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ABSTRACT

Road pavements have considerable environmental burdens associated with their initial construction, maintenance, and usage, which has led the pavement stakeholder community to 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 LCA. 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 standardized framework for performing a road pavement LCA that can be adapted to various tools and (2) local databases of materials and processes that 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.

A “twining” activity was initiated in 2014 between the LCE4ROADS consortium (FP7 European Union-funded project Grant Agreement nº 605748), led by ACCIONA, and the U.S. National Sustainable Pavements Consortium pooled fund effort, led by the Virginia Department of Transportation (VDOT), supported by the U.S. Federal Highway Administration (FHWA) and three other state Departments of Transportation (DOTs), and managed by the Virginia Tech Transportation Institute (VTTI). This cooperative initiative resulted from an arrangement signed in Washington on February 12, 2013, by the European Commission (EC) and the U.S. 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 across 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 road pavement construction and maintenance practices;

(2) Life cycle cost analysis (LCCA) for pavements and integration of use phase models, including analysis of the influence of pavement deterioration on vehicle fuel consumption and emissions and the interaction between pavement, 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 LCA, 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 levels of accuracy within chosen functional units and system boundaries. They can be global, national, or even regional or local. They have also been developed for different purposes (e.g., research, consulting, and decision making), and their domain of applicability is tailored for different phases of a project’s life cycle (e.g., 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 users to use their own data, to choose the database that best match the features of the case study, or even to 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 (LCI) 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. The tools selected were (1) PaLATE V2.2, (2) VTTI/UC asphalt pavement LCA model, (3) GaBi; (4) DuboCalc, and (5) ECORCE-M.

Background

Over the last few years, many LCA tools have been developed for assisting decision makers in evaluating the environmental performance of their pavement-related decisions. 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*). Commercial LCA tools, such as *SimaPro* (*15*) and *GaBi* (*16*), despite being not specifically designed for pavement-specific LCA, have been used for that purpose (*17*, 18) since they are quite complete in terms of the elementary flows inventoried and unit processes taken into account, some of which are particularly applicable 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 are highlighted. An overview of the impact categories included in each tool is 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, maintenance and rehabilitation (M&R), transportation of materials, work-zone (WZ) traffic management, usage, and end-of-life (EOL) phases of the life cycle of a flexible road pavement located in the United States. It was developed as a collaborative effort between the University of Coimbra, Portugal, 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 LCI for the Greenroads® Rating System. 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 US 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).

GaBi

GaBi software was developed by PE international in collaboration with the 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. For modeling the life cycle of the road, ACCIONA has used the available database modules from GaBi to account for specific processes and materials for the 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 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-point indicators in the framework of LCA resulting from various technical choices performed during the call for the tender phase, project execution phase, or upon final completion of the work. These choices involve (1) construction and structural maintenance of pavements on road corridors; (2) installation of the foundation layer; (3) preparation of the upper part of the 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 two anonymous reviewers).

METHODOLOGY

Goal and Scope Definition

This paper presents and compares the results of an LCA of a pavement reconstruction project on a Spanish road section, N-340, 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 *1 km of mainline pavement and year*. The analysis period is 20 years and comprises the maintenance of the top layer of the pavement structure at year 10. The assessed road section is 1,568 m long and has four lanes, divided into two roadways separated by a central separator. The inputs (raw materials and energy consumption) 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 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 International Organization for Standardization (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: (1) materials extraction and production, (2) transportation of materials, and (3) construction and M&R. The environmental impacts related to the usage phase and the traffic disruption caused by the performance of M&R activity were not assessed because not all of 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*). For further information on the definition of the phases mentioned above, the reader is referred to Santos et al. (*13*).

As far as the materials extraction and production phase is concerned, it must be noted that at least 99% of material 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 the 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 their negligible contribution in this specific case study. When modeling the transportation of materials phase, an average distance of 20 km was considered for all concrete-based materials, since there is a concrete plant near 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 an LCA aims to identify and quantify the environmentally significant inputs and outputs of a system by means 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 life cycle. 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 an 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 combined using a final weighting, which is based on socio-political preferences and leads to a unique score as result.

In this study, the classification and characterization steps were performed by applying several impact assessment methods, which depended 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). Alternatively, 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 the CO_2 emissions exclusively into account.

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

On the x-axis, the percentages (%) next to each material identifier show the coefficient of variation (CV) of the values (calculated as the ratio of standard deviation to mean) 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 that are able to consider the impact category under evaluation.

At first glance, it is clear that the impacts per kilogram of material differ largely among 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 C15, and concrete brick also exhibit high CV values (86% to 111%), though the LCIs associated with these materials are well defined and have been 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 that present high levels of variability. 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, such as water, formwork, and glass fibers are more difficult to quantify in an accurate fashion, and, thus, have been either 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 other hand, 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 from this case study. Furthermore, this discrepancy also illustrates the importance of using consistent sources and local databases as different materials may have different sources or may be produced by using different processes with different environmental loads.

LCIA 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 impact scores when compared with the other evaluated tools. Interestingly, the POC scores associated with stages 1 and 2 possess a negative value. This result indicates that in these stages there is a mitigation effect on the POC impact category.

To the contrary, PaLATE V2.2 was found to produce the highest scores for the two impact categories that 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 stage 3. The VTTI/UC and ECORCE-M tools denoted similar CC and energy consumption scores. This result contrasts 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. The DuboCalc tool produced intermediate scores relative to those generated by GaBi and VTTI/UC for the CC and energy consumption indicators. However, the AC, EU, and POC scores computed by DuboCalc for stages 3, 4, and 5 were the highest among those calculated by all the compared tools.

Regarding the relative contributions of each construction stage to the total scores, Figure 2 (right) shows that construction stage 1 is the smallest contributor for each impact category, regardless of the LCA tool considered. Construction stage 3 was found to be the main contributor. The only exception to this uniform outcome was obtained with PaLATE V2.2. As explained before, the quantity of soil used in stage 4 combined with the LCA approach adopted by PaLATE V2.2 led to a higher relative contribution from this stage to both CC and energy consumption indicators.

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 boundaries and allocation methods; and (7) process modeling 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 databases that feed the tools include the same materials. For example, the material “Glass fibers filaments” is only 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 databases connected to the tools obviously lowers the accuracy of the assessment, and, therefore, explains 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. 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 (i.e., GaBi, DuboCalc, ECORCE-M, and PaLATE V2.2) while others (VTTI/UC) account exclusively for airborne emissions. Such simplifications may lead to less-accurate scores for the impact categories that 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 datasets in values of individual substances and substance categories. Also, because the naming of the substances and substance categories listed in the various inventory datasets can often vary, it is not clear exactly which substances compose 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 approaches to LCA: P-LCA and 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, 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 the others 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 noticeably depending on the impact category, though the influence seems to be small in the CC impact category. Impact assessment methods are often primarily modeled on a global average basis. That means that the modeling 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 in which the substances contributing for those impact categories stem from a large number of sources and may be sensitive to where they are emitted. Therefore, if the LCIA methods under comparison use distinct approaches in the consideration of site-dependent CF for a given impact category, it is likely that the calculated scores will show some level of variability. However, this aspect does not seem to be particular relevant for this case study, in the sense that the majority of the LCA tools being compared adopt the same LCIA method (i.e., CML 2001), the only exception being 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 factor 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 is closely linked to technological representativeness. The technological representativeness of a process or system identifies how well the inventory data represent its true technological or technical characteristics. Geographical representativeness relates to the technical condition of the process or system due to regulations and the degree of technological development in each country and region, and how well the inventory data represent it.

The “concrete C20” material, whose inventory data show a high level of 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 reasonable to say that the majority of the variability associated with the concrete production stems from the concrete mixing process. Figure 1b reveals that concrete mixing process is an energy-demanding process, with electricity being one of the main energy sources.

The production and efficiency of electricity depend very much on time, place, and source of primary energy mix. In addition, the reference year for electricity production varies from database to database. Thus, this variation affects the environmental impact of the material production processes. These facts may 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 the energy mix used and update the data on a regular basis.

System Boundaries and Allocation Methods

In this case study, the system boundaries were clearly defined and taken into account by the different tools when conducting the LCA. The processes belonging to the foreground systems were fairly described in the Methodology - System Boundaries and General Assumptions section. 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 in the inventory datasets. This is a relevant issue, as Santos et al. (*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 through explicitly stated cut-off criteria.

Process Modeling Approach

Models and parameter 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 construction equipment. However, VTTI/UC implements the methodology adopted by the U.S. Environmental Protection Agency’s (EPA’s) NONROAD 2005 model (*26*), which considers the degradation of emission rates throughout the lifespan of the construction equipment. It also assumes that whenever a construction vehicle reaches its life expectancy, it is replaced by a new one with an engine that meets the legislation regarding emissions limits in force at that time.

Another source of variability worth mentioning pertains to the production of aggregates. The data referring to this process can vary considerably depending on the place of mining, 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 investigates the extent to which the choice of an LCA tool may influence the LCA results for 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 impact scores computed with the different LCA tools for each impact category. In particular, this case study demonstrates that the impacts of the most common materials are less sensitive to the choice of the LCA tool, in contrast with less-common materials, which in some circumstances might not even be 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 several construction stages in driving the overall environmental performance of the analyzed system.

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. The environmental impacts presented in this study are only applicable to the considered case study. The impacts of road projects, the most-contributing processes and the scores for the different impact categories, will vary for any given project based on environmental burden associated with its life cycle stages, and material and processes therein.

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

- There is a need for a formal consensus framework and PCR specific for pavements so that a standardized framework can be adapted to the various tools.
- Local databases of materials and processes should be developed that, for the sake of consistency, comply with national and international standards regarding technical, geographical, and temporal representativeness requirements. Those databases should be built based primarily on tight, 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 use phase outside of its scope as most of the tools cannot include it. Therefore, it is recommended that similar studies be conducted 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.

REFERENCES

1. Glass, J., T. Dyer, C. Georgopoulos, C. Goodier, K. Paine, T. Parry, H. Baumann, and P. Gluch. Future Use of Life-Cycle Assessment in Civil Engineering. *Proceedings of the ICE: Construction Materials*, Vol. 106, No. 4, 2013, pp. 204–212.
2. Birgisdóttir, H., K. Pihl, G. Bhander, M. Hauschild, and T. Christensen. Environmental Assessment of Roads Constructed With and Without Bottom Ash from Municipal Solid Waste Incineration. *Transportation Research Part D: Transport and Environment*, Vol. 11, No. 5, 2006, pp. 358–368.
3. PaLATE v2.2 for Greenroads, 2011 Software and User Guide modified by Civil & Environmental Engineering Department, University of Washington, Seattle. https://www.greenroads.org/. Accessed June, 2011
4. Huang, Y., R. Bird, and O. Heidrich. Development of a Life Cycle Assessment Tool for Construction and Maintenance of Asphalt Pavements. *Journal of Cleaner Production*, Vol. 17, 2009, pp. 283–296.

5. *ROADEO toolkit user manual. User manual: model framework and assumptions*. The World Bank, 2010, pp. 1–109.
6. Fox, J., D. Bell, G. Edmond, P. Cummings, and J. Langstraat. A Practical Tool for Low-Carbon Road Design and Construction. *Proceedings of the ICE - Transport*, Vol. 164, No. 3, 2011, pp. 165–179.
7. Mukherjee, A., and D. Cass. Project Emission Estimator: Implementation of a Project-Based Framework for Monitoring Pavement Greenhouse Gas Emissions. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2282, 2012, pp. 91–99.
8. Melanta, S., E. Miller-Hooks, and H. Avetisyan. Carbon Footprint Estimation Tool for Transportation Construction Projects. *ASCE- Journal of Construction Engineering and Management*, Vol. 139, 2013, pp. 547–555.
9. Dauvergne, M., A. Jullien, Y. Boussafir, P. Tamagny, and C. Proust. *Logiciel ECORCE-M, version multilingues,* 2014.
10. *DuboCalc version 4.01.1.* Rijkswaterstaat, 2015.
11. Fernández-Sánchez, G., A. Berzosa, J. M. Barandica, E. Cornejo, and J. M. Serrano. Opportunities for GHG Emissions Reduction in Road Projects: A Comparative Evaluation of Emissions Scenarios Using CO_2NSTRUCT. *Journal of Cleaner Production*, Vol. 104, 2015, pp. 156–167.
12. Santos, J., A. Ferreira, and G. Flintsch. A Life Cycle Assessment Model for Pavement Management: Methodology and Computational Framework. *International Journal of Pavement Engineering*, Vol. 16, No. 3, 2015, pp. 268–286.
13. Santos, J., J. Bryce, G. Flintsch, A. Ferreira, and B. Diefenderfer. A Life Cycle Assessment of In-Place Recycling and Conventional Pavement Construction and Maintenance Practices. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, Vol. 11, No. 9, 2015, pp. 1199–1217.
14. *Impact Estimator for Highways: User Guide*. Athena Sustainable Materials Institute (ASMI), 2012, pp. 1–11.
15. *SimaPro Tutorial*. PRé Consultants, 2016, pp. 1–89.
16. *GaBi Manual*, PE International, 2012, pp. 1–380.
17. Blankendaal, T., P. Schuur, and H. Voordijk. Reducing the Environmental Impact of Concrete and Asphalt: A Scenario Approach. *Journal of Cleaner Production,* Vol. 66, No. 1, 2014, pp. 27–36.
18. Turk, J., A. M. Pranjić, A. Mladenovič, Z. Cotič, and P. Jurjavčič. Environmental Comparison of Two Alternative Road Pavement Rehabilitation Techniques: Cold-In-Place-Recycling Versus Traditional Reconstruction. *Journal of Cleaner Production*, Vol. 121, 2016, pp. 45–55.
19. Horvath, A., S. Pacca, E. Masanet, and R. Canapa. *Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects*. Consortium on Green Design and Manufacturing, University of California, Berkeley, 2007.
20. Fernández, R. Environmental Product Declaration of “N-340” Road (Elche, Alicante). Reg. no. S-EP-00516, 2013.
21. *ISO 14025: Environmental Labels and Declarations-Type III Environmental Declarations-Principles and Procedures,* 2006.
22. *PCR CPC 53211 Highways (Except Elevated Highways), Streets and Roads,* 2013.

23. Guinée, J. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Series: Eco-efficiency in Industry and Science*. Kluwer Academic Publishers, Dordrecht, 2002.
24. Bare, J. TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. *Clean Technologies and Environmental Policy*, Vol. 13, 2011, pp. 687–696.
25. Finnveden, G., M. Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, R., S. Hellweg, A. Koehler, D. Pennington, and S. Suh. Recent Developments in Life Cycle Assessment. *Journal of Environmental Management*, Vol. 91, 2009, pp. 1–21.
26. *User's Guide for the Final NONROAD2005 Model*. Report EPA420-R-05-013. U.S. Environmental Protection Agency, Washington, D.C., 2005, pp. 1–202.

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TABLE 4 Impact Categories Computed by the Different LCA Tools

Impact category	GaBi	PaLATE V2.2	DuboCalc	VTTI/UC	ECORCE-M
Abiotic depletion	-	-	Y	-	-
Climate change (CC)	Y	Y	Y	Y	Y
Ozone depletion	Y	-	Y	-	-
Photochemical ozone creation (POC)	Y	-	Y	Y	Y
Acidification (AC)	Y	-	Y	Y	Y
Eutrophication (EU)	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

Notes: [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

TABLE 5 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

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 flows with the highest characterization factors per impact category; CF – characterization factor;

N/A – not applicable

Note: 1 kg = 2.202 lb

TABLE 6 Input Materials as Modeled in 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 m^3	soil movement (3 km)	-	gravel, grain size 2/32	accounts for soil, impact similar to aggregate	-
	water	627 m^3	-	water (no environmental impacts)	water	water	tap water
	selected material (soil)	13256 m^3	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 m^3	soil from local project (15 km)	-	gravel, grain size 2/32	accounts for soil, impact similar to aggregate	-
	water	124 m^3	-	water (no environmental impacts)	water	water	tap water
	graded aggregates	3187 m^3	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; does not 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	modeled 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	modeled 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; does not differentiate emulsion & PG bitumen	PG 70-22 binder
	concrete (brick)	310 m^3	concrete C20/25 (CEM I)	concrete, at mixing plant	concrete (stones, bricks)	modeled as individual materials	concrete (brick)
	glass fibers filaments	92 m^3	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	modeled 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	modeled 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	modeled as individual materials	asphalt concrete AC 22 Bin S
	prime coat	13 t	bituminous emulsion (proxy)	bituminous emulsion	asphalt binder	prime coat; does not 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.

$1\ m^3 = 35.7\ ft^3$

1 t = 2202 lb

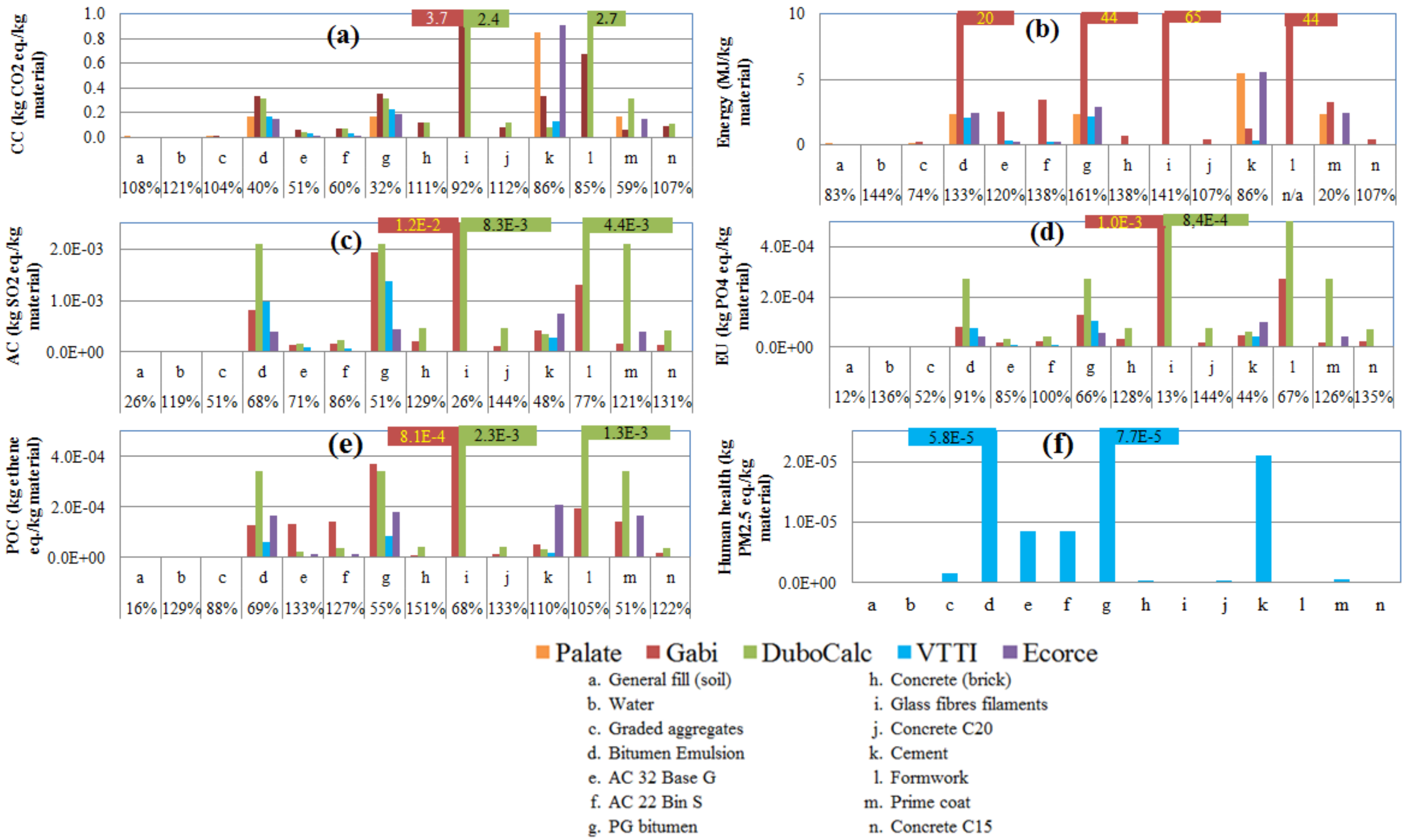

FIGURE 3 Environmental impacts per kg of product, calculated with the five different tools for six environmental impact categories (a) CC; (b) energy consumption; (c) AC; (d) EU, (e) POC, and (f) human health.

Note: 1 kg = 2.202 lb

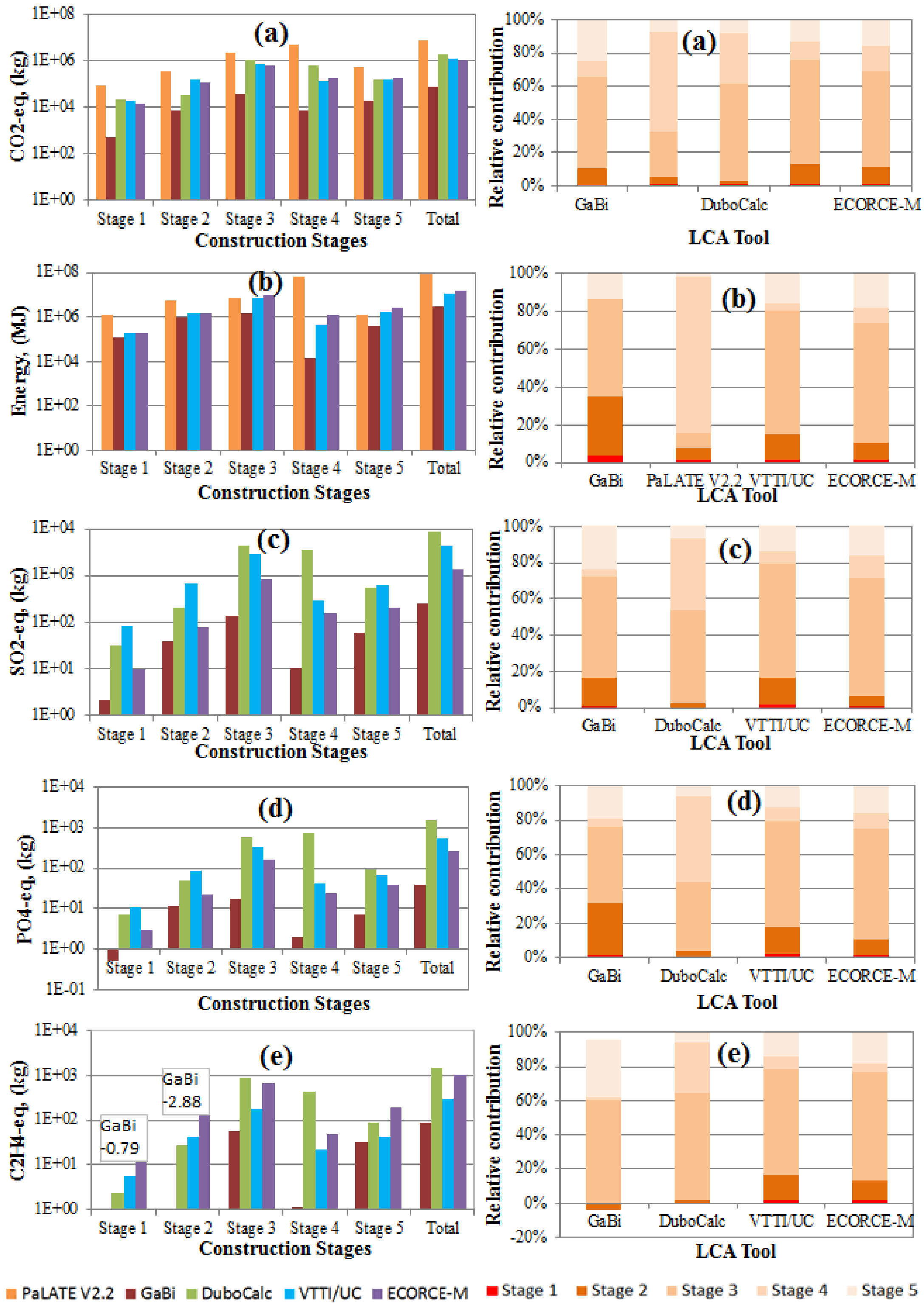

FIGURE 4 Comparison of the impact categories scores (left) and percentage contribution (right) from different LCA tools for the following impact categories and indicators: (a) CC, (b) energy consumption, (c) AC, (d) EU, and (e) POC.

Note: 1 kg = 2.202 lb