LCA WITH UNCERTAINTY ANALYSIS: LITERATURE REVIEW AND POTENTIAL APPLICATION IN BRAZILIAN FEDERAL HIGHWAYS

ACV COM ANÁLISE DE INCERTEZAS: REVISÃO DA LITERATURA E POTENCIAL EMPREGO NAS RODOVIAS FEDERAIS BRASILEIRAS

ACV CON ANÁLISIS DE INCERTIDUMBRE: REVISÓN DE LA LITERATURA Y POTENCIAL EMPLEO EN LAS CARRETERAS FEDERALES DE BRASIL

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ABSTRACT
The article offers a systematic review of the literature, highlighting recent advances in the use of Life Cycle Assessment Methodology (LCA) in highway projects, combining it with uncertainty analysis techniques. Considering the significant investments planned for the Brazilian federal road network in the coming years, it is essential that project solutions be developed with a view to mitigating their environmental impacts. However, Brazil faces challenges related to the availability and quality of environmental data on the main road inputs, in addition to the lack of use of the ACV methodology as a management tool for federal highways. The methodology used prioritized the search for scientific articles on the Web of Science database in the period between 2010 and 2023. The results highlight the main deficiencies and advances observed in the research and indicate alternatives for the development of a case study aiming to better investigate the feasibility of jointly using the LCA methodology with uncertainty analysis techniques in the national context.

KEYWORDS
Life cycle assessment; uncertainty; federal highways; Brazil.

RESUMO
O artigo oferece uma revisão sistemática da literatura, destacando os recentes avanços no uso da Metodologia de Avaliação do Ciclo de Vida (ACV) em projetos rodoviários, combinando-a com técnicas de análise de incertezas. Considerando os expressivos investimentos previstos para a malha rodoviária federal brasileira nos próximos anos, é essencial que as soluções de projeto sejam desenvolvidas visando mitigar os seus impactos ambientais. No entanto, o Brasil enfrenta desafios relacionados à disponibilidade e qualidade de dados ambientais dos principais insumos rodoviários, além da ausência de emprego da metodologia ACV como ferramenta de gestão das rodovias federais. A metodologia empregada priorizou a busca de artigos científicos na base de dados da Web of Science no período entre 2010 e 2023. Os resultados destacam as principais deficiências e avanços observados nas pesquisas, e indicam alternativas para o desenvolvimento de um estudo de caso visando melhor investigar a viabilidade do uso conjunto da metodologia ACV com técnicas de análise de incerteza no contexto nacional.

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PALAVRAS-CHAVE
Avaliação do ciclo de vida; incertezas; rodovias federais, Brasil.

RESUMEN
El artículo ofrece una revisión sistemática de la literatura, destacando los avances recientes en el uso de la Metodología de Evaluación del Ciclo de Vida (LCA) en proyectos de carreteras, combinándola con técnicas de análisis de incertidumbre. Considerando las importantes inversiones previstas para la red vial federal brasileña en los próximos años, es esencial que las soluciones del proyecto se desarrollen con miras a mitigar sus impactos ambientales. Sin embargo, Brasil enfrenta desafíos relacionados con la disponibilidad y calidad de datos ambientales en las principales entradas de carreteras, además de la falta de uso de la metodología ACV como herramienta de gestión de carreteras federales. La metodología utilizada priorizó la búsqueda de artículos científicos en la base de datos Web of Science en el período comprendido entre 2010 y 2023. Los resultados resaltan las principales deficiencias y avances observados en la investigación, e indican alternativas para el desarrollo de un estudio de caso con el objetivo de investigar mejor la viabilidad de utilizar conjuntamente la metodología ACV con técnicas de análisis de incertidumbre en el contexto nacional.

PALABRAS CLAVE
Evaluación del ciclo de vida; incertidumbres; carreteras federales, Brasil.

1. INTRODUCTION

Transport infrastructure plays a crucial role in the social and economic development of any nation and must be adequately planned to meet the growing demand for passenger and cargo mobility. The International Energy Agency (IEA) estimates that by 2050, global passenger and freight travel will double compare to 2010 levels, requiring the construction of nearly 25 million kilometers of new paved roads and cumulative investments totaling 45 trillion dollars (Dulac, 2013). In Brazil, in one of the scenarios simulated by the National Logistics Plan 2035 (PNL 2035), it is estimated that 246 billion dollars will be invested in transport infrastructure projects by 2035, with a return to growth in the Gross Domestic Product (GDP) of 11% (EPL, 2021).

However, the key role of the transportation sector is not limited to economic and social aspects; it also has a significant impact on the environment. It is estimated that approximately 25% of global CO2 emissions are attributed to the transportation sector, whose current rate is projected to grow by 60% by 2050 if appropriate measures are not taken to curb its expansion (WORLD BANK, 2021).

According to Diaz-Sarachaga et al. (2017), the influence of the transportation sector on the environment becomes even more relevant for emerging economies that are planning significant investments in the expansion and maintenance of their transportation infrastructure, such as Brazil. Brazil's transportation matrix is dominated by the road mode, with a total of approximately 1.72 million kilometers of roads at the federal, state and municipal levels. Out of this total, approximately 1.35 million kilometers consist of unpaved roads (78.5%), and another 157,000 kilometers are planned roads (9.1%), which, when combined, represent a potential of approximately 1.5 million kilometers of roads to be paved in the coming years (DNIT, 2023a).

In addition to the potential growth margin of the Brazilian road network, it is important to consider the existence of approximately 64,000 kilometers of paved federal highways, with a significant portion of this road network exhibiting service levels that require increasingly intensive and robust maintenance actions, including the replacement of some existing assets with new ones (Mello; Queiroz, 2017).

However, the National Department of Transport Infrastructure (DNIT), which is responsible for developing research and technical standards related to transportation infrastructure and for executing a significant portion of highways projects in Brazil, lacks a technical specification to characterize and quantify the environmental impacts associated with the engineering alternatives or solutions outlined in its project manuals (DNIT, 2023b). A difference in environmental impact between various possible pavement solutions, for example, can become a crucial criterion for selecting the project alternative to be implemented.

It can be observed that the challenge facing Brazil has two major interconnected aspects. The first is the need to increase and adequately maintain its road transportation infrastructure. The second aspect, related to Brazil's commitments made at the 27th Conference of the Parties (MMA, 2022) to achieve net-zero emissions of greenhouse gases, lies in the challenge of reconciling the advancements driven by road construction and maintenance with the negative impacts on the environment (Santero; Masanet; Horvath, 2011a; Santos et al., 2018a). The balance between these two challenges could be achieved with the Life Cycle Assessment (LCA) methodology (ABNT NBR ISO 14040, 2014; ABNT NBR ISO 14044, 2014) in Brazilian highways projects.

The effective implementation of LCA in Brazilian highways projects as a decision-support tool depends, however, on the availability and quality of environmental data associated with the production of supplies such as steel, cement and asphalt. According to Vigon et al. (2017), Brazil and other emerging countries have made significant advancements in LCA but still have product inventories with many shortcomings, such as incomplete documentation and the absence of review and validation of information by independent sources. Therefore, life cycle assessments of highways in Brazil should address not only the environmental impacts related to different design options, but also the implications in terms of uncertainty in LCA results due to the quality of environmental data for materials or products.

In this context, this study aims to identify the main findings from the international literature regarding the use of uncertainty analysis techniques in LCA studies and to analyze the characteristics of LCA studies in highways. The primary objective of this research is to evaluate the feasibility of applying the LCA methodology with uncertainty analysis to projects involving Brazilian federal highways.

2. METHODOLOGY

The research methodology adopted in this article is a Systematic Literature Review (SLR), which involves examining research and discussions carried out by other authors on the topic that will be addressed in this article (Galvão; Ricarte, 2020). It was conducted using the SLR methodology known as the Consolidated Meta Analytical Approach Theory (TEMAC) (Mariano; Rocha, 2017), and the analysis of the articles was divided into two subthemes, as shown in Figure 01.

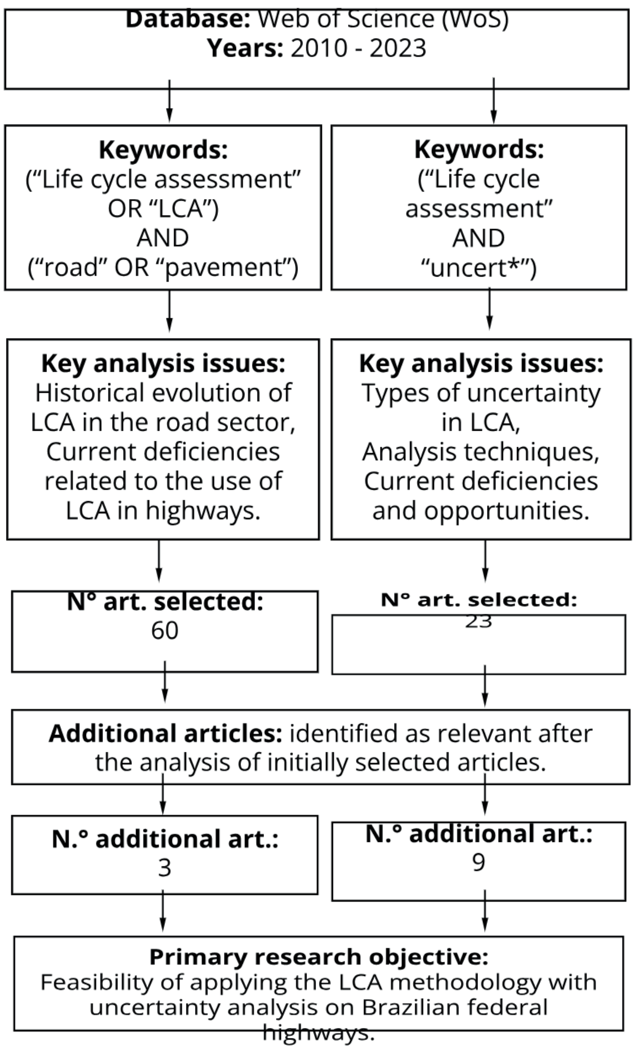

Figure 01: Flowchart of the systematic literature review.
Source: Authors.

Figure 01 depicts the process of scientific article research, conducted through the consultation of the Web of Science (WoS) database, covering the period from 2010 to 2023. This research was guided by two axes of keywords and fundamental questions, as detailed in the flowchart. Additionally, after the analysis of initially selected articles, it was identified that there was a need to evaluate articles deemed relevant to the subthemes, even if they were published before 2010. This resulted in a total of 63 articles related to the topic of LCA in highways or pavements (LCA in the road sector), along with 32 articles addressing LCA and uncertainties (LCA with uncertainties).

The systematic literature review will support the primary objective of this research.

3. RESULTS AND DISCUSSION

3.1. LCA in the road sector

The first records of studies related to the application of LCA methodology in the road sector date back to the late 1990s, with publications focusing on the construction of road pavements, including asphalt and concrete pavements, and on the extraction of raw materials from nature and the manufacturing of products (Stripple, 2001). However, the initial investigations of the literature revealed that research on LCA in highways lacked uniformity in terms of defining indicators, quantification, and objective assessment of the environmental impacts caused by the different phases of a highway's life cycle. These observations were initially made by Santero et al. (2011a, 2011b), who conducted one of the first and most comprehensive literature reviews on the environmental impacts of highways based on the methodology provided by the International Organization for Standardization (ISO) standards: ISO 14040 (2006a) and ISO 14044 (2006b). These publications summarize advances on the topic up to 2011. Other important publications have been made on the subject recently, also as literature reviews (Anthonissen; Van Den Bergh; Braet, 2016; Aryan; Dikshit; Shinde, 2023; Azarijafari; Yahia; Ben Amor, 2016; Hasan; Whyte; Al Jassmi, 2019; Inyim et al., 2016).

The current concept of the LCA methodology brings an approach based on the assessment of environmental impacts of a system that encompasses the life cycle of a product (systems and materials) or service (activity or process). Therefore, there is no direct association of this methodology with specific cases or study situations, with the evaluator defining the boundary conditions and applicable adaptations for each situation (FHWA, 2016). The stages and data flows (inputs and outputs) related to the typical life cycle stages of a road pavement are represented in Figure 02.

Figure 02 simplifies the discrepancies in pollutant emissions between the phases that make up the life cycle of a road infrastructure. The main impacts are associated with the operation or use, construction or manufacturing, and material processing phases. Additionally, it illustrates the various options for utilizing some materials after the end-of-life phase of the structures.

The environmental impact assessment process based on the LCA methodology is governed by the ISO

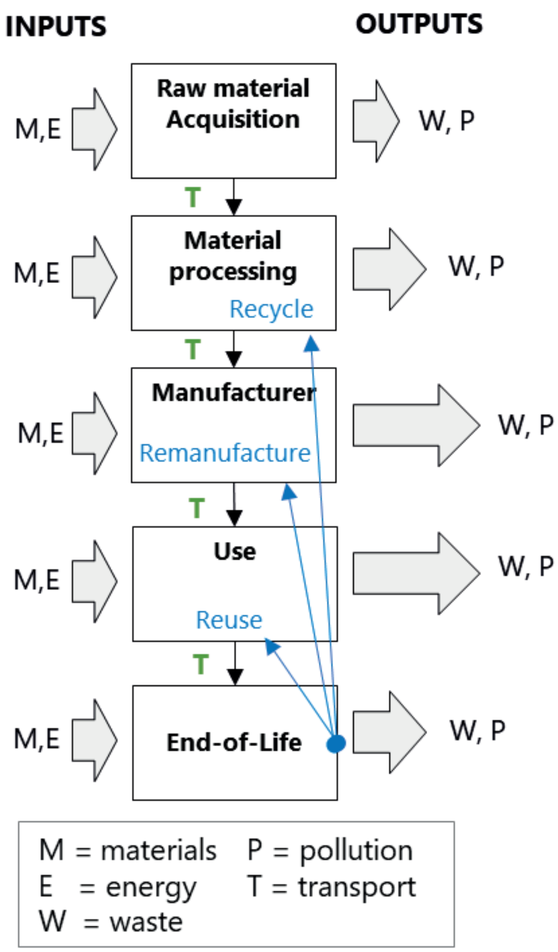

Figure 02: Typical phases of a road pavement.
Source: Adapted from Kendall (2012).

standards (14040 and 14044), incorporated by the Brazilian Association of Technical Standards through the ABNT NBR ISO 14040 (2014) and ABNT NBR ISO 14044 (2014) standards. According to these standards, an LCA study consists of four interrelated phases: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase.

However, despite recent advances in research related to the application of the LCA methodology in the transport sector, there are still several questions raised in the literature about how to implement it consistently for decision-making. Therefore, the next topics will detail the main findings in the literature on the application of LCA in the road sector, focusing on the goal and scope definition and inventory analysis phases, as they are the central basis of LCA studies.

3.1.1. The goal and scope definition

The methodological principles associated with the goal and scope stage encompass definitions such as the intended application, the rationales behind conducting the study, the intended audience, data and its prerequisites, system boundary, functional unit, allocation procedures, impact assessment methodology, types of impact, and limitations of the study (ABNT NBR ISO 14040, 2014).

The goals associated with highway LCA studies are numerous. Typically, comparative analyses are conducted between rigid pavements (Portland cement) and flexible pavements (asphalt cement), as exemplified by the studies conducted by Kucukvar and Tatari (2012), Batouli, Bienvenu and Mostafavi (2017), Boonpoke et al. (2018), and Nascimento et al. (2020). Out of the 63 publications that were analyzed, 11 (17%) contained this comparative analysis. Other research efforts were aimed at investigating the environmental impacts caused by different types of materials, mostly aimed at reducing the consumption of cement, natural aggregates, or asphalt (Anastasiou; Liapis; Papayianni, 2015; Chen; Wang, 2022; Osorto; Casagrande, 2023; Plati; Tsakoumaki, 2023; Selvam et al., 2021; Shi et al., 2019). Some studies conducted a combined evaluation of environmental impacts with economic and social aspects, a relatively recent and less represented approach in the sample of consulted publications (Choi et al., 2016; Gravina da Rocha et al., 2022; Zheng et al., 2019). Santos et al. (2018) assessed the environmental impacts of different pavement maintenance and restoration plans, focusing only on the combination with economic aspects. The studies conducted by Batouli et al. (2017) and Hong et al. (2018) also demonstrates the combination of LCA methodology with economic aspects in the analysis of different pavement solutions or scenarios.

The functional unit is of fundamental importance for the analysis of highway LCA results, as it is associated with the goal and scope definition phase. It is defined by ABNT NBR ISO 14040 (2014) as a reference for input and output data that is normalized. It provides a performance parameter for infrastructures that integrate highways. Therefore, it must have a measurable and comparable property.

Different functional units were used in the articles researched: linear extension-bearing tracks (Plati; Tsakoumaki, 2023); platform area (Chen et al., 2021); linear extension and average annual volume of vehicles (Jullien; Dauvergne; Cerezo, 2014) and pavement performance parameters, such as its longitudinal irregularity and permanent deformation (Jiang et al., 2020; Santos et al., 2018a; Xu et al., 2019). Nonetheless, it is evident that the absence of uniformity in the functional units employed in the selected research renders comparative analysis of the results impracticable, corroborating observations made in this regard by some authors consulted (Santero; Masanet; Horvath, 2011a; Xu et al., 2019).

The goal and scope phase of an LCA study also encompasses the definition of the analysis system, the establishment of geographic and temporal limitations, and the establishment of data quality prerequisites for the execution of the study. Regarding the latter, it is noteworthy that the characterization of qualitative parameters of environmental data utilized in highway LCA studies is uncommon, as is the analysis of the impact of uncertainties inherent in the input data on the results of the studies (Aryan; Dikshit; Shinde, 2023). In any case, the literature indicates that definitions related to the goal and scope phase are influenced by the availability and quality of available environmental data (Alam; Hossain; Bazan, 2022).

In relation to the delimitation of analysis systems in highway LCA studies, it was observed that many tools to support calculations offer previously defined systems and environmental databases. However, many of these tools are not used by entities linked to the transportation sector because they have systems with very broad limits, and which do not reflect the real situations linked to the design, construction, maintenance and operation stages of highways (Mattinzioli et al., 2020). The primary tools used in highway LCA studies are presented in Table 01, along with some of their characteristics.

Software	Owner/Country	Scope	LCA Phase	Database
MOVES	U.S.EPA USA	Road	T, U	N
INVEST	FHWA USA	Road	T, R, MP, C, U	N
BREEAM Infrastructure	BREEAM UK	Varied	T, R, MP, C, U	N, I
PaLATE	UC. Berkely USA	Road	T, R, MP, C, U	N
LCA Pave Tool	FHWA USA	Road	T, R, MP, C	N
Athena Pav. LCA	Athena Inst. USA CAN	Road	T, R, MP, C, U, E	N
SimaPro	PRéu Stainability/NL	Varied	T, R, MP, C, U, E	N, I
Carbon Gauge	TAGG AUS NLD	Road	T, R, MP, C, U	N, I
OpenLCA	Green Delta/DE	Varied	T, R, MP, C, U, E	N, I
asPECT	TRL UK	Road	T, R, MP, C, E	N, I

Acronyms: T – transport; R – raw material; MP – material processing; C – construction; U – use; E – end-of-life; N – national; I – international.

Table 01: The primary tools utilized in highway LCA studies.
Source: Authors.

Table 01 illustrates that the tools used to support highway LCA studies are concentrated in North America and Europe. Also shows that many of the tools use environmental data and engineering standards related to their country of origin, although some of them allow modifications to their technical premises or original databases, such as the Athena Pavement LCA software (Athena; Canada, 2018) and Carbon Gauge (Dilger et al., 2013).

Furthermore, the individual analysis of software with free access demonstrates that their methodological bases require, before any environmental calculation, the description of the service items (i.e., selection of equipment, materials and their respective quantities) necessary for the execution of the works, therefore the same basic routines for preparing an engineering budget. Because of this, the main difference between these LCA tools is that they add environmental data and environmental impact methodologies to traditional budgeting rules. This is evident in tools that jointly analyze the economic and environmental aspects associated with the construction of a highway, such as INVEST (Reid et al., 2018) and the LCA Pave Tool (Meijer et al., 2021).

In Brazil, the main methodological reference for developing budgets in transport infrastructure is the Reference Cost System for Works (SICRO) (DNIT, 2023c). In addition to establishing budget specifications, SICRO also follows the specifications of the Transport Research Institute (IPR/DNIT) in terms of project design and execution of road services, in addition to making details available in its database regarding the type of fuel and its average consumption by the various equipment used to carry out the works. Due to these specificities, SICRO could be an alternative for developing the methodological basis for LCA studies on Brazilian federal highways.

The publications consulted present significant variations in terms of the period and phases of the studies' life cycle, which must also be defined in the scope and objective definition stage. Research with similar scopes and objectives has significantly different analysis periods, such as the research developed by Mascarenhas et al. (2022) and Chen et al. (2018). Despite encompassing identical phases of the highways' life cycle, the research conducts investigations for useful life spans of structures of 20 and 40 years, respectively. In relation to the life cycle phases, it is possible to identify studies with the presence of systems that consider a single phase (Yu; Lu, 2014) or all phases of the life cycle of a highway (Zhang et al., 2010). Out of the 63 articles selected, 53 (84%) consider the phases of raw material extraction, transport, processing, construction, maintenance, or end-of-life in highway LCA studies. However, despite being considered one of the main contributors to the total emission of greenhouse gases (GHG) (Santero; Masanet; Horvath, 2011b), the use phase was considered in only 10 (16%) articles (Alam; Hossain; Bazan, 2022; Araújo; Oliveira; Silva, 2014; Jiang et al., 2020; Loijos; Santero; Ochsendorf, 2013; Santos et al., 2018b; Santos; Ferreira; Flintsch, 2015; Wang et al., 2012; Xu et al., 2019; Zhang et al., 2010; Zheng et al., 2019).

3.1.2. The life cycle inventory analysis

The second stage of LCA is Life Cycle Inventory Analysis (LCI). The ABNT NBR ISO 14040 (2014) standard clarifies that at this stage data collection and the definition of calculation procedures must occur with the purpose of quantifying the inputs and outputs of information classified as relevant to a given system. The data associated with a system's processes can be classified as follows: a) energy inputs, raw material inputs, auxiliary inputs, other physical inputs; b) products, co-products and waste; c) atmospheric emissions, discharges to water and soil, and d) other environmental aspects.

The databases used in LCA studies of road pavements are diverse, and for some phases (such as the extraction of raw materials from nature and manufacturing) there is a greater diversity of information sources available, such as those coming from entities public and private (ASTM INTERNATIONAL, 2023; CRSI, 2022; EUROBITUME, 2020; PCA, 2023) and literature publications themselves (Rosado et al., 2017; Stripple, 2001); while for the operation phase it is common to obtain data indirectly through calculation models, such as the total amount of GHG emitted into the atmosphere by motor vehicles, including variations depending on the functional conditions of the pavement over time (Santos et al., 2018a), and the albedo effect of pavements (Yu; Lu, 2014). The Figure 3 provides a comprehensive overview of the main sources of free and accessible environmental databases, both national and international, that can be used to conduct LCA studies on highways.

Figure 3 illustrates the difference between the number of environmental data sources available in developed and developing countries. This disparity also highlights deficiencies in the establishment and utilization of regional environmental bases by emerging nations, such as Brazil, Malaysia and Thailand, which possess

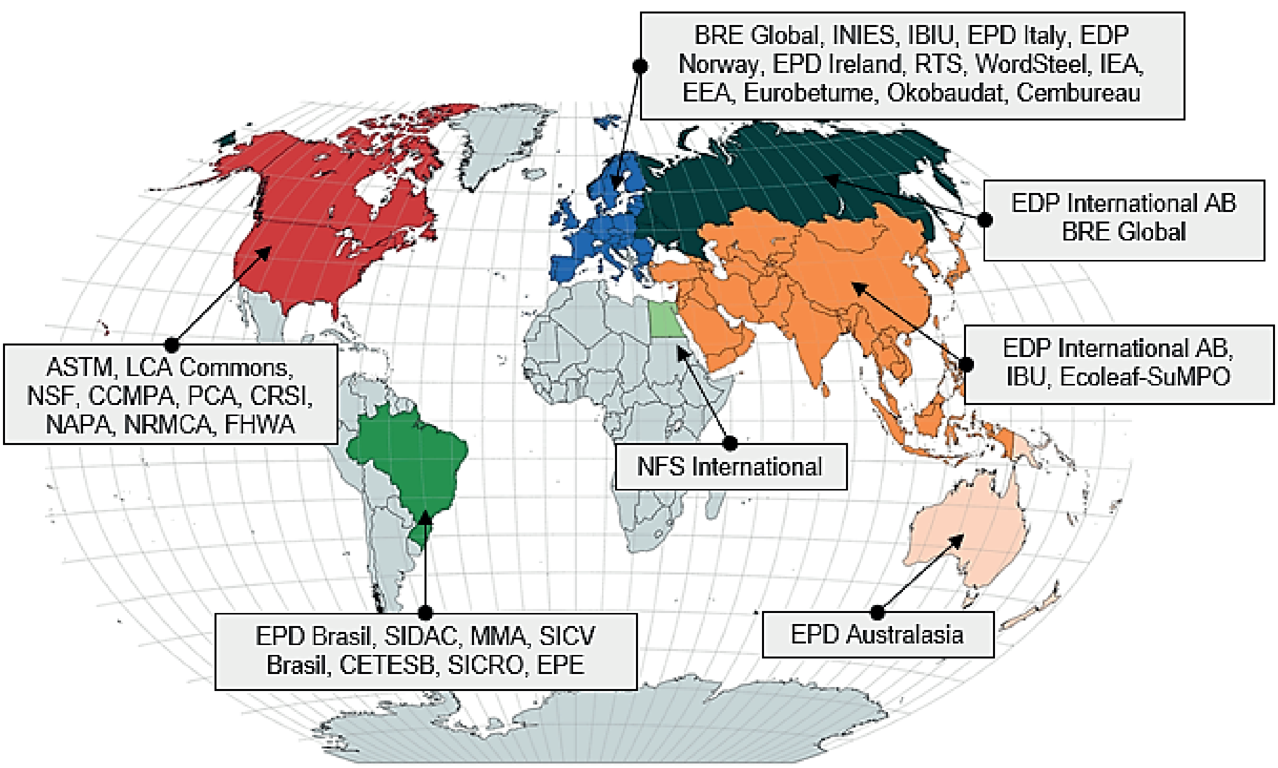

Figure 03: Example of countries with free and accessible environmental databases.
Source: Authors.

inventories that lack a comprehensive account of the assumptions adopted and their validation by an independent source (Vigon et al., 2017).

The availability of environmental information related to the production of the main components or materials used in road infrastructure was limited for the Brazilian context. However, it is possible to note that public national sources that have self-declared inventory data in accordance with the standards ABNT NBR ISO 14040 (2014) and ABNT NBR ISO 14044 (2014), such as the Construction Environmental Performance Information System (SIDAC) (Belizario et al., 2022), the Environmental Product Declarations (EPD) published by companies operating in the national Portland cement and steel production sector (INTERNATIONAL EPD®, 2023), and the National Bank of Life Cycle Inventories of Brazilian Products (SICV Brasil) (IBICT, 2023).

Other sources of information with public access may also be applicable to highway LCA studies, such as the SICRO equipment performance parameters (DNIT, 2023c), already highlighted, and the vehicle emissions reports published by the Environmental Company of the State of São Paulo (CETESB) (BRUNI et al., 2022).

The public availability of environmental databases represents an important advance for LCA studies conducted in Brazil, but it is still insufficient for the development of a study that covers all the materials contained in an executive road engineering project, the quantity of which can exceed 150 different types of inputs (DNIT, 2022). One way to increase environmental information on inputs produced in the Brazilian economy would be the creation of new EPD's, whose editing and validation process is regulated by the Brazilian Life Cycle Assessment Program (PBACV) (MDIC, 2016), with the National Institute of Metrology, Quality and Technology (INMETRO) being one of the main public agents responsible for conducting this program. However, according to INMETRO (INMETRO, 2023), there is still no EPD published within the scope of PBACV, which is partly due to difficulties related to the lack of interest from the private sector. This indicates the need to evaluate new government actions to encourage the development and use of EPD in Brazil.

The lack of environmental data on products from the Brazilian economy has led to the partial or complete use of data from other countries in national highway LCA research, as shown in Table 02.

Table 02 shows that national highway ACV research uses data on the production of inputs such as cement, steel and bitumen from Europe and the United States, while the main sources of environmental data in Brazil are the EPE

Author	Phase ACV	Environmental databases		
		Brazil	EUA	Europe
(Osorto; Casagrande, 2023)	R, MP, T, C	EPE, SICRO	U.S. EPA	
(Luvizão; Trichês, 2023)	R, MP, T, U	SICRO		Ecoinvent
(Gravina da Rocha et al., 2022)	R, MP, T, C			Ecoinvent
(Mascarenhas et al., 2022)	R, MP, T, C	EPE, SICRO		Ecoinvent Eurobitume
(DONATO et al., 2022)	R, MP, T, C			Ecoinvent
(GRAEL et al., 2021)	R, MP, T, C	EPE		Ecoinvent
(PILGER et al., 2020)	R, MP, T, C	EPE		Ecoinvent
(NASCIMENTO et al., 2020)	R, MP, T, C			Ecoinvent
(ROSADO et al., 2017)	R, MP, T, C	EPE	USLCI	Ecoinvent
(SAVIETTO, 2017)	R, MP, T, U, E	SICRO	USLCI	

Acronyms: T– transport; R– raw material; MP– material processing; C– construction; U– use; E– end-of-life; EPE– Empresa de Pesquisa Energética; EPA- U.S. Environmental Protection Agency; US LCI- U.S. Life Cycle Inventory Database.

Table 02: LCA research of highways in Brazil, with the phases and some environmental databases considered.
Source: Authors.

(energy matrix) and parameters operation of SICRO equipment. However, in some research, it is difficult to determine whether the data obtained from the Ecoinvent database is specific to Brazil, related to other countries or generic.

Furthermore, it was found that the use of foreign data in these research is not accompanied by the assessment of the uncertainties inherent to this type of boundary condition. Another observation is that national studies focus on comparing different paving solutions and the use of alternative materials, such as recycled asphalt and recycled aggregates, in pavement structures. National research is concentrated in the phases of extracting raw materials from nature, manufacturing, transport and construction.

A striking characteristic of both national and international highway LCA studies is the absence of analyses that encompass all aspects of a road infrastructure, including bridges, earthworks and drainage, i.e., services that extend beyond the layers of a pavement.

3.2. LCA and uncertainties

The ABNT NBR ISO 14040 (2014) standard defines uncertainty analysis in LCA studies as a systematic procedure to quantify the uncertainty introduced into the results of a life cycle inventory analysis due to the cumulative effects of model inaccuracy, input uncertainty and data variability. The standard also highlights that the quantification of uncertainty can be determined through the probability distribution or probability ranges of the results, without, however, presenting more details on how to use this technique in LCA studies.

Although it also does not provide a calculation procedure to quantify uncertainty in LCA studies, the ABNT NBR ISO 14044 (2014) standard recommends that the results be accompanied by sensitivity analysis and quantification of uncertainties in cases of comparative studies. This same recommendation is contained in the ILCD Handbook (EUROPEAN COMMISSION, 2010).

Although there are no standards to quantify uncertainties in LCA, it is possible to note in the literature research that is dedicated to the topic and that can be divided into two groups. The first aims to establish concepts and procedures for the characterization, quantification and analysis of uncertainties in LCA, without necessarily involving a specific field of application, but focusing on the assessment of uncertainties in inventory data (Canter et al., 2002; Kennedy; Montgomery; Quay, 1996; Weidema B. P. et al., 2013). The second group is correlated with the application of the principles outlined by the initial group in LCA case studies. Table 03 shows examples of life cycle assessment studies in the road and civil construction areas, as well as the connection between these groups and the studies.

Table 03 shows that, irrespective of the sector in which the LCA study is being utilized, such as roads or civil construction, the conceptual references utilized to quantify uncertainties are essentially identical, albeit some of them have been published for more than 20 years.

Among the articles initially selected (23), at least one of the authors from "Group 1" in Table 3 was utilized to substantiate or elaborate on the methodology employed for evaluating the uncertainties of the studies.

3.2.1. Types and sources of uncertainty

According to Lloyd and Ries (2007), uncertainties in LCA studies can be divided into three types: parameter, scenario, and model. This division represents activities of a typical modeling process, such as defining input data, selecting analysis scenarios, and building the mathematical model. The uncertainties attributed to these three categories are detailed below:

Area	Group 1 Definition of concepts	Group 2 Use of concepts
Road	(Weidema, 1998; Weidema B P et al., 2013)	(Abed et al., 2023)
	(Canter et al., 2002; Lloyd; Ries, 2007; Mark A.J. Huijbregts et al., 2001; Weidema, 1998)	(Yoo; Ozer; Ham, 2019)
Civil construction	(Canter et al., 2002; Huijbregts; Wim Gilijamse; Lucas Reijnders, 2003; Maurice et al., 2000; May; Brennan, 2003; Pedersen Weidema;	(Hong et al., 2016)
	Suhr Wesnaes, 1996; Weidema, 1998)	
	(Huijbregts, 1998; Lloyd; Ries, 2007; Mark A.J. Huijbregts et al., 2001; Pedersen Weidema; Suhr Wesnaes, 1996; Weidema B P et al., 2013)	(Baiochi; Silva, 2021)

Table 02: Example of LCA studies with quantification of uncertainties (Group 2) and the main references used in research (Group 1).
Source: Authors.

a) models' uncertainties: involve the mathematical models and characterization factors used in the life cycle impact assessment phase to express reality (IPCC, 2006);
b) scenario uncertainties: refer to choices related to the construction of scenarios, such as the functional unit, allocation procedures, weight of emission factors and time horizons (Huijbregts, 1998), and
c) parameter uncertainties: related to inventory data and can be characterized as: data inaccuracy; lack of data; data gaps; non-representative data; temporal variability; spatial variability, and technological variability (Huijbregts, 1998; Lloyd; Ries, 2007; Pedersen Weidema; Suhr Wesnaes, 1996; Weidema, 1998).

Despite the types of uncertainty mentioned, it is possible to note that some of the recent publications that deal with the quantification of uncertainties in highway LCA do not present clear definitions regarding the type (whether model, scenario, or parameter) and the sources of uncertainty that are being considered in the research, as shown in Table 5. According to Gregory et al. (2016), scenario and parameter uncertainties are often analyzed together when they should be analyzed separately. The studies carried out by Azarijafari, Yahia and Amor

(2018) and Ziyadi and Al-Qadi (2019) are specific cases of highway LCA in which the types of uncertainty were defined and evaluated individually.

The literature also shows that research on highway LCA has focused mainly on evaluating parameter uncertainties using sensitivity analysis techniques, data quality index and probabilistic simulation (Abed et al., 2023; Bressi; Primavera; Santos, 2022; Cao et al., 2019; Mattinzioli et al., 2021; Umer et al., 2017; Yoo; Ozer; Ham, 2019). According to Ziyadi and Al-qadi (2019), the complex task of measuring uncertainties related to the model and the scenario makes it difficult to establish systematic methodologies for their quantification, possibly contributing to the scarcity of research in the road area that addresses such types of uncertainties.

Table 04 presents the relationship between the LCA phases, the main types of uncertainty and the techniques used for their evaluation or reduction, while Table 5 presents some of the characteristics of the LCA studies of highways in which uncertainties were quantified and analyzed.

4. CONCLUSION

The study in question was conducted using an SRL with the main objective of evaluating the feasibility of applying the LCA methodology with uncertainty analysis techniques to projects involving Brazilian federal highways. In this sense, the methodology used proved to be adequate, as it made it possible to identify the advances and knowledge gaps in the subject with the indication of alternatives that can be applied to the national context.

Research on LCA of highways is focused on the investigation of the environmental impacts of the phases of extraction of raw material from nature, manufacturing, transport and construction of road pavements. This is a striking feature in national research, in addition to the preponderance of analyses aimed at comparing rigid and flexible pavement solutions, combined or not with the use of alternative materials. However, the phase of operation or use of the highway, indicated by some authors consulted as the main responsible for the total GHG of road infrastructures, was little explored in the research (16%). Elements of road infrastructure such as bridges and drainage devices, and earthmoving services are little explored in LCA studies of highways.

Another striking feature is the lack of uniformity in relation to the functional units used in LCA studies, which hinders the comparative analysis of the published results. This same observation was made in 2011 by Santero, Masanet and Horvath (2011a), and remains in the most recent research.

Regarding the availability of environmental data, especially of basic inputs such as cement, steel and bitumen, it was found that the main sources of information with free access are concentrated in North America and Europe. Brazil still has a limited number of environmental data on inputs produced in its economy. Despite the advancements observed, such as the establishment of the public database SICVBrasil and the Program PBACV, the environmental data of Brazilian products currently available is insufficient for the LCA study of a road construction project, where the number of inputs can exceed 150 (DNIT, 2022).

The lack of environmental information on Brazilian inputs explains the use of data from foreign products in national surveys (Table 2). As a highlight, the operational parameters of the SICRO equipment and the data published by EPE (energy matrix) are the main sources of national information. However, despite the use of foreign data in national studies, the quantification and analysis of the uncertainties related to this type of boundary condition was not verified.

The analysis of the main software used in the LCA of highways shows that they have the basic rules of preparation of a traditional road budget, with the inclusion of environmental data of the inputs and methodologies of environmental impact. In this sense, it was identified that SICRO can be a national alternative for the development of LCA calculation models for highways projects, especially because it contemplates the IPR/DNIT project design parameters and the operating parameters of the equipment used in field services.

Regarding the combined use of the LCA methodology with uncertainty analysis, it was found that the main conceptual references used in recent research are practically the same, although some of them exceed 20 years of publication. The uncertainties in LCA studies are divided into three groups: model, scenario and parameter.

LCA studies are focused on the investigation of parameter uncertainties with the use of techniques such as sensitivity analysis, data quality index and probabilistic simulation. It was also identified a lack of studies dedicated to the quantification of model and scenario uncertainties, may be a motivation for new research on the theme LCA of highways.

No national surveys were identified in the road sector with the joint application of LCA and uncertainty analysis techniques.

Given this context, it can be concluded that the

Types of uncertainty	LCA Phases		
	Purpose and scope	Inventory	Impact assessment
Inaccuracy of data		✓ P, MQD, IQD, MA, AS, AHP, ED, EB, SMP	✓ P, MQD, IQD, MA, AS, AHP, ED, EB, SMP
Lack of data		✓ RBD, EP, MA, RC	✓ RBD, EP, MA, RC
Data gap		✓ RBD, EP, MA, RC	
Non-representative data		✓ RBD, MQD, IQD, MA, RC, AS, AHP, MC	
Temporal variation		✓ MD, AS, AHP, ED, EB, MC	✓ MD, AS, AHP, ED, EB, MC
Spatial variation		✓ MD, AS, AHP, ED, EB, MC	✓ MD, AS, AHP, ED, EB, MC
Technological variation		✓ MA, AS, AHP, ED, EB, MC	✓ MA, AS, AHP, ED, EB, MC
Scenario	✓ RC, AS, AHP	✓ RC, AS, AHP	✓ RC, AS, AHP
Model		✓ MD, AS, AHP, MC	✓ MD, AS, AHP, MC
Techniques to reduce or assess uncertainty in LCA			
RC – Critical review	It ensures that the methods, data and interpretations used are appropriate and reflect the objectives of the study.		
P – Standardization	Adopting sets of predefined procedures has the potential to increase the reliability of studies and reduce errors.		
AHP – Hierarchical analysis	It offers the possibility of assigning different weights to the data, reflecting the relative importance of the data as a function of the greater or lesser potential of its environmental impact, or the different uncertainties associated with them.		
SMP – Probabilistic Simulation	Used to estimate the range and probability of the possible values of a study based on the propagation of the uncertainties of the input data in the result.		
RBD – Database review	It allows the identification of possible factors that may impair the quality of the study, such as measurement errors, or the identification of other databases with better quality or that are more appropriate to the situation under study.		
MQD – Data Quality Goals	It lists the desirable qualitative characteristics for the input data of the LCA study.		
ED – Basic descriptive statistics	It encompasses the analysis of data with the aid of classical statistics, such as: mean, median, standard deviation and variance.		
EB – *Bayesian Statistics*	Some subjective uncertainties can follow a frequency of occurrence and be treated with the use of basic statistics.		
MC – Scenario Modeling	The evaluation of different scenarios allows us to observe the reflections of the choices in the results of the LCA study.		
AS – Sensitivity analysis	Recommended to identify which input data have the greatest contribution to the uncertainty of the result, as well as what the effects on the results of a study are as a function of the methods and data selected.		
MD – Detailed models	Improving the structure of the models and their parameterization can result in a better understanding and characterization of errors.		
MA – Additional measures	The random errors of a sample can be reduced by increasing the number of measurements.		
EP – Parameter estimation	Data obtained from literature references or estimated based on processes of similar systems.		
DQI – Data Quality Index	Parameters assigned to the inventory data and that allow to measure its overall quality.		

Table 04: Relationship between LCA phases, types of uncertainty and techniques for their assessment or reduction.
Source: IPCC (2006), Hujibregts (1998) and ABNT NBR ISO 14044 (2014).

Ref.	Country	Phases ACV	Goal	Uncertainty				
				Parameter	Scenario	Model	Analysis technique	*Software*
(ABED et al., 2023)	England	MP, C, U, F	Quantify and incorporate uncertainties associated with the durability of the asphalt pavement surface in LCA results.	✓			Sensitivity Monte Carlo¹ Statistics	SimaPro
(BRESSI; SPRING; SANTOS, 2022)	Italy	MP	Compare environmental impacts between rigid and flexible pavement solutions with uncertainty analysis.	✓	*		Sensitivity Monte Carlo¹	N.A.
(MATTINZIOLI et al., 2021)	Spain	MP, C	To investigate the influence of data variability and uncertainty on LCA results of asphalt pavements.	✓	*		Sensitivity Monte Carlo¹	N.A.
(CAD et al., 2019)	China	MP, C, R, F	LCA study with uncertainties in the comparative analysis of asphalt pavement solutions with tire residues.	✓			Sensitivity Monte Carlo	N.A.
(ZIYADI; AL-QADI, 2019)	Germany	U	Establish a LCA study methodology with the individualized analysis of different types of uncertainty and apply it in a case study of highway operation.	✓	✓	✓	Monte Carlo¹ Machine L. Bayesian Sensitivity	N.A.
(YOO; OZER; HAM, 2019)	USA	MP	Quantify the uncertainties and environmental impacts in the main pavement construction processes.	✓	*		AHP Monte Carlo¹	SimaPro
(YU; LIU; GU, 2018)	China	MP	Calculate the consumption of primary energy in the production of paving materials with the inclusion of uncertainties in the results.	✓	*		AHP Monte Carlo¹	Crystal Ball
(AZARIJAFARI; YAHIA; LOVE, 2018)	Canada	MP, C, R, F	To evaluate the individual and combined effects of data uncertainty and variability in the LCA comparison of rigid and flexible pavements.	✓	✓		Sensitivity Monte Carlo¹	SimaPro
(UMER et al., 2017)	Canada	R	Evaluate the environmental impacts and costs of three types of pavements with the quantification of uncertainties.	✓			Fuzzy	N.A.
(LIU; WANG; LI, 2017)	China	MP, C	Quantify CO2 emission with uncertainties for different rigid and flexible pavements.	✓	*		Statistics	N.A.
(GREGORY et al., 2016)	USA	MP, C, R, F	Propose a LCA methodology with uncertainties and apply it in a pavement case study.	✓			Monte Carlo¹ Sensitivity	N.A.
(NOSHADRAVAN et al., 2013)	USA	R	LCA analysis between rigid and flexible floors with the quantification of uncertainties of the input data.	✓			Monte Carlo¹	N.A.

Table 05: Highway LCA studies with uncertainty quantification and analysis.
Source: Authors.
Note: (1) Data quality index and probabilistic simulation techniques were combined.
(*) Type of uncertainty that was not explicitly stated, but there is doubt as to its consideration in the study;
N.A: Information not shown.

application of the LCA methodology with uncertainty analysis in projects of Brazilian federal highways appears to be possible, especially when considering the stages of extraction of raw material from nature, manufacturing, transportation and construction, phases of the life cycle of highways with more expressive advances in terms of national LCA research. Furthermore, due to the limitations associated with the availability and quality of environmental data on local road inputs, it is important to develop research that considers the uncertainties of the input parameters of national studies. The impacts in terms of variability of the results of the LCA study can be significant, depending on the quality and origin of the data.

However, for a definitive conclusion on the technical feasibility of using the LCA methodology with uncertainty analysis, it is crucial to advance in additional research in the area, preferably with case studies that incorporate DNIT's executive highways projects, including all its service families, and not only the inputs and services related to the pavement.

Finally, this article presents elements that can be used as starting points for the development of new research on the subject at the national level.

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