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Life Cycle Assessment Applied to Railway Infrastructure: A Proposed Method

Filipe Batista Ribeiro[1]; Marcelino Aurélio Vieira Da Silva[2]
[1]Doctoral Student, Rio De Janeiro Federal University, Transport Engineering Program – COPPE, Av. Horácio Macedo, Ilha Do Fundão – Rio De Janeiro, RJ - Brazil.
[1]filiperibeiro@pet.coppe.ufrj.br
[2]Professor, Ph.D, Rio De Janeiro Federal University, Transport Engineering Program – COPPE, Av. Horácio Macedo, Ilha Do Fundão – Rio De Janeiro, RJ - Brazil.
[2]aurelio@pet.coppe.ufrj.br

Abstract
Based on mitigation strategies for the rational use of resources and conscious consumption of inputs, it is important to develop tools that allow the measurement of environmental impacts and greenhouse gas emissions, for better decision-making in the planning of railway infrastructure activities. Therefore, this article presents a method for evaluating railway infrastructure projects, having as a parameter the potential impact of global warming when different materials are used in the sub-ballast, to improve the support capacity of the railway pavement. As a technical criterion for evaluation, the mechanical behavior of the subgrade was considered in a condition of moisture above the optimal level, with a sub-ballast composed of sandy material as a baseline for comparison. The results, considering the environmental impact, clearly indicated that the use of a soil-cement mixture in the sub-ballast was the best option. Furthermore, even in the face of more frequent renovation of the permanent way, the reference scenario was more attractive than those with use of a combination of soil-emulsion and hot mix asphalt.

Key-words: Life Cycle Assessment, Railway, Potential Impact of Global Warming.

1. Introduction

According to Knott *et al.* (2019) in their study of the effect of climate on the management of pavement, the emission of greenhouse gases (GHGs) has been causing significant climate changes, in turn posing threats to transportation assets (Koks *et al.*, 2019). In this respect, the report of the Intergovernmental Panel on Climate Change (IPCC, 2014) contains relevant considerations on the mitigation measures aimed at reducing the quantity of GHG emissions. Among these measures is the use of intermodal freight transportation where priority is given to modes that generate lower emissions,

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such as railway instead of roadway transport. Table 1 below presents comparison of the emission indices and potential impact on global warming, segregated by transport mode and life cycle stage.

Table 1 - CO_2 Emissions and Potential Impact on Global Warming of Different Cargo Transport Modes

Impact Criteria and Emissions (by life cycle stage)	**Cargo Transport**							
	Air Transport		*Roadway Transport*		*Waterway Transport*		*Railway Transport*	
	g/tkm	%	g/tkm	%	g/tkm	%	g/tkm	%
Total CO_2	**931.5**	**100%**	**93.6**	**100%**	**37.8**	**100%**	**33.6**	**100%**
Vehicle operation	895.1	96%	77.5	83%	29.7	79%	23.7	71%
Construction and maintenance of infrastructure	9.4	1%	13.9	15%	7.3	19%	6.0	18%
Operation of infrastructure	26.8	3%	0.1	0%	0.2	1%	2.2	7%
Production and maintenance of vehicles	0.18	0.02%	2.1	2%	0.5	1%	1.7	5%
Total CO_2 Equivalent	**945.5**	**100%**	**95.9**	**100%**	**38.3**	**100%**	**36.0**	**100%**
Vehicle operation	907.2	96%	78.6	83%	29.8	79%	25.4	71%
Construction and maintenance of infrastructure	9.8	1%	14.9	15%	7.7	19%	6.4	18%
Operation of infrastructure	28.3	3%	0.1	0%	0.2	1%	2.3	7%
Production and maintenance of vehicles	0.19	0.02%	2.3	2%	0.6	1%	1.9	5%

Source: Adapted from Umweltbundesamt (2013)

In light of Kelvin (1889), various studies in the area of railway infrastructure have been conducted for the purpose of obtaining a tool to measure or translate into numbers the impacts of emissions with global warming potential (Bortoli, Bouhaya & Feraille, 2020; Mathieu, Pavaux & Gaudry, 2013; Stripple & Uppenberg, 2010). Finally, based on efforts to achieve carbon neutrality of railway transport, as described by Logan *et al.* (2020), the development of tools for planning activities related to railway infrastructure is relevant and aligned with current demands.

2. Bibliographic Review

According to Lazorenko *et al.* (2019), the subgrade is the most deformable and heterogeneous component of railway infrastructure, whose physical condition is the main factor determining the efficiency of the permanent way, and also the main cause of premature degradation of the components composing the railway pavement. That observation is in line with the proposals of Selig and Li (1994) about the track modulus, that the subgrade has a significant influence on the mechanical performance of the platform. In this vein, Lazorenko *et al.* (2019) stressed that among the different factors such as load per axle and its cyclical impact effects, one of the parameters that most affects the subgrade is the moisture of this layer, as shown in Table 2.

Table 2 - Sources of Problems Related to Moisture of the Permanent Way

Type of failure or deformation	**Possible reasons**	**Characteristics and description**
1. Progressive failure due to shear	1.1. Repeated application of overload on the subgrade; 1.2. Subgrade composed of fine-grained soils; 1.3. High moisture.	▪ Plastic slumping near the subgrade surface; ▪ Pumping of fines, increasing the relief between sleepers and shoulders; ▪ Depression under the sleepers.
2. Expansion/contraction	2.1. Highly plastic soils; 2.2. Variation of moisture; 2.3. Combination of rainfall with alkaline soils; 2.4. Soils with high silt percentage in the sugared or sub-ballast.	▪ Irregularity of the surface of the track
3. Abrasion by mud pumping	3.1. Application of repeated load from the ballast penetrated in the subgrade; 3.2. Elevated height of the ballast; strain in the subgrade; 3.3. Rocks or soils rich in clay; 3.4. High moisture in contact with the surface of the subgrade.	▪ Worn out ballast. ▪ Inadequate subgrade; ▪ Ballast with insufficient drainage.

Source: Adapted from Lazorenko *et al.* (2019)

Lazorenko *et al.* (2019) proposed solutions to promote stability of the foundation of the permanent way under freight trains. Among the three main types of solutions mentioned by the authors (protective layers, soil improvement and structural solutions), examples are the use of a reinforcement layer employing hot mix asphalt (HMA); and mixtures of soil-cement and soil-asphaltic emulsion.

Aligned with this concept, Veit and Holzfeind (2009) described the use of asphaltic materials in railway infrastructure, with focus on managing the cost over the life cycle. In that study, the authors stated that *"a good track behaves well, a poor one deteriorates faster"*. Based on this, the study showed that in the proposed model the deterioration of the track depends on the level of quality ($Q = Q_0 \, x \, e^{bt}$, where Q is the track quality, Q_0 is the initial investment, b is a constant based on analysis of field data and t is time).

Also involving the track life cycle, but with focus on the impacts and emissions, Bortoli, Bouhaya and Feraille (2020) and Mathieu, Pavaux and Gaudry (2013) proposed methods to measure these environmental criteria with applications to railway infrastructure, as summarized in Table 3, which can be utilized as guides for further studies in the area.

Table 3 - Impacts of Potential Global Warming on Railway Infrastructure

Source	**Exclusion of scope**	**Elements considered**	**Units**	**Construction stage**	**Maintenance stage**
Mathieu, Pavaux & Gaudry (2013)	Excluding the civil construction of structures (auxiliary works, external connections to existing lines and stations)		(gCO2eq/km)	.	
Bortoli, Bouhaya & Feraille (2020)		Subgrade	[(g CO2eq) / (km.year)]	5,900,000	
		Construction equipment		2,000,000	
		Ballast		3,140,000	
		Concrete sleepers		2,830,000	
		Track		5,790,000	
		Fastening elements		139,000	
		Energy system		1,280,000	
		Viaducts		3,740,000	
		Transport of materials		2,570,000	

Therefore, motivated by the explicit demand for carbon neutrality in the area of transport infrastructure, the aim of this study was to develop a comprehensive method of life cycle assessment (LCA) based on components with clear and reusable life cycle inventories (LCIs) for elements of railway transport infrastructure, as well as to evaluate the potential environmental impact of global warming on their useful lifetime. In this respect, we compared four different railroad pavement sections, considering the subgrade under inadequate moisture conditions. We evaluated all the railway pavement elements (track, fasteners, sleepers, ballast, sub-ballast and subgrade), considering all the life cycle steps (extraction of raw material, transport of materials, production of inputs, and construction and maintenance of the permanent way), using the impact of global warming (gCO2eq) on each kilometer constructed. We stress that the other infrastructure elements, such as drainage works, viaducts/trestles and tunnels, were not considered in the scope of this study. The initial focus was creation of a baseline for use as a reference for comparison with other scenarios. The baseline, called Scenario 1, served to evaluate the potential impact of global warming with use of sub-ballast composed of granular material (sand), without use of materials to improve the mechanical performance. The other three scenarios involved evaluation of the impact of GHG emissions on the use of alternative materials as sub-ballast, with the employment of a mixture of soil-Portland cement (Scenario 2), soil-emulsion

(Scenario 3) and hot-mix asphalt – HMA (Scenario 4), according to the solutions proposed by Lazorenko *et al.* (2019). In all the scenarios, we employed a single track section. Finally, to define the end of the useful lifetime of the structure, we used the concepts of pavement mechanics (Medina & Motta, 2015), by the criterion of application of repeated loads until fatigue of the subgrade. It should be noted that due to the limitations of the software used, the conditions of the mechanical behavior of the structure for analysis were considered to be fixed during the entire life of the permanent way, which does not fully represent reality.

3. Methods and Materials

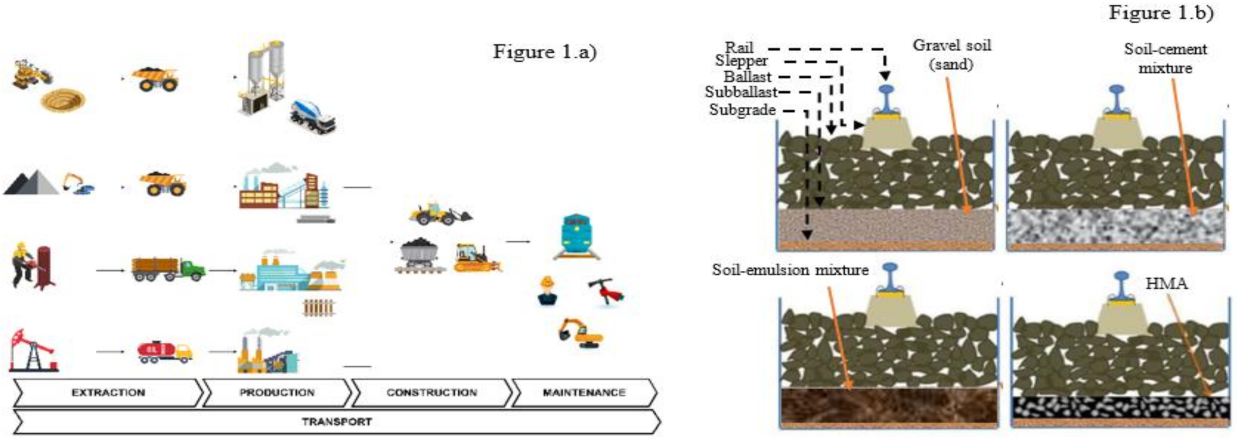
According to Hauschild, Rosenbaum and Olsen (2018), the applications of LCA are varied. In this study of permanent way infrastructure, LCA is combined with civil engineering analysis, more specifically pavement mechanics. Table 4 identifies the LCA steps applied in this study.

Table 4 - Live Cycle Assessment Steps

Scope	*Inventory*	*Impact Assessed*	*Analysis of Results*
Evaluation of measures to improve the load capacity of railway infrastructure in light of the state of the subgrade in conditions with moisture greater than the optimal level of railway pavement (tracks, fasteners, sub-ballast and subgrade)	EcoInvent® (native in SimaPro)	Global warming (greenhouse gas emission – CO_2eq)	Comparison between selected scenarios using gCO_2eq/km as the indicator

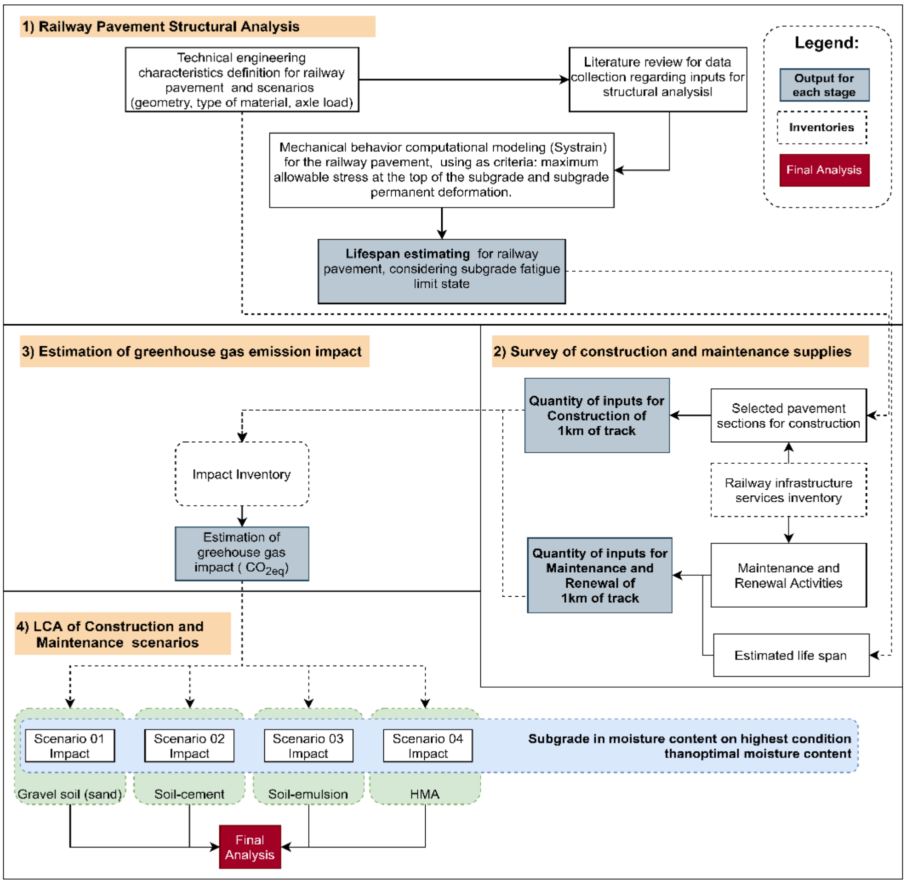
After defining the elements to be submitted to LCA, we selected the railway pavement scenarios, as shown in Figure 1b. In summary, four railway pavement sections were initially chosen, in which variation occurs basically in the type of material applied in the sub-ballast, with use of material such as granular sandy soil, soil-cement, soil-emulsion and hot-mix asphalt (HMA), considering the behavior of the subgrade under conditions of an approximate increase of 2% in relation to optimal moisture content. In other words, the structure will work on the wet side of the compaction curve. Having defined the steps composing the life cycle assessment, In Figure 1a we identify the stages considered, ranging from extraction of the materials to their maintenance.

Figure 1 - a) Stages of the Life Cycle Considered; b) Sections of Railway Pavement Selected for Analysis. Adapted from Sol-Sánchez et al. (2016).



Finally, the flowchart presented in Figure 2 shows the steps employed regarding pavement mechanics combined with LCA, and the assessment of the different scenarios considered. Starting with structural analysis of railway pavement, the main outputs of this step are estimates of the useful life of the subgrade, given the number of standard railway axles that pass over the track until it reaches the final fatigue state.

Figure 2 - Flowchart of the Life Cycle of the Four Scenarios



For this mechanical analysis, we used the stress-deformation analysis tool called Systrain to identify the effective stresses at the top of the subgrade. The information obtained was then used as input in the models of Heukelom and Klomp (1962) and Guimarães (2009), respectively, for analysis of stress and analysis of permanent deformation. Taking a conservative stance, we adopted the lowest value found between the two analyses. Besides this, the relevant outputs were the technical characteristics, such as the materials employed, which were considered in the second step. At this moment, by combining the characteristics of the design sections, we analyzed the quantities of inputs necessary for each scenario, both in the construction and maintenance stages, utilizing the System of Reference Costs of Works (*Sistema de Custos Referenciais de Obras* - SICRO) for inventory of railway infrastructure services. The services used to estimate the quantity of inputs of this study were based on the Ferrogrão project (ANTT, 2016). In step 3, using the SimaPro® software, we employed the data obtained from the EcoInvent® 3.0 inventory to measure the impacts on GHGs. Finally, in step 4, the results of the four scenarios were compared based on the reference criterion defined (quantity of gCO2eq/km) in light of the different materials used.

With regard to the maintenance activities and their timing for the different elements of the permanent way, we considered the strategies described by Bortoli, Bouhaya and Feraille (2020) and Krezo *et al.* (2016), as shown in Table 5. For the renewal activity, we used the reuse criteria defined by Caetano and Teixeira (2016): 40% of the ballast, 31% of the sleepers and 16% of the tracks.

Table 5 - Activities to Maintain the Permanent Way for Different Elements

Component	**Activity**	**Frequency (years)**	**Segment treated**	**Period analyzed (years)**
Renovation of the permanent way	Substitution	30	100%	200
Track	Milling	1	100%	
Ballast	Tamping	1	85%	
	Complementation	10	15cm	
Geometry car	Technological control	1	100%	

Most of the data regarding structural modeling of the pavement using the Systrain v.1.84 software was obtained from the literature, as indicated in Table 6. Only the data on the subgrade were obtained through laboratory tests. To model the resilient modulus (RM) of the materials, we use the compound model, with the coefficients k1 and k2, instead of mean values.

Table 6 - Database for Structural Modeling of Railway Pavement

Scenario	**Track ME (GPa)**	**Sleeper ME (GPa)**	**Ballast RM (MPa)**		**Subgrade**			**Subgrade (granular soil)**			**Source of sub-ballast**
			k1	k2	**Material**	**RM (MPa)** k1	**RM (MPa)** k2	**Moisture**	**RM (MPa)** k1	**RM (MPa)** k2	
1	210* TR-68	32* Concreto	2466,8*** Brita	0,7803***	Granular soil	2182	0.687	≈ hót+2%	23.202	-0.187	SELIG *et al.* (1979)
2					Soil-cement	6680.8	0.429				MACÊDO (2004)
3					Soil-emulsion	1300	0.290				MICELI JR (2006)
4					HMA	4000	-				ALVES (2018)

* Askarinejad & Dhanasekar (2016); **Default Systrain; *** Delgado (2019)

Finally, to compare the scenarios, we defined the maximum use of the permanent way for a period of 200 years, with yearly maintenance activities. However, the differentiation involved the frequency of the renovation activities, which is associated with the period of occurrence of the last fatigue state of the subgrade layer. In other words, the variation of the sub-ballast materials is reflected at this moment.

4. Results

To obtain the main result - the values of the impact on the greenhouse gasses (GHGs) emitted in the construction and maintenance steps – the initial input of the analysis was obtained from the structural modeling of railway pavement, as presented in Table 7. Considering the criteria of fatigue effective stress at the top of the subgrade and permanent deformation of the same layer as final conditions for use of the structure, in a conservative approach, we adopted the lowest value of the effective N (by stress or permanent deformation) to estimate the time of use of the permanent way, where N is the number of axle load passed over the permanent way.

Table 7 - Results of the Structural Modeling of Railway Pavement

Scenario	**Deviation stress (kPa)**	**Confining stress (kPa)**	**RM Subgrade layer (Mpa)**	**Design N (RFFSA)**	**Admissible stress (kgf/cm²)**	**Effective stress on the subgrade (kgf/cm²)**	**Effective N (by stress)**	**Effective N (by deformation)**	**Time until final condition (years)**
1	44.80	56.10	39.76	2.22E+06	0.438	0.448	1.51E+06	1.47E+06	13
2	38.10	66.90	38.47	2.22E+06	0.42	0.38	1.69E+07	1.70E+07	153
3	43.70	61.30	39.11	2.22E+06	0.43	0.44	1.75E+06	1.72E+06	15
4	37.70	71.00	38.05	2.22E+06	0.42	0.38	1.67E+07	1.68E+07	151

It is necessary to stress that the models of stress and permanent deformation used in this analysis were developed for conditions of N below those obtained in this study. Therefore, we used a period of 200 years as the limit for the scenarios considered. In any event, the values of deviation stress at the top of the subgrade in Table 6 are coherent with those reported by Indraratna and Ngo (2018), i.e., on the order of 50 kPa.

With the previous results from use of the SICRO employed in the Ferrogrão Project (ANTT, 2016) and the dimensions considered as inputs in the modeling software, it was possible to obtain the quantities of inputs to estimate the GHG emissions. Due to the specificities, the renewal services were separated from maintenance, to permit a better analysis. Table 7 presents the composition of the inventory of EcoInvent®3, the native base of the SimaPro 9.2 software, which enabled quantifying the emission inventories, in turn used to calculate the impacts of the scenarios studied. Once again, because of the specific characteristics of the renewal activity, it was analyzed separately from the maintenance services. Table 8 shows the results of quantifying the impacts considering the different elements of the railway infrastructure.

The results obtained for the total impact of GHG emissions in scenarios 1, 2 and 3 for the construction stage, in Table 8, have the same order of magnitude as the values presented in Table 3 by Mathieu, Pavaux and Gaudry (2013), as well as the observation that the track is the element that contributes most to the impacts, as also found by Krezo *et al.* (2016) and Stripple and Uppenberg (2010). In this respect, steelmakers are currently making efforts to produce “green steel”, mainly involving replacement of natural gas with hydrogen (Vogl, Åhman & Nilsson, 2020).

Finally, comparison of the elements considered by Bortolli, Bouhaya and Feraille (2020), as presented in Table 9, with the structures analyzed in this study, shows that with use of granular soil and the soil-emulsion mixture in the sub-ballast layer, the impact is nearly double the reference value adopted, involving ideal conditions for functioning of the permanent way. In turn, with use of the soil-cement mixture, the values are near the reference ones. Finally, in the scenario where HMA is used in the sub-ballast, the relevant contribution of this material regarding the impact on global warming is evident.

Table 8 - Quantification of the Impacts on Global Warming with Use of EcoInvent Inventories on SimaPro Software

CATEGORY	ACTIVITIES	UN	CONSTRUCTION				MAINTENANCE				RENEWAL				COMMENTS
			SCENARIOS				Geometric Measurement	Ballast Replacement	Rail Milling	Ballast Tamping	SCENARIOS				
			01 and 02	03 and 04	05 and 06	07 and 08					01 and 02	03 and 04	05 and 06	07 and 08	
Materials and Settings	Steel, low-alloyed, hot rolled {GLO}| market for| Cut-ff, U	kg	135.120,00	135.120,00	135.120,00	135.120,0					113.430,00	113.430,00	113.430,00	113.430,00	Material for rail
	Fibre-reinforced concrete {BR}| market for fibre-reinforced concrete, steel | Cut-off, U	m3	260,05	260,05	260,05	260,05					179,44	179,44	179,44	179,44	Material for sleeper
	Reinforcing steel {GLO}| market for |Cut-off, U	kg	16.579,32	16.579,32	16.579,32	16.579,32					11.506,78	11.506,78	11.506,78	11.506,78	Material for sleeper
	Plasticiser, for concrete, based on sulfonated melamine formaldehyde {GLO}| market for	kg	909,80	909,80	909,80	909,80					630,94	630,94	630,94	630,94	Material for sleeper
	Sodium silicate, solid {GLO}| market for| Cut-off, U	kg	16.528,70	16.528,70	16.528,70	16.528,70					11.471,65	11.471,65	11.471,65	11.471,65	Material for sleeper
	White mineral oil, at plant/ RNA System - Copied from USLCI	kg	411,47	411,47	411,47	411,47					285,58	285,58	285,58	285,58	Material for sleeper
	Concrete sleeper manufacting - Concrete block {BR}| concrete block production| Cut-off, U	kg	536.690,65	536.690,65	536.690,65	536.690,65					370.316,55	370.316,55	370.316,55	370.316,55	Sleeper production
	Material for fastening - Steel, low-alloyed, hot rolled {GLO}| market for| Cut-off, U	kg	5.334,40	5.334,40	5.334,40	5.334,40					4.478,40	4.478,40	4.478,40	4.478,40	Material for fastening
	Track bolts - Steel, low-alloyed, hot rolled {GLO}| market for| Cut-off, U	kg	20,02	20,02	20,02	20,02					17,51	17,51	17,51	17,51	Track bolts
	Rail joints - Steel, low-alloyed, hot rolled {GLO}| market for| Cut-off, U	kg	267,20	267,20	267,20	267,20					233,80	233,80	233,80	233,80	Rail joints
	Tie plates- Steel, low-alloyed, hot rolled {GLO}| market for| Cut-off, U	kg	71.280,92	71.280,9	71.280,9	71.280,9					49.473,32	49.473,32	49.473,32	49.473,32	Tie plates
	Synthetic rubber {GLO}| market for| Cut-off, U	kg	18.153,63	18.153,63	18.153,63	18.153,63					15.246,00	15.246,00	15.246,00	15.246,00	Rail pad
	Building, hall, steel construction {GLO}| market for| Cut-	m2	0,71	0,71	0,71	0,71					0,49	0,49	0,49	0,49	Building for the sleeper precast factory
	Gravel, crushed {RoW}| market for gravel, crushed| Cut-off, U	kg	16.430,0	16.430,0	16.430,0	16.430,0					9.858,0	9.858,0	9.858,0	9.858,0	Material for ballast
	Sand {BR}| market for sand | Cut-off, U	kg	965.280,0	926.668,8	926.668,8						965.280,0	926.668,8	926.668,8	926.668,8	Material for subballast
	Cement, limestone 6-10% {BR}| market for cement, limestone 6-10%| Cut-off, U	kg		86.027,10								86.027,10			Material for subballast - Soil-cement mixture
	Bitumen seal {GLO}| market for| Cut-off, U	kg			86.027,10								86.027,10		Material for subballast - Soil-emulsion mixture
	Bitumen adhesive compound, hot {GLO}| market for| Cut-off, U	kg				1.668.000,0								1.668.000,0	Material for HMA (production and transport)
	Lubricating oil {RoW}| market for lubricating oil| Cut-off, U	kg	0,02	0,02	0,02	0,02					0,01	0,01	0,01	0,01	Lubricant (locomotive)
	Lubricating oil {RER}| market for lubricating oil| Cut-off, U	kg	382,20	382,20	382,20	382,20					272,85	272,85	272,85	272,85	Lubricant (locomotive)
	Diesel {BR}| market for diesel| Cut-off, U	kg	27.715,66	27.715,66	27.715,66	27.715,66					19.787,39	19.787,39	19.787,39	19.787,39	Locomotive fuel
Processes	Locomotive {GLO}| market for| Cut-off, U	un	0,00027	0,00027	0,00027	0,00027					0,00022	0,00022	0,00022	0,00022	Locomotive - considered useful life of 30 years
	Maintenance, locomotive {GLO}| market for| Cut-off, U	un	0,00027	0,00027	0,00027	0,00027					0,00022	0,00022	0,00022	0,00022	Admitted 1 maintance per year to locomotive
	Goods wagen {GLO}| market for| Cut-off, U	un	0,00024	0,00024	0,00024	0,00024					0,00024	0,00024	0,00024	0,00024	Wagon - considered useful life of 30 years
	Maintenance, goods wagon {GLO}| market for| Cut-off, U	un	0,00024	0,00024	0,00024	0,00024					0,00024	0,00024	0,00024	0,00024	Admitted 1 maintance per year to wagon
	Machine operation, diesel, < 18.64 kW, steady-state {GLO}| Cut-off, U	h	32,71	32,71	32,71	32,71					50,82	50,82	50,82	50,82	The greater amount of hours in Renewal is due to the Demolition activity of the railroad.
	Machine operation, diesel, >= 74.57 kW, underground mining {GLO}| Cut-off, U	h	542,59	587,35	587,35	473,40		178,7	1,19	4,1	973,98	983,14	983,14	605,97	The greater amount of hours in Renewal is due to the Demolition activity of the railroad.
	Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| Cut-off, U	h	87,09	87,09	87,09	87,09	0,04				65,80	65,80	65,80	65,80	
	Aplicação de CBUQ - Machine operation, diesel, >= 74.57 kW, underground mining {GLO}| Cut-off, U	h				47,55								47,55	Equipment for applying HMA as subballast layer
	Machine operation, diesel, < 18.64 kW, generators {GLO}| Cut-off, U	h	10,44	10,44	10,44	10,44					7,25	7,25	7,25	7,25	
	Agricultural trailer {GLO}| market for| Cut-off, U	kg	800,00	800,00	800,00	800,00		400,0			800,00	800,00	800,00	800,00	

Table 9 - Measurement of the Impact on GHG Emissions of Railway Infrastructure

CENÁRIO	CONSTRUÇÃO (tCO2eq/km)	MANUTENÇÃO (tCO2eq/km)				RENOVAÇÃO (tCO2eq/km)	TOTAL (tCO2eq/km)	COMPARATIVO BORTOLLI, BOUHAYA & FERAILLE (2020)		
		Aferição	Complemento	Fresagem	Socaria			Elementos de infraestrutura	Subtotal (tCO2eq/km.ano	Total (tCO2eq/km) - 200
1	658,65	0,64	92,35	8,74	30,12	7.964,49	8.755	Sublastro /Equip. Construção /Lastro /Dormente / Trilho / Elementos fixação / Transporte de materiais	22,39	4.478
2	731,93					3.617,65	4.481			
3	756,87					8.162,49	9.051			
4	1.491,03					8.114,23	9.737			

Comparison of the scenarios defined in this study with those of Bortolli, Bouhaya and Feraille (2020) regarding the variability of the moisture conditions of the subgrade indicates that even when employing identical materials in the permanent way, the preservation of the ideal working conditions of the subgrade is essential for it to have the least impact on global warming, due to the lower frequency of maintenance/renewal activities. Besides this, it is possible to state that the use of artificial materials to improve the support capacity of the subgrade layer can increase the impact by about 3% in the case of the soil-emulsion mixture, making the use of this alternative unattractive according to the criterion of impact on global warming when compared with the layer composed only of sandy soil. In contrast, the soil-cement mixture has a considerable advantage in comparison with Scenario 1. However, when using HMA, the increase of the potential impact on global warming is approximately 11% in comparison with the use of the reference material, sandy soil. This shows that even with the distinct frequencies of the maintenance and renewal activities of the scenarios analyzed, considering the condition for use of the track with the subgrade having moisture higher than ideal, based on the parameter of the impact on global warming, the results indicate that the use of stabilized natural materials such as Portland cement for the subgrade layer can be an attractive alternative in decisions on railway infrastructure projects. Nevertheless, the same cannot be said regarding the use of asphaltic materials such as emulsion and HMA. That conclusion depends on the performance deterioration model adopted.

5. Final Conclusions

A better understanding of the impacts caused by human action allows defining action strategies that range from the broadest level, such as management based on ecosystems as proposed by Sudmeier-Rieux *et al.* (2021), to operational measures, such as implementation of environmental impacts as a criterion for public spending on railway infrastructure projects, as suggested by Landgraff, Schirmer and Marschnig (2021). Both approaches are focused on offering practical instruments to society to measure uncertainties regarding the various impacts to which the planet is subject, such as the potential for global warming.

Thus, the present study focused on the development of a method to quantify the many impacts and emissions generated in the processes of constructing and maintaining railway infrastructure, through life cycle assessment with the application of civil engineering tools, such as pavement mechanics, with the use of emission inventories and impacts recognized internationally.

To apply this method, we selected three engineering solutions to improve the mechanical performance of the railroad subgrade, as proposed by Lazorenko *et al.* (2019). The result of using the degradation model applied here indicated that the use of asphaltic materials is not attractive from the standpoint of the potential impact on global warming in comparison with other materials, such as Portland cement or even fine natural aggregates without mixtures.

For future studies, we can suggest using other solutions described by Lazorenko *et al.* (2019), as well as variation of the materials in different permanent way elements, such as wood versus steel sleepers, or even the use of steel slag as an input for the sub-ballast layer. This last analysis would be relevant from the standpoint of LCA, since slag is a byproduct of the end of the life cycle of other materials. Therefore, it would be possible to obtain a broader view and obtain relevant information about the performance of using these inputs from a life cycle perspective.

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