23	14800		Trifluoromethyl sulphur pentafluoride [Inorganic emissions to air]	17700		air CH_4	25
		air trifluoromethylsulfur pentafluoride	18000		air methane, dichlorodifluoro-, CFC-12	10900		Nitrogen fluoride [long-term to air]	17200		air N_2O	299
		air nitrogen fluoride	17000		air ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-,CFC-114	10000		Nitrogentriflouride [Inorganic emissions to air]	17200		N/A	N/A
		air ether, pentafluoromethyl-, HFE-125	15000		air tetrafluorocarbon	7400		R E125 [Halogenated organic emissions to air]	14900		N/A	N/A
POC (kg C_2H_4-eq/kg)	135	air benzene, 1,3,5-trimethyl-	1,38	91	air 1-pentene	1,059	203	1,3,5-Trimethylbenzene [Group NMVOC to air]	1,381	4	air SO_x	0,048
		air benzene, 3,5-dimethylethyl-	1,32		air propylene	1,03		3,5-Diethyltoluene [Group NMVOC to air]	1,295		air NO_x	0,028
		air toluene, 3,5-diethyl-	1,30		air ethylene	1		1,2,4-Trimethylbenzene [Group NMVOC to air]	1,278		air CO	0,027
		air benzene, 1,2,4-trimethyl-	1,28		air xylene-m	0,993		1,2,3-Trimethylbenzene [Group NMVOC to air]	1,267		air CH_4	0,006
		air benzene, 1,2,3-trimethyl-	1,27		air butene	0,992		Propene (propylene) [Group NMVOC to air]	1,123		N/A	N/A
	5	air nitrogen dioxide	0,50	3	air NH_3	1,6	51	Ammonium	3,2	3	air NH_3	1,6

Category	#	Flow	CF	#	Flow	CF	#	Flow	CF	#	Flow	CF
AC (kg SO$_2$-eq/kg)		air nitrogen oxides	0,50		air SO$_x$	1,2		Ammonia	1,6		air SO$_2$	1,2
		air nitric oxide	0,76		air NO$_x$	0,5		Hydrogen sulphide	1,6		air NO$_x$	0,5
		air sulfur dioxide	1,20		N/A	N/A		Sulphur dioxide	1,2		N/A	N/A
		air ammonia	1,60		N/A	N/A		Phosphoric acid	0,834		N/A	N/A
EU (kg PO$_4$-eq/kg)	19	air phosphorus	3,06	15	air phosphorus	3,06	119	Phosphorus	3,06	2	air NH$_3$	0,35
		water phosphorus	3,06		water phosphorus	3,06		Phosphoruos-pent-oxide	1,34		air NO$_x$	0,13
		soil phosphorus	3,06		soil phosphorus	3,06		Phosphate [Inorganic emissions to sea water]	1		N/A	N/A
		air phosphorus pentoxide	1,34		air phosphorus pentoxide	1,34		Phosphoric acid	0,97		N/A	N/A
		water phosphorus pentoxide	1,34		water phosphorus pentoxide	1,34		Nitrogen	0,42		N/A	N/A
		soil phosphorus pentoxide	1,34		N/A	N/A		N/A	N/A		N/A	N/A

"#" represents the total amount of characterized flows within each tool; "Top 5" represents the five flow with the highest characterization factors per impact category; CF- Characterization factor; CC- climate change; POC- photochemical ozone formation; AC- acidification; EU- eutrophication

N/A – not applicable

The results of the DuboCalc calculation are automatically weighted with the Dutch set of shadow prices for the construction sector. In this way, all environmental impacts can be described in a single value, the MilieuKostenIndicator (MKI). For the analysis in this study, the non-weighted values were copied manually from the DuboCalc database in order to be able to compare them with the values of the other tools.

ECORCE-M

ECORCE-M stands for ECO- comparison Road Construction and Maintenance, and is a software tool developed by IFSTTAR in collaboration with CEREMA of the French Ministry of Ecology, Sustainable Development and Energy (MEDDE). It aims to provide a robust assessment for calculating a set of mid-points indicators in the framework of LCA resulting from various technical choices performed during the call for tender phase, project execution phase or upon final completion of the works. These choices involve (1) construction and structural maintenance of pavements on road corridors; (2) installation of foundation layer; (3) preparation of the upper part of earthworks; and (4) construction of fills. ECORCE-M uses LCI data gathered from the scientific literature and validated during a standard review processes implemented by international publications (consisting of at least 2 anonymous reviewers).

METHODOLOGY
Goal and Scope Definition
This paper presents and compares the results of a LCA of a pavement reconstruction project on a Spanish road section, N340 located in Elche (Alicante), performed through the application of several LCA tools.

Functional Unit
The function of the product system is to provide safe, comfortable, economical and durable driving conditions over the project analysis period. The functional unit considered as a reference basis is the quantified function provided by the product system. In this case study it is defined as *1km of mainline pavement and year*. The analysis period is 20 years and comprises the maintenance of the top pavement structure layer at year 10. The assessed road section is 1568 m long and has 4 lanes, divided into two roadways separated by a central separator. The inputs (raw materials and energy consumptions) were collected and quantified from the ACCIONA work site in 2012.

System Boundaries and General Assumptions
The N-340 road received an EPD in December of 2013 (20). EPD is an Eco-label type III that aims to communicate transparently the environmental performance of a product, process or system. It follows the rules established both in the ISO 14025 (*21*) and in the PCR guideline. In this project, the PCR named "highways, streets and roads" (*22*) was used.

To compare the different LCA tools in a fair way, only the pavement life cycle phases and sub-phases that can be assessed with all five LCA tools were included in the analysis. They are as follows: (1) materials extraction and production, (2) transportation of materials, and (3) construction and maintenance and rehabilitation (M&R). The environmental impacts related to the usage phase and the traffic disruption caused by the performance of the M&R activity were not assessed because not all the tools evaluated in this study are capable of assessing these phases. Finally, the EOL was not taken into account because of its negligible contribution to the environmental life cycle impacts (<1%) (*22*).

As far as the materials extraction and production phase is concerned, it must be noted that at least the 99% of materials and energy requirements during the pavement life cycle were considered. The construction stages accounted for in this study are as follows:
(1)   Demolition of the old pavement and fence;
(2)   Soil excavation and movement;
(3)   Pavement structure construction;
(4)   Road sub-structure construction (e.g., drainage system);
(5)   M&R of the top layer
Other stages, such as production of traffic control devices (for signposting and for diverting traffic) and the construction of tunnels and bridges were not included in the analysis due to its negligible contribution in this specific case study. When modelling the transportation of materials phase, an average distance of 20 km was considered for all concrete-based materials as there is a concrete plant nearby the road. For the borrowed soil and aggregates/gravel materials, an average distance of 15 km was assumed. With regard to the transportation of the soil removed from the work site, a 3-km long hauling movement was adopted.
Finally, the environmental impacts stemming from the construction of the infrastructure associated with intermodal activities, the operation of vehicles for loading and uploading at terminals, the production of manufacturing equipment and personnel activities were also disregarded.

LIFE CYCLE INVENTORY
The LCI stage of a LCA aims to identify and quantify the environmentally significant inputs and outputs of a system by mean of mass and energy balances. Specifically, it consists of a detailed compilation of environmental inputs, such as material and energy, and elementary outputs, such as air emissions, water effluents and solid waste disposal at every phase of the product's lifecycle. In turn, the elementary output flows are inventoried according to the methodology of each tool and the databases that feed them. Table 3 summarizes the type of materials applied in each construction stage considered in the case study.

Life Cycle Impact Assessment
In the LCIA stage of a LCA, the LCI 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 the LCI flows may have in producing the associated impact (12). Additionally, there may be a later phase of normalization, in which the results of each impact category are scaled by a reference number and a combined using a final weighing, which is based on socio-political preferences and leads to a unique score as result.

TABLE 3 Input Materials as Modelled in the Different Tools

Stage	Baseline	Quantity	DuboCalc	ECORCE-M	Gabi	PaLATE V2.2	VTTI/UC
1	total energy consumption	32779 kWh	grey electricity, NL	energy consumption of construction equipment & hauling trucks	electricity grid mix (ES)	default construction & transportation equipment;	US diesel for non-road engines
2	total energy consumption	250686 kWh	included in soil processing data	energy consumption of construction equipment & hauling trucks	electricity grid mix (ES)	default construction & transportation equipment;	US diesel for non-road engines
	general fill (soil)	1797 m³	soil movement (3 km)	-	gravel, grain size 2/32	accounts for soil, impact similar to aggregate	-
	water	627 m³	-	water (no environmental impacts)	water	water	tap water
	selected material (soil)	13256 m³	soil movement (3 km)	-	gravel, grain size 2/32	accounts for soil, impact similar to aggregate	-
3	total energy consumption	415021 kWh	included in soil processing data	energy consumption of construction equipment & hauling trucks	electricity grid mix (ES)	default construction & transportation equipment;	US diesel for non-road engines
	soil from borrowed site	398 m³	soil from local project (15 km)	-	gravel, grain size 2/32	accounts for soil, impact similar to aggregate	-
	water	124 m³	-	water (no environmental impacts)	water	water	tap water
	graded aggregates	3187 m³	gravel from rivers (15 km)	aggregates, in quarry	limestone, crushed gravel, grain size 2/16	graded aggregates	limestone; quartzite
	bitumen emulsion	24 t	bituminous emulsion	bituminous emulsion	bitumen emulsion	bitumen emulsion; don't differentiate emulsion & PG bitumen	bitumen emulsion 65%
	asphalt concrete AC 32 Base G	5395 t	stone mastic asphalt, 0% recycled content	hot asphalt mixes, in gas plant	asphalt supporting layer	modelled as individual materials	asphalt concrete AC 32 Base G
	asphalt concrete AC 22 Bin S	2324 t	AC Surf, dense asphalt concrete	hot asphalt mixes, in gas plant	asphalt pavement	modelled as individual materials	asphalt concrete AC 22 Bin S
	penetration grade (PG) bitumen	320 t	bituminous emulsion (proxy)	bitumen, 20 to 220 grade	bitumen (grade)	PG bitumen; don't differentiate emulsion & PG bitumen	PG 70-22 binder
	concrete (brick)	310 m³	concrete C20/25 (CEM I)	concrete, at mixing plant	concrete (stones, bricks)	modelled as individual materials	concrete (brick)
	glass fibers filaments	92 m³	plastic fibers (sub process from "fiber reinforced concrete")	-	glass fibers mesh	glass fibers filaments	-

4	total energy consumption	3820 kWh	included in soil processing data	energy consumption of construction equipment & hauling trucks	electricity grid mix (ES)	default construction & transportation equipment;	US diesel for non-road engines
	concrete C20	510 m^3	concrete C20/25 (CEM I)	concrete, at mixing plant	concrete C20/25	modelled as individual materials	concrete HM20
	soil	200893 m^3	soil movement (3 km)	-	gravel	accounts for soil, impact similar to aggregate	-
	formwork	0.04 m^3	traditional formwork (converted to m^2)	-	laminated wood	-	-
	concrete C15	41 m^3	concrete C12/15 (CEM I)	concrete, at mixing plant	concrete C12/15	modelled as individual materials	concrete HM15
5	total energy consumption	106562 kWh	included in soil processing data	energy consumption of construction equipment & hauling trucks	Electricity grid mix (ES)	default construction & transportation equipment; specific details not available	US diesel for non-road engines
	asphalt concrete AC 22 Bin S	2324 t	AC Surf, dense asphalt concrete	hot asphalt mixes, in gas plant	asphalt pavement	modelled as individual materials	asphalt concrete AC 22 Bin S
	prime coat	13 t	bituminous emulsion (proxy)	bituminous emulsion	asphalt binder	prime coat; don't differentiate emulsion & PG bitumen	prime coat (bituminous emulsion)

Note: The "baseline" was the starting point of all tools.
- means that this process was not available in the specific tool and was excluded in calculations.

In this study the classification and characterization steps were performed by applying several impact assessment methods, which depend on the tool being used. The Center for Environmental Studies of the University of Leiden's "CML 2001" impact assessment method (*23*) is implemented by several tools, either in a direct way (i.e., Gabi) or by adapting the original indicators (i.e., ECORCE-M and DuboCalc). In turn, the VTTI/UC pavement LCA tool adopts the Tool for the Reduction and Assessment of Chemical and other environmental Impacts 2.0 (TRACI 2.0) method (*24*). In the case of PaLATE V2.2 only the CC impact category is considered, taking exclusively into account the CO_2 emissions.

The LCIA indicators were calculated at mid-point level from (1) resource consumption flows, e.g., energy, (2) air emissions flows, e.g., the 100-year horizon CC, etc., and (3) air, soil and water pollutants flows, i.e. toxicity indicators.

RESULTS AND DISCUSSION
Impacts on a material level
Figure 1 shows the potential environmental impacts of the materials used in this case study, per kilogram of material, and calculated by the different tools. All axes are cut-off and the scores greater than the cut-off threshold are displayed in boxes. In x-axis, the percentages (%) next to each material show the covariation of the values per material in each impact category. Furthermore, because not all tools cover the same impact categories (as shown in TABLE 1), the graphs present only the results obtained with the tools which are able to consider the impact category under evaluation.

At first glance, it is clear that the impacts per kilogram of material differ largely amongst the tools for some of the materials, while other materials have rather comparable impacts. Taking the CC impact category as an example, Figure 1a shows that the CV values range approximately from 32 to 121%. Water and concrete C20 present the highest variability (121% and 112%, respectively). Cement, concrete brick, and concrete C15 also exhibit high CV values (86 to 111%), though the LCI associated with these materials are well defined and quantified by researchers for many years. On the contrary, asphalt concrete, bitumen and bitumen emulsion denote the lowest variability (30 to 60%). In general, the scores for the remaining materials have a much lower impact than the materials which present high levels of variability. Hence, one can conclude that the generality of the most common and bulk materials are well researched and represented by the tools, while the LCIs of more specific materials like water, formwork and glass fibers are more difficult to quantify in accurate fashion, and, thus, have been disregarded by several tools or based on proxy elements.

When comparing the CV values of the same material across the several impact categories, the CC impact category was found to exhibit the lowest levels of variability for the generality of the materials. This result is explained by the fact that all the LCIA methods adopted by the tool use the characterization factors based on the Intergovernmental Panel on CC model. On the opposite side, the energy consumption indicator generates the highest CV values. To a great extent this outcome can be explained by the fact that the impact category scores calculated with the Gabi tool are extremely high for the majority of the materials in comparison to the scores calculated with the other tools. Such a result suggests that Gabi might have other definitions for these materials or consider different system boundaries, which might influence the conclusions drawn on this case study. Furthermore, this discrepancy also illustrate the importance of using consistent sources and local databases as different materials may have different sources or may be produced

using different processes with significantly different environmental loads. For example, different form materials may be used in different regions.

Life Cycle Impact Assessment Comparison

Figure 2 presents the environmental impacts associated with each construction stage considered in the case study and the relative contributions to the total score on various impact categories that are computed by the majority of the LCA tools.

In general, considerable variation was observed within each impact category computed by the different LCA tools. The GaBi tool was found to yield the lowest impacts scores when comparing with the other evaluated tools. Interestingly, the PCO scores associated with stages 1 and 2 possesses a negative value. This result indicates that in these stages there is a mitigation effect on PCO impact category.

On contrary, PaLATE V2.2 was found to produce the highest scores for the two impact categories which it is able to account for (i.e, CC and energy consumption). The only exception to this general trend was observed in the case of the energy consumed during the stage 3. In turn, VTTI/UC and ECORCE-M tools have denoted similar CC and energy consumption scores. This result contrast with those observed for the remaining impact categories, as they were found to vary considerably. Also, the scores obtained with VTTI/UC and ECORCE-M tools were higher than those generated by GaBi for all impact categories. Regarding the DuboCalc tool, it produced intermediate scores relatively to those generated by Gabi and VTTI/UC tools for the CC and energy consumption indicators. However, the AC, EU and POC scores computed by DuboCalc for the stages 3, 4 and 5 are the highest amongst those calculated by all the compared tools.

Regarding the relative contributions of each construction stage to the total scores, Figure 1 (right) shows that the construction stage 1 is the least contributor for each impact category, regardless the LCA tool considered. On contrary, the construction stage 3 was found to be the main contributor. The only exception to this uniform outcome was obtained with the PaLATE V2.2. As explained before, the quantity of soil used in stage 4 combined with the LCA approach adopted by PaLATE V2.2 has led to a higher relative contribution from this stage in both CC and energy consumption indicators.
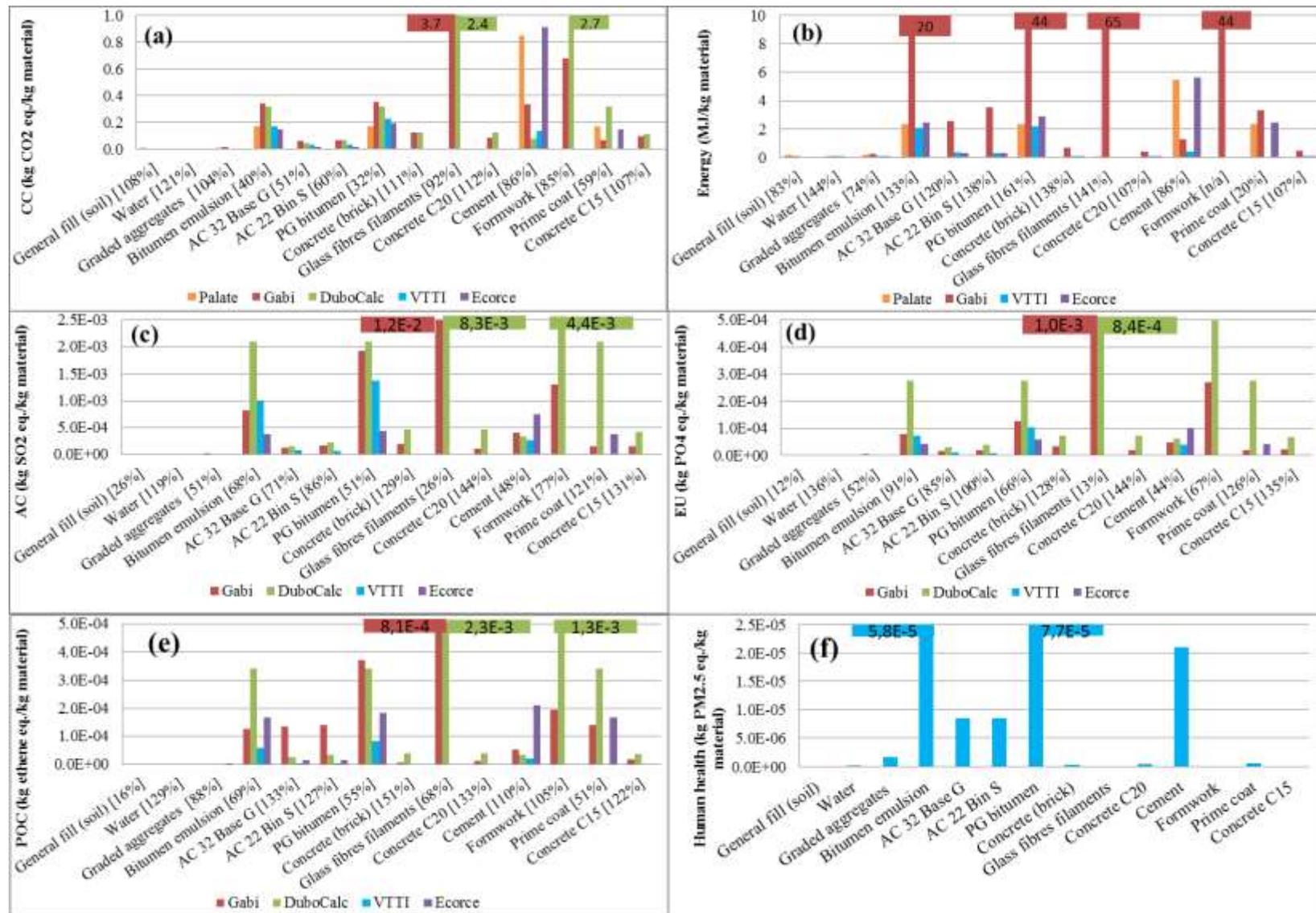
FIGURE 1 **Environmental impacts per kilogram of product, calculated with the five different tools for six environmental impact categories (a) CC; (b) energy consumption; (c) AC; (d) EU, (e) POC and (f) human health.**
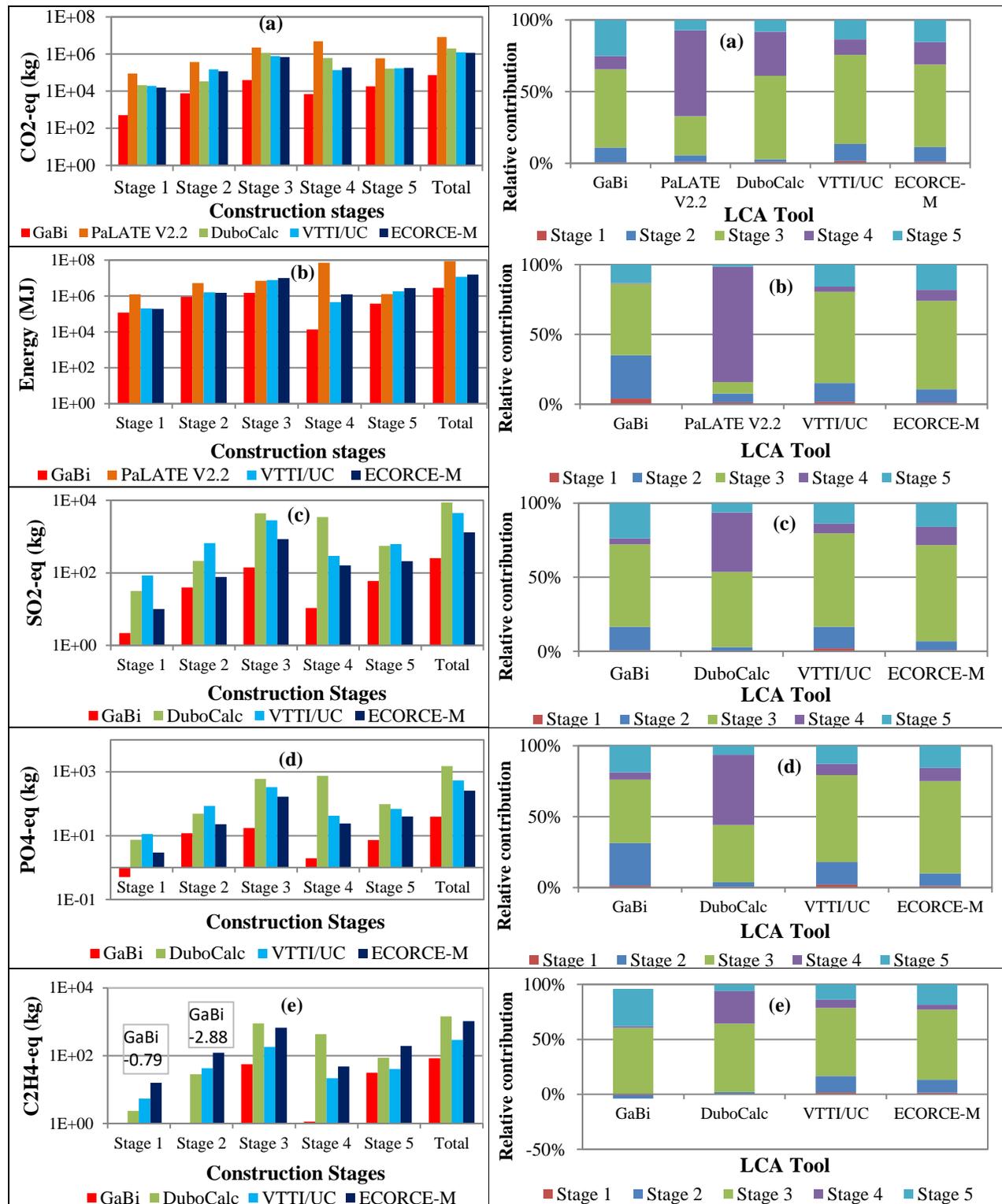
FIGURE 2 Comparison of the impact categories scores (left) and percentage contribution (right) from different LCA tools for the following impact categories and indicators: (a) CC; (b) energy consumption; (c) AC; (d) EU, and (e) POC.

Explaining the differences
The results presented in the previous sections show that there is a non-negligible difference in the impact category scores calculated with the different tools under evaluation. Several factors can explain, totally or partially, such differences. Furthermore, some of these factors are related to each other, which leads to an overlapping of their effects. The factors that may explain the differences include: (1) database comprehensiveness; (2) level of categorization of LCI flow data; (3) LCA approach; (4) LCIA method; (5) technical, temporal and geographical representativeness; (6) system boundary and allocation method; and (7) process modelling approach. These factors are analyzed and discussed in the following sub-sections.

Database Comprehensiveness
Data quality is composed of accuracy (i.e. representativeness and methodological appropriateness and consistency), precision/uncertainty and completeness of the inventory. As far as the last characteristic is concerned, Table 3 shows that not all the database that feed the tools comprise the same materials. For example, the material "Glass fibers filaments" is exclusively considered by Gabi and PaLATE V2.2. In turn, DuboCalc adopts an analogous material as a proxy, while the remaining tools do not consider this element at all. This aspect is particularly important since the environmental impacts associated with the production of a unitary quantity of this material are the highest amongst all materials (Figure 1). Despite the low quantity of "Glass fibers filaments" required in this case study, its absence from the majority of database connected to the tools obviously lowers the accuracy of the assessment, and, therefore, explain to some extent the differences observed in the impact category scores.

Level of Characterization of LCI Flow Data
Some LCI datasets specify all individual substances. On contrary, others report only the main ones, thus providing less detailed information. A reduced LCI will, thus, produce a simplified calculation of the environmental impacts. That is the case of the database hosted by the VTTI/UC, as denoted in Table 2. Furthermore, some tools report emissions to air, water and soil (Gabi, DuboCalc, ECORCE-M and PaLATE V2.2) while others (VTTI/UC) accounts exclusively for the airborne emissions. Such simplifications may lead to less accurate scores for the impact categories which rely on a higher number and type of elementary flows. Fortunately, in practice it is often only a rather limited number of emissions and processes that relevantly contribute to the overall impacts. Hence, for the sake of a better allocation of resources (e.g., time, money, etc.) to the data collection process, it is of crucial importance to correctly identify and focus on the main flows.

Moreover, some substances, such as hydrocarbons and sulfur oxides, are commonly categorized in an aggregated way, leading to differences between inventory data sets in values of individual substances and substance categories. Also, because the naming of the substances and substance categories listed in the various inventory data sets can often vary, it is not clear exactly which substances comprise the substance categories, and, thus, double counting errors may arise due to an incorrect use of characterization factors.

LCA Approach
In general, there are two main different basic approaches to LCA: a P-LCA and an EIO-LCA. While the P-LCA approach assesses specific product types, the EIO-LCA approach uses aggregate data representing the averages of several sectors of an economy. However, amongst other features, those data are generally several years old, and, thus, assessing rapidly developing sectors and new

technologies may introduce errors because of base-year differences between the product system under study and the input-output data. From the LCA tools compared in this case study, the PaLATE V2.2 uses primarily EIO data, while all the other rely on process-based datasets. This fact may explain why the impact assessment scores obtained with this tool are in general higher than those provided by the remaining tools.

LCIA Method
The use of different LCIA methods may affect LCA results remarkably depending on an impact category, though the influence seems to be small in CC impact category. Impact assessment methods are often primarily modelled on a global average basis. That means that the modelling is performed by assuming average conditions, regardless of where the production takes place and conditions of the source. While for some impact categories, such as CC and stratospheric ozone depletion, this issue is not relevant, since the impacts are aggregated and are independent of the source of the emissions (*25*), other impact categories exist which stem from a large number of sources and may be sensitive to where they are emitted. Therefore, if the LCIA methods under comparison present a distinct approach as it pertains to the consideration of site dependent characterization factors for a given impact category, it is likely that the calculated scores denote some level of variability. However, this aspect seems not to be particular relevant for this case study, in the sense that the majority of LCA tools being compared adopt the same LCIA method (i.e., CML 2001), being the only exception the VTTI/UC tool which adopts the TRACI 2.0 method. Therefore, any explanation for the differences observed in the impact assessment scores related to the choice of the LCIA methodology is more likely to be related to the number and accuracy of the LCI elementary flows tracked by the LCA tools than to the methods themselves (i.e., the characterization factors values).

Technical, Temporal and Geographical Representativeness
Technical, temporal and geographical representativeness of the inventory data have the potential to play an important role in explaining a considerable portion of the differences observed in the impact category scores.

Temporal representativeness refers to the actual time being represented and determined, and, therefore, it is closely linked to technological representativeness. In turn, technological representativeness of a process or system identifies how well the inventory data represents it regarding its true technological or technical characteristics. Finally, geographical representativeness relates to technical condition of the process or system due to regulations and degree of technological development in each country and region, and how well the inventory data represents it.

For example, the "concrete C20" material, whose inventory data present a high level variability (see Figure 1), can be used to illustrate these aspects. Concrete production can be roughly divided into three processes: aggregates production, cement production and concrete mixing process. Since the production of aggregates and cement are among the processes that possess the lowest variability, it seems to be reasonable to say that the majority of the variability associated with the concrete production stem from the concrete mixing process. Complementary, Figure 1b reveals that concrete mixing process is a very energy demanding process, being the electricity one of the main energy sources.

The electricity production mix and efficiency depends very much on time and place. In addition, the reference year for the electricity production varies from database to database. Thus,

this variation naturally affects the environmental impact of the material production processes. The facts above mentioned may very well explain a considerable portion of the variability, in the sense that each tool used in this case study considered the electricity mix of the country of origin. For this reason, it is important to present a clear description of energy mix used and update the data on a regular basis.

System Boundary and Allocation Method
In this case study the system boundaries were clearly defined and taken into account by the different tools when conducting the LCA. In this sense, the processes belonging to the foreground systems were fairly described in section Methodology - System Boundaries and General Assumptions. However, the same cannot be said with regard to the processes pertaining to the background system. For instance, in some inventory datasets, it is not clear whether or not the environmental burdens related to the production of the energy sources required to power some of the background processes connected to the foreground processes are included into the inventory datasets. This is a relevant issue, as (*13*) have demonstrated that the inclusion of the environmental impacts associated with the production of the energy sources required by a single process in the LCA can notably affect the final results depending on the impact category under study. Thus, any exclusion of relevant individual processes or activity types should be justified at light of a cut-off criteria properly enounced.

Process Modelling Approach
Models and parameters values used in the calculations of the environmental burdens of several processes and activities differ depending on the tool being considered. For instance, the majority of the compared tools rely on constant emission factors to estimate the substances released during the operation of the construction equipment. On contrary, the VTTI/UC implements the methodology adopted by the US EPA's NONROAD 2005 model (*26*) which considers the degradation of the emission rates throughout lifespan of the construction equipment. Complementarily, it also assumes that whenever a construction equipment reaches its life expectancy, it is replaced by a new one with an engine that meets the legislation in force at that time, regarding emissions levels limits.

Another source of variability worthy of mention pertains to the production of aggregates. The data referring to this process can vary considerably depending on the mining place, size of the quarry, dimension of the aggregates, type of stone, transportation movements within the quarry facility, etc. Hence, the environmental burdens arising, for instance, from the production of "1 tonne of gravel" are very context sensitive.

SUMMARY AND CONCLUSIONS
The research work described in this paper investigate the extent to which the choice of a LCA tool may influence the LCA results for a road pavement infrastructure. Several tools with different functionalities and geographic contexts were compared by applying them to a Spanish case study.

The results indicate that there is a considerable variability in the environmental impacts scores computed with the different LCA tools for each impact category. In particular, this case study demonstrate that the impacts of the most common materials are less sensitive to the choice of the LCA tool, in contract with the more specific materials, which in some circumstance might even be not included in the databases connected to the tools. Moreover, the comparison also

showed that the several tools agreed fairly well on the relative importance of the several construction stages in driving the overall environmental performance of the system analyzed.

However, the analyst should be careful when using a particular tool for conducting a pavement LCA, as even in the case of using the same stages, materials and equipment the results can vary considerably.

Based on the findings of this case study, the following recommendations can be made to improve the LCA tools and databases connect to them, and the LCA practices in general:

• There is a need for a formal consensus framework and PCR specific for pavements, so that it can be adapted to the various tools;

• Local databases of materials and processes should be developed, which for the sake of consistency, comply with the national and international standards regarding technical, geographical and temporal representativeness requirements. Those databases should be built based primarily on a tight and international cooperation between academia and industry and updated on a regular basis. The availability of such a database would improve the reliability of LCA and thereby stimulate its application;

• The accuracy and comprehensiveness level of the datasets should be tailored to the impact category and impact assessment method;

• A sensitivity analysis is necessary to ascertain the uncertainty, and, thus, the credibility and value of the final results.

Finally, it is important to mention that this paper focused only on the construction and maintenance phases of the pavement LCA, leaving the most significant use phase outside of the scope of the study as most of the tools can not include it. Therefore, it is recommended to conduct similar studies using the use phase. One additional difficulty for this follow up comparison will result from the need to adopt consistent and reliable pavement deterioration models for the various stages of the pavement life-cycle.

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