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Social life cycle assessment of railway track substructure alternatives

Ignacio J. Navarro [a,*], Ignacio Villalba [b], Lorena Yepes-Bellver [c], Julián Alcalá [d]

[a] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022, Valencia, Spain
[b] Department of Transport Engineering and Infrastructure, Universitat Politècnica de València, Camino de Vera s/n, 46022, Valencia, Spain
[c] Department of Mechanics of Continuous Media and Theory of Structures, Universitat Politècnica de València, Camino de Vera s/n, 46022, Valencia, Spain
[d] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, Camino de Vera s/n, 46022, Valencia, Spain

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ABSTRACT

The sustainable design of infrastructure involves assessing economic, environmental, and social impacts. While significant progress has been made in evaluating economic and environmental life cycle impacts since the Paris Agreement, there's a notable gap in techniques for assessing social aspects in infrastructure design. This study introduces social indicators tailored for evaluating the lifecycle of railway infrastructures. The indicators are applied to assess the social impacts of three common railway track substructure solutions: conventional ballasted track, embedded slab track (BBEST solution), and sleeper-based, ballastless (RHEDA2000) substructure solutions. Using the Analytic Network Process (ANP), the social performance of each alternative is synthesized into a single indicator for comparison. Results indicate that the conventional ballasted track outperforms, scoring 12% higher than BBEST and 61% better than RHEDA in social terms. This is attributed to its reliable capacity for generating high-quality employment and fostering economic activities in the defined product system regions.

1. Introduction

1.1. Sustainability and social assessment in the railway sector

Transport is the largest contributor to global Greenhouse Gas (GHG) emissions among all economic sectors except for the energy sector, being responsible for 24.6% of CO2 equivalent emissions in the European Union (European Commission, 2020). Fostering a more sustainable transportation system and diminishing its carbon footprint are imperative endeavors to pave the way towards a cleaner society and achieve the aspirations declared by the society through initiatives such as the Sustainable Development Goals (SDGs) or the European Green Deal. In particular, the SDGs emphasize global efforts to combat climate change, with Goal 13 specifically targeting significant reductions in greenhouse gas (GHG) emissions. Similarly, the European Green Deal places a central focus on achieving climate neutrality by 2050, outlining policies and actions to mitigate GHG emissions and transition towards a greener and more sustainable European economy. The fact that railways contribute only 0.5% of the CO2 equivalent emissions in the EU-27's transport sector explains the current trend of promoting railways across the EU as a means to reduce the environmental impact of transportation.

Nevertheless, constructing and maintaining railway tracks also bear a noteworthy environmental impact concerning GHG emissions and the utilization of raw materials. The construction sector, in fact, being a significant environmental stressor, plays a crucial role in achieving the Sustainable Development Goals that the society aims to accomplish by 2030. As a consequence, the scientific community has put lots of effort during the past recent years to investigate on the environmental and economic impacts associated to a variety of structures, such as earth retaining walls (Pons et al., 2018), bridges (Pang et al., 2015; Penadés-Plà et al., 2019; Yepes-Bellver et al., 2022), asphalt pavements (Hasan et al., 2022; Torres-Machí et al., 2014), or concrete repair solutions (Renne et al., 2022), among many others.

In this context, and due to the efficiency of the railway transport system, particular interest has been put in the recent past in the sustainability assessment of railway infrastructures in order to optimize the sustainability performance associated to their construction and maintenance (Martínez-Fernández et al., 2019, 2022; Zhang et al., 2016). Given the high consumption of materials related to the construction of railway infrastructure, a wide portion of the research conducted to date is associated to the assessment of the track itself and of the track substructure. Celauro et al. (2023) assesses different material compositions for 2 alternatives of embankment for a double track railway line from an economic and environmental life cycle perspective. Following a similar

* Corresponding author.
E-mail address: ignamar1@upvnet.upv.es (I.J. Navarro).

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approach, Samuelsson et al. (2023) evaluates 3 different embankment fill methods, namely crushed bedrock, cement-stabilized till and foam glass. Morata et al. (2017) investigates on the economic and environmental performance of recycle aggregates for railways track beds. The work by Pons et al. (2020) compares the environmental impacts along the life cycle of ballasted and ballastless railway track substructure. Giunta et al. (2018) assesses the life cycle costs of the reduced maintenance associated to bitumen-stabilized ballasted track solutions.

Other researchers focus their works on the assessment of impacts associated to the production and maintenance of sleepers. Lim et al. (2023) compares the environmental and economic life cycle performance of two types of sleepers, namely those made of concrete and those made of engineered cementitious composites. In this line, Rempelos et al. (2020) focuses on the Greenhouse Gas Emissions related to the four common sleeper types in the UK rail network. It is also noteworthy the research conducted on the significant wastes generated by the construction of the railway infrastructure. Zhang et al. (2021) evaluates the Global Warming mitigation potential from recycling subway-related excavation wastes.

However, it shall be noted that putting the efforts in diminishing GHG emissions of railway sector or in optimizing the economic life cycle of railway infrastructures is not enough to fully align with the sustainable future envisioned by the SDG's. The Sustainable Development Goals (SDGs) assign significant importance to the societal impacts across a diverse array of Goals, such as SDG 1 (No poverty), SDG 3 (Good health and wellbeing), SDG 4 (Quality education), SDG 5 (Gender equality), SDG 8 (decent work and economic growth), SDG 10 (reduced inequalities), and others. In view of the above, it is crucial to acknowledge that sustainable and responsible product design should extend beyond the commonly considered sustainability dimensions, namely economy and environment. Consequently, more emphasis shall be put on the assessment techniques and criteria of the often-unnoticed social dimension (Hendiani et al. 2019). Even though high-level social factors are usually taken into account when making strategic decisions in the larger context of territorial planning, there is a substantial knowledge gap when it comes to developing practical and objective criteria for micro-scale infrastructure design. In essence, tools currently exist to socially justify the implementation of one transportation system over another to enhance regional connectivity. However, once a specific project has been chosen, designers lack the necessary tools to further pursue the social optimization of their designs. Developing quantifiable and optimization-oriented social indicators, along with corresponding assessment techniques, is essential to achieve infrastructure designs that are socially optimized. Bridging this gap becomes imperative to ensure that infrastructure projects are genuinely sustainable and aligned with society's aspirations.

1.2. Aim of the study

The profound impact of transportation on global Greenhouse Gas (GHG) emissions demands a shift toward more sustainable practices. While the promotion of railways as an environmentally friendly alternative gains traction, the environmental and social implications of constructing and maintaining railway tracks warrant careful consideration. The construction sector's role as an environmental stressor emphasizes the urgency to align infrastructure development with Sustainable Development Goals (SDGs) by 2030.

This study addresses the identified gaps in understanding the social dimensions of railway infrastructure sustainability. The overarching aim is to introduce a novel approach for conducting a comprehensive social life cycle assessment (SLCA) throughout the entire life cycle of railway infrastructures. The specific objectives include developing quantifiable and optimization-oriented social indicators, drawing inspiration from proven criteria in bridge structure assessments (Navarro et al., 2018), and employing an Analytic Network Process (ANP)-based ranking methodology. In the absence of a standardized ISO-based SLCA framework, this research incorporates fundamental steps and concepts outlined in the ISO 14040 and ISO 14044 framework.

By focusing on social optimization in infrastructure design, this study not only contributes to the ongoing development of SLCA but also aligns with broader societal goals outlined in the SDGs. Through a meticulous examination of three distinct track alternatives for a railway infrastructure, this study aims to determine the most socially advantageous design alternative and underscores the importance of considering social factors alongside economic and environmental dimensions in sustainable infrastructure development.

2. Literature review

Over the past years, the economic and environmental design of infrastructures has undergone significant standardization. However, a notable gap remains in the field of social life cycle assessment (SLCA) of products. While the environmental ISO 14040 and ISO 14044 standards have provided a foundation for environmental (and to a great extent, economic) life cycle assessments, the only available guidelines for SLCA are the 'Guidelines for social life cycle assessment of products' (UNEP/SETAC, 2020). Following the same approach as the environmental ISO 14040 and ISO 14044, the 'Guidelines' aim to provide a systematic framework for assessing and integrating social impacts into product life cycle assessments. Efforts are underway to address this gap, with the ISO technical committee ISO/TC 207/SC 5 currently working on developing a standardized framework for the social assessment of products. However, it's important to note that this standard is still in its early stages of development. The aforementioned 'Guidelines' emphasize the urgent need for the life cycle-based social assessment of products to be applied, as this would contribute to the further development, practicality, and validity of SLCA. Since the publication of the 'Guidelines,' efforts have been made to implement them in various case studies involving different products, such as fertilizers (Martínez-Blanco et al., 2014), electronics (Wilhelm et al., 2015), and food industry products (De Luca et al., 2015), among others.

During the past recent years, SLCA has started to be implemented to case studies based on the built environment, accounting for both building and infrastructure design. In the field of buildings, a wide variety of studies exist in the recent past investigating both on the material selection for particular building elements (Bezama et al., 2021; Balasbaneh et al., 2021) and on the complete building system (Janjua et al., 2019; Kim et al., 2021). However, given the scope of the present research, and given the evident design differences existing between building and infrastructure design, the spotlight of this literature review is put on the approaches followed when conducting SLCA in infrastructures.

In the field of infrastructure, it is common practice to conduct the SLCA based on the methodology presented in ISO 14040 and 14044 for environmental life cycle assessment, irrespective of the type of infrastructure assessed (Balasbaneh and Marsono, 2020; Hossain et al., 2018). While the studies based on ISO 14040 present similarities in the definition of goal and scope, the functional unit, or the criteria considered for the establishment of the product system boundaries, among others, there are significant differences in the assessment of impacts. Even though the Guidelines are commonly held as the basis to identify the stakeholders and impacts relevant to the case studies, depending on the infrastructure and its social context the social indicators vary. Safarpour et al. (2022) considers 11 indicators covering the social impacts on workers, local community and consumers when assessing the life cycle of wastewater systems, while Yang et al. (2022) considers 10 indicators to assess the totality of stakeholders recognized by the Guidelines, namely workers, users, society, value chain participants, and local community while evaluating the social impacts associated to the transport infrastructure in China. The choice on the particular indicators that are relevant to the case studies in question can be based on a variety of methods, such as word heat maps applied to databases resulting from literature reviews (Blaauw et al., 2021; Gompf et al., 2022), or the most frequently used Social Hotspot Database (Serreli et al., 2021).

There are also differences in the way the chosen indicators are evaluated. A great portion of the analyzed studies base their research on qualitative indicators that are then quantified through stakeholder or expert surveys. Oladazimi et al. (2021) evaluates the social impacts of the construction of steel and concrete frames focusing on four impact categories, namely health and safety, fair salary, local employment generation and local community acceptance. Barrio et al. (2021) construct a social criteria set based on the 'Guidelines', considering four stakeholders (local community, value chain actors, workers and society) to assess the social impact of a particular type of panels for construction applications. Aung et al. (2021) establishes a set of 24 social criteria to evaluate a hydropower project. Singh and Gupta (2018) also consider 20 social criteria based on the 'Guidelines' to assess socially the steel Indian sector. The abovementioned studies base the quantification of the social indicator sets on questionnaires. Such questionnaire-based evaluation of impacts has a major advantage, as the community is actively involved in the decision-making process. Such approach is usually rewarded in the currently existing sustainability certifications for infrastructures, such as ENVISION or BREEAM Infrastructure. However, a key limitation of this approach is that it cannot be used for comparative studies or design optimizations, where quantitative and more objective indicators are required. To that end, some researchers base their studies on the use of SLCA-oriented, well recognized databases, such as PSILCA, to assess infrastructure (Serreli et al., 2021) or optimize structural designs (Penadés-Plà et al., 2020). Others, on the contrary, define their own quantitative indicators to fit more accurately the specific social context and the particularities of the infrastructure to be assessed, to either address the social impacts of a particular design (Zheng et al., 2019, 2020) or to evaluate different design alternatives (Navarro et al., 2018).

Regarding the field of railways, and to the best of the authors' knowledge, only the study conducted by Yang et al. (2022) evaluates the social impacts of railway infrastructures from a life cycle perspective. However, no studies have been found that focus on the track alternative selection at the design scale. Here, a design-scale methodology is proposed to investigate on the social consequences of different railway track alternatives, combining the common aspects of the reviewed SLCA studies on infrastructures, and defining a set of criteria applicable to the railway track selection. The primary objective of the proposed set of criteria is to function as a tool for optimizing railway track designs on a quantitative and objective scale, and being aligned with the approach followed by the 'Guidelines'. The proposed assessment criteria are intended to serve as a guiding framework for both researchers and practitioners, ensuring a systematic and comparable evaluation of social aspects across diverse railway infrastructure projects. With a harmonized set of social indicators and quantitative tools aligned with SLCA principles, the method enables rigorous comparative studies and facilitates informed design optimizations. Specifically tailored for the railway sector, the methodology offers valuable insights into the social consequences of different track alternatives at the design scale, addressing a crucial research gap. The proposed method is intended to enhance the practicality, validity, and applicability of SLCA in infrastructure design, promoting a more holistic and sustainable approach to decision-making processes.

3. Materials and methods

3.1. Social life cycle assessment – goal and scope definition

The existing SLCA builds upon the approach outlined in the environmental norms ISO 14040 and ISO 14044, which delineate the procedure for evaluating the life cycle of products. As per these standards, every life cycle assessment must adhere to a sequential four-phase framework encompassing scope definition, inventory compilation, assessment methodology, and interpretation of the outcomes.

This analysis focuses on assessing the social life cycle impacts of a 1 km long segment of a high-speed railway twin-track system that connects Madrid and Oropesa (Spain), projected to operate for a life span of 100 years (Indraratna et al., 2011).

The present evaluation is intended to quantify the social life cycle impacts of three alternative designs for the functional unit defined. The first design, namely the conventional design, consists of a railway track composed by precast concrete sleepers over an aggregate-based substructure. This design embodies the standard railway track solution commonly found in Spain (Villalba Sanchis et al., 2021). The second design option under analysis is the so-called Beatty Embedded Slab Track (BBEST henceforth). This option is a ballastless track system characterized by a reinforced concrete slab embedding steel rails and is commonly used in high-traffic rail environments where durability and reduced maintenance are essential. The third design alternative considered in the current social assessment is the Rheda 2000 solution. This solution, like the previously mentioned alternative, belongs to the category of ballastless track systems. In the Rheda 2000 solution, a robust concrete sub-base forms the foundation, upon which precast sleepers are securely positioned. These sleepers, strategically fixed onto the surface, contribute to the stability and load distribution of the track. This innovative configuration offers advantages in terms of maintenance efficiency, track longevity, and overall operational performance. For every sleeper-based alternative, sleepers are assumed to be spaced 650 mm apart from each other, and CEN60-E1 rails are assumed. BBEST design uses different rail profiles, namely BB14072 profiles.

The product system being examined accounts for the impacts associated with the production processes of all materials utilized in the construction and maintenance of each alternative (Fig. 1). This also extends to the impacts stemming from the construction and maintenance activities for each of these alternatives. In this comparative cradle-to-grave approach, impacts that are considered identical for every alternative, or those whose effect can be neglected, have been cut off from the assessment (Martínez-Blanco et al., 2014). Hypothetical end-of-life social impacts resulting from the demolition of the alternative solutions have also been excluded from the analysis, given the high uncertainties related to the social context in that time horizon. It must be kept in mind that the social assessment conducted here is focused on the selection of materials and track/substructure solutions. Assessing the effect of macro-scale decisions, such as the selection of different transport systems, or the selection of different track alignments or track origin and destination, is out of the scope of this assessment.

3.2. Inventory analysis and impact assessment methodology

In order to assess objectively the social impacts of each track option throughout their life cycle, it is necessary to establish a collection of measurable criteria. For the present work, a group of six indicators has been chosen that serve to cover the impacts on the stakeholders. The identification of these stakeholders aligns with the categories outlined in the 'Guidelines' (UNEP/SETAC, 2020). The 'Methodological sheets for subcategories in Social Life Cycle Assessment' (UNEP/SETAP, 2021) have served as a basis for selecting the social indicators considered relevant. From the 40 subcategories reflected in this document, attention has been paid only to those that simultaneously: allow for a direct quantification, reflect actual social problems in the context of a developed country as the one considered for the case study, could be affected by the functional unit under assessment, and would result in different impact on the society depending on the alternative considered. The indicators considered in the present study encompass regional economic development, equitable remuneration as a gauge of working conditions, gender disparity, local employment generation, the health and safety standards associated with the produced work, and public opinion. The social impacts are measured by means of so-called activity variables. In SLCA, an activity variable refers to a quantifiable factor linked with a specific activity or process within a product's life cycle. These variables

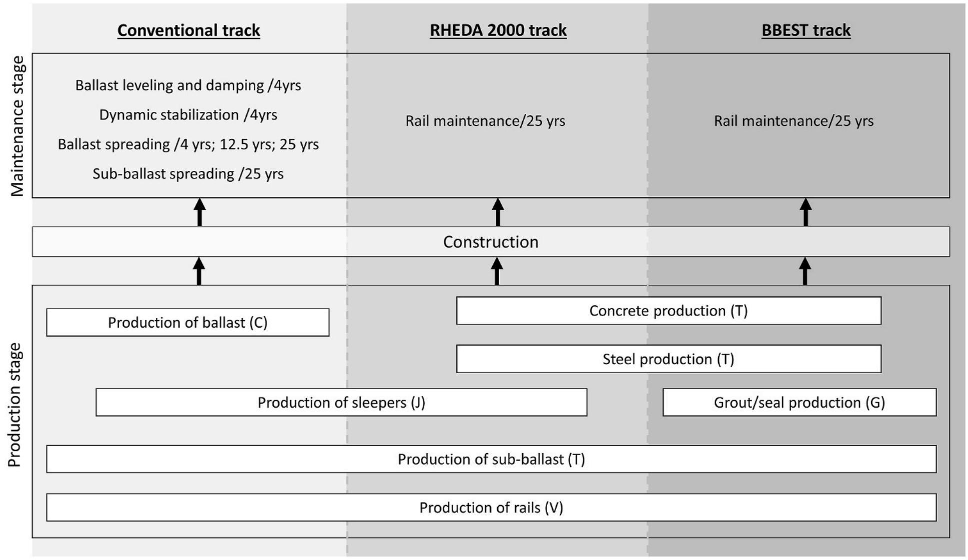

Fig. 1. Product system of the substructure alternatives (T = Toledo; C = Cáceres; J = Jaén; V = Valladolid; G = Guadalajara).

are intended to estimate the potential positive or negative social effects of the activity or process under consideration throughout a product's life cycle.

In the present assessment, a separate variable has been chosen for each stakeholder. The first stakeholder under consideration here is the society and, in particular, the economic development of the regions where the economic activities resulting from the defined product system take place. The activity variable enabling the assessment of this impact is the economic inflow associated with the payment for materials and construction services provided by their respective suppliers, measured in €. The second stakeholder considered in this study are the workers. In particular, to measure the social impact on the workers, an activity variable is chosen that accounts for the total amount of employment generated along the life cycle of each design option. The last stakeholder considered in the present assessment includes both the users of the railway system as well as the people living in the area of the construction site. As the maintenance requirements of an alternative increase, so does the negative impact on the comfort and convenience of rail users. Furthermore, a higher frequency of maintenance activities needed by an alternative corresponds to increased externalities like dust, noise, or vibrations, which consequently have a greater influence on the nearby communities. The activity variable chosen to quantify the effect of each alternative on users and local communities is the number of maintenance activities required by each activity.

However, it shall be noted that these activity variables alone are not sufficient to estimate the social impacts of each activity of the product system under evaluation. To that end, the effect of these variables in the social system where they are involved shall be taken into account. The Guidelines propose an assessment approach based on the so-called Performance Reference Points. These are meant to give a measure of how a product or an activity impact on different aspects of its social context. Consequently, the activity variables suggested here are referred to the maximum, minimum or average values associated to the different Spanish regions for the particular social aspects under consideration. Utilizing the referenced values, activity variables are normalized and converted into subcategory indicators, spanning from 0 to 1, where 1 signifies the optimal scenario within the Spanish context. Guidance on the construction of such indicators is provided in the Methodological Sheets for Subcategories in Social Life Cycle Assessment (UNEP/SETAC, 2021).

For the case of the economic development of regions, an indicator is constructed in such a way that the effect of the activity variable, namely the economic inflows, is less the greater the economic wealth of the receiving region is. In other words, the indicator is formulated so that alternatives that generate more economic inflows in poorer regions are rewarded, as they contribute to the economic and social equity of the system. In order to consider this beneficial social impact, the subsequent indicator is proposed, serving the purpose of assigning weight to the economic inflows directed towards distinct production centers:

$$X_{econ.\ devel.} = 1 - (gdp - GDP_{min})/(GDP_{max} - GDP_{min}) \quad (1)$$

where gdp stand for the Gross Domestic Product of the region where the particular activity takes place, and GDP_{max} and GDP_{min} stand, respectively, for the maximum and minimum regional Gross Domestic Product along the Spanish territory.

Regarding the social impact on the workers, a set of four criteria has been assumed to consider the main relevant aspects affecting employment conditions in Spain (Navarro et al., 2018), namely fair salary, gender discrimination, workers' safety, and unemployment. In the assessment of these four employment-related sectors, four indicators are formulated to account for the social context. These indicators are designed to assign appropriate weight to the employment generated by each activity within the product system. For instance, if the activity is measured in terms of "hours of work generated", these hours are adjusted to reflect the actual impact of these working hours on the society, considering the unique conditions of the production sites involved. This social significance of the working hours is recognized to vary based on the local context. An hour of work generated in an area with high unemployment rates is acknowledged to have a different impact compared to an hour generated in an area where unemployment is scarce. By incorporating this contextual perspective, the assessment acknowledges the unequal social implications of employment across different regions. Consequently, the set of four indicators presented below aims to reward the alternatives that result in a greater reduction of the unemployment of a region, in employment created in fairly paid regions and sectors, in employment generated in regions and sectors that contribute to reduce gender inequalities, or where worker's safety is ensured.

In order to consider equitable salary conditions, the following indicator is constructed:

$$X_{salary} = (s - S_{min})/(S_{max} - S_{min}) \quad (2)$$

where s represents the average regional salary where the production activity is occurring, and S_{max} and S_{min} stand, respectively, for the maximum and minimum mean regional salary along the Spanish territory.

The second indicator related to the stakeholder workers aims to consider to what extent the employment generated contributes to reduce the regional unemployment:

$$X_{local\ empl.} = (ur - Ur_{min})/(Ur_{max} - Ur_{min}) \quad (3)$$

where ur is the regional unemployment rate representative of the region where the production activity takes place, and Ur_{max} and Ur_{min} represent, respectively, the highest and lowest regional unemployment rates across the Spanish territory.

A third indicator is formulated in order to weight the employment generated assessing the extent to which this generated employment helps in reducing the sectorial and regional gender gap:

$$X_{gender\ gap} = 0.5 \min\{1\text{-}|Ur_m/Ur_{mean}\text{-}1|;1\text{-}|Ur_w/Ur_{mean}\text{-}1|\} + 0.5 \min\{1\text{-}|S_m/S_{mean}\text{-}1|;1\text{-}|S_w/S_{mean}\text{-}1|\} \quad (4)$$

Here, Ur_m and Ur_w represent the average unemployment rates for men and women at the region where the activity takes place, while Ur_{mean} signifies the average unemployment rate at the activity location. S_m and S_w respectively denote the average salaries for men and women in the region where the activity occurs, and S_{mean} indicates the average salary in that region.

Finally, the safety of workers engaged in the product system for each alternative is considered through the utilization of the following indicator:

$$X_{safety} = 1 - (ar - Ar_{min})/(Ar_{max} - Ar_{min}) \quad (5)$$

where ar stands for the average sectorial accident rate for the specific activity at the region of the production center, and Ar_{max} and Ar_{min} stand, respectively, for the maximum and minimum regional accident rate for the specific activity across the Spanish territory.

In order to measure the social impact to both the users and the local community resulting from aspects as delays or externalities caused by maintenance activities, the following impact score is defined that rewards those alternatives with reduced maintenance:

$$X_{public\ opinion} = 1 - N/\max\{N_i\} \quad (6)$$

where N is the estimated number of maintenance activities required by the alternative under assessment throughout its entire life cycle, and $\max\{N_i\}$ is the maximum number of maintenance operations required among the alternatives under study.

Once the activity variables p_{ij} and the social indicators X_{ij} have been obtained for each of the social impact categories i selected and for each of the design alternatives j under study, the social impact I_{ij} of the alternative j on each of them can be calculated by simply multiplying both values:

$$I_{ij} = X_{ij} \cdot p_{ij} \quad (7)$$

Table 1 shows the inventory data regarding the main activity variables associated to the production stage of the different alternatives under analysis. Information related to the material and economic flows, as well as the employment generated, are included. It shall be noted that, while the material flows are expressed per m of track, the amount of employment generated, as well as the economic flows provided in the table are associated to the functional unit (F.U.) described above of 1000 m long track.

The inventory data including the activity variables for each alternative during the construction and maintenance stage of their life cycles are included in Table 2. Again, the amount of employment generated, and the economic flows provided are associated to the functional unit (F.U.) described above of 1000 m long track, while the material flows are expressed per m of track.

The inventory data required to evaluate the social context-based indicators formulated above is provided in Table 3. This data has been gathered from official, up-to-date databases available for the Spanish territory, namely the Spanish Tax Office and the Spanish National Statistics Institute. The values included in Table 3 correspond to 2023 values.

3.3. Analytic Network Process based sustainability indicator

Sustainable design involving a wide variety of criteria is usually considered as a decision-making problem, and so is the case when only the social aspects are considered. Similarly, a variety of social impacts of different nature are involved, and a decision-making approach can offer a great advantage in normalizing and aggregating these impacts into a single, synthetizing social score. In order to rank the different design alternatives under analysis based on their social impact and considering the six social criteria presented above, the ANP method (Saaty, 1996) is

Table 1
Activity variables for the production stage.

Material production activity		Production Center	Quantity/m	Employment Generated/F.U.	Economic Flow/F.U.
Conventional ballast track					
Sub-ballast	Aggregates	Toledo	7200 kg/m	90 h	39.98×10^3 €
Sleepers	Concrete	Jaén	770 kg/m	138.6 h	–
	Steel	Jaén	18.8 kg/m	7.8 h	–
	Manufacture	Jaén	1.5 units/m	1061.5 h	106.55×10^3 €
Ballast		Cáceres	5304 kg/m	66.3 h	50.56×10^3 €
Rails		Valladolid	240 kg/m	99.3 h	41.22×10^3 €
RHEDA 2000					
Sub-ballast	Aggregates	Toledo	4000 kg/m	50 h	22.21×10^3 €
	Cement	Toledo	266 kg/m	43.9 h	7.87×10^3 €
	Steel	Toledo	56 kg/m	23.2 h	34.72×10^3 €
Sleeper	Concrete	Jaén	536 kg/m	96.5 h	–
	Steel	Jaén	9 kg/m	3.7 h	–
	Manufacture	Jaén	1.5 units/m	1061.5 h	106.55×10^3 €
In-situ concrete	Concrete	Toledo	258 kg/m	46.5 h	8.38×10^3 €
	Steel	Toledo	43 kg/m	17.8 h	26.77×10^3 €
Rails		Valladolid	240 kg/m	99.3 h	41.22×10^3 €
BBEST					
Sub-ballast	Aggregates	Toledo	1890 kg/m	23.6 h	10.49×10^3 €
	Cement	Toledo	250 kg/m	41.3 h	7.40×10^3 €
	Steel	Toledo	26.5 kg/m	11 h	16.43×10^3 €
In-situ concrete	Concrete	Toledo	2672 kg/m	481 h	86.57×10^3 €
	Steel	Toledo	232 kg/m	96 h	143.84×10^3 €
Grout, Seal		Guadalajara	110 kg/m	19.8 h	116.60×10^3 €
Rails		Valladolid	296 kg/m	122.4 h	41.22×10^3 €

Table 2
Activity variables for the construction and maintenance stages.

Construction/ Maintenance operation	Quantity/m	Employment Generated/F.U.	Economic Flow/F.U.
Conventional ballast track – Construction stage			
Sub-ballast spreading	7200 kg/m	1181 h	46.76×10^3 €
Ballast spreading	5304 kg/m	2358.9 h	78.17×10^3 €
Rail and sleeper installation	–	5066.2 h	51.65×10^3 €
Rail welding	0.0139 units/m	144.4 h	3.40×10^3 €
Conventional ballast track – Maintenance stage (100 years)			
Ballast leveling and damping/4 yrs.	–	575 h	80.50×10^3 €
Dynamic stabilization/4 yrs.	–	50 h	33.50×10^3 €
Ballast spreading/4 yrs.	265.2 kg/m	59054.8 h	160.91×10^3 €
Ballast spreading/12.5 yrs.	1591.2 kg/m	19030.1 h	308.94×10^3 €
Sub-ballast spreading/ 25 yrs.	7200 kg/m	4900.5 h	346.95×10^3 €
Ballast spreading/25 yrs.	5304 kg/m	9580 h	514.91×10^3 €
RHEDA 2000 – Construction stage			
Sub-ballast spreading	4000 kg/m	656.1 h	25.98×10^3 €
Rail and sleeper installation	–	5066.2 h	51.65×10^3 €
Rail welding	0.0139 units/m	144.1 h	3.40×10^3 €
In-situ concreting	0.10 m^3/m	64.7 h	2.35×10^3 €
Reinf. steel installation	43.1 kg/m	991.3 h	23.71×10^3 €
RHEDA 2000 – Maintenance stage (100 years)			
Rail maintenance/25 yrs.	296 kg/m	19769.7 h	310.36×10^3 €
BBEST – Construction stage			
In-situ concreting	1.07 m^3/m	668.0 h	24.28×10^3 €
Reinf. steel installation	232 kg/m	5336.0 h	127.60×10^3 €
Grout and sealing	110 kg/m	22000.0 h	28.37×10^3 €
Rail installation	–	820 h	2.85×10^3 €
Rail welding	0.0139 units/m	144.1 h	3.40×10^3 €
BBEST – Maintenance stage (100 years)			
Rail maintenance/25 yrs.	296 kg/m	19769.7 h	310.36×10^3 €

Table 3
Parameters defining the social context of the regions involved in the production system.

	Toledo	Jaén	Cáceres	Valladolid	Guadalajara
Gross Domestic Product GDP (x10^6 €)	915.66	593.51	675.88	716.95	335.95
Mean unemployment rate (%)	14.08	20.37	17.64	8.47	10.83
Men's mean unempl. rate (%)	9.16	14.81	16.98	8.4	7.86
Women's mean unempl. rate (%)	19.98	27.6	18.46	8.56	14.42
Mean salary (€)	18230	14261	15869	21380	21128
Men's mean salary (€)	20085	15371	17115	23985	23852
Women's mean salary (€)	15777	12807	14417	18400	17877
Accident Rate (*A.R.*) – Construction	8.73	6.44	6.13	5.62	9.91
A.R.- Specialized construction activities	7.67	5.65	5.38	4.94	8.71
A.R.- Industry	6.90	5.09	4.84	4.44	7.84
A.R. - Metalworking	8.10	5.97	5.69	5.21	9.20
A.R. – Extractive industry	7.27	5.36	5.11	4.68	8.26

used. ANP is a decision-making technique for evaluating multiple criteria and is built upon the familiar Analytic Hierarchy Process (AHP) framework introduced by Saaty in the early 1980s (Saaty, 1980). While AHP works well for problems with straightforward hierarchies, ANP extends beyond this limitation, offering a more flexible approach for complex decision structures. ANP employs a network structure, allowing the modeling of intricate relationships and dependencies that may not follow a hierarchical pattern. This is particularly valuable when dealing with real-world decision problems where elements interact in non-linear and interdependent ways. Unlike AHP, ANP excels in handling dependence and feedback. AHP assumes independence among criteria or alternatives, making it less suitable for dynamic scenarios. ANP, on the other hand, accommodates dependencies and feedback loops, capturing the dynamic and interactive nature of decision problems. The flexibility of ANP in dealing with inconsistencies further sets it apart. It can handle inconsistencies more gracefully by allowing for nuanced modeling and reducing the impact of inconsistencies in pairwise comparisons. Consequently, ANP's ability to model complex relationships, dependencies, and feedback makes it more suitable for complex sustainability-related decision problems.

In ANP, decision-makers evaluate and compare various criteria and alternatives based on their relative importance and performance. The method involves breaking down the decision problem into a hierarchical network of elements, where elements can represent criteria, sub-criteria, alternatives, and interactions among them. These interactions are captured using pairwise comparisons, similar to AHP. However, ANP introduces the concept of "superiority" and "dependence" between different levels of the hierarchy. Superiority captures the relative importance of elements at different levels, while dependence captures the impact of one element's performance on another element's performance.

Following the ANP technique, criteria and alternatives are grouped into so-called clusters. In this context, clusters refer to groups of elements that share common characteristics or interact closely with each other within the decision-making network. This technique enables the consideration of connections between clusters in both directions. It allows for the modeling of influences between elements within one cluster on elements in another cluster, and vice versa. Additionally, ANP accommodates the representation of relationships within clusters. These relationships are categorized as internal and external influences.

The construction of the relational network that represents the decision problem is an essential step in applying ANP. The decision maker must decide which criteria and alternatives will impact his/her decision, group them into clusters, and establish the relationships based on their expertise and understanding of the problem. This model is then presented in the form of a relational supermatrix. This matrix contains entries of either 1 or 0, indicating the presence or absence of a relationship between elements in the rows and columns, respectively. Constructed in this way, the supermatrix is a composite representation that consolidates the information from all the pairwise comparisons made between elements within and across clusters, providing a comprehensive view of the entire network structure and captures how the elements are interconnected and affect each other.

Once the relational supermatrix is completed, the expert must replace each "1″ with the actual relationship between rows and columns. This is done using the traditional AHP method, which helps determine the level of influence each element from a row with a "1″ has on the specific element in the column being analyzed. The outcome is an unweighted supermatrix. However, this matrix isn't balanced; in other words, the elements in each column don't add up to 1. To achieve a balanced supermatrix, the elements in each column need to be multiplied by the weight of the cluster they belong to. This weight is determined again using the conventional AHP approach.

The weighted supermatrix that results serves as the foundation for the final stage of the process. This step involves repeatedly raising the weighted supermatrix to a power until each column becomes the same.

The elements within this ultimate matrix, known as the "limiting supermatrix," offer both the final weights for each criterion and the evaluation of each alternative based on these criterion weights.

4. Results of the life cycle assessment

4.1. SLCA impact results

The first step to determine the social impacts along the life cycle of each alternative consists in obtaining the social indicators that will serve to weight the activity variables defined for each stakeholder. These indicators depend solely on the social context of the region where each activity takes place and is independent from the activity variable itself. From the inventory data shown in Table 3, the weighting social indicators defined above can be directly obtained for each production center and activity (Table 4):

Regarding the construction and maintenance stage, the indicators take the values shown in Table 5:

Using the previously outlined SLCA approach, the social effects related to the three distinct life cycle stages examined in this study—namely material production, construction, and maintenance—are computed for the three available track design alternatives (Figs. 2–4). It shall be highlighted that the indicator system presented here is constructed in such a way that, the higher the score, the more positive the impact is for the society. The values shown in Figs. 2–4 correspond to the activity variables presented in Tables 1 and 2, weighted by the social indicators defined above and presented in Tables 4 and 5 depending on the life cycle stage involved. It shall be noted that in those figures, the left vertical axis serves to represent the social impacts on local employment, gender, safety and fair salary, expressed in effective working hours. The secondary vertical axis stands to represent the social impact on the economic development of regions, expressed in euros.

It is observed that, as far as the production stage is concerned, the alternative BBEST scores very little if compared to ballast-based and Rheda 2000 alternatives in generating quality employment. However, the economic flows derived from such alternative are significantly higher (approximately 70% greater) than for the other two alternatives (Fig. 2).

In summary, for the material production stage, each design alternative has its strengths in different impact categories. The ballast-based design seems to excel in local employment, gender, and safety. The BBEST design, on the other hand, emphasizes fair salary and economic development. Rheda 2000 falls in between the other designs in most categories.

However, when it comes to the social impacts associated to the construction stage (Fig. 3), it is precisely BBEST the alternative that both generates more employment and contributes more to the economic development of regions.

The BBEST design stands out across all impact categories with notably higher values compared to the other designs. It appears to have the most significant positive effects on local employment, gender, safety, fair salary, and economic development. The ballasted and the Rheda 2000 alternatives, while still impactful, have lower values across the board in comparison to the BBEST design.

Finally, the impacts resulting from maintenance over a 100-year period for each of the three design alternatives are presented in Fig. 4. It is evident that the high maintenance demands associated with the conventional ballasted track contribute to consistent employment generation over an extended period. This significantly boosts economic prosperity in the affected activity locations by more than 300% when compared to the RHEDA 2000 and BBEST solutions. However, the positive impact on public opinion stemming from the absence of maintenance is negligible for the conventional track, as per the proposed impact indicators. In contrast, RHEDA 2000 and BBEST alternatives, with minimal discernible effects on users and local communities throughout their life cycles, achieve nearly perfect scores of 1 for this decision criterion.

4.2. MCDM-based sustainability life cycle assessment

After determining the social impacts for each stage and option, the decision model is created using the ANP approach. The construction of this model involved the collaboration of three experts. Table 6 provides a concise overview of each expert's academic and professional background.

In the current decision-making scenario, variables have been categorized into four clusters. The first cluster comprises the three design alternatives, the second involves the four employment-related criteria, the third pertains to the socio-economic criterion, and the fourth addresses the impact on public opinion. It is important to note that

Table 4
Social indicators for the production stage.

Material production activity		Local employment ($X_{local\ empl}$)	Gender ($X_{gender\ gap}$)	Safety for workers (X_{safety})	Fair salary (X_{salary})	Economic development ($X_{econ.\ devel}$)
Conventional ballast track						
Sub-ballast	Aggregates	0.371	0.723	0.227	0.319	0.760
Sleepers	Concrete	0.680	0.772	0.666	0.000	0.853
	Steel	0.680	0.772	0.666	0.000	0.853
	Manufacture	0.546	0.931	0.725	0.129	0.830
Ballast		0.095	0.925	0.822	0.571	0.818
Rails		0.680	0.772	0.666	0.000	0.853
RHEDA 2000						
Sub-ballast	Aggregates	0.371	0.723	0.227	0.319	0.760
	Cement	0.371	0.723	0.227	0.319	0.760
	Steel	0.371	0.723	0.227	0.319	0.760
Sleeper	Concrete	0.680	0.772	0.666	0.000	0.853
	Steel	0.680	0.772	0.666	0.000	0.853
	Manufacture	0.371	0.723	0.227	0.319	0.760
In-situ concrete	Concrete	0.371	0.723	0.227	0.319	0.760
	Steel	0.095	0.925	0.822	0.571	0.818
Rails		0.680	0.772	0.666	0.000	0.853
BBEST						
Sub-ballast	Aggregates	0.371	0.723	0.227	0.319	0.760
	Cement	0.371	0.723	0.227	0.319	0.760
	Steel	0.371	0.723	0.227	0.319	0.760
In-situ concrete	Concrete	0.371	0.723	0.227	0.319	0.760
	Steel	0.371	0.723	0.227	0.319	0.760
Grout, Seal		0.095	0.925	0.822	0.571	0.818
Rails		0.211	0.757	0.000	0.551	0.928

Table 5
Social indicators for the construction and maintenance stages.

Construction/Maintenance operation	Local employment ($X_{local\ empl}$)	Gender ($X_{gender\ gap}$)	Safety for workers (X_{safety})	Fair salary (X_{salary})	Economic development ($X_{econ.\ devel}$)
Construction stage (common to every alternative)					
Ballast, BBEST, RHEDA 2000	0.371	0.723	0.227	0.319	0.760
Conventional ballast track – Maintenance stage					
Ballast and sub-ballast production	0.546	0.931	0.725	0.129	0.830
Ballast and sub-ballast spreading, leveling and damping	0.371	0.723	0.227	0.319	0.760
RHEDA 2000 – Maintenance stage					
Steel production	0.095	0.925	0.822	0.571	0.818
Rail installation	0.371	0.723	0.227	0.319	0.760
BBEST – Maintenance stage					
Steel production	0.095	0.925	0.822	0.571	0.818
Grout production	0.211	0.757	0.000	0.551	0.928
Rail installation	0.371	0.723	0.227	0.319	0.760

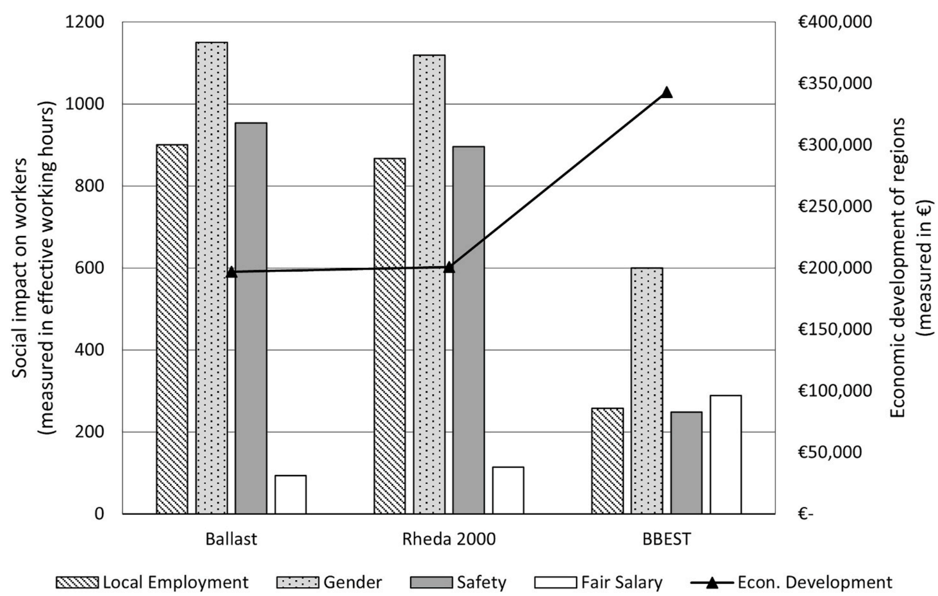

Fig. 2. Social impacts associated to the material production stage.

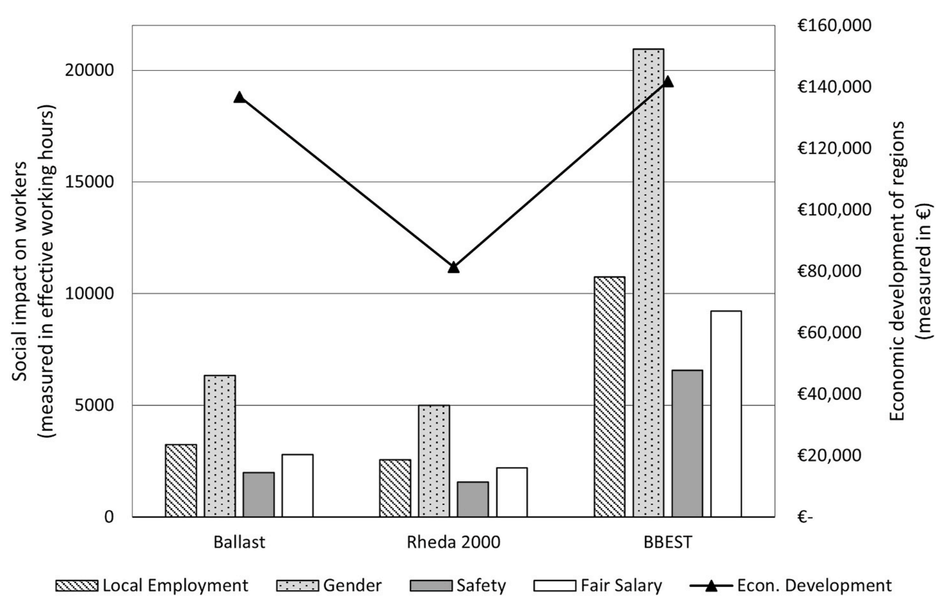

Fig. 3. Weighted social impacts associated to the construction stage.

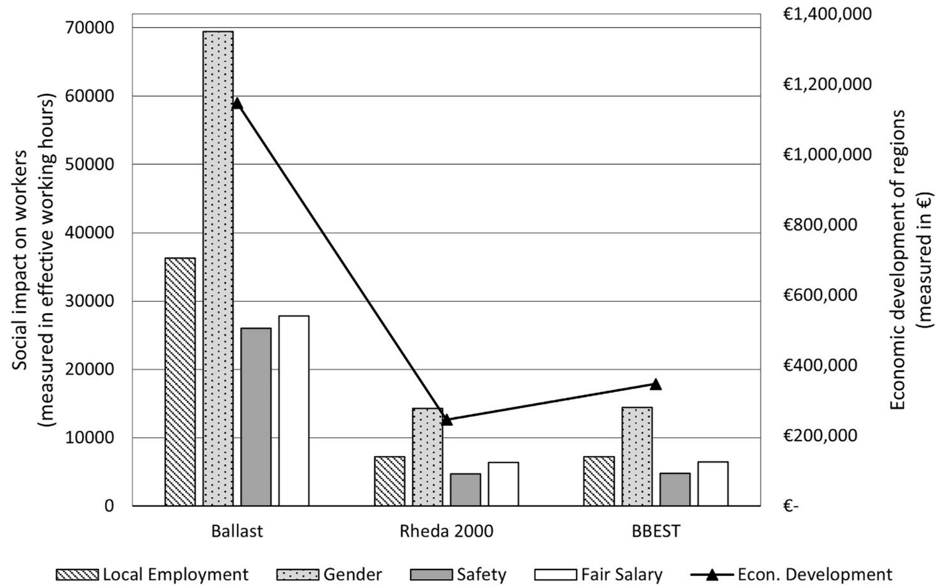

Fig. 4. Social impacts associated to the maintenance stage.

Table 6
Description of the panel of experts.

	Expert 1	Expert 2	Expert 3
Years of profesional experience	8	21	17
Advanced degree	PhD	PhD	MSc
Expertise level in construction design	8/10	10/10	10/10
Expertise level in structural design	10/10	8/10	10/10
First author in JCR articles	9	14	4

alternatives have an impact on criteria, and vice versa, establishing a reciprocal influence. As such, the respective cells in the supermatrix are designated with a value of 1, signifying this mutual influence. Here, no specific relationships between the alternatives themselves is assumed. The detailed relationships, both among alternatives and criteria, are illustrated in Fig. 5, focusing solely on expert 1. In this section, supermatrices will be shown exclusively related to expert 1 to maintain clarity and simplicity. Fig. 5 reveals the understanding of expert 1 of how criteria are related to each other. In addition, and following the conventional procedure in ANP, it can be observed that every criteria is related to every alternative and vice-versa.

After the model is built and in accordance with the ANP process, the cells in the influential supermatrix that were previously assigned a value of 1 are subsequently replaced with the factual influence that the elements in each row exert on the elements in each column. This is done to create the unweighted supermatrix, which is illustrated in Fig. 6. As explained above, the unweighted supermatrix is constructed by combining the matrices of pairwise comparisons from all levels of the decision hierarchy. This results in a matrix that captures the relationships and dependencies between elements across clusters and levels. Since the social criteria set in this analysis consists of quantitative factors, the initial three rows and three columns can be directly populated using the impact values depicted in Figs. 2–4.

In order to establish a stochastic, weighted supermatrix, it is necessary to evaluate the impact that each cluster has on the others. This evaluation can be accomplished through the conventional AHP method, focusing solely on the pairwise comparison of clusters with interconnected elements (refer to Fig. 7).

After quantifying these relationships, the stochastic and weighted decision supermatrix can be generated (Fig. 8). The elements of this matrix correspond to the elements of the unweighted supermatrix (Fig. 6) multiplied and normalized by the weight of the cluster they belong to. This precedes the calculation of criteria weights and alternative scores.

The final phase of the ANP procedure involves repeatedly raising the prior supermatrix until it reaches convergence, resulting in what is referred to as the limiting supermatrix. In this limiting supermatrix, each column is identical. For this particular decision-making problem, the values obtained for each column in the limiting supermatrix and, consequently, the results of the ANP method, are displayed in Fig. 9.

Analyzing the outcomes, it becomes evident that, in the specific scenario under consideration and in alignment with the expert's perspective on the matter, greater significance is attributed to the potential impacts of each alternative on regional economic development

	Ballast	Rheda 2000	BBEST	Local Employment	Gender	Safety	Fair Salary	Econ. Development	Public Opinion
Ballast	0	0	0	1	1	1	1	1	1
Rheda 2000	0	0	0	1	1	1	1	1	1
BBEST	0	0	0	1	1	1	1	1	1
Local Employment	1	1	1	0	1	1	1	1	0
Gender	1	1	1	0	0	0	0	0	1
Safety	1	1	1	0	0	0	0	0	1
Fair Salary	1	1	1	0	0	0	0	1	0
Econ. Development	1	1	1	1	0	0	1	0	0
Public Opinion	1	1	1	0	1	0	0	0	0

Fig. 5. ANP-based decision model for the social assessment of railway tracks.

	Ballast	Rheda 2000	BBEST	Local Employment	Gender	Safety	Fair Salary	Econ. Development	Public Opinion
Ballast	0	0	0	0.5837	0.5768	0.6070	0.5545	0.5214	0
Rheda 2000	0	0	0	0.1534	0.1532	0.1501	0.1569	0.1856	0.5
BBEST	0	0	0	0.2630	0.2700	0.2429	0.2886	0.2930	0.5
Local Employment	0.2360	0.2367	0.2372	0	1	1	1	1	0
Gender	0.1240	0.1230	0.1199	0	0	0	0	0	0.7
Safety	0.3294	0.3510	0.3727	0	0	0	0	0	0.3
Fair Salary	0.3106	0.2893	0.2702	0	0	0	0	1	0
Econ. Development	1	1	1	1	0	0	1	0	0
Public Opinion	1	1	1	0	1	0	0	0	0

Fig. 6. Unweighted supermatrix.

<table>
<tr><th></th><th>Ballast</th><th>Rheda 2000</th><th>BBEST</th><th>Local Employment</th><th>Gender</th><th>Safety</th><th>Fair Salary</th><th>Econ. Development</th><th>Public Opinion</th></tr>
<tr><td>Ballast</td><td colspan="3" rowspan="3">0</td><td colspan="4" rowspan="3">0.4854</td><td rowspan="3">0.800</td><td rowspan="3">0.667</td></tr>
<tr><td>Rheda 2000</td></tr>
<tr><td>BBEST</td></tr>
<tr><td>Local Employment</td><td colspan="3" rowspan="4">0.0540</td><td colspan="4" rowspan="4">0.2193</td><td rowspan="4">0.200</td><td rowspan="4">0.333</td></tr>
<tr><td>Gender</td></tr>
<tr><td>Safety</td></tr>
<tr><td>Fair Salary</td></tr>
<tr><td>Econ. Development</td><td colspan="3">0.5891</td><td colspan="4">0.1551</td><td>0</td><td>0</td></tr>
<tr><td>Public Opinion</td><td colspan="3">0.3568</td><td colspan="4">0.1401</td><td>0</td><td>0</td></tr>
</table>

Fig. 7. Influence of each cluster on the rest.

	Ballast	Rheda 2000	BBEST	Local Employment	Gender	Safety	Fair Salary	Econ. Development	Public Opinion
Ballast	0	0	0	0.4424	0.3314	0.4181	0.3131	0.3476	0
Rheda 2000	0	0	0	0.1162	0.0880	0.1034	0.0886	0.1238	0.3333
BBEST	0	0	0	0.1993	0.1551	0.1673	0.1629	0.1953	0.3333
Local Employment	0.0128	0.0128	0.0128	0	0.2596	0.3112	0.2551	0.1667	0
Gender	0.0067	0.0066	0.0065	0	0	0	0	0	0.2333
Safety	0.0178	0.0190	0.0201	0	0	0	0	0	0.1
Fair Salary	0.0168	0.0156	0.0146	0	0	0	0	0.1667	0
Econ. Development	0.5891	0.5891	0.5891	0.2421	0	0	0.1804	0	0
Public Opinion	0.3568	0.3568	0.3568	0	0.1659	0	0	0	0

Fig. 8. Stochastic weighted supermatrix.

	Ballast	Rheda 2000	BBEST	Local Employment	Gender	Safety	Fair Salary	Econ. Development	Public Opinion
Ballast	***0.410***	0.410	0.410	0.410	0.410	0.410	0.410	0.410	0.410
Rheda 2000	***0.254***	0.254	0.254	0.254	0.254	0.254	0.254	0.254	0.254
BBEST	***0.336***	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336
Local Employment	***0.131***	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131
Gender	***0.062***	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062
Safety	***0.037***	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
Fair Salary	***0.084***	0.084	0.084	0.084	0.084	0.084	0.084	0.084	0.084
Econ. Development	***0.439***	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439
Public Opinion	***0.248***	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248

Fig. 9. Results of the limiting supermatrix (normalized).

(normalized importance approximately 43%) and fostering a positive public opinion (importance around 25%). This emphasis outweighs the attention placed on generating favorable employment-related impacts. Given these relevance metrics, the track alternative that contributes most positively in social terms over a 100-year analysis timeframe is the conventional ballast track (social score of 41%), closely pursued by the BBEST alternative (social score of 34%).

5. Discussion of the results

This study emerges from the acknowledgment that current efforts to reduce greenhouse gas emissions and optimize economic life cycles within the railway sector fall short of aligning with the multifaceted objectives outlined in the Sustainable Development Goals (SDGs). The literature review established that, despite the increasing attention to SLCA in various industries, there is a distinct lack of studies focusing on the social consequences of railway track alternatives at the design scale. The existing body of research tends to emphasize qualitative indicators based on stakeholder or expert surveys, limiting the potential for comparative studies or design optimizations. In response to this gap, this study introduces a novel and practical approach, proposing a set of quantitative and objective criteria tailored for railway infrastructure design.

The proposed set of social indicators allow for an objective evaluation of the social performance of railway infrastructure, directly related to the achievement of the SDG. In particular, it allows for specific metrics to evaluate the accomplishment of several targets related to SDG #8 *Decent work and economic growth*, such as target 8.1 (Sustainable economic growth) or 8.5 (Full employment and decent work with equal pay); SDG #5 *Achieve gender equality and empower all women and girls*, SDG 10 *Reduce inequality within and among countries*.

Considering how the construction and maintenance of railway tracks may affect the generation of quality employment, aid in reducing the gender gap, generate public acceptance of the affected communities, and contribute to the economic development in regions, it has turned out that the conventional, ballasted track solution performs best than the ballastless solutions. The economic flows generated by the product system, together with the quality employment generated along the life cycle of the conventional design, are the impacts that mostly contribute to the competitive social performance of this solution. The outstanding performance in the different impact categories considered in this study compensate the negative impact that such conventional solutions have on the public opinion of the local communities, resulting from the high maintenance demands of this alternative.

Considering the environmental dimension of sustainability, Pons et al. (2020) evaluated the environmental life cycle performance of similar track solutions and concluded that the ballasted track design also performs better from an environmental perspective. The high environmental impact associated with concrete and steel production is a key factor causing ballastless solutions to fare worse than ballasted track alternatives. Consequently, it seems reasonable to assert that ballasted solutions appear to pave the way for the sustainable future of railway infrastructures, notwithstanding their associated high maintenance requirements.

6. Concluding remarks

Assessing the social effects of infrastructure during the design phase remains a significant hurdle, yet it's vital to address for reaching the 2030 SDGs. As the construction sector plays a crucial role in enhancing local economies and creating jobs, it's essential to design infrastructure that maximizes these beneficial societal outcomes. This effort is integral to getting closer to the sustainable future the society aims for. However, the lack of standardized guidelines for defining measurable and unbiased social indicators underscores the urgent requirement for engineers to establish such criteria in order to evaluate their designs effectively.

The present communication focuses on the social life cycle assessment of railway infrastructures. To that end, a set of six quantitative social criteria has been developed, covering aspects such as employment generation and its quality (gender discrimination, fair salary, safety and fight against unemployment), the economic development of regions, and the affection to public opinion derived from track maintenance operations. Such quantitative set allows not only for the optimization of track designs in social terms, but also for the selection of the design alternatives that most contribute to the social development of the regions affected by them. As a case study, a social life cycle assessment of three different twin-track design alternatives, namely a conventional ballasted track, and the ballastless solutions Rheda 2000 and BBEST, is presented. The analysis comprises the social impacts along the production, construction and maintenance life cycle stages, covering a period of analysis of 100 years.

Considering the intricate relationships that can exist among social criteria, the final evaluation of the alternatives has been carried out using the ANP MCDM technique. This approach permits modeling such influences through a network-based strategy.

Considering the social impacts from the material production stage, BBEST alternative demonstrates minimal impact on generating quality employment if compared to conventional ballast-based and Rheda 2000 alternatives. However, BBEST shows significantly greater economic flows, approximately 70% greater than the other alternatives. Each track alternative has strengths in different impact categories: conventional track design excels in local employment, safety and gender; BBEST stands out for fair salary and economic development of regions; and Rheda 2000 falls between the other alternatives in most impact categories.

Moving to the construction stage, BBEST emerges as the standout alternative for generating employment and contributing to regional economic development. It excels across all impact categories, surpassing other designs notably in local employment, gender equality, safety, fair salary, and economic development. This stage highlights BBEST as a promising choice for fostering social progress and economic growth within affected regions.

Accounting for the social impacts during the maintenance stage, conventional ballasted track demonstrates consistent employment generation over a 100-year period due to high maintenance demands, boosting economic prosperity significantly compared to Rheda 2000 and BBEST solutions. On the contrary, the positive impact on the public opinion from the absence of maintenance is negligible for the conventional track. Rheda 2000 and BBEST solutions achieve nearly perfect scores for public opinion due to minimal discernible effects on users and local communities throughout their life cycles. This indicates that while the conventional track may have economic benefits, it may face challenges in maintaining positive public perception, whereas Rheda 2000 and BBEST solutions maintain favorable public opinion with fewer maintenance-related disruptions.

In general, the findings indicate that the conventional ballasted track solution outperforms the RHEDA 2000 and BBEST designs in social terms. This is attributed to its consistent ability to generate high-quality employment and stimulate economic activities in the regions covered within the scope of the defined product system. It is important to acknowledge that the outcomes presented in this study are constrained by the involvement of a limited panel of three experts in constructing the ANP network.

The methodology presented in this paper to assess the life cycle of railway infrastructures from a social point of view provides an effective tool to quantify the contribution of different designs to the society. Based on an objective and quantitative methodology, it allows for the optimization of designs to maximize the social benefits along the life cycle of railway infrastructure designs. Furthermore, it contributes to the ongoing development of Social Life Cycle Assessment (SLCA), as the indicators align with the provisions of the 'Guidelines' and its associated methodological sheets. It is noteworthy that the assessment of social impacts based on this methodology is non-subjective, ensuring consistent SLCA results regardless of the designer involved.

It shall also be noted that the methodology introduced in the present research can be applied for the social assessment of infrastructures of any kind, such as bridges, roads or port structures, for example. But the adaptability of this methodology has the potential to extend its applicability to different sectors beyond transportation, such as buildings. As per future lines of research, the set of quantitative social indicators can be applied, combined with ANP, to optimize the selection of the value chain actors involved in the product system in order to maximize the positive impact on the society. Further research is intended to apply this methodology, formulated on a quantitative basis, for the selection of construction materials that maximize the positive social impact along the life cycle of railway infrastructures.

CRediT authorship contribution statement

Ignacio J. Navarro: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Ignacio Villalba:** Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lorena Yepes-Bellver:** Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Julián Alcalá:** Visualization, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

Aung, T.S., Fischer, T.B., Azmi, A.S., 2021. Social impacts of large-scale hydropower project in Myanmar: a social life cycle assessment of Shweli hydropower dam 1. Int. J. Life Cycle Assess. 26, 417–433. https://doi.org/10.1007/s11367-021-01868-3.

Balasbaneh, A.T., Marsono, A.K.B., 2020. Applying multi-criteria decision-making on alternatives for earth-retaining walls: LCA, LCC, and S-LCA. Int. J. Life Cycle Assess. 25, 2140–2153. https://doi.org/10.1007/s11367-020-01825-6.

Balasbaneh, A.T., Yeoh, D., Juki, M.I., Gohari, A., Abidin, A.R.Z., Marsono, A.K.B., 2021. Applying three pillar indicator assessments on alternative floor systems: life cycle study. Int. J. Life Cycle Assess. 26, 1439–1455. https://doi.org/10.1007/s11367-021-01881-6.

Barrio, A., Francisco, F.B., Leoncini, A., Wietschel, L., Thorenz, A., 2021. Life cycle sustainability assessment of a novel bio-based multilayer panel for construction applications. Resources 10, 98. https://doi.org/10.3390/resources10100098.

Bezama, A., Hildebrandt, J., Thrän, D., 2021. Integrating regionalized socioeconomic considerations onto life cycle assessment for evaluating bioeconomy value chains: a case study on hybrid wood–concrete ceiling elements. Sustainability 13, 4221. https://doi.org/10.3390/su13084221.

Blaauw, S.A., Maina, J., W, Grobler, L.J., 2021. Social life cycle inventory for pavements – a case study of South Africa. Transp. Eng. 4, 100060 https://doi.org/10.1016/j.treng.2021.100060.

Celauro, C., Cardella, A., Guerrieri, M., 2023. LCA of different construction choices for a double-track railway line for sustainability evaluations. Sustainability 15, 5066. https://doi.org/10.3390/su15065066.

De Luca, A.I., Iofrida, N., Strano, A., Falcone, G., Gulisano, G., 2015. Social life cycle assessment and participatory approaches: a methodological proposal applied to citrus farming in Southern Italy. Integr. Environ. Assess. 11, 383–396. https://doi.org/10.1002/ieam.1611.

European Commission, 2020. Directorate-General for Mobility and Transport, EU Transport in Figures – Statistical Pocketbook 2020. Publications Office of the European Union. https://data.europa.eu/doi/10.2832/491038.

Giunta, M., Bressi, S., D'Angelo, G., 2018. Life cycle cost assessment of bitumen stabilised ballast: a novel maintenance strategy for railway track-bed. Construct. Build. Mater. 172, 751–759. https://doi.org/10.1016/j.conbuildmat.2018.04.020.

Gompf, K., Traverso, M., Hetterich, J., 2022. Applying social life cycle assessment to evaluate the use phase of mobility services: a case study in Berlin. Int. J. Life Cycle Assess. 27, 603–622. https://doi.org/10.1007/s11367-022-02051-y.

Hasan, U., Whyte, A., Al Jassmi, H., Hasan, A., 2022. Lifecycle cost analysis of recycled asphalt pavements: determining cost of recycled materials for an urban highway section. Civ. Eng. 3, 316–331. https://doi.org/10.3390/civileng3020019.

Hossain, M.U., Poon, C.S., Dong, Y.H., Lo, I.M.C., Cheng, J.C.P., 2018. Development of social sustainability assessment method and a comparative case study on assessing recycled construction materials. Int. J. Life Cycle Assess. 23, 1654–1674. https://doi.org/10.1007/s11367-017-1373-0.

Hendiani, S., Bagherpour, M., 2019. Developing an integrated index to assess social sustainability in construction industry using fuzzy logic. J. Clean. Prod. 230, 647–662. https://doi.org/10.1016/j.jclepro.2019.05.055.

Indraratna, B., Salim, W., Rujikiatkamjorn, C., 2011. Advanced Rail Geotechnology-Ballasted Track. CRC Press.

Janjua, S.Y., Sarker, P.K., Biswas, W.K., 2019. Sustainability assessment of a residential building using a life cycle assessment approach. Chem. Eng. Transactions 72. https://doi.org/10.3303/CET1972004.

Kim, R., Lim, M.-K., Roh, S., Park, W.-J., 2021. Analysis of the characteristics of environmental impacts according to the cut-off criteria applicable to the streamlined life cycle assessment (S-LCA) of apartment buildings in South Korea. Sustainability 13, 2898. https://doi.org/10.3390/su13052898.

Lim, T.H., Ellis, B.R., Skerlos, S.J., 2023. Life cycle assessment of railway ties fabricated with ductile cementitious composites and carbonation curing. J. Clean. Prod. 413, 137276 https://doi.org/10.1016/j.jclepro.2023.137276.

Martínez-Blanco, J., Lehmann, A., Muñoz, P., Antón, A., Traverso, M., Rieradevall, J., Finkbeiner, M., 2014. Application challenges for the social life cycle assessment of fertilizers within life cycle sustainability assessment. J. Clean. Prod. 69, 34–48. https://doi.org/10.1016/j.jclepro.2014.01.044.

Martínez-Fernández, P., Villalba Sanchis, I., Yepes, V., Insa Franco, R., 2019. A review of modelling and optimisation methods applied to railways energy consumption. J. Clean. Prod. 222, 153–162. https://doi.org/10.1016/j.jclepro.2019.03.037.

Martínez-Fernández, P., Villalba Sanchis, I., Insa Franco, R., Yepes, V., 2022. Slab track optimization using metamodels to improve rail construction sustainability. J. Construct. Eng. Manag. 148 https://doi.org/10.1061/(ASCE)CO.1943-7862.0002288.

Morata, M., Saborido, C., 2017. Recycled aggregates with enhanced performance for railways track bed and form layers. J. Sustain. Metall. 3, 322–335. https://doi.org/10.1007/s40831-016-0095-z.

Navarro, I.J., Yepes, V., Martí, J.V., 2018. Social life cycle assessment of concrete bridge decks exposed to aggressive environments. Environ. Impact Asses. 72, 50–63. https://doi.org/10.1016/j.eiar.2018.05.003.

Oladazimi, A., Mansour, S., Hosseinijou, S.A., Majdfaghihi, M.H., 2021. Sustainability identification of steel and concrete construction frames with respect to triple bottom line. Buildings 11, 565. https://doi.org/10.3390/buildings11110565.

Pang, B., Yang, P., Wang, Y., 2015. Life cycle environmental impact assessment of a bridge with different strengthening schemes. Int. J. Life Cycle Assess. 20, 1300. https://doi.org/10.1007/s11367-015-0936-1.

Penadés-Plà, V., García-Segura, T., Yepes, V., 2019. Accelerated optimization method for low-embodied energy concrete box-girder bridge design. Eng. Struct. 179, 556–565. https://doi.org/10.1016/j.engstruct.2018.11.015.

Penadés-Plà, V., Martínez-Muñoz, D., García-Segura, T., Navarro, I.J., Yepes, V., 2020. Environmental and social impact assessment of optimized post-tensioned concrete road bridges. Sustainability 12, 4265. https://doi.org/10.3390/su12104265.

Pons, J.J., Penadés-Plà, V., Yepes, V., Martí, J.V., 2018. Life cycle assessment of earth-retaining walls: an environmental comparison. J. Clean. Prod. 192, 411–420. https://doi.org/10.1016/j.jclepro.2018.04.268.

Pons, J.J., Villalba Sanchis, I., Insa Franco, R., Yepes, V., 2020. Life cycle assessment of a railway tracks substructures: comparison of ballast and ballastless rail tracks. Environ. Impact Asses 85, 106444. https://doi.org/10.1016/j.eiar.2020.106444.

Rempelos, G., Preston, J., Blainey, S., 2020. A carbon footprint analysis of railway sleepers in the United Kingdom. Transp. Res. D. – Tr. E 81, 102285. https://doi.org/10.1016/j.trd.2020.102285.

Renne, N., Kara De Maeijer, P., Craeye, B., Buyle, M., Audenaert, A., 2022. Sustainable assessment of concrete repairs through life cycle assessment (LCA) and life cycle cost analysis (LCCA). Infrastructures 7, 128. https://doi.org/10.3390/infrastructures7100128.

Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York, NY.

Saaty, T.L., 1996. Decision Making with Dependence and Feedback: the Analytic Network Process. RWS Publications, Pittsburgh.

Safarpour, H., Tabesh, M., Shahangian, S.A., Hajibabaei, M., Sitzenfrei, R., 2022. Life cycle sustainability assessment of wastewater systems under applying water demand management policies. Sustainability 14, 7736. https://doi.org/10.3390/su14137736.

Samuelsson, I., Spross, J., Larsson, S., 2023. Integrating life-cycle environmental impact and costs into geotechnical design. P. I. Civil Eng. – Eng. Su. https://doi.org/10.1680/jensu.23.00012.

Singh, R.K., Gupta, U., 2018. Social life cycle assessment in Indian steel sector: a case study. Int. J. Life Cycle Assess. 23, 921–939. https://doi.org/10.1007/s11367-017-1427-3.

Serreli, M., Petti, L., Raggi, A., Simboli, A., Iuliano, G., 2021. Social life cycle assessment of an innovative industrial wastewater treatment plant. Int. J. Life Cycle Assess. 26, 1878–1899. https://doi.org/10.1007/s11367-021-01942-w.

Torres-Machí, C., Chamorro, A., Videla, C., Pellicer, E., Yepes, V., 2014. An iterative approach for the optimization of pavement maintenance management at the network level. Sci. World J. 2014, 524329 https://doi.org/10.1155/2014/524329.

UNEP/SETAC, 2020. Guidelines for social life cycle assessment of products, united nations environment program. In: Paris SETAC Life Cycle Initiative United Nations Environment Programme.

UNEP/SETAC, 2021. Methodological sheets for subcategories in social life cycle assessment. In: Paris SETAC Life Cycle Initiative United Nations Environment Programme.

Villalba Sanchis, I., Insa Franco, R., Martínez-Fernández, P., Salvador Zuriaga, P., 2021. Experimental and numerical investigations of dual gauge railway track behaviour. Construct. Build. Mater. 299 https://doi.org/10.1016/j.conbuildmat.2021.123943.

Wilhelm, M., Hutchins, M., Mars, C., Benoit-Norris, C., 2015. An overview of social impacts and their corresponding improvement implications: a mobile phone case study. J. Clean. Prod. 102, 302–315. https://doi.org/10.1016/j.jclepro.2015.04.025.
Yang, F., Yu, J., Li, X., Qiu, W., 2022. An SLCA method based framework of large-scale transportation infrastructure in China. Environ. Impact Asses 93, 106716. https://doi.org/10.1016/j.eiar.2021.106716.
Yepes-Bellver, L., Brun-Izquierdo, A., Alcalá, J., Yepes, V., 2022. CO_2-optimization of post-tensioned concrete slab-bridge decks using surrogate modeling. Materials 15 (14), 4776. https://doi.org/10.3390/ma15144776.
Zhang, N., Zhang, H., Schiller, G., Feng, H., Gao, X., Li, E., Li, X., 2021. Unraveling the global warming mitigation potential from recycling subway-related excavated soil and rock in China. Life cycle assessment. Integr. Environ. Assess. Manag. 17 (3), 639–650. https://doi.org/10.1002/ieam.4376.
Zhang, R., Liu, P., Zhou, C., Amorelli, A., Li, Z., 2016. Configuration of inter-city high-speed passenger transport infrastructure with minimal construction and operational energy consumption: a superstructure based modelling and optimization framework. Comput. Chem. Eng. 93, 87–100. https://doi.org/10.1016/j.compchemeng.2016.06.003.
Zheng, X., Easa, S.M., Yang, Z., Ji, T., Jiang, Z., 2019. Life-cycle sustainability assessment of pavement maintenance alternatives: methodology and case study. J. Clean. Prod. 213 (10), 659–672. https://doi.org/10.1016/j.jclepro.2018.12.227.
Zheng, X., Easa, S.M., Ji, T., Jiang, Z., 2020. Modeling life-cycle social assessment in sustainable pavement management at project level. Int. J. Life Cycle Assess. 25, 1106–1118. https://doi.org/10.1007/s11367-020-01743-7.