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Potential for improving the environmental performance of railway sleepers with an outer shell made of recycled materials

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ABSTRACT

An innovative sleeper with a pre-stressed reinforced concrete inner structure wrapped by an outer shell manufactured with end-of-life tires powder and recycled plastics has been recently designed by the Greenrail company. The external protection is aimed at increasing its lifetime and reducing the maintenance requirements of the railway lines. This study evaluates the environmental performances of this sleeper, under different operational conditions, in comparison with traditional pre-stressed reinforced concrete sleepers, using the Life Cycle Assessment methodology.

The assessment includes 16 environmental, energy, and human health impact categories. It is performed considering the following functional unit: *1 railway sleeper, including the fastenings of the rail to the sleeper and the portion of the track bed underneath it, over one year of operation.* The evaluated system includes the sleeper production, its installation, the railway maintenance, the sleeper removal at its end-of-life and the final recovery. Moreover, the ballast is included in the analysis considering its mining and transportation to the railway line, the partial replacement during maintenance operations, the removal during a track renewal, and the end-of-life management.

For the worst operational conditions of the Greenrail sleeper, the potential impacts between the two sleeper typologies differ by < 10% for most of the examined categories, meaning that no significant environmental differences are observed. In the average conditions, impact reductions for the Greenrail sleepers result bigger than 10% for 7 out of 16 categories. Finally, for the best conditions, benefits are in the range 20% - 30% for 11 impact categories.

1. Introduction

One of the main components of a railway track structure is the sleeper. Among the conventional materials, pre-stressed concrete has become widely and successfully accepted for railway sleepers, especially in high speed lines (Manalo et al., 2010). At the moment, this sleeper typology is popular and widely used in North America, Europe, Asia, and Australia (Taherinezhad et al., 2013).

The relevant costs of maintenance and the environmental problems of conventional sleepers have motivated to consider alternatives made of composite materials (Ferdous et al., 2015). Despite their global market is rapidly increasing, they show a limited acceptance by the railway industry, due to several obstacles to their widespread application. For example, recycled plastic sleepers can show low strength and stiffness, low anchorage capability of holding screws, formation of voids in the body of the sleeper, permanent deformation due to creep and temperature variations, and insufficient lateral resistance. Moreover, the relevant cost of high fiber containing sleepers restricts their applications in rail track (Ferdous et al., 2015).

Alternatively, traditional sleepers can be reinforced with wraps that can guarantee the protection from degradation by improving the structural performances and the effectiveness in its interaction with the other components of the track superstructure. An example is represented by a polyurethane-base elastomeric element placed under the sleeper (under sleeper pad - USP); it is a solution that improves the characteristics of pre-stressed concrete sleepers in providing stability to the track geometry, allows to decrease ballast deterioration, and extends the tamping intervals with potential economic and environmental benefits (IRS, 2018; Ortega et al., 2018a; Gräbe et al., 2016). In recent years, sleeper with USPs were widely employed in countries such as Austria, Czech Republic, and Germany. Moreover, in counties such as Australia, China, and Sweden, pilot tests were performed (Kaewunruena et al., 2017).

Starting from the experience of sleepers equipped with USPs, in the last few years, an innovative sleeper in which an inner core of pre-stressed reinforced concrete is wrapped by an outer shell made of a mixture of end-of-life tires (ELTs) powder and recycled plastics was developed. From an environmental perspective, the outer shell is designed to decrease the ballast

Abbreviations: CDW, construction and demolition waste; CFF, circular footprint formula; ELTs, end-of-life tires; EWC, European waste catalogue; HDPE, high density polyethylene; LCA, life cycle assessment; LHW, lower heating value; PE, polyethylene; PEF, product environmental footprint; PEFCRs, Product Environmental Footprint Category Rules; PET, polyethylene terephthalate; PP, polypropylene; USP, under sleepers pad; SRF, solid recovered fuel.

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consumption with the consequent reduction of the maintenance operation required on the railway line (including the minor need of new ballast infill), the reduction of particulate release in the air, and the limitation of the acoustic impact deriving from the train transit. In addition, the outer shell protects the inner core from ballast friction, as well as from weathering. Therefore, the lifespan of Greenrail sleepers is expected to be longer compared to that of traditional pre-stressed reinforced concrete sleepers.

These aspects allow for environmental benefits that can be assessed by means of a life cycle thinking perspective. To the authors' knowledge, a limited number of studies applied this approach on railway sleepers. In Bolin and Smith (2013) a Life Cycle Assessment (LCA) of wooden sleeper is carried out, including a comparison with concrete and plastic composite sleepers for the United States context. A comparison of concrete, steel, and wooden sleeper was performed by Werner (2008) focusing on the German railways. Finally, in Crawford (2009) the life cycle greenhouse gases emissions associated with timber and reinforced concrete sleepers are investigated for the Australian railways. Moreover, results vary among the studies: according to Bolin and Smith (2013) and Werner (2008), the wooden sleepers cause generally the lowest environmental impacts; on the contrary, in Crawford (2009), a significant advantage in using reinforced concrete sleepers is shown. Focusing on wrapped sleepers, a life cycle perspective was applied in Ortega et al. (2018b) with a carbon footprint performed in order to evaluate the effects of installing USPs. The results show that the use of USPs could allow for a CO_2 emissions reduction but the benefits from the minor requirement of maintenance can be lower to the additional impacts related to the use of the USP when it is manufactured with non-recycled rubber (Ortega et al., 2018b).

Building up on previous findings, the present study aimed to evaluate the environmental sustainability and the performances of the Greenrail sleepers, by means of the LCA methodology, in order to understand their potential benefits compared to traditional sleepers.

2. Materials and methods

The assessment was conducted in the framework of the rules reported in the Recommendation of the European Commission of 9 April 2013 - Product Environmental Footprint (PEF) Guide (EC - European Commission, 2013) on the use of common methods to measure and communicate the life cycle environmental performance of products, which represents the most up-to-date guidelines to measure the environmental performance of a good throughout its life cycle.

The goals of the performed LCA, the functional unit, the analyzed systems, and the considered characterization methods are described in Sections 2.1 to 2.4. Then, aspects subjected to sensitivity analysis are discussed in Section 2.5. Finally, the life cycle inventory is detailed in Section 2.6.

2.1. Goals definition

First of all, the present study evaluates the environmental performances of the Greenrail sleepers under different operational conditions. In detail, the analysis focuses on the *GR 260 WHS* sleeper, 260 cm long and designed for high speed lines with a top speed of over 250 km/h. In addition, a comparison with a traditional pre-stressed reinforced concrete sleeper suitable for high speed lines (*RFI 260* typology) is performed.

2.2. Functional unit

In the assessment, the following functional unit was defined: *1 railway sleeper, including the fastenings of the rail to the sleeper and the portion of the track bed underneath it, over one year of operation.*[1] The fastenings, preassembled on the sleeper during its production, were included in the analysis because their lifespan is connected to the lifespan of the sleeper. On the contrary, the rails were excluded as their substitution can be independent from that of sleepers (the life time of rails is generally lower than that of the sleepers). Moreover, a portion of track bed (only the ballast was considered) was included in the analysis because sleepers heavily affect the ballast consumption: different typologies of sleepers require different maintenance frequency of the railway line, which can include the ballast tamping and substitution.

2.3. Analyzed systems and scenarios

A cradle-to-grave analysis was performed. For both sleeper typologies, the analyzed system included the life cycle of all the sleeper components and the parts of the railway track whose performances and lifespan are directly related to the sleeper.

In detail, the *GR 260 WHS* sleeper system is characterized by the following life-cycle stages:

- manufacturing - it comprises the sleeper production including all its components and the fastenings of the rail to the sleeper;
- use - it comprises the sleeper transportation, its installation on the railway line, and the railway line maintenance (including ballast mining, transportation, and use);
- end-of-life - it comprises the sleeper and the ballast management at the end of their useful life.

The sleeper system based on the reference *RFI 260* is similar, with the exclusion of the outer shell production and its subsequent management at the end of the sleeper lifetime.

Fig. 1 shows the schematic representation of the system boundary using a flow diagram. In addition, the life cycle of machinery and consumables was considered. In the analysis, the Italian context was considered for the production, the use and the end-of-life of the sleeper. Accordingly, Italian data were considered for aspects such as the electricity production, the railway lines characteristics, and the plants location.

The real performances of the *GR 260 WHS* sleeper will allow verifying the potential benefits that could be achieved thanks to the role of the outer shell. They are related to the following aspects:

- the sleeper lifetime (the outer shell is supposed to extend the lifetime of the sleeper thanks to the protection of the concrete inner core from ballast frictions and from atmospheric agents);
- the tamping interval (the outer shell has an important influence on the interaction sleeper - ballast thanks to the mechanical and structural properties of the plastic-rubber composite material; these aspects are under investigation with laboratory and in-line tests);
- the interval between two ballast cleanings with complete ballast substitution;
- the frequency of intermediate ballast cleaning with ballast reintegration.

For the traditional pre-stressed reinforced concrete *RFI 260* sleeper system, the values of parameters assumed for these aspects are reported in Table 1. Their rationale is described in detail in Section 2.6. The effects of the potential benefits of the *GR 260 WHS* sleeper on these aspects were evaluated by means of three scenarios, described in Table 1, defined in the attempt to cover a wide range of performances during the use stage. A minimum improvement was assumed for the Worst scenario considering a lifetime similar to that of traditional pre-stressed reinforced concrete sleepers and benefits on maintenance similar to those achievable with concrete sleepers with USPs (see Sections 2.6.9 and 2.6.10). More improvements were considered in the Baseline and the Best scenarios.

The real performances will be better defined with tests and with the sleeper application on railway lines, though the first experimental vibration tests, performed on an Italian line and concerning the comparison between Greenrail and traditional sleepers, showed significant vibration reductions after the installation of the Greenrail sleepers

[1] Life cycle impacts are scaled to be consistent with the reference time considered (one year).

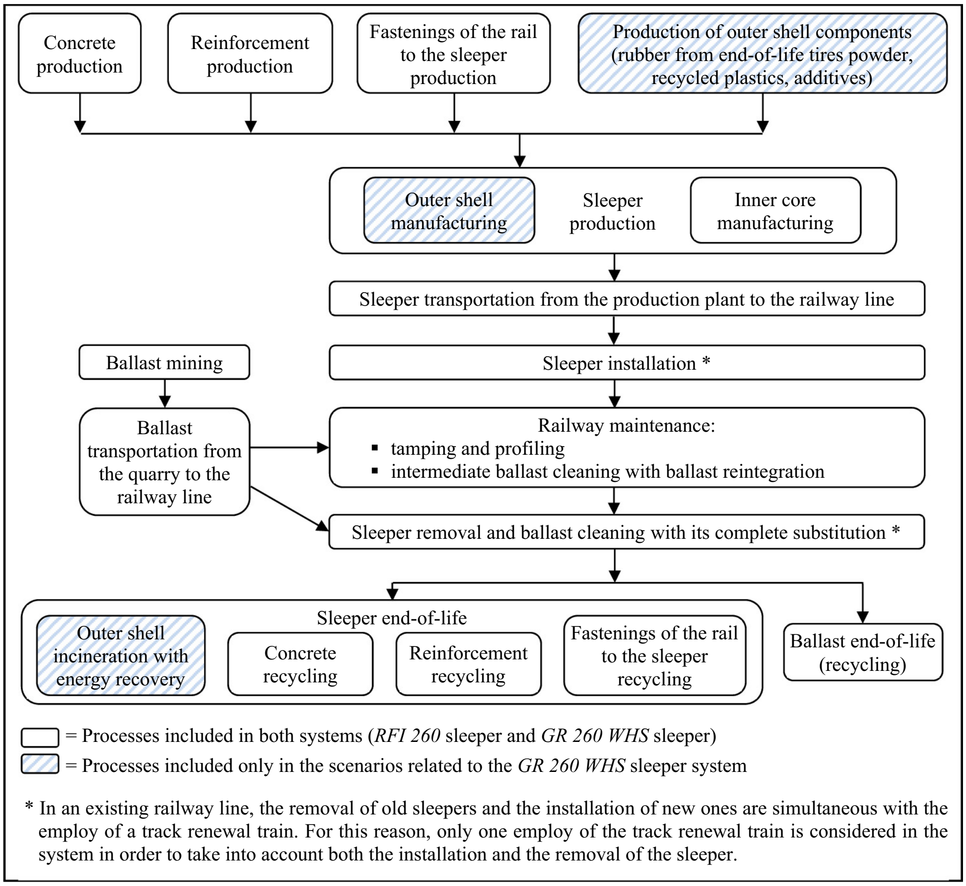

Fig. 1. Boundary of the analyzed systems.

(iPOOL, 2018) in the range of frequencies associated to the sleeper-ballast resonance (Kouroussis et al., 2015):

- 24.5% (1–100 hertz) and 26.1% (1–1000 Hz) 7.5 m far from the railway line;
- 41.5% (1–100 hertz) and 38.7% (1–1000 Hz) 15 m far from the railway line.

The scenario without any improvement compared to the traditional pre-stressed reinforced concrete sleeper, improbable based on the first experimental tests, was not analyzed. It would simply lead to higher environmental impacts (the impacts for the outer shell production and management at the end-of-life added to the impacts of the traditional concrete sleeper).

2.4. Impact categories and characterization methods

According to the PEF Guide (EC - European Commission, 2013), 15 environmental and human health impact categories, evaluated at the mid-point level, shall be considered for PEF studies: climate change; ozone depletion; human toxicity (cancer and non-cancer effects); particulate matter/respiratory inorganics; ionizing radiation (human health effects); photochemical ozone formation; acidification; terrestrial, fresh water, and marine eutrophication; ecotoxicity for aquatic fresh water; land transformation/occupation; water resource depletion; mineral and fossil resource depletion.

For each of the considered impact categories, the PEF Guide (EC - European Commission, 2013) also indicates the impact category indicator and the assessment model (reported in Table S1 of the Supplementary Material).

In addition to the default 15 impact categories, the characterization method Cumulative Energy Demand was considered to assess the energy performance of the system. This method, calculated as described in Hischier et al. (2010), focuses on the consumption of energy resources including both direct and indirect uses (e.g. due to the use of construction materials or raw materials).

The optional steps of normalization and weighting were not performed in this assessment.

2.5. Sensitivity analysis

According to the PEF Guide (EC - European Commission, 2013), the equation described in the Annex V of this document, commonly known as

Table 1
Scenarios evaluated for the *GR 260 WHS* sleeper and the *RFI 260* sleeper systems, with the corresponding parameters.

Parameter	*GR 260 WHS* sleeper system scenario			*RFI 260* sleeper system
	Worst	Baseline	Best	
Sleeper lifetime (years)	30	40	50	30
Tamping interval (years)	4	5	6	2
Interval between two ballast cleaning with its complete substitution (CS) (years)	30	30	35	25
Intermediate ballast cleaning with the reintegration of 50% of the track bed	15 years after CS	15 years after CS	17.5 years after CS	12.5 years after CS

end-of-life formula, shall be applied in case of multi-functionality of products in recycling or energy recovery situations. This formula has recently been replaced by the Circular Footprint Formula for materials (CFF), introduced and described in the Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs; EC, 2017). The CFF formula is described in Section 2 of the Supplementary Material (Eq. (S1)).

A different approach in modeling systems where recycling occurs can lead to different impacts as stated in Mengarelli et al. (2017) and Allacker et al. (2017), in which different end-of-life formulas were identified and analyzed. As there exists no purely natural-science-based approach to separate the different products in an overall system where recycling occurs (Allacker et al., 2017), a sensitivity analysis was performed to evaluate the influence of the CFF on results. In this case, the CFF was not applied: when a recycled material is employed in the system (rubber, plastics, and steel for the sleeper manufacturing), the modeling included the impacts for the collection, sorting, and recycling of the waste materials (not giving to the recycled material any impact related to the production of the virgin material); when a material is sent to recycling at its end-of-life (inner core and fastenings of the sleeper and ballast), the system included the impacts for its collection, sorting, and recycling and the avoided impacts for the corresponding virgin substituted materials.

2.6. Life cycle inventory of scenarios

This section provides a description of the approach, assumptions, and main data used for modeling the production, the use, and the end-of-life of the two typologies of sleeper (*GR 260 WHS* and *RFI 260*). Inventory data of the ecoinvent database (version 3.3 with the *allocation, recycled content* approach; ecoinvent center, 2016) were used in support of the analysis when primary data were not available.

2.6.1. Sleeper manufacturing - concrete production

The process *Concrete, sole plate and foundation, concrete production, for civil engineering, with cement CEM I* of the ecoinvent database was considered to model the extraction, the production, and the transformation of concrete components. The volume of concrete necessary for one sleeper (0.150 m^3) as well as the concrete composition (amount of sand, gravel, water, and cement) are primary data related to the *GR 260 WHS* sleeper (Table 2). The same composition was considered for the *RFI 260* sleeper for which a volume of 0.154 m^3 was assumed, as average of four examined models.

The ecoinvent process also includes the concrete production. For this stage, which is part of the sleeper production and occurs in the sleeper manufacturing plant (see Section 2.6.5), the Italian electricity mix and the European heat production were considered.

Table 2
Concrete components of the *GR 260 WHS,* with the respective amount.

Component	Amount (kg/m^3)	Mass per sleeper (kg)
Sand	677	101.8
Gravel	1109	166.7
Cement	420	63.1
Water	130	19.5
Total	2336	351.1

2.6.2. Sleeper manufacturing - reinforcement production

According to primary data provided by the Greenrail company, for the reinforcement of the concrete inner core (rod and other components), 14.57 kg of secondary steel per sleeper are employed. The same amount was assumed for the *RFI 260* sleeper. For the specific emissions and resources consumed arising from the recycling process of the recycled material, the ecoinvent process *Steel, low-alloyed, steel production, electric, low-alloyed* was considered. The modeling of this stage with the CFF is detailed in Table S2 of the Supplementary Material.

2.6.3. Sleeper manufacturing - fastenings of the rail to the sleeper production

For both the examined sleepers, a Vossloh fastening system is considered. Accordingly, each component of this fastening typology was identified with the corresponding material, weight, and ecoinvent database process for the modeling of its production (Table 3). For the tension clamp and the screw, the European mix between primary and secondary steel was assumed (40% of the European steel is secondary; World Steel Association, 2019). The modeling of this stage with the CFF is detailed in Table S2 of the Supplementary Material.

2.6.4. Sleeper manufacturing - outer shell components production

The reinforced concrete inner core of the *GR 260 WHS* sleeper is surrounded by an outer shell whose components are a mix of recycled rubber (ELTs powder) and recycled plastics (polyethylene - PE and polypropylene - PP) - 18.2 kg per sleeper (67% by weight) and a polymer based additive and magnesium hydroxide based flame retardant - 8.9 kg (33%). To the purposes of this research, primary data on the outer shell composition and production process have been provided by the Greenrail company. However, being that the disclosure of these information may affect the competitive advantage of the company, it has been asked not to publish full details in this paper. For further information on this aspect please contact the authors.

2.6.4.1. Rubber (end-of-life tires powder). The system boundary includes the ELTs collection, their subsequent transportation from the collection center to the recycling plants, and the recycling process that consists in the granulation of tires. For these processes, primary data provided by *Ecopneus*, the Italian consortium that coordinates the collection, the preparation for the recovery, and the recovery of ELTs, according to the obligation of the Italian Ministry Decree 82/2011, were considered. These data are referred to the average Italian situation for the collection and the transportations, while an Italian best practice process is assumed for the recycling process. In

Table 3
Fastenings of the rail to the sleeper components with the respective materials, masses, number per sleeper, and ecoinvent processes considered for the modeling.

Fastening system component	Material	Mass (g)	Number per sleeper	Ecoinvent process
Angular guide plate	Nylon (virgin)	170	4	*Nylon 6–6, glass filled, production*
Tension clamp	Steel (European mix primary/secondary)	496	4	*Steel, low-alloyed, steel production, electric, low-alloyed* (recycled) *Steel, unalloyed, steel production, converter, unalloyed* (virgin)
Screw	Steel (European mix primary/secondary)	636	4	*Steel, low-alloyed, steel production, electric, low-alloyed* (recycled) *Steel, unalloyed, steel production, converter, unalloyed* (virgin)
Dowel	50% nylon (virgin) 50% high density polyethylene - HDPE (virgin)	60	4	*Nylon 6–6, glass filled, production* *Polyethylene, high density, granulate, production*
Rail pad	Polyurethane (virgin)	273	2	*Polyurethane, foam, production* modified to consider the flexible elastomer production (a 100:30 ratio by weight between polyol and isocyanate was considered according to the technical datasheet of a polyurethane elastomer; Axson technologies, 2017)

detail, the collection is performed for an average distance of 37 km per metric ton with light commercial (30%) and heavy goods vehicles (70%), while an average distance of 132 km between the collection center and the recycling plant was considered (transportation by heavy goods vehicles). For the tires granulation, the consumptions of electricity (170 kWh/t ELTs), diesel fuel (2 L/t ELTs), LPG (0.6 L/t ELTs), and water (97.9 L/t ELTs) were included (values referred to 1 metric ton of ELTs were assumed identical for the three materials obtained with the recycling process - rubber, steel, and textiles). The modeling of this stage with the CFF is detailed in Table S2 of the Supplementary Material. For the final transportation of the powder (by heavy goods vehicles) to the user, a 70 km distance was considered.

2.6.4.2. Plastics (recycled PE; recycled PP). The system boundary includes first of all the collection of the municipal plastic waste considering the typical situation of Northern Italy, where the different plastic polymers are collected together with a curbside system. Then, the sorting process of the separately collected plastic waste (that mainly comprises polyethylene terephthalate - PET, PE, and PP) is performed. The light fraction obtained with the sorting process is the *polyolefins mix*, that includes PE and PP. Both the typologies of plastic employed in the manufacturing of the *GR 260 WHS* sleeper outer shell are part of this fraction. In the recycling process, polyolefins are shredded, washed, dried, densified, and finally sent to granulation. For all the described stages, primary data related to the Northern Italy waste management system were considered (Rigamonti et al., 2013; Grosso et al., 2012; Rigamonti and Grosso, 2009). In particular, the collection is performed for an average distance of 49 km per metric ton by light commercial (59%) and heavy goods vehicles (41%). During the sorting process, polyolefins are separated from other plastic polymers with a consumption of 26.6 kWh of electricity and 84 MJ of diesel fuel per metric ton of input plastic. An average distance of 50 km between the sorting and the recycling plant was considered (waste is transported by means of heavy goods vehicles). For the recycling, the consumptions of electricity (506 kWh per metric ton of recycled polyolefins), water (1780 L/t), and methane (650 MJ/t) were included. A 60% recycling efficiency was considered. Residues (40%) are sent to a cement kiln as solid recovered fuel (SRF), considering a distance equal to 50 km. SRF is assumed to be used in substitution of a certain amount of petcoke, calculated based on their lower heating values (LHVs). For the final transportation of recycled polyolefins (by heavy goods vehicles) to the user, a 70 km distance was assumed. The modeling of the plastic recycling by means of the CFF is detailed in Table S2 of the Supplementary Material.

2.6.4.3. Additive and flame retardant. The production of the polymer based additive used in the outer shell composition mix has been modeled according to well established ecoinvent processes.

The production of the magnesium hydroxide based flame retardant was modeled starting from the ecoinvent 2 process *Magnesium, at plant* (Hischier, 2007). This process, not present in the ecoinvent 3 database, models the magnesium production starting from magnesium hydroxide in turn produced from dolomite and seawater. The amounts of reactants, the energy consumptions, and the emissions were changed according to literature data; the detailed modeling is reported in Section 3.1 of the Supplementary Material. In addition the flame retardant includes virgin HDPE modeled according to the ecoinvent process *Polyethylene, high density, granulate, production.*

2.6.5. Sleeper production

For the *RFI 260* sleeper, the sleeper manufacturing is a concrete production process, described in Section 2.6.1. The *GR 260 WHS* sleeper manufacturing plant will also include an additional section for the outer shell manufacturing (an injection molding process). Currently, the Greenrail sleepers are produced in a pilot plant (the dedicated production plant is only projected). For this reason, this stage is modeled according to the ecoinvent process *Injection molding, processing* (which energy consumption was verified according to the plant project) applied to the outer shell components described in Section 2.6.4. The process was modified in order to consider the Italian electricity mix and the Italian (from natural gas) and European (from other fuels) heat production.

2.6.6. Sleeper transportation to the railway line

For the modeling of this stage, the current Italian situation of the prestressed reinforced concrete sleepers manufacturing plants was considered. Table S4 of the Supplementary Material indicates the manufacturing plants and their location.

The sleeper transportation mainly occurs by train (*Transport, freight train*), with the sleepers of each company being generally installed in different geographical areas irrespective of the plant location. For this reason, the distances between the freight yard nearest to each plant and each of the three main Italian railway centers (Milan for Northern Italy; Rome for Central Italy, and Naples for Southern Italy) was calculated according to railway distances provided by the Italian railway network manager (RFI, 2020a). The average distance resulted equal to 385 km. An additional transportation by truck for 20 km (*Transport, freight, lorry > 32 metric ton, EURO3*) to cover the distance between the manufacturing plant and the nearest freight yard was considered, since most of the manufacturing plants are not directly linked to a freight yard. The modeling was the same for both systems.

2.6.7. Ballast mining

Table S5 of the Supplementary Material lists the excavation companies that produce the ballast suitable for high speed lines (excluding quarries in the Sicily and Sardinia regions), the location of the quarry, and the ballast typology (RFI, 2020b). According to this information, the most common rock employed for the ballast production is basalt. Its mining, crushing, washing, and classification were modeled according to the ecoinvent process *Basalt quarry operation.* The most important contributions to the potential impacts (>53% for all the considered impact categories excluding land transformation, and >95% for 11 of them) are related to the use of electricity, diesel fuel, and blasting. The respective consumptions were therefore changed according to 10-years data related to >35 Italian basalt quarries that produce on average 2.2 million metric tons per year of basalt crushed stones (Regione Siciliana, 2008) and resulted: 2.73 kWh (electricity), 41.4 MJ (diesel fuel), and 0.0139 kg (blasting) per metric ton of basalt. In addition, the Italian (for electricity) and the European contexts (for diesel fuel) were considered.

First of all, the volume of the track bed was calculated in order to define the amount of basalt corresponding to 60 linear centimeters of ballast: the length of track per sleeper to be considered is based on the distance between two consecutive sleepers, generally equal to 60 cm for Italian railways. For the Italian more recent high speed double-track railway lines (distance between running lines equal to 3.0 m), the track bed is an isosceles trapezium with the bases equal to 8.2 m and 10.0 m and an height of 0.575 m (35 cm in addition to the sleeper thickness equal on average to 22.5 cm) (D'Elia et al., 2012; RFI, 2017). The corresponding volume is 5.24 m^3 per m of track bed. Therefore, for a single track and for a 60 cm length, a volume of 1.57 m^3 was considered. Moreover, this value was reduced to 1.42 m^3 considering the volume of one sleeper (0.15 m^3) because there is one sleeper every 60 cm. In the track bed, a 35% void volume is considered according to the value indicated by Sussmann et al. (2012) for the consolidated ballast. Finally, the mass of ballast was calculated considering the specific weight of basalt (2900 kg/m^3, according to EduMine, 2020) and resulted 2680 kg per 60 cm of track bed.

2.6.8. Ballast transportation

For the modeling of this stage, the current Italian situation was considered. As shown in Table S5 of the Supplementary Material, there is a good number of ballast quarries that are scattered across the whole country. For this reason, only the distances between each quarry location and the nearest main railway center (Milan for Northern Italy; Rome for Central Italy, and Naples for Southern Italy) were calculated, with the average distance resulting equal to 360 km. Due to the lack of more detailed information and considering that most of the quarries are far from the railway lines, 50% of the transportation is assumed to be performed by truck (*Transport, freight, lorry > 32 metric ton, EURO3*) and 50% by train (*Transport, freight train*).

2.6.9. Sleeper installation and removal (including ballast complete substitution)

In an existing railway line, the removal of old sleepers and the installation of new ones take place simultaneously by means of a track renewal train. For this reason, only one use of the track renewal train is considered in the system to take into account both the installation and the removal of the sleeper. For traditional pre-stressed reinforced concrete sleepers, this operation takes place every 30 years on average, since this is the duration requested by the Italian standards (RFI, 2017). This value was assumed for the conventional *RFI 260* sleeper, while for the *GR 260 WHS* sleeper, the lifetime was changed across the scenarios, as shown in Table 1.

For what concern the ballasted track bed, the intervals between two cleanings can be very different depending on aspects such as the typology and the frequency of the railway traffic, the geometry of the railway line, the ballast typology and the tamping frequency. A 25-years interval between two ballast cleanings with its complete substitution (2680 kg per 60 cm of track bed) was assumed as reference for the *RFI 260* sleeper. Numerous tests showed that the use of sleepers with USPs allows for the reduction of ballast degradation (abrasion and splitting), as reported by Li and McDowell (2018), Gräbe et al. (2016), Navaratnarajah et al. (2016), and Indraratna et al. (2014). Therefore, the lifetime of the ballasted track bed can be longer. Similarly, for the use of *GR 260 WHS* sleepers, a 30-years interval between two cleanings with the complete ballast substitution was assumed in the Worst and Baseline scenarios. This was increased to 35 years for the Best scenario (Table 1).

For the described operations, the consumption of diesel fuel for the main machineries is detailed in Table S6 and resulted 0.484 kg per 60 cm of track bed (track renewal) and 0.996 kg per 60 cm (ballast cleaning). Machineries were defined according to typical work trains, while consumptions were calculated according to the power and the working speed of each machinery (an average of different machineries was considered for each typology).

2.6.10. Railway maintenance

The maintenance includes the leveling, the lining, and the tamping. For these operations, the use of a tamping machine (2 passages) and of a ballast regulator was assumed. The consumption of diesel fuel for these machineries is detailed in Table S6 and resulted equal to 0.124 kg per 60 cm of track bed. The occurrence of these operations is very variable on the different railway lines, depending on aspects such as the typology and the frequency of the railway traffic, the geometry of the railway line, and the ballast typology. For traditional railway lines with heavy traffic, an interval of 2 years between two subsequent tamping interventions can be assumed on average, as reported by Fimor (2013) and Riessberger and Veit (2008). This interval was then assumed for the conventional *RFI 260* sleeper. When sleepers with USPs are employed, according to Gräbe et al. (2016), Fimor (2013), Potocan (2013), Schilder (2013), Lakuši et al. (2010), and Loy (2008), the interval between two subsequent tamping operations is at least 2 times longer compared to traditional sleepers. For the *GR 260 WHS* sleeper, a situation similar to the use of sleepers with USPs (4 years interval) was considered in the Worst scenario. This aspect was then changed across the scenarios, as shown in Table 1.

In addition, during its lifetime, the railway line is generally characterized by intermediate ballast cleaning operations with ballast reintegration (as for the tamping, the frequency of this operation is very variable). In the present study, a ballast cleaning at half of the interval between two ballast complete substitutions was considered (see Table 1), with the reintegration of 50% of the track bed (2680*0.5 kg ballast per 60 cm of railway line). The diesel consumption during this operation was assumed identical to that for the ballast cleaning with the complete substitution of ballast (Table S6).

2.6.11. Sleeper end-of-life - recovery

Conventional *RFI 260* sleepers are generally managed as construction and demolition waste (CDW), after the end of their useful life, with the 17 09 04 European waste catalogue - EWC - code.

Considering the management system in Lombardy (Borghi et al., 2018), the Italian region generating about 22% of the national production (ISPRA, 2019), sleepers are generally mixed with other CDW and sent to facilities where they are ground in order to separate the different components. The same treatment was considered for the *GR 260 WHS* sleeper. For both sleeper typologies, the concrete and the reinforcement steel were assumed to be totally recycled (currently only about 3% of the CDW is landfilled in Lombardy). The outer shell of the *GR 260 WHS* sleeper was assumed to be sent to a waste-to-energy plant, since currently no technologies are available for its recycling.

2.6.11.1. Concrete. For the concrete recycling process, the CFF was applied as described in Table S3 of the Supplementary Material. The emissions and resources consumed arising from the concrete recycling process, including transportations, were modeled according to the current management system of the Lombardy region described in Borghi et al. (2018). It comprises two main typologies of recycling facilities: stationary plants powered by electricity (14%) and diesel fueled mobile plants (86%). In the system modeling, the following consumptions were assumed, according to primary data gathered from 9 recycling plants:

- stationary plants: electricity (1.13 kWh per metric ton of treated CDW) and diesel fuel (0.25 L/t);
- mobile plants: diesel fuel (0.64 L per metric ton of treated CDW) and water (1.56 L/t).

All the recycled aggregates produced have a medium or low quality (Type B or Type C), according to the Italian legislation. They can be employed for road construction, as unbound material in the embankment body and in subbase, anti-freezing, anti-capillary, and drainage layers (B) or for environmental reclamations and fillings, for example in depleted quarries and landfill sites (C).

The emissions and resources consumed arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials were also modeled as described in Borghi et al. (2018). Recycled aggregates of types B and C generally substitute the unprocessed natural raw material. For this reason, only the avoided consumption for the extraction phase (0.39 L of diesel per metric ton) was included.

2.6.11.2. Reinforcement. The steel of the reinforcement, after the separation from the inert mineral fraction, is recycled (the parameters assumed for the application of the CFF are described in the Table S3 of the Supplementary Material). For the emissions and resources consumed arising from the recycling process, the ecoinvent process *Steel, low-alloyed, steel production, electric, low-alloyed* was considered. The emissions and resources consumed arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials were included as modeled in the process *Steel, unalloyed, steel production, converter*.

2.6.11.3. Outer shell. The composite material of the outer shell was assumed to be sent to a waste-to-energy plant with recovery of electricity and heat. For the modeling of this process, the Circular Footprint Formula for energy, introduced in the Guidance for the development of PEFCRs (EC, 2017), shall be taken into account. This formula is described in Section 2 of the Supplementary Material (Eq. (S2)).

Gaseous emissions, solids residues generation, and resources consumed in the energy recovery process were modeled according to the environmental declaration of one of the biggest Italian waste-to-energy plants located in Milan (A2A Ambiente, 2017). The ash content of the outer shell was assumed equal to 10%, a typical value for plastic.

The lower heating value (LHV) of the outer shell has been estimated equal to 30.5 MJ/kg, based on its composition. For the energy recovery, the net efficiency for heat generation was 24.2%, while the net efficiency for electricity 19.8% (A2A Ambiente, 2017).

The electric energy generated was assumed to be introduced into the Italian distribution network, where it has priority compared to fossil fuel plants (Consonni et al., 2005). For this reason, the replacement of electricity produced by a natural gas combined cycle was assumed (combined cycle plants contribute to the majority of the thermoelectric production, but they represent a marginal technology mainly linked to the fluctuation of residual demand). Based on these assumptions, the avoided electricity production was modeled with the ecoinvent process *Electricity, high voltage, electricity production, natural gas, combined cycle power plant*, related to the Italian context. For the avoided thermal energy modeling, the local heat district network was considered. The avoided heat production from natural gas boilers with an average 90% efficiency (Lopriore, 2016) was considered, including the avoided consumption of natural gas and the corresponding combustion emissions. The latter were modeled according to Italian emission factors (ISPRA, 2015), to the EMEP/EEA air pollutant emission inventory guidebook 2016 (EEA, 2017), and to the database of the Italian Agenzia Nazionale per la Protezione dell'Ambiente (ANPA, 2000).

2.6.11.4. Fastening of the rail to the sleeper. The fastening system is made of different materials as detailed in Table 3. Steel components are assumed to be recycled as described for the reinforcement, while nylon, HDPE, and polyurethane components are assumed to be sent to a waste-to-energy plant, as modeled for the outer shell (their average LHV is 31.7 MJ/kg).

2.6.12. Ballast end-of-life - recycling

According to the current situation of the Lombardy region, the ballast is managed by the CDW processing plants described in Section 2.6.11. Ballast can be classified as hazardous (EWC 17 05 07*) or non-hazardous waste (EWC 17 05 08). In the years 2012, 2013, and 2014, >98% of ballast managed in the plants of the Lombardy region resulted non-hazardous. Its treatment was therefore modeled as described for the concrete of the sleepers.

During the ballast cleanings with complete substitution (see Section 2.6.9), the employed ballast (2680 kg per 60 cm) was assumed to be sent to the described treatment. A certain amount of ballast is lost for pulverization during the railroading. This amount is not precisely quantifiable and, in addition, the modeling of particulate diffuse emissions (in time and space) is still currently not possible in the LCA. For these reasons, the total amount of employed ballast was assumed to be sent to recycling. Similarly, during the intermediate cleaning, the ballast added (see Section 2.6.10) was assumed to substitute an equal amount of no more suitable ballast. The latter was therefore assumed to be sent to recycling.

3. Results and discussion

3.1. PEF impact assessment results

Table 4 reports the potential impacts for the 15 selected categories and for the Cumulative Energy Demand indicator for the *RFI 260* sleeper and the potential impact change for the Worst, the Baseline, and the Best scenarios of the *GR 260 WHS* sleeper compared to the *RFI 260* (results of the *GR 260 WHS* sleeper are presented for the three scenarios in Table S7 of the Supplementary Material). For the Worst scenario, the differences are lower than 10% for most of the examined impact categories (9 out of 16). In the Baseline scenario, impact reductions for the *GR 260 WHS* sleeper bigger than 10% are observed for 7 out of 16 categories. Finally, for the Best scenario, reductions are significant (in the range 20% - 30%) for 11 impact categories with important benefits for the categories with a lower uncertainty (see Section 3.5): Climate change, Photochemical ozone formation, Acidification, Terrestrial eutrophication, and Marine eutrophication.

3.2. Assessment of data quality

Five criteria were considered to assess the quality of the data, according to the Recommendation of the European Commission of 9 April 2013 (EC - European Commission, 2013f): technological, geographical and time-related representativeness, completeness, and precision of inventory data. Their evaluation is reported in Section 4.1 of the Supplementary material.

3.3. Identification of environmental hotspots

To understand which processes are mostly affecting the results, an impact contribution analysis was performed for the *GR 260 WHS* sleeper (Fig. 2 for the Baseline scenario), making explicit the following stages:

- sleeper manufacturing (including the production of components);
- sleeper transportation from the manufacturing site to the railway line;
- track renewal (sleeper installation and removal);
- ballast cleaning (ballast mining, transportation from the quarry to the railway line, and operations of removal and substitution);
- railway maintenance (leveling, lining, and tamping);
- intermediate ballast cleaning (ballast mining, transportation from the quarry to the railway line, and removal and substitution operations);
- ballast end-of-life (including ballast from both cleaning operations);
- sleeper end-of-life.

The sleeper manufacturing is the most important contribution for 10 out of 16 impact categories. The sleeper end-of-life is instead the most relevant stage for Human toxicities (cancer and non-cancer effects) whereas the

Table 4
Potential impacts of the *RFI 260* (results are reported per FU) and potential impact changes in the Worst, Baseline, and Best scenarios of the *GR 260 WHS* sleeper.

Impact category		Potential impact *RFI 260*	*GR 260 WHS* Potential impact change e.g.: (Worst - *RFI 260*)/*RFI 260*		
			Worst scenario	Baseline scenario	Best scenario
1 Climate change	kg CO_2 eq	6.38E+00	7%	−9%	−25%
2 Ozone depletion	kg CFC-11 eq	7.33E-07	−3%	−12%	−26%
3 Human toxicity (non-cancer effects)	CTUh	2.45E-06	9%	−13%	−30%
4 Human toxicity (cancer effects)	CTUh	2.05E-06	4%	−20%	−36%
5 Particulate matter/respiratory inorganics	kg $PM_{2.5}$ eq	4.56E-03	9%	−4%	−20%
6 Ionizing radiation (human health effects)	kBq U^{235} eq	5.17E-01	27%	7%	−11%
7 Photochemical ozone formation	kg NMVOC eq	3.92E-02	−2%	−12%	−26%
8 Acidification	mol_c H^+ eq	3.90E-02	8%	−5%	−21%
9 Terrestrial eutrophication	mol_c N eq	1.43E-01	−6%	−15%	−28%
10 Fresh water eutrophication	kg P eq	9.14E-04	37%	11%	−9%
11 Marine eutrophication	kg N eq	1.32E-02	−4%	−13%	−27%
12 Ecotoxicity for aquatic fresh water	CTUe	4.99E+01	17%	−6%	−23%
13 Land transformation/occupation	kg C deficit	2.52E+02	−15%	−16%	−28%
14 Water resource depletion	m^3 water eq	1.27E-02	72%	38%	12%
15 Mineral and fossil resource depletion	kg Sb eq	1.46E-04	341%	245%	179%
16 Cumulative Energy Demand	MJ	8.34E+01	39%	17%	−3%

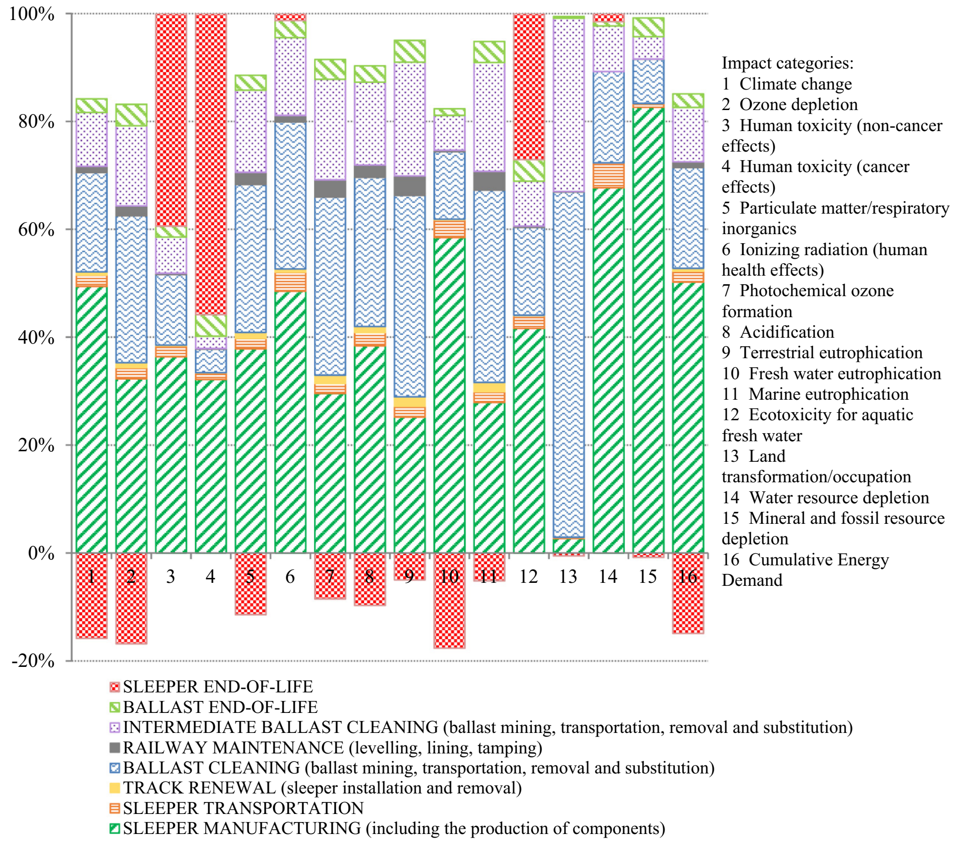

Fig. 2. Impact contribution analysis for the Baseline scenario of the *GR 260 WHS* sleeper, for the examined categories.

ballast cleaning is the most important contribution for the remaining 4 impact categories, with a maximum equal to 65% for Land transformation/occupation.

The impact of the sleeper end-of-life is negative (i.e. an environmental benefit) for 11 impact categories thanks to the electricity and heat recovered by means of the outer shell incineration, that substitute energy produced from conventional fuels.

Less relevant is the contribution of the sleeper transportation (always lower than 5%), the track renewal (<2%), the railway maintenance (<4%), and the ballast end-of-life (<6%).

Similar results were observed for the other scenarios as shown in Table S10 of the Supplementary Material.

To better analyze the sleeper manufacturing contribution, this is split into three main stages:

- inner core components production (concrete and reinforcement) and inner core manufacturing;
- fastenings of the rail to the sleeper production;
- outer shell components production and outer shell manufacturing.

As shown in Fig. S1 of the Supplementary Material, the impact related to the outer shell is the major contribution for 8 categories out of 16. In detail, its contribution ranges from a minimum (12%) for Human toxicity (cancer effects) to a maximum (92%) for Mineral and fossil resource depletion. On the contrary, for the other 8 categories, the contribution of the outer shell production is lower than that of the inner core production.

To further investigate the sources of the outer shell impacts, a contribution analysis (Fig. 3) was performed on the production of the different outer shell components and on the outer shell manufacturing process. The impact related to the outer shell manufacturing (an injection molding process), ranging from 5% to 73%, is the major contribution for almost all the impact categories (14 out of 16), mainly due to the energy consumption.

Concerning the ballast cleaning stage, its main contribution is the ballast transportation from the quarry to the railway line for all the impact categories excluding Particulate matter/respiratory inorganics and Land transformation/occupation, where the contribution of the mining is equal to 97%; finally, the ballast removal and substitution contribution is always lower than 13%. Similar results are found for the intermediate ballast cleaning, but the relevance of ballast mining and transportation is slightly lower, while the ballast removal and substitution contribution increases for all the impact categories (up to 23%).

3.4. Sensitivity analysis

The influence of the Circular Footprint Formula for materials on the results is observed to be relevant in the sleeper production stage in which recycled rubber, plastics, and steel are employed. As shown in Fig. 3, the use of the rubber shows generally an appreciable contribution (ranging from 12% to 93%) in the outer shell manufacturing. When the CFF is not applied (i.e. not allocating to the recycled material any impact related to the production of the virgin material, but only the impacts of the collection, sorting, and recycling), the contribution for the production of the ELTs powder is substantially lower (ranging from 2% to 6%). Under this condition, the contribution of plastics is also lower (always <9%).

Table 5 reports the potential impact change for the scenarios of the *GR 260 WHS* sleeper compared to the *RFI* 260 sleeper, when the CFF is not applied. The comparison with results of Table 4 shows a more favorable situation for the *GR 260 WHS* sleeper for all the scenarios and all the examined impact categories (excluding Fresh water eutrophication for Baseline and Best scenarios).

Analyzing the results in detail, in the Baseline scenario impact reductions for the *GR 260 WHS* sleeper bigger than 10% are observed for 11 out of 16 categories, with results similar to those of the Best scenario with

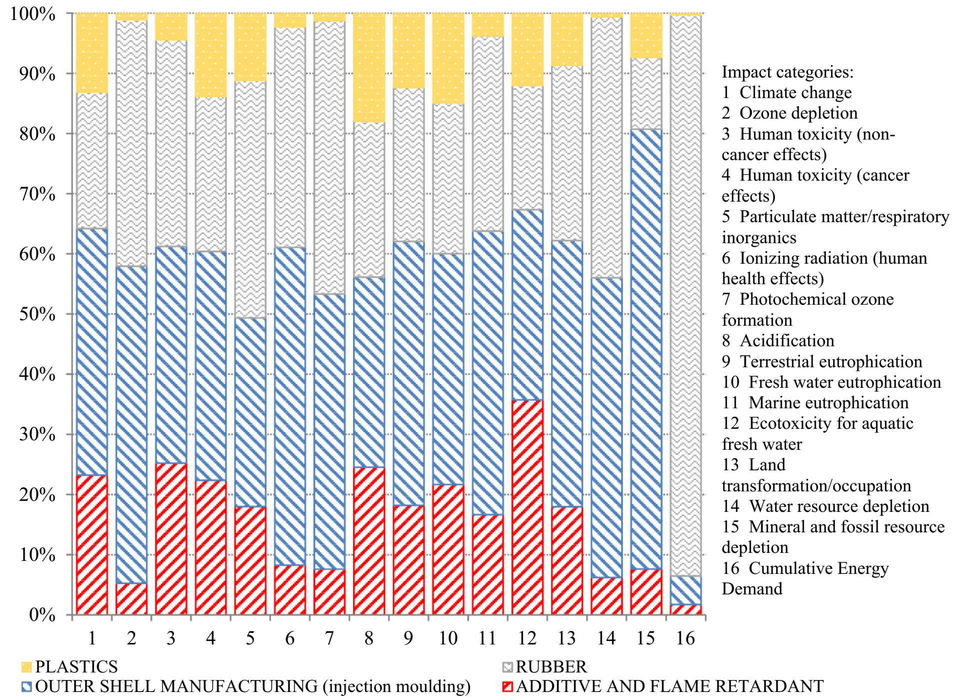

Fig. 3. Impact contribution analysis of the outer shell components production and manufacturing for the scenarios of the *GR 260 WHS* sleeper, for the examined categories.

the application of the CFF. Finally, for the Best scenario, reductions are in the range 19% - 38% for 14 impact categories.

3.5. Estimation of uncertainty

The Monte Carlo method was applied to estimate an uncertainty range of the calculated results. This numerical technique takes a random value from the uncertainty distribution of each input data and calculates the LCA results for this set of sampled values. The procedure is repeated with 1000 iterations; the result is an uncertainty distribution. In this study, no uncertainties of primary data were available; the method was therefore applied to evaluate the uncertainty deriving from secondary data (secondary data uncertainties and their uncertainty distributions are assumed as defined in the ecoinvent database; ecoinvent center, 2016). The final outcome is reported in Section 4.3 of the Supplementary Material.

The coefficient of variability (i.e. the ratio between the standard deviation and the mean) is a useful parameter for the evaluation of the uncertainty magnitude. It is below 15% for Climate change, Photochemical ozone formation, Terrestrial eutrophication, Marine eutrophication, and Acidification. On the contrary, it is very high for categories such as Land transformation/occupation and above all Water resource depletion for which the uncertainty is very high.

4. Conclusions

GR 260 WHS sleeper is an innovative product, where the conventional structure made of pre-stressed reinforced concrete is wrapped inside an

Table 5
Potential impacts of the *RFI 260* sleeper (results are reported per FU) and potential impact changes in the Worst, Baseline, and Best scenarios of the *GR 260 WHS* sleeper when the CFF is not applied.

Impact category		Potential impact *RFI 260*	*GR 260 WHS* Potential impact change (no CFF) e.g.: (Worst - *RFI 260*)/*RFI 260*		
			Worst scenario	Baseline scenario	Best scenario
1 Climate change	kg CO_2 eq	5.84E+00	−4%	−16%	−30%
2 Ozone depletion	kg CFC-11 eq	7.55E-07	−18%	−22%	−34%
3 Human toxicity (non-cancer effects)	CTUh	3.72E-06	3%	−19%	−35%
4 Human toxicity (cancer effects)	CTUh	3.44E-06	1%	−22%	−38%
5 Particulate matter/respiratory inorganics	kg $PM_{2.5}$ eq	3.98E-03	−5%	−11%	−25%
6 Ionizing radiation (human health effects)	kBq U^{235} eq	5.75E-01	11%	−5%	−21%
7 Photochemical ozone formation	kg NMVOC eq	3.76E-02	−10%	−16%	−29%
8 Acidification	mol_c H^+ eq	3.69E-02	−1%	−11%	−25%
9 Terrestrial eutrophication	mol_c N eq	1.44E-01	−11%	−17%	−30%
10 Fresh water eutrophication	kg P eq	5.94E-04	33%	14%	−5%
11 Marine eutrophication	kg N eq	1.32E-02	−8%	−15%	−29%
12 Ecotoxicity for aquatic fresh water	CTUe	6.95E+01	7%	−14%	−30%
13 Land transformation/occupation	kg C deficit	2.53E+02	−16%	−16%	−29%
14 Water resource depletion	m^3 water eq	1.32E-02	63%	31%	7%
15 Mineral and fossil resource depletion	kg Sb eq	1.63E-04	9%	−3%	−19%
16 Cumulative Energy Demand	MJ	8.12E+01	9%	−4%	−20%

outer shell made of a mixture of ELTs powder and recycled plastics. This LCA evaluated the environmental performances of this sleeper under different assumed operational conditions and, in addition, compared it with traditional sleepers, not equipped with the outer shell.

The results showed relevant differences among the scenarios, with the comparison with the traditional concrete sleeper being strongly influenced by the examined parameters: the sleeper lifetime, the tamping interval, the interval between two ballast cleanings with complete ballast substitution, and the frequency of intermediate ballast cleaning. Therefore, their exact definition is a very important aspect, although it will require several years of use on railway lines. Currently, the first experimental vibration tests after the application on a railway line show encouraging results. For the worst operational conditions of the *GR 260 WHS* sleeper, the potential impacts differences between the two sleeper typologies are lower than 10% for most of the examined categories, meaning that no significant environmental differences are observed. In the average conditions, impact reductions for the *GR 260 WHS* sleeper result bigger than 10% for 7 out of 16 categories. Finally, for the best conditions, reductions are in the range 20% - 30% for 11 impact categories.

Focusing on the outer shell manufacturing, the impacts contributions analysis, the injection molding process impact is the major contribution for almost all the impact categories, mainly due to the energy consumption. This aspect allows to suggest possible impact reductions that might be achieved by decreasing the amount of materials molded (for example reducing the thickness of some parts of the outer shell) or with a greater use of electricity from renewable energy sources.

Finally, according to the performed sensitivity analysis, the influence of the CFF on results is relevant in the sleeper production stage in which recycled materials are employed: when it is not applied, the impact for the production of outer shell components is substantially lower.

CRediT authorship contribution statement

Giovanni Dolci: Conceptualization, Methodology, Formal analysis, Data curation, Investigation, Writing - original draft. **Lucia Rigamonti:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration. **Mario Grosso:** Conceptualization, Writing - review & editing, Supervision, Project administration.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trip.2020.100160.

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