Environmental performance analysis of bitumen stabilized ballast for railway track-bed using Life-Cycle Assessment

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Abstract

Bitumen stabilized ballast (BSB) is a novel and promising construction or maintenance strategy of traditional ballasted track-bed that consists in the use of bitumen emulsion (BE), which is poured or sprayed at ambient temperature onto the ballast. The bound aggregates show high resistance to degradation and allows increasing intervals between both minor and major maintenance activities.

This paper presents the results of a life cycle assessment (LCA) undertaken to compare the potential environmental impacts associated with the use of bitumen stabilized ballast (bound with BE) with those associated to traditional ballast (unbound aggregates) layers.

Afterwards, for a more comprehensive understanding of the advantages related to the use of BSB, the complete structure of the track-bed, which in addition to the ballast layer also includes other components, such as sleepers, fastening systems and rails, has been considered.

Furthermore, multiple analyses were performed by considering different scenarios involving the comparison of different maintenance timing of BSB and traditional ballast depending on traffic level and/or standard deviation limit (SD) of track irregularities. When the analysis considers the life cycle of the complete structure of the track-bed one can conclude that, overall, the use of BSB contributes positively to the reduction of the environmental impacts, independently of the track quality level and the cumulated traffic values considered. Indeed, the higher durability of BSB allows reducing the frequency of replacement of the elements composing the track-bed leading to considerable improvements in the life cycle environmental performance of the entire infrastructure.

Keywords: Bitumen stabilized ballast, Life Cycle Assessment, maintenance, railway track-bed

Highlights:

- A comparative LCA between bitumen stabilized and traditional ballast is performed
- BSB does not reduce all the environmental impacts when the single layer is analyzed
- BSB reduces all the environmental impacts when the complete track-bed is considered
- Benefits of using BSB are independent of cumulated traffic and track quality level

1. Introduction

The increasing evidences of the impact of greenhouse gas (GHG) emissions on global warming and its negative effects has urged the international community to strengthen the worldwide commitment to implement far-reaching actions towards low-carbon and climate-resilient growth [1-2].

With the transport sector contributing to around a quarter of the European Union’s (EU's) GHG emissions, making it the second-biggest emitting sector after energy, it surely holds the keys to decarbonize the European economy [3]. Although within this sector, road transport is by far the biggest emitter accounting for more than 70% of all GHG emissions from transport in 2014, the role the railway mode, and particularly its infrastructure, can play in the EU’s low-emission mobility strategy cannot be neglected [4]. First, the construction of new and the improvement of the existing railway infrastructures is expected to continue its growing trend in the years to come as the EU aims for implementing and completing the Trans-European Transport Network (TEN-T) core network by 2030 and the TEN-T comprehensive network by 2050 [4]. Second, as the EU’s answer to the emission reduction challenge in the transport sector comprises the deployment of low-emission alternative energy sources, it is likely that vehicles become more energy-efficient, and then energy use and GHG emissions during the construction, maintenance and disposal of railway infrastructure might increase their share in the environmental impact of the life cycle’s railway system. Last, but not the least, as a considerable portion of the Europe’s rail network was constructed in a time where the construction methods were not as advanced as those currently available, it is likely that the combined effects of inadequate levels of investment, poor maintenance strategies, and adverse climatic events, result in important elements of the existing rail networks, such as the track-bed structure, requiring frequent maintenance activities [5], thereby increasing the environmental footprint associated with the railway infrastructure’s life cycle.

Ballasted track is the most common type of track superstructure supported on a layer of granular material (ballast) [6-7]. Despite the benefits of this track-bed structure and the robustness of experiences in this type of construction, it presents certain limitations and drawbacks, mainly associated with geometry degradation due to ballast settlement [8-9-10]. Therefore, periodic and costly minor and major maintenance operations are required to provide a granular layer with adequate characteristics, which leads to an important consumption of non-renewable resources and energy while frequent traffic interruptions take place. Thus, for some specific line, ballasted tracks can be considered less convenient from the life cycle standpoint, due to the higher frequency of maintenance and the lower durability, with respect to slab tracks [11-12-13-14-15]. Furthermore, the aggregates used for the ballast must comply with strict requirements. For this reason, when satisfactory quality aggregates are not available nearby the construction/rehabilitation site the environmental and economic burdens increase as a consequence of, for instance, longer hauling distance.

Notwithstanding the facts pointed out above, ballasted track continues to be widely adopted because of the skills acquired by railways authorities in implementing this solution and the relatively low construction costs [6-14-16].

However, in order to not compromise the global efforts to lower the environmental impacts produced by the transportation sector, and the railway transportation mode in particular, it is of paramount importance to develop new materials and construction technologies that prove to be efficient in reducing the ballasted track-bed maintenance burdens, and thereby attenuating the effects related to the shifting of environmental burdens from one railway system’s life cycle phase to another.

In this context, bitumen stabilized ballast (BSB) has been recently proposed as novel and more economical solution [17] to slow down the loss in track quality associated with ballast settlement and particle degradation. It is designed to be used either for reinforcing existing track-beds, reducing the need of both minor and major maintenance, or during the construction of new ones, thus extending the time period between the construction and the first maintenance operation [18-19-20]. Similarly to stabilization by polymers or resins [21 - 23], this technology consists of pouring bitumen emulsion (BE) at ambient temperature with an optimum dosage equal to 1.44% by weight of the ballast underlying the sleeper/ballast contact area [19]. Only the ballast subjected to the highest contact pressure [24] is stabilized, therefore it is considered that one third of the sleeper length per sleeper end should be treated by this operation (Figure 1a). When applied during routine maintenance, it is performed by raising the sleeper (Figure 1b), whereas during the construction the BE is spread before placing the sleepers [20].

In order to ascertain if the BSB track-bed is indeed better than the traditional ballasted track-bed from the environmental perspective, it is crucial to adopt a life cycle approach to identify and quantify the potential environmental burdens arising from the use of this solution. This need can be accomplished with the support of the Life-Cycle Assessment (LCA) methodology [25]. LCA, which is a data-driven, systematic methodology, has proven to be effective in estimating the environmental burdens caused by a product, process, or service throughout its life cycle [26]. LCA quantifies the environmental impacts of the complete life cycle of products which include processes, or services and encompasses the extraction and processing of raw materials, manufacturing, transportation, maintenance, use, and end-of-life (EOL) [27]. Among other capabilities, LCA assesses the impacts of the emissions released to the environment as a consequence of the energy and material consumed and waste treatment processes and identifies opportunities for environmental improvements and sustainable use of natural resources.

Historically, LCA is not new, as it started being used in the seventies. However, the application of the LCA to railway infrastructures is relatively recent [28-29-30] and the analysis is often focused on the comparison of different modes of transport [31-32]. In the analyzes of the materials, processes and transport emissions related to construction, maintenance and EOL phases, Milford and Allwood [33] concluded that by maximizing the durability of the track-bed components it is possible to reduce significantly the emissions of CO_2 during the life cycle of the infrastructure. Moreover, by replacing all the components at the same time (similar service life), instead of individual dismantling activities for each component, allows reducing the environmental impacts. Therefore, alternative solutions, typically ballasted and ballastless technologies, for the railway track-bed construction have been compared with the aim of finding potential benefits in terms of energy and natural resource consumption and emissions of pollutants [34]. Even if ballastless slab track has higher durability, it does not always seem to reduce the environmental impacts of the overall infrastructure [35]. Moreover, it is worthy mentioning that the technical challenges faced during the construction process, and the way they are handled, play a key role in determining the environmental profile of the infrastructures [36].

In view of these issues related to the technical and environmental performance of other solutions described in the literature, the aim of this research work is twofold: (i) to introduce the BSB technology as an innovative solution for the construction and maintenance of the track, and; (ii) to present a comparative LCA of traditional ballasted track-bed and BSB track-bed implemented in a rail track.

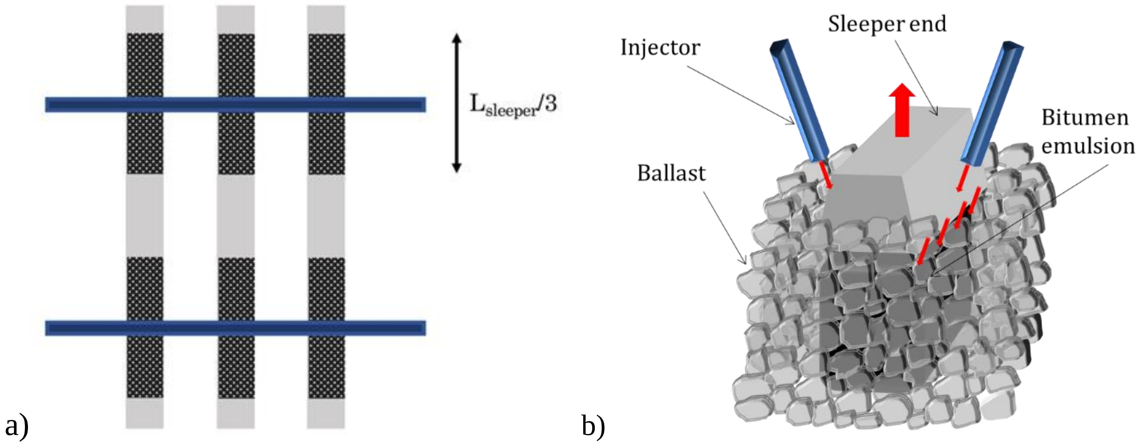

Figure 1. Schematic illustration of ballast stabilisation process with bitumen emulsion [20].

2. Methodology

A comparative attributional [37] and process-based LCA study is performed according to the ISO 14040 series [25, 38]. It calculates and compares the potential environmental impacts associated with the construction and maintenance of traditional ballasted and BSB track-bed.

The stages adopted in this study include goal and scope definition, inventory analysis, impact assessment, and interpretation.

2.1. *Goal and scope definition*

2.1.1. *Goal*

The main goal of this work is to quantify the potential life cycle environmental impacts arising from the use of BSB technology as construction and maintenance practice. The results are compared with the potential life cycle environmental impacts arising from the use of traditional ballast.

The findings of this study are intended to be used by engineering experts and practitioners to make more assertive judgments on the advantages and disadvantages associated with the use of emerging and commonly called sustainable strategies and practices for railway track-bed construction and maintenance and rehabilitation (M&R).

2.1.2. *System description and boundaries*

The LCA was performed according to a *cradle-to-grave* perspective, i.e., from the resource extraction and composite materials production and including all the movements related to the transportation of materials, to the machinery operation during ordinary (tamping) and major (renewal) maintenance activities, with the ultimate goal of highlighting the principal potential differences, in terms of environmental burdens arising from the use of BSB and traditional ballast. A scheme of the life cycle phases included in the system boundaries adopted is presented in Figure 2. The transportation distances considered for each material used in this case study are shown in Table 1.

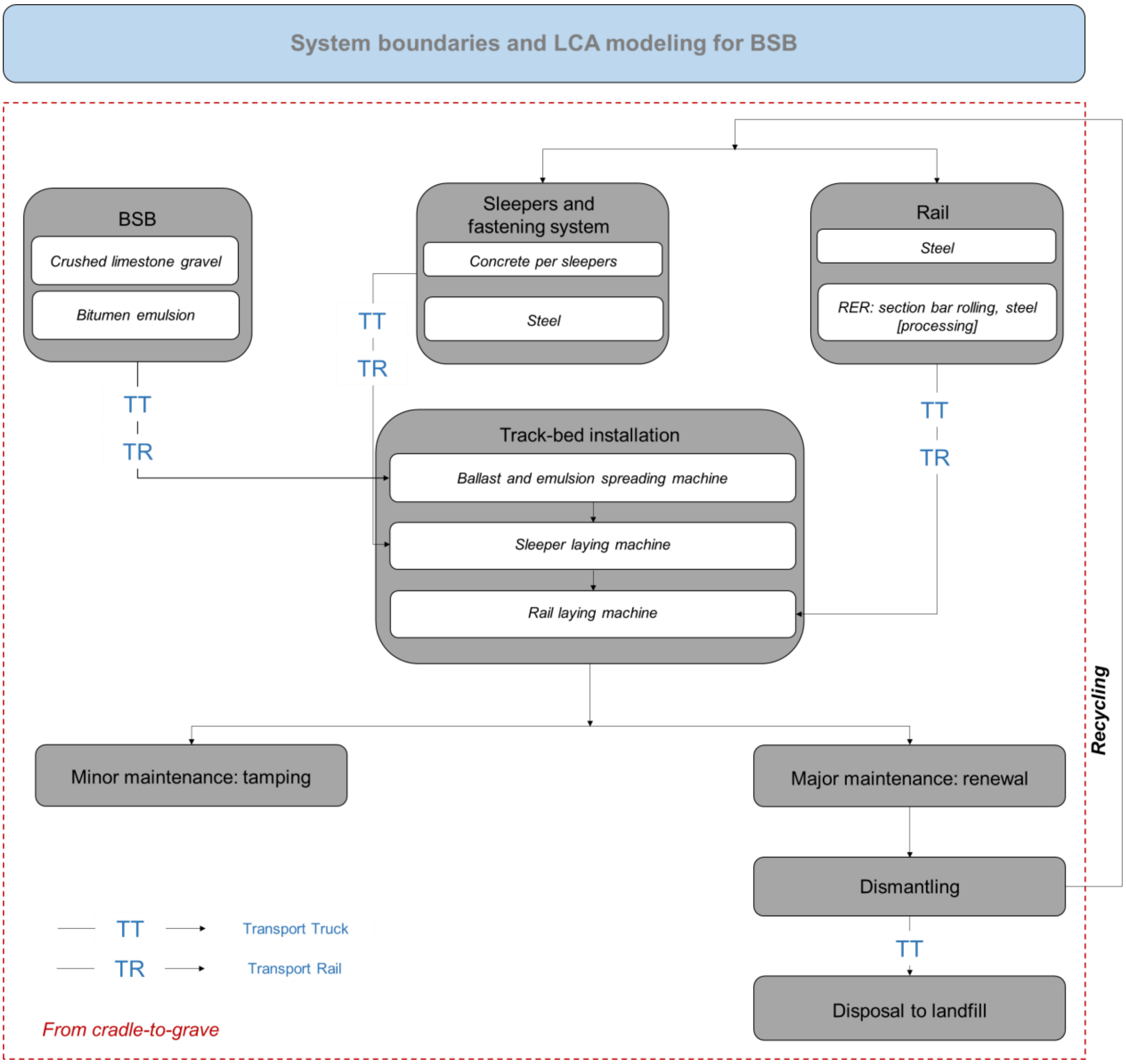

Figure 2. Schematic representation of the life cycle stages and main processes considered when a BSB layer is placed in the track-bed infrastructure.

Table 1. Transportation distances considered in the case study and displayed in Figure 2.

Type of material	Transport Truck (TT) [km]	Transport Rail (TR) [km]
BSB/aggregates	100	100
Sleepers and fastening system	85	100
Rail	5	160
Materials dismantled	100	-

The resources extraction and composite materials production consists of the acquisition and processing of raw materials, such as the bitumen production at refinery; extraction, crushing and sieving of aggregates; steel making processes; production of the sleepers (concrete), fastening system, and rails. The construction phase includes the ballast spreading and the laying operations of sleepers and rails with the use of specific construction equipment and machinery. The maintenance phase accounts for the operations involved in the performance of minor and major maintenance activities. The transportation of materials to and from the construction site and between intermediate facilities are also considered.

2.1.3. *Functional unit*

The railway track-bed case study was the doubling track line Florence-Viareggio in the Pistoia-Montecatini Terme section, in Italy. The functional unit (FU) of the case study presented in this paper is the maintenance of the quality level of 1 km-length track over 60 years for an initial traffic load of 20 Million Gross Tons (MGT) with a growth rate of 0.5% per year. The railway track is composed of rails, sleepers, fastening system and ballast. The thickness and width of the ballast layer are respectively 35 cm and 3.5 m, being equal for both solutions (i.e. traditional ballast and BSB).

2.2. *Life cycle inventory*

The life cycle inventory (LCI) phase consists of the primary and secondary data collection and modelling of the system. Primary data are specifically related to the processes required and modelled for obtaining the product or service studied in the LCA. In turn, secondary data represent generic or average data related to the product or service subject to analysis. The provenience of that data includes the literature, research groups, national and international database and expert’s opinion [39]. Therefore, the data sources were selected in order to be, as much time, geographical and technological representative as possible. That means that the most recent and truthful data representing Italian processes and conditions were used as inputs when modelling the processes covered by the sub-components integrating the system boundaries. In the present research work, both primary and secondary data were considered as detailed in the following sub-sections. Specifically, the *Construction materials (CM) database extension* of the Gabi software, the Railway Tie Association Reports [40] and the Wordsteel association [41] were used as main sources of data for the LCI of the materials involved in the system. The data sets rely on long-term co-operation between industry as well as patent, technical and scientific literature [52].

Reference values for the productivity and working hours of the machinery (pavers and rollers) considered for the laying operations and compaction of all the elements involved were collected from Kiani et al. [42].

2.2.1. *Rail production sub-phase*

In Europe, rails are classified by standards depending on the weight per unit of length and the quality of the steel. In the railway line considered in this case study, the type of rail 60E1 (60 UIC) with steel type R260 commonly used in Italy was placed. The characteristics of this type of rail are summarized in Table 2.

Table 2. Main characteristics of the rail used in the case study.

Type of steel	Chemical composition						Tensile yield stress (N/mm^2)	Minimum elongation (%)	Stiffness (HB)	Weight (kg/m)
	C (%)	Mn (%)	Si (%)	Cr (%)	P (%)	S (%)				
R260	0.60-0.82	0.65-1.25	0.13-0.60	≤ 0.15	max 0.03	max 0.03	880-1030	min. 10	260-300	60.21

The *Rail* module was built taking into account the main production processes of unbound steel in an integral cycle plant, including also other input materials used in the converter and casting processes. The data used to model this sub-phase was taken from the *CM database* and refers to European industrial plants. Afterwards, the module *section bar rolling, steel [processing]* was selected because it includes the rolling process of the section and the cut of the piece of desired length. Also, in this case the data refers to European industries. The output of this process envisages the production of rails (120 kg/FU) and steel scrap products (0.4 kg/FU) [42].

2.2.2. *Sleeper and fastening system production sub-phase*

Currently, on the standard and high-speed lines of Italian railroads, pre-compressed vibratory reinforced monoblock concrete sleepers are required. Table 3 summarizes the characteristics of the sleepers adopted in the case study.

Table 3. Main characteristics of the sleepers used in the case study (RFI-240).

Parameter	Value
Length (mm)	2400
Thickness (mm)	300
Width (mm)	300
Weight[a] (kg)	285
Mass of reinforcement bars[b] (kg)	8
Fastening systems and clips[b] (kg)	9
Sleepers spacing (mm)	714
Inclination supporting surface rail	1/20

Notes: [a]"RFI Specifica Tecnica di Fornitura RFI TCAR SF AR 03 002 E" [43]; [b]Kiani et al. [42].

Based on the data presented in Table 3 and the feature of the case study, the weight of the concrete sleeper was equal to 303 kg and includes pre-stressed steel cables. They were assumed to be placed at 714 mm, meaning that 1400 sleepers were placed in the railway section. Elastic fastening systems and clips made of steel were also included in the inventory. LCI data associated with their production were obtained from previous detailed studies [44-

45-46] and combined with the *CM database*. The inventory data referring to the production of sleepers and fastening system is summarized in Table 4.

Table 4. Inventory associated with the production of one sleeper (reinforced concrete monoblock and fastening system).

Item	Quantity	Unit
Concrete C30-37[a]	285	kg
Steel rebar [Metals][b]	8	kg
RER: steel, converter, unalloyed, at plant	9	kg
IT: Electricity, medium voltage, production IT, at grid [production mix][c*]	128	kWh
Natural gas Italy [Natural gas at production][c]	7.4	m^3
RER: natural gas, burned in boiler[c]	6.24	kWh
CH: Diesel fuel, at refinery[c]	1.4	kg
CH: light fuel oil, burned in boiler 100 kW [heating system][c]	0.512	KWh
Gasoline (regular) [refinery products][c]	0.07	kg
Biomass (solid) [Biomass fuels][c]	1.6	kg
Energy unspecific [Energy resources][c]	21	MJ
Coal coke [Coke at production][c]	7.8	kg
RER: Tap water, at user[c]	320 kg	kg
Hard coal Italy [Hard coal (resource)][c]	44	kg
Uranium oxide (U_3O_8) [Uranium (resource)][c]	0.000091	kg
Crude oil Italy [Crude oil (resource)][c]	7.82	kg
Natural gas Italy [Natural gas (resource)][c]	1,48	kg
Biomass (MJ) [Renewable energy resource][c]	0.0000051	MJ
Energy, potential (in hydropower reservoir), converted [Renewable energy resources][c]	38	MJ
Use of renewable primary energy resources[c]	2.6	MJ
Ore mined [Non renewable resource][c]	717	kg

Notes: [a]Crawford (2009) [45]; [b]Smartrail (2015) [46]; [c]Bolin and Smith (2013) [44].

2.2.3. *BSB and ballast production sub-phase*

The virgin aggregates required for the ballast were modelled as crushed gravel and the inventory data associated with their production were obtained from the *CM database*. The process *Limestone*, *crushed gravel* has been selected and it comprises all the flows of materials and energy associated with the extraction in the quarry, the cleaning, the two stages of crushing, the organization of the production and the transport. The finished product is the crushed gravel (dried) at the factory gate. For modeling the production of BSB material it is necessary to model the production of BE. The *CM database* was also used as the data source for modelling the BE production. It comprises all the flows of materials and energy associated with the extraction, transport and refinement of crude oil. The system boundaries of BE are represented by the finished product with a percentage of bitumen equal to 40%. Table 5 summarizes the principal characteristics of traditional ballast and BSB.

Table 5. Main characteristics of traditional ballast and BSB.

Type of solution	Components	Component density (kg/m^3)	Bulk density (kg/m^3)	Total quantity of ballast (kg/m)	Quantity of ballast stabilised with bitumen emulsion (kg/m)*	Total quantity of bitumen emulsion (kg/m)
Traditional ballast	Crushed gravel	2700	1600	1980	-	-
BSB	Crushed gravel	2700	1623	1980	372.7	5.367
	Bitumen emulsion	1060				

Notes: *Portion of ballast under one third of the sleeper length per sleeper (Figure 1a).

2.2.4. *Construction phase*

To build a ballast track it is necessary to spread the ballast (35 cm thickness) and install sleepers, fastening system and rails. The productivity and fuel consumption of the machinery used during the installation of each component of the track-bed is presented in Table 6 [42].

Table 6. Productivity and fuel consumption of the machinery used in the case study.

Machinery	Construction speed (hour/km)	Diesel fuel consumption (hour/km)	Diesel fuel consumption (kg/km)
Ballast spreader	12	10	99.6
Sleepers laying machine	14	5	58.1
Rail laying machine	37	5	153.6

In the case of BSB, it is necessary to pour the BE, at ambient temperature, onto the ballast. This construction activity requires the use of rail cargo-tank containing BE in addition to the ballast-spreading machine. Therefore, in this solution the fuel consumption refers to the operation of both machines and was modelled by means of the process "*operation, maintenance, railway track [Railway]*" available in the *CM database*.

2.2.5. *Transportation of materials phase*

The crushed gravel limestone, sleepers and rail must be transported to the construction site. It was assumed that the materials were hauled from the quarry and plants by truck until Piombino station, Italy. Afterwards, from the station to the construction site the different elements were transported on freight trains. Therefore, the environmental impacts resulting from the transportation of materials are due to the emissions released by the combustion process of the transportation vehicles and the electricity employed by the rail cargo. All materials were assumed to be hauled by heavy duty vehicles, and the process "*GLO: Truck, Euro 3, 20 - 26t gross weight / 17.3 t payload capacity ts <u-so>*" existing in the *CM database* was used to determine the environmental burdens associated with the transportation of materials on the road. The extraction and processing of the fuel is included. The production of the vehicle is not included in the balancing (Gabi ts). Additionally, the transportation movements performed by train cargo were modelled by means of the "*GLO: Rail transport cargo - Electric, average train, gross tonne weight 1000t / 726t payload capacity ts <u-so>"* existing in *CM database*.

The transport distances between the different sites are outlined in Table 1. The haul distances correspond to the estimated average from production/supply sites to the construction site.

2.2.6. *Maintenance phase*

The minor and major maintenance operations considered in this phase, i.e. tamping and renewal, were scheduled once critical levels of track geometry and ballast layer contamination are reached.

2.2.6.1. *Degradation prediction models*

In order to estimate the application time of the maintenance activities for BSB track-bed and traditional track-bed (unbound), an integrated model proposed by D’Angelo et al. 2018 [20] was used. Its development was based on laboratory tests simulative of field conditions and combines the evolution of standard deviation (SD) of vertical alignment (track geometry degradation) and the level of contamination of ballast layer with traffic.

SD of track irregularities is an indicator of the quality of the track, measured over a typical length (200 m). In turn, the ballast contamination from particle breakage and wear due to traffic loading and maintenance represents the highest source (with more than 70%) of ballast layer fouling [16-47]. This phenomenon jeopardizes the rapid draining and elastic characteristics of the ballast layer, as well as its ability to be effectively maintained by tamping [16-48].

The application years of minor and major maintenance operations were then triggered when the SD limit and the contamination limit were reached, respectively, as a function of the cumulated traffic expressed in MGT.

As baseline scenario, a SD limit of 2 mm was established for track quality level [49] while a 30% of materials passing the 22.4 mm sieve was considered as contamination limit [50].

2.2.6.2. *Minor maintenance: tamping*

From the sixties on, automatic tamping has been the most used method to correct track geometry defects. The vibrating action of its tines allows the re-arranging of particle position, thus restoring the original position of the track. In this case study, the tamping timing is defined as a function of traffic for both traditional ballast and BSB (tamping plus BE spreading) solutions and considering a SD limit of 2 mm [20, 49]. Figure 3 represents the evolution over time of the SD of the vertical alignment as well as the timing of the tamping activities to be carried out in this specific case study for BSB and traditional ballast.

As it is possible to observe from Figure 3, the number of tamping operations over the Project Analysis Period (PAP) is considerable lower for BSB (6 applications) in relation to that of the traditional ballast (17 applications). The dosage of BE for BSB is the same as that used for construction (see Table 5).

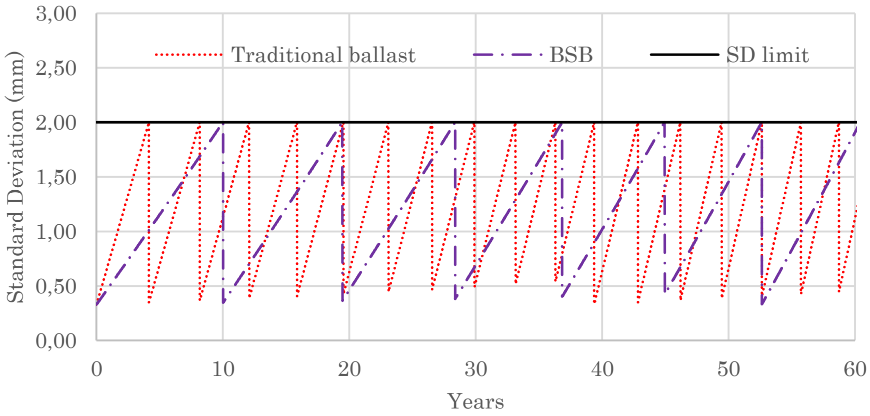

Figure 3. Evolution of SD of track irregularities (20 MGT) for reference ballast and BSB solutions, considering an SD limit of 2 mm [20].

The background LCI dataset for tamping operations of traditional ballast and BSB is provided in Table 7. In particular, the consumption of electricity refers to the Italian energy mix at medium voltage.

Table 7. Inventory associated with the tamping operations per meter of track-line [42].

Item	Quantity	Unit
Diesel [Refinery products]	0,40	kg
IT: electricity, medium voltage, production IT, at grid [production mix]	1,82	MJ
Bitumen emulsion [Plastics]^a	5,37	kg
Datasets	**Use**	

CH: operation, maintenance, railway track [Railway]	Tamping plus bitumen emulsion spreading
CH: operation, maintenance, railway track [Railway]	Bitumen emulsion storage tank

Notes: [a]Only when BSB is considered.

2.2.6.3. *Major maintenance: renewal*

The fouling conditions of the ballast are divided and described in different categories from ballast clean (<2% fouling), moderately clean (2 to <9.5% fouling), moderately fouled (9.5 to <17.5% fouling), fouled (17.5 to <34%) and highly fouled (≥34% fouling) [51]. When the contamination level reaches its critical limit, specifically the 30% limit for particles passing the 22.4 mm sieve [50] the ballast layer needs to be renewed (fouled ballast). In this case the difference between the first renewal of traditional ballast and BSB is equal to approximately 14 years (Figure 4). It is interesting to note that if a lower critical limit is selected for the renewal (i.e. 20%) this difference decreases (10 years). Nevertheless, in this case for the traditional ballast the renewal should be performed two times instead of one.

Ballast track-bed is renewed during its life cycle following the same specifications as for the first construction. Therefore, the same processes as those adopted in the construction were used, including the replacement of sleepers, fastening system and rail [42].

Figure 4 shows the evolution of ballast contamination over the PAP as well as the timing of the renewal activities to be carried out for BSB and traditional ballast solutions, considering a 30% limit of particles passing the 22.4 mm sieve and an initial volume of traffic equal to 20 MGT. As it is possible to see from Figure 4, the ballast contamination rate for the BSB solution is lower than that for the traditional ballast solution. Although for the PAP considered the number required of renewal activities is the same for both solutions, in the long-term the traditional ballast will require the application of a greater number of renewal activities comparatively to that of the BSB solution.

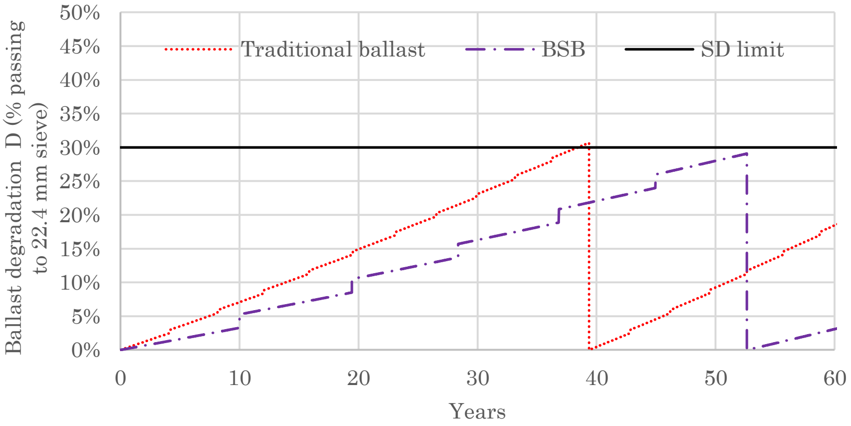

Figure 4. Evolution of ballast contamination over the PAP as well as the timing of the renewal activities to be carried out in the case study for BSB and traditional ballast solutions, considering a 30% limit of particles passing the 22.4 mm sieve [20].

2.2.7. *Dismantling, recycling of materials and disposal*

When the renewal is performed the different materials are dismantled, and then either recycled or landfilled. The EOL phase includes: i) dismantling of the track-bed; ii) transport of removed materials to waste processing; iii) waste processing for reuse or recycling; and iv) materials landfill [52].

In particular, the present research work assumes that:

- The steel used in rails, reinforcement bars and fastening system was recycled at a rate of 85% [42, 53]. This percentage corresponds to the recycled content (RC) and together with the primary resources were modelled as inputs in the life cycle of the materials used for the railway track [54, 55]. The remaining percentage of steel was landfilled and the following dataset in Gabi software was used "*disposal, steel, 0% water, to inert material landfill [inert material landfill facility]*". The LCA of metal recycling was modelled according to the closed-loop recycling approach [56, 57, 58]. It relies on the assumption that steel is infinitely recycled without the loss of key properties, such as strength, ductility or formability [57].

- After dismantling the concrete sleepers, they undergo the common process of crushing, extracting both the steel reinforcement and a part of the rail fastening system with the help of magnets. The steel is recycled as described above and the crushed concrete is used as embankment material to fill low road construction [59]. This is possible because no chemical agents are used during dismantling and there is no risk of groundwater contamination or other harmful effects [59]. For modelling the EOL phase of the sleepers an "open-loop different primary route" approach was selected [39], because the material does not maintain its inherent properties and it is recycled into a different product with a different function (embankment material). Indeed, the recycled concrete is not recommended for structural use [58]. Therefore, the burdens related to the treatment of the material and landfill are completely included in the current system boundaries because this system is responsible of the EOL product [39]. For the recycled concrete the pre-treatment processes (extracting steel, crushing) are within the responsibility of the first system. These processes are necessary to make sure that the product has no negative market value [39]. Moreover, it was assumed a RC for the concrete equal to 62% [60] and the following datasets in Gabi software were selected "*disposal, building, concrete gravel, to recycling [Recycling]*". For the remaining percentage of concrete considered as solid waste the following dataset was selected: "*disposal, limestone, 5% water, to inert material landfill [inert material landfill facility]*".
- Due to the high level of contamination at the end of its service life, the ballast was considered as gravel for embankment material to fill road construction (96% of recycled material) without any structural role [61]. Therefore, similarly to the sleepers, an "open-loop- different primary route" approach was adopted. BSB contains residual bitumen from BE and it could be recycled in upper layers of the road

structure, similarly to Reclaimed Asphalt Pavement (RAP). Nevertheless, without sufficient information about the recycling process and performance of this material, a conservative approach was adopted by considering the dismantled BSB as an inert material for embankment (the same percentage and allocation of traditional ballast).

- During maintenance activities (tamping) no material is added or removed and dismantled in the railway structure. Only in the case of BSB, BE is spread onto the ballast layer.
- The energy consumed for dismantling was assumed to be equal to that considered for the construction energy [42].

The recycling rates, solid waste and type of recycling (closed-loop or open-loop) of the different components of the railway structure are summarized in Table 8.

Table 8. Recycling characteristics associated with elements of the track after dismantling.

Element of railway structure	Recycling content (RC) (% of mass)	Recycling approach	Type of use	Reference
Rail, reinforcement bars and fastening systems	85	Closed-loop recycling	Steel for rail	[39] [42] [53] [53]
Concrete sleepers	62	Open-loop recycling-different primary route	Embankment material (excluded from the system)	[39] [54] [60]
Ballast or BSB	96	Open-loop recycling-different primary route	Embankment material (excluded from the system)	[39] [42] [54]

2.3. *Life Cycle Impact assessment*

The life cycle impact assessment (LCIA) stage of the standardized LCA methodology comprises several steps, namely, classification, characterization, normalization, group and weighting [25]. Among these steps, classification and characterization were undertaken in this study.

The LCA was modeled in Gabi Professional Academy LCA software® (GaBi ts Software 7.3.3). The calculation of the impact category indicator results was performed at midpoint level by applying the ReCiPe impact assessment method [62]. Only the analysis at midpoint level was conducted without aggregating results at endpoint level in order to keep the uncertainty as low as possible. Indeed, each aggregation step, contributes to increase the uncertainty in the results [63].

Specifically, the following impact categories were considered: climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, marine ecotoxicity, marine eutrophication, metal depletion, ozone layer depletion, particulate matter formation, terrestrial acidification, terrestrial ecotoxicity and water depletion. The "land use" impact category was not considered in this analysis due to the high uncertainty level involving the quantification of its score [64].

3. Results and discussion

3.1. *Environmental impact profile for ballast layer*

Figure 5 shows the potential relative life cycle environmental impacts of the BSB layer for all categories, calculated in relation to those of the traditional ballast layer. Those results are to be understood as follows: positive relative numbers mean that the BSB solution improve the LCIA results in relation to those associated with the traditional ballast while negative numbers represent a worsening of the environmental profile.

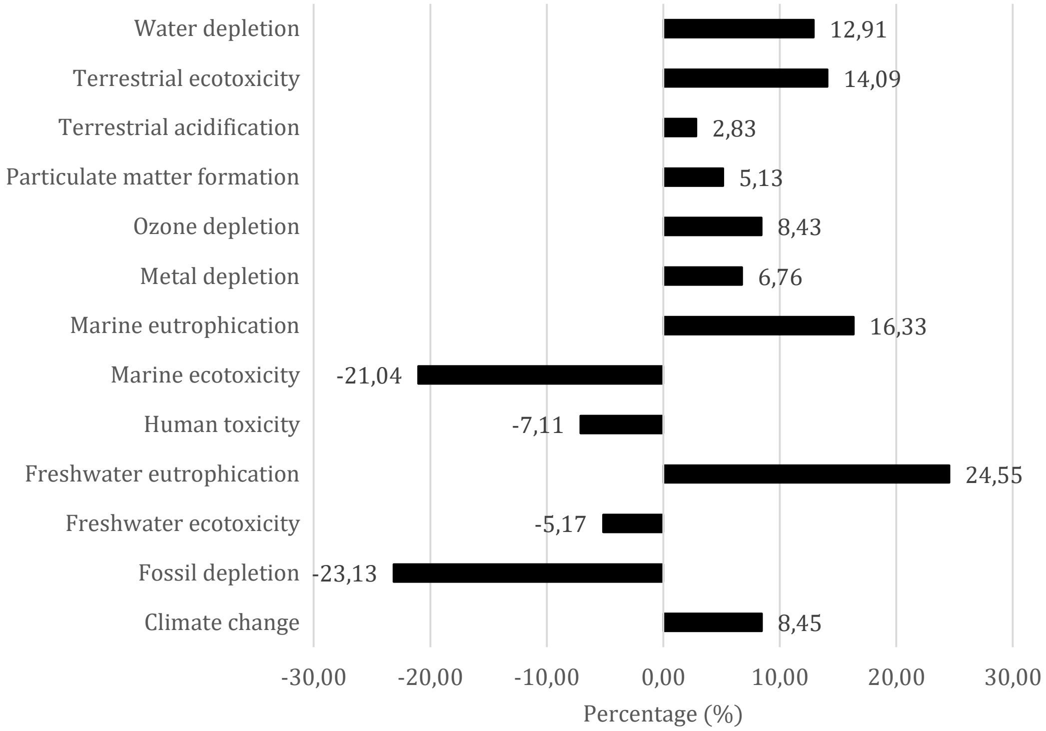

Figure 5. Potential relative life cycle environmental impacts of the BSB solution calculated in relation to those of the base solution, i.e. the traditional ballast.

As it can be seen from Figure 5 the use of BSB solution leads to an improvement in the majority of the impact categories, particularly in the case of the impact categories freshwater eutrophication, (24.55%), marine eutrophication (16.33%), terrestrial ecotoxicity (14.09%) and water depletion (12.91%). On the contrary, the BSB solution entails higher environmental impacts than the reference solution in the impact categories fossil depletion (23.13%), marine ecotoxicity (21.04%), human toxicity (7.11%) and freshwater ecotoxicity (5.17%). This means that the use of BE originates such a high level of impact on certain categories that they cannot be compensated by the reduction of the need of minor and major maintenance activities over the PAP that are allowed by using the BSB solution.

In order to provide further details on the root causes behind some of the results presented previously, Figures 6 shows the contributions given by the construction and maintenance operations, the latter discretized per type of maintenance activity, for the results observed in the impact categories marine ecotoxicity (Figure 6a), fossil depletion (Figure 6b), freshwater eutrophication (Figure 6c) and marine eutrophication (Figure 6d). As illustrated in Figures 6a and 6b, the contributions of the construction and minor maintenance activity (i.e., tamping) to the marine ecotoxicity and fossil depletion impact categories are higher in the case of the BSB than in the case of the reference solution. Although the use of the BSB solution entails a reduction of those impact categories scores associated with the application of the renewal maintenance, it is not enough to offset the contributions of the construction and minor maintenance activities. For the construction activity, this result was expected because the use of BE required by the BSB solution is expected to increase the environmental burdens. However, the same cannot be straightforwardly said for the minor maintenance, given that the total amount of tamping operations required when the solution BSB is adopted is considerably inferior to that of the traditional ballast (more precisely 5.94 times against 16.43). This result demonstrates that for a few impact categories, among which the marine ecotoxicity and fossil depletion are the best examples, it happens that the decrease of the environmental impacts associated with the renewal activity is not sufficient to balance the higher environmental impacts arisen from the construction and minor maintenance of the BSB solution. This result is certainly due to the use of BE during the construction and tamping operations.

Nevertheless, for the majority of the impact categories, such as for instance the freshwater and marine eutrophication (Figure 6c and 6d), the lower amount of tamping operations required when the solution BSB is adopted offsets the environmental shortcomings associated with the use of BE.

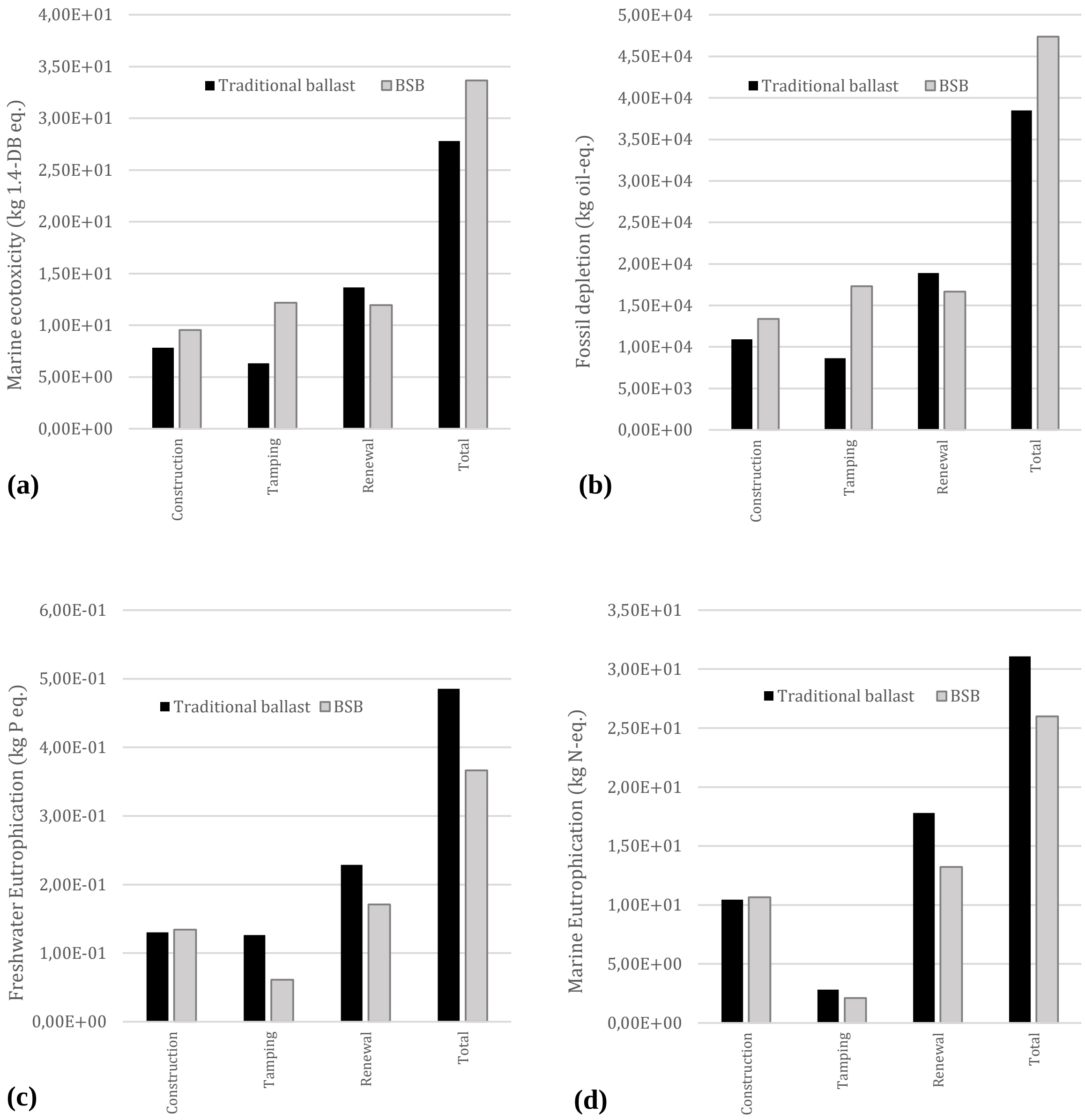

Figure 6. Contributions given by the construction and maintenance operations for the results observed in the impact categories (a) marine ecotoxicity, (b) fossil depletion, (c) freshwater eutrophication and (d) marine eutrophication.

3.2. *Environmental impact profile for the complete track-bed structure*

For a better and more comprehensive understanding of the advantages related to the use of BSB, it is important to consider the complete structure of the track-bed, which in addition to the ballast layer, also includes other components, such as sleepers, fastening systems and rails.

Figure 7 shows the potential relative life cycle environmental impacts of the track-bed structure with a BSB layer, calculated in relation to those of the base scenario, i.e. the track-bed with a traditional ballast layer. Similarly to Figure 5, those results are to be understood as follows: positive relative numbers mean that the BSB improve the LCIA results in relation to those associated with the traditional ballast while negative numbers represent a worsening of the environmental and energy profile.

As illustrated by Figure 7, a track-bed structure with a BSB layer brings remarkable improvements in the environmental impact profile of the infrastructure. Indeed, all the impact categories show improvements. Those that beneficiated the most were freshwater eutrophication (19.10%), water depletion (15.36%), marine eutrophication (14.83%) and terrestrial acidification (14.52%). In turn, other impact categories, such as metal depletion (4.36%) and marine ecotoxicity (4.57%) experienced improvements that are more tenuous.

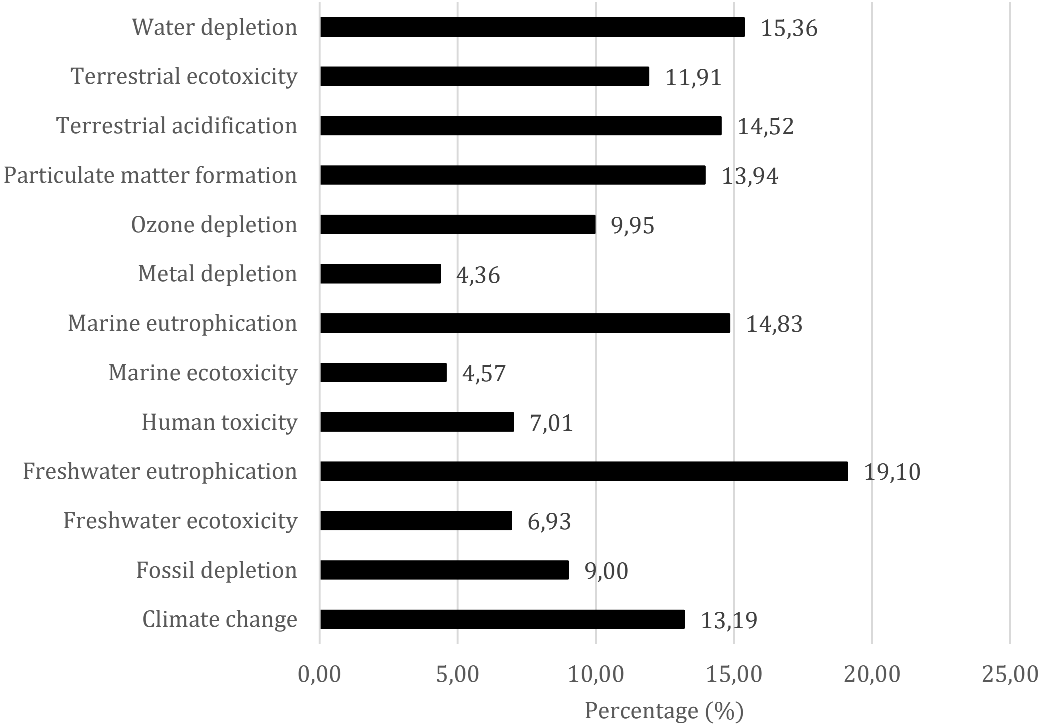

Figure 7. Potential relative life cycle environmental impacts of the track-bed structure with a BSB layer calculated in relation to those of the base solution, i.e. the traditional ballast.

Figures 8 shows the contributions given by the construction and maintenance operations for the results observed in the impact categories freshwater eutrophication (Figure 8a), that presents the greatest improvement (19.10%), and metal depletion (Figure 8b), that presents the lowest improvement (4.36%). From this figure it can be seen that regardless of whether the BSB solution entails greater or lower impacts than those of the reference solution during the implementation of the tamping maintenance, it always leads to improvements in the environmental profile of the infrastructure’s life cycle. The explanation for this results lays on the combined effect of the preponderance acquired by the resource extraction and composite materials production phase (that also includes the production of sleepers, fastening system and rails when the all railway infrastructure is taken into account) and the lower number of renewal activities required by the BSB solution in comparison to that of the traditional solution.

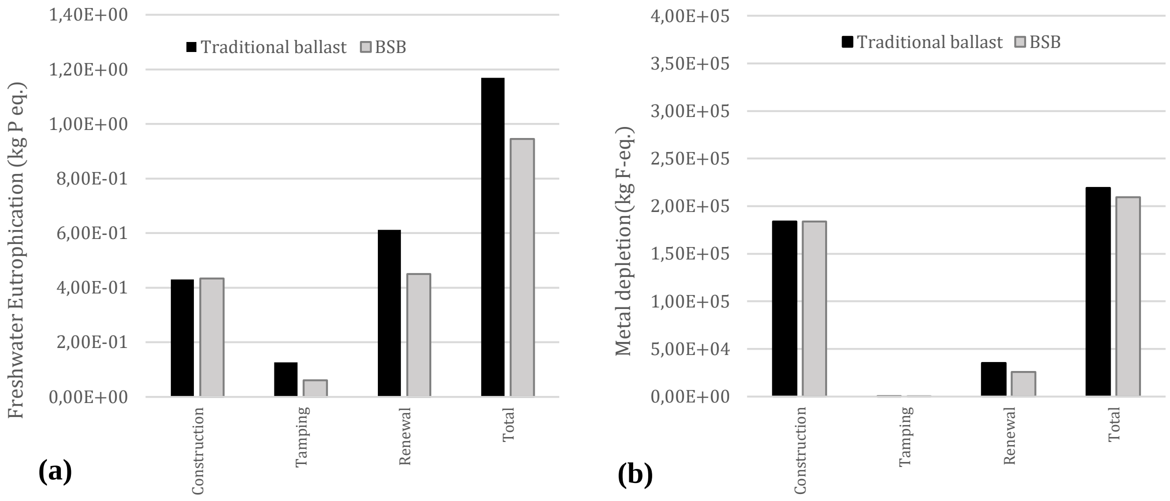

Figure 8. Contributions given by the construction and maintenance operations for the results observed in the impact categories (a) freshwater eutrophication and (b) metal depletion.

3.3. *Influence of the extraction and production of the different materials on the environmental impacts*

The materials extraction and the production of composite materials is the construction activity with the highest environmental impact and energy consumption [29, 65, 66]. Given the importance of these phases in driving the life cycle environmental performance of the solutions studied, Figures 9 displays the relative contribution of the extraction and production of the several materials to the total environmental impacts arisen from this phase.

As detailed in Figures 9, the production of sleepers and fastening system is the main source of impacts for 8 out 13 categories, followed by the production of rails (5 out 13 categories). In turn, the production of the traditional ballast and BSB is responsible by the lowest share of the impact scores. In the case of the production of sleepers and fastening system its contribution can be as high as 68.3% and 68.1% for the impact category terrestrial acidification, respectively in the baseline and alternative scenarios, while the maximum contribution given by the production of rails can amount to 90.8% for the impact category metal depletion in both scenarios. Regarding the production of ballast and BSB, their maximum contributions is observed for the impact category water depletion, which can total 40.9% and 42.0%, respectively in the baseline and alternative scenarios. However, in 6 out of 13 impact category their share do not go beyond 10%.

Taking into account the weight denoted by the production of sleepers, fastening system and rails for the environmental profile of the infrastructure, it is then clear that the adoption of a solution that allows a reduction in the number of the maintenance activities requiring the replacement of those components (i.e., the renewal) over the infrastructure's life cycle, such as it is the case of the BSB solution, entails substantial savings in terms of environmental impacts. That is why in the previous section it was observed that the implementation of the BSB solution encompasses improvements in all impact categories when the whole infrastructure is accounted for.

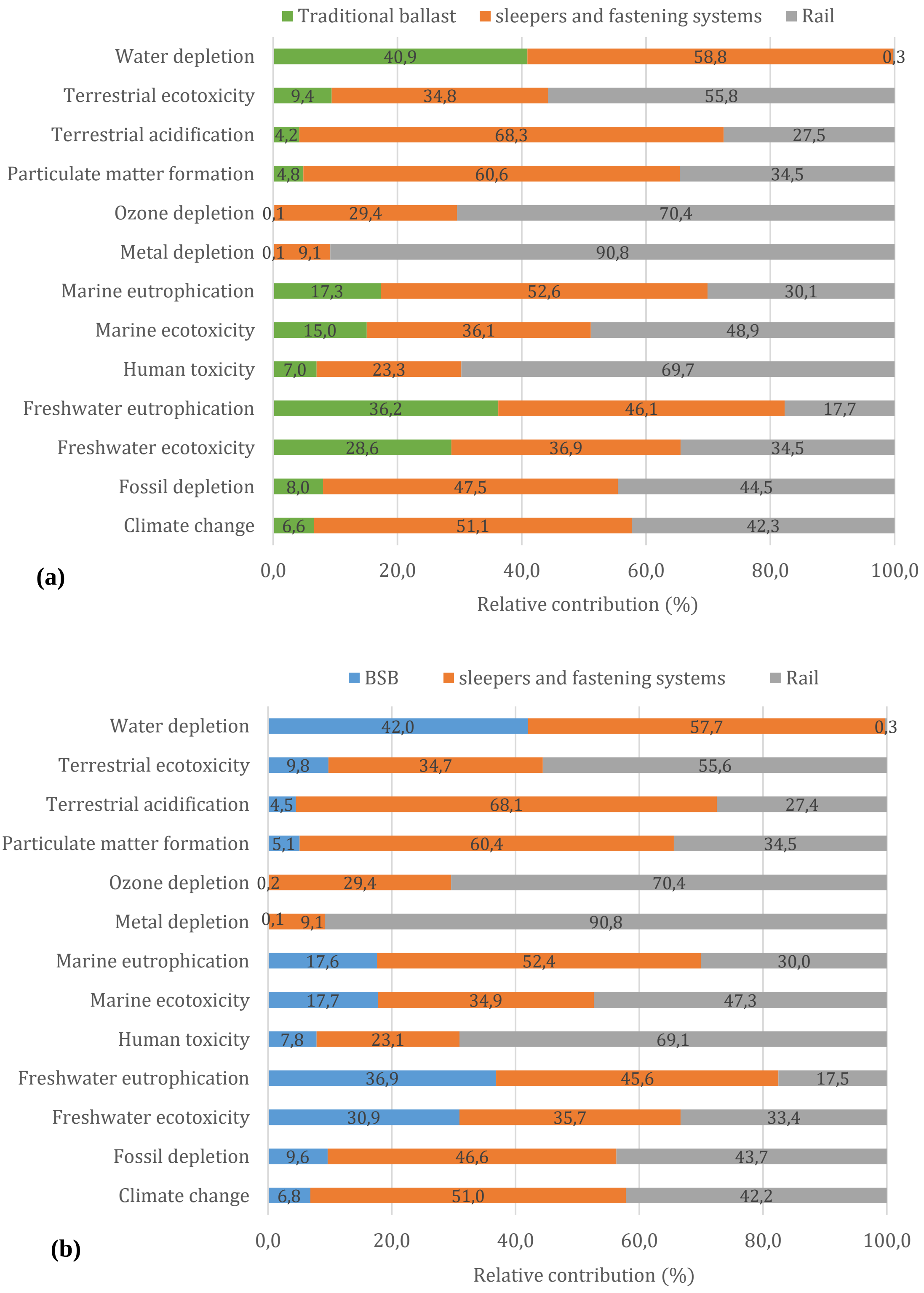

Figure 9. Relative contribution of the several elements produced during the material extraction and composite materials production phase for the total environmental impacts arisen from this phase in the track-bed infrastructure due to the use of (a) traditional ballast layer and (b) BSB layer, respectively.

3.4. ***Sensitivity analysis***

In order to understand how variations of certain parameters and modelling assumptions affect the outcomes, and consequently the advantages of using BSB instead of traditional ballast, a sensitivity analysis was carried out. Thus, the relative effects of different factors may be evaluated and compared. In this case study, the “One-(factor)-At-a-Time” (OAT) sensitivity analysis method was employed. According to this method, output variations are induced by varying one input factor at a time, while all others are held at their default values [67].

In this study, two different values of two parameters were considered: SD limit and annual MGT. The standards prescribe maximum allowable values for SD that can be different for different countries. Varying SD means that the acceptable track quality level changes, and thereby the timing for minor maintenance activities. Therefore, the sensitivity analysis was firstly carried out by considering two alternative values for the SD limit, namely 1.5 and 2.5 mm [49], while keeping the value of the initial traffic volume constant and equal to 20 MGT. Afterwards, the sensitivity of the LCIA results to the variation of the cumulated traffic, expressed in MGT, was ascertained by considering two additional values, namely 10 and 40 MGT (heavy traffic) [68], while keeping constant the initial SD limits. Figures 10 and 11 report the relative variation of the environmental advantages (i.e., reduction of the LCIA results) arising from the use of BSB instead of traditional ballast layer in the track-bed structure for the several SD limits and traffic values considered.

The results displayed in Figures 10 and 11 show that regardless of the SD limit and traffic values considered, the adoption of a BSB layer always leads to the reduction of the environmental impacts. For the lowest SD limit (1.5 mm) the benefits of using BSB vary across the impact categories from 2.93% (marine ecotoxicity) to 21.46% (freshwater eutrophication) (Figure 10). Compared to the reference SD limit of 2 mm, the lowest reduction in the environmental benefits was observed in the impact category freshwater eutrophication (0.09%), while the highest one was registered by the impact category marine ecotoxicity (3.83%). In turn, for the highest SD limit (2.5 mm) the benefits range between 5.75% (metal depletion) and 22.90% (freshwater eutrophication). In this case compared to the reference SD limit, the lowest reduction in the environmental benefits was observed in the impact category metal depletion (0.67%), while the highest one was registered by the impact category freshwater ecotoxicity (3.42%).

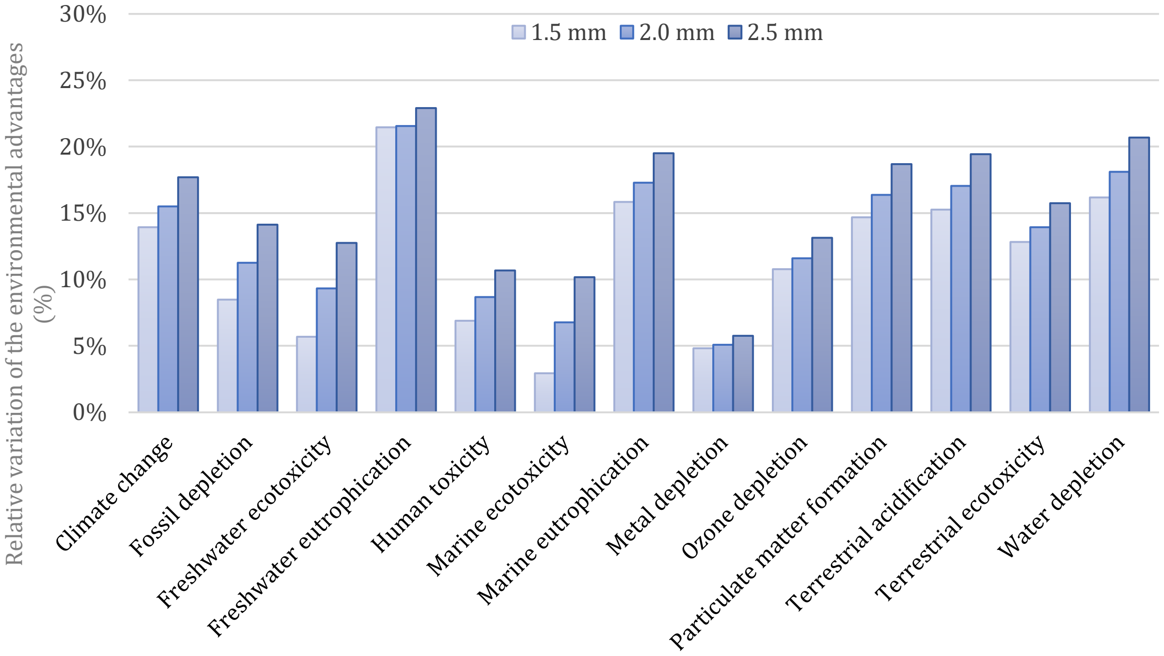

Figure 10. Relative variation of the environmental advantages (i.e., reduction of the LCIA results) arising from the use of BSB instead of traditional ballast layer in a track-bed structure for the three alternative SD limits considered.

In Figure 11 it is possible to observe the variation related to the traffic values considered. For the lowest traffic volume (10 MGT) the benefits of using BSB vary across the impact categories from 2.22% (marine ecotoxicity) to 14.81% (freshwater eutrophication). Compared to the reference scenario of 20 MGT traffic volume, the lowest reduction in the environmental benefits was observed in the impact category metal depletion (2.38%), while the highest one was registered by the impact category freshwater eutrophication (6.74%). In turn, for the highest traffic volume (40 MGT) the benefits range between 8.05% (metal depletion) and 24.77% (freshwater eutrophication). In this case compared to the reference scenario of 20 MGT the lowest reduction in the environmental benefits was observed in the impact category marine ecotoxicity (1.32%), while the highest one was registered by the impact category ozone depletion (4.04%).

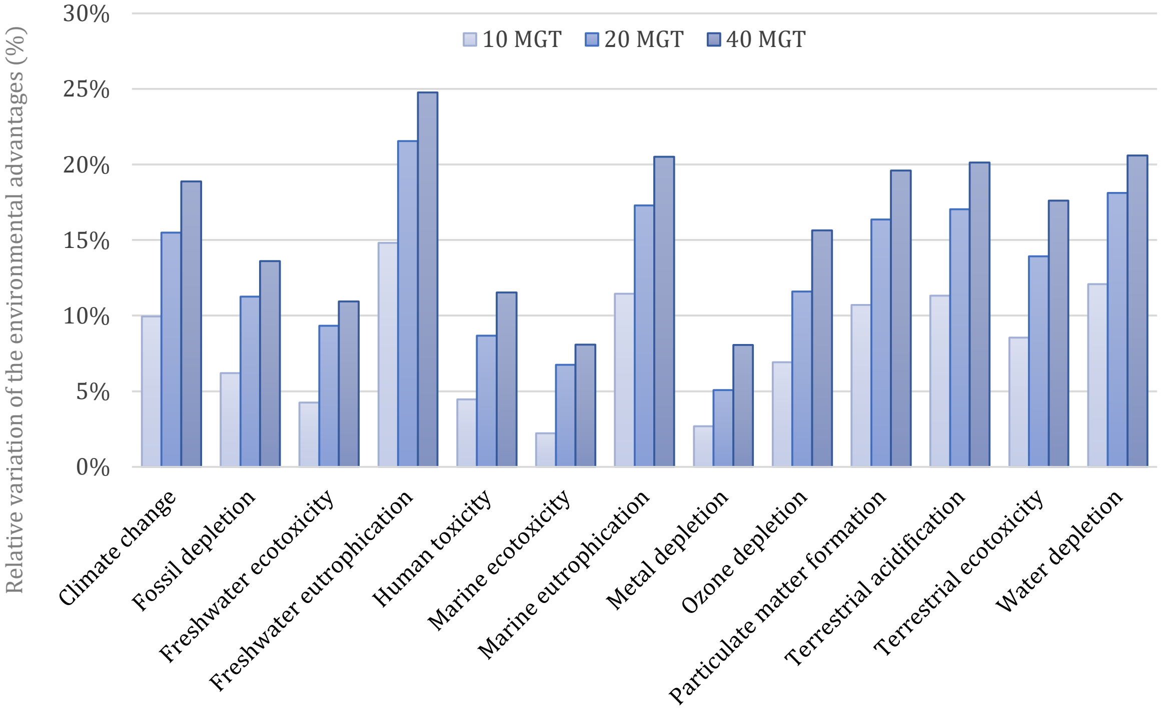

Figure 11. Relative variation of the environmental advantages (i.e., reduction of the LCIA results) arising from the use of BSB instead of traditional ballast layer in a track-bed structure for the three alternative traffic values considered.

4. Summary and conclusions

In this paper, the results of a process-based LCA study of an Italian railway track-bed section incorporating a BSB layer were presented and compared with those in which a traditional ballast layer is adopted.

When the analysis performed focused only on the ballast layer (i.e., the remaining components of the track-bed section are disregarded) the results showed that the use of BSB instead of the traditional ballast reduces the scores of the majority of the impact categories, most notably those of the freshwater and marine eutrophication and terrestrial ecotoxicity. The main advantage resulting from the use of BSB is related to the frequency of the application of the renewal maintenance activity. The reason for this result is related to the fact that the BSB technology ensures both a higher durability of the layer and track quality than that accomplished with the traditional ballast layer. Nevertheless, certain impact categories (i.e., fossil depletion, marine ecotoxicity, human toxicity and freshwater ecotoxicity) were found to exhibit a worsening of their scores. In those impact categories, the advantage provided by the use of BSB when the renewal maintenance activity is performed was not sufficient for reducing the global impact over the entire service life of the layer.

For a more comprehensive and exhaustive analysis of the potential benefits associated with the use of BSB in detriment of the traditional ballast, an analogous analysis was performed but including all the elements above the ballast layer, namely the sleepers, the fastening system and the rails. Based on the features of the case study and the system boundaries considered, the LCA results showed that a BSB-based track-bed allows reducing the scores of all the impact categories, particularly those of the freshwater eutrophication, water depletion, marine eutrophication and terrestrial acidification.

The examination of the contribution of the several life cycle phases to the total environmental impacts showed that the role played by the materials extraction and composite materials production phase is the most prominent due to the environmental burdens associated with the production of the sleepers, fastening system and rails. For this reason, it can be said that the reduction of the frequency of replacement of those elements results in considerable improvements in the life cycle environmental performance of the entire infrastructure.

Finally, a sensitivity analysis was undertaken to evaluate the extent to which the LCA results change due to variations in the values of some of the most relevant inputs triggering the execution of maintenance activities of the track-bed: the acceptable track quality level and the annual traffic value. The analysis showed that the use of BSB contributes positively to the reduction of the environmental impacts, independently of the track quality level and the cumulated traffic values considered.

The work presented in this paper offers an overview on the environmental sustainability assessment of bitumen stabilized ballast compared to the traditional ballast. The calculations performed were based on several context-sensitive hypothesis and thus cannot be considered neither exhaustive nor generalized. Moreover, the availability of data to be used in the LCA of these type of materials is still very limited. Therefore, further research efforts should be employed to produce a more complete and robust LCI that will certainly improve the overall quality of the LCA.

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