sustainability

MDPI

Article

LCA of Different Construction Choices for a Double-Track Railway Line for Sustainability Evaluations

Clara Celauro [1], Andrea Cardella [1] and Marco Guerrieri [2,*]

[1] Dipartimento di Ingegneria, Università degli Studi di Palermo, Viale delle Scienze, 90128 Palermo, Italy
[2] DICAM (Department of Civil, Environmental and Mechanical Engineering), University of Trento, Via Mesiano 77, 38123 Trento, Italy
* Correspondence: marco.guerrieri@unitn.it

Abstract: The international commitment to achieve carbon neutrality in the next few decades has oriented human activities towards the preservation of natural and non-renewable resources. In this context, a great research effort has been devoted to the search for sustainable solutions for the infrastructure construction sector, based on a thorough assessment of the environmental impact (EI). In this regards, Life Cycle Assessment (LCA) is considered one of the main components of Environmental Impact Assessment (EIA) and, for a comprehensive analysis, all the costs incurred by stakeholders during the useful life of the infrastructure should also be taken into account, applying the Life Cycle Cost (LCC) methodology. So far, there is a lack of combined LCA and LCC analyses of railway projects to support a proper sustainable decision-making process at a project level. Therefore, this study aimed to contributed to this topic by determining the environmental effect and related costs of different planning and construction choices in terms of material and maintenance strategies. For this purpose, first, an LCA of typical railway infrastructures with a ballasted track was developed. The case study considered two different functional units of a double-track railway line: 1 km of embankment section and 1 km of a cut section, in straight alignment. After defining five alternative railway infrastructure scenarios with different materials (virgin or recycled material) and construction methods (e.g., lime stabilization), two different railway track maintenance approaches were analysed. SimaPro was used to analyse the case study, and the results were compared with those obtained using the PaLATE software, suitably adapted for use in the railway sector. Finally, a cost analysis was carried out using Life Cycle Cost (LCC) methodology for all the scenarios analysed. The results obtained in terms of EI and related costs of each scenario provide useful information, allowing a sustainable planning approach: as a general result, the initial construction phase always involves the larger part of the total environmental impact while the material production is the most polluting phase, reaching percentages always higher than 50% of the total.

Keywords: LCA; LCC; railway; transport infrastructures; recycled materials; soil stabilization

check for updates

Citation: Celauro, C.; Cardella, A.; Guerrieri, M. LCA of Different Construction Choices for a Double-Track Railway Line for Sustainability Evaluations. *Sustainability* **2023**, *15*, 5066. https://doi.org/10.3390/su15065066

Academic Editors: Rosolino Vaiana and Vincenzo Gallelli

Received: 29 January 2023
Revised: 2 March 2023
Accepted: 8 March 2023
Published: 13 March 2023

1. Introduction

Environmental impact (EI) reduction is one of the major focal points of the scientific and political communities; this target passes through correct assessment of several impact types.

In recent years there has been growing attention in the transport sector, no longer only concerning emissions from different means of transport vehicles, but also the EI caused by the construction of new infrastructures and the maintenance processes of existing ones.

In the last twenty years, several studies have been developed for evaluating the environmental impact of the railway sector. In these studies, there is great heterogeneity in the methodological approach, analysis period, railway type, software and data set used. Moreover, different railway systems are considered, including high-speed rail (HSR), ordinary rail, tramways and light rail transit. It is not easy to make a rigorous comparison of these studies as they present different methodologies and limitations. Nevertheless, the most relevant results related to Life Cycle Assessment (LCA) are briefly analysed in this article. A comprehensive approach should consider both the construction activities and the maintenance works of the railway and the use phase. Focusing only on the railway infrastructure, the elements to consider are different from the railway track to the signal and telecommunication systems.

This clarifies why it is not possible to determine a standard impact value of a railway infrastructure section of a given length, because the presence or absence of railway facilities and structural elements depends on a huge number of factors, such as land topography, energy sources, urbanisation, etc. Therefore, it is clear how important the examination of the railway infrastructure during the construction and maintenance phases is for the assessment of the EI.

A very interesting study covering all LCA phases of a HSR is that of Stripple et al. [1] regarding the Bothnia Line in Sweden. In this research, a "top-down" approach is applied for an entire construction site by measuring the energy consumption, materials waste, and emissions related to cut sections, embankments, tunnels and bridges sections. Another important aspect of this approach was the division of the whole railway infrastructure into several structural components: foundations, tracks, power supply systems, tunnels, bridges, stations, etc.

Chang and Kendall [2] conducted a study on California's high-speed rail system (HSR), showing that 80% of the total impact derives from material production while railway transport activities only accounted for 15% of the total.

The International Union of Railways [3] has estimated that rails production accounts for 50% of the total impacts related to railway lines construction. This result cannot be generalized, because in several cases the site preparation (vegetation cutting, removal of organic soil layers, etc.) and construction of the embankment body can be very relevant.

As a matter of fact, for instance, the study [4] shows that the environmental impacts of railway infrastructure are correlated to land topography. Another example is given by the study [5] which analyse the "Follo Line" in Norway whose railway infrastructure runs for 90% of its length in tunnels and therefore the EI arises mainly from the construction of the railway tunnels; similar results are described in [6].

In connection with the occurrence of bridges and tunnels, it is interesting to note the study by Yue et al. [7]; in it, 1318 km of HSR between Beijing and Shanghai are analysed. The authors carried out analyses of different scenarios in which the percentage values of the length of the bridges with respect to the total line length are in the range of 50–80.4%. The research pointed out that a reduction of tunnels, bridges, and reinforced underpasses brings significant benefits in terms of environmental emissions, but without safety and efficiency reduction.

Taking into account the high impact related to the construction phase of railway infrastructures, other studies [8,9] have proposed alternative construction solutions in order to reduce EI of the construction and maintenance phases by specific measures for increasing the useful life. Giunta et al. [8] considered a different solution for track-bed characterized by the use of bitumen-stabilized b (BSB); in comparison to traditional railway tracks, the use of BSB produces a significant reduction of the number of maintenance activities during the railway life cycle, with a consequential decrease in environmental impacts and costs.

After calculating the EI, it is appropriate to monetize the same through an economic evaluation. As also indicated in the "Handbook on the External Costs of Transport" by the European Commission [10], environmental costs must be taken into account as external costs for a complete LCC. Of course, these costs are not directly linked to maintenance or management activities, but the emissions from such activities, therefore, have environmental and social impacts.

The ISO 14008 [11] provides a framework that includes the principles and guidelines for monetizing EI, but despite the current legislation, there are several methods for monetizing impacts, also with significant differences [12].

An example of EI monetization in the railway sector is given by Giunta et al. [8], which refers to monetization with an ECO-COST approach, i.e., considering the costs required to reduce pollution and resource depletion.

The advantage comes from the possibility of having a single indicator that is not only useful for the railway infrastructure manager, but understandable for all stakeholders, and of course provides a link between environmental and economic aspects, but we must not believe that economic compensation can solve the problems arising from the impacts under consideration. Ultimately, this process allows these costs to be integrated into a broader economic view, the LCC, which allows for an economic assessment of the work over its entire useful life, taking into account all associated costs.

So far, there is a lack of LCA and LCC analysis of railway projects to support a proper sustainable decision-making process when selecting construction techniques, materials, and maintenance strategies and the purpose of this study is to provide a contribution to it. Therefore, Life Cycle Assessment (LCA) was first carried out for a standard double-track rail-way line, considering the railway entirely in an embankment or in a cut section. Different construction and maintenance techniques of railway bodies and superstructures were analysed for each section. For a correct analysis of LCA, it is necessary to collect the data from an environmental LCA database, such as EcoInvent, UCSL, or others, integrated into the LCA analysis tools including, for example, SimaPro, PaLATE [13], OpenLCA [14], GaBi [7], KCL-ECO [1] or GREET [15]. Since several technical software on LCA are available today [16,17], in this article a comparison is given of the results obtained using two of the most widely used: SimaPro and PaLATE.

Following the LCA technique, the environmental impacts were monetized in order to perform the LCC analysis, with the aim to estimate the total costs associated with the entire useful life of the analysed railway functional units.

For both analyses, two sustainable construction techniques were considered: one is based on the use of secondary materials, such as the reclaimed asphalt pavement (RAP) produced in road maintenance activities (to be used for the bituminous sub-ballast in railway sections), and the second is the lime treatment of fine soils for embankment and/or subgrade construction. In fact, in countries with developed railway networks, railway projects (new constructions, doubling projects, removal of level crossings, etc.) often involve road-related structures and, consequently, reclaimed asphalt pavement (RAP) is frequently available as a secondary material recovered by the project itself. Furthermore, RAP may also be available as a secondary material coming from other construction activities (road maintenance activities, for instance, produce huge volumes of RAP that is not always possible to fully reuse in new pavement structures). Therefore, in the view of circularity in an infrastructure project and for maximizing the use of secondary materials, it is important to evaluate the benefits of the use of RAP in different percentages for the bituminous sub-ballast layers, as a strategy for increasing the environmental sustainability of railway projects thanks to the saving of virgin aggregates and binder. Indeed, a few studies have already proved that a bituminous sub-ballast layer with reclaimed asphalt—thanks to proper mix design—is adequate for guaranteeing mechanical performance comparable with those of traditional sub-ballast, with virgin components only, but there is a need for future studies for developing sound technologies for this purpose [18,19].

On the other hand, earthmoving activities for railway construction produce huge volumes of different types of soils and, amongst these, fine clayey soils that, due to their poor mechanical properties, are considered for backfilling only or as waste material to be dumped. Indeed, lime stabilization is a well-known sustainable and cost-effective technique [20–22], since it allows for reusing these fine soils for structural purposes in linear infrastructures (in embankment layers or even as subgrade), thanks to the improved mechanical resistance developed after mixing the soil with lime, thus saving volumes of valuable natural and non-renewable materials.

Considering the discussion above, the aim of this paper is to evaluate the effect of different planning and construction choices in railway projects, in terms of material and maintenance strategies for supporting sustainable decisions at projects level: therefore, the study was intentionally focused on the environmental benefits only of the above sustainable techniques, in terms of EI and related life cycle costs.

2. Methods

2.1. Life Cycle Assessment

LCA is universally acknowledged to be the best approach for assessing EI because it is an objective process for evaluating the environmental loads associated with a product, process, or activity.

The main international regulations are represented by ISO standard series [23] UNI EN ISO 14040:2021 and UNI EN ISO 14044:2021. In accordance with the ISO 14040 standard series, an LCA study comprises four steps that affect one another (Figure 1):

1. Definition of goal, scope, and functional unit:

In this stage, the aims of the study, the functional unit, the system analysed, the data requirements and the boundaries of the study are declared.

2. Life cycle inventory (LCI):

In this stage, the full inventory of the in-out flows of the system, concerning the individual operations, is defined. The result will be an inventory table, showing all resource uses and emissions associated with the functional unit.

3. Life cycle impact assessment (LCIA):

In this stage, the potential impact deriving from the elementary flows is assigned to several classes and quantified.

4. Interpretation:

This is the final step of LCA, where the results are evaluated with respect to the aims and scope for writing the conclusion and recommendations. In this phase, a sensibility analysis is extremely important for formulating correct advice to improve the process.

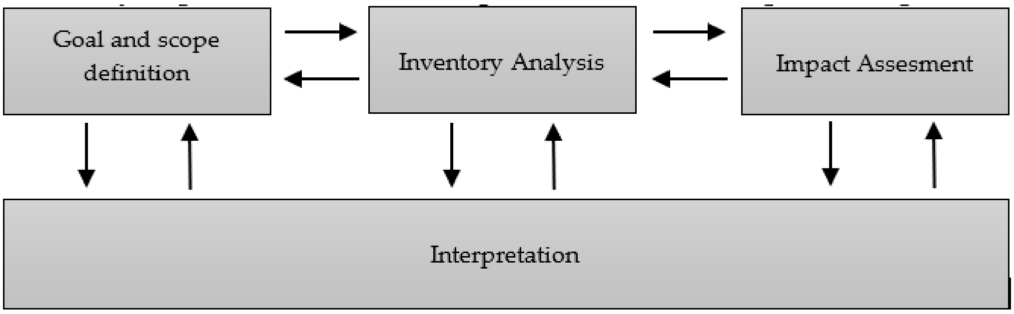


Figure 1. Life Cycle Assessment framework (adapted from ISO 14044 regulations).

2.2. SimaPro Software

The software used for analysing the case study is the SimaPro; it is one of the most widely used and established LCA analysis software: it allows us to collect, monitor, and analyse the environmental performance of products and services following the recommendations of the ISO 14040 standard series.

For this study, for modelling the inventory phase, the EcoInvent database was applied, and to calculate the impacts, the EPD (Environmental Product Declarations) method was used.

2.3. PaLATE Software

PaLATE (Pavement Life Cycle Assessment Tool for Environmental and Economic Effects) software is an Excel-based tool specifically designed for the pavement LCA model.

The adaptability of this software makes it very versatile, which is why it was chosen for the study [13].

2.4. Life Cycle Cost

LCC is a methodology of economic evaluation by which all relevant costs over the useful life of a given project (e.g., transportation infrastructures) are calculated. LCC is not only useful to determine the cost of the infrastructure but is also helpful in the decision-making process of design and maintenance, etc., since it allows us to define all of costs associated with the system's life cycle [24] including research, development, production, construction, maintenance and disposal costs at the end-of-life phase.

The fundamental aspect of LCC is to determine all the parameters to be evaluated in order to make a correct estimate. For a correct analysis of railway infrastructure, it is necessary to consider the following main costs:

- Agency cost, supported by the infrastructure manager responsible for the design, construction, maintenance, renewal and modernization of the railway line. In this study, the agency cost is estimated based on [25].
- Delay costs, i.e., the variety of costs associated with train delays experienced by all the users and stakeholders [26]. Generally, these costs are caused by the work zones. In detail, delay costs comprise:
    - Operator cost, related to the use of the trains, energy and fuel consumption, and the crew; for these costs reference was made to [26].
    - Users' cost, concerning the use of the railway line. Data were for the Palermo-Catania railway line (year 2019): user time value was estimated using data from [27].
- External costs, relating to monetization of the EI. This economic analysis was carried out regarding the values [28].

With regard to the value of time (VOT) and vehicle operating cost (VOC), reference was made to the values processed by [29] based on HEATCO data [29]. According to these sources, the VOC is determined on the basis of components such as repair and maintenance of vehicles, fuel, staff and all costs related to the use of the train, obviously related to the reference country.

Regarding users' costs, this is the most controversial point to determine, since it is necessary to monetize the user's time: to evaluate the VOT, the approach proposed by previous studies [29] takes into account the average salary of the country and additional costs such as taxes, etc.

Therefore, depending on the maintenance plans considered, the delays of the line are estimated, taking into account that there is no interruption in service but a reduction of speed.

In this study, all the above costs are properly actualized, considering a discount rate equal to 1.2%, determined as the difference between the average inflation rate of 2.06% and the average annual average nominal interest rates derived from the annual BTP yield of 3.25%.

3. Case Study

The first step of a LCA study is the definition of the functional unit. In this study the functional unit of 1 km of double-track railway line is split into two functional units; in detail, defined are a typical embankment section of 1 km and a typical cut section of 1 km, both in straight alignment. The distance between the natural ground surface and the top surface of the rails was set equal to 2.25 m for the cross-section in the embankment and to 1.00 m for the cut section.

3.1. Material and Scenarios

For a correct LCA analysis, it is essential to define the materials and scenarios under consideration. The whole life cycle of a railway infrastructure may be subdivided into five main phases: (1) material production phase; (2) construction phase; (3) use phase; (4) maintenance and rehabilitation phase; and (5) end-of-life phase.

In this study, ten different scenarios were analysed: 5 for the embankment section and 5 for the cut section. These scenarios include different construction techniques based on the use of virgin material only, the reuse of discarded materials (i.e., recycled asphalt pavement, RAP), as well as in situ stabilization of fine-grained soils with lime in order to improve soil performances.

In detail, the following techniques and materials are considered:

- Use of lime stabilization of clayey soils, in the case of soils unsuitable to be used for construction purposes;
- Use of different percentages of reclaimed asphalt pavement (RAP) for the bituminous sub-ballast layer.

Table 1 summarizes the main characteristics of the 10 scenarios considered in this study and the percentages of RAP and stabilization of fine-grained soils with lime. For instance, in Scenario 5 the sub-ballast contains 40% of recycled material.

Table 1. Scenarios definition for embankment and cut sections.

Embankment Section					
Layer	**1**	**2**	**3**	**4**	**5**
Sub-ballast	V	V	V	V + 40%R	V + 40%R
Highly compacted soil	V	V	L (5.5%)	V	L (5.5%)
Embankment body	V	L (2.5%)	L (2.5%)	V	L (2.5%)
Impermeable layer	V	V	V	V	V
Cut Section					
Layer	**1**	**2**	**3**	**4**	**5**
Sub-ballast	V	V	V	V + 40%R	V + 40%R
Highly compacted soil	V	V	L (5.5%)	V	L (5.5%)
Embankment body	V	L (2.5%)	L (2.5%)	V	L (2.5%)

(V = Virgin material, R = recycled material, L = lime stabilization).

These railway construction techniques were compared in order to identify the best scenario in terms of environmental impacts.

It is clear that earthmoving phases have a fundamental role during the construction phase. Table 2 shows the type and classification of soils considered for each layer of the railway infrastructure.

Table 2. Type and HRB-AASHTO classification of soils used for the construction of the analysed railway infrastructure.

Layer	**Natural Subgrade**	**Upper Layer of the Embankment**	**Embankment Body**	**Capillary-Break**	**Soil Used for Remediation**
Classification	A7-6	A1-b	A2-7	2/25 mm	A1-b

For scenarios in which lime stabilization is considered, the in situ availability of subgrade soils of class A7-6 was assumed. Another important hypothesis is to consider RAP as already present in the production plant because RAP is a recycled product, and therefore the impacts of its previous life are not considered.

Regarding the railway superstructure, the main characteristics common for the two railway functional units are:

- UIC60 rails (weight: 60.4 kg/m; grade 900A steel that combines high strength with moderate ductility and high strain hardening rate);
- Pandrol fastenings;
- Concrete sleepers (weight: 260 kg; module: 60 cm);
- Ballast layer (depth: 50 cm; Los Angeles index lower than 20–25; granular materials ranging between 15–20 and 60–65 mm in size).

The height of the top surface of the rails with respect to the natural ground surface was set at 2.55 m and 1.00 m for the embankment and the cut section, respectively (cf. Figures 2 and 3).

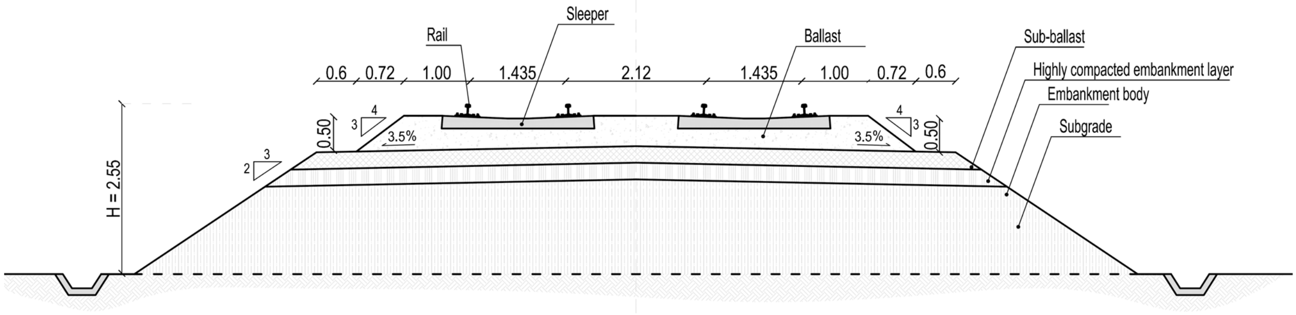


Figure 2. Railway embankment cross-section under analysis.

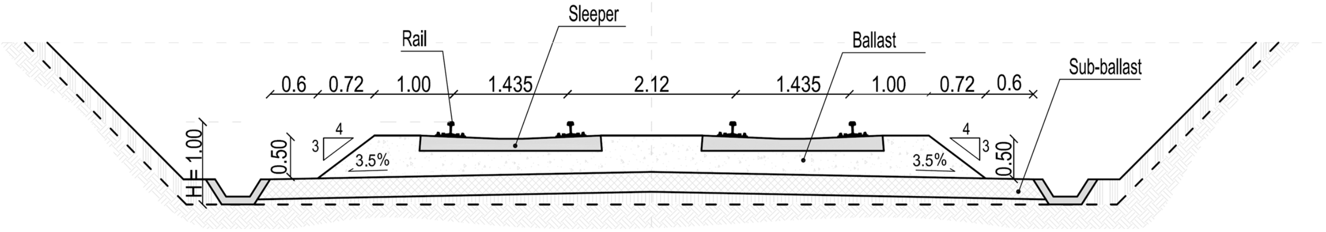


Figure 3. Railway cut cross-section under analysis.

Based on data concerning the construction of new railway lines in Italy, it was considered that virgin and recycled materials were transported by road transportation systems using heavy-duty dump trucks (20 t mass) with diesel engines. The average values of the transport distances considered in the present study are summarized in Table 3 [9]. These values were inferred from recent railway works in Italy (see Table 3). For in situ lime stabilization, an average transport distance of 1 km was considered.

Table 3. Average transport distances.

Transport Distances	km
Rails	900.00
Sleepers	800.00
Bitumen and emulsion plant	110.00
Lime plant	110.00
Asphalt plant	35.00
Landfill	20.00
Quarry site	15.00
Soil for earthmoving	15.00
Water	5.00

3.2. Useful Life and Manutention

A complete life cycle of a railway infrastructure can be subdivided into the following five phases:

- Materials production

All phases of the material production process, from the extraction of raw materials to transformation into the finished product that will be used in the railway infrastructure. It also includes transport from the quarry or production site to the construction site.

- Construction

All the required operations, works, and equipment for constructing the railway infrastructure are considered, particularly the different equipment used and their associated consumption.

- Use

This is the longest phase of the life cycle. In this phase, it is necessary to consider energy consumption due to the railway infrastructure deterioration and to evaluate the polluting emissions deriving from railway traffic.

- Maintenance and Rehabilitation

All interventions to guarantee the highest standards of quality, safety, and reliability of the infrastructure must be considered. According to the railway service life, these interventions may concern the railway track and the railway body (in these cases, they are expected to take place every 60–100 years).

For every maintenance operation (generally scheduled by “on condition” logic) the raw materials production, the demolition activities, the total materials to be sent to the landfill and the transport must always be considered.

- End of life

Depending on the assumptions made at the beginning of the study, there may be two different options: complete disposal to landfill or partial recycling of the railway infrastructure components.

In this study, the analysis of the use phase is excluded, because it is assumed to be identical for the different hypothesized scenarios, and therefore is not significant for comparison purposes. Similarly, the delay times are not considered in the construction and maintenance phases.

The traffic level is hypothesized to be in the range 350–700 million gross tonnes (only passenger services).

The maintenance of the railway superstructure is supposed to be “on condition” and according to the scientific literature [30–32] two very different maintenance plans have been considered:

- (A) Maintenance Plan A: intervention every 5 years;
- (B) Maintenance Plan B: intervention every 10 years.

In order to maintain the superstructure in good functional condition, each maintenance activity requires the following interventions:

- Tamping of the ballast;
- Grinding of the ballast;
- Rails brushing and profiling.
- In both maintenance plans, the replacement of the concrete sleepers and the ballast is scheduled at the end of the 30th year, starting from the construction of the railway infrastructure.

Ordinary maintenance is not considered because it requires the use of low quantities of materials and energy, and therefore is negligible with respect to the aforementioned maintenance operations.

To make the following data easier to read, Figure 4 clarifies the nomenclature used and Table 4 provides a summary of the main characteristics of each scenario.

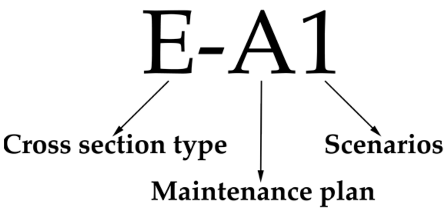


Figure 4. Nomenclature associated with each scenario.

Table 4. Summary of analysis scenarios.

Cross-Section Type	Maint. Plan	Scenarios				
E	*A*	1	2	3	4	5
Embank.	Every 5 years	All virgin material	Lime stabilization for embankment body	Lime stabilization for embankment body and highly compacted soil	RAP for sub-ballast layer	Lime stabilization for embankment body and highly compacted soil, use of RAP for sub-ballast layer
	B Every 10 years					
C	*A*	1	2	3	4	5
Cut	Every 5 years	All virgin material	Lime stabilization for embankment body	Lime stabilization for embankment body and highly compacted soil	Use of RAP for sub-ballast layer	Lime stabilization for embankment body and highly compacted soil, use of RAP for sub-ballast layer
	B Every 10 years					

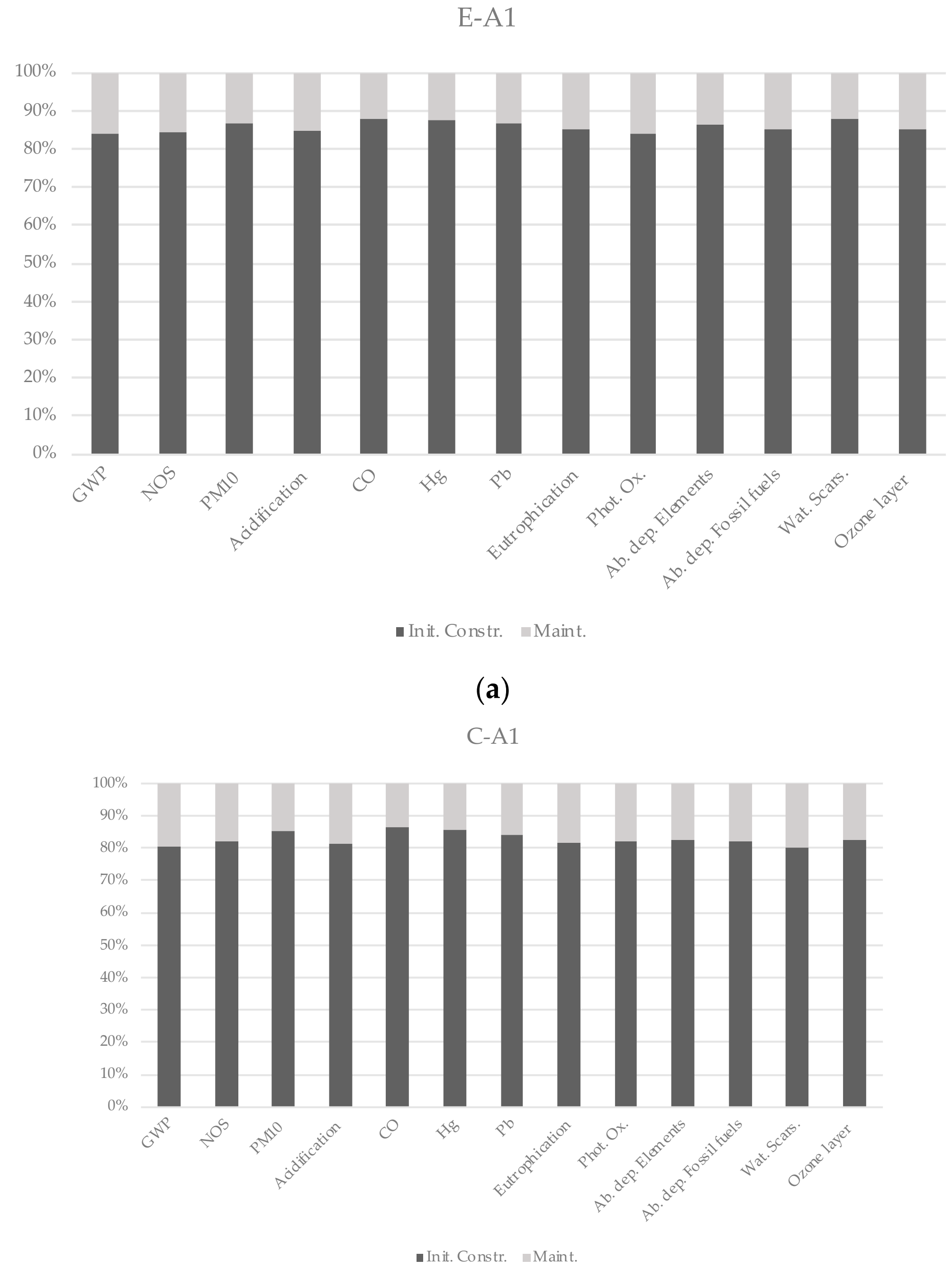
4. Results

To obtain the most exhaustive outcomes possible, we have selected some of the most important impact parameters related to railway infrastructure construction and maintenance phases. All impact categories and substances considered in the LCA analysis are listed in Table 5 with their acronyms and units of measurement.

Table 5. List of abbreviations used for impact categories and substances.

	Impact Categories/Substance	Unit
GWP	Global warming (GWP100 a)	kg CO_2 eq
NOx	Nitrogen oxides	kg
PM10	Particulate matter	kg
Acidif.	Acidification (fate not incl.)	kg SO_2 eq
CO	Carbon monoxide	kg
Hg	Mercury	kg
Pb	Lead	kg
Eutroph.	Eutrophication	kg PO_4 eq
Phot. Ox.	Photochemical oxidation	kg NMVOC
Ab. dep. Elements	Abiotic depletion, elements	kg Sb eq
Ab. dep. Fossil fuels	Abiotic depletion, fossil fuels	MJ
Wat. Scars.	Water scarcity	m^3 eq
Ozone layer	Ozone layer depletion (ODP)	kg CFC-11 eq

In the first phase of the research, the environmental impacts of the construction and maintenance phases were estimated. Figure 5 shows the results obtained from the analysis of the first scenarios, i.e., embankment and cut sections and Maintenance Plan A (scenarios E-A1 and C-A1, respectively).



(**a**)

(**b**)

Figure 5. Initial construction/maintenance comparison: Maintenance Plan A. (**a**) Embankment section; (**b**) cut section.

The results are consistent with those of other studies [5,33]; in fact, the impacts of the initial construction phase are higher than those of the maintenance phase (Table 6). Similar outcomes were found for the alternative scenarios considered (see Table 1).

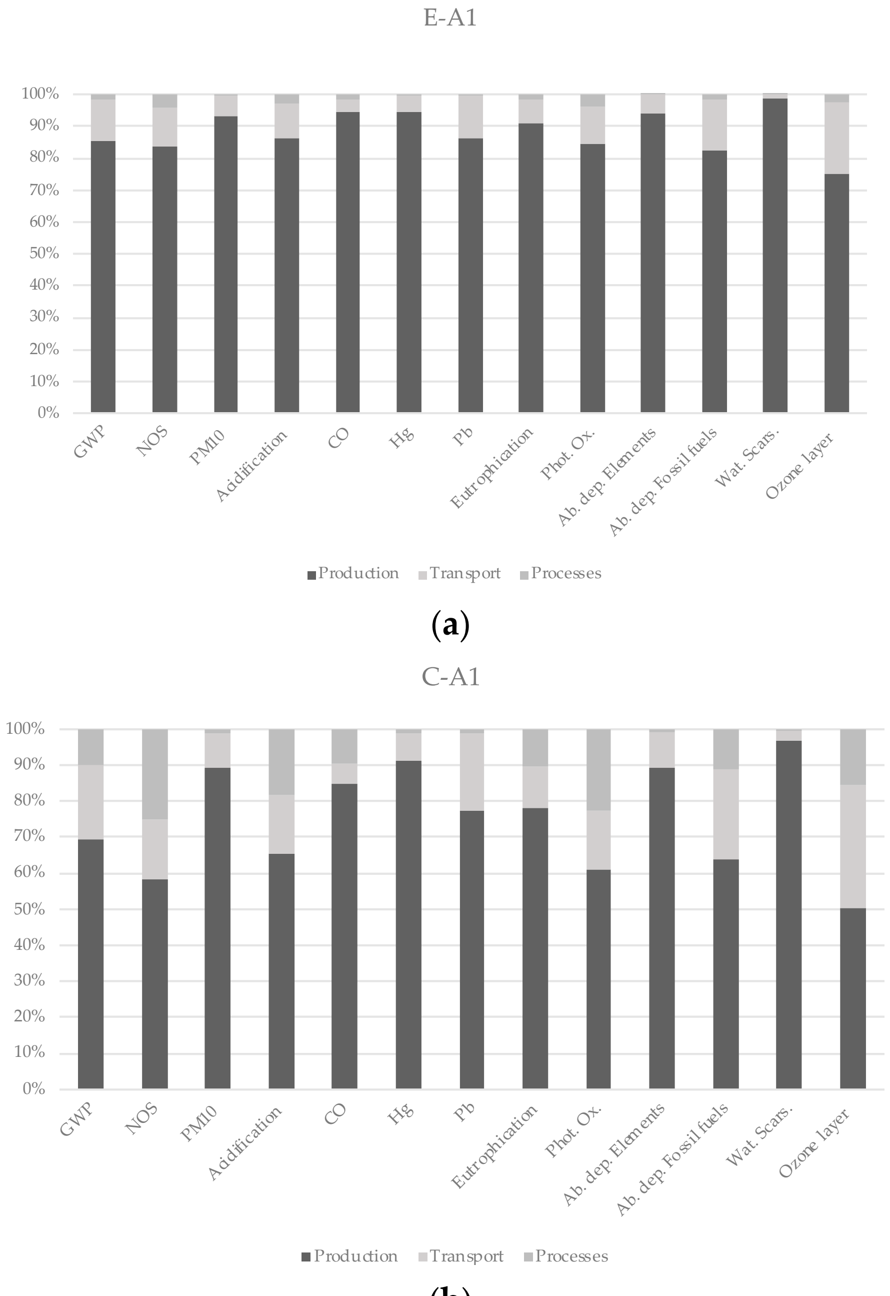
Table 6. LCA results of 1 km of railway infrastructure in embankment (E) and cut (C) sections for different scenarios (cf. Table 1).

E-A1														
Scenario		**GWP**	**NOS**	**PM_{10}**	**Acidif.**	**CO**	**Hg**	**Pb**	**Eutroph.**	**Phot. Ox.**	**Ab. Dep. Elements**	**Ab. Dep. Fossil Fuels**	**Water Scarcity**	**Ozone Layer**
	N° and Phase	**kg CO_2 eq**	**kg**	**kg**	**kg SO_2 eq**	**kg**	**kg**	**kg**	**kg PO_4 eq**	**kg NMVOC**	**kg Sb eq**	**MJ**	**m^3 eq**	**kg CFC-11 eq**
1	Constr.	2.00×10^{6}	8.26×10^{3}	1.56×10^{3}	1.03×10^{4}	1.46×10^{4}	8.24×10^{-2}	3.16×10^{0}	3.41×10^{3}	1.10×10^{4}	1.64×10^{1}	2.40×10^{7}	1.27×10^{6}	2.01×10^{-1}
	Maint.	3.86×10^{5}	1.54×10^{3}	2.34×10^{2}	1.86×10^{3}	2.02×10^{3}	1.19×10^{-2}	4.79×10^{-1}	5.87×10^{2}	2.08×10^{3}	2.58×10^{0}	4.15×10^{6}	1.72×10^{5}	3.50×10^{-2}
2	Constr.	1.80×10^{6}	7.64×10^{3}	3.65×10^{3}	9.47×10^{3}	1.35×10^{4}	8.50×10^{-2}	3.82×10^{0}	3.15×10^{3}	1.02×10^{4}	2.44×10^{1}	2.12×10^{7}	8.67×10^{5}	1.77×10^{-1}
	Maint.	3.86×10^{5}	1.54×10^{3}	2.34×10^{2}	1.86×10^{3}	2.02×10^{3}	1.19×10^{-2}	4.79×10^{-1}	5.87×10^{2}	2.08×10^{3}	2.58×10^{0}	4.15×10^{6}	1.72×10^{5}	3.50×10^{-2}
3	Constr.	1.71×10^{6}	7.32×10^{3}	4.72×10^{3}	9.06×10^{3}	1.29×10^{4}	8.59×10^{-2}	4.08×10^{0}	3.05×10^{3}	9.84×10^{3}	2.76×10^{1}	1.99×10^{7}	6.91×10^{5}	1.66×10^{-1}
	Maint.	3.86×10^{5}	1.54×10^{3}	2.34×10^{2}	1.86×10^{3}	2.02×10^{3}	1.19×10^{-2}	4.79×10^{-1}	5.87×10^{2}	2.08×10^{3}	2.58×10^{0}	4.15×10^{6}	1.72×10^{5}	3.50×10^{-2}
4	Constr.	1.99×10^{6}	8.18×10^{3}	1.50×10^{3}	1.02×10^{4}	1.45×10^{4}	8.23×10^{-2}	3.15×10^{0}	3.40×10^{3}	1.09×10^{4}	1.64×10^{1}	2.39×10^{7}	1.26×10^{6}	2.00×10^{-1}
	Maint.	3.86×10^{5}	1.54×10^{3}	2.34×10^{2}	1.86×10^{3}	2.02×10^{3}	1.19×10^{-2}	4.79×10^{-1}	5.87×10^{2}	2.08×10^{3}	2.58×10^{0}	4.15×10^{6}	1.72×10^{5}	3.50×10^{-2}
5	Constr.	1.70×10^{6}	7.24×10^{3}	4.67×10^{3}	8.98×10^{3}	1.29×10^{4}	8.58×10^{-2}	4.07×10^{0}	3.04×10^{3}	9.74×10^{3}	2.76×10^{1}	1.98×10^{7}	6.87×10^{5}	1.65×10^{-1}
	Maint.	3.86×10^{5}	1.54×10^{3}	2.34×10^{2}	1.86×10^{3}	2.02×10^{3}	1.19×10^{-2}	4.79×10^{-1}	5.87×10^{2}	2.08×10^{3}	2.58×10^{0}	4.15×10^{6}	1.72×10^{5}	3.50×10^{-2}
C-A1														
Scenario		**GWP**	**NOS**	**PM_{10}**	**Acidif.**	**CO**	**Hg**	**Pb**	**Eutroph.**	**Phot. Ox.**	**Ab. Dep. Elements**	**Ab. Dep. Fossil Fuels**	**Water Scarcity**	**Ozone Layer**
	N° and Phase	**kg CO_2 eq**	**kg**	**kg**	**kg SO_2 eq**	**kg**	**kg**	**kg**	**kg PO_4 eq**	**kg NMVOC**	**kg Sb eq**	**MJ**	**m^3 eq**	**kg CFC-11 eq**
1	Constr.	1.60×10^{6}	7.12×10^{3}	1.37×10^{3}	8.07×10^{3}	1.28×10^{4}	7.10×10^{-2}	2.49×10^{0}	2.60×10^{3}	9.41×10^{3}	1.21×10^{1}	1.91×10^{7}	6.83×10^{5}	1.66×10^{-1}
	Maint.	3.86×10^{5}	1.54×10^{3}	2.34×10^{2}	1.86×10^{3}	2.02×10^{3}	1.19×10^{-2}	4.79×10^{-1}	5.87×10^{2}	2.08×10^{3}	2.58×10^{0}	4.15×10^{6}	1.72×10^{5}	3.50×10^{-2}
2	Constr.	1.52×10^{6}	6.87×10^{3}	2.20×10^{3}	7.75×10^{3}	1.23×10^{4}	7.20×10^{-2}	2.75×10^{0}	2.49×10^{3}	9.11×10^{3}	1.53×10^{1}	1.80×10^{7}	5.25×10^{5}	1.57×10^{-1}
	Maint.	3.86×10^{5}	1.54×10^{3}	2.34×10^{2}	1.86×10^{3}	2.02×10^{3}	1.19×10^{-2}	4.79×10^{-1}	5.87×10^{2}	2.08×10^{3}	2.58×10^{0}	4.15×10^{6}	1.72×10^{5}	3.50×10^{-2}
3	Constr.	1.48×10^{6}	6.73×10^{3}	2.67×10^{3}	7.57×10^{3}	1.21×10^{4}	7.24×10^{-2}	2.86×10^{0}	2.45×10^{3}	8.94×10^{3}	1.67×10^{1}	1.74×10^{7}	4.48×10^{5}	1.52×10^{-1}
	Maint.	3.86×10^{5}	1.54×10^{3}	2.34×10^{2}	1.86×10^{3}	2.02×10^{3}	1.19×10^{-2}	4.79×10^{-1}	5.87×10^{2}	2.08×10^{3}	2.58×10^{0}	4.15×10^{6}	1.72×10^{5}	3.50×10^{-2}
4	Constr.	1.59×10^{6}	7.04×10^{3}	1.32×10^{3}	7.99×10^{3}	1.27×10^{4}	7.09×10^{-2}	2.47×10^{0}	2.58×10^{3}	9.31×10^{3}	1.21×10^{1}	1.90×10^{7}	6.79×10^{5}	1.65×10^{-1}
	Maint.	3.86×10^{5}	1.54×10^{3}	2.34×10^{2}	1.86×10^{3}	2.02×10^{3}	1.19×10^{-2}	4.79×10^{-1}	5.87×10^{2}	2.08×10^{3}	2.58×10^{0}	4.15×10^{6}	1.72×10^{5}	3.50×10^{-2}
5	Constr.	1.47×10^{6}	6.65×10^{3}	2.62×10^{3}	7.49×10^{3}	1.21×10^{4}	7.23×10^{-2}	2.85×10^{0}	2.44×10^{3}	8.84×10^{3}	1.66×10^{1}	1.73×10^{7}	4.44×10^{5}	1.50×10^{-1}
	Maint.	3.86×10^{5}	1.54×10^{3}	2.34×10^{2}	1.86×10^{3}	2.02×10^{3}	1.19×10^{-2}	4.79×10^{-1}	5.87×10^{2}	2.08×10^{3}	2.58×10^{0}	4.15×10^{6}	1.72×10^{5}	3.50×10^{-2}

The material production phase is the most onerous in terms of impacts. These results are consistent with previous studies on the LCA of transport infrastructures [2,3].

After the material production phase, material transport is the highest in terms of produced impacts. The processes phase (that is the one that accounts for all the operations necessary for the construction of the infrastructure, from the laying of the materials and the earthworks operations for embankment construction, to the positioning of the tracks and the sleepers) is more impacting in the cut-section scenarios due to the impacts related to the soil excavation phase.

The impact of material production, transportation, and processes for the first scenarios of the embankment and cut sections are shown in Figure 6.



(**a**)

(**b**)

Figure 6. Material production/transport/process comparison. (**a**) Embankment section; (**b**) cut section.

The results of the alternative scenarios confirm the trend of Figure 6.

As for the two different maintenance plans, only the frequency of pressing, grinding, brushing and profiling varies. Table 7 shows the percentage incidence of the two maintenance plans in relation to the total impact of the different scenarios.

It is evident that the two different solutions do not bring significant changes in terms of impact. In this connection, it can be noted that the difference between the incidence of a maintenance strategy in Scenario 5 for NOS in the cut is 0.004% at maximum.

Because of what has been said, the subsequent evaluations consider the maintenance of the superstructure every 5 years (Maintenance Plan A).

This research shows interesting results in terms of emissions associated with the railway infrastructure life cycle, summarized below:

- Lime stabilization allows us to obtain good benefits in terms of NO_X and SO_2 CO_2 reduction but gives rise to a significant increase in terms of PM_{10};
- The use of RAP in the sub-ballast layers produces a decrease in CO_2 NO_X and SO_2, also yielding a good result for PM_{10} and a slight improvement for CO Hg and Pb.

Table 8 shows the performance of scenarios 2–4 with respect to scenario 1 (cf. Table 1), for embankment and cut sections, respectively. Scenario 4 slightly improves all impact categories compared to the results obtained in the other scenarios. Scenarios 2, 3, and 5 improve all impact categories, except for PM10-, mercury-, lead- and abiotic-depletion elements.

The increase in PM10 in the lime stabilization scenario is very high, reaching 176.25% in the embankment section of scenario 3; this is attributable to the use of fine material which tends to volatilize.

SimaPro-PaLATE Comparison

Table 9 shows the comparison between the most important environmental impacts, obtained using SimaPro and PaLATE software.

There are some notable differences in all impact categories. The biggest differences are given in the calculation of mercury and PM_{10}; the percentage variations are, respectively, 3661.01% for mercury in cut 5 and 2615.04% for PM10 in the embankment section of scenarios 4 and 5. Other major differences are in NOx and Pb values, although in general, all impact categories present substantial differences.

Indeed, the differences in the emissions estimated with the two different software used for this study were somehow expected, since the PaLATE is specifically developed for road infrastructures and takes into account typical construction operations such as those for embankment construction or other materials that are common for linear infrastructures (including those for the trackbed layers). Nevertheless, when it comes to the railway superstructure, the SimaPro software (being a versatile LCA tool for a variety of different applications) allows a much more detailed modelling of elements that are not easy to consider in PaLATE, such as the rail fastening system or sleepers, etc. Therefore, the results obtained with SimaPro are more representative and, thus, reliable.

Table 7. Maintenance strategy incidence.

Embankment Section														
Scenario and Maint. Strategy		**GWP**	**NOS**	**PM_{10}**	**Acidif.**	**CO**	**Hg**	**Pb**	**Eutroph.**	**Phot. Ox.**	**Ab. Dep. Elements**	**Ab. Dep. Fossil Fuels**	**Water Scarcity**	**Ozone Layer**
1	A	16.22%	15.72%	13.06%	15.29%	12.16%	12.61%	13.16%	14.67%	15.92%	13.55%	14.73%	11.94%	14.83%
	B	16.22%	15.72%	13.06%	15.29%	12.16%	12.61%	13.16%	14.68%	15.92%	13.55%	14.73%	11.94%	14.83%
2	A	17.69%	16.78%	6.03%	16.40%	13.04%	12.27%	11.13%	15.71%	16.90%	9.55%	16.36%	16.53%	16.48%
	B	17.69%	16.79%	6.03%	16.40%	13.04%	12.27%	11.13%	15.71%	16.90%	9.55%	16.36%	16.53%	16.48%
3	A	18.45%	17.38%	4.73%	17.01%	13.52%	12.16%	10.50%	16.14%	17.45%	8.55%	17.26%	19.89%	17.41%
	B	18.45%	17.39%	4.73%	17.02%	13.52%	12.16%	10.50%	16.14%	17.45%	8.55%	17.27%	19.89%	17.42%
4	A	16.28%	15.85%	13.48%	15.39%	12.19%	12.62%	13.20%	14.73%	16.04%	13.57%	14.79%	11.97%	14.92%
	B	16.28%	15.85%	13.48%	15.39%	12.19%	12.62%	13.20%	14.73%	16.04%	13.57%	14.80%	11.97%	14.92%
5	A	18.52%	17.54%	4.78%	17.14%	13.56%	12.17%	10.53%	16.21%	17.59%	8.55%	17.35%	19.99%	17.54%
	B	18.53%	17.55%	4.78%	17.14%	13.56%	12.17%	10.53%	16.21%	17.59%	8.55%	17.36%	19.99%	17.54%
Cut Section														
Scenario and Maint. Strategy		**GWP**	**NOS**	**PM_{10}**	**Acidif.**	**CO**	**Hg**	**Pb**	**Eutroph.**	**Phot. Ox.**	**Ab. Dep. Elements**	**Ab. Dep. Fossil Fuels**	**Water Scarcity**	**Ozone Layer**
1	A	19.49%	17.80%	14.57%	18.70%	13.64%	14.35%	16.15%	18.43%	18.10%	17.55%	17.87%	20.08%	17.41%
	B	19.49%	17.80%	14.57%	18.70%	13.64%	14.35%	16.15%	18.43%	18.10%	17.55%	17.87%	20.08%	17.40%
2	A	20.29%	18.33%	9.62%	19.34%	14.06%	14.17%	14.84%	19.05%	18.59%	14.45%	18.77%	24.65%	18.26%
	B	20.29%	18.32%	9.62%	19.34%	14.06%	14.17%	14.84%	19.05%	18.58%	14.45%	18.77%	24.65%	18.26%
3	A	20.72%	18.64%	8.07%	19.71%	14.30%	14.11%	14.34%	19.33%	18.88%	13.40%	19.28%	27.72%	18.75%
	B	20.72%	18.63%	8.07%	19.71%	14.30%	14.11%	14.34%	19.33%	18.87%	13.40%	19.27%	27.72%	18.75%
4	A	19.58%	17.97%	15.10%	18.86%	13.68%	14.37%	16.21%	18.52%	18.26%	17.59%	17.96%	20.18%	17.53%
	B	19.58%	17.97%	15.10%	18.85%	13.68%	14.37%	16.21%	18.52%	18.26%	17.59%	17.96%	20.18%	17.53%
5	A	20.82%	18.82%	8.22%	19.88%	14.35%	14.13%	14.39%	19.43%	19.05%	13.43%	19.39%	27.91%	18.89%
	B	20.82%	18.81%	8.22%	19.88%	14.35%	14.13%	14.39%	19.43%	19.04%	13.43%	19.39%	27.91%	18.89%

Table 8. Performance of scenarios 2–5 with respect to scenario 1.

Embankment													
Scenario	**GWP**	**NOx**	**PM_{10}**	**Acidif.**	**CO**	**Hg**	**Pb**	**Eutroph.**	**Phot. Ox.**	**Ab. dep. Elements**	**Ab. dep. Fossil fuels**	**Wat. Scars.**	**Ozone layer**
2	8.31%	6.33%	−116.63%	6.77%	6.75%	−2.77%	−18.24%	6.58%	5.78%	−41.92%	9.98%	27.77%	10.01%
3	12.08%	9.58%	−176.25%	10.16%	10.07%	−3.70%	−25.29%	9.06%	8.75%	−58.58%	14.68%	39.99%	14.85%
4	0.37%	0.82%	3.09%	0.66%	0.25%	0.12%	0.33%	0.40%	0.75%	0.17%	0.44%	0.29%	0.59%
5	12.45%	10.40%	−173.16%	10.82%	10.33%	−3.58%	−24.96%	9.46%	9.50%	−58.41%	15.12%	40.27%	15.44%
Cut													
Scenario	**GWP**	**NOx**	**PM_{10}**	**Acidif.**	**CO**	**Hg**	**Pb**	**Eutroph.**	**Phot. Ox.**	**Ab. dep. Elements**	**Ab. dep. Fossil fuels**	**Wat. Scars.**	**Ozone layer**
2	3.96%	2.85%	−51.45%	3.29%	3.00%	−1.24%	−8.84%	3.28%	2.61%	−21.46%	4.80%	18.51%	4.66%
3	5.96%	4.47%	−80.70%	5.11%	4.64%	−1.71%	−12.64%	4.65%	4.09%	−30.94%	7.31%	27.55%	7.16%
4	0.45%	0.93%	3.45%	0.81%	0.29%	0.14%	0.41%	0.50%	0.86%	0.22%	0.53%	0.48%	0.70%
5	6.40%	5.39%	−77.25%	5.92%	4.93%	−1.57%	−12.23%	5.15%	4.95%	−30.72%	7.84%	28.03%	7.86%

Table 9. SimaPro/PaLATE impact comparison.

Embankment								
		GWP	**NOS**	**PM_{10}**	**Acidif.**	**CO**	**Hg**	**Pb**
1	Production	−35.67%	−49.48%	1267.19%	−72.90%	−80.16%	3098.63%	−45.20%
	Transportation	−69.20%	266.79%	616.28%	−62.93%	−21.27%	−82.75%	−91.10%
	Processes	27.14%	224.74%	2188.43%	−74.16%	1.83%	222.69%	175.46%
2	Production	−39.45%	−23.74%	368.31%	−49.35%	−76.45%	3006.99%	−52.09%
	Transportation	−73.96%	201.79%	487.94%	−66.31%	−30.63%	−82.58%	−92.35%
	Processes	10.99%	273.89%	2501.08%	−70.26%	17.01%	222.67%	136.10%

Table 9. *Cont.*

Embankment								
		GWP	**NOS**	**PM_{10}**	**Acidif.**	**CO**	**Hg**	**Pb**
3	Production	−36.68%	4.47%	219.39%	−24.96%	−71.90%	2980.41%	−51.52%
	Transportation	−76.09%	175.70%	436.08%	−67.75%	−34.48%	−82.58%	−92.94%
	Processes	2.85%	293.06%	2615.04%	−68.76%	22.96%	−100.00%	125.98%
4	Production	−39.18%	4.47%	219.39%	−24.96%	−71.90%	2980.41%	−51.52%
	Transportation	−76.09%	175.70%	436.08%	−67.75%	−34.48%	−82.58%	−92.94%
	Processes	2.85%	293.06%	2615.04%	−68.76%	22.96%	−100.00%	125.98%
5	Production	−39.18%	−53.35%	1222.45%	−75.64%	−81.87%	3099.22%	−47.75%
	Transportation	−68.95%	269.75%	624.94%	−62.61%	−20.60%	−82.64%	−90.83%
	Processes	−5.20%	272.14%	2484.31%	−70.27%	16.44%	−100.00%	106.38%
Cut								
		GWP	**NOS**	**PM10**	**Acidif.**	**CO**	**Hg**	**Pb**
1	Production	−41.18%	−35.69%	1013.30%	−64.69%	−80.06%	3658.40%	−31.62%
	Transportation	−68.82%	290.90%	641.82%	−63.98%	−21.69%	−85.01%	−91.07%
	Processes	−65.65%	−13.21%	510.94%	−93.09%	−72.91%	−10.04%	−26.02%
2	Production	−44.02%	−21.48%	515.33%	−51.46%	−78.54%	3607.93%	−37.32%
	Transportation	−70.71%	265.95%	594.41%	−65.27%	−25.26%	−84.96%	−91.67%
	Processes	−67.34%	−9.85%	529.23%	−92.79%	−71.89%	−10.07%	−28.78%
3	Production	−42.53%	−3.24%	374.27%	−35.64%	−76.27%	3590.45%	−37.53%
	Transportation	−71.47%	255.14%	573.29%	−65.86%	−26.85%	−84.96%	−91.83%
	Processes	−68.47%	−8.09%	543.00%	−92.67%	−71.31%	−10.07%	−31.52%
4	Production	−45.70%	−40.51%	956.39%	−68.75%	−82.04%	3661.01%	−34.94%
	Transportation	−71.47%	255.14%	573.29%	−65.86%	−26.85%	−84.96%	−91.83%
	Processes	−68.47%	−8.09%	543.00%	−92.67%	−71.31%	−10.07%	−31.52%
5	Production	−48.02%	−9.02%	329.29%	−39.83%	−78.48%	3591.63%	−40.46%
	Transportation	−70.10%	269.20%	607.18%	−64.51%	−23.73%	−84.37%	−91.40%
	Processes	−70.99%	−10.71%	402.17%	−92.96%	−72.06%	−24.55%	−60.55%

5. LCC Results

The economic analysis was carried out taking into account the prices related to the construction costs defined by the Italian "Rete Ferroviaria Italiana" (RFI) rail company [25]: for VOC and VOT, reference was made to the data estimated by the European Commission for the HEATCO project [27]. Finally, also with regard to the monetization of impacts, reference was made to the value of monetization used by the European Commission [28,29].

The first outcomes show that the cut section is more expensive than the embankment section. By analysing Table 10, scenario 5, in which both lime stabilization and RAP are used, it proves to be the most advantageous one, reaching a saving up to 5.35% and 3.55% for embankment and cut sections, respectively.

Table 10. Railway infrastructure total costs.

		Net Present Value [€]				
Section	**Maint. Plan**	**1**	**2**	**3**	**4**	**5**
Embank.	A	3,244,012.53€	3,141,938.70€	3,076,981.96€	3,242,179.96€	3,075,150.70€
	B	3,179,341.37€	3,077,267.53€	3,010,675.39€	3,177,510.10€	3,008,844.12€
Cut	A	3,732,961.79€	3,620,736.54€	3,604,204.95€	3,731,123.63€	3,602,366.80€
	B	3,668,288.16€	3,556,062.91€	3,539,531.33€	3,666,450.01€	3,537,693.17€

Figure 7 shows the average incidence of costs; it can be noted that the agency costs related to construction and maintenance reach 87.74% of the total costs for the embankment section and maintenance scenario A, and 90.95% for the cut section.

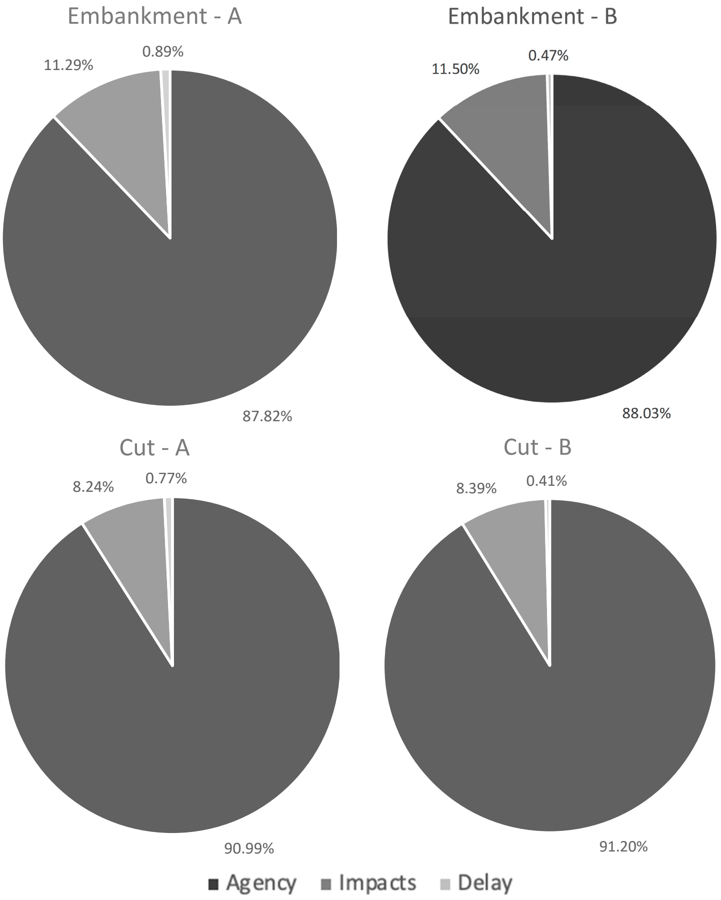


Figure 7. Average percentage incidence of costs.

Another important point of view concerns the impact, which ranges from 8.24% to 11.50%.

The delay costs are between 0.41% and 0.89% of the total costs, but they depend to a large extent on traffic and utilization of the railway line under consideration.

It can be noted that a different configuration and materials of the railway track could produce even improvement in all environmental impacts including PM10 emissions. In order to select the best railway track layout, future studies could use TRIZ (a Russian acronym for the "Theory of Inventive Problem Solving") strategies [34].

It is worth underlying that the outcomes of this research could be used for choosing better construction techniques to guarantee the environmental sustainability of the railway system at the regional or national level.

6. Conclusions

The construction of transport infrastructures, such as railways, can have a huge environmental impact (EI). This observation gives rise to the need to assess environmental impacts and evaluate alternative construction techniques and maintenance plans to reduce them. The present research examines different construction techniques and maintenance plans in railway infrastructure in order to evaluate their environmental, energy, and economic effects. The study demonstrates that the initial construction phase always involves no less than 80% of the total environmental impact related to the railway's useful life. In addition, material production is the most polluting phase, reaching percentages always higher than 50% of the total.

The scenarios related to the embankment section cause major EI with respect to the cut section; this is due to the high use of raw materials required for the realization of the roadbed.

The use of construction techniques such as lime stabilization can produce good results in all impact categories, with the exception of PM10 due to the presence of fine material.

However, the lime stabilization technique is recommended as it allows the use of soils that would otherwise result in waste material pending the possibility of levelling cut and filled soils. Compensation reduces the impact in terms of waste materials and raw materials needed for the realization of the embankment.

The use of recycled materials such as RAP (recycled asphalt pavement) is recommended as they reduce the impact, too.

In this research study, a comparative analysis of LCA was carried out using two specialized software: PaLATE and SimaPro. The comparison of LCA outputs obtained using the two software shows remarkable differences due to several reasons, including differences in the reference database and calculation algorithms, but PaLATE proved to have some limitations when modeling elements of the railway superstructure, being specifically developed for road infrastructures, not for railways. On the other hand, SimaPro proved to be easily applicable to the case of railways, after a proper definition of the functional unit and the related inventory analysis. In terms of costs, both construction techniques considered are efficient and bring significant cost savings of up to 5.34% in the embankment section and maintenance plan B compared to standard scenarios (E-B1). These savings could increase even further as, especially if excavated soil is reused particularly as regards EI costs, there are savings of up to 14%.

Although this research project analyses only embankment and cut sections of double-track railway lines, nevertheless the initial results are encouraging, since the proposed methodology is "general" and, consequently, it can also be applied to single-track railway lines and high-speed railway lines, as well as to analyse the environmental impacts of railway bridges and railway tunnels. Indeed, future works will have to involve many other construction and maintenance techniques and materials and specific sensitivity analyses will have to be carried out in order to properly evaluate the effect of each variable.

Author Contributions: Conceptualization, C.C.; Methodology, C.C.; Software, A.C.; Validation, C.C.; Formal analysis, M.G.; Investigation, A.C.; Data curation, A.C. and M.G.; Writing—original draft, C.C., A.C. and M.G.; Supervision, M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Stripple, H.; Uppenberg, S. *Life Cycle Assessment of Railways and Rail Transports-Application in Environmental Product Declarations (EPDs) for the Bothnia Line the Report Can Be Ordered Via*; IVL Svenska Miljöinstitutet: Göteborg, Sweden, 2010.
2. Chang, B.; Kendall, A. Life Cycle Greenhouse Gas Assessment of Infrastructure Construction for California's High-Speed Rail System. *Transp. Res. Part D Transp. Environ.* **2011**, *16*, 429–434. [CrossRef]
3. International Union of Railway. *Carbon Footprint of Railway Infrastructure Comparing Existing Methodologies on Typical Corridors Recommendations for Harmonized Approach*; International Union of Railway: Paris, France, 2016.
4. Olugbenga, O.; Kalyviotis, N.; Saxe, S. Embodied Emissions in Rail Infrastructure: A Critical Literature Review. *Environ. Res. Lett.* **2019**, *14*, 123002. [CrossRef]
5. Viak, A. *New Double Track Line Oslo-Ski Life Cycle Assessment of the Follo Line-Infrastructure*; Norwegian National Rail Administration: Oslo, Norway, 2011.
6. Hertwich, E.; Johan Pettersen, E.; Grossrieder, C. *Life-Cycle Assessment of Future High-Speed Rail in Norway*; Norwegian University of Science and Technology: Trondheim, Norway, 2011.
7. Yue, Y.; Wang, T.; Liang, S.; Yang, J.; Hou, P.; Qu, S.; Zhou, J.; Jia, X.; Wang, H.; Xu, M. Life Cycle Assessment of High Speed Rail in China. *Transp. Res. Part D Transp. Environ.* **2015**, *41*, 367–376. [CrossRef]
8. Giunta, M.; Bressi, S.; Losa, M. Sustainability in Railway Construction: Lca-Lcc Based Assessment of Alternative Solutions for Track-Bed. In Proceedings of the 2020 Joint Rail Conference JRC2020, St. Louis, MO, USA, 20–22 April 2020. [CrossRef]
9. Pons, J.J.; Villalba Sanchis, I.; Insa Franco, R.; Yepes, V. Life Cycle Assessment of a Railway Tracks Substructures: Comparison of Ballast and Ballastless Rail Tracks. *Environ. Impact Assess. Rev.* **2020**, *85*, 106444. [CrossRef]
10. European Commission. *Handbook on the External Costs of Transport*; European Commission: Brussels, Belgium, 2019.
11. *ISO 14008*; Monetary Valuation of Environmental Impacts and Related Environmental Aspects. International Organization for Standardization: Geneva, Switzerland, 2019.
12. Arendt, R.; Bachmann, T.M.; Motoshita, M.; Bach, V.; Finkbeiner, M. Comparison of Different Monetization Methods in LCA: A Review. *Sustainability* **2020**, *12*, 10493. [CrossRef]
13. Nasti, M. *LCA Di Una Infrastruttura Ferroviaria: Applicazione al Km Tipo*; Università degli Studi di Palermo: Palermo, Italy, 2015.
14. de Bortoli, A.; Bouhaya, L.; Feraille Fresnet, A.; de Bortoli, F.A.; Bouhaya, L.; Feraille, A. A Life Cycle Model for High-Speed Rail Infrastructure: Environmental Inventories and Assessment of the Tours-Bordeaux Railway in France. *Int. J. Life Cycle Assess* **2020**, *2020*, 814–830. [CrossRef]
15. Hanson, C.S.; Noland, R.B.; Porter, C.D. Greenhouse Gas Emissions Associated with Materials Used in Commuter Rail Lines. *Int. J. Life Cycle Assess* **2016**, *10*, 475–484. [CrossRef]
16. Sollazzo, G.; Longo, S.; Cellura, M.; Celauro, C. Impact analysis using life cycle assessment of asphalt production from primary data. *Sustainability* **2020**, *12*, 10171. [CrossRef]
17. Vaiana, R.; Rossi, C.; Perri, G. An eco-sustainable stabilization of clayey road subgrades by lignin treatment: An overview and a comparative experimental investigation. *Appl. Sci.* **2021**, *11*, 11720. [CrossRef]
18. Jadidi, K.; Esmaeili, M.; Kalantari, M.; Khalili, M.; Karakouzian, M. A review of different aspects of applying asphalt and bituminous mixes under a railway track. *Materials* **2020**, *141*, 169. [CrossRef] [PubMed]
19. Xiao, X.; Cai, D.; Lou, L.; Shi, Y.; Xiao, F. Application of asphalt based materials in railway systems: A review. *Constr. Build. Mater.* **2021**, *304*, 124630. [CrossRef]
20. Locat, J.; Bérubé, M.-A.; Choquette, M. Laboratory investigations on the lime stabilization of sensitive clays: Shear strength development. *Can. Geotec. J.* **1990**, *27*, 294–304. [CrossRef]
21. Bell, F.G. Lime stabilization of clay minerals and soils. *Eng. Geol.* **1996**, *42*, 223–237. [CrossRef]
22. Rosone, M.; Celauro, C.; Ferrari, A. Microstructure and shear strength evolution of a lime-treated clay for use in road construction. *Int. J. Pavement Eng.* **2020**, *21*, 1147–1158. [CrossRef]

23. *ISO 14040: 2006*; Environmental Management–Life Cycle Assessment—Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006. Available online: https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en (accessed on 28 January 2023).
24. Blanchard, B.S.; Verma, D.C.; Peterson, E.L. *Maintainability: A Key to Effective Serviceability and Maintenance Management*; John Willey and Sons Inc.: New York, NY, USA, 1995.
25. RFI, Italian Railways Construction Costs. 2021. Available online: https://www.rfi.it/it/fornitori-e-gare/regole-e-documentazione/tariffe-di-prestazioni-e-lavori.html (accessed on 28 January 2023).
26. Lovett, A.H.; Dick, C.T.; Barkan, C.P.L. Determining Freight Train Delay Costs on Railroad Lines in North America. In Proceedings of the International Association of Railway Operations Research (IAROR) 6th International Conference on Railway Operations Modelling and Analysis, Tokyo, Japan, 23–26 March 2015.
27. Bickel, P.; Friedrich, R.; Burgess, A.; Fagiani, P.; Hunt, A.; De Jong, G.; Laird, J.; Lieb, C.; Lindberg, G.; Mackie, P.; et al. Developing Harmonised European Approaches for Transport Costing and Project Assessment, HEATCO. 2004. Available online: https://trimis.ec.europa.eu/project/developing-harmonised-european-approaches-transport-costing-and-project-assessment (accessed on 28 January 2023).
28. Smith, M.; Moerenhout, J.; Thuring, M.; de Regel, S.; Altman, M.; European Commission. Trinomics. *External Costs: Energy Costs, Taxes and the Impact of Government Interventions on Investments: Final Report*; European Commission: Brussels, Belgium, 2020; ISBN 9789276231288.
29. Sartori, D. *Guida All'analisi Costi-Benefici Dei Progetti d'investimento: Strumento Di Valutazione Economica per La Politica Di Coesione 2014–2020*; European Commission, Directorate-General for Regional and Urban Policy: Brussels, Belgium, 2015; ISBN 9789279347962.
30. Lichtberger, B. *Track Compendium*; Eurail Press: Utrecht, The Netherlands, 2010.
31. Guerrieri, M. Railway Track Deterioration and Monitoring. In *Fundamentals of Railway Design. Springer Tracts in Civil Engineering*; Springer: Cham, Switzerland, 2023. [CrossRef]
32. Celauro, C.; Corriere, F.; Guerrieri, M.; Lo Casto, B.; Rizzo, A. Environmental analysis of different construction techniques and maintenance activities for a typical local road. *J. Clean. Prod.* **2017**, *142*, 3482–3489. [CrossRef]
33. Banar, M.; Özdemir, A. An Evaluation of Railway Passenger Transport in Turkey Using Life Cycle Assessment and Life Cycle Cost Methods. *Transp. Res. Part D Transp. Environ.* **2015**, *41*, 88–105. [CrossRef]
34. Spreafico, C. Can TRIZ (Theory of Inventive Problem Solving) strategies improve material substitution in eco-design? *Sustain. Prod. Consum.* **2022**, *30*, 889–915. [CrossRef]