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LIFE CYCLE ASSESSMENT OF FREIGHT RAILROADS: A CRITICAL ANALYSIS AND GUIDELINE PROPOSAL

AVALIAÇÃO DO CICLO DE VIDA DE FERROVIAS DE CARGA: UMA ANÁLISE CRÍTICA E UMA PROPOSTA DE DIRETRIZ

EVALUACIÓN DEL CICLO DE VIDA DE LOS FERROCARRILES DE MERCANCÍAS: ANÁLISIS CRÍTICO Y PROPUESTA DE DIRECTRICES

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ABSTRACT

This study conducts a review of several articles inside the context of railroads, where the life cycle assessment methodology (LCA) is applied. Using the ProKnow-C methodology, seven review and 85 original papers applying the LCA methodology to railroads are analyzed, and several important gaps were identified, mainly concerning the lack of disclosure of information about parameters, software and other important decisions made during the works that would allow other researchers to replicate the results in order to compare them to other railroads or different circumstances. Currently, there are no ISO standards addressing the LCA of railroads, so this work seeks to provide an initial set of guidelines facilitating the elaboration of such a norm and providing support and direction for researchers in the field.

RESUMO

Este estudo realiza uma revisão de vários artigos no contexto de ferrovias, em que a metodologia de avaliação do ciclo de vida (LCA) é aplicada. Usando a metodologia ProKnow-C, foram analisados sete artigos de revisão e 85 artigos originais que aplicam a metodologia de ACV a ferrovias, e foram identificadas várias lacunas importantes, principalmente no que diz respeito à falta de divulgação de informações sobre parâmetros, software e outras decisões importantes tomadas durante os trabalhos que permitiriam a outros pesquisadores replicar os resultados para compará-los com outras ferrovias ou circunstâncias diferentes. Atualmente, não há normas ISO que abordem a ACV de ferrovias, portanto, este trabalho busca fornecer um conjunto inicial de diretrizes, facilitando assim a elaboração de tal norma e fornecendo suporte e orientação para pesquisadores da área.

RESUMEN

Este estudio realiza una revisión de varios artículos dentro del contexto de los ferrocarriles, en los que se aplica la metodología de la evaluación del ciclo de vida (ECV). Utilizando la metodología ProKnow-C, se analizan siete artículos de revisión y 85 originales que aplican la metodología del ACV a los ferrocarriles, y se identifican varias lagunas importantes, principalmente relativas a la falta de divulgación de información sobre parámetros, software y otras decisiones importantes tomadas durante los trabajos que permitirían a otros investigadores replicar los resultados para compararlos con otros ferrocarriles o circunstancias diferentes. Actualmente, no existen normas ISO que aborden el ACV de los ferrocarriles, por lo que este trabajo pretende proporcionar un conjunto inicial de directrices, facilitando así la elaboración de dicha norma y proporcionando apoyo y orientación a los investigadores en este campo.

INTRODUCTION

Freight railroads are three to four times more fuel efficient than trucks on average, which means that moving freight by train instead of truck can reduce greenhouse gas (GHG) emissions by up to 75% (Association of American Railroads, 2023). Although railroads are environmentally friendly when compared to other transport modes, their construction, operation, maintenance, and demolition impacts on the environment can still be significant (Dincer & Zamfirescu, 2016; Fridell, Bäckström, & Stripple, 2019). Therefore, the whole lifecycle of railroads should be considered when evaluating their environmental performance, accounting for the inputs and outputs of all phases, and LCA is a tool that helps achieve this goal.

The LCA methodology is a recognized tool for scientifically assessing the impact of human activity from an environmental point of view (Baitz et al., 2013) , taking into consideration the whole life cycle of a system or product (Vieira, Calmon, & Coelho, 2016). The boundary expansion, enabled through the LCA, helps keep the impacts from each production stage separated (Zang, Li, Wang, Zhang, & Xiong, 2015).

Although there are many ISO standards for applying LCA to different fields, such as ISO 13315-1:2024 or ISO 13315-2:2014, which contains guidelines specifically for concrete applications and its environmental impacts, there are no ISO standard for the environmental management of railroads. There are, however, ISO standards regulating railroad infrastructure, operations and rolling stock. Examples include ISO 23054-1:2022, which concerns track geometry; ISO 4975:2022, which covers braking systems; and ISO 22888:2020, which includes concept definitions and basic requirements for railway operations planning in the event of earthquakes. ISO standards can be thought of as formulas that describe the best way of doing something: it could be about making a product, managing a process, delivering a service, or supplying materials – standards cover a huge range of activities. They are elaborated by the International Organization for Standardization, which is an international standard development organization composed of representatives from the national standards organizations of member countries. Therefore, there are no guidelines for papers on how to manage and present fundamental environmental information about railroads, which would facilitate comparison among different studies in the field.

In this study, a few review papers in the field of LCA applied to railroads have been considered, even though they do not count with a common review method between them, and each one covers a determinate subdivision of the railroad theme. For instance, Jiang, Wan, Yang, and Zhang (2021) explored the impacts of high-speed rail projects on CO_2 emissions due to modal interactions; Xiao, Cai, Lou, Shi, and Xiao (2021) focused on the application of asphalt-based materials in railway systems; Olugbenga, Kalyviotis, and Saxe (2019) analyzed exclusively embodied emissions in rail infrastructure; Dincer and Zamfirescu (2016) reviewed novel energy options for cleaner rail applications; and Du and Karoumi (2014) researched the LCA framework applied to railroad bridges.

Since a railroad system comprises several subsystems, most published papers focus on one specific subsystem, such as infrastructure, operation, bridges, rolling stock, or design.

Through the results obtained from the analysis carried out in this study, a guideline is proposed, which intends to facilitate future works on the field by bringing forth a set of common procedures to be followed by researchers. An LCA study involves many subjective decisions because, for instance, the analyst is free to determine boundaries and goals. Therefore, guidelines will help overcome some areas of disparity in the field, such as the selection of representative functional units, sensitivity analysis parameters and methods.

METHODOLOGY

SYSTEMATIC REVIEW METHODOLOGY

To ensure the non-bias and relevance of the results, the literature review was based on the constructivist knowledge development process (ProKnow-C) methodology developed by Ensslin, Ensslin, Lacerda, and Tasca (2010). The ProKnow-C process comprises four steps: (a) selection of a portfolio of articles on the research topic; (b) bibliometric analysis of the portfolio; (c) systemic analysis; and (d) definition of the research question and research objective) (Ensslin et al., 2010). The first step consists of selecting a portfolio of articles aligned with the topic of interest to the researcher and with scientific recognition; in this case, the topic is LCA applied to railroads. In the second stage, the bibliometric analysis is carried out when the methods proposed by Aria and Cuccurullo (2017) and Pagani, Kovaleski, and Resende (2015) are used. In the third stage, a systematic analysis is carried out to identify existing gaps in the current state of the topic, which will help identify opportunities for new studies. Finally, in the fourth and final stage, the purpose of the research is defined, and its goal, scope and objectives are set - Vaz, Tasca, Ensslin, Ensslin, and Selig (2012).

The classification equation proposed by the Methodi Ordinatio is called InOrdinatio and consists of a “Multiple Criteria Decision Analysis” (MCDA) method for classifying papers:

$$InOrdinatio = \alpha * IF + \beta * [10-(Research\ Year - Publication\ Year)] + \gamma * Ci \quad (1)$$

Where:

α = Impact Factor Weight. Originally 1.

IF = JCR Impact Factor of the journal where the article was published.

β = Weight of the most recent publication. Usually 1, ranging from 1 to 10.

γ = Weight of the number of citations of the paper. Originally 1.

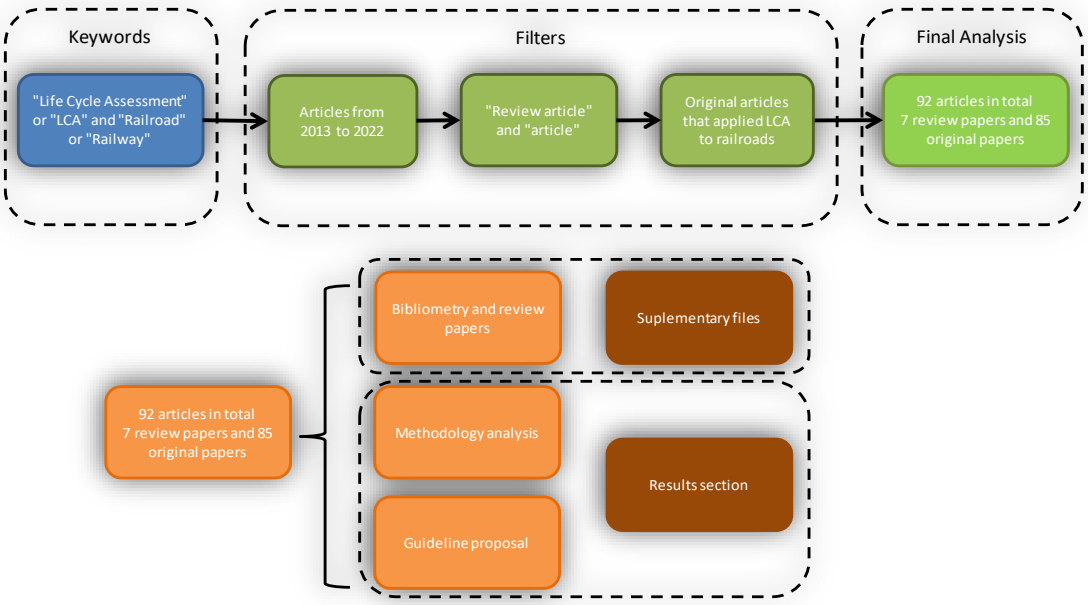
Ci = Number of Citations of the paper.

Web of Science and Scopus were selected as the repositories for the review, being relevant and well known by the scientific community. The keywords used for the research were ‘life cycle assessment’ or ‘LCA’ and ‘railroad’ or ‘railway’. To ensure the novelty of the research, the review considered results from the years 2013 to 2022.

Bibliometric Analysis

The search results consisted of 215 articles, and after the duplicates were removed, 194 articles remained. After the abstracts were read, papers mentioning LCA but which did not apply on railroads were excluded, resulting in 85 original and 7 review papers (Figure 1). Next, papers were classified by the type of railroad they discussed, such as metro, highspeed, freight, passenger, or heavy haul. From that classification, the researchers identified that most of the papers (58%) related to passenger transportation and only 4% to heavy haul railroads. This shows a gap in the literature, providing opportunities for new research in the field.

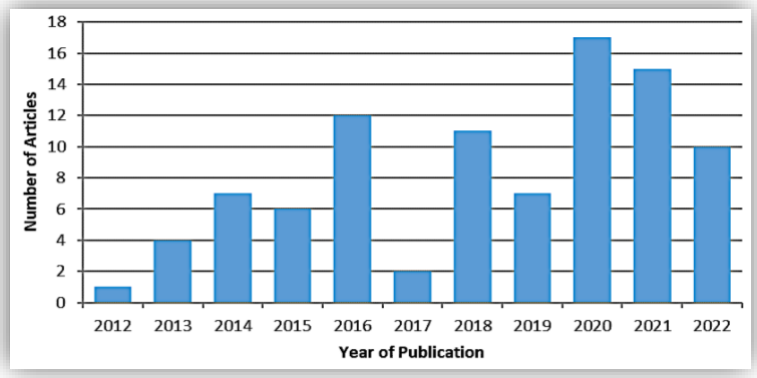
Figure 1. Paper selection methodology



Source: Research data (2023).

Knowledge of articles' publication year is essential to correlate the patterns with events in the scientific field. The recent growing interest of researchers in LCA applied to railroads resulted in the increase of published literature available. Almost half (46%) of the papers were published between 2020 and 2022, while 13% were published between 2012 and 2014 (Figure 2), which shows an increase in studies in the field. The average number of publications per year was eleven (11).

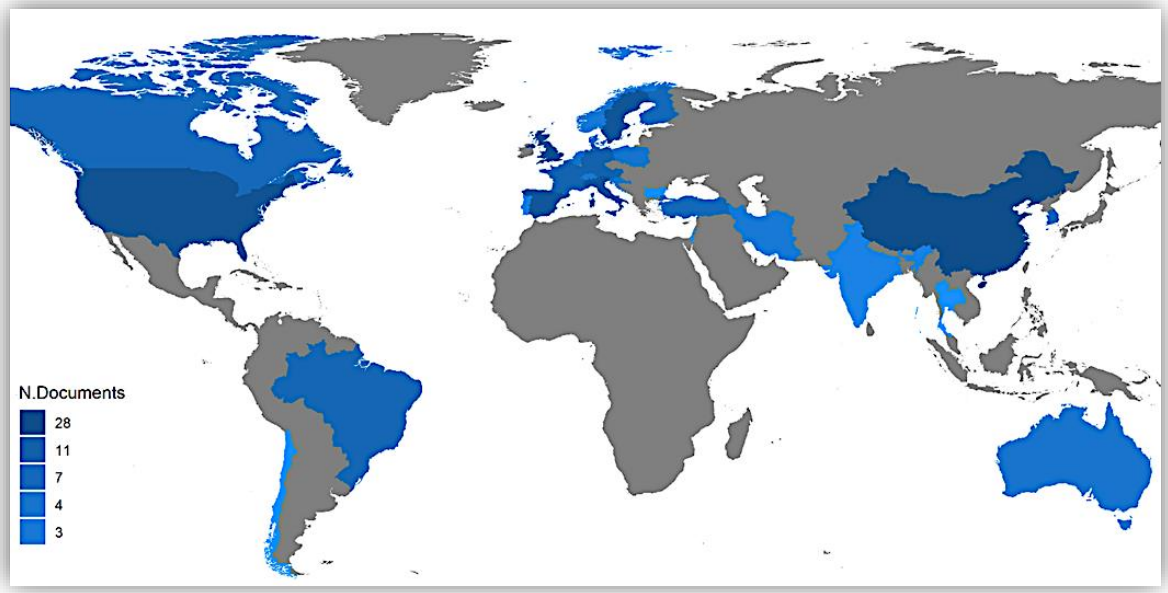
Figure 2. Publications by year



Source: Research data (2023).

In terms of the country of the lead author, China has the highest percentage of papers among the selected publications (14.44%), followed by the USA and the UK with 11.34% each (Figure 3). Most publications come from Asia, North America and Europe, or developed countries in other regions.

Figure 3. Publications per country according to lead author nationality



Source: Research data (2023).

Seven review articles were identified during the literature search. The articles present overviews on LCA applied to railroads in the literature, including topics such as emissions, infrastructure, and alternative fuels for locomotives (Table 1). The reviews presented relevant information on the state of the art of LCA applied to railroads and suggestions for future works in the field, such as exploring natural gas as a viable option for railroads even though it is a nonrenewable source and comparing it to renewable alternatives such as biodiesel or hydrogen, which might seem counterintuitive, as shown by Dincer and Zamfirescu (2016). Jiang et al. (2021) state that the literature on high-speed rail (HSR) CO2 and greenhouse gases is still in a relatively premature state, even though most papers examined in this work (58%) relate to passenger transportation, as mentioned previously. Finally, Trevisan and Bordignon (2020) found that many discrepancies exist in literature that compares modal transport emissions since their scope, geographic perimeter, calculation methods and sets of assumptions strongly vary. Their work reviews CO2 and GHG emissions data from the literature analyzing air, road, and rail transport and shows that similar contributor patterns can be found within each mode, allowing the identification of important parameters to focus on the further development of multimodal comparative LCAs.

Table 1. Key points of review studies

Citation	Main topic	Results and conclusion
(Dincer & Zamfirescu, 2016)	A review of novel energy options for clean rail applications	A novel criterion used to assess the environmental impact is suitable for pollutant-emitting applications such as railway transportation. Natural gas appears to be a key potential option for use on railways.
(Du & Karoumi, 2014)	LCA for railway bridges	A literature review is performed, and current developments regarding LCA for railway bridges are presented. A systematic LCA framework for quantifying environmental impacts for railway bridges is introduced and interpreted as a potential guideline.
(Olugbenga et al., 2019)	Embodied greenhouse gas (GHG) emissions in rail infrastructure	The state of knowledge in quantifying the embodied greenhouse gas (GHG) emissions in rail infrastructure is investigated, and a sketch model for estimating the GHG impact of rail infrastructure based on the literature is developed. The literature review identifies 22 publications, containing 57 case studies for different types of rail infrastructure.
(Jiang et al., 2021)	Emissions of high-speed rail projects	The literature on the CO2 emissions of high-speed rail (HSR) projects is reviewed, and the literature is found to still be in a relatively premature state. Future research opportunities are also identified.
(Trevisan & Bordignon, 2020)	Emissions for multimodal comparative LCA	CO2 and GHG emission data from the literature are reviewed, analyzing air, road, and rail transport. Important parameters to focus on for the further development of multimodal comparative LCAs are identified.
(Xiao et al., 2021)	Applications of asphalt-based materials (ABM)	Existing applications of asphalt-based materials (ABM), including its use as ballast, is evaluated, focusing on the advancements in material property, structural design methods, LCA and the optimization of materials and structures.
(Diaz, Scouse, & Kelley, 2022)	Railroad crossties comparison using full-cost accounting	Environmental full-cost accounting (FCA) is applied to compare a series of chemically treated wooden and concrete railroad crossties.

Source: Research data (2023).

BIBLIOMETRIC ANALYSIS

The 85 original articles were analyzed according to how they applied the LCA methodology. ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) served as baselines to evaluate papers and help construct the guidelines. The former provides a description and framework for LCA studies, while the latter includes the guidelines and requirements (Rebello, Roque, Gonçalves, Calmon, & Queiroz, 2021). Neither ISO standard specifically addresses the LCA of railroads. A proper scope definition states the analyzed systems, functional units and boundaries. Criteria for assessing the LCI phase included which kind of data was used (foreground or background) along with the database. The software used during the LCIA phase, as well as the methodology, categories and approach (endpoint or midpoint) were evaluated. Finally, guidelines were proposed based on the results.

RESULTS

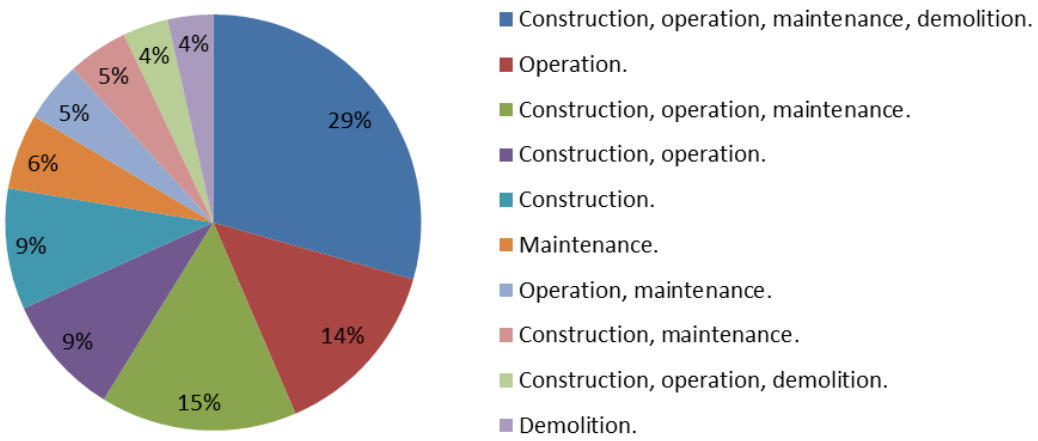
Distribution of published works

To inform the construction of the guidelines, a review of the current literature was conducted first, and then an analysis of the shortcomings and gaps in the literature was performed. To facilitate the identification of relevant literature, researchers should know which journals publish the most. The Journal of Cleaner Production, together with Transportation Research Part D: Transport and Environment, had the most publications, each accounting for 13% of the selected works thus covering 26% of the publications. The University of Birmingham, located in the UK, had the largest number of articles of any institution. The second was Valencia Polytechnic University, located in Spain. Tsinghua University, from China, came in third. Five institutions from China, the USA and Italy tied for fourth. Various other institutions accounted for 76.29% of the research produced. As can be seen, the distribution of the published works indicates a moderate concentration of papers by the two main journals on the field, accounting for over a quarter of the published studies.

Goal and Scope Definition

In addition to examining the spread of articles across publications, patterns in the stated goals and scopes of the articles were examined. All 85 articles clearly stated the goal of the study; nonetheless, 5% of the papers did not mention the functional unit. The functional unit passenger x kilometer (pkm), when per passenger emissions were accounted for, was used in 19% of the papers, while the equivalent for freight, tonne x kilometer (tkm), a consolidated and conventional form of measurement for transporting a payload over a distance, was used in 15% of the studies. Regarding the boundaries, all four phases (construction, operation, maintenance and demolition) were discussed in 29% of the papers, 15% did not consider demolition, and 14% considered only the operation phase. Furthermore, 9% considered both the construction and operation, 9% only construction, 6% only maintenance, 5% operation and maintenance, and 5% construction and maintenance. Finally, 4% excluded maintenance in their analysis, and 4% considered only the demolition phase (Figure 4).

Figure 4. Boundaries of the LCA studies



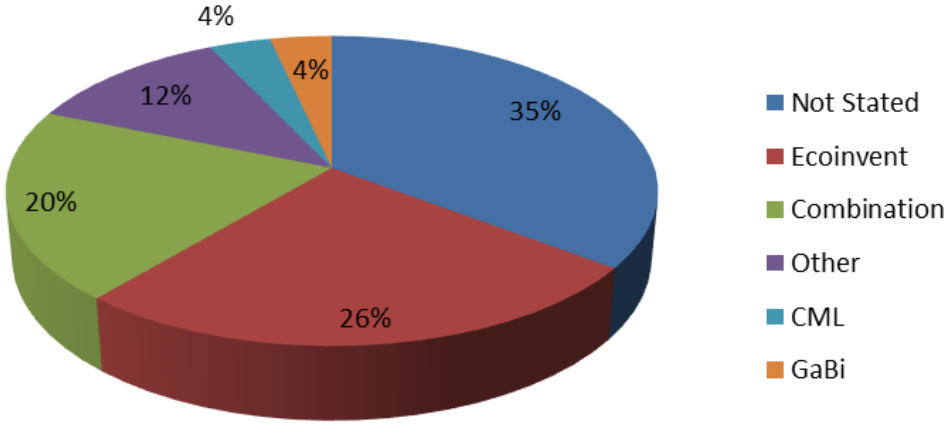
Source: Research data (2023).

Earles and Halog (2011) state that, change of flows caused by demand variations are described by consequential LCA. In a consequential LCA, the impact on a system's operational flow is measured through and evaluation derived from economic data. On an attributional LCA, resources, energy, emissions and other immediate physical flows are measured (Rebello et al., 2021). Notably, 88% of the studies omitted whether a consequential or attributional LCA was used, while 8% applied an attributional approach and 4% a consequential one. The lack of a statement about the method being used is a problem that has been identified in fields other than railroad evaluations (Weidema, Pizzol, Schmidt, & Thoma, 2018).

Life cycle Inventory Analysis

Of the 85 papers selected, 47% used a combination of primary and secondary data from the literature and databases, 32% used primary data, and 21% used secondary data. Ideally, specific criteria, such as a data quality matrix should support the decision to use primary data, secondary data or both. Ecoinvent® was the most used database in the selected works, accounting for 26% of the studies. Twenty percent used a combination of more than one database source, 4% used CML, and 4% used GaBi. Other databases, including DBEIS, Stripple, ICE, Exiobase and ELCD, were less represented and amounted to 12% of the total. While more than a third of the studies (35%) failed to state which database was used, many used primary sources supplied by companies or country/local databases, which might have led to less uncertainty in the analysis (Figure 5).

Figure 5. Databases used by the studies



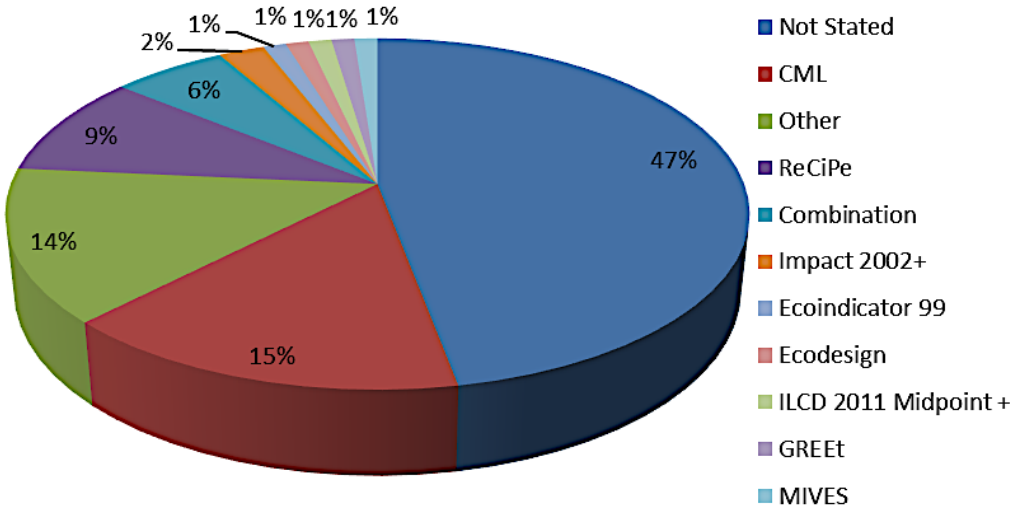
Source: Research data (2023).

Life cycle impact assessment

Of the 85 articles, 48% omitted which software was used to perform the study, while 18% stated that SimaPro® was used, 11% Gabi®, and 6% of the works opted for OpenLCA®. Other software used accounted for 18% of the total, including Microsoft Excel, Python, GAMS, eBalance, EcoTransIT or a combination of multiple software programs. Only 43% disclosed he software version, which may cause difference in results, especially when the software directly includes methodology assessment methods and the database, as is the case for SimaPro® (Rebello et al., 2021).

Next, 47% of the articles did not state which impact methodology was adopted (Figure 6). The most commonly used methodologies were CML (15%), ReCiPe (9%), and a combination of two or more methodologies (6%). Additionally, two studies used IMPACT 2002+. All other methodologies, including Ecodesign, Eco-indicator 99, ILCD 2011 Midpoint+, GREEt, and MIVES, were used only once, and one article even proposed a new methodology.

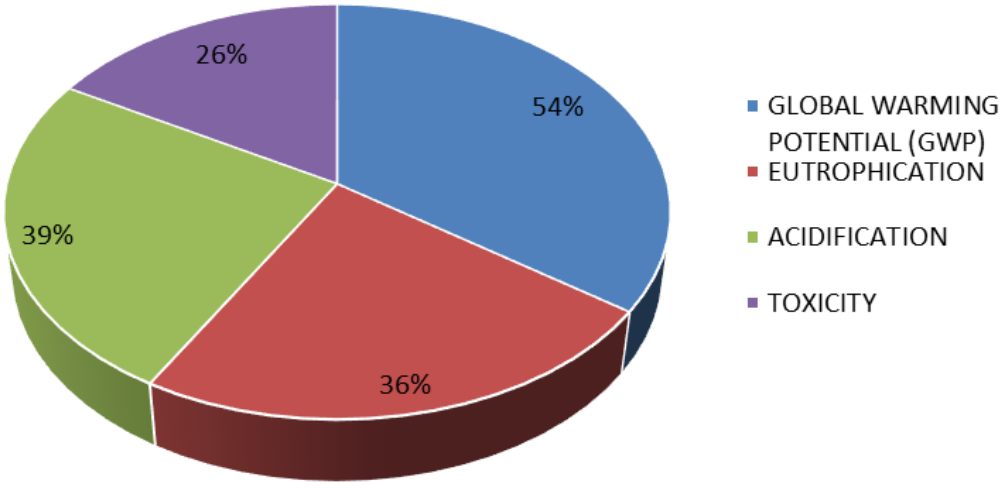
Figure 6. LCIA methodologies applied to railroads



Source: Research data (2023).

Most of the studies (91%) used midpoint categories, while 4% used endpoints and 5% used both. The most important indicators used in the studies were global warming potential (GWP), present in 54% of the articles, acidification (39%), eutrophication (36%) and toxicity (26%) (Figure 7).

Figure 7. Most common indicators used in the studies



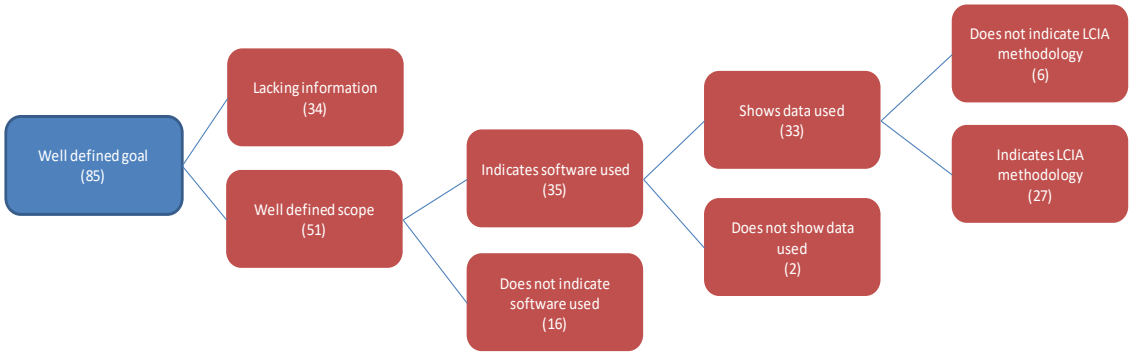
Source: Research data (2023).

Uncertainty and sensitivity analysis is recommended for LCA studies to ensure the reliability of the results obtained. Forty-one percent of the papers presented either an uncertainty or sensitivity analysis. Of those, 71% did not state which method was used. The methods applied, when indicated, were Monte Carlo simulation, standardized regression coefficients, Latin hypercube sampling, one-at-a-time (OAT) and pedigree matrix. In summon, the data showed that more transparency is needed when assessing these topics during an LCA study.

Aspects of the most common methodologies

As seen in the previous subsection, the results indicate notable gaps in the information provided in existing studies. Providing basic information in articles is paramount, as is highlighted by this subsection, showing the most significant points analyzed in this study. The main shortcomings identified were a lack of information on the definition of the study's scope, LCI, and LCIA, functional unit definition, data quality and availability. As a result, only 32% of the papers are considered to be replicable - less than one third of the total (Figure 8). Therefore, the analysis demonstrates the importance of having guidelines or a protocol for conducting LCA of railroads, and the following sections provide suggestions for tackling the main identified shortcomings.

Figure 8. Research significant points



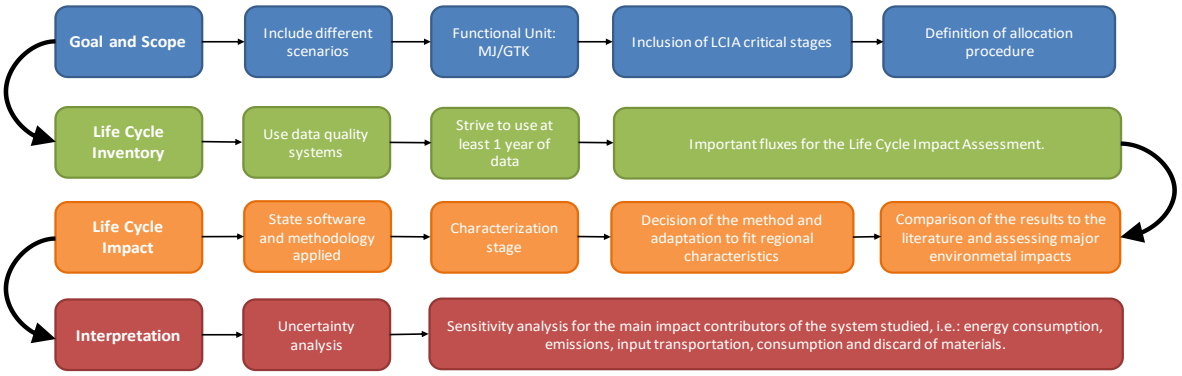
Source: Research data (2023).

PROPOSED GUIDELINES

Aspects of the most common methodologies

Since the previous section indicates omission of information by the studies, this subsection outlines a proposition of guidelines to overcome that. The guidelines are intended to facilitate the development of railroad LCA, initiating a debate that may lead to a finalized standard or protocol. The proposal follows a simple logic: first, wherever there was insufficient information provided for a third party to replicate the work, a recommendation based on that is included in the guidelines. For instance, most of the works omitted the software and version used; hence, the information on the software and the methodology applied should appear in the life cycle impact section. Second, if there is a widespread, common practice in the field, such as the functional unit of a load transported through a distance being measured as tonne-kilometer for railroads and energy consumption being commonly accounted for in megajoules, that practice should be listed under the goal and scope section. Sensitivity analysis was performed in only 41% of the studies; hence, under the interpretation section, uncertainty analysis should be performed for the main impact contributors of the system (Figure 9).

Figure 9. Guidelines outline. Data from each of the phases – Goal and Scope, Life Cycle Inventory, Life Cycle Impact and Interpretation - should be disclosed to assure the replicability of the work



Source: Research data (2023).

Goal and scope

Based on the literature and best practices, this work recommends the use of megajoules/gross tonnes x kilometers (MJ/GTK) for freight railroads since this unit accounts for the energy consumption of power sources, such as diesel, biodiesel, natural gas, and batteries, while also accounting for the load and distance through which that power travels.

The phase and boundaries of the study should be disclosed, whether they include the construction, operation, maintenance or demolition phases, and the boundaries should be preferably presented in the form of a diagram. Also, the study should state which kind of LCA is adopted, whether allocation or consequential. In accordance with the ISO norms already mentioned before, allocation LCA should be avoided when possible, since it may ask for allocation of arbitrary values while measuring energy content, economic value or mass, for instance. Subdividing or expanding the system generally suffices to avoid the need of allocation. Each of the functions that compose a system is built of several stages, that can be subdivided by time or space (Ekvall & Finnveden, 2001; Ekvall & Weidema, 2004), while hence the products generated by them maintain their independency, meaning that the output of a product is not affected by another output (Rebello et al., 2021). Since that in the case of railroads such subdivision does not often occur, the expansion of the boundary of the system is recommended. For consequential systems, such expansion involves the subtraction of impacts derived from additional products, and adding such impacts in the case of attributional ones (Brander & Wylie, 2011).

Life Cycle Inventory

In many developing countries, the LCI database has not yet been adapted to local reality; therefore, the researchers themselves provide most or all of the data in cases where the studied systems are not present in the database. The development of databases for these situations is encouraged, as it would cover a major gap and improve the future of LCIA.

Data quality assessment is needed for reliable studies since it decreases uncertainties, thus increasing the reliability of the results. Primary data is preferred and should be used when possible, while disclosing the date of obtention. In the case of using a database, the version should be stated along with the source(s) from which it was obtained and if it is the case, any adaptations made to the original.

The data should always be of the highest quality possible, but whenever quality is lower than desired, effort should be focused on the main fluxes, as these are the major contributors to the impacts. In tropical countries, significant weather variations occur between the seasons, therefore one year or more of data should be collected, so that these are reflected in the outputs. In order to minimize uncertainty in the results, a method of evaluating data quality should be adopted, such as a pedigree matrix or the Ecoinvent data quality assessment, between others.

Data quality assessment methods are relatively new when compared to the LCA methodology, which was created during the 60's, and can be semiquantitative – as in the case of the International Reference Life Cycle Data System (ILCD), Ecoinvent – or qualitative – as in the case of the USDA binary pedigree matrix. Even though both of them still do not meet all the parameters required by ISO 14044:2006 (Edelen & Ingwersen, 2018).

Therefore, a complete LCI must include information on (1) the database and version; (2) whether and which modifications were made to the database; (3) whether the data were derived from primary sources or were estimated; (4) if estimated, the methodology applied; (5) the data quality assessment; and (6) the process identification for the database.

Life cycle impact assessment

The LCIA methodology correlates with the software and the midpoint/endpoint categories. Studies should consider impact categories such as climate change, by measuring the global warming potential, and nonrenewable energy consumption because of their high relevance. Many of the papers analyzed omitted the phases considered for the life cycle evaluation, which would facilitate comparing studies while also highlighting the impacts on the results, separated by phase. The discussion section would improve by the comparison with similar studies and highlighting the root causes of the most relevant environmental impacts, which could lead to an overall better understanding of the systems under study.

The use of the 2016 version of ReCiPe is advised when applying LCA to railroads since it is an up-to-date methodology that is widely used in Europe and evolved from ReCiPe 2008, CML and Eco-indicator 99, all of which were well accepted by researchers at the time and some of which are still in use. ReCiPe 2016 evaluates impacts across three categories: the use of resources, the emissions of pollutants, and the effects on human health and the ecosystem. Thus, it presents the broadest set of midpoint impact categories available while using impact mechanisms that have global scope whenever possible. Overall, the use of a standardized methodology such as ReCiPe can facilitate comparisons between different products or services and promote transparency and consistency in environmental impact assessments, which goes hand in hand with the objective of this study. Since the most commonly used methodologies in the articles reviewed were CML and ReCiPe, accounting for 37% of the studies, it is only natural that its latest version, ReCiPe 2016, be adopted.

Interpretation of the Results of the Bibliometric Analysis

Sensitivity and/or uncertainty analysis was not carried out in most (59%) of the selected papers. As stated in section 3.4 of this study, only 41% of the studies included uncertainty analysis, and of those that did, only 29% reported which method was applied (e.g., a Monte Carlo simulation or standardized regression coefficients). Disclosing this information is highly recommended, especially in regard to the processes from which the main environmental impacts of the work are derived. Also, emissions, energy consumption, transportation of inputs, material consumption and discard are important topics to consider in a railroad sensitivity analysis.

There are considerable gaps throughout the papers due to nondisclosed information, which becomes clear through the data exposed in this work. For example, 88% of the studies did not mention whether an attributional or consequential methodology was adopted, 48% omitted the software used, while 47% did not state which impact methodology was adopted. This is crucial information for any party intending to replicate the study, and incomplete information makes it impossible for them to do so or for others to compare results directly with another railroad or the results of their own study, for instance.

Therefore, the standardization of LCA applied to railroads would benefit the scientific community, governments and managers, in addition to other stakeholders in the sector, as future works would become comparable by adopting the recommended standards. The authors intend for the guidelines proposed herein to facilitate the elaboration of a new ISO norm for LCA studies applied to railroads, in addition to providing direction for researchers in the field until a norm can be established.

Checklist

A checklist covering the main shortcomings identified in this study is presented in Table 2. The aim of the checklist is to improve the transparency of future works on the LCA of railroads. The checklist can be modified to optimally fit the goals and scope of future works.

Table 2. Basic checklist for railroad LCA studies. Source: Research data (2023).

Information	Check
Does the paper clearly present the goal and scope?	
Does the paper clearly state the functional unit used, reflecting the specific service provided by the railroad system, such as the transportation of a specific quantity of freight or passengers over a given distance?	
Does the paper clearly define the system boundaries, including all relevant processes and impacts associated with the railroad system, from the extraction of raw materials to the disposal of end-of-life components?	
Does the paper clearly specify which type of railroad is considered, e.g., freight, passenger, heavy haul?	
Does the paper specify the energy source and propulsion system of the locomotives, e.g., battery, electric, diesel, highspeed, other?	
Does the paper consider the source of the energy used by the railroad for propulsion, if applicable, e.g., coal, dam, eolic?	
Does the paper specify the stages of the life cycle evaluated?	
Does the paper describe which midpoint and/or endpoint indicators were used and why they were selected?	
Does the paper specify the name and version of the software used?	
Does the paper state whether it applied an attributional or consequential LCA?	
Does the paper indicate the name and version of the database used? If primary data is used, does the paper indicate the data source and quality? Is the data quality appropriate for the intended application?	
Does the paper indicate if there were made any modifications to the database?	
Does the paper indicate methodology and version for the LCIA?	
Does the paper include a sensibility and/or uncertainty analysis? If so, does it state which method was applied?	

Research Limitations and Opportunities

In future works, combining LCA with costs or social LCA, could increase the insights and deepen the knowledge on the assessed system. Regulations for the LCA of railroads could help improve studies and their worldwide comparability and are therefore highly encouraged. Additionally, coupling different LCIA methodologies or big data with LCA could help improve the reliability and accuracy of results in future works. Heavy haul railroads present an enormous opportunity for more studies, as stated, since only 4% of the papers examined in this work addressed this specific niche.

It is also due of note that the present study evaluates 92 articles and, to ensure statistical significance of the present findings, a larger pool of papers would be recommended in order to avoiding potential bias.

CONCLUSION

Most of the shortcomings identified in the papers analyzed relate to a lack of disclosure of relevant information and diverging methodological aspects, both of which compromise the transparency and comparability of the works, which is not to overlook the fact that several papers presented a very thoroughly and well-written discussion.

It could also be observed that most of the studies did not conduct an uncertainty or sensitivity analysis. Information about the collection of the data should also be disclosed, indicating how trustworthy are the sources and classifying it through a pedigree matrix or another method. In the case of adopting databases, is also valid to verify if they represent regional characteristics of where the study is being conducted.

This work provides an initial set of guidelines for developing a methodology that can be applied to railroad LCA and, in turn, lead to the creation of an official standard, thus supporting the elaboration of such a standard, in addition to providing direction for researchers in the field until the standard is established. This could lead to greater transparency and comparability in the field and between different works.

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