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Life cycle assessment of railway track substructures: Comparison of ballast and ballastless rail tracks

Joaquín J. Pons[a], **Ignacio Villalba-Sanchís**[b], **Ricardo Insa-Franco**[b] ,**Víctor Yepes**[c,*1],

[a] School of Civil Engineering, *Universitat Politècnica de València*, Camino de Vera, s/n, 46022, Valencia, Spain

[b] Department of Transport Engineering and Infrastructure, *Universitat Politècnica de València*, Camino de Vera, s/n, 46022, Valencia, Spain

[c] Institute of Concrete Science and Technology (ICITECH), *Universitat Politècnica de València*, Camino de Vera, s/n, 46022, Valencia, Spain

Abstract

The increase of train speed and axle load is an essential goal to make the railway transport more and more competitive for passengers and freights. On this basis, the unevenness of the railway track is crucial for the safety of the railway due to the high speed of the vehicle. Although ballasted tracks represent by far the most used railway track substructure, in recent years the modernization process has led the development of the ballastless track substructures.

In deciding between the use of ballasted or ballastless track substructure there are many important technical, economical and environmental factors that have to be addressed. Based on the above, the principal objective of this study was to evaluate the environmental impact of different railway track substructures including ballast, cast-in sleeper and embedded track systems on the short, medium and long term. To accomplish this task, a life cycle assessment (LCA) was carried out throughout the entire life cycle of the railway infrastructure by using the ReCiPe (H) method. Although such approach is commonly included in the environmental assessment of building products and buildings, it was rarely applied in the analysis of the environmental impacts of railway track substructure.

Thus, the result of these LCA showed that ballasted tracks cause the lowest environmental impact for service lives of up to 75 years. On the other hand, the embedded track beds cause the highest

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environmental impacts, regardless of their service life. The highest contributor for the environmental impacts of the track beds was the steel production.

The results of this study will provide relevant environmental information for engineers and decision makers to select the most adequate railway track substructures for addressing issues related to the pursuit of sustainable development.

Keywords

Life cycle assessment (LCA); High speed railway (HSR); Railway infrastructure; Railway track-bed

1. Introduction

Nowadays, concerns about the environment are rising due to the current situation of climate change and resource scarcity. One of the sectors with the most room for optimization is the transportation sector, which plays an essential role in human activities, especially in a globalized society. In 2016, transport accounted for one third (33.2%) of the energy consumed in the EU-28, while industry accounted for one quarter (25.0%), and there has been a relatively consistent pattern of rising energy consumption for transport since 1990.

Hence, railway transport plays an increasingly important role in meeting regulatory requirements and reducing air pollutants and noise. Although rail infrastructure is essential to provide an efficient transport network, it does have an environmental impact (Saxe et al., 2016). Consequently, understanding the potential impacts of the construction of railway infrastructure (Fridell et al., 2019) and improving its operation and maintenance procedures is a matter of utmost priority (Slivers and Walsh, 2014).

At present, the design and performance of railway track systems has to conform to both technical and legal requirements. In particular, two main types of railway track substructures are currently used worldwide: ballasted and ballastless track systems. In the first case, ballasted tracks consist of a pair of rails, sleepers, and fastenings systems, supported by the ballast layer. The main advantage lies in their low construction cost and their good drainage performance, but a regular maintenance routine is always required (Nimbalkar et al., 2012; Sadeghi et al., 2018). In the second case, ballastless track systems are those in which rails are rigidly fastened to the slab. The principal advantages lie in their low maintenance costs, high availability, and long service life. However, their disadvantages are a higher construction cost, the difficulty of repairing relevant differential settlement, and higher noise radiation (Darr and Fiebig, 2006; Esveld, 2003; Lichtberger, 2005).

With the previous considerations, the selection of one particular railway track system should take into careful consideration not only the construction and maintenance costs but also the environmental impacts during the lifespan. In the pursuit of comparing two railway track systems, Life Cycle Assessment (LCA) is an approach for assessing the social, environmental, and economic impacts of a product or system. In fact, some previous studies have used LCA for various common structures used in civil engineering, like earth-retaining walls or bridges (Navarro et al., 2018b; Navarro et al., 2019; Penadés-Plà et al., 2018; Pons et al., 2018; Sánchez-Garrido and Yepes, 2020; Zastrow et al., 2017). Even though there is a growing acceptance and knowledge of LCA in construction, its applications in rail projects are still limited.

Recently, some studies have begun to incorporate the LCA method to assess the environmental impacts of rail transport. Rozycki et al. (2003) analyzed the German High-Speed Rail (HSR) network, concluding that energy consumption from infrastructure construction represented the largest amount of energy used. Chester and Horvath (2010) compared the impact of the California HSR system with the alternatives (automobiles, heavy rail, and aircraft) and determined that rail transport may have lower emissions under particular occupancy conditions. Akerman (2011) used the LCA approach for a Swedish HSR track, showing a significant benefit in terms of greenhouse gas (GHG) emissions due to the modal shift from road to rail. Yue et al. (2015) studied several key factors of the Chinese HSR system by using the China-specific Life Cycle Inventory (LCI) database, which makes this approach difficult to implement in other areas. Banar and Özdemir (2015) analyzed the railway passenger transportation system in Turkey by developing a cost model for internal and external cost categories. Jones et al. (2017) assessed the environmental impacts of the Portuguese HSR by processing the main operations performed on track and trains and concluded that train operation generated the largest amount of environmental emissions. Merchan et al. (2017) analyzed the environmental impact of Belgian rail freight transport considering the LCI of the Belgian railway infrastructure. However, these previous studies do not consider different rail track substructure solutions and the associated environmental impacts of the railway infrastructure design, construction, maintenance, and dismantlement of the track.

More recently, Practico and Giunta (2018a) developed a methodology to analyze different track solutions, considering both Life Cycle Cost Analysis (LCCA) and RAMS (Reliability, Availability, Maintainability, Safety) approaches. To accomplish this task, a key performance indicator was proposed. However, the indicator is mainly focused on technical and financial aspects. In order to compare different track solutions, a promising LCCA approach was also proposed based on ISO 15686-5:2008 (Practico and Giunta, 2018b). Nevertheless, the differences obtained become too small to yield sound conclusions. Thus, a systematic research on the environmental impacts of different railway track substructures across the entire life cycle is still missing. In particular, the quantification of externality costs is still difficult and some aspects such as water pollution, eutrophication, and solid waste generation should be set out in more detail.

In the present paper, the LCA method ReCiPe 2008 is proposed to evaluate the potential impacts of competing track solutions. To accomplish this task, three different railway track substructures were selected and compared over the short, medium, and long term. The LCA method provides both a complete environmental profile of every impact and an easier to interpret summary of the damage caused to three main categories: ecosystems, human health, and resources. The environmental impacts occurring during the construction, maintenance, and renewal activities and limitations are also discussed.

2. Methodology

The LCA methodology provides an effective approach to determine the potential environmental impacts of any product or process throughout its life cycle. In this case, the LCA has been applied to analyze different railway track solutions, following the standard ISO 14040 series (ISO, 2006) and particularized for the specific characteristics of Spanish HSR lines, which are representative of the modern railway lines. To accomplish this task, the process can be divided into four steps: definition of the goal and scope, inventory analysis, impact assessment, and interpretation of the results. In particular, the life cycle impact assessment (LCIA) method employed in the present analysis was ReCiPe 2008 (Goedkoop et al., 2008), and the Ecoinvent 3.3 database (Ecoinvent Center, 2016) with the cut-off system was selected.

2.1. Goal and scope definition

2.1.1 Goal

The main goal of this study was to perform LCA of three different railway tracks designs: a ballast, a cast-in sleeper, and an embedded track system. Therefore, the results of these designs were compared with each other. The findings provide useful data and insights that can be used by engineers and decision makers to make more assertive judgments on the environmental impacts generated during construction, operation, and maintenance of railway tracks (Bressi et al., 2018).

2.1.2 System definition and boundaries

The LCA method was carried out following a "cradle to grave" approach, from the extraction of raw materials and their processing and transportation to the construction site to the machinery required for construction and maintenance of the track during its service life, including its dismantlement and disposal or recycling of its materials.

The LCA has been divided into four phases, as shown in **Fig. 1**. The production phase considers the extraction and processing of raw materials. The construction phase includes transportation from raw-material processing plants to the construction site, as well as the machinery operations and activities carried out to build the track. The use and maintenance phase includes every maintenance activity, both the minor and ordinary ones like ballast tamping and the major ones like the renewal of various components once their service life is over, including the production of these materials during the maintenance phase. Finally, the end-of-life phase includes the dismantlement operations of the railway track and the disposal, landfilling, or recycling activities. Given that the present assessment is intended to compare the environmental performance between different alternatives, those processes considered to be identical between the analysed alternatives are excluded from the assessment (Martínez-Blanco et al., 2014; Navarro et al., 2018a).

In order to study the impacts, five different service lives have been considered: 0, 25, 50, 75, and 100 years. These service lives have been selected according to the average frequency of the major maintenance activities, such as the renewal of the ballast track bed, rails, and sleepers. While ballasted track is renewed every 25 years on average, ballastless tracks systems are expected to last at least 60 years, so their renewal has not been considered during the service life of the infrastructure, which will be further discussed in Section 2.2.4.

On the basis of the above, the present LCA focuses on the railway track substructure itself to identify the most significant impacts and the processes or materials that contribute most to the environmental burden of the construction of the railway track substructure.

2.1.3 Functional unit

In the latest years, many countries have built and developed HSR infrastructure to connect major cities. In order to analyzed this situation, it is necessary to determine a generic functional unit that accurately defines the product properties and functionalities. Thus, the functional unit considered was 10 km of straight twin-track for high-speed transport of passengers and the tonnage carried was assumed to be the same for the three different track beds. Furthermore, different service lives were considered for the project, specifically, 0, 25, 50, 75, and 100 years. This additional consideration allows the assessment of every alternative over the short and long term, depending on the maintenance and renewal activities required during its service life. The durability of every component and the frequency of the maintenance activities were considered according to the average values provided by Kiani et al. (2008) and the Technical Specifications for Interoperability (TSIs), which are mandatory for all railway lines of the Trans-European Network for Transport (TEN-T) and being used for railways around the world. In this way, only the processes related with the railway track substructure itself have been considered, excluding those like the catenary and signaling systems, since they would be the same for the three alternatives, providing no additional differences.

2.2. Inventory analysis

The LCI requires the compilation of data and modeling of the system. To ensure that the analysis is at the right level, data must be as representative as possible, due to differences in the geographical location, the technology, the time when the data were collected, and so on. In the present study, most of the processes were mainly modeled using the Ecoinvent database and previous scientific studies (Bressi et al., 2018; Chester and Horvath, 2010; Lee et al., 2008; Kiani et al., 2008), with some adjustments made for our case study. Therefore, most of the data sets were the result of cooperation between industry companies and scientific research organizations.

2.2.1. Software

The database chosen for this study is the Ecoinvent database (Frischknecht and Rebitzer, 2005), which is the world's leading LCI database (Pascual-González et al., 2016). The processes have been chosen from those located in Europe whenever they were available, considering that most other rail transportation LCAs use the same database (Von Rozycki et al., 2003; Jones et al., 2017), allowing comparative analysis. Additionally, to implement the data and analyze the results, the software OpenLCA (GreenDelta, GmbH, Berlin, Germany) was employed. It is an open source tool that allows the scientific community to conduct various environmental studies at different levels of detail, depending on their needs and scope (Ciroth, 2007). Furthermore, the materials and processes have been grouped according to different factors such as the location, technology, or time period, among others.

2.2.2. Uncertainty

Various uncertainties associated with the use of an existing database appear. They are due to various factors such as the differences in geographical location, technology used, and time of data collection. Thus, to create the life cycle model, these variations and uncertainties must be considered.

To introduce the uncertainty into the model, a pedigree matrix (Ciroth et al., 2016) was employed. The matrix introduces an uncertainty factor as a function of five indicators: reliability, completeness, temporal correlation, geographical correlation, and further technological correlation. To define the total uncertainty, a basic factor was used along with the pedigree matrix, which provides the standard deviation of the lognormal distribution. Thus, the scores for the data inventory have been selected according to the different indicators and the basic factor for each process.

2.2.3. Track design

To evaluate a set of railway track substructure solutions, three representative examples of track systems were chosen. Firstly, ballast track was represented by a conventional substructure composed of an aggregate foundation and pre-cast concrete sleepers, which is the most widespread in the Spanish HSR lines. On the other hand, when considering ballastless track systems, some different solutions were developed during the latest decades. In case of Spain, the first ballastless system used for high-speed lines was the Balfour Beatty Embedded Slab Track (BBEST) in the year 2000, which is composed of a concrete sub-base with an embedded steel rail. Since that moment, the most widely used solution is the Rheda 2000, composed of a concrete sub-base and pre-cast sleepers, which has already been used in some tunnels. Thus, their components and their amounts were selected according to Kiani et al. (2008).

The composition of every track was based on the EU standards for the nominated tracks and its equivalence in Ecoinvent processes is shown in **Table 1**. Therefore, a depth of 300 mm was considered and sleepers were spaced 650 mm apart. Ballasted and Rheda 200 tracks use a CEN60-E1 rail profile with 60 kg of steel per meter, while the BBEST system uses a BB14072 profile, which requires 74 kg. In addition, ballasted track uses the Pandrol Fastclip system for its fastenings, while the Rheda 2000 uses Vossloh 300-1 clips. On the other hand, the BBEST system uses a glass fiber shell, a rubber seal, and grout instead of a traditional fastening system. Finally, in order to allow comparisons, 10 km of straight twin-track with the same groundwork was considered, excluding it from the analysis.

2.2.4. Life cycle model description

As previously mentioned, the life cycle was divided into four phases. Every material and activity has been chosen from the Ecoinvent database. Nevertheless, the machinery required for the construction and maintenance operations have been modeled as new elements, considering their operation times and fuel consumption (Kiani et al., 2008) and transforming them into the Ecoinvent processes, as shown in **Table 2**.

Firstly, the production phase includes the activities needed to produce all materials required to construct the track bed, considering the transformation processes and their transportation distances using average market distances. Regarding the steel bars of the concrete, fastenings and rails, the use of recycled steel is considered taking into account two main production methods: Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF). In BOF method, iron is combined with less than 30% of steel scrap, while in EAF around 90–100% of steel scrap is employed. In the case of Spain, around two thirds of steel are produced using EAF and one third of BOF. Accordingly, a 75% steel recycling rate is considered. For the ballast track, the excavation and crushing of stone have been considered, as well as the excavation of aggregate for the sub-base, the production of concrete for the pre-cast sleepers, the production and hot rolling of steel for the rails and fastenings, and so on. For the Rheda 2000 system, the same processes were considered, excluding the ballast production and including higher amounts of concrete, as well as reinforcement bars and cement. The BBEST system requires higher amounts of concrete and steel due to its characteristics, as well as other additional materials like glass fiber shells, grout, and a seal. For the rail pads, every system uses rigid polyurethane-based pads.

Secondly, the construction phase includes the machinery operations and activities required to build the track. Thus, the transportation of the finished products to the construction site was considered. An average distance of 100 km was considered for the transportation of ballast, aggregates, pre-cast concrete products, and other rail components by truck, while an average of 150 km was considered for the transportation of the rails by train. For the construction and renewal of the ballasted tracks, hydraulic diggers were required to form the sub-base, as well as ballast-spreading machines. Rail and sleeper-laying machines were used for the construction and renewal of the other elements. On the other hand, for the ballastless track systems, an in situ concrete slab former machine was used along with rail-laying machines. For the rail fastenings, an automatic bolt tightening machine was used. Finally, the land transformation processes from natural land to a railway embankment and railway traffic area were considered too.

Thirdly, the use and maintenance phase include all maintenance activities and operations required throughout the track system's entire service life. Thus, ballastless track systems do not require any minor maintenance, due to their long lifetime. However, an average value of 25 years was considered for the replacement of the rails, pads, and fastenings. For the maintenance of the ballasted tracks, ballast is tamped 1.5 years and cleaned every 12.5 years, and the other components of the bed itself have to be renewed every 25 years, on average. The ballast tamping has a frequency of 1.5 years on average and 5% new ballast is added during the tamping activities, while around 30% is added during the ballast cleaning activity. Furthermore, up to 75% of the steel materials are recycled, reducing the required production of new materials. However, the renewal of the ballastless track systems was not considered due to their long lifetime, which is considered to be the same as the service life of the analysis. The impacts caused by the land occupation of the infrastructure were also considered per year.

Finally, considering that it is difficult to collect data because there is no data of dismantling the whole track system after having completed the life cycle, the dismantlement of the track was considered to have the same energy consumption as its construction, the crushing of concrete, the separation of the reinforcement steel using magnets, the transport of the materials to recycling plants and their recycling processes, mainly for steel, and so on. Additionally, a landfill was created for the disposal of those materials that could not be recycled, like some of the aggregate and ballast used, and so on. The average distance considered from the dismantlement site to the recycling plant was 100 km, while for the landfill, 5 km was considered. Revegetation processes and the transformation of the occupied land back to natural land, which make a positive contribution to the environment, were also considered. Overall, the objective of this phase was to reduce the impacts caused throughout the entire life cycle by making a positive contribution through the recycling of components and other processes. Accordingly, the model takes into account material production, renewal works, maintenance, and the dismantlement of the track, as shown in **Fig. 2**.

2.3. Impact assessment

In this step, the environmental impacts were classified and evaluated to translate them into environmental indicators or themes. To accomplish this task, the LCIA method chosen was ReCiPe 2008 (Goedkoop et al., 2008). This method consists of two common LCIA indicators, CML and Eco-Indicator 99, which are a midpoint and an endpoint indicator, respectively. These indicators use two different approaches, allowing the results of both to be presented with a higher or lower level of detail.

The midpoint approach comprises the results in 18 impact categories: agricultural land occupation (ALO), global warming potential (GWP), fossil depletion (FD), freshwater ecotoxicity (FEPT), freshwater eutrophication (FEP), human toxicity (HTP), ionizing radiation (IRP), marine ecotoxicity (MEPT), marine eutrophication (MEP), metal depletion (MD), natural land transformation (NLT), ozone depletion (ODP), particulate matter formation (PMF), photochemical oxidant formation (POFP), terrestrial acidification (TAP), terrestrial ecotoxicity (TEPT), urban land occupation (ULO), and water depletion (WD). These environmental impact categories have an elevated level of detail, providing precise results, although they are harder to interpret.

Furthermore, the endpoint approach considers various impact categories grouped into three different damage aspects. The first, human health, was measured by considering disability adjusted life years (DALY). The second, ecosystems, was considered in terms of species per year. Finally, the availability of resources was measured in U.S. dollars. This approach has the advantage of being easier to interpret and understand; however, the uncertainty of the results increases due to the elevated level of integration.

In order to include the long-term scenario, the hierarchist (H) perspective was used and damage categories were normalized by means of the Europe ReCiPe H/H [person/year] characterization. This approach allows us to obtain a score for the total environmental impact caused by the structure throughout its complete service life. This global score is measured in points, and every endpoint damage category has the same weight, so they are considered to be equally important.

2.4. Interpretation

The last phase was the life cycle interpretation. Interpretation of the results requires an understanding of their accuracy, an evaluation of the sensitivity of the significant data elements and, finally, an assessment of the completeness of the study before drawing well-substantiated conclusions and recommendations.

In this particular study, the main goal was to select which railway track substructure design has least environmental impact depending on the service life considered. Consequently, for the interpretation of the results, it is extremely helpful to provide the midpoint scenario, for which a detailed impact can be studied, and the end-point scenario, which can be useful to interpret every result depending on its damage category.

3. Results and discussion

In order to estimate the uncertainty, Monte Carlo simulations with 1000 iterations were used for every model. The accuracy level of Monte Carlo simulation can be measured using the coefficient of variance. Thus, for every impact and damage category, there is a mean value and a coefficient of variation. However, to compare the different alternatives, the mean value is displayed on the figures to provide a visualization of the results that is easier to understand. Furthermore, after a sensitivity analysis, no significant discrepancies were found between the values of the coefficient of variation of different track design alternatives. The slight differences between the uncertainties can be explained by various external factors, such as the location of the ballast quarry, the technology available, and the time and place where the data were gathered, among others.

As was to be expected, the ballasted tracks have lower impacts on every category during their initial construction and the first years of their service lives. However, the results change as their service lives increase, due to their higher maintenance requirements. Therefore, two approaches to characterization can take place: midpoint and endpoint. Characterization using midpoint models the impact using an indicator located somewhere along the life cycle. The results are more reliable since the uncertainty is smaller because they are not aggregated. Meanwhile, the endpoint approach calculates the environmental impact at higher aggregation levels such as human health, biodiversity, and resource scarcity, but it involves a considerable degree of uncertainty.

3.1. Midpoint approach

As mentioned before, the midpoint approach provides a comprehensive and complete environmental perspective with regard to the particular impacts caused by the rail substructure during its entire service life. These impact categories have a direct effect on the environment, even though, due to their high number, they are harder to interpret. However, they can be especially useful when there is a shortage of a specific resource, such as water or oil, in the area or when there are emission standards for various categories, such as CO_2, SO_2, and so on.

Table 3 shows the full results obtained from the midpoint approach, considering a service life of 75 years. The values obtained were relatively similar for both ballastless tracks. However, values were slightly higher for the BBEST track due to the larger amounts of steel that it requires. On the other hand, the ballasted track has a slightly higher uncertainty for almost all of its impacts, particularly for the natural land transformation. Particularly, the maximum coefficient of variation for ballasted track was 15,26% for the NLT impact category, while 13,15% and 13,98% were for the Rheda 2000 and BBEST tracks for ULO. The higher uncertainty was caused by the ballast production processes, because depending on the geology of the area or the country, sometimes ballast stones has to be imported from a long distance where there are suitable quarries. The high volumes of rocks that have to be excavated also cause the natural Land Transformation to have a higher value for the ballast track, as well as a higher uncertainty for the previously mentioned reasons. However, since these uncertainties are to be expected from the differences between the model and the real construction sites where they could be applied, a comparison was carried out between the mean values of the impact categories, considering that every project will have its differences and may need to consider slightly higher or lower values for these results.

Since every impact category is measured in different units, it would not be possible to graphically compare all of them simultaneously with their precise values. For this reason, **Figs. 3–5** display every midpoint impact caused by the three alternatives, considering service lives of 50, 75, and 100 years, respectively. To compare all the midpoint impacts on the same graph, they are represented relative to the biggest impact for each category. For instance, for the GWP and a service life of 50 years, the highest result is 2.34E+07 kg CO_2 for the BBEST. Therefore, it represents an impact of 100%, while by dividing the values of the other alternatives, 1.52E+07 and 2.06E+07 for the ballasted and Rheda 2000 tracks respectively, by the highest result, it is found that they represent 65% and 88% of the highest impact. This graphical representation is useful to see which particular impacts could be greatly reduced or to decide which alternative is better when there is a tie, considering other endpoint impacts. Accordingly, the ballasted track has the lowest impacts for service lives of 0 and 25 years, as expected.

For a service life of 50 years, as can be seen in **Fig. 3**, for almost every midpoint impact category, the BBEST is the worst solution, while the ballasted track is usually the best, excluding the impacts related to ULO and ALO. This is mainly due to the higher volumes of material that have to be excavated, both for ballast and for the sub-base aggregate. Overall, for short and medium service lives, the ballasted track has the least impact and the BBEST system the highest. Taking into account a service life of 75 years, the results are displayed in **Fig. 4**, including the uncertainty. The ballasted track becomes the worst option for various impact categories, like ALO and ULO, Natural Land Transformation (NLT), WD, TETP, ODP, and IRP. This is mainly caused by the additional maintenance and renewal activities that would be required for the ballasted track over its service life. Furthermore, for a service life of 100 years, shown in **Fig. 5**, if the concrete track beds were to last this long, the ballasted track would become the worst alternative for most impact categories, excluding the GWP, FD, MEP, and MD, which would have a higher impact for the BBEST, mainly due to its higher steel content. Consequently, in general terms, ballasted track would be better for the environment for a service life of 75 years. From that moment onwards, the Rheda 2000 system would become the best solution, which is related to its better adaptability and lower maintenance costs in the same environmental conditions.

Considering the importance of CO_2 emissions for climate change, the GWP is highlighted. Thus, **Fig. 6** represents the total amount of CO_2 emissions caused throughout the life cycle, depending on service life. The ballasted track causes the lowest emissions for service lives of 50 and 75 years, while for 100 years, Rheda 2000 causes 5% less emissions than the ballasted track. The BBEST is the worst alternative in terms of CO_2 emissions regardless of its service life, mainly due to its high concrete and steel contents. The ballasted track continuously causes CO_2 emissions throughout its entire life cycle due to the machinery and operations required for its maintenance, such as ballast tamping and cleaning, along with the production of other materials for the renewal of its components, including the ballast bed. On the other hand, while the concrete track beds have much higher initial emissions due to the concrete production required for their construction, they require almost no maintenance, just the renewal of their rails, fastenings, pads, and so on. Therefore, by considering the life cycle perspective, even if concrete elements are thought to be much more carbon intensive than ballast initially, over longer periods of time, the maintenance required by the ballast may eventually make it worse than some concrete slabs, if they are able to outlast their initial design lives, which depends on various traffic and environmental factors.

3.2. Endpoint approach

The endpoint approach combines the impacts into three damage categories, providing results that are easier for decision makers to interpret in order to choose the ideal solution. Areas with resource scarcity may want to focus on reducing their consumption, while urban areas could focus on reducing the damage caused to human health, and the areas that are close to conservation areas may prefer to decrease any effects on ecosystems. The endpoint damage categories can be normalized to obtain a global environmental impact score, considering every category to be as important as the others. Nevertheless, the uncertainty of the endpoint results increases due to the aggregation of the uncertainties of the midpoint results. However, the endpoint results are better to obtain wider perspectives on the damage caused to the environment without focusing on details.

The damage caused to the ecosystems is shown in **Fig. 7**, which is measured in lost species per year. If the concrete track beds were to last 50 years without being replaced, the ballast track beds would remain the cleanest solution, causing 16% less damage than the Rheda 2000 track and 26%

less than the BBEST. However, if the concrete track beds slightly outlast their design life, with a total service life of 75 years, the Rheda 2000 becomes slightly better, around 5% less impactful than the ballast track bed, while the BBEST track would remain the worst option with 11% higher impact. If the service life of the concrete track beds were to reach 100 years, the results would be very different: the ballasted track would become the worst alternative, with a similar but slightly higher impact than the BBEST track and causing 24% more damage than the Rheda 2000 track. These results are mainly due to the high impact caused by the production processes of steel and concrete, which emit high volumes of emissions that damage the ecosystems. The impact of Rheda 2000 system on the ecosystems would be slightly lower than when using ballast if it slightly outlasted its service life, reaching around 75 years. If the track bed could significantly outlast its service life, the Rheda 2000 system would be much cleaner than using ballast due to the amount of maintenance that it would require over that period. The BBEST system causes the highest amount of damage normally, due to the higher amounts of steel and concrete that are required for its construction, but if it lasted for 100 years, it would have similar results to the ballasted track for this category.

Considering human health, the damage caused by the different track systems is shown in **Fig. 8** and measured in DALYs. Ballasted tracks are the best alternative for shorter service lives, reducing the amount of damage by 19% for a service life of 50 years. Even if the service life of the concrete track beds were to increase slightly to around 75 years, the ballasted track would remain the best alternative, but only by a slight difference of 4% when compared with the Rheda 2000. However, if the service life of the concrete track beds were to increase significantly, the Rheda track would become the best alternative, causing 8% less damage than the ballasted track. Nevertheless, the BBEST track system causes more damage than the other alternatives for any service life, even though the gap closes as the service life increases. This is due to its bigger rail profile, which requires larger amounts of steel to be produced throughout its service life for rail renewal, whereas the other two track bed designs use the same smaller rail profile. The rail fastenings have to be replaced in every track bed design too, which also requires additional steel. Consequently, steel production is the most harmful process to human health among those used for the track beds. Furthermore, concrete production is significantly more harmful than ballast production, but due to the additional ballast production and the maintenance activities required throughout the service life of a ballasted track, concrete track beds could become more competitive and even better than ballast ones as their service life increases.

The damage caused to resources is shown in **Fig. 9**, which is measured in U.S. dollars ($). The best alternative in terms of resource consumption, for short or medium service lives, is the ballasted track. For a service life of 50 years, the ballast track bed is 12% cheaper than the Rheda 2000 and 20% cheaper than the BBEST. This is due to the fact that ballast production is significantly cheaper than concrete, even though ballast layer requires resurfacing or replacement during its service life, as well as several maintenance activities with vehicles that consume fuel and electricity. Despite this, as the service life increases, the additional ballast production and maintenance activities increase the resource consumption of the ballasted track; for a service life of 75 years, it is almost same as that of the Rheda Track. Among other components, the rails, pads, and fastenings of the concrete track beds have to be replaced throughout their service lives, but the ballast track beds have much higher maintenance and renewal costs. Therefore, even if their initial cost and resource consumption is significantly lower than for concrete track beds, it also increases significantly faster due to the maintenance and renewal activities as its service life becomes longer. Thus, if the Rheda 2000 outlasts its initial design life of 60 years, it consumes only 2% more resources than a ballasted track for a service life of 75 years, and if it lasts even further, for a service life of 100 years it would consume 7% less resources than a ballasted track. However, the BBEST system has the highest resource consumption regardless of the service life, and even though the difference between it and the ballast track becomes smaller for longer service lives, this is not enough to make it a better alternative in terms of its resource consumption. As previously mentioned, this is mainly caused by its higher consumption of steel and the renewal of those components, mainly the rails.

Each of these damage categories could be deemed to be more important depending on the location of the infrastructure or other external factors, such as the availability of resources, the existence of urban settlements or rural population nuclei, and so on. For this reason, the results are separated into different figures to allow the reader to apply his or her judgment when making decisions about which alternative is better for his or her situation. When every damage category is harmonized, a global environmental impact score can be obtained. An example is shown in **Fig. 10**, in which every damage category has the same weight, to obtain a balanced score, using the normalization set Europe ReCiPe H/H. For shorter service lives, the ballast track bed is the best alternative from the environmental point of view, as has been explained previously. Between the concrete track beds, the BBEST system is worse than the Rheda 2000, regardless of the service life, due to the higher consumption of concrete and other materials for its track bed but also mainly due to its requirement for greater amounts of steel for its bigger rail profiles, since the steel components of the track have to be renewed throughout the service life of the infrastructure. However, as the service life of the railway track bed increases, the Rheda 2000 system becomes competitive with the ballasted track, because the latter requires maintenance activities and the renewal of the ballast as well, whereas the Rheda 2000 only requires the renewal of the rails, fastenings, pads, and so on. If the Rheda 2000 system could outlast its initial design life of 60 to 75 years, it would have almost the same total impact as the ballast track – just 2% higher – but if it reached a service life of 100 years, it would have 7% less total impact than the ballast track, so it could outperform the latter for a service life of around 80 years.

Furthermore, to understand the relative importance of every LCA phase for the total environmental impact, **Fig. 11** represents the contribution of the processes associated with a phase toward the global impact score for each design with a service life of 50 years. For both of the concrete track bed designs, the distribution is similar. Around 64% of the impact occurs during the production phase, when the raw materials are extracted and transformed into the final products required for the construction of the railway track. This phase is responsible for the majority of the impacts caused by the concrete track beds throughout their entire service life, mainly due to the production of concrete and steel for the slab, but also due to the production of other materials required for the sub-base, rails, fastenings, rail pads, grout, and so on. The construction phase is responsible for around 4% of the total impact, a low proportion, as it only involves the transport of the materials, the construction machinery, and the operations required to build the infrastructure for the first time. The maintenance and renewal phase makes a higher contribution of around 30%, because it involves the renewal activities of the rails, fastenings, and other components of the track that have to be changed. These activities require the production of additional materials as well as recycling of the steel for the new rails, fastenings, and reinforcement bars, a process that also requires around 25% new steel. Finally, the end-of life phase makes the lowest contribution – around 1.7% – because it involves the activities required for the dismantlement of the railway track and the recycling and landfilling of the different materials.

On the other hand, for the ballasted track, the production phase is responsible for 37.7% of the total impact, which is lower than that for concrete track beds, because the production of ballast is better for the environment than the production of concrete. The ballasted track requires the production of concrete for its sleepers, but the overall amount is minimal when compared with the requirements of the concrete track beds. However, due to its high maintenance requirements, as well as the further addition of ballast, the renewal of rails, sleepers, fastenings, and the bed itself around every 20–30 years, the use and maintenance phase makes the highest contribution: 58.6%. Its contribution becomes greater the longer the service life of the infrastructure becomes. The construction and end-of-life phases make the lowest contributions for the same reason as mentioned for the ballastless alternatives, and its end-of-life phase in particular is smaller because the ballast is already crushed, whereas ballastless tracks have to be crushed for dismantlement.

4. Conclusions

The present study assesses and compares the potential environmental impacts occurring throughout the entire life cycle of three different railway track substructure designs: a ballasted track, a cast-in sleeper track system, and an embedded track system. Based on the results obtained, for service lives of between 50 and 60 years, the ballasted track is usually the best solution in terms of its environmental impact, regardless of the damage category. However, if the ballastless tracks systems were to last around 75 years, the Rheda 2000 system would have almost the same impact as the ballasted track but would cause less damage to ecosystems. Moreover, the BBEST system has more impact than the other alternatives regardless of its service life, mainly due to its high steel requirements.

Steel is the material that makes the biggest contribution to the environmental impact; therefore, using more recycled steel and improving the recycling techniques could greatly reduce the environmental burden of track construction. If the concrete slab tracks were to last up to 100 years, the Rheda 2000 system would become the best solution for every damage category in terms of its environmental impact, due to the high maintenance requirements of the ballasted track for long periods of time. This study also provides previously unknown data on various impacts of railway track bed construction, such as water pollution, eutrophication, and solid waste generation.

From an environmental perspective, embedded track systems should only be used when they are completely necessary for technical reasons, such as for urban tramways, where there are intersections with road traffic, or when there is a need to reduce the gauge, such as in tunnels. Between the traditional ballasted tracks and the cast-in sleeper tracks, even though the impact and manufacturing embodied energy of the concrete slab track are much higher than those of the ballasted track, its longer life expectancy and reduced maintenance requirements make it a competitive alternative. For this reason, further research in developing durable concrete could be greatly beneficial for the environment. Therefore, even though these systems are being applied in moderate volume around the world, rather than becoming widespread, mainly due to the high level of initial investment required for their construction, by considering their costs and impacts through a life cycle perspective, they are shown to be better for the environment as well as offering other advantages in the long term.

Regarding the limitations of this study, the results could be useful for further studies to provide engineers and stakeholders with additional information for the decision-making process of transportation infrastructure projects. However, it is clear that maintenance and renewal processes affect the environmental impacts, depending on transport demand and future scenarios. For instance, a future study could assess the differences in train operation depending on the track bed design. Finally, it should be noted that the present study is limited to the sustainability assessment of different railway track substructure solutions and does not consider the rest of the elements of the rail infrastructure to which it belongs.

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List of Figures

List of Tables

Type of track	Components	Ecoinvent process	Amount (t/FU)
Ballast	Sub-base	Aggregate, natural	72000
	Sleepers	Concrete block	7700
		Reinforcing steel	188.2
	Ballast	Gravel, crushed	53040
	Rails	Steel, low alloyed, hot rolled	2400
	Fastenings	Steel, low alloyed, hot rolled	616
	Rail Pads	Polyurethane, rigid foam	20.4
Rheda 2000	Sub-base	Aggregate, natural	40000
		Cement, Portland	2660
		Reinforcing steel	560
	Precast concrete	Concrete block	5360
		Reinforcing steel	90
	In-situ concrete	Concrete, 35 MPa	25860
		Reinforcing steel	431
	Rails	Steel, low alloyed, hot rolled	2400
	Fastenings	Steel, low alloyed, hot rolled	616
	Rail Pads	Polyurethane, rigid foam	20.4
BBEST	Sub-base	Aggregate, natural	18900
		Cement, Portland	2500
		Reinforcing steel	265
	In-situ concrete	Concrete, 35 MPa	26720
		Reinforcing steel	2320
	Rails	Steel, low alloyed, hot rolled	2960
	Seal	Seal, natural rubber based	8
	Grout	Adhesive mortar	1100
	Shell	Glass fibre reinforced plastic	100
	Rail Pads	Polyurethane, rigid foam	34

Table 1. Amount of materials per functional unit

Type of track	**Activity**	**Construction speed** (h/km)	**Diesel Fuel consumption** (l/h)	**Total energy consumption** (MJ/FU)	**Ecoinvent process**
Ballast	Sleeper laying	14	5	25200	Diesel, burned in building machine
	Rail laying	37	5	66600	
	Ballast spreading	12	10	43200	
	Tamping	32	15	172800	
	Ballast changing	17	15	91800	
	Ballast cleaning	17	15	91800	
Rheda 2000	In-situ slab former	22	10	79200	
	Rail laying	37	5	66600	
	Concrete train	37	5	66600	
BBEST	In-situ slab former	22	10	79200	
	Rail laying	37	5	66600	
	Concrete train	37	5	79200	

Table 2. Construction and maintenance machinery

Acronym	Unit	Ballast Track		Rheda Track		BBEST Track	
		mean	cv (%)	mean	cv (%)	mean	cv (%)
ALO	m^2*a	7.19E+05	7.17	5.08E+05	5.63	6.27E+05	6.01
GWP	kg CO_2 eq	2.01E+07	7.72	2.23E+07	5.19	2.60E+07	5.93
FD	kg oil eq	4.94E+06	8.00	4.43E+06	5.15	5.74E+06	5.19
FEPT	kg 1,4-DB eq	5.17E+05	9.35	5.09E+05	6.72	5.33E+05	7.21
FEP	kg P eq	1.04E+04	9.14	1.05E+04	6.48	1.11E+04	6.53
HTP	kg 1,4-DB eq	1.57E+07	9.43	1.57E+07	6.72	1.62E+07	7.44
IRP	kg U235 eq	1.53E+06	8.58	1.16E+06	5.22	1.30E+06	6.41
MEPT	kg 1,4-DB eq	5.01E+05	9.31	4.92E+05	6.71	5.14E+05	7.21
MEP	kg N eq	4.78E+03	7.63	4.29E+03	5.10	6.85E+03	6.25
MD	kg Fe eq	1.35E+07	6.40	1.57E+07	8.90	1.84E+07	9.25
NLT	m^2	5.09E+03	15.26	2.39E+03	6.85	2.99E+03	6.83
ODP	kg CFC-11 eq	1.75E+00	8.05	1.45E+00	4.83	1.57E+00	5.33
PMFP	kg PM10 eq	6.77E+04	7.88	6.49E+04	5.60	7.14E+04	5.93
POFP	kg NMVOC	1.09E+05	7.30	9.95E+04	4.98	1.16E+05	4.85
TAP	kg SO_2 eq	9.61E+04	7.99	8.55E+04	5.15	1.02E+05	5.49
TETP	kg 1,4-DB eq	2.86E+03	9.14	2.27E+03	5.79	2.41E+03	5.29
ULO	m^2*a	7.77E+05	9.27	4.94E+05	13.15	4.96E+05	13.98
WD	m^3	8.99E+07	8.92	8.48E+07	6.42	8.95E+07	7.45

Table 3. Impacts occurring throughout a service life of 75 years. Mean value and coefficient of variation (cv)