Framework for Life Cycle Railway Sustainability Assessment: A Methodological Approach Based on Advanced Methods and Tools

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Abstract. Railway corridors improvement and development are the most appropriate answer to the need of providing sustainable transportation of people and goods. Indeed, rail is the greener transportation mode since it contributes to the reduction of carbon footprint and energy consumption within the global transportation system. From this perspective, continuing to pursue sustainability objectives, any intervention on railway lines and particularly on track must be focused on the use of materials, components, and techniques able to guarantee the best environmental performances in service life span, also according to Agenda 2030 goal 13 action climate. To this purpose, the decision process at any life stage of construction and maintenance of the track can be supported by advanced methods and tools able to correctly address the right solutions through the quantitative assessment of the related environmental burdens. This study delivers a framework of methods and tools in use for the assessment of the sustainability. An application to a case study is also reported and discussed. Results demonstrated that there is room for the enhancement of environmental behavior of the track during its life cycle by means the suitable selection of materials and techniques for construction and maintenance. Further, the proposed methods have a great potential to support decision-makers.

Keywords: Railway · Track · Sustainability · Life Cycle Assessment · Circularity Index · Artificial Intelligence

1 Introduction

Climate change arisen by the increasing of greenhouse gas emissions (GHGs) emphasizes the urgent need for countries to prioritize sustainable transportation infrastructure as a crucial sector for climate action, as required by Agenda 2030 Goal 13. Indeed, transport represents almost a quarter of Europe's greenhouse gas emissions in addition to being the main cause of air pollution in cities [1]. On the other hand, climate change represents a threat for transport infrastructures they self, due to design features (e.g. low resistance to storms) or location (e.g. in flood-prone areas, landslides) that can make them vulnerable to climate actions Extreme weather events (extreme precipitation

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and floods, occurrences of extreme low or high temperatures, rising sea level, strong wind) resulting from changing climatic condition can damage or render unfit for use the infrastructures. The aspect of the climate change must be accounted together with the increasing awareness of the need of sustainable management and conservation of the resources. In this sense, apply the principles of circular economy and use energy from renewable sources are nowadays essential elements in the design, construction, and management of transport infrastructures.

Among the transportation mode, the rails satisfy the 8% of global passengers and freights demand and are responsible for only 4% of the total emissions generated by the whole transportation system. In this sense, it can affirm that rail is the main pillar of the transformative climate action in transport sector being the fastest and most cost-efficient way to decarbonize people's daily mobility and logistics chains [2, 3]. Railway corridors improvement and development are the most appropriate answer to the need of providing sustainable transportation of people and goods, for the lowest production of the emissions [4–7]. In rail lines enhancement and expansion, the sustainability must be considered as a pivot around which revolve the conception, construction and management phases. It is essential to take into consideration the entire life cycle of infrastructures to avoid the circumstance that optimal solutions in the short term are then unsustainable or less sustainable if regarded in the long-term of the service life.

One of the fundamental components of railways is the track for which the objectives of sustainability call for the careful and conscious adoption of solutions and materials able to improve more and more the environmental performances. In fact, the construction of new tracks and the maintenance of the existing ones are activities resource demanding and emissions discharging and therefore environmentally impacting [8].

In the sustainability assessment is fundamental to consider the life cycle of track, because at any stage of the life the decision-making process can affect the sustainability. More specifically, in design and construction stages, the selection of the more appropriate suitable track system (ballasted or ballastless) in function of the expected traffic, axle loads and train speeds, the type of materials and components and their supply mode and hauling distance as well as the construction schedule are elements which greatly affect the sustainability. In service life, maintenance strategies, materials, and equipment and machineries are important aspects to consider. At this stage is fundamental to forecast the degradation of the geometric and structural quality of the track and the maintenance interventions needed to ensure efficiency, safety, and regularity of the trains service. Track deterioration models mechanistic or physics-based, empirical, data-driven or hybrid or the ones based on Artificial Intelligence (AI) [9, 10] are useful tools in addressing the in-service behavior. In the end-of-life (EoL) the re-use/recycling of the dismantled materials and components, or the landfill, in case in whcih recycling/reuse is partially or totally not allowed, differently affect the sustainability.

This paper provides a framework of the methods for the assessment of the rail track sustainability in the life cycle. To demonstrate the suitability of the application of proposed approaches a case study referred to the comparison of two track systems, ballasted and ballastless, is reported and results discussed.

2 Track System: Materials and Components

The rail track is a complex system that consists of several components each of which plays a crucial role in ensuring the smooth and safe movement of the trains.

Two types of track systems operate in the word: ballasted and ballastless (see Figs. 1 and 2). Basically, in the first, the rails sit above sleepers, which distribute the load on a bed of ballast posed on subgrade soil; instead, in the second case, the rails are supported by concrete slabs which also rest on subgrade soil [11, 12].

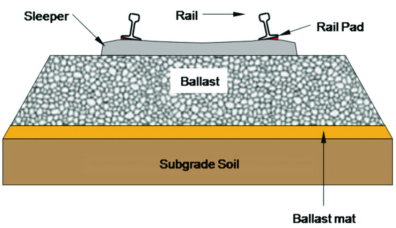


Fig. 1. Ballasted track system

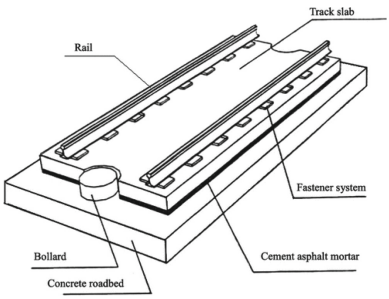


Fig. 2. Ballastless or slab track system

The two systems exhibit different performance in terms of service life and maintenance and in the selection of the more suitable system many important technical, economic and environmental factors have to be taken into account [12]. Their main components and function are synthetically reported in the Table 1.

The inevitable functional and structural decay of these components under the effect of train loads and speeds requires maintenance activities over the time aimed at extending the life of the rail component. Typical activity maintenance on track components are specified in the Table 1.

3 Life Cycle Stages of Rail Track

In the construction sector, looking at the whole project life cycle is a new trend in sustainability analysis. According to the current ISO 21931-2 [13], four stages characterize the life cycle of the track (see Fig. 3):

- the production stage which encompasses three modules: the raw material extraction (e.g. steel, cement, water, aggregate) (module A1), the transport of raw materials to components manufacturing factory (module A2), the components manufacturing (module A3) (e.g. rails, sleepers, ballast, fastening);
- the construction stage, divided in transport of components to construction site (module A4), and construction/installation process (module A5) (track construction);
- the use stage which includes use, maintenance, repair, replacement, refurbishment (modules B1-B5) of all track components and the operational energy and water use (modules B6 and B7);

Table 1. Railroad track component.

Component	Material	Function	Maintenance
Rails	Steel	Guidance Support Smoothness Safety	Grinding Lubrication Inspection
Fastenings	Steel	Rail Fixation Shock Absorption Load Distribution	Retightening Replacing Lubrification Corrosion and Rust Prevention
Sleepers	Wooden Concrete Steel	Rail support Load distribution Sound and Vibration Absorption	Cleaning Tamping Repositioning
Ballast	Crushed stone Gravel	Stability Drainage Load distribution Track alignment Vibration and Noise Reduction	Tamping Cleaning Resurfacing Monitoring
Slab	Concrete	Rail Fixation Rail support Load distribution	

- the end-of-life stage which considers deconstruction/demolition, transport, waste processing and disposal (modules C1-C4) of all components of the track.

Additional information beyond the life cycle and system boundaries, such as reuse, recycling, energy and other recovery, can be also considered (module D).

In addition to these stages, the previous non-construction stages are also crucial to obtain the most optimal solution for a given design task. The stages not related with the construction works are referred to the planning, the study/analysis and the design stage.

3.1 Framework for Track Sustainability Assessment

Figure 3 details the construction work of track and reports for each module the materials and components that must be considered. Further, specific milestones (cradle, gate, site, practical completion, end-of-life, grave) are identified. Based on these milestones, it can be considered different life cycle models to be implemented:

- Cradle-to-gate: is a partial life cycle assessment which considers only the phase resource extraction (cradle) to the factory gate (the transport to the construction site is excluded) (Stages 1). This assessment is sometimes the basis for environmental product declarations (EPD).

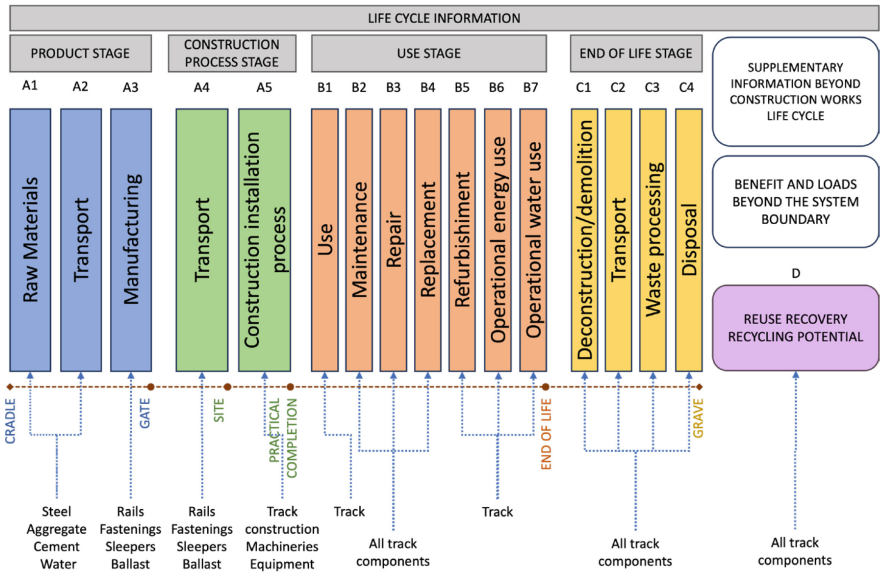


Fig. 3. Framework for the assessment of the environmental, social and economic performance of rail track.

- Cradle-to-grave: is a full life cycle assessment that includes all the four stages from resource extraction ('cradle') to disposal phase ('grave') and allows to estimate the complete environmental footprint, from start to end. (Stages 1–4).
- Cradle-to-cradle: is a particular cradle-to-grave assessment, where the end-of-life disposal step coincides with a recycling process that makes materials or components reusable for another product allowing therefore to "close the loop" (Stages 1–4, with 4 being equivalent to another Stage 1).

There are various life cycle assessments that aim to quantify and measure sustainability using a specific methodology and accurate data so that alternative solutions can be compared. It is noteworthy to highlight that the sustainability is founded on three fundamental pillars environmental, economic and social then discussions about achieving sustainability of rail track usually satisfy a holistic and integrated assessment of these three pillars [14, 15] (see Fig. 4).

Indeed, life cycle information allows to perform Life Cycle Sustainability Assessments (LCSA) focused on environmental (Life Cycle Assessment - LCA), economic (Life Cycle Cost - LCC) and social (Social - Life Cycle Analysis) aspects.

Life Cycle Assessment (LCA) is a comprehensive methodology used to evaluate and quantify the environmental impacts of products and services [16, 17]. LCA studies can help to address the decision-making process when applied to rail track by adding environmental factors to economic and mechanical performance [18–20]. An LCA study consists of four stages:

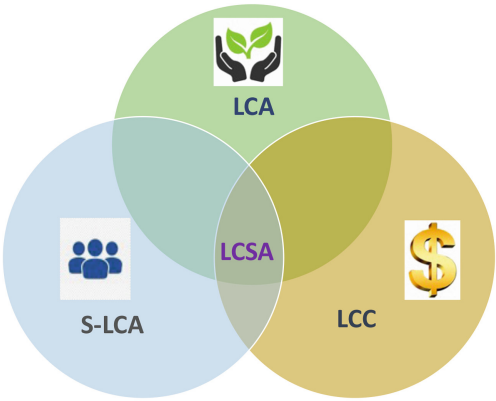


Fig. 4. Scheme for Life Cycle Sustainability Assessment (LCSA).

- Stage 1 - Goal and scope: which aim to define the objective of the study, the part of life cycle taken in assessment (i.e. cradle to gate or cradle to grave) and the functional unit to consider.
- Stage 2 - Inventory analysis: provides a description of the amount of material and energy flows with particular focus on the interaction with environment, on the consumed raw materials, and on emissions to the environment.
- Stage 3 - Impact assessment: the results of this step are associated to all impact categories considered; processes such as normalization and or weighting allow to assess the importance of every impact category.
- Stage 4 - Interpretation: this stage involves the critical appraisal of the life cycle outcomes, the determination of data sensitivity, and the result presentation.

As for Life Cycle Cost (LCC), according to ISO 15686-5 [21] it can be defined as "the cost of an asset or its parts throughout its life cycle, while fulfilling the performance requirements". The LCC analysis allows comparing the economic performance of different alternatives (e.g. ballasted/ballast-less track). Minimizing the track system life cycle costs (usually the present value PV) will increase the economic sustainability of the rail superstructure. The life cycle costs for each track solution encompass company (construction, inspection, maintenance, and renewal), user (time, accidents,….), and environmental (e.g., CO_2e emissions, etc.) costs. The trends of these cost during the lifespan allow to carry out complete evaluations for identifying the most convenient solution [22–24]. It is important to highlight that the expenditures happen at different moments of the life so that it can distinguished among the initial cost, usually corresponding with the construction cost, the recurrent costs due to maintenance and renewal, the disposal cost and the residual value at the end of life (Fig. 5). Discounting allows expressing future costs at today's equivalent by applying the discount (r) rate The amount of discount rate to be applied is often controversial and the accurate application of the right discount rate is, on the ither side, pivotal because it affects the results.

The social life cycle assessment (S-LCA) is a method able to assess the social and sociological aspects of a product and their actual and potential positive as well as negative

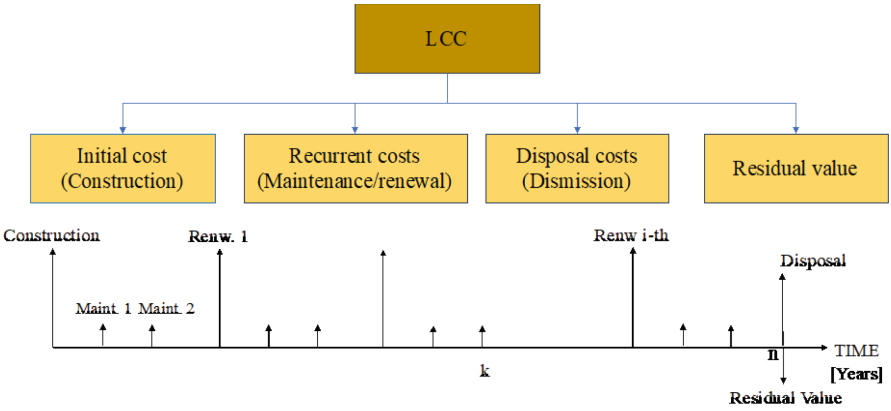


Fig. 5. Life Cycle Cost (LCC).

impacts along the lifespan. Data to perform S-LCA can be generic or site-specific, quantitative, semi-quantitative or qualitative, and results complements the LCA and LCC. The UNEP Guidelines for Social Life Cycle Assessment of Products [25] proposes a methodology to develop life cycle inventories starting from the identification of the stockholders (workers, local communities, society, consumers, value chain actors), the impact categories (human rights, working conditions, health and safety, cultural heritage, governance, socio economic repercussions), the subcategories, the inventory indicators and the inventory data. The social sustainability of track is the least represented in research, due to the complexity of quantification and interpretation of the impacts [14].

One of the critical aspects of the life cycle assessment of the rail track relies on the use stage and concerns the forecasting of the maintenance activities and renewal. Establish in advance at what time and where to carry out interventions on track is a task as difficult as it is important for reliable assessment of the life cycle performance and comparative evaluation among different alternatives.

Maintenance activities on track (renewal and re-construction) and its components (ballast cleaning, resurfacing, rail-head grinding) are costly and environmental impacting because of the use of resources and diesel power machineries [8].

To optimize the maintenance activity under all the standpoints technical, economic and environmental several issues must be addressed: planning of the inspection interval to detect the need of intervention, identification of the type of intervention and prioritization, timing and mode of intervention. Forecast track degradation by means a reliable model is the best way for identifying the appropriate time for condition-based maintenance in railway track.

The great quantity of materials used in construction and maintenance of rail tracks, calls for the application of the principles of Circular Economy: reducing, reusing, and recycling of the materials and the extending useful life through maintenance and repair (stage D). Circularity indices [26] providing information about the quantity, in percent, of recirculated material is in a product or component clearly express the circularity of a system. To this purpose the Circular Material Use rate (CMU rate), defines the ratio of the circular use of materials (U) to the overall material use (M) while the End-Of- Life Recycling Input Rate (EOL-RIR) measures, for a given raw material, how much of its input into the production system comes from recycling of “old scrap”.

Synthesis of method and tools for the sustainability assessment of the railway track is reported in Fig. 6.

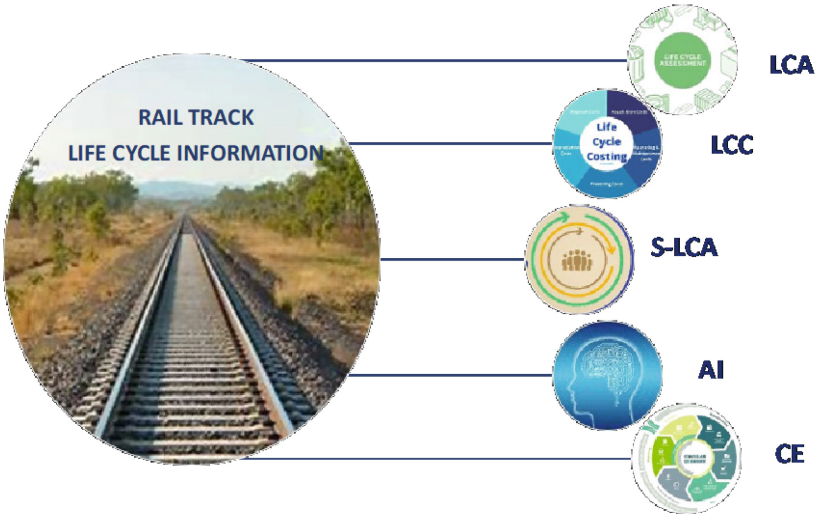


Fig. 6. Method and tools in the sustainability assessment of the rail track.

4 A Case Study on the Integrative Approach LCC-LCA

To prove the potentials of the methods discussed, an integrative approach LCC-LCA is applied to the case study of the comparison of two track system: the traditional ballasted track and innovative slab track [23, 24].

The appraisal of the two alternatives is referred to a double track line 1-km long. Main characteristics of the track components and related service are shown in Table 2.

The economic appraisals consider all the costs, from the construction to the end of life, split in costs of the company which built and manage the track (C_{comp}), costs of users (C_{users}) of the railway service, here referred to the cost of delay due to the maintenance and renewal activities which inevitably affect the regular service of the railway line, and environmental costs (C_{env}) here referred to the emissions of CO_2e arising from the construction and maintenance processes. The applied discount (r) rate is 4%. Figure 7 shows the trend of the total costs of the two alternatives the ballasted (continuous line) and the slab track (dashed line) in a lifespan comprised between 0 and 60 years.

It is worthy to note that at the end of the construction (year 0), the slab track exhibits a total cost 1.5 times higher than the one of the ballasted track, according with literature results. At year 0, the total cost consists of the construction cost and the environmental cost while the user cost is null. A breakeven of the total costs can be observed after about 26 years, after that the total cost of slab track remains lower, albeit slightly, than the ballasted one.

Table 2. Features of track component and expected life.

Track component	Type	Dimensions	Service life [Years]
Rail	60 E1	Mass = 60,1 kg/ml	28
Sleepers - Fastenings	RFI-260 VN AV equipped with the fastening system Vossloh W14	Length 2.60 m, mass 325 kg	40
Ballast	Crushed stones	Depth 500 mm	40
Subballast/ Road-bed	Cement layer	Depth 200 mm	40
Slab	Pre-stressed concrete linked with cylindrical bollard	4,93 m × 2,34 m × 0,19 m mass = 5 tons	60

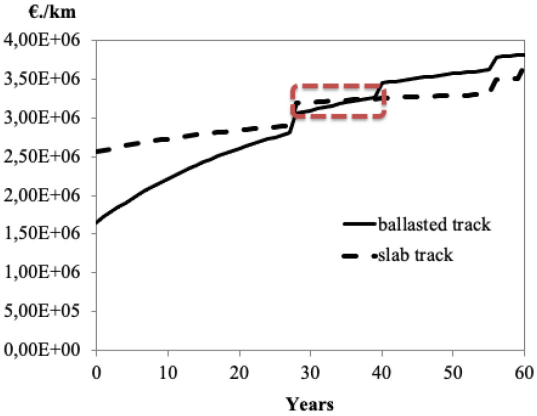


Fig. 7. Trend of total costs for ballasted and slab track.

For a better understanding of the sustainability of the two solutions, company costs, user costs and environmental costs have been calculated in different time frame 0, 30, and 60 years and represented the Figs. 8 and 9.

From the break-down of the costs it is possible to observe that the company costs (construction, maintenance and renewal), are lower at construction stage and in the short period for the ballasted track while reach a value 1.15 times higher than that of the slab track in long term because of the high frequency of maintenance activities. The user costs for ballasted track, lower in the short period, become, in the long-term perspective, 2.3 times higher than the ones exhibited by the slab track. The environmental costs display a reverse trend for the two solutions due to the carbon footprint of the cement/concrete that is very high if compared with the ballast. This makes the slab track less preferable, than the traditional ballasted track from the environmental standpoint.

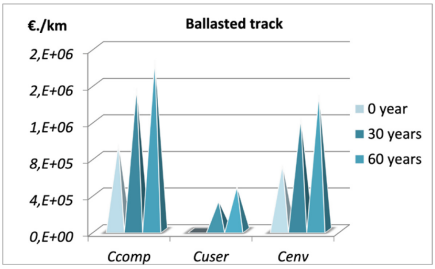


Fig. 8. Trend of costs for ballasted track.

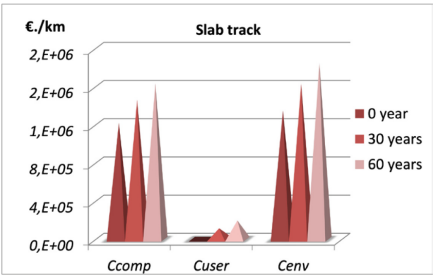


Fig. 9. Trend of costs for slab track.

The integrated evaluation of the environmental and economic aspects allows to do more complete considerations in the decision-making process of the selection of the more suitable solution.

5 Conclusion

This study delivers a framework of methods and tools in use for the sustainability assessment ai rail track. The proposed methods have a great potential to support decision-making process as demonstrated by the proposed case study where the LCC and LCA integrated method is applied. In fact, the results of the analyses carried out on the two ballasted and ballastless track systems, following the integrated method, confirms that a comprehensive evaluation of different track options needs the consideration of company, user and externality costs. This also applies when they compare alternative materials and components within the same track system. In fact, company, user and environmental costs govern the suitability of a track to fit technical as well as environmental demand. Considering and integrating technical and environmental issues is sometimes a trickly exercise, especially because several data are requested to do reliable evaluation, but it remains the right way for a comprehensive and complete comparison among different design and maintenance track solutions.

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