Life Cycle Cost Assessment of Bitumen Stabilised Ballast: a novel maintenance strategy for railway track-bed

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Abstract

In railway sector, the high quality of the track is ensured by adequate construction methods and frequent maintenance. To reduce the maintenance frequency diverse techniques have been recently developed. Among others, bitumen stabilised ballast (BSB) represents an innovative solution designed to increase ballast service life and reduce overall maintenance burdens. This technology, which can be used for new track-beds as well as to reinforce existing ones, consists of the use of bitumen emulsion (BE) poured or sprayed at ambient temperature onto the ballast. The objective of the present work is to assess the economic feasibility, encompassing the estimation of the costs of the environmental impacts, of this innovative technology (BSB), compared to the traditional ballast (TB). This purpose is achieved using a lifecycle approach where economic and environmental impacts are combined to return an integrated model. Results of Life Cycle Cost Assessment carried out for the baseline scenarios (with respect to traffic level and quality level set for the infrastructure) indicated that: the BSB technology, used since the construction stage and during the routine tamping, can provide economical savings. Sensitivity analysis to main parameters affecting results showed that these savings can vary significantly, especially in relation to the traffic and the discount rate.

Keywords: Bitumen stabilised ballast, traditional ballast, Lifecycle cost, maintenance, railway track-bed

1. Introduction

Railways require relevant resources to ensure efficiency and functionality along the time. In Europe, the construction cost of track ranges from 2 to 4 million of euros/km for single track, while the maintenance costs can vary from 30.000 to 100.000 €/km per year [1-3]. The main part of the total cost of maintaining the railway infrastructure arises from the track, thus the interest towards innovative and effective construction and maintenance techniques of the track is continuously growing.

“Climate and resource challenges require drastic action” [4], this is the imperative priority declared in the European strategic energy and climate targets for Smart, sustainable and inclusive growth and Smart, green and integrated transport by 2020. Indeed, greenhouse gas (GHG) emissions and their negative effects on global warming has urged the international community to strength the worldwide commitment to implement fair-reaching actions towards low-carbon and climate-resilient growth. Transport sector contributing to around a quarter of the European Union’s (EU's) GHG emissions. Road transport is the biggest emitter accounting for more than 70% of all GHG emissions from transport in 2014. In the light of this, the railway mode can play a crucial role in the EU’s low-emission mobility strategy [5]. Indeed, rail is the only major mode of transport that is currently able to shift from using fossil fuels to renewable energy without the need for further major technological innovations [6]. Therefore, at least in EU, rail represents a preferable mode of transport for achieving in the future a satisfactory balance in terms of environmental, economic and social impacts, as demonstrated by programs such as s2rail (http://shift2rail.org/). The construction of new and the improvement of the existing railway infrastructures is expected to continue its growing trend in the next years 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 [5,7]. This is in line with the EU objective that aims to achieve a sustainable growth exploiting modern, sustainable infrastructure. Sustainable growth means building a resource efficient, sustainable and competitive economy, through the development of new processes and technologies, including green technologies. In order to meet these targets and ensure the transition to a low-carbon economy, it is necessary to modernize infrastructures, especially railway, through the application of best practices, optimizing recycling chains and promoting an efficient infrastructure management. This will allow reducing costs of maintaining the existing surface transport infrastructure networks.

Ballasted track is the most common type of track superstructure supported on a layer of granular material (ballast) [8, 9] 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 [10-14]. Settlement occurs in different phases of lifecycle: 1) immediately after track construction, tamping or renewal, due to the consolidation of ballast; 2) in a second phase, during the exercise, with a slower settlement rate that generally can be approximated by a linear deterioration with the logarithm of the number of load cycles. This settlement is associated to a further reduction of volume due to ballast particles rearrangement and breakdown caused by fracture and abrasive wear of the individual stones; 3) a third phase with a quasi-exponential degradation that would mark the end of track life that occurs if the track does not undergo to a correct frequency of maintenance [13].

Due to the different mechanisms of settlement, periodic and costly minor and major maintenance operations are required to provide a granular layer with adequate characteristics.

Automatic tamping is the most used method worldwide to correct track geometry defects. The vibrating action induced by tamping machine allows re-arranging the particle positions, thus restoring the original position of the track. However, this operation causes certain detrimental effects: i) vibrating tines disturb and dilate the densely packed ballast layer, degrading particles and reducing track stability [13-15]; ii) track profile may quickly revert back to its original state, a phenomenon known as *ballast memory* [16]; iii) tamping produces high amount of fines (up to 4 kg of fines/sleeper/tamp) [17] increasing progressively the contamination (fouling) of the ballast layer. For this reason, tamping typically reduces its efficiency after every application [18] and may not produce a durable high quality level of track geometry.

In order to face the discussed drawbacks of the tamping diverse maintenance-based solutions, such as polyurethane-based ballast stabilisation, ballast bonding by resins, cement grouts, etc. have been developed in last decades with the aim of reducing maintenance frequency [19]~~.~~

In this context, given the need to develop innovative solutions to increase the durability and geometric quality of ballasted tracks while reducing costs associated with their maintenance, bitumen-stabilised ballast (BSB) has recently been proposed by [20-23] because of its easy and quick applicability and the relatively low cost of the bonding agent. This technology, designed to be used for new track-beds as well as to reinforce existing ones, consists of the use of bitumen emulsion (BE), which is poured or sprayed at ambient temperature onto the ballast. BSB has been developed through model-scale and full-scale laboratory tests simulative of field conditions, optimising the main factors affecting the stabilising process and BSB behaviour.

The bitumen stabilisation would be ideally applied during a routine maintenance operation to correct track geometry such as tamping or stoneblowing by a system analogous to that used by the stoneblower when the sleeper is raised during the maintenance process.

Further details of BSB maintainability over the whole service life are reported in [23].

The mechanical behaviour and the durability have been analysed in simulative laboratory tests [20-22], nevertheless the use of BSB needs to be supported by environmental and economical evaluation to highlight the potential benefits in terms of reduction of costs, natural resources employed in the construction and maintenance/rehabilitation and mitigation of negative impacts for the community.

To this purpose, the main goal of this work is to evaluate the economic feasibility and quantify the potential benefits arising from the use of BSB technology as construction and maintenance practice, encompassing the estimation of the costs of the environmental impacts. The results are compared with the costs arising from the application and use of traditional ballast.

This purpose is achieved using a lifecycle approach in which economic and environmental aspects are modelled and integrated [24].

A comparative attributional and process-based Life Cycle Cost Analysis (LCCA) study is performed according to the ISO 15686-5 2008 [25] integrating the contributions and the outcomes of Life Cycle Assessment (LCA) [26-27]. The proposed method calculates and compares the potential economic benefits associated with the construction and maintenance of traditional ballasted and BSB track-bed. The study includes also a sensitivity analysis to ascertain the effects on life cycle costs of possible variation of certain input parameters.

The integrated approach may represent a useful tool in decision-making process for implementing and optimizing track management system, taking into account long-term costs and environmental impacts.

2. Methodology

2.1 Principles of Life Cycle Cost Analysis

Life-Cycle Cost Analysis (LCCA) is an effective technique that enables to quantify the costs of alternative options for a given project. Life Cycle Cost Analysis is a systematic process that taking into account different impacts can offer a long-term evaluation of a project. The process requires the sum of the monetary equivalency of all advantages, disadvantages and costs at their respective time of occurrence throughout the period of analysis. Subsequently, they are converted into a common time domain so that different solutions may be compared on the same time scale [28]. A robust LCC framework will be able to link life cycle analysis studies to the monetary cost systems used by business decision-makers. To do so, discount rate is a fundamental parameter allowing to every cost to the reference time. This last parameter can be estimated as defined by ISO 15686-5 [25]. By referring to the interest rate used to determine the present value of future costs, the discount rate is generally determined as interest of the national bonds when the analysis is for public sector projects. Usually LCCA considers only the investments from one actor, i.e. agency, and thus focuses only on financial aspects (construction, maintenance/renewal, disposal costs) [29]. This type of approach is also called conventional LCC [30]. In certain cases, the user costs are included as well. A comprehensive LCCA extends the analysis to the external costs in addition to agency and user costs (environmental LCC) [30, 31]. Several definitions of external costs (or externalities or externality costs) can be find in literature: (a) costs that the transport user causes to a third party and for which he does not pay [32]; (b) undesirable side effects of production and consumption processes, borne by third parties [33]; (c) difference between the private and the social costs where social costs are defined as “all costs occurring due to the provision and use of transport infrastructure”, while private costs are defined as “costs directly borne by the transport user” [34].

European Transport White Paper [35] recommends to account for external costs in case of road and rail infrastructure design and projects. However, when external costs are considered many issues have to be addressed: the categorisation of the external costs, the monetary evaluation, the discounting. Regarding the categorisation, [32] consider four different categories: accidents, congestion, environmental costs and infrastructure costs. In the present work, only the environmental costs have been considered. For the monetary evaluation, two main approaches allow the conversion of environmental impacts into monetary costs [36, 37]. The first is the Damage-based approach, i.e. the monetary cost is assigned at the end of the life cycle impact assessment (LCIA) stage. This cost expresses the amount of wellness losses due to the impacts of a product or activity. The second is the Prevention-based approach (also known as Marginal Abatement Cost) [38]. In this latter case, the damage cost depends on the policy targets established by each government regarding each specific environmental problem. The approach used in this work is a prevention-based method named Eco-cost approach, that differs from the Marginal Abatement Cost because the goal is not based on policy targets, but rather established by “the earth’s estimated carrying capacity” [39].

The discounting of environmental costs is a very debated issue [40] because low discount rates could be used to give a relevant value to the consequences in the future but could compromise investments on project that might result environmentally damaging, on the contrary high discount reduces the costs of environmental degradation to later generations, and similarly to the previous case could reduce the attractiveness for long-term environmentally favourable projects.

2.2 Comprehensive and integrated lifecycle cost analysis

To evaluate economically the novel BSB technique a comprehensive lifecycle cost analysis (LCCA) has been framed and applied to two different alternatives: traditional ballast (TB) and bitumen stabilized ballast (BSB) (see Fig. 1).

LCCA accounts for three main cost categories:

- agency costs which refer to the construction, maintenance and renewal expenditures;
- user costs mainly related to the costs of delays in the railway service caused by maintenance and renewal activities on the ballast layer;
- externality costs associated to the impacts on the environment produced by activities and processes carried out during construction/maintenance/renewal, (i.e. transportation, quarrying, landfill use) [41].

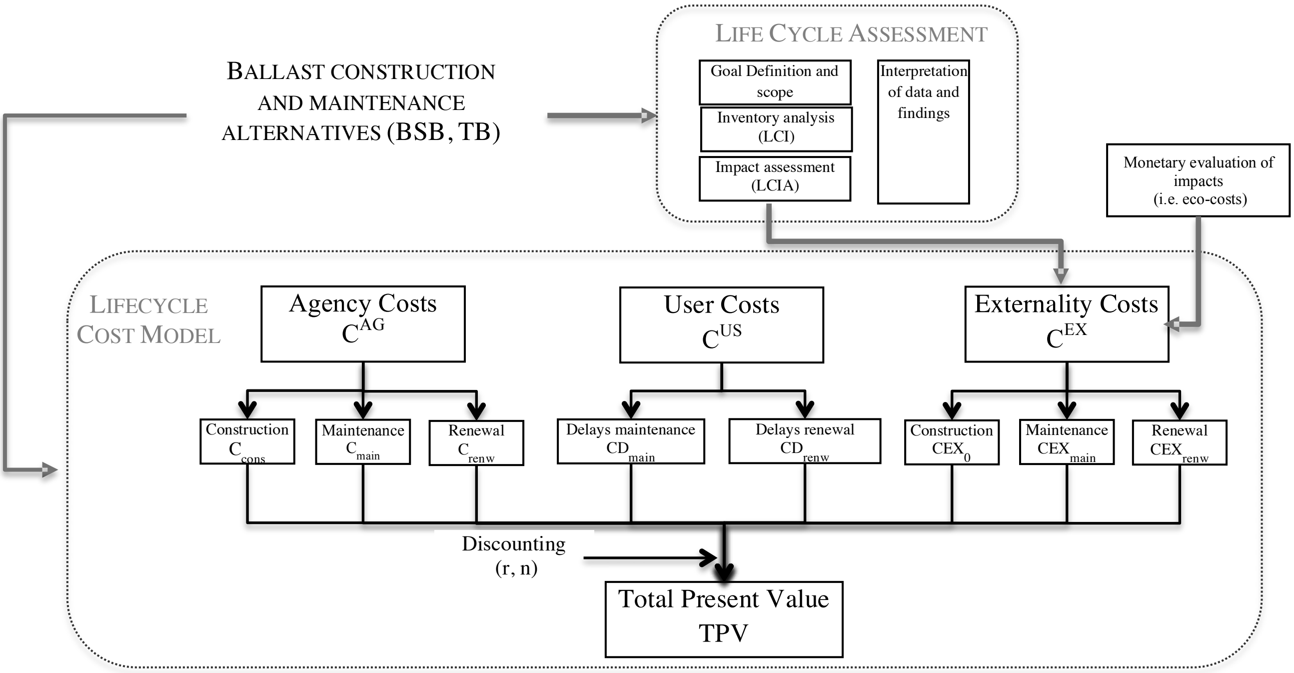

Fig. 1. Lifecycle Cost Modelling

For each ballast construction/maintenance alternative, the total cost (C^{TOT}) is defined as in Eq. (1):

$$C^{TOT} = C^{AG} + C^{US} + C^{EX} \quad (1)$$

where C^{AG}, C^{US}, C^{EX} are respectively the agency costs, the user costs and the externality costs.

The agency costs can be divided into: initial cost for ballast construction (C_{cons}) and running costs for maintenance (C_{main}) and renewal (C_{renw}) as expressed in Eq. (2):

$$C^{AG} = C_{cons} + C_{main} + C_{renw} \quad (2)$$

Costs of construction mainly depend on the expense for materials (supply, transportation, etc.) and construction processes; they can be estimated based on executed or on going railway projects.

Maintenance encompasses all the minor and major activities that aim to ensure the stability and serviceability of the track. Maintenance costs during lifecycle are affected by the traffic, typically expressed in Millions Gross Tonnes (MGT): the higher the traffic the lower the interval between two maintenance activities and consequently the higher the maintenance costs. Obviously, the maintenance approach adopted by the owner and established since the design stage affects the schedule of the activities (type and timing of the interventions) and the related costs [24, 42-44].

Renewal, in this work, is indented as the replacement of the old ballast layer with a new material. This activity is performed at End-of-Life of this track component and the related costs include the disposal and reconstruction costs.

The user costs are mainly related to the delays originated by restrictions (reduced speed, inoperativeness of railway components, etc.) due to the work zones. According to Lovett et al., [45] delays can be divided into two general categories: routine (experienced during normal operations, including crew changes, meets, passes, and civil speed restrictions) and irregular (maintenance, accidents, and short-term speed restrictions based on track conditions). As regards the ballast maintenance, it should be highlighted that most maintenance operations such as tamping are performed during non-operative time (maintenance night shifts) and therefore they can be considered as non-disruptive. However, as tamping operations become more and more demanding they could interfere with the normal operation of infrastructure, causing delays and trains cancellation.

The cost of train delay per hour varies based on a variety of factors divided into five main categories: crew, cars, lading, locomotives, and fuel and most of these costs vary with train composition [45]. There have been many attempts to determine the cost of delays for railroads, which resulted in values ranging from €. 200 to more than €. 900 [46-49]. Assuming an average train composition, then crew, car, lading, and locomotive, costs are approximately assumed equal to 900 €/train-hour. Based on the above, the following Eq. (3) applies:

$$C^{US} = CD_{main} + CD_{renw} = TD_{main} \cdot N_{train} \cdot C_{train} + TD_{renw} \cdot N_{train} \cdot C_{train} \tag{3}$$

where CD_{main} and CD_{renw} are the costs for delays caused by maintenance and renewal activities respectively, TD_{main} and TD_{renw} are the average length in hour of delays for maintenance and renewal, C_{train} the average cost of train-hour and N_{train} number of trains affected by delays. The number of trains in the present paper have been calculated based on the level of traffic (MGT) considered and taking into account the maximum load allowed in the railway lines (i.e. 1600 tonnes in Italy).

The externality costs refer to the sum of all costs of environmental impacts produced during the construction and the lifecycle of the ballast (CEX_{kj}). To each *j-th* impact produced by the *k-th* process (Q_{kj}), can be associated a unit cost (UP_{kj}). Having in mind the symbols already defined, the externality costs can be calculated as in Eq. (4):

$$C^{EX} = \sum_{k}\sum_{j} CEX_{kj} = \sum_{k}\sum_{j} Q_{kj} \cdot UP_{kj} \tag{4}$$

In the present paper the environmental burdens associated to the construction, maintenance, renewal activities have been estimated by using a process-based Life Cycle Assessment (LCA) study according to the ISO 14040 series [26-27]. This allowed comparing the potential environmental impacts associated with the construction and maintenance of TB and BSB track-bed [41]. The LCA methodology is described by four phases: (1) goal and scope definitions, (2) inventory analysis (LCI), (3) impact assessment (LCIA), and (4) interpretation of data and findings [50]. The previous LCA study was modelled in Gabi Professional Academy LCA software® [51]. The calculation of the values for each impact category was performed at midpoint level by applying the impact assessment method ReCiPe [52]. 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, water depletion, and primary energy demand. These categories have been evaluated for construction, tamping and renewal stages of the two competing solutions.

After having calculated the values obtained from LCA for each above-mentioned impact category the key step was to define the monetization of the externalities that can meet different interpretations and results [53, 54].

In this paper the monetary evaluation was performed using the eco-costs, which are measures to express the amount of environmental burden of a product considering as a basis the prevention of that burden. Eco-costs represent the expenditures to reduce the environmental pollution and materials depletion to a level which is in line with the carrying capacity of our earth. Eco-costs are virtual costs, hidden obligations, because they are not yet integrated in the real life costs of current production chains (Life Cycle Costs).

All the above-discussed costs (agency, user, externality) occur at different time as represented in Fig. 2 therefore discounting is needed to express future costs at today's equivalent by applying the discount (r) rate. Notwithstanding discounting is generally accepted, the amount of discount rate applied is often controversial. In business circles high discount rates are applied and consequently financial flows have a higher weight. In contrast, from a societal or environmental point of view, low discount rates are preferred to avoid the fact that current activities impose large costs on future generations [55].

Another important cost to be taken into account is the Salvage Value, defined as the net worth at the end of the LCCA period of analysis of a component of a system. It can be positive or negative. A negative residual value indicates that there is value associate with the asset. This concept aims to embody the notion that the asset is not completely worn out or retains some value for future use. For instance, a track-bed recently replaced could ensure service for more than 30 years so that if this operation is carried out right before the end of the period of analysis there will be the need to take into account the residual 'benefit' because, under steady-state assumptions, some subsequent uses would not need to start from scratch. For this reason, LCCA generally includes residual value as this is a tangible asset [56].

The salvage values of construction and maintenance operations, such as those considered in this study, with remaining service life can be calculated as a crude approximation, by linearly prorating their total initial costs [56], as in Eq. 5:

$$S = \frac{r\text{esidual service life}}{t\text{otal service life}} * initial \text{ total cost} \tag{5}$$

As for all the other costs, also this negative cost is discounted (at the last year of the period of analysis – 60t^{h} year).

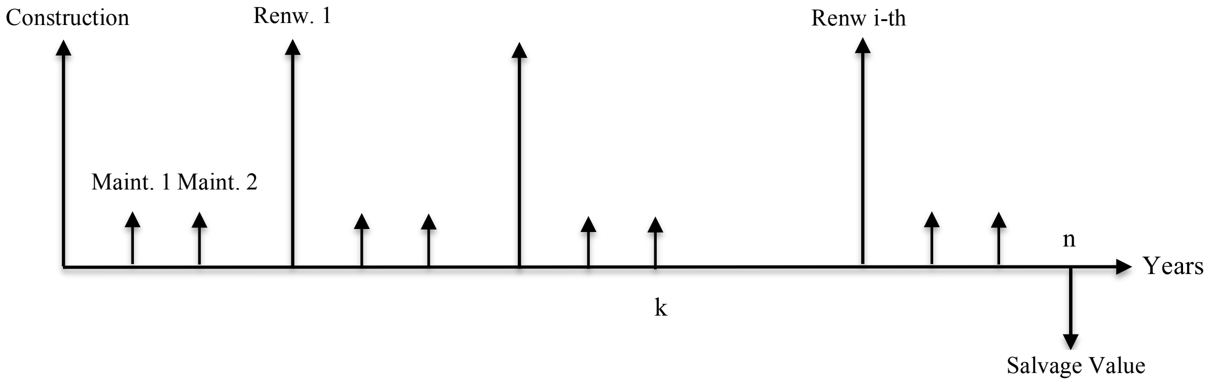

Fig. 2 Example of expenditure stream diagram

Taking into account all the above-mentioned factors, the total present value of each solution is calculated applying Eq. (6):

$$TPV = \sum_{k=1}^{n}\left(\frac{C_x}{(1+r)^k} - \frac{S}{(1+r)^n}\right) \tag{6}$$

where C_x are all the costs the lifecycle (agency, user, and externality), r is the discount rate, assumed constant, k *is* the year of occurrence of the expenditures, S is the salvage value, n is the period of analysis in years.

The difference of the TPV associated to the two alternatives at a certain time of the life span allows estimating the potential economic benefits of a solution when it is compared to another. Gain (G) can be defined as in Eq. (7).

$$G = TPV^{TB} - TPV^{BSB} \tag{7}$$

3. Case study

The railway track-bed case study was the doubling track line Florence-Viareggio in the Pistoia-Montecatini Terme section, in Italy. All costs of the case study presented are referred to a typical section of 1-km length, composed of a ballast layer having thickness of respectively 35 cm and 3.5 m, being equal for both solutions (i.e. traditional ballast and BSB). It should be noted that, to provide more general and usable results for other researchers, we have considered for the economic and environmental aspects the geometry of single track section.

The period of analysis was equal to 60 years. The traffic at the beginning of the service life was assumed to be equal to 20 MGT. This is the traffic volume expected for the medium term of the doubled line. The traffic growth rate was assumed to be 0.5% per year. These input data are consistent with the ones used in the LCA of the BSB construction/maintenance strategy [41].

Two scenarios were compared: the first one is a traditional ballast layer and tamping as main maintenance technique, the second one considers a ballast layer realized and maintained according to the novel bitumen stabilized technique.

The main characteristics of traditional and bitumen stabilized ballast are reported in Table 1.

Table 1. 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 (tonne/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				

Table 2 reports the values of the parameters used in the economic model based on calculations and literature sources, all the evaluation are referred to the present (year 2017). In the study-case it was assumed a complete dismantling of the BSB during the track-bed renewal and no recycling of material.

Table 2. Parameters and values used in the economic model.

Acronym	Parameter	Value	Source
C_{cons} (TB)/C_{renw}(TB)	Construction /Renewal cost TB [k€/km]	95.00	[57, 58]
C_{cons} (BSB)/ C_{renw}(BSB)	Construction/Renewal cost BSB [k€/km]	97.00	[57, 58]
C_{main} (TB)	Cost of tamping [k€/km]	7.20	[59]
C_{main}(BSB)	Cost of tamping +BSB [k€/km]	9.50	[60]
CD_{main}	Cost of delay [k€./train-hour]	0.9	[46, 47]
TD_{main} (TB)	Duration of tamping [hour/Km]	1.16	[61, 18]
TD_{main} (BSB)	Duration of tamping + BSB [hour/Km]	1.79	[59]
TD_{renew}	Duration of renewal [hour/Km]	13.33	[57]
n_e	Period of analysis [years]	60	
i	Discount rate [%]	4	[62]

The unit costs of environmental burdens are reported in Table 3.

Table 3. Monetary evaluation of environmental burdens

Environmental impacts	Unit	Monetary evaluation [euro]	References
Climate change	kg CO2-Equiv.	0.116	[63]
Terrestrial acidification	kg SO2 eq	8.83	[63]
Freshwater Eutrophication	kg P eq	4.17	[63]
Ozone depletion	kg CFC-11 eq	331.5	[64]
Fossil depletion	kg oil eq.	0.8	[63]
Freshwater ecotoxicity	kg 1,4-DB eq	55	[63]
Human toxicity	kg 1,4 DB eq	1.4	[65]
Marine ecotoxicity	kg 1,4-DB eq	55	[63]
Metal depletion	kg Fe eq	0.035	[63]
Particulate matter formation	kg PM10 eq	34	[63]
Terrestrial ecotoxicity	kg 1,4-DB eq	55	[63]
Water depletion	m^3	1.06	[63]
Marine Eutrophication	kg N-Equiv.	4.17	[63]

To estimate maintenance strategies (minor and major operations schedule) for both TB and BSB, the performance-based integrated model proposed by [23] was used. This model was based on laboratory results simulating the ballast layer behaviour under repeated traffic loading for both traditional ballast and BSB. A more detailed explanation of the methodology used to build the model from laboratory data can be found in [23]. The number and timing of maintenance interventions evaluated through this model is mainly dependent on the traffic level and the quality level set for the infrastructure, in particular the limits for (i) standard deviation (SD) of track irregularities (longitudinal level) and (ii) ballast contamination level.

The baseline scenario refers to a traffic level of 20 MGT (medium traffic railway line) [66] (Hensley and Rose, 2000); a traffic growth rate of 0.5%; a SD limit of 2 mm [67]; and a 30% limit for particles passing the 22.4 mm sieve [68].

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 for BSB and TB considering the baseline scenario parameters. In order to take into account the progressive loss of effective- ness of maintenance, an efficiency of 95% in restoring the geometry after tamping, compared to the previous intervention, was assumed. This parameter, which determines the progressive increase of the initial value of standard deviation (A) after each maintenance operation, was assumed constant in this model. Nevertheless, high level of ballast contamination may further reduce the effectiveness of maintenance Thus, future versions of the proposed model should consider also this variable [23]. As it is possible to observe from Fig. 3, the number of tamping operations over the period of analysis is considerable lower for BSB (6 applications) in relation to that of the traditional ballast (17 applications).

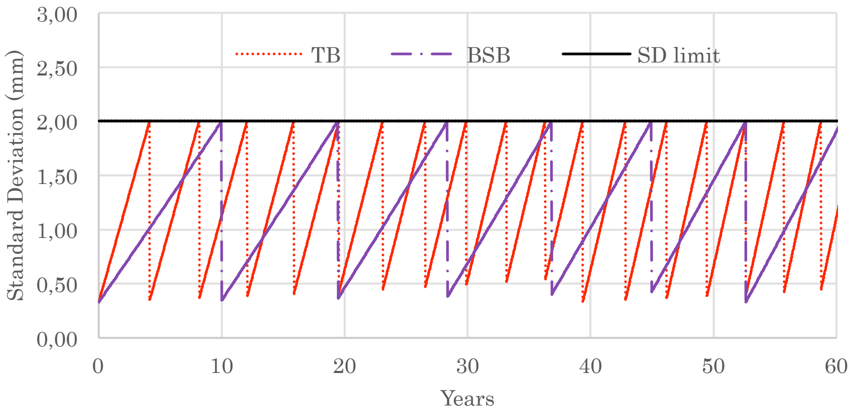

Fig. 3. Evolution of SD of track irregularities (20 MGT) for TB and BSB, considering an SD limit of 2 mm (after [23]).

Figure 4 shows the evolution of ballast contamination over the period of analysis as well as the timing of the renewal activities to be carried out for BSB and TB. As it is possible to see from Fig. 4, the ballast contamination rate for the BSB solution is lower than that for the TB solution. Although for the period of analysis 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. The economic advantage of the BSB solution, also in the considered period of analysis, can be highlighted accounting for the salvage value.

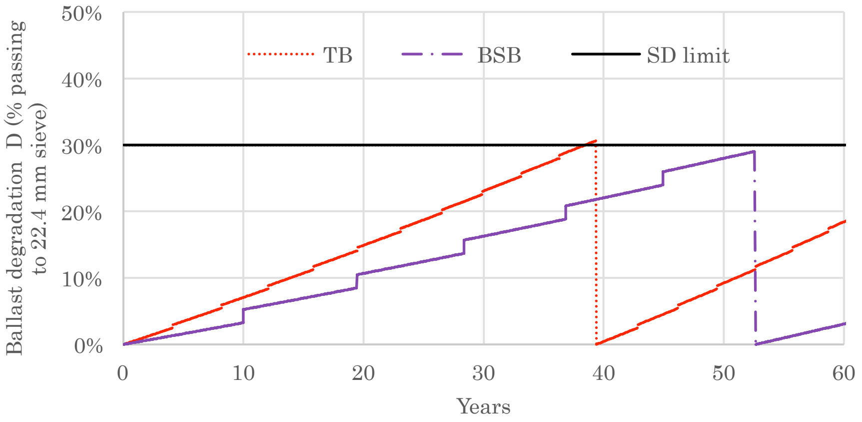

Fig. 4. Evolution of ballast contamination over the PAP as well as the timing of the renewal activities to be carried out for BSB and traditional ballast solutions, considering a 30% limit of particles passing the 22.4 mm sieve and a volume of traffic equal to 20 MGT.

4. Results and discussion

Results of lifecycle cost analysis are reported in Fig. 5 where the evolution of the costs in the period of analysis of 60 years for TB and BSB is represented. As regard the total cost, despite a little increase of the construction cost of BSB and a substantially breakeven until to 30 years from construction, in the long term (40-60 years) the BSB solution appears more convenient than the traditional ballast. This result is mainly due to the reduced frequency of the minor and major maintenances of BSB for its durability and higher resistance to settlement.

The evolution of the three components of the total cost (agency, user and externality) highlights how the agency cost of BSB, after an initial higher value, is always lower than TB agency cost for the period of analysis. This is obviously due to the reduced frequency of tamping and renewal needs. The difference between the agency costs of the two alternatives increases over time and at the end of the period of analysis the results show a saving for BSB of approximately 22%.

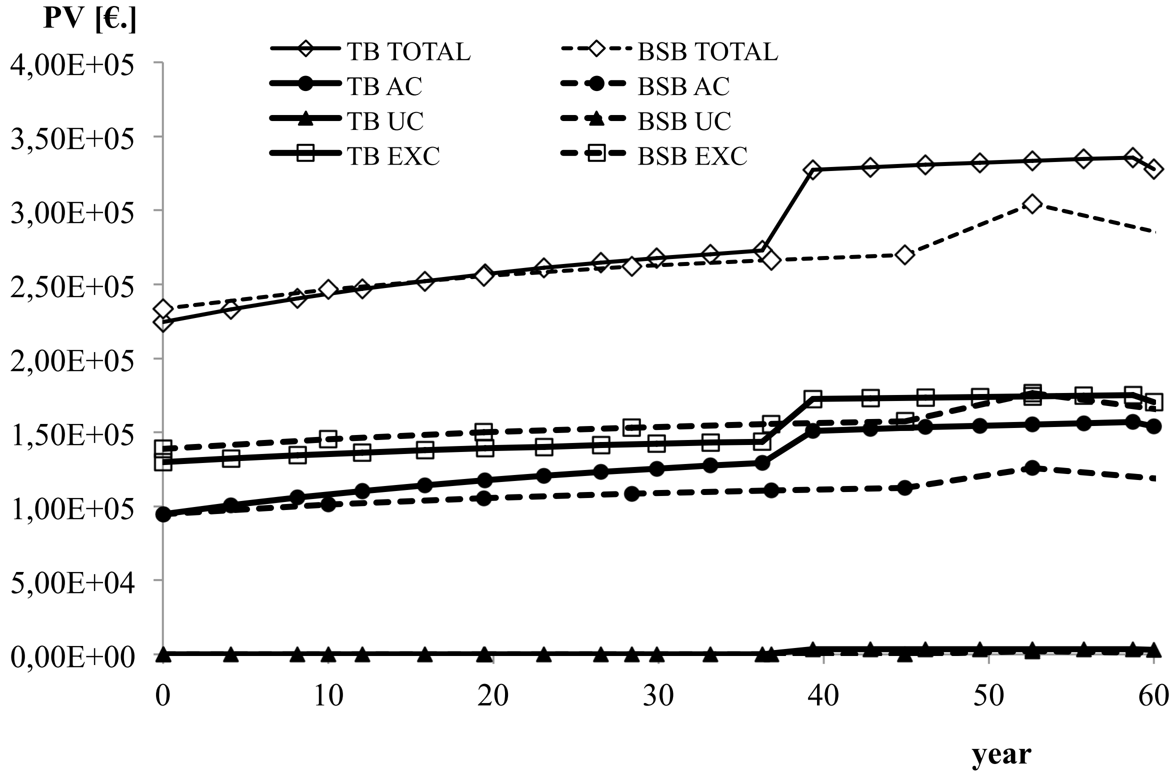

Fig. 5. Trend of costs in the period of analysis

It worthy to note that the greater durability and geometric stability of BSB positively affect the routine maintenance on the rails and sleepers. By considering the entire track the economic benefits of BSB are probably higher than the ones estimated in this paper.

The trend of the user cost is affected by the assumption that user cost for tamping can be considered null since this activity usually is performed during non-operative time of the railway track, conversely it assumes a significant role for the renewal. In the present case (20 MGT and SD 2.00 mm) the user cost for the two solutions is null until the first renewal activity of TB. Starting from this time, user cost of TB is higher than the one of BSB. It is worthy to note that the user costs are significantly lower than the agency costs.

The externality cost shows a value comparable to the one of the agency cost, but the trend is opposite. In the short and medium term, the externality cost of BSB is higher, albeit little, than the one of TB. A breakeven point can be observed at 37-th year (renewal), after the BSB externality cost is lower or equal.

In Table 3 the percentage of the contributions to the total externality cost of each impact category is reported for construction, renewal and maintenance phases.

Table 3 Contribution to the total externality of each impact category in all stages

Impact categories	Percentage of contribution to externality cost			
	Cons/Renw TB	Cons/Renw BSB	Tamping TB	Tamping BSB
Climate change	3.38%	3.30%	1.69%	2.23%
Fossil depletion	6.72%	7.70%	14.53%	23.71%
Freshwater ecotoxicity	0.39%	0.41%	0.47%	0.72%
Freshwater eutrophication	0.00%	0.00%	0.00%	0.00%
Human toxicity	1.02%	1.09%	1.54%	2.17%
Marine ecotoxicity	0.33%	0.38%	0.72%	1.15%
Marine eutrophication	0.03%	0.03%	0.02%	0.02%
Metal depletion	0.00%	0.00%	0.00%	0.00%
Ozone depletion	0.00%	0.00%	0.00%	0.00%
Particulate matter formation	0.71%	0.70%	0.40%	0.61%
Terrestrial acidification	0.51%	0.51%	0.37%	0.55%
Terrestrial ecotoxicity	0.02%	0.02%	0.02%	0.02%
Urban land occupation	0.00%	0.00%	0.00%	0.00%
Water depletion	78.66%	76.94%	67.08%	48.40%
Primary energy demand	8.21%	8.91%	13.16%	20.43%

From Table 3 it is possible to note that the major contributions are given by the following impact categories: climate change, fossil depletion, primary energy demand, and water depletion.

To understand how the use of BSB technique affects the cost of environmental impacts, the two solutions have been compared in terms of incidence on the total externality cost related to construction and tamping (renewal is neglected because considered similar to the construction stage), of the four main impact components (Fig. 6).

It is possible to observe that climate change and the sum of all the other impact categories, exhibit low variations for both BSB and TB and for the stages of construction and maintenance, while notable differences can be appreciated when fossil depletion and water depletion are considered and energy demand. For these impacts the use of bitumen emulsion play a crucial role especially in tamping phase. Indeed, the use of bitumen emulsion originates a high level of impact on certain categories such as fossil depletion, marine ecotoxicity, human toxicity and freshwater ecotoxicity [41]. In the case of fossil depletion this contribution is more evident because the values of this impact is higher than the other impacts.

During BSB construction, despite the use of bitumen, other resource, i.e. aggregates, and processes lead to an increase of water depletion, which is undoubtedly the main component of externality cost.

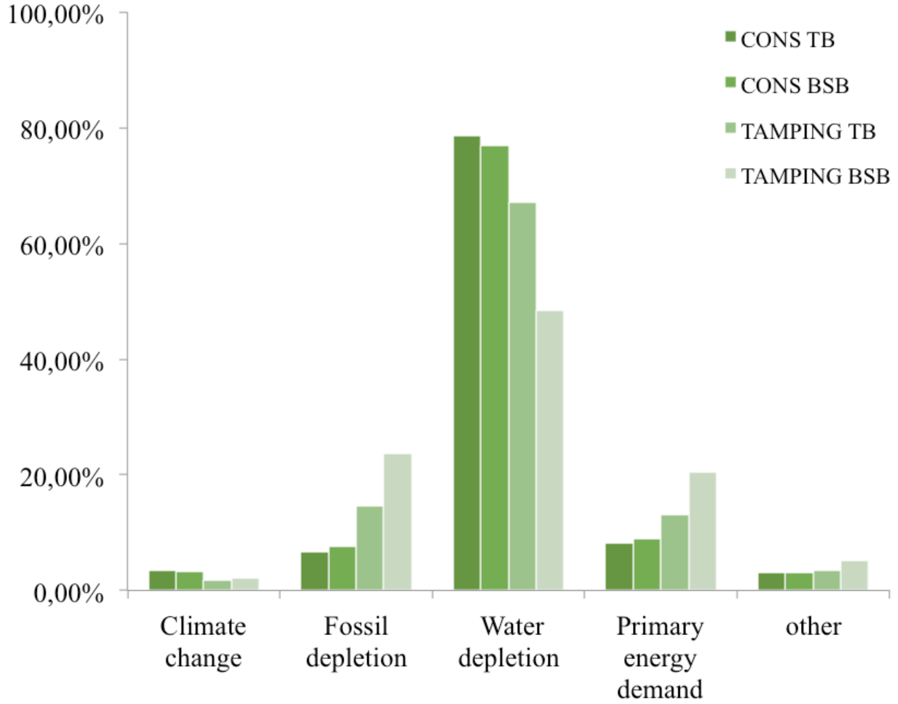

Fig. 6. Contribution of the main impact categories to the externality cost associated to construction and tamping of TB and BSB

3.1 Sensitivity analysis

In this section a sensitivity analysis is proposed to evaluate the effects on life cycle costs of possible variation of certain input parameters. This analysis consists in the iteration of regular and independent variations of each input variable (One-At-a-Time), keeping the other parameters constant [69]. Lifecycle cost have been evaluated varying the following input data:

- standard deviation (SD): the limit value for this parameter can be different depending on the countries. Varying SD means that the acceptable track quality level changes and thereby the timing for minor maintenance activities. The sensitivity analysis has been carried out by considering two alternative values for the SD limit of 2.0 mm, precisely 1.5 mm and 3.0 mm [67];
- traffic load: cost estimations have been performed in this work considering 20 MGT (medium traffic) as initial traffic volume. The sensitivity of LCC results have been assessed considering two additional values 10 MGT (low traffic) and 40 MGT (high traffic);
- discounting rate: TPV, calculated with reference to a constant discount rate of 4%, has been further evaluated considering also 2% and 6%. These discounting rates have been assumed constant in the period of analysis.

Results of sensitivity analysis are shown in Fig. 7. The percentage of gain (G/TPV^{TB}), referred to the total cost, for BSB and TB, is illustrated by varying the values of the parameters considered (SD, MGT or r). The sensitivity of the gain to the variation of one parameter is evaluated considering the other parameters in their respective baseline conditions.

The results displayed in Fig. 7 show that, regardless of the SD limit, traffic volume and discount rate considered, the adoption of a BSB layer always leads to the increase of the gain meaning that BSB is always more convenient than TB. For SD the benefits range between 10% and 13% for SD=1.5 mm and SD=2.0 mm respectively. For traffic volume and discount rate the range of benefits are wider. More precisely, for MGT the gain percentage ranges between 3% in case of low traffic and 19% in case of high traffic. This result was expected because traffic affects significantly the degradation of the track and the evolution of track irregularities. This evolution is faster for TB than for BSB and consequently also the maintenance activities are more frequent for TB compared to BSB. Therefore, the higher the level of traffic the higher the gain obtained with the BSB. An opposite trend can be observed for the discount rate: the lower the discounting rate, the higher the percentage of gain.

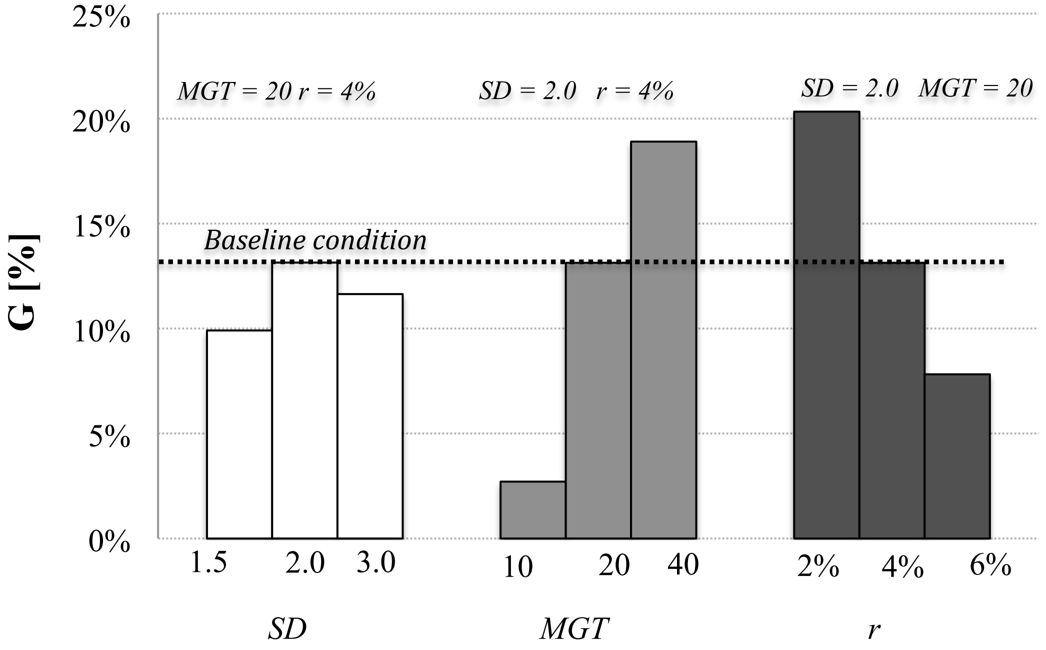

Fig. 7. Relative variation of the percentage of gain at the end of the period of analysis 60 years (G/TPVTB)% arising from the use of BSB instead of TB for the three alternative SD, MGT and r limits considered.

A discount rate of 2% produces a percentage of gain little higher than 20%, while a discounting rate of 6% leads to a lower gain percentage of 8%. This result can be explained considering that the lower the discount rate the higher the present value of the future cash flows. In case of TB the future cash flows are higher than BSB due to the need of more maintenance interventions and associated economic burdens. High discount rate (6%) leads to decrease the percentage of gain for the same considerations: the impact of future expenses in the present value is lower because their higher discounting, consequently the gain associated to the BSB can decrease until 8%.

5. Conclusions

In this paper, the results of an economic evaluation of bitumen stabilized ballast (BSB) layer were presented and compared with those related to a traditional ballast layer (TB).

For this purpose, a LCCA-based model integrated with the results of LCA analysis have been defined and applied to a case study.

Results of the analyses carried out considering a SD of 2.0 mm and a traffic level of 20 MGT highlight that: BSB technique, used since the construction stage and during the routine tamping, is substantially equal to the one of the traditional ballast in the short (20 years) ad medium term (40 years). The main advantage resulting from the use of BSB is related to long term analysis (between 40 and 60 years). This evolution of the total cost is the result of the two opposite contributions: the agency cost and externality cost. In fact, the agency costs are always lower for BSB, because of its higher resistance to settlement (SD limit is reached after) and durability (renewal is postponed because of the higher resistance of BSB to degradation). The difference of the agency present values of the two solutions increases when the period of analysis increases. On the contrary the externality cost is higher for the BSB in the short and medium term, while it is lower in the long term. This is due to the additional environmental burdens and related costs cause by the addition of the bitumen emulsion. Therefore, in the agency perspective the BSB technique appears sharply preferable if a standard LCC study is applied. The LCCA model proposed, accounting for the environmental costs, returns a comprehensive evaluation that resizes the economic benefit of BSB solution. However, this economic benefit depends also on the baseline conditions considered and particularly on SD, traffic volume and discount rate as highlighted by the sensitivity analysis. The level of traffic and the discounting rate affect notably the results. This last parameter is certainly the most critical in life cycle evaluation because of its uncertainty and difficult prediction.

Disclaimer

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement. Moreover, this paper does not constitute a standard, specification, or regulation.

References

[1] J.P. Baumgartner, Prices and costs in the railway sector, École Polytechnique fédérale de Lausanne. Laboratoire d'Intermodalité de Transports et de Planification. 2001

[2] O. Stalder, International benchmarking of track cost. (Tech. Rep). UIC (International Union of Railways). Paris, 2002.

[3] N. Jimenez-Redondo, N. Bosso, L. Zeni, A.Minardo, F. Schubert, F. Heinicke, F., A. Simroth, Automated and cost effective maintenance for railway (acem-rail), Transport Research Arena 48 (2012): 1058–1067. doi: 10.1016/j.sbspro. 2012.06.1082.

[4] Europe 2020 – A European strategy for smart, sustainable and inclusive growth" COM(2010) 2020 of 3 March 2010.

[5] EC, EU Reference Scenario 2016: Energy, transport and GHG emissions - Trends to 2050, Publications Office of the European Union, Luxembourg, 2016.

[6] UIC- International Union of railways 2015. Rail Transport and Environment Facts and Figures.

[7] J. Åkerman, The role of high-speed rail in mitigating climate change – The Swedish case Europabanan from a life cycle perspective, Transportation Research Part D: Transport and Environment, Vol. 16, Issue 3, (2011) Pages 208–217.

[8] G. Michas, Slab Track Systems for High-Speed Railways. Master Degree Project. Division of Highway and Railway Engineering Department of Transport Science. School of Architecture and the Built Environment, Royal Institute of Technology, SE-100 44 Stockholm, Sweden, 2012.

[9] UIC, 2016. http://www.uic.org (accessed 17.08.09).

[10] W. Salim, Deformation and degradation aspects of ballast and constitutive modelling under cyclic loading. University of Wollongong, 2004.

[11] T. Dahlberg, Railway track settlements - a literature review. Report for the EU project SUPERTRACK, Linkoping University, Sweden, 2004.

[12] D. Read, D. Li, Research Results Digest 79. Transit Cooperative Research Program, Sponsored by the Federal Transit Administration. Washington, D.C. 2006.

[13] H. Guler, S. Jovanovic, G. Evren, Modelling railway track geometry degradation, Proc. Inst. Civil Eng. Transport 164 (2011) 65-75.

[14] J.C.O. Nielsen, X. Li, Railway track geometry degradation due to differential settlement of ballast/subgrade e Numerical prediction by an iterative procedure Journal of Sound and Vibration 412 (2018), 441-456.

[15] B. Indraratna, W. Salim, C. Rujikiatkamjorn, Advanced Rail Geotechnology - Ballasted Track. CRC Press, Taylor and Francis Group, 2011.

[16] E. T.Selig, J.M. Waters, Track Geotechnology and Substructure Management. T. Telford, 1994.

[17] P. Fair, The geotechnical behaviour of ballast materials for railway track maintenance, University of Sheffield, 2003

[18] J. Pires, Integrated maintenance model for heavy haul tracks, Lausanne, EPFL , 2016. Doi 10.5075/epfl-thesis-6914.

[19] M. Sol-Sánchez, G. D'Angelo Review of the design and maintenance technologies used to decelerate the deterioration of ballasted railway tracks. Construction and Building Materials 157 (2017), 402–415.

[20] G. D'Angelo, N. Thom, D. Lo Presti, Bitumen stabilized ballast: A potential solution for railway track-bed. Constr. Build. Mater., 124 (2016), 118-126.

[21] G. D'Angelo, M. Sol-Sánchez, F. Moreno-Navarro, D. Lo Presti, N. Thom, Use of bitumen stabilised ballast for improving railway track-bed conventional maintenance. Geotech. 2017 https://doi.org/10.1680/jgeot.17.P.022.

[22] G. D'Angelo, N. Thom, D. Lo Presti, Optimisation of bitumen emulsion properties for ballast stabilisation. Mater. Constr., 67 (2017), 1-10.

[23] G. D'Angelo, S. Bressi, M. Giunta, N. Thom, D. Lo Presti, Novel performance-based technique for predicting maintenance strategy of bitumen stabilised ballast. Construction and Building materials, 161 (2018), 1–8.

[24] F.G. Praticò, M. Giunta, Proposal of a Key Performance Indicator (KPI) of railway track based on LCC and RAMS analyses. J. Constr. Eng. Manage., 144(2) (2018): 04017104-1- 04017104-10.

[25] International Standard Organization (ISO), ISO 15686-5 2008. Buildings and Constructed Assets – Service-Life Planning – Part 5: Life-Cycle Costing. International Organization for standardization, Geneva (Switzerland), 2008.

[26] International Standard Organization (ISO), ISO 14040: 2006. International Standard ISO 14040: Environmental Management - Life Cycle Assessment: Principles and Framework, October. Geneva (Switzerland), 2006.

[27] International Standard Organization (ISO), ISO 14044:2006. International Standard ISO 14044: Environmental Management - Life Cycle Assessment: Requirements and Guidelines, October. Geneva (Switzerland), 2006.

[28] FHWA-NJ-2003-012 submitted by K. Ozbay, N. Parker, D. Jawad, S. Hussain, Guidelines for Life Cycle Cost Analysis. Final report, 2003.

[29] B. Ness, E. Urbel-Piirsalu, S. Anderberg, L. Olsson, Categorising tools for sustainability assessment. Ecological Economics 60 (2007): 498-508.

[30] D. Hunkeler, K. Lichtenvort, G. Rebitzer, Environmental life cycle costing. SETAC, Pensacola, FL (US) in collaboration with CRC Press, Boca Raton, FL, USA, eds. 2008.

[31] K. De Langhe, The importance of external costs for assessing the potential of trams and trains for urban freight distribution. Research in Transportation Business & Management 24 (2017), 114-122.

[32] G. Blauwens, P. De Baere, E. Van de Voorde, Transport economics (6th ed.) Antwerp: De Boeck, 2016.

[33] A. Verbruggen, Economische benadering van milieu en milieubehoud. Antwerpen: Garant, 2008.

[34] A. Korzhenevych, N. Dehnen, J. Bröcker, M. Holtkamp, H. Meier, G. Gibson, V. Cox, Update of the handbook on external costs of transport (final report for the European Commission: DG Move). DIW, CAU, Ricardo-AEA139, 2014.

[35] European Commission, European Transport White Paper, 2011.

[36] M.S.S. de Bruyn, M. Korteland, A. Markowska, M. Davidson, F. de Jong, M. Bles, , Shadow Prices Handbook—Valuation and Weighting of Emissions and Environmental Impacts, CE Delft, Delft, the Netherlands, 2010.

[37] K. Allacker, L. De Nocker , An approach for calculating the environmental external costs of the Belgian building sector, J. Ind. Ecol. 16 (2012), 710–721, http://dx.doi.org/10.1111/j.1530-9290.2011.00456.x.

[38] T. Oka, M. Ishikawa, Y. Fujii, G. Huppes, Calculating cost-effectiveness for activities with multiple environmental effects using the maximum abatement cost method, J. Ind. Ecol. 9 (2005) 97–103, http://dx.doi.org/10.1162/108819805775248007.

[39] J.G. Vogtländer, A. Bijma, H.C. Brezet, Communicating the eco-efficiency of products and services by means of the eco-costs/value model, J. Clean. Prod. 10 (2002) 57–67, http://dx.doi.org/10.1016/S0959-6526(01) 00013-0.

[40] S. Hellweg, T.B. Hofstetter, K. HungerbühlerDiscounting and the Environment Should Current Impacts be Weighted Differently than Impacts Harming Future Generations? Int J LCA 8 (1) (2003) 8 – 18.

[41] S. Bressi S., G. D'Angelo, J. Santos, M. Giunta, Life cycle assessment of bitumen stabilized ballast: a new maintenance strategy for railway ballast. Submitted to Structure & Infrastructure Engineering, unpublished results 2018.

[42] M. Giunta, Assessment of the sustainability of traditional and innovative rail track system, in Proceedings of International Conference on Traffic and Transport Engineering, 24-25 November, Belgrade, Serbia, 2016.

[43] F.G. Praticò, M. Giunta, Assessing the sustainability of design and maintenance strategies for rail track by means life cycle cost analysis, in Proceedings of COMPRAIL 2016 15th International Conference on Railway Engineering design and operation, July 19-21Madrid, Spain, 2016.

[44] F.G. Praticò, M. Giunta, Issues and perspectives in railway management from a sustainability standpoint, in Proceedings of International Conference on Transportation Infrastructure and Materials, July 16-18, Xian, China, 2016.

[45] A.H. Lovett, C.T. Dick, C.J. Ruppert, Jr., C.P.L. Barkan, Cost and delay of railroad timber and concrete crosstie maintenance and replacement. Transportation Research Record: Journal of the Transportation Research Board Vol. 2476 (2015), 37–44.

[46] D.H.Schafer, C.P.L Barkan, A Prediction Model for Broken Rails and an Analysis of their Economic Impact. Proceedings of the American Railway Engineering and Maintenance-of-Way Association Annual Conference. Salt Lake City, UT, 2008.

[47] M.H. Dingler, Y.C. Lai, C.P.L. Barkan, Economics of Expanding Capacity on a Single Track Heavy Haul Railway Line. Proceedings of 11th International Heavy Haul Railway Conference, Calgary, Canada, 2011.

[48] B.W. Schlake, C.P.L. Barkan, J.R. Edwards, Train delay and economic impact of in-service failures of railroad rolling stock. Transportation Research Record: Journal of the Transportation Research Board, 2261 (2011), pp.124–133.

[49] Y.-C.Lai, C.P.L. Barkan, Enhanced Parametric Railway Capacity Evaluation Tool. Transportation Research Record: Journal of the Transportation Research Board, 2117(1) (2009), 33–40.

[50] L.A.Curran, Life cycle assessment: Principles and practise. National Risk Management Research Laboratory – Office of Research and Development. U.S. Environmental Protection Agency. Cincinnati, 2006

[51] GaBi ts Software 7.3.3 & Databases 2017 Edition. Manual.

[52] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, R. van Zelm, ReCiPe 2008- a life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level, Ministerie van VROM, Den Haag, 2013.

[53] M. Pizzol, B.Weidema, M. Brandao, P. Osset, Monetary valuation in Life Cycle Assessment: a review. Journal of Cleaner Production 86 (2015), 170-179.

[54] J.H. Miah, S.C.L. Koh, D. Stone, A hybridised framework combining integrated methods for environmental Life Cycle Assessment and Life Cycle Costing. Journal of Cleaner Production 168 (2017), 846-866.

[55] R. Hoogmartens, S. Van Passel, K. Van Acker, M. Dubois, Bridging the gap between LCA, LCC and CBA as sustainability assessment tools, Environmental Impact Assessment Review 48 (2014) 27–33.

[56] D.B. Lee, Fundamentals of Life-Cycle Cost Analysis, Transportation Research Record: Journal of the Transportation Research Board, 2 (2002), pp. 203–210.

[57] M. Shimatake, A track maintenance model for high-speed rail: a system dynamic approach. Massachusetts Institute of Technology, USA, 1997.

[58] SMARTRAIL, 2014. Optimized Whole Life Management of Rail Infrastructure Elements. Available at: http://smartrail.fehrl.org/?m=1.

[59] P. McMichael, A. McNaughton, The Stoneblower-Delivering the Promise: Development, Testing and Operation of a New Track Maintenance System, in Transportation Research Board annual meeting CD-ROM. Washington, D.C, 2003.

[60] E. Moreno-Martinez, Survey, 2016.

[61] C. Calla, Two Layered Ballast System for Improved Performance of Railway Track. Coventry University, 2003.

[62] J.Y. Lee, B.R. Ellingwood, Ethical discounting for civil infrastructure decisions extending over multiple generations, Structural Safety 57 (2015), 43–52.

[63] http://www.ecocostsvalue.com

[64] B. Steen, R. Carlson, F. Lyrstedt, G. Skantze, Sustainability Management of Businesses through Eco-efficiency – An Example. CPM – Center for Environmental Assessment of Product and Material Systems, Goteborg, Sweden, 2009. http://www.cpm.chalmers.se/document/reports/09/2009_3%20SD%20management%20through%20EE.pdf>.

[65] B., Desaigues, D. Ami, A. Bartczak, M. Braun-Kohlov, S. Chilton, M. Czajkowski, V. Farreras, A. Hunt, M. Hutchison, C. Jeanrenaud, P.M. Kaderjak, P., V. Maca, O. Markiewicz, A. Markowska, H. Metcalf, S. Navrud, J.S. Nielsen, R. Ortiz, S. Pellegrini, A. Rabl, R. Riera, M. Scasny, M.E. Stoeckel, R. Szanto, J. Urban, Economic valuation of air pollution mortality: a 9-country contingent valuation survey of value of a life year (VOLY). Ecol. Indic. 11(2011), 902-910.

[66] M. Hensley, J.G. Rose, Design, construction and performance of hot mix asphalt for railway trackbeds, 1st World Conference of Asphalt Pavements, Sidney, Australia, 2000.

[67] BS EN 13848-5:2008+A1:2010, Railway Applications – Track – Track Geometry Quality – Part 5: Geometric Quality Levels – Plain Line, 2010.

[68] A. Nurmikolu, Degradation and frost susceptibility of crushed rock aggregates used in structural layers of railway track degradation and frost susceptibility of crushed rock aggregates used in structural layers of railway track. PhD Thesis, Tampere University Technology, Finland, 2005.

[69] A. Saltelli, Sensitivity Analysis for Importance Assessment. Risk Analysis. 22 (3) (2002): 1–12.