Article

Environmental impact of steel/concrete composite bridges and reinforced concrete bridges: a comparative analysis through Life Cycle Assessment

Impacto Ambiental de pontes mistas de aço/concreto e pontes de concreto armado: uma análise comparative por meio da Avaliação do Ciclo de Vida

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Abstract

Climate change presents a challenge for the construction industry to develop modern building materials that must not only meet functional performance criteria but also reduce the environmental impact associated with their production. In this context, the primary objective of this study is to apply the Life Cycle Assessment (LCA) technique to the superstructures of steel/concrete composite bridges and reinforced concrete bridges, aiming to identify potential environmental impacts and opportunities for enhancing environmental performance, especially concerning the use of materials and services. The study was based on the ISO 14040 and ISO 14044 guidelines and employed the International Reference Life Cycle Data System (ILCD); Evah OzLCI2019 database; data collected by the Construction Environmental Performance Information System (SIDAC); OpenLCA software version 2.0, and the ReCiPe 2016 Midpoint (H) method. The results indicated that, in general, reinforced concrete bridges had a lower environmental impact compared to composite bridges, with the exception of some indicators such as freshwater eutrophication and ionizing radiation. Therefore, the use of steel in composite bridges has proven to be a significant source of environmental impact, especially when used as a substitute for concrete.

Keywords: Life Cycle Assessment (LCA). Bridges. Environmental impact.

Resumo

As mudanças climáticas apresentam um desafio significativo para o setor da construção civil. Nesse contexto, o objetivo principal deste estudo é aplicar a técnica de Avaliação do Ciclo de Vida (ACV) nas superestruturas de pontes mistas de aço/concreto e de concreto armado, com o propósito de identificar os possíveis impactos ambientais e oportunidades de aprimoramento no desempenho ambiental, especialmente no que se refere ao uso de materiais e serviços. O estudo se fundamentou nas diretrizes da ISO 14040 e ISO 14044 e utilizou o Sistema Internacional de Dados do Ciclo de Vida de Referência (ILCD); banco de dados Evah OzLCI2019; os dados coletados pelo Sistema de Informação do Desempenho Ambiental da Construção (SIDAC); o software OpenLCA versão 2.0 e o método ReCiPe 2016 Midpoint (H). Os resultados apontaram que, em geral, as pontes de concreto armado tiveram menor impacto ambiental em comparação às pontes mistas, com exceção de alguns indicadores, como Eutrofização de água doce e Radiação ionizante. Portanto, o uso do aço nas pontes mistas revelou-se uma fonte significativa de impacto ambiental, especialmente quando utilizado em substituição ao concreto.

Palavras-chave: *Avaliação do Ciclo de Vida (ACV). Pontes. Impacto Ambiental.*

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Introduction

Globally, we are facing a climate crisis. As a result of this event, radical changes in current practices are urgently required to prevent irreversible damage to life as we know it (Morris; Allen; Hawkins, 2021; Wang *et al.*, 2021). In this context, the construction industry has a significant environmental impact on society, as it currently consumes over one-third of the energy produced and emits approximately 39% of the greenhouse gases generated globally by human activities (Gu *et al.*, 2021). The construction of buildings and the manufacturing of construction materials account for 11% of these emissions within the sector. The demand for materials in the construction industry leads to significant environmental effects due to the high consumption of finite natural resources (Ahmed *et al.*, 2022). In particular, cement production contributes to 5 to 8% of global CO_2 emissions, primarily due to the use of clinker (Quintana-Gallardo *et al.*, 2021). In the pursuit of reducing environmental harm, there arises a need to identify alternative materials that can replace the conventionally used virgin materials (Sandanayake; Law; Sargent, 2022), so as to not only meet functional performance criteria but also reduce the environmental impact associated with their production (Fořt; Kočí; Černý, 2021). Given the significance of achieving this objective, numerous scientists have been dedicated to analyzing current construction processes in order to enhance and optimize sustainable practices. Researchers have been investigating emissions produced by construction materials (Antunes *et al.*, 2021; Ramírez-Villegas; Eriksson; Olofsson, 2019; Sinka *et al.*, 2020) and the steel industry (Gu *et al.*, 2015). Several studies have focused on assessing the sustainability of construction and demolition waste (CDW) (Ferronato *et al.*, 2022; Iodice *et al.*, 2021; Melo; Ferreira; Costa, 2013; Sahoo; Bergman; Runge, 2021; Waskow *et al.*, 2021). Furthermore, other researchers have examined the environmental impacts of concrete with waste additives (Dandautiya; Singh, 2019; Hafez *et al.*, 2021; Liu *et al.*, 2022).

In this context of studies, one of the widely recognized and developing techniques is Life Cycle Assessment (LCA), as described in ISO 14040 (ISO, 2009). LCA assesses the environmental aspects and potential impacts throughout the life of a product (id est, from "cradle to grave"), from raw material acquisition, through production, use, and disposal (ABNT, 2009). This aspect of LCA is crucial, as it not only examines the impacts generated during a product's production but also takes into account its use and how it is disposed of at the end of its life cycle (Lvel *et al.*, 2020).

LCA enables the measurement of environmental impacts, such as quantifying CO_2 emissions throughout the life cycle of reinforced concrete structures (Li *et al.*, 2019), greenhouse gas emissions (CH_4, N_2O, etc.) in cementitious materials (cements, pastes, and mortars) based on calcined waste (Hadj Sadok *et al.*, 2022) and the impacts of global warming, eutrophication, acidification, and photochemical pollution in the production of concrete with recycled aggregate (Galvín *et al.*, 2014; Han *et al.*, 2021; Marinković *et al.*, 2010). LCA is a globally recognized technique applied in mitigating these damages, though studies on LCA in bridges are scarce (Ma *et al.*, 2021).

Bridges, as fundamental components of transportation infrastructure, are complex structures involving various materials that cause significant environmental harm. Many of these bridges are reaching the end of their lifespan and require well-informed decisions from designers regarding the materials and construction processes to be adopted, in order to achieve reductions in environmental impacts (Raeisi *et al.*, 2021).

In addition to their material composition, other variables influence their environmental impact, such as the type of bridge, construction method employed, and span length. A study (Martínez-Muñoz; Martí; Yepes, 2021) demonstrated the relevance of recycling and reusing structural steel in the design of bridge decks with spans ranging from 25 to 40 meters. In a Brazilian study, the environmental impacts of 405 small span bridges, ranging from 6 to 20 meters, were quantified, considering different types of bridges, such as steel/concrete composite bridges, cast in place reinforced concrete bridges, and precast reinforced and prestressed concrete bridges. The results indicated that the steel/concrete composite bridge, with two steel girders, presented the lowest environmental impact (Milani; Yepes; Kripka, 2020).

Understanding and quantifying the environmental effects associated with different types of bridges play a pivotal role in advancing the fields of sustainability and civil engineering, providing support for decision making strategies related to materials used in bridge projects. Therefore, the primary objective of this study is to apply the Life Cycle Assessment (LCA) technique to the superstructures of small span bridges, aiming to identify potential environmental impacts and damages throughout the life cycle of these bridges. In doing so, the intention is to mitigate environmental effects and reduce resource consumption.

To achieve the stated objective, two bridge designs were developed: one using a reinforced concrete superstructure and the other employing a steel/concrete composite superstructure. This approach allowed for the investigation of both the environmental impact of the steel structure in bridges and the use of recycled aggregates as substitutes for natural aggregates in concrete. In the study's second phase, a contribution analysis was conducted to identify the materials present in the bridge that had the greatest impact on the environment. Finally, a sensitivity analysis was carried out, considering different scenarios of variation for the materials identified as having the most significant contribution to environmental impacts.

The study was conducted using Life Cycle Assessment (LCA), following the guidelines of ISO 14040 (ABNT, 2009) and ISO 14044 (ABNT, 2014) the International Reference Life Cycle Data System (ILCD) (EC, 2010); the Evah OzLCI2019 database (The Evah Institute, 2023); data collected by the Construction Environmental Performance Information System (SIDAC) (Oliveira; John, 2023); OpenLCA software version 2.0 (The Evah Institute, 2023) and the ReCiPe 2016 Midpoint (H) method (Huijbregts *et al.*, 2016)

This study provides relevant guidance for decision making in the construction industry, with a strong emphasis on sustainability, promoting responsible practices aligned with the environmental needs of society. This enables engineers, designers, and decision makers to take environmental aspects into account when designing and constructing bridges.

Method

The Materials and Methods section was divided into two subsections:

(a) bridge design; and

(b) Life Cycle Assessment (LCA).

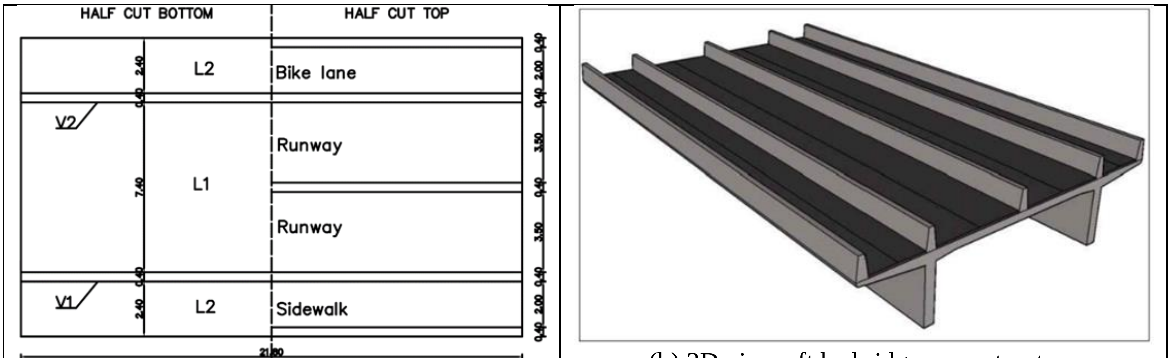
Bridge design

The object of study is the superstructure of a precast bridge, with dimensions of 13m in width and 21.8m in length. The bridge consists of two traffic lanes, a cycle path, and a sidewalk, as shown in Figure 1a. Regarding classification, it was considered a class 45 bridge according to the Brazilian standard NBR 7188 (ABNT, 2013), based on a design vehicle with a total weight of 450 kN. The structural elements are divided into two deck slabs (L1 and L2) and two longitudinal girders (V1 and V2). Precast reinforced concrete elements with a strength of 35 MPa were adopted for the deck slabs. As for the girders, different types were selected, ranging from steel "I" beams to precast reinforced concrete girders with a strength of 35 MPa. Additionally, to ensure safety and prevent potential accidents, protective barriers were provided, using the New Jersey barrier model, as illustrated in Figure 1b.

Based on this information, the structural elements were designed and the quantification of materials to be used was carried out. For the comparative analysis of environmental impacts, two solutions for the superstructures were formulated: a reinforced concrete bridge composed of reinforced concrete beams and slabs (PCA); and a steel/concrete composite bridge (PMA) composed of steel beams and reinforced concrete slabs.

The common elements present in these two solutions are: a bonding layer between the slab and the asphalt pavement, a layer of Hot Mix Asphalt (HMA) 5.0 cm thick, a drainage system through PVC drains, and reinforced concrete barriers. Figure 2a and Figure 2b show the cross sections of the reinforced concrete bridges and the composite bridges, as well as the dimensions of their components.

Figure 1 – **Top view of the bridge**



(a) Top view and cross section of the bridge

(b) 3D view oft he bridge superstructure

In order to assess the effects of environmental impacts across different compositions of the superstructure's structural elements, six bridge models were considered:

1. Reinforced concrete beams and slabs bridge (PCA).

2. Reinforced concrete beams and slabs bridge with 50% replacement of natural aggregate by recycled aggregate (PCA-50%).

3. Reinforced concrete beams and slabs bridge with 100% replacement of natural aggregate by recycled aggregate (PCA-100%).

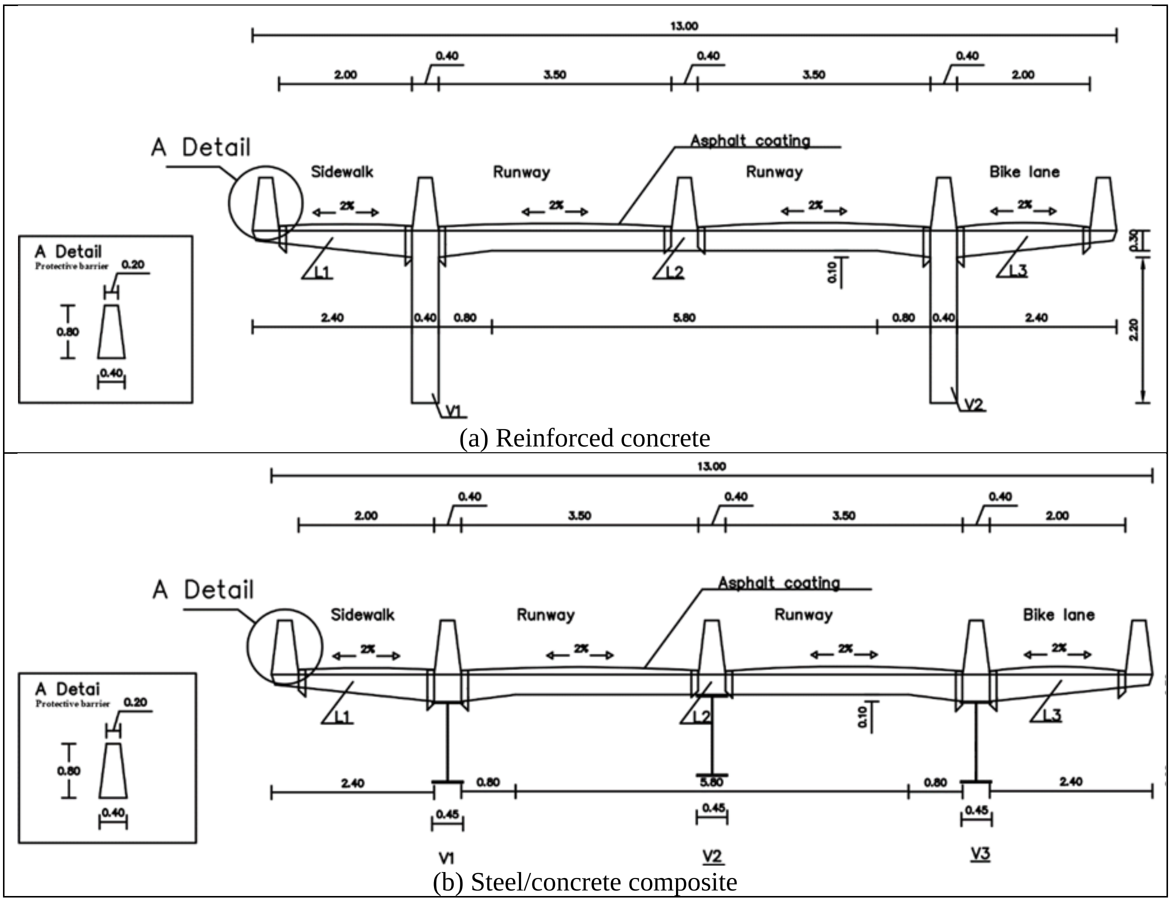
4. Steel beams and reinforced concrete slabs composite bridge (PMA).

5. Steel beams and reinforced concrete slabs composite bridge with 50% replacement of natural aggregate by recycled aggregate (PMA-50%).

6. Steel beams and reinforced concrete slabs composite bridge with 100% replacement of natural aggregate by recycled aggregate (PMA-100%).

Table 1 presents the quantification of materials consumed in the production of the superstructure for the reinforced concrete bridge (PCA) and the steel/concrete composite bridge (PMA). The main difference between the two is the material used in the deck beam, which can be either steel (PMA) or reinforced concrete (PCA). To facilitate the material quantification, the superstructure was divided into three parts: deck slab (reinforced concrete slab), deck beam (steel or reinforced concrete beam), and auxiliary services (asphalt pavement, barriers, and drainage). Additionally, Table 1 also provides the distances for material transportation to the construction site, considering the hypothetical scenario in the city of Recife, within the Brazilian context. These values are input into the OpenLCA software, which, through its database, analyzes and monitors the sustainability performance parameters of products and services.

Figure 2 – **Cross section of the bridge**



(a) Reinforced concrete

(b) Steel/concrete composite

Table 1 – **Quantification of materials and transportation distances for bridge superstructures**

Material	Description	Unit	Quantity	Distance of Transport (km)
Deck slab	Concrete with a compressive strength of 35 MPa	m³	85.37	19.5
Deck slab	Reinforcement for concrete	kg	4798.91	28.7
Deck slab	Formwork using white wood	m²	358.60	10.0
Deck beam (PCA)	Reinforcement for concrete.	kg	12697.20	28.7
Deck beam (PCA)	Concrete with a compressive strength of 35 MPa	m³	38.46	19.5
Deck beam (PCA)	Formwork using white wood	m²	230.24	10.0
Deck beam (PMA)	Steel I-beam, A572 Grade 50	m³	2.04	28.7
Ancillary Services	Concrete for protective barrier	m³	26.16	19.5
Ancillary Services	Protective barrier reinforcement	kg	810.96	28.7
Ancillary Services	Protective barrier formwork	m²	221.71	10.0
Ancillary Services	Bonding paint with RR-1C emulsion	m²	239.80	27.8
Ancillary Services	Pavement with applied hot mix asphalt (HMA), wearing layer, with a thickness of 5.0 cm.	m²	239.80	27.8
Ancillary Services	PVC drain with a diameter of 100 mm, unit length = 60 cm.	und	8	66.1

Life Cycle Assessment (LCA)

Objective, scope, and functional unit

The objective of the life cycle assessment is to identify and quantify potential environmental impacts associated with the production of reinforced concrete bridges and steel/concrete composite bridges, aiming to assess potential environmental impacts and damages throughout the life cycle of these bridges. This assessment aims to assist the designer in making sustainable choices. The geographical scope of the study was developed considering the Brazilian context, specifically the city of Recife, where the studied bridges will be constructed. The scope of this research covers the cradle-to-gate stages, encompassing raw material acquisition, transportation, processing, and the manufacturing of composites used in bridge construction.

Two data sources were utilized: the database from the Construction Environmental Performance Information System (SIDAC) (Oliveira; John, 2023), consisting of inventories tailored to the Brazilian context, providing greater accuracy to the study; and databases from the International Reference Life Cycle Data System (ILCD)(EC, 2010) and Evah OzLCI201 (The Evah Institute, 2023) 9, which supplement missing or incomplete information in the SIDAC. The reference flow adopted for this work was substances per cubic meter of the constructed bridge. The study was conducted using the OpenLCA tool, a free and open source software available for professional life cycle modeling. The employed method was ReCiPe 2016 Midpoint (H) (Huijbregts *et al.*, 2016).

Life Cycle Inventory (LCI)

Figure 3 presents the inventory modeling of this study, constructed based on the elementary flows and product flows of the system. It considers processes from the extraction of raw materials to transportation to the precast industry. After the pieces are manufactured, they are transported to the construction site, with the transportation distance being accounted for. The inventory is divided into four elementary processes: concrete production at the batching plant, transportation, reinforced concrete fabrication at the construction site, and bridge superstructure production.

Table 2 presents the origin of the databases used for the civil construction materials employed and consists exclusively of secondary data since they were not collected directly by the authors but rather from sources such as the Brazilian SIDAC system (Oliveira; John, 2023) and international databases such as Evah OzLCI2019 (The Evah Institute, 2023) and ILCD (EC, 2010). Initially, the inventory was developed based on the data made available by SIDAC, which is grounded in information from the national civil construction industry. To complement the gaps in data on construction materials that could not be directly obtained through SIDAC, information from the Evah OzLCI2019 and ILCD international databases was utilized.

Life Cycle Inventory (LCI)

The method adopted in this study was ReCiPe 2016 Midpoint (H) (Huijbregts *et al.*, 2016a), which represents an advancement from the Eco-indicator 99 and CML 2002 methods, effectively combining midpoint and endpoint approaches (Joint Research Centre – JRC, 2010). Using this method, the following categories of environmental impacts were calculated: FPMF Fine Particulate Matter Formation; FRS-Fossil Resource Scarcity; FE-Freshwater Ecotoxicity; FEU-Freshwater Eutrophication; GW-Global Warming; HCT-Human Carcinogenic toxicity; HNCT-Human Non-Carcinogenic Toxicity; IR-Ionizing Radiation; LU-Land Use; ME-Marine Ecotoxi-city; MEU-Marine Eutrophication; MRS-Mineral Resource Scarcity; OFHH-Ozone Formation, Human Health; OFTE-Ozone Formation, Terrestrial Ecosystems; SOD-Stratospheric Ozone Depletion; TA-Terrestrial Acidification; TE-Terrestrial Eco-toxicity; WC-Water Consumption. This comprehensive and detailed analysis enabled the assessment of the effects of constructing the bridge superstructures throughout the product's life cycle.

Figure 3 - **Bridge Superstructure Inventory**

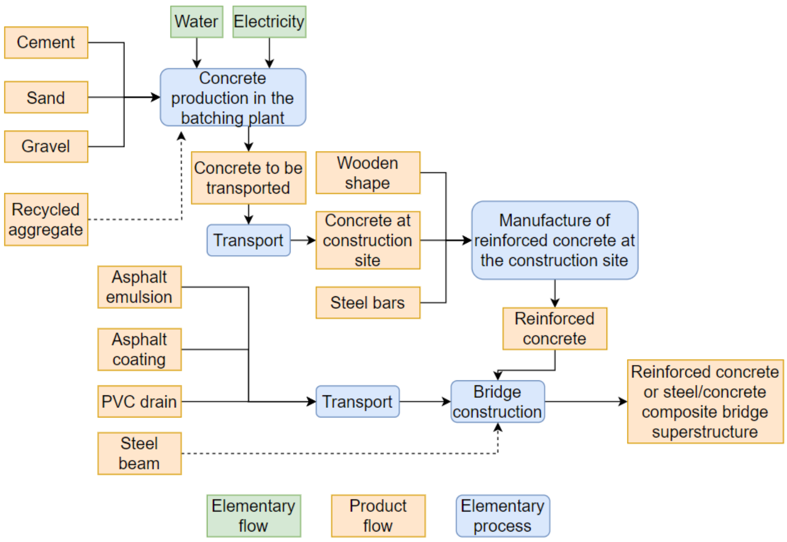


Table 2 - **Data used in the LCI**

Material/Activity	Data Base
Drain	Evah OzLCI2019
Steel Bars	SIDAC
Sand	SIDAC
Gravel	SIDAC
Recycled Aggregate	SIDAC
Cement	SIDAC
Diesel Fuel	ILCD
Steel Beam	Evah OzLCI2019
Electricity	ILCD
Transport	ILCD
Water	ILCD
Wood Formwork	SIDAC
Asphalt Coating	Evah OzLCI2019
Asphalt Emulsion	Evah OzLCI2019

Contribution analysis

With the aim of directing efforts towards processes that contribute most to environmental impacts, a contribution analysis was conducted for the main materials or services of bridge construction: PVC pipe, reinforcing steel, concrete, wooden formwork, asphalt paving, asphalt primer, transport, and steel structure. This analysis evaluated the contribution of each material or service to hybrid steel/concrete and reinforced concrete bridges in six scenarios: PCA, PCA-50%, PCA-100%, PMA, PMA-50%, and PMA-100%, using the ReCiPe 2016 Midpoint (H) method.

Sensitivity analysis

The sensitivity analysis followed the guidelines of ISO 14044 (ABNT, 2014) and allowed for the identification of variables that have the greatest impact on the results, providing a deeper understanding of the study's sensitivity to different scenarios of variation. This analysis helps identify which variables have the greatest impact on the results and provides a deeper understanding of the study's sensitivity to different variation scenarios. From the results of the contribution analysis, it became evident that steel and concrete in the steel/concrete composite structures (PMA) had a greater contribution to environmental impacts. Therefore, analyses were conducted considering variations in the volume of steel in the PMA bridge, encompassing reductions of 30%, 20%, and 10%, as well as increases of 10%, 20%, and 30%, consequently altering the volume of concrete used in the structure (Table 3).

After conducting sensitivity analysis regarding the volume of steel in bridge PMA, the indicators that showed the largest variations, deemed the most relevant, were identified. Subsequently, these results were overlaid with sensitivity analysis regarding the data sources used, considering two scenarios: the first scenario utilized national data from SIDAC along with international data from Evah OzLCI2019 and ILCD, while the second scenario considered only international data from Evah OzLCI2019 and ILCD. This approach allowed for the assessment of the effects of data source selection on the study results and understanding the variability associated with the data used.

Results and discussions

LCA analysis

The results of the indicators for different bridge models are illustrated in Figure 4 using the ReCiPe 2016 Midpoint (H) assessment method (Huijbregts *et al.*, 2016). Each indicator is presented relative to the maximum result, which is defined as 100%, and the results of the other variants are displayed in relation to this reference value.

The results revealed that, overall, the mixed bridges (PMA, PMA-50%, and PMA-100%) exhibited a higher environmental impact compared to the reinforced concrete bridges (PCA, PCA-50%, and PCA-100%), except for the FEU, HCT, HNCT, IR, and MEU indicators. The most significant disparity was observed in the Water Consumption parameter, where reinforced concrete bridges consumed only 2.5% of the total water volume used by the mixed bridges. This difference is attributed to the additional water consumption in cooling and vaporization processes during steel production in the steel industry (Gu *et al.*, 2015). On the other hand, it was found that mixed bridges showed lower values in terms of Human Carcinogenic Toxicity compared to reinforced concrete bridges, although both demonstrated low levels. The emission of substances such as arsenic, sodium dichromate, and hydrogen fluoride has been identified as the main cause of this impact (Acero; Rodríguez; Ciroth, 2017), and it is not common in the production of steel and concrete, as it is mainly associated with electricity generation from fossil sources. However, it is important to note that the addition of chemical additives to concrete can introduce substances classified as carcinogenic or that may have other adverse health effects.

In most of the investigated cases, the replacement of natural aggregate with recycled aggregate resulted in stagnation or an increase in environmental impact. However, an exception was noted in the slight decrease of 1% compared to the maximum value in the indicator of Fossil Resource Scarcity. This reduction is attributed to the recycling capability of aggregates, which allows for the reuse of existing materials, thus avoiding the need for additional extraction of natural resources (Marinković *et al.*, 2010).

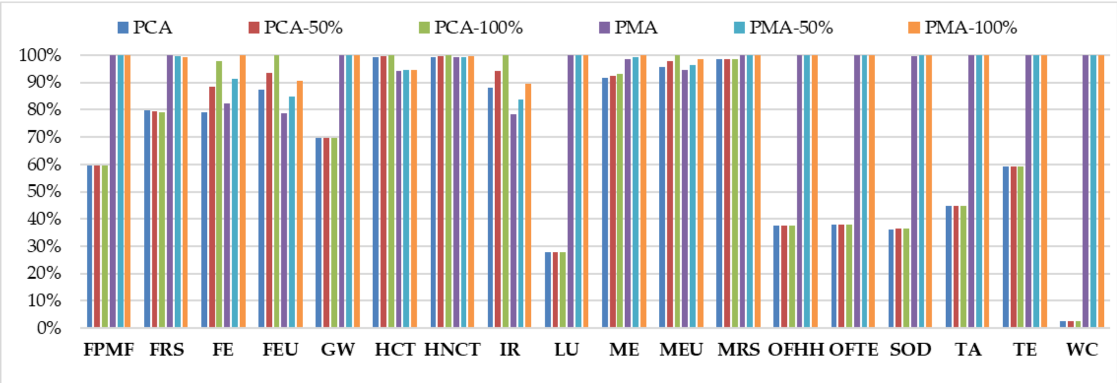
Based on the results presented in Figure 5, it is evident that the main source of contribution to environmental impacts was concrete, with the exception of the WC, OFTE, OFHH, and LU indicators. The largest contributions attributed to concrete occurred in the clinker production phase and the associated energy consumption. In indicators such as Mineral Resource Scarcity, where concrete played a significant role in environmental impact in bridges PCA, PCA-50%, and PCA-100%, it was found that only clinker production was responsible for 76.41% of the total impact related to that specific indicator. These results highlight the importance of seeking more sustainable alternatives for clinker production and reducing the consumption of natural resources in the concrete sector.

In general, regarding the increase in the proportion of recycled aggregate in concrete, significant variations were not observed among the studied bridges. However, considerable changes were identified in the indicator of Freshwater Ecotoxicity, with increasing values of 71.70% (PCA), 74.70% (PCA-50%), and 77.11% (PCA-100%). These changes indicate a gradual increase in the influence of this indicator as the proportion of recycled aggregate in the concrete used increases. A similar pattern was identified in the indicator of Freshwater Eutrophication, with increasing values of 75.79% (PCA), 77.44% (PCA-50%), and 78.88% (PCA-100%). The concern lies in the potential occurrence of material segregation failures that may be associated with toxic substances such as asbestos and lead containing paints (Galvín *et al.*, 2014). These substances can be released into the water during the leaching process, thus increasing levels of freshwater ecotoxicity and eutrophication. Moreover, deficiencies in waste management and production have been identified in recycling plants located in the region where the bridges were constructed (Melo; Ferreira; Costa, 2013). These issues emphasize the importance of adopting proper waste recycling practices, including the implementation of effective waste control and management measures to prevent contamination and the release of harmful substances into the aquatic environment.

Table 3 – **Variation of metallic structure volume for sensitivity analysis in bridges**

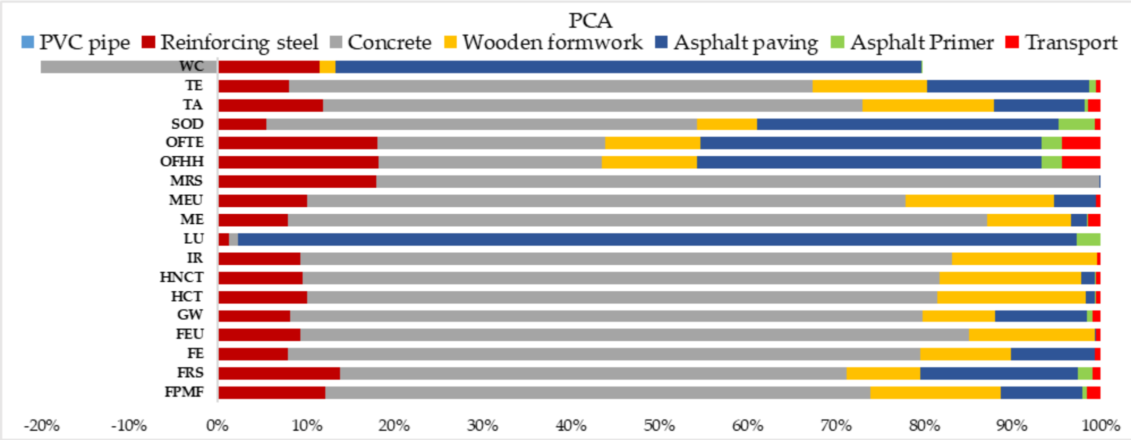
Bridge	Concrete volume (m^3) (1)	Steel structure volume (m^3) (2)	(1)/(2)
PMA/-30%	123.11	1.42	86.38
PMA/-20%	119.28	1.63	73.22
PMA/-10%	115.44	1.83	62.99
PMA	111.60	2.04	54.81
PMA/+10%	107.76	2.24	48.11
PMA/+20%	103.93	2.44	42.53
PMA/+30%	100.09	2.68	37.81

Figure 4 – **Comparison of Environmental Impact per m³ for Different Types of Bridges Under Analysis; ReCiPe 2016 Midpoint (H) Method**

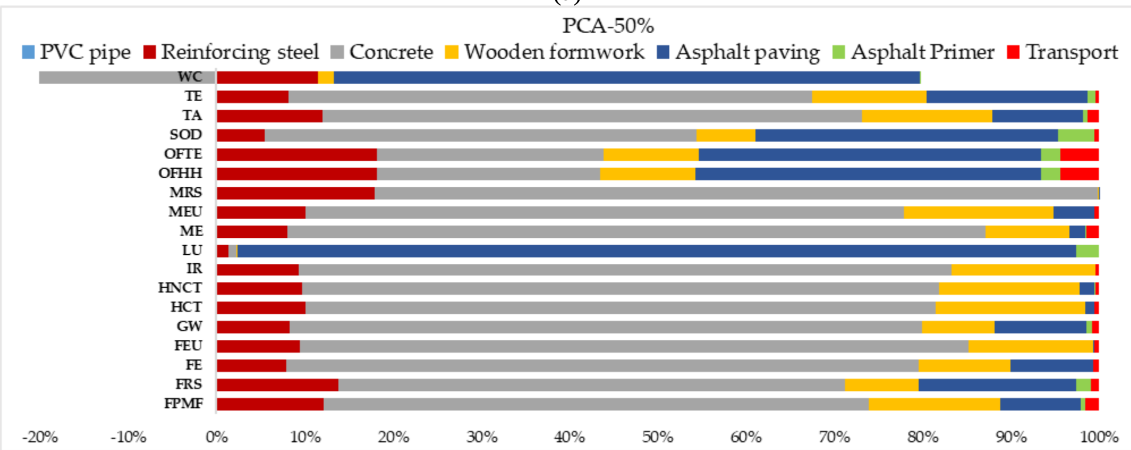


Note: FPMF-Fine Particulate Matter Formation; FRS-Fossil Resource Scarcity; FE-Freshwater Ecotoxicity; FEU-Freshwater Eutrophication; GW-Global Warming; HCT-Human Carcinogenic toxicity; HNCT-Human Non-Carcinogenic Toxicity; IR-Ionizing Radiation; LU-Land Use; ME-Marine Ecotoxicity; MEU-Marine Eutrophi-cation; MRS-Mineral Resource Scarcity; OFHH-Ozone Formation, Human Health; OFTE-Ozone Formation, Terrestrial Ecosystems; SOD-Stratospheric Ozone Depletion; TA-Terrestrial Acidification; TE-Terrestrial Ecotoxicity; WC-Water Consumption.

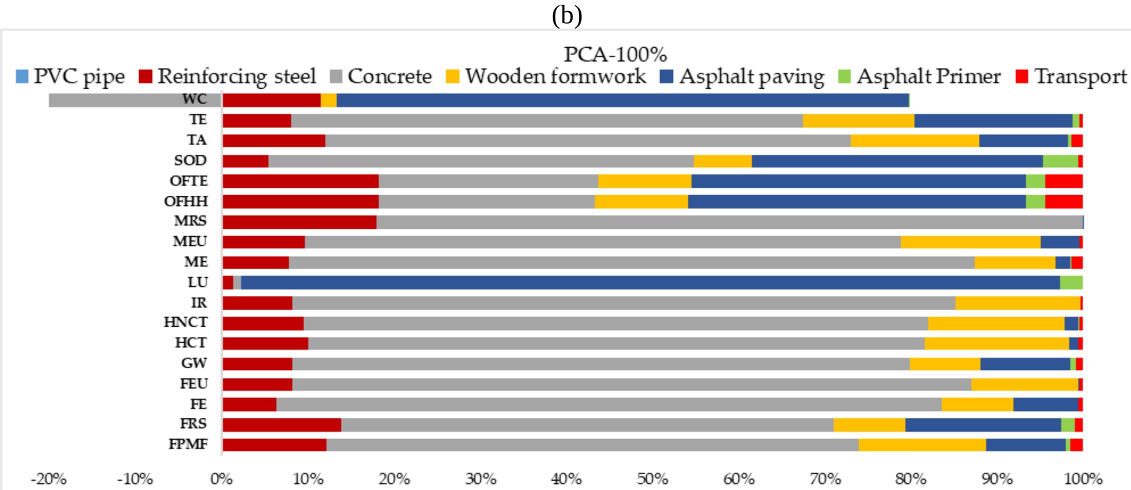
Figure 5 - **Environmental impact contribution analysis for 1 m³ of the following bridges**



(a)



(b)



(c)

Note: (a) PCA; (b) PCA-50%; (c) PCA-100%. FPMF-Fine Particulate Matter Formation; FRS-Fossil Resource Scarcity; FE-Freshwater Ecotoxicity; FEU-Freshwater Eutrophication; GW-Global Warming; HCT-Human Carcinogenic toxicity; HNCT-Human Non-Carcinogenic Toxicity; IR-Ionizing Radiation; LU-Land Use; ME-Marine Ecotoxicity; MEU-Marine Eutrophication; MRS-Mineral Resource Scarcity; OFHH-Ozone Formation, Human Health; OFTE-Ozone Formation, Terrestrial Ecosystems; SOD-Stratospheric Ozone Depletion; TA-Terrestrial Acidification; TE-Terrestrial Ecotoxicity; WC-Water Consumption.

The asphalt pavement stood out as the second most influential material in the environmental damage of the studied bridges, particularly in the Land Use indicator, contributing to 95.03% of the impacts. Its installation and maintenance require extensive land areas and involve the extraction of nonrenewable resources, such as petroleum or bitumen, resulting in significant environmental damage, including the destruction of natural habitats and soil and water pollution. Steel bars occupied the third position in terms of contribution, with averages of 11.01%, 10.57%, and 10.82% in the PCA, PCA-50%, and PCA-100% bridges, respectively. The indicators most sensitive to the presence of steel bars were OFTE, OFHH, and MRS. These results highlight the influence of steel bars on environmental impacts, especially in aspects related to ozone formation and mineral resource scarcity. However, concerning the Land Use indicator, the contribution of steel bars was lower compared to other materials analyzed. This indicates that their influence on land use is relatively minor compared to other sources of impact in the studied bridges.

Although not highly significant, the most substantial contribution of wooden formwork to environmental impact was related to the Human Carcinogenic Toxicity indicator. This indicator assesses the potential of chemical substances present in wood to cause harm to human health, specifically in terms of carcinogenic effects. Therefore, the presence of carcinogenic substances in wood can increase environmental impact, particularly concerning human health. Furthermore, the Mineral Resource Scarcity indicator showed a lower contribution compared to other analyzed indicators. This suggests that the use of wooden formwork could be a more sustainable alternative in terms of mineral resource consumption. Asphalt priming and transportation contributed similarly, approximately 1% each, to environmental impact emissions due to the low volume of material used and short transportation distances. Asphalt priming had a greater impact on the Stratospheric Ozone Depletion indicator, while transportation had a greater impact on the Formation of Ozone in Terrestrial Ecosystems and Formation of Ozone in Human Health indicators. On the other hand, the contribution of PVC drains was considered insignificant due to their low quantity used. The results in Figure 6 show the cumulative contribution of materials and activities defined in the LCA for each impact category considered in the PMA, PMA-50%, and PMA-100% bridges.

When conducting the contribution analysis for the construction of the mixed bridges PMA, PMA-50%, and PMA-100%, Figure 6 reveals that concrete remains the material with the greatest environmental impact. However, it is noticeable that the steel structures have emerged as a relevant contender in terms of the magnitude of environmental impacts, occupying the second position. Furthermore, the substitution of concrete bridges with mixed bridges resulted in an overall increase in environmental impact, with the exception of the FEU, HCT, HNCT, IR, and MEU indicators. It is important to highlight that steel structures exhibit greater durability compared to concrete structures, which can be considered a positive factor in terms of longterm sustainability. This increased durability may lead to a reduced need for largescale interventions throughout the bridge's lifespan, thereby reducing potential environmental impacts associated with such interventions. Therefore, even though the use of steel structures may initially generate higher environmental impact due to their production and installation, in the long term, they can become an advantageous strategy to mini-mize environmental impact by avoiding frequent reconstruction of concrete bridges.

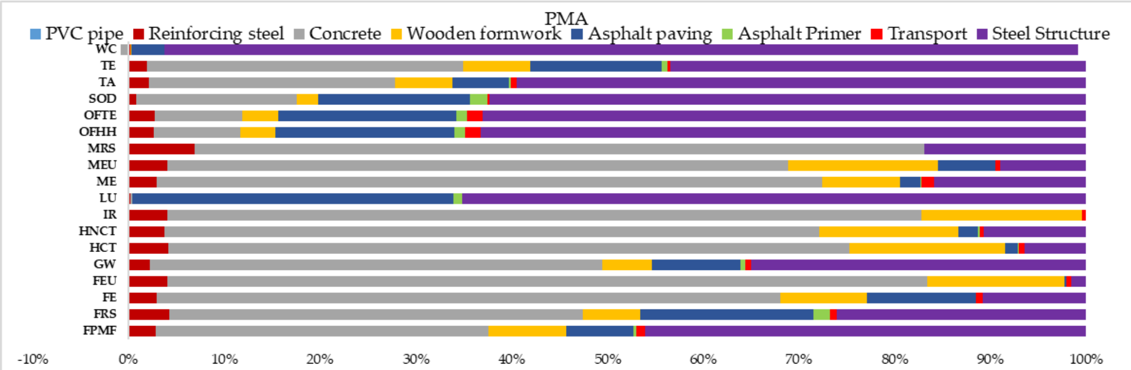
The substitution of natural aggregate with recycled aggregate in the mixed bridges resulted in either stagnation or an increase in environmental impact. There was a linear increase in the indicators of Freshwater Ecotoxicity and Freshwater Eutrophication as the substitution rate increased. When substituting 100% of natural aggregate with 100% recycled aggregate, the impact on the FE and FEU indicators increased by 21.95% and 15.19%, respectively. These indicators measure different aspects of environmental damage related to freshwater.

Figure 5, when analyzing the average contributions of materials and activities to environmental impacts in the three reinforced concrete bridges, it was observed that Concrete was responsible for the largest contribution, accounting for 53.55% of the total impact. Following that, it was identified that Asphalt paving contributed with 23.45%, the Wooden formwork used in construction represented 10.22%, Reinforcing steel contributed with 10.8%, Transport accounted for 1.01% of the impact, Asphalt Primer contributed with 0.96%, and PVC pipes contributed only 0.02%.

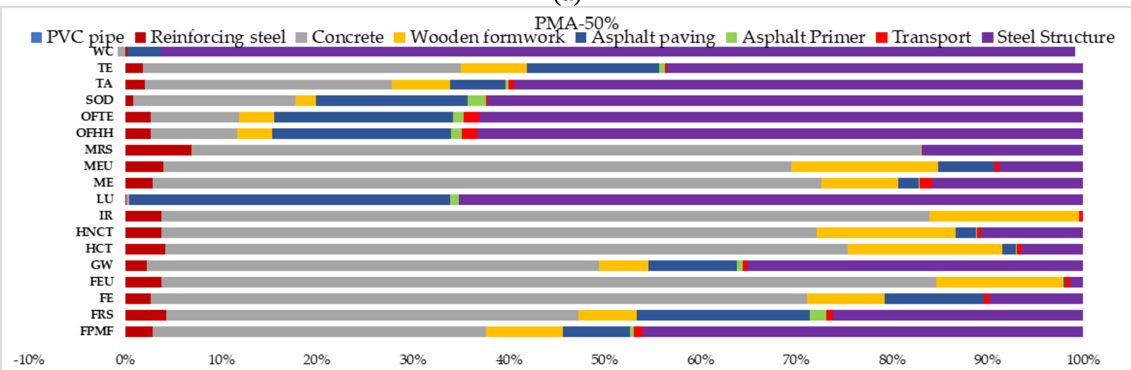
When considering the use of steel structures in the three mixed bridges shown in Figure 6, there was a change in the average contributions of materials and activities. Concrete showed a reduction in its contribution, accounting for 44.39% of the total impact, while the Steel Structure began to contribute with 35%. Additionally, Asphalt paving contributed with 9.23%, the Wooden formwork used in construction represented 7.4%, Reinforcing steel contributed with 2.87%, Transport accounted for 0.6% of the impact, Asphalt Primer contributed with 0.5%, and PVC pipes had a minimal contribution of 0.01%.

These differences indicate that the use of steel structures in mixed bridges led to a reduction in the contribution of concrete, which is the main environmental impact driver. However, the total environmental impact increased due to the significant involvement of steel structures, replacing materials with lower environmental impact, such as asphalt pavement, wooden formwork, and reinforcing steel. Since these materials are the main contributors, a sensitivity analysis was performed without the addition of recycled aggregates to assess the influence of steel structures and reinforced concrete on the environmental impact of the bridges.

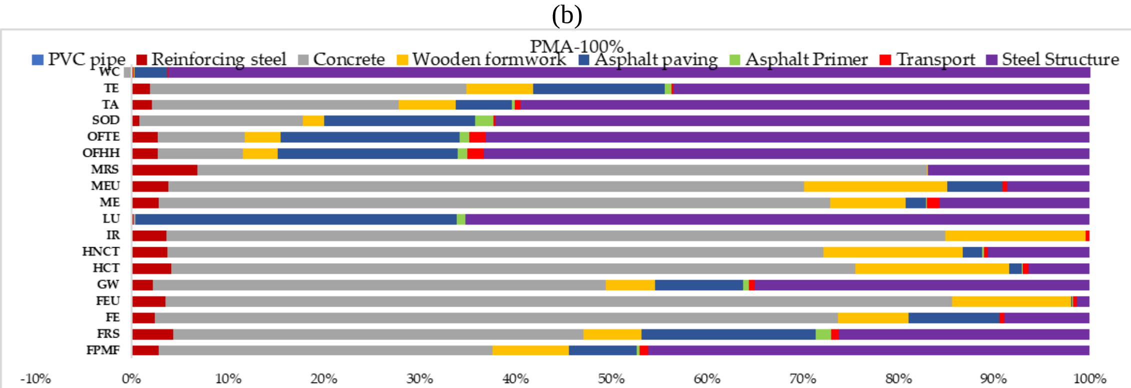
Figure 6 - **Contribution analysis of environmental impact per 1 m³ for the following bridges**



(a)



(b)



(c)

Note: (a) PMA; (b) PMA-50%; (c) PMA-100%. FPMF-Fine Particulate Matter Formation; FRS-Fossil Resource Scarcity; FE-Freshwater Ecotoxicity; FEU-Freshwater Eutrophication; GW-Global Warming; HCT-Human Carcinogenic toxicity; HNCT-Human Non-Carcinogenic Toxicity; IR-Ionizing Radiation; LU-Land Use; ME-Marine Ecotoxicity; MEU-Marine Eutrophication; MRS-Mineral Resource Scarcity; OFHH-Ozone Formation, Human Health; OFTE-Ozone Formation, Terrestrial Ecosystems; SOD-Stratospheric Ozone Depletion; TA-Terrestrial Acidification; TE-Terrestrial Ecotoxicity; WC-Water Consumption.

Sensitivity analysis

The sensitivity analysis was conducted to examine the behavior of certain environmental impact indicators when varying the involvement of steel structures in the mixed bridges. For this purpose, analyses were performed considering variations in the volume of steel in the PMA bridge, including reductions of 30%, 20%, and 10%, as well as increases of 10%, 20%, and 30%. This approach enabled the evaluation of the effects of these variations on the environmental performance of the bridge and understanding how the volume of steel influences environmental impacts.

Figure 7 depicts the relative results of the indicators for the various steel structure involvement variations in the mixed bridges, using the ReCiPe 2016 Midpoint (H) evaluation method. Each indicator is presented in relation to the maximum result, which is defined as 100%, and the results of the other variants are shown in relation to this reference value.

Based on the results shown in Figure 7, it was evident that the increase in the steel structure's contribution to the mixed bridge led to a significant increase in environmental impacts for the indicators LU, GW, FPMF, FRS, OFHH, OFTE, SOD, TA, TE, and WC. Conversely, a significant reduction in environmental impacts was observed for the indicators IR, HNTC, FE, FEU, HCT, ME, MEU, and MRS.

Figure 8 below provides a snapshot of the sensitivity analysis regarding the variation in the steel metal structure in relation to the indicators that showed the most significant increases (LU and GW) and the most significant reductions (IR and HNCT). These results were obtained through the combination of national and international data, allowing for a more realistic assessment of the environmental impacts in the geo-graphical context of the study, as not all necessary national data were available. For the purpose of comparison, in the same graph, the results were overlaid with those obtained exclusively from the available international data. This overlay aimed to analyze the sensitivity of the change in data source on the study's outcomes.

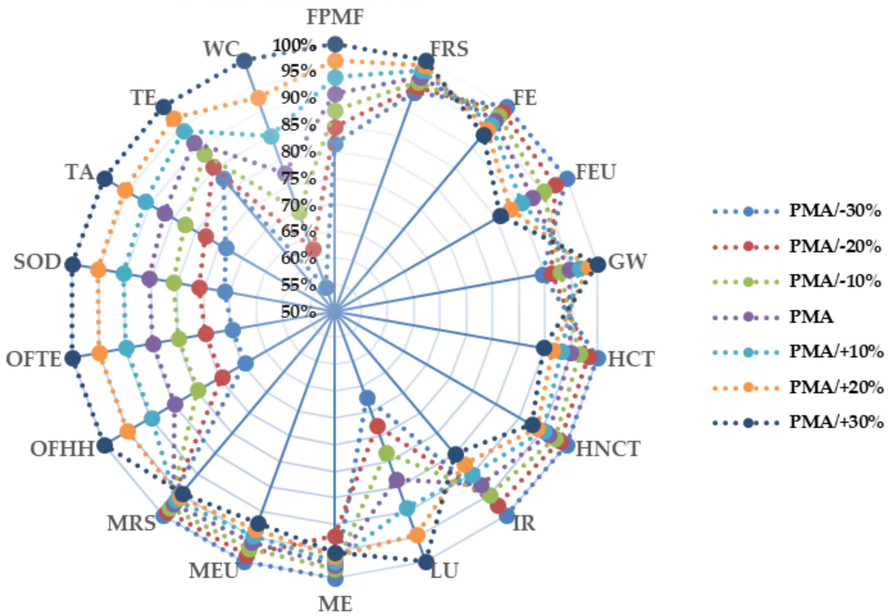
From the analysis conducted in Figure 8, a linear increase is observed in the LU and GW indicators as the participation of the steel structure volume in the bridge increases. This suggests that the mixed bridge, with a higher use of steel, has a more significant environmental impact in relation to these indicators than the concrete bridge. Furthermore, the indicators calculated using the combination of national and international data showed lower values compared to the indicators calculated solely from international data.

However, as the participation of the steel structure increases, this difference tends to decrease, bringing the values closer between the two data sources. This discrepancy is more significant when evaluating the bridge with a lower volume of steel, indicating that the lack of accurate national data that reflects the local construction reality may have a greater impact on result accuracy, especially in cases with lower steel usage.

Regarding the IR and HNCT indicators, Figure 8 illustrates a linear decrease in the combined analysis of national and international data. However, when examining the results using only international data, it is observed that for the IR indicator, the value remains constant at 0.105 kBq Co-60 eq, whereas the HNCT indicator shows a linear increase, following an opposite trend to the combined analysis of national and international data.

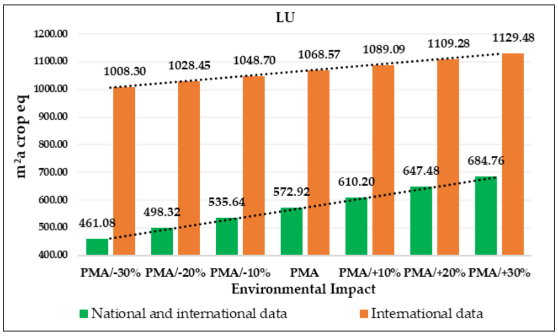
Therefore, obtaining accurate and relevant primary data is essential for a more accurate assessment of the environmental impacts of bridges, especially when construction materials with higher environmental impact, such as steel structural elements, are involved.

Figure 7 – **Sensitivity analysis of PMA bridges: PMA/-30%, PMA/-20%, PMA/-10%, PMA, PMA/+10%, PMA/+20%, PMA/+30%**

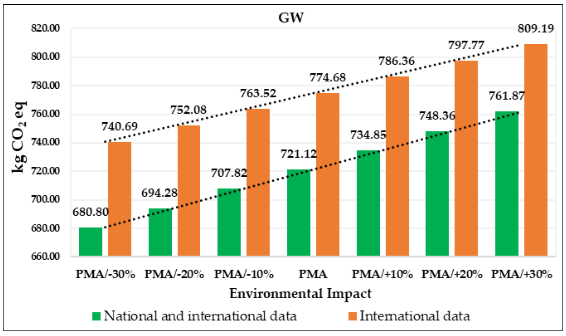


Note: FPMF-Fine Particulate Matter Formation; FRS-Fossil Resource Scarcity; FE-Freshwater Ecotoxicity; FEU-Freshwater Eutrophication; GW-Global Warming; HCT-Human Carcinogenic toxicity; HNCT-Human Non-Carcinogenic Toxicity; IR-Ionizing Radiation; LU-Land Use; ME-Marine Ecotoxicity; MEU-Marine Eutrophi-cation; MRS-Mineral Resource Scarcity; OFHH-Ozone Formation, Human Health; OFTE-Ozone Formation, Terrestrial Ecosystems; SOD-Stratospheric Ozone Depletion; TA-Terrestrial Acidification; TE-Terrestrial Ecotoxicity; WC-Water Consumption.

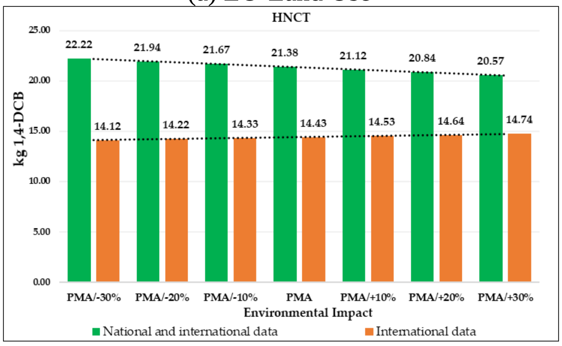
Figure 8 - **Sensitivity analysis result**



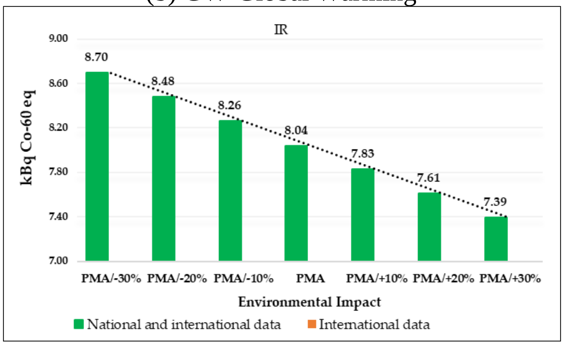
(a) LU-Land Use



(b) GW-Global Warming



(c) HNCT-Human Non-Carcinogenic Toxicity



(d) IR-Ionizing Radiation

Conclusions

The construction sector plays a pivotal role in climate change, making environmental assessments essential to comprehend the impact of this industry and seek sustainable solutions. In this context, a significant study was conducted employing Life Cycle Assessment (LCA) on two types of bridge superstructures, coupled with contribution and sensitivity analyses. The purpose is to ensure that current choices do not compromise the wellbeing of our planet for future generations. Based on the research conducted, the following key conclusions can be highlighted:

(a) although the cement industry, and consequently the production of concrete, is the most significant activity in terms of environmental impacts in large constructions, the results revealed that replacing concrete with steel in composite bridges resulted in a greater environmental impact, especially regarding water consumption during steel manufacturing. This suggests that the pursuit of new materials or low environmental impact alternatives should be accompanied by studies on mitigating impacts throughout their production chain;

(b) the substitution of natural aggregates with recycled aggregates showed a stagnation or even an increase in environmental impact indicators such as Freshwater Ecotoxicity and Freshwater Eutrophication. These results emphasize the importance of proper management and effective waste recycling practices to prevent contamination and the release of harmful substances into the aquatic environment; and

(c) the results highlight the importance of considering not only individual materials but also their interactions when assessing the environmental impact of infrastructure such as bridges. While the use of steel structures reduced the contribution of concrete, it also replaced materials with lower environmental impact, such as asphalt pavement, wooden forms, and steel bars.

For future research, it is recommended to consider additional life cycle stages of bridges, including the maintenance and end-of-life phases of superstructures, to gain a more comprehensive understanding of environmental impacts. This approach would be particularly relevant for bridges with steel structures, allowing for an assessment of their environmental impacts throughout their lifespan compared to reinforced concrete bridges. When addressing the end-of-life phase, it would be possible to investigate the environmental impact resulting from the dismantling and disposal of steel bridges in comparison to reinforced concrete ones. Aspects such as material recycling and waste management could be taken into account, contributing to a better understanding of the environmental impacts associated with different types of bridges.

References

ACERO, A. P.; RODRÍGUEZ, C.; CIROTH, A. **LCIA methods**: impact assessment methods in Life Cycle Assessment and their impact categories. **Greendelta**, n. February 2014, p. 1–23, 2017.

AHMED S. N. *et al*. Life cycle assessment of substitutive building materials for landfill capping systems in Vietnam. **Applied Sciences**, v. 12, n. 6, 2022.

ANTUNES, A. *et al*. Environmental impacts and benefits of the end-of-life of building materials: database to support decision making and contribute to circularity. **Sustainability**, v. 13, n. 22, 2021.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 7188**: carga móvel rodoviária e de pedestre em pontes, viadutos, passarelas e outras estruturas. Rio de Janeiro: ABNT, 2013.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR ISO 14040**: gestão ambiental: avaliação do ciclo de vida: Princípio e estrutura. Rio de Janeiro, 2009.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR ISO 14044**: avaliação do ciclo de vida: requisitos e orientações. Rio de Janeiro: 2014.

DANDAUTIYA, R.; SINGH, A. P. Utilization potential of fly ash and copper tailings in concrete as partial replacement of cement along with life cycle assessment. **Waste Management**, v. 99, p. 90–101, 2019.

EUROPEAN COMMISSION. **International Reference Life Cycle Data System (ILCD) Handbook:** general guide for life cycle assessment, detailed guidance March 2010.

FERRONATO, N. *et al*. Environmental assessment of construction and demolition waste recycling in Bolivia: Focus on transportation distances and selective collection rates. **Waste Management and Research**, v. 40, n. 6, p. 793–805, 2022.

FOŘT, J.; KOČÍ, J.; ČERNÝ, R. Environmental efficiency aspects of basalt fibers reinforcement in concrete mixtures. **Energies**, v. 14, n. 22, 2021.

GALVÍN, A. P. *et al*. Leaching assessment of concrete made of recycled coarse aggregate: physical and environmental characterisation of aggregates and hardened concrete. **Waste Management**, v. 34, n. 9, p. 1693–1704, 2014.

GU, H. *et al*. Mass timber building life cycle assessment methodology for the U.S. regional case studies. **Sustainability**, v. 13, n. 24, p. 1–16, 2021.

GU, Y. *et al*. Calculation of water footprint of the iron and steel industry: a case study in Eastern China. **Journal of Cleaner Production**, v. 92, p. 274–281, 2015.

HADJ SADOK, R. *et al*. Life cycle assessment of cementitious materials based on calcined sediments from Chorfa II dam for low carbon binders as sustainable building materials. **Science of the Total Environment**, v. 826, p. 154077, 2022.

HAFEZ, H. *et al*. Assessing the sustainability potential of alkali-activated concrete from electric arc furnace slag using the ECO2 framework. **Construction and Building Materials**, v. 281, p. 122559, 2021.

HAN, Y. *et al*. Environmental and economic assessment on 3D printed buildings with recycled concrete. **Journal of Cleaner Production**, v. 278, p. 123884, 2021.

HUIJBREGTS, M. *et al*. **ReCiPe 2016**. National Institute for Public Health and the Environment, 2016.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **ISO 14040**: environmental assessment: life cycle assessment: principles and framework. Geneve, 2009.

IODICE, S. *et al*. Sustainability assessment of Construction and Demolition Waste management applied to an Italian case. **Waste Manageme**nt, v. 128, p. 83–98, 2021.

LI, H. *et al.* Assessing the life cycle CO2 emissions of reinforced concrete structures: four cases from China. **Journal of Cleaner Production**, v. 210, n. 38, p. 1496–1506, 2019.

LIU, S. *et al.* A comparative study on environmental performance of 3D printing and conventional casting of concrete products with industrial wastes. **Chemosphere**, v. 298, n. February, p. 134310, 2022.

LVEL, J. *et al.* Life cycle analysis of concrete and asphalt used in road pavements. **Environmental Engineering Research**, v. 25, n. 1, p. 52–61, 2020.

MA, M. *et al.* Exergy-based life cycle assessment model for evaluating the environmental impact of bridge: principle and case study. **Sustainability**, v. 13, n. 21, p. 1–19, 2021.

MARINKOVIĆ, S. *et al.* Comparative environmental assessment of natural and recycled aggregate concrete. **Waste Management**, v. 30, n. 11, p. 2255–2264, 2010.

MARTÍNEZ-MUÑOZ, D.; MARTÍ, J. V.; YEPES, V. Comparative life cycle analysis of concrete and composite bridges' varying steel recycling ratio. **Materials**, v. 14, n. 15, p. 1–22, 2021.

MELO, A. V. S.; FERREIRA, E. de A. M.; COSTA, D. B. Fatores críticos para a produção de agregado reciclado em usinas de reciclagem de RCC da região nordeste do Brasil. **Ambiente Construído**, Porto Alegre, v. 13, n. 3, p. jul./set. 99–115, 2013.

MILANI, C. J.; YEPES, V.; KRIPKA, M. Proposal of sustainability indicators for the design of small-span bridges. **International Journal of Environmental Research and Public Health**, v. 17, n. 12, p. 1–23, 2020.

MORRIS, F.; ALLEN, S.; HAWKINS, W. On the embodied carbon of structural timber versus steel, and the influence of LCA methodology. **Building and Environment**, v. 206, n. July, p. 108285, 2021.

OLIVEIRA, L. S.; JOHN, V. J. **Sidac - Sistema de Informação do Desempenho Ambiental da Construção**. Disponível em: https://sidac.org.br/conteudo_tecnico. Acesso em: 20 mar. 2023.

QUINTANA-GALLARDO, A. *et al*. Waste valorization of rice straw as a building material in Valencia and its implications for local and global ecosystems. **Journal of Cleaner Production**, v. 318, n. July, 2021.

RAEISI, F. *et al.* Reducing carbon dioxide emissions through structural health monitoring of bridges. **Journal of Civil Structural Health Monitoring**, v. 11, n. 3, p. 679–689, 2021.

RAMÍREZ-VILLEGAS, R.; ERIKSSON, O.; OLOFSSON, T. Life cycle assessment of building renovation measures–trade-off between building materials and energy. **Energies**, v. 12, n. 3, 2019.

SAHOO, K.; BERGMAN, R.; RUNGE, T. Life-cycle assessment of redwood lumber products in the US. **International Journal of Life Cycle Assessment**, v. 26, n. 8, p. 1702–1720, 2021.

SANDANAYAKE, M.; LAW, D.; SARGENT, P. A new framework for assessing the environmental impacts of circular economy friendly soil waste-based geopolymer cements. **Building and Environment**, v. 210, n. December 2021, p. 108702, 2022.

SINKA, M. *et al*. Fast setting binders for application in 3d printing of bio-based building materials. **Sustainability**, v. 12, n. 21, p. 1–12, 2020.

THE EVAH INSTITUTE. **Evah OzLCI2019 Free Database**. Disponível em: https://nexus.openlca.org/database/OzLCI2019. Acesso em: 12 abr. 2023.

WANG, Y. *et al.* Life cycle assessment of a novel biomass-based aerogel material for building insulation. **Journal of Building Engineering**, v. 44, n. July, p. 102988, 2021.

WASKOW, R. *et al.* Environmental performance of construction and demolition waste management strategies for valorization of recycled coarse aggregate. **Journal of Environmental Management**, v. 295, n. October 2020, p. 113094, 2021.

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