Life Cycle Assessment in Road Pavement Infrastructures: A Review

Bruno Guida Gouveia 1*, Marina Donato 1, Marcelino Aurélio Vieira da Silva 1

1 Transportation Engineering Program – COPPE, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil.

Received 01 April 2022; Revised 26 May 2022; Accepted 29 May 2022; Published 01 June 2022

Abstract

The need to meet society's demands for road infrastructure while minimizing the resulting environmental impacts is a source of great complications. In this context, Life Cycle Assessment (LCA) can be useful by applying a set of rules and processes for the environmental assessment of projects. The objectives of this study were to present the main environmental impact categories associated with emissions from the life cycle phases of a road pavement and how to estimate them. In addition, this paper provides examples of LCA applications on these infrastructures. In view of the evolution of research on LCA, a compilation was made on: the main categories of environmental impact associated with emissions; phases of life cycle impact assessment; and procedures and methods of impact estimation. The impact categories presented are associated with climate change, acidification, ozone depletion, tropospheric ozone formation, eutrophication, and Particulate Matter Formation. Not all methods are able to generate indicators for all types of impact and, depending on the type of materials and services that make up the inventory of the alternatives analyzed, one specific method may be more appropriate to use. The conclusions are that for each environmental impact, the results depend on the input parameters, such as energy flows and materials, along with their processing by methods of life cycle impact assessment. Besides this, despite the great diversity of the databases for the steps of life cycle assessment of roadway pavement, there is a general consensus about the nature of these steps.

Keywords: Life Cycle; Infrastructure; Environmental Impact; Transport.

1. Introduction

Because there is a limit on the ability of the biosphere to absorb the effects of human activities, and because these actions are mutable and subordinated to the degree of technological development and social, economic, and cultural organization, the concept of sustainable development has emerged. It consists of the idea that it is possible, through the combination of supply and demand management of productive resources and incentives for technological improvements, to generate economic growth for the current generation without compromising the ability of future generations to meet their needs [1].

Life cycle assessment (LCA) is inserted in this context. The processes and rules for conducting LCA were originally defined by the International Organization for Standardization (ISO) in its family of standardization [2]. The criteria for carrying out LCA are general since the objective is to guide analysis of any type of undertaking. Therefore, its application in pavement projects requires very precise specifications. The orientation is generally developed by the relevant industries and other stakeholders, such as researchers and public agencies [3].

*Corresponding author: brunoguida@pet.coppe.ufrj.br

http://dx.doi.org/10.28991/CEJ-2022-08-06-015

© 2022 by the authors. Licensee C.E.J, Tehran, Iran. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (http://creativecommons.org/licenses/by/4.0/).
Interest has been growing among transportation planners to determine the environmental impacts generated by all the steps of the life cycle of transportation infrastructure, from extraction until final disposal or recycling of materials. In this respect, although the environmental impact of products or services could be determined by other methods, LCA has gained space as the most appropriate tool to accomplish this type of task since it is able to qualify, quantify, and compare the repercussions of the structures studied. Finally, this type of capacity allows determining how a project can be implemented while minimizing the negative impacts on the environment [4, 5]. According to Alshehry & Belloumi, 2017 [6], 20% of global energy resource consumption and 25% of global GHG emissions are associated with transportation systems. However, 75% of those emissions come from road systems. In addition, pavement construction is recognized as one of the three most relevant activities in terms of natural resource consumption and, specifically within the road pavement life cycle, pavement construction can emit up to twice as many pollutants as motor vehicle operation [7, 8].

A road pavement is a layered structure that is generally sub-base, base, and surface course. As the layers underlying the surface course generally do not exert much influence on design processes, one of the main ways of classifying pavement is associated with the material that makes up this layer, which can be asphalt concrete and conventional concrete mixes [9, 10]. In Brazil, 65% of freight transport and 95% of passenger transport is carried out by road mode. Brazilian's road density if about 25,1 km/1000 km², with 99% asphalt-paved. In comparison, to other countries like China, USA, Russia, Argentina and Canada they have, respectively, 452,1 km/1000 km², 437,8 km/1000 km², 54,3 km/1000 km², 42,3 km/1000 km² and 41,6 km/1000 km² with some type of surface course, Brazil have much to expand [11].

Since asphalt-paved roads are more common, this study may focus on this type of pavement. Therefore, it is necessary to point out that asphalt mixtures are usually composed of aggregates, fillers, binders, and sometimes additives. Approximately 85% to 95% of the mix is composed of aggregate and fillers, the rest is filled by asphalt [9, 10, 12].

Chen et al. 2021 [13] analyzed the effect of global warming on asphalt-paved roadway deterioration. In this regard, they used a mechanistic-empirical pavement design method to simulate the effect of temperature. They concluded that an increase in global temperature would accelerate the deterioration of asphalt pavement leading to an escalation in maintenance demand, which would consequently require more raw material, plant production, transportation, and field construction. This growth in the amount of services generates an increase in the amount of CO₂ emitted over the life cycle of the pavement, which, although it performs better in the use phase, does not pay off. It is evident then, that the life cycle of road pavement influence and are affected by climate change. In addition to these impacts such as acidification and particulate matter emissions are widely analyzed [14].

As a contribution to less environmentally offensive roadway, this article presents a short review of concepts and paradigms for conducting life cycle assessment, focused on roadway infrastructure. The objectives were to present the main midpoint environmental impact category associated to emissions, the main methods used to translate the effects of human activities into the units generally used for each environmental impact and the life cycle stages usually adopted in life cycle assessment of a roadway pavement. In addition, this paper brings some examples of LCA searches with their combinations of sources inventories bases, stapes of life cycle considered, methods to estimate impacts. The article is organized into five sections including this introduction. Section 2 defines the general concepts for conducting life cycle assessment for any type of product or service; section 3 identifies some specifications necessary to apply LCA to roadway pavement products; section 4 summarizes some examples of studies that have applied LCA for this purpose; and section 5 contains our conclusions and some proposals for future works.

2. Life Cycle Assessment

Life cycle assessment can be subdivided into four steps: objectives and scope; life cycle inventory; environmental impact assessment; and interpretation. Figure 1 depicts a graphic representation of the LCA steps and their interdependence. The step of defining the objectives and scope consists of determining parameters, such as: (1) functional units, which are connected to a specific input or output, to enable comparison between different projects, such as kilometers of road constructed per CO₂ equivalent emitted; (2) frontiers of the system, among them the life cycle phases of the product or service and the types of impacts considered; (3) period of evaluation of the product, which in the case of pavement can extend beyond the service life; and (4) general specifications, such as a complete description of the data sources, methods and tools used to guarantee the reproducibility, replicability and auditing of the studies and evaluations [15, 16].
A life cycle inventory (LCI) is basically a list of inputs and outputs associated with all the steps of the LCA of a determined product [19]. There are three approaches most often applied for LCI. The first is known as process analysis or the bottom-up approach, in which the life cycle of the product is segmented into various production subsystems. The second is the top-down approach, which is based on macroeconomic diagnoses through input-output analysis. The third method incorporates characteristics of the first two procedures [20, 16].

Different substances may have the ability to generate the same environmental effects, but with different potentials. In view of this, standardization is necessary. In most cases, the intensity of the effects that a given quantity of a given substance causes on an environmental quality parameter is taken as the basis. Each effect then has its own basic substance of comparison. In addition, the same substance can contribute to several negative impacts. For a deeper understanding of the theory adopted by the life cycle assessment it is important to note that each environmental impact will have consequences on areas of protection. Usually, but not exclusively, these areas are: usually human health; ecosystem quality or natural environment; natural resources and ecosystem services. It is evident that each intermediate impact can affect more than one area of protection [19]. In this respect, Table 1 reports some of the main midpoint environmental impact category associated to emissions and Ecosystem quality or natural environment.

| Midpoint Environmental Impact     | Characterization Factor          | Unit       | Area of Protection | References                  |
|-----------------------------------|----------------------------------|------------|--------------------|-----------------------------|
| Climate Change                    | Global Warming Potential (GWP)   | kg CO$_2$-eq | Ecosystem quality or natural environment | IPCC, 2014 [21] |
| Stratospheric Ozone Depletion     | Ozone Degradation Potential (ODP) | kg CFC-11-eq |                     | Hauschild et al. 2018 [19]  |
| Photochemical Ozone Formation     | Photochemical Formation Potential (POPC) | kg NO$_x$-eq |                     | Van Zelm et al. 2016 [22]  |
| Acidification                     | Acidification Potential (TAP)    | kg SO$_2$-eq |                     | Roy et al. 2014 [23]       |
| Eutrophication                    | Freshwater Eutrophication Potential (FEP) | kg PO$_4$-eq |                     | Helmes et al. 2012 [24]   |
| Particulate Matter Formation      | Particulate Matter Formation Potential (PMFP) | kg PM$_{2.5}$-eq |                     | Van Zelm et al. 2016 [22] |

* Source: Adapted from [25-28].

Life cycle impact assessment phase apply procedures that transform different emissions in a cause-effect chain into different estimates of environmental impacts of interest susceptible to assessment. An example is the conversion of direct emissions of one ton of any gas into a carbon dioxide equivalent (CO$_2$eq) to determine the potential contribution to the greenhouse effect, such as methane gas (CH$_4$). This conversion enables comparing different substances from the standpoint of global warming potential. This step tends to be highly automated, having a great amount of different computer programs available, depending on the product analyzed and the impacts targeted for estimation [19]. Table 2 exhibits the methods developed to translate the effects of human activities into the units generally used for each environmental impact. It is pertinent to point out that for each midpoint environmental impact there is a diversity of models and considerations. For this reason, but not only, comparisons between different studies should be made with caution, as each method may use different procedure to estimate each midpoint environmental impact. In addition, it is important to note that not all methods are able to generate indicators for all types of impact. Another important issue is that, depending on the type of materials and services that make up the inventory of the alternatives analyzed, one specific method may be more appropriate to use [15, 19].
### Table 2. Methods developed to translate the effects of human activities into the units generally used for each environmental impact*

| Method               | Name                          | Description                                                                                                                                   | Developer                      | Year   | Source                                      |
|----------------------|-------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|--------|---------------------------------------------|
| TRACI                | Tool for Reduction and Assesment of Chemical and other environmental Impacts | An LCA program based on SimaPro specifically for use in the USA.                                                                          | U.S. Environmental Protection Agency (EPA) | 1995   | Bare, 2002 [29]                            |
| Eco-indicator 99     |                               | The methodological procedure adopts a combination implementation of the end environmental impact-oriented approach.                         | Pré Consultants (product ecology consultants) | 1997   | Goedkoop et al. 1998 [30]; Goedkoop & Spriensma 2001 [31] |
| ERM                  | Elementary Road Modulus       | A parametric environmental assessment tool developed by replicating LCA and adapted specifically for road structures.                         | Laboratoire Central des Ponts et Chaussées (LCPC) | 1998   | Hoang et al. 2005 [32]                      |
| CML                  | Centrum Milieukunde Leiden   | Developed determination of intermediate environmental impacts.                                                                             | Institute of Environmental Sciences at the University of Leiden | 2001   | Guinée et al. 2002 [33]; VAN Caneghem et al. 2010 [34] |
| Athena               | Athena Impact Estimator       | A free LCA software application aimed specifically at the construction and maintenance stages of highways in Canada and the USA.            | Athena Sustainable Materials Institute | 2002   | Stek et al. 2011 [35]                       |
| PaLATE               | PAVEMENT LIFECYCLE ASSESSMENT TOOL FOR ENVIRONMENTAL AND ECONOMIC EFFECTS | An Excel®-based LCA tool focusing on economic and environmental effects.                                                                  | University of California, Berkeley | 2003   | Horvath, 2004 [36]; Maenisch, 2010 [37]    |
| ROAD-RES             | Road construction and disposal of residues | An LCA tool focused on comparing the utilization of waste from incineration processes and virgin materials.                               | Technical University of Denmark | 2005   | Birgisdottir, 2005 [38]; Birgisdottir et al. 2007 [39]; Maenisch, 2010 [37] |
| ReCiPe               |                               | The ReCiPe LCA method was developed to provide factors to characterize intermediate and final environmental impacts.                     | RIVM, Radboud University Nijmegen, Leiden University and Pré Consultants. | 2008; updated 2016 | Goedkoop et al. 2009 [40]; Goedkoop et al. 2013 [41]; Huijbregts et al. 2016 [42] |
| ECOCE      | ECO-comparator applied to Road Construction and Maintenance | A JAVA®-based LCA tool dedicated to road pavement for the construction and maintenance phases with a focus on material, water and energy reduction. | French Institute of Science and Technology in Transportation, Planning and Networks | 1.0 (2008); 2.0 (2013); M (2014) | Julien et al. 2015 [43] |
| CHANGER             | Calculator for Harmonised Assessment and Normalisation of Greenhouse-gas Emissions for Roads | A calculation tool for monitoring, estimations, evaluation and normalization of GHG emissions from road construction.                      | International Road Federation (IRF) | 2009   | Huang et al. 2013 [44]                       |
| Roadprint            |                               | A free LCA software for evaluating new and rehabilitated road pavement, which can be considered as an evolution of PaLATE.                | University of Washington       | 2012   | Muench et al. 2014 [45]                      |
| AsPECT              | Asphalt Pavement Embodied Carbon Tool | An LCA tool for calculating carbon dioxide equivalent emissions from asphalt mixtures.                                                      | Transport Research Laboratory | 2009   | Nicuță, 2011 [46]                          |
| PE-2                | Project Emission Estimator    | Pavement GHG emissions monitoring program.                                                                                                | Michigan Technological University | 2012   | Mukherjee & C., 2012 [47]; Mukherjee et al. 2013 [48] |
| EcoConcrete          | Eco-friendly Concrete         | Interactive Excel®-based tool specially designed for quantifying the life cycle environmental impacts of concrete products.             | Joint Project Group (JPG)      |        | Evangelista & De Brito, 2007 [49]           |
| IMPACT 2002+         |                               | The methodological procedure adopts an implementation through a combination of the approach to intermediate and final environmental impacts. | Swiss Federal Institute of Technology Lausanne (EPFL), currently maintained and improved by IMPACT Modeling Team. |        | Jolliet et al. 2003 [50]; Humbert et al. 2012 [51] |

* Source: Adapted from [15, 25, 28, 52, 53].

Hoxha et al. 2021 [54] reviewed Life cycle assessment of roads exploring research trends and harmonization challenges. They concluded that, although theoretically unexpected, the software used for analysis affects the results and possible comparisons between studies, even if they contain the same databases and methods. In addition, they noted that most studies estimated impacts on climate change, leaving other impacts relegated to the background. Furthermore, they pointed out that publicizing the impacts that road infrastructure can generate for climate change is important as it can raise awareness.

Finally, the objective of the interpretation step is to summarize, identify and evaluate the results of the LCI and LCIA, and to draw some conclusions regarding the project of interest. This step generally consists of three elements: identification of relevant questions based on the results of the LCI and LCIA; evaluation of the sensitivity of the problems identified and verification of the consistency and completeness of the results; conclusions, limitations of the study and recommendations for future research [15].
3. Life Cycle Assessment on Pavement

LCA is a structured method to determine the types and quantities of impacts generated during the life cycle of a supply chain, by examining the inputs and outputs of a product or system. In the case of roadway pavement, the life cycle can cover the following phases: (1) extraction of raw materials (virgin inputs); (2) transport of inputs; (3) milling or other processing of the input materials; (4) transport of the processed paving materials; (5) construction of the pavement; (6) maintenance and recuperation; (7) operation; (8) recycling; (9) demolition; and (10) reconstruction [3, 16, 55].

Figure 2 (adapted from [15, 18, 55]) contains a representation of a roadway pavement life cycle phases connection and the processes customarily allocated to them. It is possible to note the phases chronological order of linkage and the contribution of a single phase to multiple other phases (e.g., the production of materials feeds the construction and maintenance phases). Another observation is the participation of transport in all the phases, although with different relevance levels. Finally, the phases of use/operation and maintenance/recuperation, although occurring in the same period (during the life cycle of the pavement), are considered separately, in attempt to rationalize organization, since the desire is to verify the effects of different processes that in final analysis are associated with the users or managers of the road. The reason is that the flows of materials and energy that feed each phase have different levels, and hence different environmental impacts.

According to Xiao et al. 2019 [15], a LCA of a pavement have different designations depending on the steps life of cycle included into the analysis, namely: (i) from cradle to gate, when the phases of extraction, processing of inputs and construction are considered; (ii) from cradle to grave, when the phases of use/operation, maintenance/recuperation and end of life are added to those mentioned in (i), without considering total recycling of the elements composing the pavement; and (iii) from cradle to cradle, when the study covers all the phases plus the recycling of the elements that compose the pavement, to start the chain again.

There are at each stage of the pavement life cycle a number of processes. Figure 3 attempts to illustrate the fact that each process requires different types and amounts of materials and energy to complete them. For example, to prepare the asphalt mixture it is necessary to have asphalt, aggregates and additives, which need to be heated and mixed together. The result is not only the desired product, but also substances that can affect the soil, land and air [19, 56].
The stage of extraction and supplies production includes the processes of extraction and beneficiation of raw materials to produce the materials that will be used in the phases of construction, maintenance and recuperation of the pavement. These mainly consist of mixtures of aggregates with a wide granulometric range and asphaltic binders [3, 57].

The phase of materials production has the objective of gathering the different inputs from the extraction phase and processing. With regard to asphaltic mixtures, the typical steps are: (1) drying and heating of the aggregates; (2) heating of the binder; and (3) mixture of the aggregates with binder. With regard to the materials composing the other pavements layers namely, base, sub-base and subgrade, the following steps occur: (4) granulometric stabilization; and (5) chemical stabilization [18]. The transport of materials is involved in all the other steps of the life cycle of a roadway pavement. For example, in the case of the construction of a new pavement or maintenance/recuperation of an old one, it will be necessary to transport the binder and different aggregates to the worksite. In the case of maintenance/recuperation, it will also be necessary to transport old material for recycling or final disposal. The environmental impacts of this transport will be mainly influenced by: engine technology of the transport vehicle; load capacity of the vehicle; shifting distances; transportation speed and weight of the materials to be carried [57].

The environmental impacts usually considered in construction phase and maintenance/recuperation phase depends on equipment combustion: (1) of the fuel used by the construction equipment at the site and vehicles that carry the materials; and (2) the extra fuel consumed by vehicles that must wait idling, travel at reduced speed and/or take detours around the construction site [3, 57]. Some of the main aspects that directly interfere in the intensities of environmental impacts in practically all stages are: service life, with several methods for estimation; frequency and type of maintenance, which also has a great diversity of possibilities and effects [58]. During pavement use stage, impacts are normally around the construction site [3, 57]. Some of the main aspects that directly interfere in the intensities of environmental impacts are: service life, with several methods for estimation; frequency and type of maintenance, which also has a great diversity of possibilities and effects [58]. During pavement use stage, impacts are normally associated to vehicles consumption affected by vehicles-pavement interactions.

Table 3 presents some pavement life cycle assessment studies. Consensus can be observed on phases definitions, but there is no agreement on which steps to be taken account. This seems to corroborates that, these aspects must be determined by the team of researchers according to the objectives and scope of the study. Other aspect to note is that the majority decided to estimate climate change, acidification contributions and energy consumption. Those aspects are in line with Meijer et al. (2018) [14].

Table 3. Papers Collection that applied LCA in highway pavement studies, showing the steps considered and the environmental impact indicators used*

| Studies                                      | Life cycle steps | Environmental Impact Indicators |
|----------------------------------------------|------------------|--------------------------------|
|                                              | Extraction / Production | Transport of materials | Construction | Use | Maintenance | Recycling | Greenhouse Gases (CO2, et al) | Energy Consumption (MJ) | Carbon Dioxide (CO2) | Carbon Monoxide (CO) | Methane (CH4) | Sulfur Oxides (SOx) | Nitrogen Oxides (NOx) | Nitrogen Oxide (NO) | Particulate Matter (PM) | Volatile Organic Compounds (VOC) |
| Huang et al. (2009) [59]                     | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Yu et al. (2012) [60]                        | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Yu et al. (2013) [61]                        | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Chou et al. (2013) [62]                      | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Yu et al. (2014) [63]                        | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Araújo et al. (2014) [64]                    | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Santos et al. (2015a) [57]                   | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Santos et al. (2015b) [65]                   | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Liu et al. (2015) [66]                       | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Mauro et al. (2016) [67]                     | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Chen et al. (2016) [68]                      | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Chong & Wang (2017) [52]                     | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Santos et al. (2017b) [69]                   | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Moretti et al. (2017) [70]                   | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Liu et al. (2018) [71]                       | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Hong et al. (2018) [72]                      | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Gulotta et al. (2019) [73]                   | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
4. Life Cycle Assessment on Pavement Applications

Table 4 presents a compilation of pavements life cycle assessments studies exposing: objectives and scopes; sources of data used; LCIA method adopted. Objectives includes comparison of asphalt mills versus asphalt plants and virgin aggregates versus recycled aggregates. The majority of works estimated contributions made on climate change, acidification, degradation of the ozone layer, formation of tropospheric ozone and eutrophication. Regarding to data inventories, there was no consensus on national and international databases use. About LCIA method, no particular preference was observed.

| Reference | Objectives | Life cycle Steps | Database Source | LCIA Methods | Software | Environmental Impact Indicators | Database Source |
|-----------|------------|------------------|-----------------|--------------|----------|-------------------------------|----------------|
| Wang et al. (2019) [74] | Comparison of the environmental impacts associated with the production of HMA with virgin and recycled aggregates. | Cradle-to-site: Transportation; extraction & machining; construction | Regional data; Ecoinvent v.3 e USLCI (United States life cycle inventory) | TRACI | SimaPro | ODP, GWP, POPC, TAP, FEP, Ecotoxicity, Fossil Fuel Depletion, Human Health Damage | Vega et al. 2020 [28] |
| Cong et al. (2020) [56] | Comparison of the economic and environmental impacts of using different materials for pavement layers. | Cradle-to-site: Transportation; extraction & machining; construction | Regional data; Ecoinvent v.3, literature review | CML Baseline | SimaPro | GWP, Fossil Fuel Depletion | Nascimento et al. 2020 [76] |
| Huang et al. (2021) [75] | Comparison of the environmental impacts associated with the production of HMA with virgin and recycled aggregates. | Cradle-to-site: Transportation; extraction & machining; construction | Regional data; Ecoinvent v.3 | IMPACT 2002+ | SimaPro | GWP, TAP, OD, FEP, Ecotoxicity, Fossil Fuel Depletion | Martinez-Agueu et al. 2019 [27] |
| | | | | TRACI | | GWP, TAP, OD, POPC, FEP, Danos a saúde Ecotoxicity | Sha et al. 2019 [77] |
| | Comparison of the environmental impacts associated with the production of HMA with virgin and recycled aggregates. | Cradle-to-site: Transportation; extraction & machining; construction | Regional data; Oklahoma DOT AADT Traffic Counts | | | | |
| | | | | | | | |
| | Comparison of the environmental impacts associated with the production of HMA with virgin and recycled aggregates. | Cradle-to-site: Transportation; extraction & machining; construction | Regional data; Ecoinvent v.3 | IMPACT 2002+ | SimaPro | GWP, TAP, OD, POPC, FEP, Ecotoxicity, Fossil Fuel Depletion | Rosado et al. 2017 [78] |
| | | | | | | | |
| | Comparison of the environmental impacts associated with the production of HMA with virgin and recycled aggregates. | Cradle-to-site: Transportation; extraction & machining; construction | Regional data; Ecoinvent v.3 | IMPACT 2002+ | SimaPro | ADP, GWP, OD, POPC, TAP, FEP | Braga et al. 2017 [79] |
| | | | | | | | |
| | Compare the differences between the environmental impacts generated by recycled and virgin aggregates. | Cradle-to-site: Transportation; extraction & machining; construction | Regional data | IMPACT 2002+ | SimaPro | GWP, TAP, OD, POPC, FEP, Ecotoxicity, Fossil Fuel Depletion Human Health Damage | Hossain et al. 2016 [80] |
| | | | | | | | |
| | Compare the environmental impacts associated aggregates for asphalt mixtures: (i) virgin; (ii) recycled in a mill plant; (iii) recycled in a mobile plant. | Cradle-to-site: Transportation; extraction & machining; construction | Regional data | Eco-indicator 99, CML Baseline and Cumulative Energy Demand | SimaPro | GWP, TAP, OD, POPC, FEP, Ecotoxicity, Fossil Fuel Depletion | Estanquero et al. 2016 [81] |

*Source: Adapted from [76].

5. Conclusion

Transport infrastructure affects the environment in several ways. Directly, by demanding natural resources that will form the materials used in the construction and conservation of pavements. Indirectly, by demanding fuel to operate vehicles and construction equipment. To decrease the negative environmental effects of infrastructure, it is necessary to compare which alternative designs cause the lowest environmental impacts. That is the context of the application of life cycle assessment. This article presented a short review of concepts and paradigms for conducting life cycle assessments, focusing on highway infrastructure.
A compilation of the main midpoint environmental impact category associated with emissions was shown. As discussed, different substances may have the ability to generate the same environmental effects but with different potentials. Each effect then has its own basic substance of comparison. The impact categories presented are associated with climate change, acidification, ozone depletion, tropospheric ozone formation, eutrophication, and Particulate Matter Formation.

The life cycle impact assessment phase applies procedures that transform different emissions in a cause-effect chain into different estimates of environmental impacts of interest susceptible to assessment. This step tends to be highly automated, with a greater number of different computer programs available depending on the product analyzed and the impacts targeted for estimation. Not all methods are able to generate indicators for all types of impact and, depending on the type of materials and services that make up the inventory of the alternatives analyzed, one specific method may be more appropriate to use. Comparisons between different studies should be made with caution, as each method may use a different procedure to estimate each midpoint environmental impact. In addition, the methods used to determine these indicators vary widely in the sample analyzed, indicating lack of consensus about it and constant technology update.

There is no way to indicate the best database to use is to recommend the adoption of a database that best represents the alternatives, since the precision of the results of LCA depends on the reliability of the data employed for characterization of the inputs. The diversity of selections that have to be made by researchers to apply the LCA methodology and the inherent diversity of the infrastructure project alternatives being compared makes quantitative comparisons difficult, because the final analysis will correspond to the characteristics of the chosen parameters for the inventory. In order to use LCA as a reliable and replicable tool to evaluate the environmental impacts that highways can generate, all the parameters and considerations adopted to perform the analysis must be established and made evident. Finally, a proposal for future studies would be to evaluate the effects on the LCA of a pavement that would suffer under the variation of construction materials, construction techniques, and pavement management strategies.

6. Declarations

6.1. Author Contributions

Conceptualization, B.G.G., and M.D.; methodology, B.G.G., and M.D.; software, B.G.G., and M.D.; validation, B.G.G., and M.D.; formal analysis, B.G.G., and M.D.; investigation, B.G.G., M.D., and M.A.V.S.; resources, B.G.G., M.D., and M.A.V.S.; data curation, B.G.G., M.D., and M.A.V.S.; writing—original draft preparation, B.G.G., M.D., and M.A.V.S.; writing—review and editing, B.G.G., M.D., and M.A.V.S.; visualization, M.A.V.S.; supervision, M.A.V.S. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001 and Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brasil (CNPq).

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Brundtland, G. H., Khalid, M., Agnelli, S., Al-Athal, S. A., Chidzero, B., Fadika, L. M., Hauf, V., Lang, I., Ma, S., Botero, M. M., Singh, N. (1987). Our common future; by world commission on environment and development. Oxford University Press, Oxford, United Kingdom. (In Portuguese).

[2] ISO-14044. (2006). Environmental Management-Life Cycle Assessment-Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland.

[3] Harvey, J. T., Meijer, J., & Kendall, A. (2014). Tech Brief: Life Cycle Assessment of Pavement. FHWA-HIF-15-001, Federal Highway Administration (FHWA), Washington, United States. Available online: https://rosap.ntl.bts.gov/view/dot/38553 (accessed on May 2022).

[4] Crawford, R. H. (2008). Validation of a hybrid life-cycle inventory analysis method. Journal of Environmental Management, 88(3), 496–506. doi:10.1016/j.jenvman.2007.03.024.

[5] AzariJafari, H., Yahia, A., & Amor, M. B. (2016). Life cycle assessment of pavements: reviewing research challenges and opportunities. Journal of Cleaner Production, 112, 2187-2197. doi:10.1016/j.jclepro.2015.09.080.

[6] Alshehry, A. S., & Belloumi, M. (2017). Study of the environmental Kuznets curve for transport carbon dioxide emissions in Saudi Arabia. Renewable and Sustainable Energy Reviews, 75, 1339–1347. doi:10.1016/j.rser.2016.11.122.
[7] Steger, S., & Bleischwitz, R. (2011). Drivers for the use of materials across countries. Journal of Cleaner Production, 19(8), 816–826. doi:10.1016/j.jclepro.2010.08.016.

[8] Khare, P., Machesky, J., Soto, R., He, M., Presto, A. A., & Gentner, D. R. (2020). Asphalt-related emissions are a major missing nontraditional source of secondary organic aerosol precursors. Science Advances, 6(36). doi:10.1126/sciadv.abb9785.

[9] Tokedfe, O. O., Whittaker, A., Mankaa, R., & Traverso, M. (2020). Life cycle assessment of asphalt variants in infrastructures: The case of lignin in Australian road pavements. Structures, 25, 190–199. doi:10.1016/j.istruc.2020.02.026.

[10] Plati, C. (2019). Sustainability factors in pavement materials, design, and preservation strategies: A literature review. Construction and Building Materials, 211, 539–555. doi:10.1016/j.conbuildmat.2019.03.242.

[11] National Transport Confederation (2021). Pesquisa CNT de rodovias (2021). CNT survey of highways (2021). National Transport Confederation (CNT, SEST, & SENAT, Eds), Brazil, v.1, 1-234.

[12] He, M., Tu, C., Cao, D. W., & Chen, Y. J. (2019). Comparative analysis of bio-binder properties derived from different sources. International Journal of Pavement Engineering, 20(7), 792–800. doi:10.1080/10298436.2017.1347434.

[13] Chen, X., Wang, H., Horton, R., & DeFlorio, J. (2021). Life-cycle assessment of climate change impact on time-dependent carbon-footprint of asphalt pavement. Transportation Research Part D: Transport and Environment, 91. doi:10.1016/j.trd.2021.102697.

[14] Meijer, J. R., Huijbregts, M. A. J., Schotten, K. C. G. J., & Schipper, A. M. (2018). Global patterns of current and future road infrastructure. Environmental Research Letters, 13(6). doi:10.1088/1748-9326/aab442.

[15] Li, J., Xiao, F., Zhang, L., & Amirghanian, S. N. (2019). Life cycle assessment and life cycle cost analysis of recycled solid waste materials in highway pavement: A review. Journal of Cleaner Production, 233, 1182–1206. doi:10.1016/j.jclepro.2019.06.061.

[16] Hasan, U., Whyte, A., & Al Jassmi, H. (2019). Critical review and methodological issues in integrated life-cycle analysis on road networks. Journal of Cleaner Production, 206, 541–558. doi:10.1016/j.jclepro.2018.09.148.

[17] Zulu, K., Singh, R. P., & Shaba, F. A. (2020). Environmental and economic analysis of selected pavement preservation treatments. Civil Engineering Journal, 6(2), 210-224. doi:10.28991cej-2020-03091465.

[18] Zheng, X., Easa, S. M., Yang, Z., Ji, T., & Jiang, Z. (2019). Life-cycle sustainability assessment of pavement maintenance alternatives: Methodology and case study. Journal of Cleaner Production, 213, 659–672. doi:10.1016/j.jclepro.2018.12.227.

[19] Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2017). Life Cycle Assessment: Theory and Practice. Springer, Cham, Switzerland. doi:10.1007/978-3-319-56475-3.

[20] Crawford, R. (2011). Life cycle assessment in the built environment (1st Ed.). Routledge, London, United Kingdom. doi:10.4324/9780203686171.

[21] IPCC. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland. Available online: https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf (accessed on May 2022).

[22] van Zelm, R., Preiss, P., van Goethem, T., Van Dingenen, R., & Huijbregts, M. (2016). Regionalized life cycle impact assessment of air pollution on the global scale: Damage to human health and vegetation. Atmospheric Environment, 134, 129–137. doi:10.1016/j.atmosenv.2016.03.044.

[23] Roy, P. O., Azevedo, L. B., Margni, M., van Zelm, R., Deschénes, L., & Huijbregts, M. A. J. (2014). Characterization factors for terrestrial acidification at the global scale: A systematic analysis of spatial variability and uncertainty. Science of the Total Environment, 500–501, 270–276. doi:10.1016/j.scitotenv.2014.08.099.

[24] Helmes, R. J. K., Huijbregts, M. A. J., Henderson, A. D., & Jolliet, O. (2012). Spatially explicit fate factors of phosphorous emissions to freshwater at the global scale. International Journal of Life Cycle Assessment, 17(5), 646–654. doi:10.1007/s11367-012-0382-2.

[25] Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. International Journal of Life Cycle Assessment, 22(2), 138–147. doi:10.1007/s11367-016-1246-y.

[26] Santos, J., Bressi, S., Cerezo, V., & Lo Presti, D. (2019). SUP&R DSS: A sustainability-based decision support system for road pavements. Journal of Cleaner Production, 206, 524–540. doi:10.1016/j.jclepro.2018.08.308.

[27] Martinez-Arguelles, G., Acosta, M. P., Dugarte, M., & Fuentes, L. (2019). Life Cycle Assessment of Natural and Recycled Concrete Aggregate Production for Road Pavements Applications in the Northern Region of Colombia: Case Study. Transportation Research Record, 2673(5), 397–406. doi:10.1177/0361198119839955.
[28] Vega A. D. L., Santos, J., & Martinez-Arguelles, G. (2022). Life cycle assessment of hot mix asphalt with recycled concrete aggregates for road pavements construction. International Journal of Pavement Engineering, 23(4), 923–936. doi:10.1080/10298436.2020.1778694.

[29] Bare, J. C. (2002). TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. Journal of industrial ecology, 6(3-4), 49-78. doi:10.1162/108819802766269539.

[30] Goedkoop, M., Hofstetter, P., Müller-Wenk, R., & Spreijsema, R. (1998). The Eco-indicator 99 explained. The International Journal of Life Cycle Assessment, 3(6), 352-360. doi: 10.1007/BF02979347.

[31] Goedkoop, M., & Spreijsema, R. (2001). The Eco-indicator 99 - A damage oriented method for Life Cycle Impact Assessment-Methodology Annex (3rd Ed.). Pré Consultants B. V., Amersfoort, Netherlands.

[32] Hoang, T., Jullien, A., Ventura, A., & Crozet, Y. (2005). A global methodology for sustainable road-Application to the environmental assessment of French highway. 10DBMC International Conference on Durability of Building Materials and Components, 17-20 April, 2005, Lyon, France.

[33] Guinée, J. B. (2002). Handbook on life cycle assessment: operational guide to the ISO standards. The International Journal of Life Cycle Assessment, 7(5), doi:10.1007/BF02978897.

[34] Van Caneghem, J., Block, C., & Vandecasteele, C. (2010). Assessment of the impact on human health of industrial emissions to air: Does the result depend on the applied method? Journal of Hazardous Materials, 184(1–3), 788–797. doi:10.1016/j.jhazmat.2010.08.110.

[35] Stek, E., DeLong, D., McDonnell, T., & Rodriguez, J. (2011). Life Cycle Assessment Using ATHENA Impact Estimator for Buildings: A Case Study. Structures Congress 2011. doi:10.1061/41171(401)42.

[36] Horvath, A. (2004). A life-cycle analysis model and decision-support tool for selecting recycled versus virgin materials for highway applications. Final Report for RMRC Research Project No. 23, University of California, Berkeley, United States.

[37] Muench, S. T. (2010). Roadway Construction Sustainability Impacts. Transportation Research Record: Journal of the Transportation Research Board, 2151(1), 36–45. doi:10.3141/2151-05.

[38] Birgisdóttir, H. (2005). Life cycle assessment model for road construction and use of residues from waste incineration. Ph.D. Thesis, Institute of Environment & Resources, Technical University of Denmark, Lyngby, Denmark.

[39] Birgisdottir, H., Bhandar, G., Hauschild, M. Z., & Christensen, T. H. (2007). Life cycle assessment of disposal of residues from municipal solid waste incineration: Recycling of bottom ash in road construction or landfilling in Denmark evaluated in the ROAD-RES model. Waste Management, 27(8), S75-S84. doi:10.1016/J.wasman.2007.02.016.

[40] Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., & Zelm, R. V. (2009). ReCiPe2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Ministry of Housing, Spatial Planning and Environment (VROM), Barendrecht, Netherlands.

[41] Goedkoop, M., Heijungs, R., Huijbregts, M., Schryer, A. De, Struijs, J., & Zelm, R. Van. (2013). ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition (version 1.08, May 2013). Ministry of Housing, Spatial Planning and Environment (VROM), Barendrecht, Netherlands.

[42] Huijbregts, M.A.J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., R. van Zelm, (2016). Recipe2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: characterization”. RIVM Report 2016-0104. National Institute for Human Health and the Environment, Bilthoven, Netherlands.

[43] Jullien, A., Dauvergne, M., & Proust, C. (2015). Road LCA: the dedicated ECORCE tool and database. International Journal of Life Cycle Assessment, 20(5), 655–670. doi:10.1007/s11367-015-0858-y.

[44] Huang, Y., Hakim, B., & Zammataro, S. (2013). Measuring the carbon footprint of road construction using Changer. International Journal of Pavement Engineering, 14(6), 590–600. doi:10.1080/10298436.2012.693180.

[45] Muench, S. T., Lin, Y. Y., Katara, S., & Armstrong, A. (2014). Roadprint: Practical Pavement Life Cycle Assessment (LCA) Using Generally Available Data. 2014 International Symposium on Pavement Life Cycle Assessment, 249-262, October 14-16, 2014, davis, United States.

[46] Nicuta, A. M. (2011). Life cycle assessment study for new and recycled asphalt pavements. Bulletinul Institutului Politehnic din Iasi. Sectia Constructii, Arhitectura, 57(2), 81.

[47] Mukherjee, A., & Cass, D. (2012). Project emissions estimator: implementation of a project-based framework for monitoring the greenhouse gas emissions of pavement. Transportation research record, 2282(1), 91-99. doi:10.3141/2282-10.

[48] Mukherjee, A., Stawowy, B., & Cass, D. (2013). Project Emission Estimator: tool for contractors and agencies for assessing greenhouse gas Emissions of Highway construction Projects. Transportation research record, 2366(1), 3-12. doi:10.3141/2366-01.
[49] Evangelista, L., & De Brito, J. (2008). Environmental life cycle assessment of concrete made with fine recycled concrete aggregates. Portugal Sb07—Sustainable Construction, Materials and Practices: Challenge of the Industry for the New Millennium, 1-7.

[50] Jollivet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebiter, G., & Rosenbaum, R. (2003). IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. International Journal of Life Cycle Assessment, 8(6), 324–330. doi:10.1007/BF02978505.

[51] Humbert, S., De Schryver, A., Bengoa, X., Margni, M., & Jollivet, O. (2012). IMPACT 2002+: user guide. Draft for version Q. 2. Quantis-Environmental Sustainability Consultancy, Zurich, Switzerland.

[52] Chong, D., & Wang, Y. (2017). Impacts of flexible pavement design and management decisions on life cycle energy consumption and carbon footprint. International Journal of Life Cycle Assessment, 22(6), 952–971. doi:10.1007/s11367-016-1202-x.

[53] Dos Santos, J. M. O., Thyagarajan, S., Keijzer, E., Flores, R. F., & Flintsch, G. (2017). Comparison of life-cycle assessment tools for road pavement infrastructure. Transportation Research Record, 2646(1), 28–38. doi:10.3141/2646-04.

[54] Hoxha, E., Vignisdottir, H. R., Barbieri, D. M., Wang, F., Bohne, R. A., Kristensen, T., & Passer, A. (2021). Life cycle assessment of roads: Exploring research trends and harmonization challenges. Science of the Total Environment, 759, 143506. doi:10.1016/j.scitotenv.2020.143506.

[55] Chong, D., Wang, Y., Dai, Z., Chen, X., Wang, D., & Oeser, M. (2018). Multiobjective optimization of asphalt pavement design and maintenance decisions based on sustainability principles and mechanistic-empirical pavement analysis. International Journal of Sustainable Transportation, 12(6), 461–472. doi:10.1080/15568318.2017.1392657.

[56] Cong, L., Guo, G., Yu, M., Yang, F., & Tan, L. (2020). The energy consumption and emission of polyurethane pavement construction based on life cycle assessment. Journal of Cleaner Production, 256. doi:10.1016/j.jclepro.2020.120395.

[57] Santos, J., Ferreira, A., & Flintsch, G. (2015). A life cycle assessment model for pavement management: Methodology and computational framework. International Journal of Pavement Engineering, 16(3), 268–286. doi:10.1080/10298436.2014.942861.

[58] Liljenström, C., Björklund, A., & Toller, S. (2022). Including maintenance in life cycle assessment of road and rail infrastructure—a literature review. International Journal of Life Cycle Assessment, 27(2), 316–341. doi:10.1007/s11367-021-02012-x.

[59] Huang, Y., Bird, R., & Heidrich, O. (2009). Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. Journal of Cleaner Production, 17(2), 283–296. doi:10.1016/j.jclepro.2008.06.005.

[60] Yu, B., & Lu, Q. (2012). Life cycle assessment of pavement: Methodology and case study. Transportation Research Part D: Transport and Environment, 17(5), 380–388. doi:10.1016/j.trd.2012.03.004.

[61] Yu, B., Lu, Q., & Xu, J. (2013). An improved pavement maintenance optimization methodology: Integrating LCA and LCCA. Transportation Research Part A: Policy and Practice, 55, 1–11. doi:10.1016/j.tra.2013.07.004.

[62] Chou, C. P., & Lee, N. (2013). A sensitivity study of RAP cost and performance on its life cycle benefits. Advanced Materials Research, 723, 567–574. doi:10.4028/www.scientific.net/AMR.723.567.

[63] Yu, B., & Lu, Q. (2014). Estimation of albedo effect in pavement life cycle assessment. Journal of Cleaner Production, 64, 306–309. doi:10.1016/j.jclepro.2013.07.034.

[64] Araújo, J. P. C., Oliveira, J. R. M., & Silva, H. M. R. D. (2014). The importance of the use phase on the LCA of environmentally friendly solutions for asphalt road pavements. Transportation Research Part D: Transport and Environment, 32, 97–110. doi:10.1016/j.trd.2014.07.006.

[65] Santos, J., Bryce, J., Flintsch, G., Ferreira, A., & Diefenderfer, B. (2015). A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. Structure and Infrastructure Engineering, 11(9), 1199–1217. doi:10.1080/15732479.2014.945095.

[66] Liu, R., Smartz, B. W., & Descheneaux, B. (2015). LCCA and environmental LCA for highway pavement selection in Colorado. International Journal of Sustainable Engineering, 8(2), 102–110. doi:10.1080/19397038.2014.958602.

[67] Mauro, R., & Guerrieri, M. (2016). Comparative life-cycle assessment of conventional (double lane) and non-conventional (turbo and flower) roundabout intersections. Transportation Research Part D: Transport and Environment, 48, 96–111. doi:10.1016/j.trd.2016.08.011.

[68] Chen, F., Zhu, H., Yu, B., & Wang, H. (2016). Environmental burdens of regular and long-term pavement designs: A life cycle view. International Journal of Pavement Engineering, 17(4), 300–313. doi:10.1080/10298436.2014.993189.
[69] Santos, J., Flintsch, G., & Ferreira, A. (2017). Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability. Resources, Conservation and Recycling, 116, 15–31. doi:10.1016/j.resconrec.2016.08.025.

[70] Moretti, L., Mandrone, V., D’Andrea, A., & Caro, S. (2017). Comparative “from cradle to gate” life cycle assessments of Hot Mix Asphalt (HMA) materials. Sustainability, 9(3), 400. doi:10.3390/su9030400.

[71] Liu, X., Cui, Q., & Schwartz, C. W. (2018). Introduction of mechanistic-empirical pavement design into pavement carbon footprint analysis. International Journal of Pavement Engineering, 19(9), 763–771. doi:10.1080/10298436.2016.1205748.

[72] Hong, F., & Prozzi, J. A. (2018). Evaluation of recycled asphalt pavement using economic, environmental, and energy metrics based on long-term pavement performance sections. Road Materials and Pavement Design, 19(8), 1816–1831. doi:10.1080/14680629.2017.1348306.

[73] Gulotta, T. M., Mistretta, M., & Praticò, F. G. (2019). A life cycle scenario analysis of different pavement technologies for urban roads. Science of the Total Environment, 673, 585–593. doi:10.1016/j.scitotenv.2019.04.046.

[74] Wang, H., Al-Saadi, I., Lu, P., & Jasim, A. (2020). Quantifying greenhouse gas emission of asphalt pavement preservation at construction and use stages using life-cycle assessment. International Journal of Sustainable Transportation, 14(1), 25–34. doi:10.1080/15568318.2018.1519086.

[75] Huang, M., Dong, Q., Ni, F., & Wang, L. (2021). LCA and LCCA based multi-objective optimization of pavement maintenance. Journal of Cleaner Production, 283. doi:10.1016/j.jclepro.2020.124583.

[76] Nascimento, F., Gouveia, B., Dias, F., Ribeiro, F., & Silva, M. A. (2020). A method to select a road pavement structure with life cycle assessment. Journal of Cleaner Production, 271. doi:10.1016/j.jclepro.2020.122210.

[77] Shi, X., Mukhopadhyay, A., Zollinger, D., & Grasley, Z. (2019). Economic input-output life cycle assessment of concrete pavement containing recycled concrete aggregate. Journal of Cleaner Production, 225, 414–425. doi:10.1016/j.jclepro.2019.03.288.

[78] Rosado, L. P., Vitale, P., Penteado, C. S. G., & Arena, U. (2017). Life cycle assessment of natural and mixed recycled aggregate production in Brazil. Journal of Cleaner Production, 151, 634–642. doi:10.1016/j.jclepro.2017.03.068.

[79] Braga, A. M., Silvestre, J. D., & de Brito, J. (2017). Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. Journal of Cleaner Production, 162, 529–543. doi:10.1016/j.jclepro.2017.06.057.

[80] Hossain, M. U., Poon, C. S., Lo, I. M. C., & Cheng, J. C. P. (2016). Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. Resources, Conservation and Recycling, 109, 67–77. doi:10.1016/j.resconrec.2016.02.009.

[81] Estanqueiro, B., Dinis Silvestre, J., de Brito, J., & Duarte Pinheiro, M. (2018). Environmental life cycle assessment of coarse natural and recycled aggregates for concrete. European Journal of Environmental and Civil Engineering, 22(4), 429–449. doi:10.1080/19648189.2016.1197161.