National Institute for Public Health
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Application of a novel method for material loops

This is a revised version of letter report 2020-0126

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Colophon

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This investigation was performed by order, and for the account, of ProRail, within the framework of the 'Klimaat enevelop'.

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Synopsis

Safety and sustainability analysis of railway sleeper alternatives
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Every year, ProRail replaces 200,000 railway sleepers. In the last century, wooden sleepers were used treated with creosotes to preserve them. Creosotes contain substances of very high concern. More recently, sleepers have been made from concrete, but greater quantities of CO_2 are released in the manufacture of these sleepers than from wooden sleepers. To minimize CO_2 emissions and the use of substances of concern, ProRail is looking for alternative railway sleepers.

To this end, RIVM has compared six different types of sleepers with cement concrete (100 percent Portland cement). The six sleeper types are made from copper-treated wood, untreated wood, recycled steel-reinforced plastic (PE), virgin steel-reinforced plastic (PE), glass-fiber-reinforced plastic (virgin PU) and Sulphur-based concrete (instead of cement-based concrete). The comparison of the various sleepers was based on the aspects that are important for sustainability and safety of substances for the environment.

The sleepers made from recycled plastic and Sulphur-concrete are more sustainable than sleepers from concrete (Portland cement). The other types of sleepers are only favorable over concrete in certain aspects of sustainability. Based on the data available, the various types appear to be equally safe for the environment.

Part of the sustainability assessment of the sleepers is done by looking at the extent to which they release greenhouse gases and how much land is needed to extract the materials to make them. The land used to produce wooden sleepers is greater than for the other sleeper types. This is important due to the effect on biodiversity, even though less greenhouse gases are released during production compared to concrete.

The safety of the sleepers was analyzed by looking at the presence of pollutants and the degree to which these pollutants leach out. After all, any substance released during the use of the sleepers can end up in the soil and groundwater. There is legislation for all types of sleepers, the objective of which is to ensure that they are safe to use. For this study not all relevant data were available. Knowledge of the presence of any hazardous substances in sleepers is important if they are to be safely reused.

Keywords: environmental footprint, sleepers, ProRail, concrete, plastic, composite, wood preservative, recycling, safety, framework for safe and sustainable material loops, SSML

Publiekssamenvatting

Analyse duurzaamheid en veiligheid van dwarsligger alternatieven in het spoor

Toepassen van een nieuwe methode voor materiaalkringlopen

ProRail vervangt elk jaar 200.000 zogeheten dwarsliggers op het spoor. In de vorige eeuw zijn hiervoor houten bielzen gebruikt die met zogeheten creosoten zijn bewerkt om verwering te voorkomen. Creosoten bevatten Zeer Zorgwekkende Stoffen (ZZS). De laatste jaren worden dwarsliggers van beton gemaakt, maar bij de productie daarvan komt meer CO_2 vrij dan bij houten dwarsliggers. Om de CO_2-uitstoot en het gebruik van schadelijke stoffen te minimaliseren zoekt ProRail naar mogelijkheden om andere dwarsliggers te gebruiken.

Daartoe heeft het RIVM zes verschillende typen dwarsliggers vergeleken met betonnen exemplaren (100 procent Portland cement). Het gaat om dwarsliggers van met koper behandeld hout, onbehandeld hout, gerecycled plastic dat met staal is versterkt, nieuw plastic dat met staal is versterkt, (nieuw) plastic dat met glasvezel is versterkt (composiet) en beton op basis van zwavel (in plaats van cement). Bij de vergelijking is gekeken naar zaken die belangrijk zijn voor duurzaamheid en voor de veiligheid van stoffen voor het milieu.

De dwarsliggers van gerecycled plastic en van zwavelbeton zijn het meest duurzaam ten opzichte van betonnen dwarsliggers (Portland cement). De andere type dwarsliggers zijn alleen op sommige punten gunstiger. Op basis van de beschikbare gegevens lijken de verschillende typen ongeveer even veilig voor het milieu.

Bij de beoordeling van de duurzaamheid is gekeken in hoeverre er broeikasgassen vrijkomen. Ook is gekeken hoeveel land nodig is om het benodigde materiaal te winnen. Voor met koper behandelde houten dwarsliggers is het landgebruik groter dan voor de andere typen dwarsliggers, dit is belangrijk vanwege het effect op biodiversiteit, ook al komen er iets minder broeikasgassen vrij.

Bij de veiligheid gaat het erom of er verontreinigende stoffen in de dwarsliggers zitten en in welke mate zij eruit vrijkomen. Vrijgekomen stoffen kunnen namelijk tijdens het gebruik van de dwarsliggers in bodem en grondwater terechtkomen. Voor alle typen dwarsliggers bestaat er regelgeving om te zorgen dat het gebruik veilig is. Voor dit onderzoek waren niet alle gegevens beschikbaar. Kennis over de aanwezigheid van eventueel schadelijke stoffen is belangrijk om materialen voor de dwarsliggers veilig te kunnen hergebruiken.

Kernwoorden: milieuafdruk, bielzen, dwarsliggers, ProRail, beton, kunststof, composiet, verduurzaamd hout, recyclen, veiligheid, raamwerk voor veilige en duurzame materiaal kringlopen, SSML

Contents

Preface

This work on comparing railway sleeper alternatives was previously published under RIVM letter report 2020-0126. After receiving several comments pointing out shortcomings in the previous analysis, it was decided to publish a revised report. The main point for this was that data on greenhouse gas (GHG) emissions for production of the different railway sleeper alternatives did not follow the intended functional unit (FU) regarding the exclusion of the rail fastening system. The subsequent analysis of data on impact of the fastening system on overall GHG emission resulted in revision of the FU to include the fastening system. Several other parts of the study where revised, mainly related to the sustainability analysis:

- Recalculation of GHG emissions, now including the fastening system for all sleeper types based on:
    - Updated LCA inventory data
    - Inclusion of some additional uncertainties related to fastening system baseplate reuse and cement concrete service life.
    - Calculation of net GHG emissions from production and end of life scenario together.
- Clarification specific to the use of a baseline scenario for cement concrete using Portland cement (CEMI) instead of cement containing blast furnace slags (CEMIII/A). CEMIII is currently often applied in the Netherlands.
- Correction and clarification of the ZZS and other substances of concern content in different sleeper types.
- Brief discussion of alternative sleeper types available, but not further analyzed here.

Summary

Introduction
Currently cement concrete railway sleepers (NS90) are the default sleeper type that are used in the Netherlands. Only under specific conditions a limited number of wooden sleepers are applied. In light of the climate goals set in Paris, the need to reduce greenhouse gas emissions became more urgent. Since cement concrete railway sleepers using 100% Portland cement (CEM-I) have a larger carbon footprint compared to wooden sleepers, treating wood with copper-based preservatives might be a good alternative. This is however not the only alternative. There are several other types of railway sleepers on the market: among others based on Sulphur concrete, polyurethane (PU) with glass fiber and polyethylene (PE) with steel strengthening.

Methods
For this reason, the safety and sustainability benefits of these different railway sleepers are compared in order to facilitate a decision in procurement of these railway sleepers. For this assessment the Safe and Sustainable Material Loops (SSML) framework and the modules on substances of concern, environmental impact and circularity are applied. Safety was assessed based on the presence of the Dutch Substances of Very High Concern (ZZS), other substances of concern (SoC) and biocides. Available data on composition and emissions were assessed against safety thresholds with potential uncertainties reported.
The sustainability is assessed based on the carbon and land use footprints and circularity is assessed using the Material Circularity Indicator and two separate indicators for recycled or renewable content and for recyclability. The study considers a single 100 meter single track consisting of 167 sleepers including the fastening system that should last 50 years as the functional unit.

Safety analysis
The safety assessments resulted in no great difference in safety between the sleeper alternatives. However, several areas of uncertainty were identified. This uncertainty mainly lies in either availability of specific data or uncertainty in relation to quality of applied secondary materials. This does not indicate any immediate safety concern, but a practical implementation of existing safeguards is necessary, e.g. using data requirements or quality monitoring.

One area where existing safeguards might not be adequate is when emerging contaminants such as per- and polyfluoroalkyl substances or microplastics come into view. For these emerging issues new scientific evidence or new regulatory standards may alter the future appreciation of products that contain and emit them.

Sustainability analysis - environmental impact
The overall environmental impact of the Sulphur concrete sleepers and the recycled PE-steel sleeper is considerably lower than that of the Portland cement concrete baseline. This is largely due to the recycling potential of these materials and the use of secondary or residual

materials, e.g. recycled instead of virgin PE. The overall carbon footprint of the copper treated wood sleeper is also lower compared to the baseline, but the use of wood comes with a considerably higher Land use footprint compared to the baseline. Land use is an important indicator for ecosystem biodiversity and should be taken into account when deciding on a sleeper type.

In the first life cycle only the Sulphur concrete and Copper treated wooden sleepers have a lower carbon footprint compared to the baseline. The application of virgin PE-steel and PU-glass fiber sleepers give considerably larger carbon footprints for the first life cycle of the product and to a lesser extend recycled PE-steel. The overall carbon footprint also considers the future benefits due to recycling or reuse. This results in a similar and smaller carbon footprint compared to the baseline for the virgin PU-glass fiber and PE-steel sleeper, respectively. However, uncertainty of future benefits after the first life cycle, which is after 50 years, is high. Thus, both the short-term increase in carbon footprint for initial production in the first life cycle of these sleepers and the potential (more uncertain) benefit in the next life cycle should both be taken into account as separate criteria in the decision for an alternative sleeper type.

In the comparison of environmental impact, it should be noted that the carbon footprint of the Portland cement concrete baseline applied in this study is likely an overestimation due to the increased use of other cement mixes and the availability of only generic data. For instance, a Swedish study showed a significantly lower carbon footprint for cement concrete sleepers compared to the Portland cement baseline.

Sustainability analysis - circularity

All railway sleepers, except the wooden sleepers, provide an improved material circularity above the concrete sleeper. Wooden sleepers do benefit from energy recovery at their end of life, but this only affects the potential for reducing greenhouse gas emissions in the next life cycle and is not considered a circular material application. For this reason, increasing the reuse potential of wooden sleepers in the next life cycle might be an area to develop further. To do this, new methods to safely and more sustainably apply used wooden sleepers (treated or untreated) need to be developed. However, since both waste regulations and product regulations are in play, not only technical and commercial, but also regulatory obstacles need to be navigated to make this possible for wooden sleepers. The recycled PE sleeper has the highest circularity of all the alternatives.

Availability recycled material

Although the sleepers using recycled materials show a reduction in environmental impact and increased material circularity, the supply security of these secondary materials should be assessed. For recycled PE, the supply security remains uncertain as the demand of recycled PE to produce the 200.000 sleepers being replaced annually is large compared to the current supply of PE waste in the Netherlands. This means that the benefit compared to concrete cement sleepers is potentially reduced, as the projected greenhouse gas emission for production of the recycled PE sleeper will be larger due to the potential increased use of virgin PE.

Simplified overview of the safety and sustainability analysis

	Portland Cement Concrete	Sulphur Concrete	Untreated wood	Copper treated wood	Recycled PE-steel	Virgin PE	PU-glass fiber
Safety	✓ [a]	✓ [a]	✓	✓	✓ [a]	✓ [a]	✓ [a]
Net reduction environmental impact	Base-line	⊕	⊕ [b]	⊕ [b]	⊕ [c]	⊕ [c]	⊖ [d]
Material circularity	Base-line	⊕	⊖ [d]	⊖ [d]	⊕	⊕	⊕

a: Safety analysis incomplete due to limited available data, but regulatory safeguards are in place.
b: A trade-off between reduced greenhouse gas (GHG) emissions and increased land use.
c: Higher GHG emissions in the first life cycle, but with a net reduction in GHG emissions due to recycling.
d: No improvement compared to baseline

The main contribution of this analysis is to show the potential of the different sleeper systems: what are currently the hotspots? What are currently important tradeoffs (e.g. clearly visible in the wooden sleeper's discussion and the fastening systems). And, what is the potential for circularity and benefits in the future? It should be noted that this analysis is not exhaustive. For instance, there are sleepers that use recycled instead of virgin PE-glass fiber or blast furnace slags (CEM-III) instead of Portland cement which might be worth considering in more detail as these both have a lower carbon footprint compared to the baseline.

Although this type of analysis is not precise and subject to change in the near future because of technological developments the results as such provide input for strategic decision making on the direction towards a more sustainable system and which development paths you want to explore together with the foreseen suppliers.

1 Introduction

There is an increased need for taking into account environmental benefits and trade-offs (e.g. reduced greenhouse gas (GHG) emissions), in addition to the social, financial and technical aspects, in the decision-making process related to product design or procurement. These environmental benefits and trade-offs can range from climate change mitigation to protection of biodiversity in order to foster a healthy ecosystem. In general, these environmental benefits and trade-offs can have several causes, but because of the current goals related to a transition to a circular economy, the application of secondary and renewable materials and products is becoming more and more important. However, there is often uncertainty related to the safety of novel and secondary materials for humans and the environment.

Reliable information on safety is particularly important when applying residual or waste material streams in new applications. For instance, using old television glass in concrete blocks (Spijker *et al.*, 2015) or recycling of diapers (Lijzen *et al.*, 2019). This uncertainty can also affect public acceptance of a product: for example the uncertainty about the safety of rubber granules from old tires when used in artificial soccer turf was cause for public unrest (Pronk *et al.*, 2020). For this reason, the Safe and Sustainable Material Loops (SSML) framework was developed that includes a set of tools or modules that allow screening and more in depth analysis of safety issues in relation to the intended sustainability benefits (Quik *et al.*, 2019).

The SSML framework was initially aimed at comparing recycling options for residual material flows. In this study we extend the scope of the SSML framework from comparing recycling options to comparing products. To do this we apply and adjust the SSML framework to assess different railway sleepers for their potential safety concerns and sustainability benefit. This is done for ProRail, the Dutch railway infrastructure manager, as part of ProRail's incentive for producers of railway sleepers to provide alternatives that could reduce the GHG emissions related to the 200.000 sleepers replaced every year. Additionally, the railway sleepers should contribute to the transition towards a circular economy.

Currently concrete railway sleepers (NS90) are the default sleeper type that are used in the Netherlands. Only under specific conditions wooden sleepers are applied. This is for instance on bridges or in tunnels where the technical specifications of a wooden sleeper are preferred over concrete. These wooden sleepers are now applied untreated, limiting their lifespan to about 12 years, whereas in the past they were treated with creosote to extend their lifespan to about 25 to 35 years.

In light of the climate goals set in Paris, the need to reduce GHG emissions became more urgent. This is a reason to rethink the current approach to strictly using cement concrete railway sleepers as these have a larger carbon footprint compared to wood which was applied in the past (Bolin and Smith, 2013; Lindeberg *et al.*, 2018). Furthermore, in light of the transition to a circular economy the benefits of potential future reuse and recycling of railway sleepers is an important aspect to consider in further reducing GHG emissions and environmental impact in general.

As wood treated with creosote contains several substances of very high concern this is not a viable option for the future. And using untreated wood would likewise not be a viable option due to the relatively short lifespan and resulting higher frequency of work on the railways to replace them.

Although preserved wood treated with other preservatives might be a good alternative to concrete, this is not the only alternative. There are several other types of railway sleepers on the market from different types of materials such as Sulphur concrete, polyurethane with glass fiber, and plastics (e.g. polyethylene) combined with steel strengthening. Sleepers made from these types of materials have similar or longer life spans than concrete. Although they all have differences in technical capabilities, they are in theory all technically adequate for application in the railways system in the Netherlands.

The aim of this study is to assess the benefits of the different railway sleepers in contributing towards a reduction in environmental impact and to the transition towards a circular economy while also considering their safety. This means that the presence of ZZS[1], other substances of concern and biocides (preservatives) are assessed against relevant safety thresholds when data was available. Potential uncertainties are reported.

This study does not advice for or against application of any particular railway sleeper. This choice is left to the responsible party, i.e. the procurement specialist at ProRail. This study was conducted by RIVM to foremost provide information on environmental safety and sustainability of different railway sleepers for procurement. Furthermore, the study is used to learn from the application of the novel SSML framework. As the procurement of railway sleepers is applicable to the whole of the Netherlands this study is considered in interest of the general public.

In the next chapter (2) the applied methodology is explained. In chapter 3, the results from the safety assessment are presented and discussed. In chapter 4 the results from the environmental benefit and circularity assessment are presented and discussed. Chapter 5 provides a concluding discussion which includes a reflection on application of the SSML methodology.

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[1] ZZS: Zeer Zorgwekkende Stoffen are the Dutch Substances of Very High Concern (SVHC) which cover a broader range than the SVHC identified under REACH.

2 Methods

2.1 The SSML framework

2.1.1 *Background and application*

The SSML framework was developed and tested on waste streams applied in recycling solutions (Quik *et al.*, 2019). However, solutions applied in the design, construction and use phases of a product or material are likely to have an increased contribution to a circular economy because they follow strategies higher up the R-ladder, e.g. remanufacture or reduce. This makes the railway sleeper case a first test in extending the scope of application of this framework and the included methods. This also means that the approaches included in the different modules require some adaptation in order to apply for the comparison of different products. These adaptations are detailed in the following paragraphs and are closely linked with the intended scope of this safety and sustainability analysis (Figure 1).

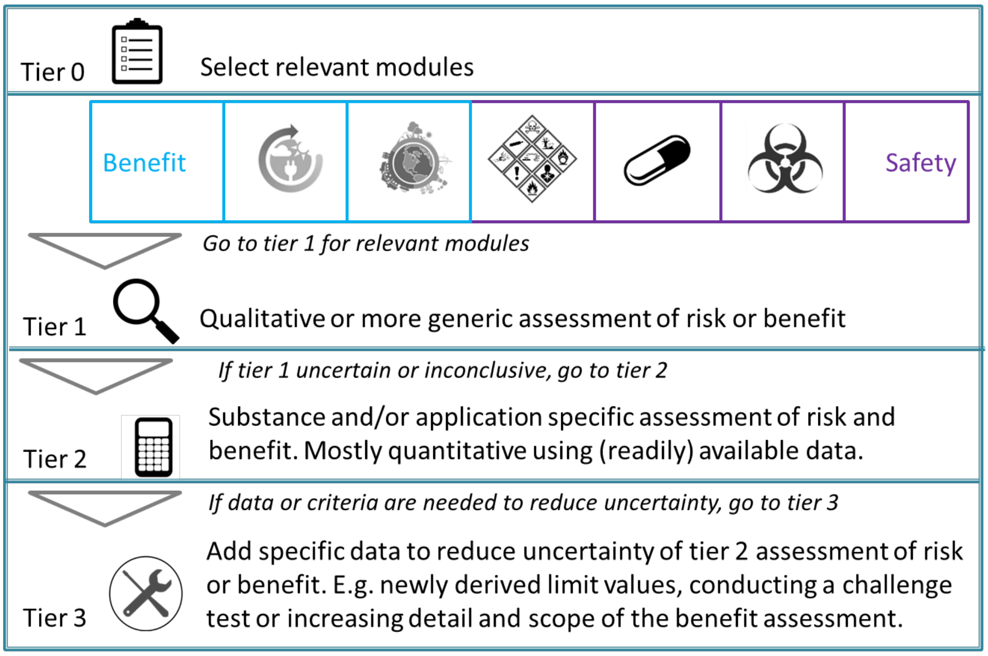

Figure 1. Basic workflow of the sustainability benefit and safety assessment as part of the safe and sustainable material loops (SSML) framework (Quik et al., 2019).

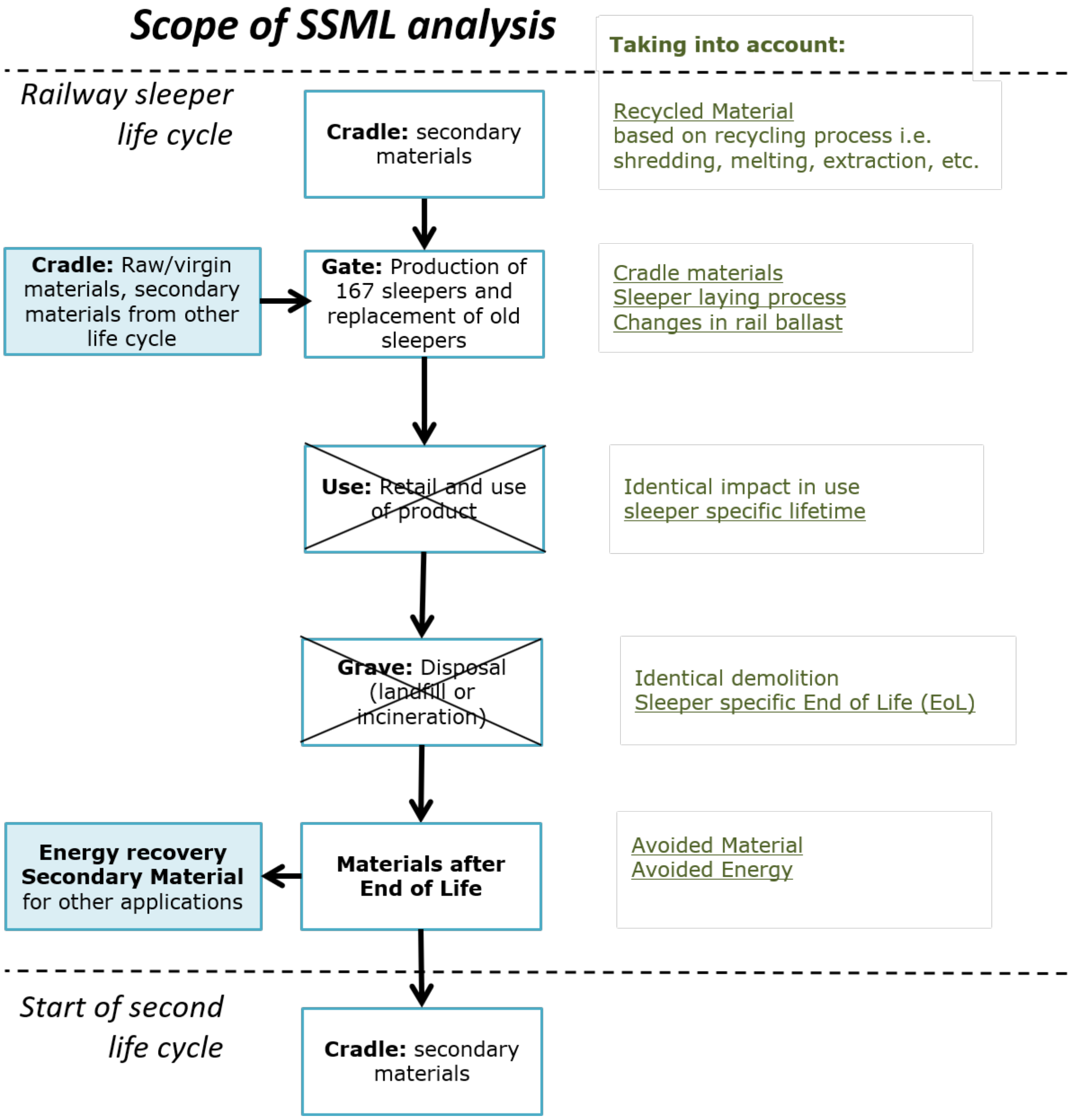

Figure 2. Lifecycle stages regarding railway sleepers and impacts taken into account in the safety and sustainability analysis.

2.1.2 *Scope*

SSML incorporates a modular and tiered approach that allows different levels of assessment based on the available data (Figure 1). For the SSML assessment of railway sleepers the environmental impact, circularity and ZZS modules were used.

The analysis of railway sleepers is applied to the following life cycle stages (Figure 2):

- The End of Life stage of the previous life cycle of any secondary materials applied in railway sleepers
- The cradle and End of Life stage of railway sleepers

- The use stage is assumed similar relative to each other, with the exception of the service life (See Table 1).
- The cradle stage of any recovered secondary materials from railway sleepers after their first life cycle.

For comparison of the different railway sleepers, the life cycle stages that are expected to be similar are excluded, i.e. the use stage. This also applies to transport during manufacturing and railway installation, thus focusing primarily on the railway sleeper materials and design.

The functional unit applied in this analysis are further detailed in the sections on the safety and sustainability analysis, but in general they are:

- 100 meter of track (167 sleepers) including track bed and fastening system.
- 50-year time span.
- Axel load of 22.5 ton at 200 kph and an axel load of 25 ton at 100 kph.

The difference between the track bed for wooden and other sleepers involves the use of 221 kg gravel per 100 meter track (Table 1).

Table 1: The main materials and end of life strategy as part of the life cycle of 7 railways sleeper types, excluding the fastening system.

	Cradle to Gate		**Grave to Cradle**
Railway Sleeper	**Raw material**	**Additional track bed**	**End of life strategy**
Portland cement concrete	Cement concrete, Steel	Yes	Recycling to 97% granulate – different appl and 3% CEMI.
Sulphur concrete	Sulphur concrete	Yes	Recycling Sulphur concrete and steel to sleeper
Wood (untreated)	Wood	No	Incineration
Wood (copper treated)	Wood, preservative	No	Incineration
Recycled PE-steel	Recycled polyethylene, Steel	No	Recycling PE and steel to sleeper
Virgin PE-steel	Polyethylene, Steel	No	Recycling PE and steel to sleeper
Virgin PU glass fiber	Polyurethane and glass fiber	No	Reuse as sleeper

2.1.3 *Data*

The required data for the safety and sustainability analysis were collected between July 2019 and April 2020, with update of some data in October 2020 when revised or more detailed LCA's were available. The update was part of the revision of the initial report (2020-0126) and update of data related to the recycled PE-steel, PU-glass fiber and Sulphur concrete sleepers. Although some generic LCA data on different cement mixes (e.g. CEM-I and CEM-III/A) was made available, the reference Portland (CEM-I) cement concrete LCA was not adapted, as it

is deemed a valid reference (2.3.1) and an update based on other cement mixes was out of scope of this study.
Overall, the analyses were based on existing data, preferably product specific data. When this was missing, generic other data sources were used, such as found in public literature, substance registration dossiers and LCI databases.
Product specific data on leaching of substances of concern from concrete products was not available to us at the time of our analysis (July 2019 – April 2020). During the revision (Oct. 2020) leaching data were made available related to Sulphur concrete sleepers and cement concrete. Due to time restrictions it was not possible to update the detailed analysis.

2.2 Safety aspects

2.2.1 *Tier 1 and 2 – basic analysis*

Although the basis of the existing ZZS module (part of the SSML framework) is used, it is extended as a more general module for the substances present in railway sleepers. The applied approach focuses on the leaching of chemicals from sleepers. In the ZZS module, tier 1 considers the (potential) presence of substances of concern (SoC/ZZS) and in tier 2 a first basic risk analysis is performed (Figure 3).

The ZZS module targeting the Dutch substances of very high concern[1] is relevant when ZZS are present in a material flow or waste stream (Quik *et al.*, 2019). Substances are deemed ZZS when they meet one of various hazard criteria like carcinogenity, reprotoxicity, and persistency in combination with bioaccumulation, or have other properties or have caused other probable serious effects of equivalent concern. For ease of reference, a non-limitative list[2] is compiled, which is updated twice a year.

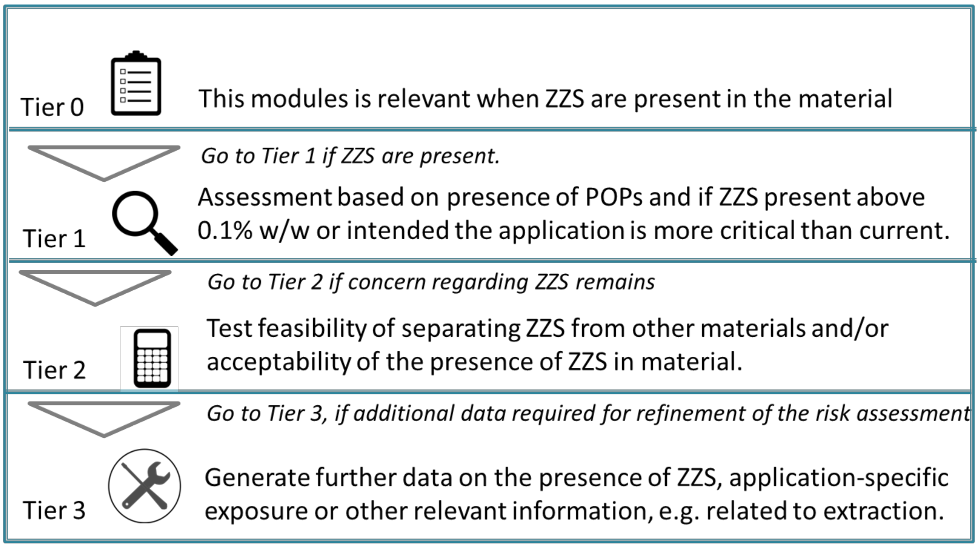

Figure 3. Overview of tiers applied in the safety assessment of railway sleepers.

In tier 1, using product information and open literature, each sleeper is screened for (potential) presence of ZZS, biocides and other substances

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[2] ZZS-list: https://rvs.rivm.nl/zoeksysteem/ZZSlijst/Index

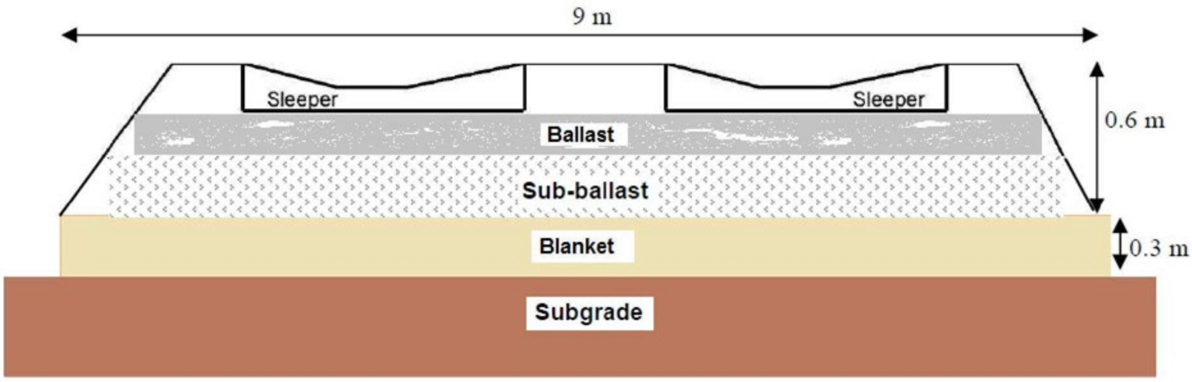
of concern. In tier 2 each sleeper is assessed by comparing substance leaching rates or concentrations to existing safety thresholds.

2.2.2 *Tier 3 – in depth analysis*

For various ZZS a more in-depth assessment (Tier 2) is necessary to conclude whether there might be a risk or not, or to come to a comparison of the different sleepers. For this purpose, we use an exposure scenario describing a track bed with two railway tracks. This enables us to compare the cumulative emissions of the selected ZZS from the respective sleepers, with environmental quality standards or material emission standards.

2.2.2.1 Methodology background and scenario

The scenario for the exposure assessment of the railway sleepers is taken from the OECD document (OECD, 2013). A schematic cross section through a railway line including ballast layers is provided in the following figure.



Blanket: Permeable layer of fine, granular material placed directly on subgrade. A blanket is only necessary if the subgrade is cohesive.
Subgrade: Natural stratum (soil or rock) or embankment (from trimming natural stratum) on which the track bed (ballast, sub-ballast and blanket) is constructed.
Figure 4: Cross section through a railway line as described in (OECD, 2013)

Where relevant, the OECD dimensions are adjusted to the Dutch dimensions.

- The lower width of the ballast is estimated to be 9 m for a track with two lines. The emission originates from two railway lines crossing a field of one hectare (one hectare = 10000 m^2, hence L x W = 1111 x 9 m). For the safety assessment there is little difference between one line or two lines, since the receiving soil volume changes accordingly. For ease of calculations, in the Dutch scenario the track bed is 10m wide (L x W = 1000 x 10m).
- In the OECD scenario, sleepers are L x W x H = 260 x 26 x 16 cm. It should be noted that the Dutch sleepers are 260 x 25 x 15 cm.
- All sides of the sleeper, except the bottom side, are expected to be vulnerable to leaching due to contact with (rain)water. For the OECD scenario the leaching surface is 1.59 m^2 per sleeper. For the Dutch scenario this is 1.505 m^2. The sleeper volume is 0.0975 m^3.

- With a distance of 0.6m between sleepers, in the OECD scenario the two tracks contain 2583 sleepers over the total length of 1111 m. In the Dutch situation, this number is 3340 sleepers over the total length of 1000m (167 sleepers per 100 m).
- The leaching surface area in the OECD scenario is 4107 m^2 per hectare. In the Dutch situation it is 5027 m^2 per hectare.
- The scenario lifetime unit for comparison is 50 years.

For all materials, the load to the environment will depend on the amount of contaminant or impurity present and in particular the amount available for leaching. The latter strongly depends on the chemical binding within the material, (changes in) structure of the material over time (increasing contact surface) and the ambient conditions (temperature, rain, UV, corrosivity, vibrations).

In the EU-based risk assessment for wood preservatives[5], the shallow groundwater (1m below soil surface) is assessed with two models. For inorganics, like copper, the soil porewater concentration is derived from a soil concentration as a result of the cumulative leaching over 20 years. It is assumed that the ballast bed is inert and does not attenuate any contaminants. The groundwater concentration is set equal to the soil porewater concentration. The soil porewater concentration is then calculated assuming a receiving soil volume is 50 cm deep, with a water volume fraction of 0.2, an organic matter content of 3.4% and a dry bulk density of 1500 kg m^{-3}. Using substance specific equilibrium-partitioning coefficients (K_{om}), describing the equilibrium in concentration between the organic matter in the soil and the porewater, the groundwater concentration is calculated (JRC, 2003). For organic compounds, the concentration in shallow groundwater (at 1m depth) is calculated using the PEARL model[3]. This model simulates the leaching of a yearly repeated dose, for 20 years, to the top soil through the soil layer, taking sorption and degradation into account for a realistic worst-case soil profile and climate scenario. In the EU assessment, a life cycle time of 20 years is assessed. However, over 50 years we look at 3 cycles of placing newly treated wood. The cumulative leaching of three service life times is assessed.

2.2.2.2 *Environmental background values and risk limits*

In this assessment of different sleepers of various compositions, we assess the cumulative emissions against environmental quality standards or emission standards for individual contaminants. In the authorization procedure for wood preservatives, data on soil ecotoxicology are provided by the applicant and environmental risk limits are derived by the competent authority. For naturally occurring substances, like metals, there are natural background values available, next to quality standards for various use functions. For heavy metals (and other) ions in stony construction materials, emission standards are available. Impurities in plastics should be present <0.1% for the plastic to be recycled. These standards are further addressed in Chapter 3.

Apart from ambient soil background values, background emissions from other sources are relevant in assessing the cumulative exposure, such as

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[3] https://www.pesticidemodels.eu/pearl/home

the overhead electricity lines. Contamination of the track bed with copper from overhead lines was documented by Ten Berg (1998). Emission rates range from <5 up to 70 g m^{-1} y^{-1}, depending on the intensity of the use. An estimated 10% is removed by the train to the washing place. It was modelled that about 40% of the emission deposits within 5 m (both ways) of the overhead lines, and about 50% is more widely dispersed. This leads to a significant addition of copper in the top soil (Eissens, 1998). When we assume 2 tracks on a 10m wide track bed, we can calculate that 1.5 times the emission value for the single line, is deposited – on average- on the 10m wide track bed. Hence the load to the track bed is in the range from <3 up to 42 g m^{-1} y^{-1}, or <60 - 840 g m^{-1} in 20 years. We divide the cumulative load (in g m^{-1}) by a receiving surface area (10 m width per meter). Assuming mixing of the complete dosage over a 50 cm soil depth, a soil concentration of <7.2 - 99 mg copper / kg fw soil is added (~ <7.8 - 112 mg copper / kg dw). The cumulative load to the top surface of a wooden sleeper amounts to <4 - 55 grams of copper per sleeper. These background concentrations are further addressed in Chapter 3.

2.3 Sustainability aspects

2.3.1 *Environmental Benefit*

The environmental benefit of the different sleeper alternatives is compared to a baseline using the SSML environmental impact module. This module assesses environmental impact based on indicators for cumulative energy demand and land use as a lower tier method (tier 2). A full Life Cycle Assessment (LCA), as dictated for higher tier assessments, is considered outside the scope of this study. The assessment (tier 2) is similar to a comparative LCA of various life cycle stages (Figure 2) where substitution of virgin materials (counterfactuals) using system expansion is applied. In a full LCA based on EN15804 a calculation of all the emissions and extractions that a product or process has during the various life cycle stages of a product is conducted to get an absolute estimate of the environmental impact. Here we apply several key simplifications in order to reduce data needs, but still be able to compare the different sleeper alternatives to each other and to the baseline sleeper. This should cover all important aspects and give information on major advantages or disadvantages between the assessed scenario's (Table 1).

Although we compare all sleeper alternatives, we apply a baseline scenario: the use of cement concrete sleepers which for over 30 years has replaced creosote treated wooden sleepers. More specifically this cement concrete sleeper is the NS90 sleeper as described in the LCA by SGS Search (2019b) consisting of concrete using CEMI cement (100% Portland), steel reinforcement and the fastening system. Recently the application of CEM-III/A cement (~50% blast furnace slags) is becoming more common in the Netherlands. However, CEMI is still the standard in the EU (CEN/TC 256, 2015) and was standard in the Netherlands in 2018 (SGS Search, 2019b, a). Furthermore, the LCA by SGS Search (2019b) was prepared for the Dutch Railway maintenance authority, ProRail, as reference. It should be noted that the GHG emissions related to the CEMI cement includes a 30% increase over the producer specific environmental product declarations following the Dutch implementation of EN-15804 (Stichting Bouwkwaliteit, 2019). Although this LCA could be updated in

several area’s it is still considered an adequate baseline for cement concrete sleepers consisting of CEMI cement.
Based on the environmental impact modules of the SSML framework we use two indicators to assesses the environmental impact. These are the carbon footprint (GHG emission) and land use related to the functional unit. We base this tier 2 assessment on available LCA’s conducted often with differences in scope or functional unit. The tier 2 assessment thus is aimed to align the functional units of the different existing LCA’s using the above-mentioned scope in order to produce a fair comparison

Essential for a (comparative) LCA is the functional unit. The functional unit is a measure that allows comparison and forms a reference to which the considered impacts relate. Here a functional unit was chosen as 100 meter of high intensity railroad track, including the track bed, over a period of 50 years, and including the fastening system. The change in height of the ballast bed is taken into account. This means that 217 kg of gravel is needed for railway sleepers with a different profile compared to a wooden sleeper. Over a period of 50 years, some sleepers will need to be replaced if 50 years surpasses the expected lifetime of the sleeper. The exact service life of sleepers has some uncertainty, for this an upper and lower service life is included in the analysis. For all the sleeper types the upper bound is at a service life of 150% of the expected service life, the lower bound is at 50% of the expected service life. The expected lifetime of the various sleepers is given in Table 2.

Table 2: Service life including the lower and upper bounds used in the uncertainty analysis, weight and available LCA studies of different sleepers, see Table A1 in appendix A for exact source of each data point.

Product	**Service life (years)**	**Material: weight (kg)**	**Data sources**
Portland cement concrete sleeper	45 (22.5-67.5)	Cement concrete: 277,5 Steel reinforcing: 5,9 Fastening system type 1	(SGS Search, 2019b)
Sulphur concrete sleeper	45 (22.5-67.5)	Sulphur concrete: 272,5 Steel reinforcing: 5,8 Fastening system type 1	(NIBE, 2020)
Wooden sleeper (untreated)	12 (6-18)	Wood: 75 Fastening system type 2	(Ecoinvent, 2017; Lindeberg *et al.*, 2018) & ProRail
Wooden sleeper (treated)[a]	25 (12.5-37.5)	Wood: 75 Preservative: 5 Fastening system type 2	(Ecoinvent, 2017; Lindeberg *et al.*, 2018) & ProRail
Recycled PE sleeper	50 (25-75)	Polymer: 50,6 Steel: 17,9 Fastening system type 2	(Tauw, 2018)
Virgin PE sleeper	50 (25-75)	Polymer: 50,6 Steel: 17,9 Fastening system type 2	(Lindeberg *et al.*, 2018)
PU-glass fiber	50 (25-75)	Glass fiber: 29 Polymer: 29 Fastening system type 2	(Lindeberg *et al.*, 2018; Ecochain, 2020)

[a] Assumed that the same amount of wood is needed with 5kg of preservative

2.3.1.1 *Greenhouse gas emissions*

The greenhouse gas (GHG) emissions are expressed in carbon dioxide equivalents (kg CO_2 eq) per functional unit (FU). We apply the scope described above and in paragraph 2.1.2. The FU is 100m of high intensity railroad track, including the track bed and rail fastening system, over a period of 50 years. GHG emissions are calculated based on the existing method for performing an LCA on building materials in the Netherlands (Stichting Bouwkwaliteit, 2019) based on EN15804. However, this is not an extensive LCA study of these different sleeper types, we use existing product specific LCA data combined with generic data from other sources, such as EcoInvent (Ecoinvent, 2017) to perform a fare comparison. The applied materials and data sources are given in Table 2. The applied inventory data is reported in appendix A, table A1. For most sleepers a product specific LCA was available. For the comparison we simplified the analysis based on the SSML environmental impact module in order to focus on the materials and recycling and reuse options they provide.

The narrower scope (par 2.1.2) of this comparative LCA focusses on extraction of the raw materials and manufacturing and placement of the sleepers. This analysis thus considers the impact of sleepers due to the production of new sleepers (module A1+A3 in EN15804) and the replacement of old sleepers (module A5 in EN15804). Impacts related to transport are excluded in this analysis. These emissions are highly dependent on the distance of the production site to the place of installation. For calculation of absolute GHG emissions transport should always be taken into account, this can account for 0,7% - 20% of GHG emissions associated with the manufacturing and installation life cycle stages (Ecochain, 2020; NIBE, 2020). The benefit of the sleepers is due to the recycling, reuse or recovery of energy from the sleepers at the End of Life as a railway sleeper (module D in EN15804).

Product level LCA's were made available for the cement concrete (SGS Search, 2019b), Sulphur concrete (NIBE, 2020) and PU-glass fiber sleepers (Ecochain, 2020) using the Dutch method based on EN-15804 (Stichting Bouwkwaliteit, 2019). The recycled PE-steel sleeper analysis is based on data of a material specific LCA on manufacturing of recycled PE deck boards and a material specific LCA for the steel strengthening (VWN, 2015). For the wooden (treated + untreated) sleepers, Virgin PE EcoInvent 3.4 is used. Additionally some data on manufacturing and installation is taken from a study by the Swedish Environmental Research Institute (Lindeberg *et al.*, 2018).

The application of wooden sleepers (treated and untreated) allows the application of 37 ton less gravel in the track bed per 100m compared to the NS90 type of sleepers. For concrete, Sulphur concrete there is 37 ton of additional gravel needed (CO2Logic, 2009). EcoInvent is used for data on the GHG emissions associated with the production of gravel. Furthermore, the GHG emissions from transportation of gravel are taken into account as a large amount of the GHG emissions for this additional gravel will be associated with the transport of gravel. 50km is assumed as the average transport distance from the production site to the application site. This is equivalent to 160 kg CO2-eq, which is added to the GHG emissions of the relevant railway sleepers (Table 1).

All the sleeper product specific LCA studies included the fastening system. For the PE-steel and wooden sleepers, the impacts of the fastening systems are calculated based on the LCA data for the concrete 14-002 sleeper (SGS Search, 2019a). Although there are small differences between the different fastening systems for each sleeper type, they can be simplified to compose of two types. One type that includes sleeper screws (kraagbout), dowels (schroefhuls), insulator pads (opsluitplaat), rail pads (beddingplaat), clips (veerklem) and retaining rings (volgring) as applied to the cement and sulphur concrete sleepers (NS90). The second type contains similar parts, but also includes extra sleeper screws, extra bolts with nuts and a set of ribbed baseplates. Particularly these ribbed base plates (2 per sleeper) are an important difference as they are made from steel weighing about 11 kilograms each. These ribbed baseplates are used in the PU+glass fiber, recycled and virgin PE-steel and wooden sleeper types. As these ribbed baseplates can be reused it is assumed that they have a service life of 50 years independent of the sleeper service life. This means that for the wooden sleepers they are not replaced every time a wooden sleeper is replaced. However, we do indicate the additional impact of replacing these ribbed baseplates every product cycle because it seems that reuse is not explicitly organized by ProRail.

Reuse, recovery and recycling of old materials can avoid the emission of GHG in a next life cycle when other materials are spared. However, the potential GHG emissions avoided by the reuse, recovery and recycling are dependent on the virgin material that is spared and the efficiency of the reuse, recovery and recycling technic. Wooden sleepers cannot be reused or recycled and can only be used for energy recovery. We assume that, within the FU, untreated wooden sleepers can replace 115 MWh and treated wooden sleepers 59 MWh, based on a dry mass of 55% and 19 MJ/kg dry weight (CO2emissiefactoren.nl, 2020). To calculate the avoided CO_2 eq. emissions of electricity production from wood, we use a 50 year weighted average which starts with 0.475 kg CO_2 eq. per kWh in 2020 and is reduced to 0.061 kg CO_2 per kWh in 2050, remaining constant until 2070. Table 3 shows which materials are spared. The producer of the Sulphur concrete, the producer of the PU-glass fiber sleeper and the producers of Recycled PE-steel sleepers all claim that their product can be reused or recycled without significant loss of material or functionality. Here, a loss of 5% of the material is assumed, as 100% recycling efficiency without loss of functionality seems to be unrealistic. In practice some loss in material quality can also be expected compared to the virgin alternative. For these reasons it is assumed that for the PE-steel, Sulphur concrete and PU-glass fiber sleepers, 95% of available material for recycling or reuse is effectively applied in the next life cycle.

Table 3: The most important potentially spared resources following the end of life strategy of the different sleepers.

Sleeper	**Spared resource**
Portland cement concrete	Gravel/CEM-I and steel
Sulphur concrete	Sulphur concrete, steel
Recycled PE-steel	Virgin PE, steel
PU-glass fiber	Virgin PU-glass fiber sleeper, steel
Wood (untreated)	Dutch electricity mix, steel
Wood (treated)	Dutch electricity mix, steel
Virgin PE-steel	Virgin PE, steel

2.3.1.2 Land use

Land use is reported in surface area used in a year adjusted for the surface bio-productivity (m^2 a crop-eq). Land-use is considered an important impact factor when assessing bio-based materials (Huijbregts, 2017). Land use is together with GHG emissions a good indicator of environmental damage. Land use is an important factor of environmental damage as it leads to the loss and modification of habitats which cause loss of biodiversity. Non-of the existing LCA studies evaluated land use, thus data from EcoInvent was used (Ecoinvent, 2017). Data from EcoInvent was used for the assessment of land needed for the raw material extraction for the sleepers for 100m railroad track for 50 years. This assessment excludes material losses that might happen during the production and assembly phase as this data was not available and most impact is expected to be associated with the raw material extraction. The applied materials and data sources are given in Table 2. The applied inventory data is reported in appendix A, table A1.

2.3.1.3 Normalization and endpoint assessment

Different environmental impacts can be added together through normalization and weighing, this makes comparison between different products more assessable. Normalization is possible from different perspectives. Here we use two different normalization sets that are available: "ILCD (EU27)" and "Milieuprijzen (NL)". The ILCD method is based on the Product Environmental Footprint (PEF) whereas the Milieuprijzen method is based on external costs (JRC, 2012; Bruyn *et al.*, 2017)

2.3.2 *Material circularity*

Material circularity is assessed based on the SSML circularity module with some modifications due to application to products instead of recycling options. These modifications are detailed below. In tier 1 it is assessed qualitatively whether the applied materials are available and what the options for recycling or reuse are. In tier 2 the secondary or renewable material content and recyclability are assessed. For this study this is also accompanied by calculation of the Material Circularity Index. based on the guidance provided by the CB'23 circularity method for building products (v1) (Platform CB23, 2019). We also calculate the material circularity indicator as this also includes the utility, life span in addition to the other two aspects in one indicator.

2.3.2.1 *Tier 1 method*

SSML tier 1 consists of answering three questions:

- Does the product contain EU critical raw materials (CRM)? For the check on critical raw materials, the list of critical raw materials is used (Deloitte *et al.*, 2017).
- Is there concern for material supply due to a significant increase in demand for the source material (Supply check)?
- Is there possibility for recycling/re-use? (This is adjusted slightly from the original question to use the waste hierarchy to classify the recycling option (Potting *et al.*, 2016)).

2.3.2.2 *Tier 2 method*

The basis of the method to asses circularity is on the one hand an indicator for closing previous material loops: the secondary or renewable content in manufacturing of a railway sleeper (R-1). This indicator was not included in the original SSML circularity module[4] and is based on the guidance provided by the CB'23 circularity method for building products (v1) (Platform CB23, 2019).
On the other hand an indicator for the future closing of material loops: the recyclability of a railway sleeper (R+1). This is the amount of materials becoming available for certain functions after the End of Life of a railway sleeper. There is a third indicator which should quantify the degree a certain (circular) product contributes to potentially closing the whole material cycle, but this is not included here. The main reason for this is that in comparing a products circularity instead of recycling options there is not much difference in recyclability and the contribution to a circular material cycle. Thus only two indicators (secondary or renewable material content and recyclability) are assessed to estimate circularity of the different sleepers. This is done using the following equations:

- SSML-1:
  Secondary or renewable content [derived from CB'23 (2019)]

$$NSx = \frac{Msi + Mni}{Mi}$$

Whereby:
NSx = Secondary or renewable content
Msi = Mass in sleeper of secondary origin
Mni = Mass in sleeper from renewable resources
Mi = Mass of sleeper

- SSML+1: Recyclability [SSML]

$$Rec = \frac{Rret}{Rta} * Qr$$

Whereby:
Rec = Recyclability
Rret = Resource returned for recycling or reuse
Rta = Total mass of resource in source product
Qr = Quality classification factor between 0 and 1

As these sleepers differ in utility, mainly the life span (e.g. between wood and PE) the material circularity indicator (MCI) is included. The

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[4] This is instead of recycling efficiency in the original SSML circularity module.

MCI is quantified following the method described by the Ellen MacArthur Foundation, with the modification made by Madaster (Ellen MacArthur Foundation, 2015; Madaster, 2019). The MCI accounts for the amount of recycled or reused material applied in a product, the life span of a product compared to the reference life span, the amount of material becoming available at end of life. The main modification included here is the addition of renewable materials as contributing to circularity similar to recycled materials. In the MCI recycling is only accounted for when it is possible to recycle the waste material into new sleepers. The full formula is given in Madaster (2019). The data required to calculate these different indicators for each sleeper type is based on data supplied by the suppliers in their product level LCA’s and as reported above in calculation of the GHG emissions.

3 Safety

Railway sleepers are shaped building materials typically consisting of several components, be it mainly wood, stony materials like concrete, or plastics. Various studies have shown that leaching of components and/or contaminants is possible, by demonstrating the presence, release, and/or effects of contaminants from various construction materials
(Xie *et al.*, 1997; Hillier *et al.*, 1999; Marion *et al.*, 2005; Verschoor and Cleven, 2009; Lalonde *et al.*, 2011; ten Broeke, 2014; Jang *et al.*, 2015; Janssen *et al.*, 2015; Park *et al.*, 2015; Gartiser *et al.*, 2017; Kuterasińska and Król, 2017).

Hence, a safety assessment based on the ZZS module is conducted.

Below we make an inventory of what is known about the leaching of ZZS from treated wood, stony materials and plastics, and the associated hazards and risks.

3.1 Basic risk analysis

The basic risk analysis is based on limited data with respect to ZZS content. In order to be able to make statements about the differences in hazards or risks, and in potential for circularity, specific data are required for each material about the presence of contaminants and about the extent of leaching over time. Here the available data on preserved wooden sleepers, concrete, and plastics sleepers is presented.

3.1.1 *Copper treated wood*

Wooden sleepers (oak, beech or fir) can be treated with wood preservatives. The use of wood preservatives as well as the placing on the market of wooden articles treated with them, is prohibited throughout the EU, unless this is approved after an extensive risk assessment (Biocidal Products Regulation 528/2012).
All wood preservatives that are authorized in the Netherlands are based on copper. In addition to copper, other substances against bacteria and fungi can be present: quaternary ammonium compounds, boron, or organic fungicides. Several wood preservative products that are permitted in the Netherlands or were described elsewhere can potentially be applied to wooden sleepers (see Table 4). For the safety assessment the Tanalith 3462 product[5] based on copper, tebuconazole and propiconazole, was selected arbitrarily. The active ingredient propiconazole of Tanalith 3462 was at the time of this assessment (December 2019) listed as a ZZS substance. Tebuconazole and propiconazole were classified as not PBT (ECHA, 2013, 2015) but may be endocrine disrupting (EC, 2016). When their authorization as wood preservatives is reviewed (within a few years), this assessment will include whether the substances actually meet the endocrine disruption criteria.

Natural, untreated wood will contain trace elements and trace concentrations of contaminants (e.g. copper, lead, chromium) taken up from the ambient air and soil. For example, oak contains copper in a concentration of about 2 mg/kg dw in the outer hearth wood (Szczepkowski and Nicewicz, 2008).

3.1.2 *Concrete sleepers*

Two types of concrete sleepers were investigated: the cement concrete sleeper (NS90) and the Sulphur concrete sleeper (Thiotrack). No information on composition or leaching of either concrete sleeper was made available. Concrete building materials are principally composed of stony materials, containing metal- and other ions in background levels. Such ions may leach in contact with water (Verschoor et al., 2006). Also, Sulphur concrete consists of up to 25% Sulphur, leaching of sulphate (after oxidation of Sulphur to Sulphite and Sulphate) is expected (Mohamed and El-Gamal, 2010). For both sleepers a Life Cycle Assessment was available, but this did not consider emissions of substances during the use phase (SGS Search, 2019b; NIBE, 2020).

3.1.3 *Plastic sleepers*

Two types of plastics sleepers were investigated: RPE sleepers and PU-glass fiber sleepers. There was no information provided on the composition of the designated plastic sleepers, other than the main components (PE and glass fiber/PU). Like for all plastics, a wide range of additives to enhance the performance of PE and PU are on the market, like plasticizers and flame retardants.
A standardized leaching test (EN 71 part 3) (CEN, 2019) with recycled (PE) plastic, steel-enforced, sleepers showed no detectable leaching of Sb, As, Ba, Cd, Cr, Pb, Hg or Se (all <1 mg/kg) (Lankhorst, 2019). Copper, plasticizers and flame-retardants were not assessed. No information on the leaching from PU-glass fiber sleepers was made available. Technical literature on glass fiber wear and abrasion is available, but this is not further examined here since it brings no information on the release rate or identity of the of released components of the designated PU-glass fiber sleepers. There is some open literature on ZZS in PE materials. In a brief exploration of existing information about the leaching of contaminants from plastic used in sheet piling, it is concluded that plasticizers (such as DEP and DEHP), fire retardants (PBDE) and other components may leach from PVC and PE (ten Broeke, 2014). PBDE and DEHP are listed as a ZZS, and DEP is not. Xie et al (1997) describe a study into the leaching of contaminants from construction material made from recycled household plastic (PE) in contact with water. The tests showed that various substances leach out, the plasticizer diethyl phthalate (DEP) being the most measured organic substance. In parallel a test with treated wood (treated with copper-chromium-arsenic, CCA) was performed. As expected, arsenic, chromium and copper leached from CCA-wood, but it is striking that almost as much copper leached from PE plastic as from the CCA wood studied. The authors concluded that, apart from the plasticizers from the plastic, various contaminants must come from the contents of the packaging from which the recycled plastic is made.

Various chemicals, like flame retardants and plasticizers are added at manufacture of plastics, but also active substances of biocides are added to protect plastic from deterioration (Nichols, 2004). A recent review presented a database with chemicals associated with plastic packaging (Groh *et al.*, 2019). However, analytical data on impurities in specifically recycled PE are not readily available in public literature (Stenmarck *et al.*, 2017; Hahladakis *et al.*, 2018).

Plastic sleepers may, depending on the wear and tear, be a source of microplastics.

Table 4: A selection of wood preservatives and their active ingredients. Tanalith is E 3462 (bold) is used for the assessment in this study.

Name product	**Basis**	**Active ingredients**				**Source**
		1	**2**	**3**	**4**	
Tanalith E 3462	**water**	**Copper (granulated) 9% (w)**	**Propiconazole 0.18% (w)**	**Tebuconazole 0.18% (w)**		**Ctgb NL-0008998-0000 (5)**
CELCURE C4	water	Copper hydroxide carbonate 16.96% (w)	Alkyl (C12-C16) benzyldimethyl-ammoniumchloride 4.47% (w)	Cyproconazole 0.1% (w)		(6)
IMPRALIT ACQ2100	water	Copper oxide 9.40% (w)	Dialkyldimethylammoniumchloride 4.60% (w)			(7)
KORASIT KS2	water	Copper hydroxide carbonate 19.2% (w)	N, N-didecyl-N methylpoly (oxyethyl) ammonium propionate 10.56% (w)			Ctgb 14595N
TANALITH E9000	water	Copper hydroxyide carbonate 14.57%	Didecyl-dimethyl-ammonium carbonate 2.0%	Propiconazole 0.16%	Tebuconazole 0.16%	EU 2017 (8)
WOLMANIT CX-8WB	water	Copper hydroxide carbonate 12.5% (w)	Bis-n-(cyclohexyldiazeniumdioxy)-copper 2.80% (w)			Ctgb 14902N
WOLMANIT CX-10	water	Copper hydroxide carbonate 16.3% (w)	Bis-n-(cyclohexyldiazeniumdioxy)-copper 3.50% (w)	Boric acid 5% (w)		(9)
QNAP8 MU (= concentrate)	Oil	Copper naphthenate 68% (w) (= 8% Cu)				(10)
SLEEPERPROTECT	Oil	Copper hydroxide	N, N-didecyl-N methylpoly (oxyethyl) ammonium propionate			(11)
TANASOTE S40	Oil	Copper hydroxide	Didecyl-dimethyl-ammonium carbonate	Penflufen		(11)

Legend: (w) = on a weight basis. Water: the product is impregnated using a water-based solution. Oil: the product is impregnated as a solution of aliphatic hydrocarbons. Note: copper hydroxide carbonate is usually a 1:1 mixture of copper-carbonate and copper-hydroxide with a copper content of 57.3% (w).

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[5] https://toelatingen.ctgb.nl/nl/authorisations/14287

[6] https://webapps.kemi.se/BkmRegistret/Kemi.Spider.Web.External/Produkt/Details?produktId=12255&produktVersionId=17271

[7] https://webcommunities.hse.gov.uk/connect.ti/pesticides/view?objectId=10180 https://tinyurl.com/y38vuvak

[8] https://echa.europa.eu/documents/10162/5c99bec7-161e-132d-3448-7b2f04212044

[9] http://www.qchem.nl/images/pdf/ATG_NL_2012.pdf

[10] http://nisuscorp.com/wood-preservation/railroad-ties-qnap

[11] https://www.baua.de/DE/Themen/Anwendungssichere-Chemikalien-und-Produkte/Chemikalienrecht/Biozide/pdf/Biozidprodukte-im-Entscheidungsverfahren.pdf

3.1.4 *Conclusions on basic risk analysis*

In this first safety screening, the potential presence of contaminants is the main driver for performing more in depth assessment. In order to make statements about the differences in hazards or risks, and in potential for circularity, specific data are required for each material about the presence of contaminants. However, the availability of data for the different sleeper types was very different and as a result a very scattered image emerges. Wood treated with biocides is extensively characterized, whereas for the other sleepers only few data on the presence of ZZS and other substances was available, mainly taken from public literature. These data do point to the potential presence of some substances of concern (Table 5), although it is not possible to distinguish from natural background levels. For various ZZS a more in-depth assessment is necessary to come to a comparison of the different sleepers.

Table 5: Overview of the basic risk analysis, indicating presence of listed ZZS (dutch SVHC) and other substances of concern.

Sleeper	**Listed ZZS present**	**Other substances of concern present**	**Information source**
Cement concrete (NS90)	metal ions like chromium, lead, mercury*	a.o. copper*	Verschoor *et al.* (2006) Appendix 12
Sulphur concrete	metal ions like chromium, lead, mercury*	a.o. sulphate	(Mohamed and El-Gamal, 2010)
Preserved wood	propiconazole	copper, tebuconazole	https://rvszoeksysteem.rivm.nl/stof/detail/1125; https://toelatingen.ctgb.nl/nl/authorisations/14287
Wood	Metals like chromium, lead, cadmium*	a.o. copper*	(Szczepkowski and Nicewicz, 2008)
Recycled PE	e.g. PBDE, DEHP	e.g. DEP	(Nichols, 2004; ten Broeke, 2014; Groh *et al.*, 2019)
PU-Glass fiber	?	?	

* Trace levels in natural materials (background levels) cannot be excluded
? no data were available to include or exclude any presence

3.2 In depth analysis of the various sleepers

In the basic analysis it was established that sleepers made of concrete, wood, or plastic, may contain ZZS. For various ZZS a more in-depth assessment is necessary to conclude whether there might be a risk or not, or to come to a comparison of the different sleepers.

In this section, the proposed methodology (section 2.2.2) is applied to the various selected sleepers:

- Cement concrete sleeper
- Sulfur concrete sleeper
- Wood treated with wood preservatives
- Wood

- Recycled PE plastic
- PU-glass fiber.

3.2.1 *Concrete sleepers*

The laying of the track bed, including the use of stony sleepers as designed building material, has to comply with the national Soil Quality Decree. All stony building materials in the entire building materials chain must comply with the maximum composition and emission values. Such values have been drawn up for substances that often occur in building materials and that influence the quality of the soil.
All building materials must be demonstrated to meet these standards set. This must be demonstrated with environmental hygiene statements and a delivery note (see e.g. (KIWA, 2016)). The environmental hygiene statement states the quality of the batch of building materials.

The maximum composition and emission values can be found in Appendix A of the Soil Quality Arrangement (NEN, 2004; Verschoor *et al.*, 2006).[12] For example, the maximum emission value for copper from molded stony construction material, found in Appendix A, is 98 mg/m^2, determined in the NEN7375:2004 test, as the cumulative emission over 64 days. For sulphate this value is 165000 mg/m^2.
The available LCA for the concrete sleepers did not consider emissions during the use phase (SGS Search, 2019b).

3.2.2 *Wood treated with wood preservatives*

3.2.2.1 Regulation of wood preservatives

The EU assessment framework for wood preservatives is in line with the approach for ZZS. The use of wood preservatives is in principle prohibited, unless the use is permitted. Preserved wood is seen as a treated article and may only be placed on the EU market if the active substances for wood preservation are approved for that intended use. The active substances, their application, and the intended use of the treated wood, are assessed for risks for humans, animals and the environment, as well as for various hazardous properties of the active substances such as carcinogenicity, mutagenicity, reproduction damage, endocrine disruption, and persistence in combination with accumulation in the food chain and (eco-)toxicity (PBT).

Authorized substances and products should meet all the criteria set in Regulation 528/2012. However, it is possible to approve substances and products while not all criteria are met. In that case, it is assessed that there is overriding societal concern to approve the substances (temporarily). The authorization of active substances is periodically reviewed (every 5-15 years). When it is time for renewal, it is possible that active substances no longer meet the risk or hazard criteria due to the introduction of new assessment criteria or guidelines, or due to new knowledge about substance properties. It is also possible that dossiers for active substances are no longer defended by applicants.

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[12] [In Dutch: Regeling van 13 december 2007, nr. DJZ2007124397, houdende regels voor de uitvoering van de kwaliteit van de bodem]. Emission threshold values apply to inorganic parameters (19 parameters, including various metals) determined using the NEN 7375:2004 standard "Leaching characteristics - Determination of the leaching of inorganic components from molded or monolithic materials with a diffusion test - Solid earthy and stony materials". The test involves submerging blocks of the material under water in controlled conditions, over a period of 64 days. The water is changed at pre-determined intervals and samples analyzed to identify any leaching of constituents.

All wood preservatives that are permitted in the Netherlands are based on copper. In addition to copper, other substances against bacteria and fungi can be present. This concerns mainly quaternary ammonium compounds, boron, or organic fungicides. See Table 4 for a selection of products that are permitted in the Netherlands or were described elsewhere. For this module the Tanalith 3462 product based on copper, tebuconazole and propiconazole, was selected.

3.2.2.2 *Risk assessment of wood preservatives*

Risks to the environment arise when the active substances leach from the wood. This leaching is determined experimentally and yields a "leaching factor" or flux (mass / area / time). This flux depends on various factors such as the dosage, presence of other substances, type of wood, water content of the wood, the execution of the impregnation process, and the method of testing the leaching rate. In the laboratory assessment a continuous immersion is applied, as if the wood is in permanent contact with (ground)water. This most likely results in higher leaching compared to a situation where contact with water is limited, due periods of dry weather, or local hydrological circumstances. The chosen flux is multiplied with the lifespan to arrive at a total load on the soil.

The use of sleepers falls under Class 4 (UC4) according to the European standard EN335: Wood constantly in contact with the ground (CEN, 2013). The various products have varying prescribed doses of copper for this usage class. The dosages for the active substances other than copper are always smaller compared to copper. We take the assessment of the environmental risks of the Tanalith 3462 product by the Board for the Authorization of Plant Protection Products and Biocides (Ctgb) as the starting point[5]. The instructions recommend that 27.8 kg Tanalith 3462 / m^3 wood is retained after impregnation (retention), for the use of this wood as sleepers. The data selected in the EU risk assessment are presented in Table 6.

Table 6: Leaching rates calculated from available Tanalith E 3462 data on UC4 timber: laboratory immersion data.

Substance	**Retention rates**	**Leached over time ($mg.m^{-2}$)**		**Daily leach rate ($mg.m^{-2}.d$)**		**Fraction of dose lost over 20 years**
	Actual test ($kg.m^{-3}$)	T1 0-30 days	T2 30 days - 20 years	T1 0-30 days	T2 30 days - 20 years	%
Copper	2.5	743.22	1765.14	23.97	0.24	1.1
Tebuconazole	0.05	26.63	78.11	0.86	0.0107	2.4
Propiconazole	0.05	31.16	125.56	1.01	0.017	3.9

For the receiving soil compartment, a soil profile of 50 cm is chosen as default, with a water volume fraction of 0.2, a bulk density of 1700 $kg.m^{-3}$ fresh weight soil (fw) or 1500 $kg.m^{-3}$ dry weight soil (dw), and organic matter content of 3.4%.

For tebuconazole (EFSA, 2014) and propiconazole (EFSA, 2017), based on their properties like soil degradation rate (mean DT50-values at 20°C are in the range of 29 – 106 days) and soil sorption (geometric mean

K_{om} values are in the range of 550 – 575 L/kg), the predicted fraction remaining in the soil (after it leached from the sleeper) after one year is 8 – 12% (RIVM, 2002). In the EU risk assessment, dissipation is accounted for in the calculations of soil[13] and groundwater concentrations[5].

The calculations in the EU assessment are done for 20 years. Over 50 years we look at 3 cycles of placing newly treated wood. Since the bulk of the leaching is achieved in the first days to years, we assume that the addition of the first 10 years of the third cycle counts as a full service life. For copper, which does not dissipate, this leads to a 3x higher concentration. For tebuconazole and propiconazole, that dissipate over time, the cumulative addition over 50 years differs very little from that over 20 years given the leaching profile, in which most is leached in the first year.

The concentrations are compared to predicted no-effect concentrations to give an estimate of the risk to the soil compartment (Table 8).

Table 7: Concentrations in soil and groundwater for copper, tebuconazole and propiconazole.

Substance	**Emission**	**Immission**	**Concentration in**			
	from sleeper $mg.m^{-2}$	into soil $kg.ha^{-1}$	soil $mg.kg^{-1}$ wwt	groundwater $\mu g.L^{-1}$	soil $mg.kg^{-1}$ wwt	groundwater $\mu g.L^{-1}$
Duration of leaching	20 years	20 years	20 years	20 years	50 years	50 years
Copper	1765.14	8.87	1.04	0.12 ([14])	3.13	0.35
Tebuconazole	78.11	0.39	0.0009	<0.1 ([15])	0.001	<0.1
Propiconazole	125.56	0.63	0.0019	<0.1 ([15])	0.002	<0.1

Table 8: Risk quotients for soil for copper, tebuconazole and propiconazole

Substance	**Concentration in soil Addition over 50 yrs**	**PNEC values ([5])**	**Risk quotient**
	$mg.kg^{-1}$ wwt	$mg.kg^{-1}$ wwt	[-]
Copper	3.13	40.35	0.078
Tebuconazole	0.001	0.1	0.01
Propiconazole	0.002	0.1	0.02

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[13] In the EU assessment[5] Table 2.8.4.3.1-3 gives the soils concentrations for leaching from treated transmission poles. These can be corrected for the differences in scenario dimensions between poles and sleepers (concentrations for sleepers are 4 times lower) and the between the OECD sleeper scenario and the Dutch sleeper scenario (section 1.3.1.1) (concentrations are 1.18 times higher in the Dutch scenario).

[14] The concentration in soil porewater C_{pw} [$mg.L^{-1}$], given a copper K_{om} of 175440 $L.kg^{-1}$, equals 0.000112*C_{soil} [$mg\ kg_{wwt}^{-1}$].

[15] Calculated using PEARL[3].

Copper also occurs as a natural element in both the work (ballast bed) and in the substrate. The Dutch negligible risk level in soil[16] is 36 mg/kg dw (equals 31.8 mg/kg ww). The Dutch Environmental Quality standard for the function class Industry, to which the work (the ballast bed) must comply, is 190 mg/kg dw (168 mg/kg ww).

We also note that in section 2.2.2.2 the contribution of copper from overhead electricity lines is calculated to be about 7 – 97 times higher than that from treated wood.

Table 9: Risk quotients in groundwater for copper, tebuconazole and propiconazole

Substance	**Concentration in groundwater** **Addition over 50 yrs**	**Groundwater standard**	**Risk quotient**
	$\mu g.L^{-1}$	$\mu g.L^{-1}$	[-]
Copper	0.35	15	0.02
Tebuconazole	<0.1	0.1	<1
Propiconazole	<0.1	0.1	<1

In the EU assessment this groundwater concentration for copper is tested against the drinking water standard for copper: 2 mg/L. The national reference value for dissolved copper in the shallow groundwater, including the background level, is 0.015 mg/L. The calculated concentration in groundwater is below both standards. For organic fungicides, the standard for groundwater is 0.1 µg//L[1]. The combination of propiconazole, tebuconazole plus their common metabolite 1,2,4-triazole remains (far) below 0.1 µg/L[1] in all scenarios[5].

The total addition of the active substances from wooden sleepers compared to (industrial) soil background levels and risk limits is acceptable.

3.2.3 *Wood*

Natural oak contains copper in a concentration of about 2 mg/kg dw in the outer hearth wood (Szczepkowski and Nicewicz, 2008). Assuming a density of about 750 $kg.m^{-3}$, this is about 0.06% of the concentration of copper in treated wood. The risk of copper leaching from natural wood is considered negligible.

3.2.4 *Plastic sleepers*

Sleepers can be made from virgin or recycled plastics. Virgin plastics will need to meet the REACH criteria where it concerns impurities and additives. Once a product has reached the end of its life, it is considered waste. In general, there are specific (administrative) rules and permit procedures under waste materials legislation for the processing, use and transport of waste materials. These rules remain formally valid until the waste status is explicitly, legally, removed. This can be done using the so-called End of Waste (EoW) mechanism under the European Waste Framework Directive, article 6. Plastic recyclate can be given EoW status only if the original plastic waste does not need to be regarded as

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[16] https://rvs.rivm.nl/

hazardous waste on the basis of the CLP and the POP regulation and the recyclate is permitted on the market under the REACH regulation. The Netherlands policy framework on waste (LAP3) includes guidance on performing this assessment[17]. In principle, impurities <0.1% allow for recycling. If ZZS substances were present >0.1%, a further risk assessment would be needed to establish safe use.

A standardized leaching test (EN 71 part 3)[18] with recycled (PE) plastic, steel-enforced, sleepers showed no detectable leaching of Sb, As, Ba, Cd, Cr, Pb, Hg or Se (all <1 mg/kg) (Lankhorst, 2019). The leaching test is normalized for toys, and the limits for the individual metals are >=25 mg/kg. The test suggest that the plastic would comply with the standards for these metals, if it were a toy. However, other substances (like other metals, plasticizers, flame retardants) were not looked for.

Microplastics
Application of plastics on a large scale should consider the potential impact from release of microplastics to the human health and the environment. For the specific case of railway sleepers there is lack of exact release rates for to their handling and use. Release can likely be expected when plastic sleepers are processed and installed (sawing, drilling and embedding in the ballast bed etcetera) before and during their installation into the ballast bed. It can also be foreseen that the minute movements against the ballast bed can result in release of microplastics. For instance, a 0.2% weight loss was measured in a wear resistance test on a PE-steel sleeper type 101 (Lankhorst, 2019), although this is in contrast to a negligible weight loss found in a wear test on PE-steel sleeper type 102. The discussion on the (eco)toxicological relevance of microplastics is far from concluded (Hale *et al.*, 2020). Current policy measures aim at reducing the release of intentionally added microplastics from products. This is an issue to consider for the PE and PU based sleepers.

3.2.5 *Discussion and conclusions*

The module on substances of concern considers active substances in treated wood, and additives or contaminants in concrete and plastic sleepers. All sleepers are regulated (be it by different legislations) and should comply with relevant environmental quality standards. These standards and approaches may differ in detail, but in general serve the same goal: ensure protection of humans and the environment. From this overall point of view, there should be no major differences between the sleeper types.

Emissions from construction materials are regulated in national legislation and the emissions from the sleepers is considered against a backdrop of the quality of the whole track bed, which is considered industrial soil. Concrete sleepers may leach (metal-) ions, but this should stay below legal emission standards. Wood preservatives are EU-wide regulated and for the Dutch situation, typically the copper-based wood preservatives are in scope. Plastic (recycled) sleepers may be a

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[17] https://lap3.nl/beleidskader/deel-b-afvalbeheer/b14-zeer/

[18] European standard EN 71 specifies safety requirements for toys. EN 71-3: Specification for migration of certain elements.

source for microplastics, plasticizers and flame retardants (DEP, DEHP, PBDE) but in principle, impurities <0.1% allow for recycling.

Only for treated wood, all relevant data are publicly accessible. Available data indicate that copper leaches from treated-wood sleepers to some extent, but that the added fractions are small compared to both the soil background levels, soil quality standards, and also to copper losses from overhead lines. Leaching of organic wood preservatives likewise occurs within regulatory acceptable risk limits. Material specific data for cement concrete sleepers, Sulphur concrete sleeper, RPE sleepers, or PU-glass fiber sleepers, were not available, with the exception of data that eight heavy metals were not detected in leachate from recycled PE.

It is to be expected that the suppliers have analytical data on the presence and/or leaching of potential contaminants available, since conformity to regulations and to company specifications must be demonstrated within the product chains.

3.3 Substances and their relation to End of Life scenarios

Considerations on safety for re-use of materials after service life of the wooden, stony, or plastic sleepers are rather similar. Once a product has reached the end of its life, it is considered waste. For the three material groups, there are differences to get to an end-of-waste (EoW) situation, in the sense of actually becoming available for reuse or recycling in the next life cycle (R+1).

Reuse of stony building materials is possible within the limits of the Soil Quality regulations discussed above.

Plastic recyclate can be given End of Waste status if the original plastic waste does not need to be regarded as hazardous waste on the basis of the CLP and the POP regulation and the recyclate is permitted on the market under the REACH regulation[19]. This assessment can be made up-front, but in particular relevant will be the criteria that apply at the moment of recycling, in combination with the quality of the materials at that moment. Clearly, contamination of the sleepers during service life should also be considered at that moment. Contamination of the track bed with copper from overhead lines was documented by Ten Berg (1998). Material may also be contaminated with oil residues.

For wood treated with wood preservatives, the current situation is different. The National waste plan 3 (Sector plan 36 Wood)[20] is clear: preserved wood is not to be re-used. It must be landfilled or burnt in a controlled manner.[21]

- In the case that EoW would be given, and preserved wood could be placed on the market as a treated article for re-use, Article 58 of the Biocidal Products Regulation 528/2012 stipulates that the wood must be labeled (specifying the active substances and

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[19] https://lap3.nl/beleidskader/deel-b-afvalbeheer/b14-zeer/

[20] https://lap3.nl/publish/pages/120639/lap3_sp36_hout_19_07_2019.pdf

[21] There are two specific exceptions permitted under REACH (Regulation 1907/2006): reuse of creosoted wood dating from before 2002 and for CCA (copper-chromium-arsenic) wood dating from before 2007. These exceptions have no relevance to the current assessment.

instructions for use) as determined in the evaluation of those substances, what further information obligation must be fulfilled (all relevant instructions for use, including precautions to be taken, if this is necessary to protect people, animals and the environment), and for which use the wood may be intended. What is possible as a new destination depends on what has been assessed in the European substance assessment, and found acceptable.
    - If, at the time of placing on the market for re-use, one or more of the active substances present are no longer permitted as wood preservatives, the preserved wood may not be placed on the market for re-use according to the BPR.
    - In the event that the active substances are authorized at that time, it is possible that not every form of re-use is permissible under the BPR. And for those uses that are authorized, the person who places the material on the market must comply with a number of obligations with regard to correctly informing customers about the presence of active substances and all instructions for use necessary to protect humans, animals and the environment.
    - The authorization of active substances is periodically reviewed (every 5-15 years). There are various factors that (in combination) can lead to active substances being no longer permitted at a given moment: new assessment criteria, new knowledge about substance properties, changes in the availability of alternatives that weigh the societal interest differently, or because a substance dossier is no longer defended (for whatever reason) by an applicant.
- In conclusion, there are currently no options for reuse of treated wood, and in the event that EoW would be given and certain uses are -at that time- indeed allowed under the BPR, in order to place the articles on the market, it will require detailed track-and-tracing of every single sleeper (since it should be declared what active substances are present) and a detailed liability to the person who places the articles on the market.

4 Sustainability

4.1 Environmental Benefit

The environmental impact assessment covers the extraction of raw materials, the manufacturing of a sleeper from raw materials, the installation in a railway and the potential benefit at end of life.

4.1.1 *Greenhouse gas emissions first life cycle*

Using secondary or renewable content reduces the emission of GHG during the raw material extraction and manufacturing of sleepers (Figure 5). This can be seen by the low impacts found for the two types of wooden sleepers (oak wood as renewable); Sulphur concrete which is based on Sulphur as residual material from hydrodesulfurization of gas and oil; the recycled PE-steel sleeper. Overall for all sleepers the impact of raw materials is higher than that of the process of sleeper manufacturing. It is also clear that the impact of the fastening system for recycled PE-steel, wooden and PU-glass fiber sleeper types is slightly higher than the impact of the fastening system used in the cement concrete baseline and therefore slightly compensating the benefit.

Sulphur concrete sleepers have the lowest GHG emissions, 7.3 ton CO_2-eq per FU. The use of virgin materials, mainly Portland cement (CEM-I) in concrete, virgin PE and virgin PU result in higher GHG emissions for the sleepers using those materials. As concrete sleepers are the baseline scenario here, there is an increase in emission of GHG when they are replaced by sleepers from PU-glass fiber (24 ton CO_2-eq), virgin PE-steel (17 ton CO_2-eq), recycled PE-steel (3.8 ton CO_2-eq) and untreated wood (0.5 ton CO_2-eq). There is a reduction in GHG emissions for the Sulphur concrete and treated wood sleepers of 11 ton CO_2-eq and 5.1 ton CO_2-eq, respectively. Again, this is when only one life time is taken into account. The benefits due to reuse and recycling are discussed below.

The uncertainty analysis for service life shows that only the Sulphur concrete sleeper has a lower GHG emission compared with the baseline which covers most of uncertainty due to a potentially higher and lower service life. For all the other sleeper types, the benefit of reduced GHG emission compared to the baseline cement concrete sleeper partially depends on the service life in practice. This is particularly the case for the recycled PE-steel, treated and untreated wood sleepers. For these three sleeper types it also becomes important to include other potentially differentiating impacts, such as differences in transport distance and maintenance, not taken into account here. This includes the further formalization of reuse of the ribbed baseplate in wooden sleepers. When new ribbed baseplates are applied on every sleeper replacement which occurs in 50 years, this means an additional emission of 26 and 8.3 ton CO_2-eq. per FU for untreated and treated wooden sleepers, respectively.

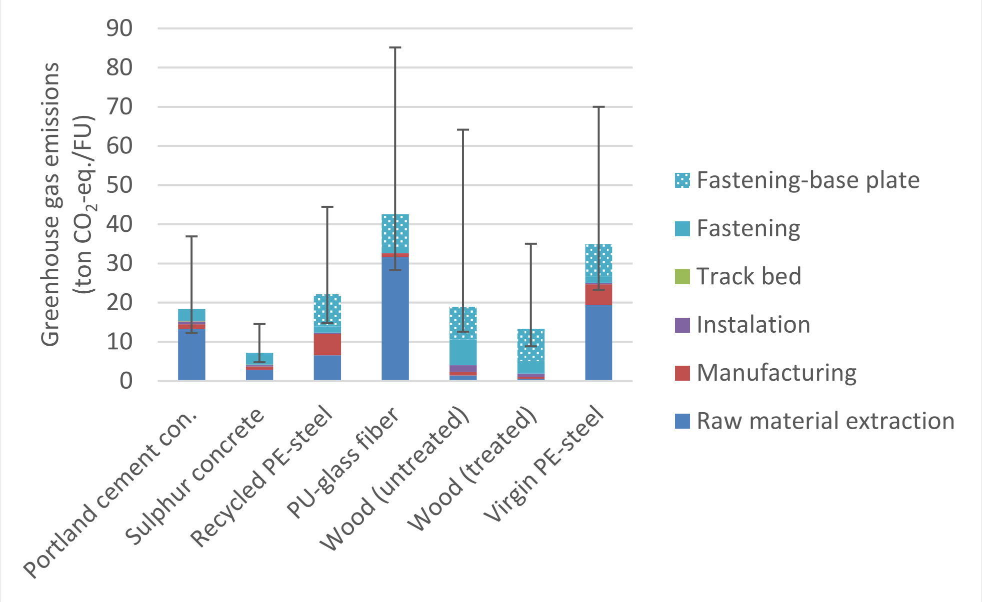

Figure 5: Greenhouse gas (GHG) emissions associated with different parts of a railway sleeper and fastening system per FU. Portland cement concrete is considered the baseline scenario. Whiskers give the upper and lower bound of GHG emissions associated with the sleepers with a longer or shorter service life and the effect of using a new steel base-plate with every wooden sleeper replacement.

4.1.2 *Avoided and net greenhouse gas emissions – next life cycle*

Reuse, recovery and recycling of old materials can avoid the emission of GHG in a next life cycle when these materials provide a benefit to a new product. The benefit of recycling and reuse depends on the replaced product (Table 3). In the analysis of the potential for avoiding GHG emissions in the future, the recycled PE-steel, virgin PE-steel, Wooden and PU-glass fiber sleepers perform better than concrete (Figure 6). The Sulphur concrete sleepers have less avoided emissions through recycling due to the low GHG emissions of the replaced materials (Sulphur concrete). This is even though in the baseline the materials can for the most part not be applied for production of new sleepers and the reclaimed Sulphur concrete can.

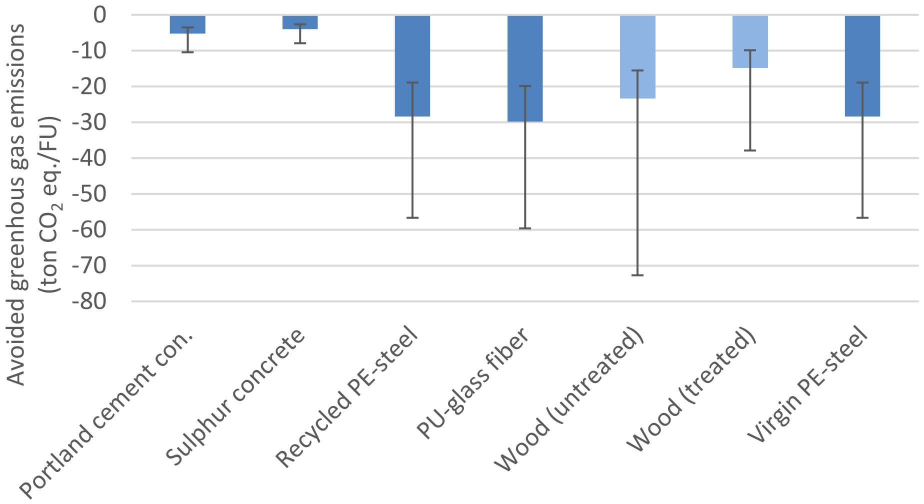

Figure 6: Potentially avoided GHG emissions in the next life cycle due to the reuse, recycling (dark blue) or energy recovery (light blue) from different railway sleepers. Portland cement concrete is considered the baseline scenario. Whiskers indicate upper and lower bound due to uncertainty in service life.

As wooden sleepers are assumed to be incinerated for the generation of electricity, it should be noted that incineration for energy recovery is likely also an option for the PU-glass fiber, and PE sleepers. This is not taken into account here as recycling is the preferred option. Moreover, the emissions avoided by the incineration of wooden sleepers is dependent on the carbon footprint of the Dutch electricity mix at the time of incineration. As the energy transition proceeds, the carbon footprint of the Dutch electricity mix will go down. Following the Paris goals, this should significantly reduce the carbon footprint of avoided ‘grey’ electricity, by as much as 90% in 2050 compared to 1990 levels. This means that although we show here the time weighted average total avoided GHG emissions over a 50 year period, the benefit for the first 12 year life cycle (2020-2032) of an untreated wooden sleeper will be higher compared to the baseline, but the last life cycle (2058-2070) the benefit is lower compared to the baseline cement concrete sleeper, because of the changing composition of the grey electricity mix.

This brief discussion of the method and results for calculating the future benefit of avoided GHG emissions illustrate the difficulty of a proper comparison of such benefits for different sleeper types. There is a large variation in uncertainty and meaning of the different amounts of GHG emission avoided. The spared resources in the next life cycle is different for the different sleepers, e.g. from energy recovery to virgin PE (Table 3). For this reason, separately comparing the benefit in the next life cycle is far from straightforward as this benefit is specific to the end of life scenario for that sleeper type. One way of illustrating the relationship between the End of Life scenario and the initial impact of sleeper production is by calculating the net potential GHG emissions by subtracting potentially avoided GHG emissions in the future from those emitted now at production (Figure 7). This makes a comparison over the overall GHG emission possible for the first and second life cycle together.

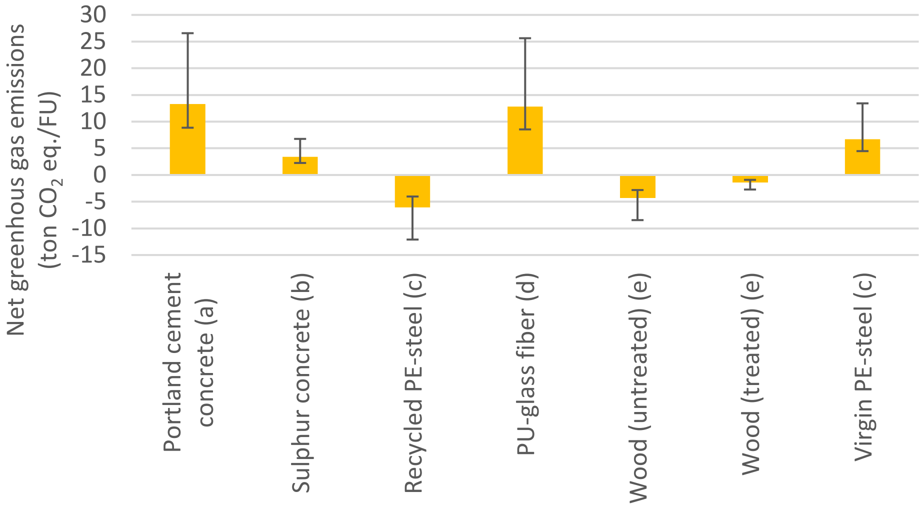

Figure 7: Net greenhouse gas (GHG) emission from production in the first life cycle and avoided GHG emissions in the next life cycle. Portland cement concrete is considered the baseline scenario. End of Life scenario consisting of (a) cement concrete and steel recycling; (b) Sulphur concrete and steel recycling; (c) PE and steel recycling; (d) PU-glass fiber sleeper reuse; I wood incineration; all scenario's include steel recycling and incineration of polymer based materials from the fastening systems. Whiskers indicate the upper and lower bound related to the uncertainty in service life.

4.1.3 *Land use*

It is clear that wooden sleepers require the most land for production, untreated wooden sleepers need 45.000 m^2a and treated wooden sleepers need 23.000 m^2a (Figure 8). The difference between treated and untreated sleepers is based on the longer life time of treated wooden sleepers. The baseline cement concrete, virgin PE-steel and PU-glass fiber sleepers require less than 1.000 m^2a. There was no data available for land use of recycled PE or Sulphur concrete, but the land use of these two sleeper types is also expected to be below 1000 m^2a. The land use of recycled PE will be lower compared to virgin PE. This brief analysis clearly shows that wood as bio-based application has a more than 100 times higher Land Use footprint compared to the cement concrete baseline. The two virgin PE-steel and PU-glass fiber sleepers both also show a higher land use footprint, but only between 2 to 7 times higher than the cement concrete baseline, respectively. Given the uncertainty of land use estimates compared to other environmental impacts, more often considered, it remains to be seen if the differences in land use footprint of the two plastic sleepers can be considered significant in terms of overall environmental impact (see section 4.3).

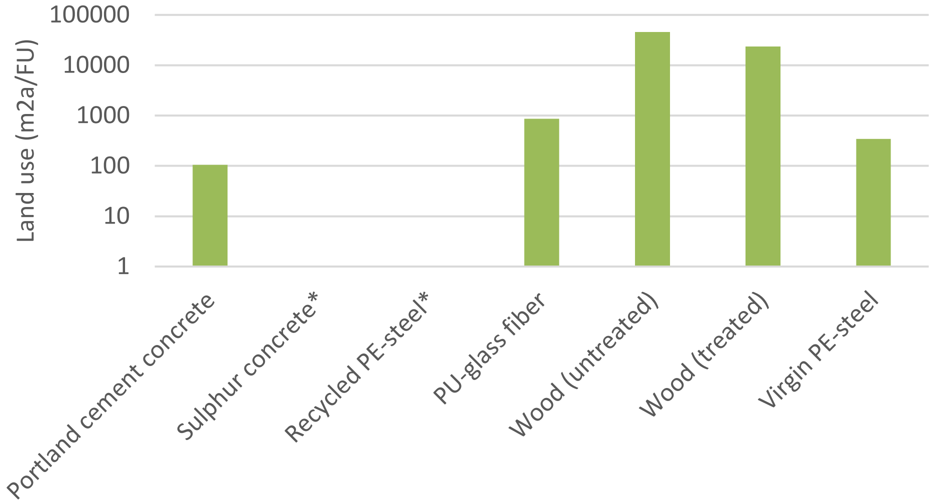

*Figure 8: Land use related to raw materials required for the functional unit: 167 sleepers per 100m of railroad track for a period of 50 years. Portland cement concrete is considered the baseline scenario. *No data on land use.*

4.2 Circularity

4.2.1 *Tier 1*

One of the first checks as part of the circularity assessment within the SSML framework is if the product consists of materials that are considered critical raw materials following the EU classification (Table 10) (Deloitte *et al.*, 2017). Another check is that for supply security, meaning that the renewable or secondary material that is used for the new product is not limited in its availability (Table 10). For the recycled PE sleepers there might be a reason for concern relate to the supply of household waste with PE and other recycled PE. Yearly around 200.000 sleepers are replaced, when all of these sleepers are replaced with recycled HDPE this might result in a potential supply problem because this consists of 42% of all recycled HDPE in the Netherlands (Kawecki *et al.*, 2018; Afvalfonds verpakkingen, 2019). When we extend the scope of supply to the whole of Europe this fraction will be lower, but this is enough reason to warrant research in transport and actual recycled PE content when such a product becomes mainstream in the Netherlands or even in Europe. For wooden sleepers the supply concern is more limited. If all sleepers would be replaced with wooden sleepers there is a need for 19 * 10^3 m^3 of non-coniferous sawlogs. This is 18% of the harvest of non – coniferous sawlogs in the Netherlands, and only 0.0644% in the EU (Eurostat, 2020). This shows that supply varies greatly based on geographical scale considered, however for Dutch sleeper production, there might be a supply concern. The current supply of Sulphur concrete is unknown, so supply security could not be assessed. No other sleepers are expected to have supply security concerns in relation to having negative consequences in other sectors that might want to use the same materials.

Table 10: presence of critical raw materials and supply security of the materials.

Sleeper type	CRM	Supply concern (>1% market share)	Is there possibility for recycling/re-use?
Portland cement Concrete	No	No[a]	No[c]
Sulphur concrete	No	-[b]	Yes
Wood (untreated)	No	Potential (NL)	No
Wood (Cu treated)	No	Potential (NL)	No
Recycled PE-steel	No	Potential (NL)	Yes
Virgin PE-steel	No	No[a]	Yes
PU-glass fiber	No	No[a]	Yes

[a]Not determined; [b]virgin material, no supply check; [c]not as a sleeper

4.2.2 *Tier 2*

Three different indicators were used to present the circularity comparison of the different sleepers: i. Renewable or secondary content (SSML-1), ii. Recyclability (SSML+1) and iii. the Material Circularity Indicator (MCI).

The wooden (treated and untreated) and recycled PE-steel sleepers have the highest percentage of renewable or secondary content (SSML-1, Figure 9). The recycled and virgin PE-steel, PU-glass fiber and Sulphur concrete have the highest recyclability (SSML+1, Figure 9). Recyclability is determined in SSML+1 based on the percentage of material becoming available for another life cycle and the quality of that released material. Although for cement concrete, all stony materials are granulated and made available for recycling, it is not used in production of new sleepers and as such the quality factor is relatively low (0.25). The recycled PE, virgin PE, PU-glass fiber and Sulphur concrete have the highest recyclability. The most determining factor of the recyclability was the quality of the recycled resource. The suppliers of the recycled PE, Sulphur concrete PE and virgin PE sleepers all argued that their sleepers are 100% recyclable into new sleepers, a recycling efficiency of 95% was assumed for these sleepers. Treated wood cannot be recycled based on existing legislation, resulting in the incineration of wood. However, the steel in the fastening system applied is recycled, resulting in a recyclability of 0.24. Untreated wood is mostly incinerated but can be recycled into chipboard. When untreated wooden sleepers are incinerated, this results in a recyclability of 0.25, as related to the steel parts, when they would be recycled into chipboard this would results in a higher recyclability.

The MCI gives an overall view of the circularity of the sleeper including the aspects of the SSML indicators and the expected life span. Cement concrete sleepers have a low MCI-score (Figure 9) because concrete sleepers are made from virgin content and there is no clear recycling strategy that enables material from old concrete sleepers to be applied into new concrete sleepers. Wooden sleepers, especially untreated, also score generally very low on the MCI as their life expectancy is lower than average and they are in general not recycled. Recycled PE sleepers score highest concerning the MCI as they consist out of recycled plastic and can be recycled into new sleepers at the end of their life cycle. The supply of secondary PE for these sleepers and its effect on overall environmental impact should be further investigated, i.e. full PE material cycle, extending beyond sleeper production. The Sulphur concrete, PU-glass fiber and Virgin PE+steel sleepers al score a MCI higher than cement concrete due to their high recyclability (SSML+1) combined with a 45 to 50 year service life.

As the lifespan of the different sleeper types is rather uncertain and depends on several factors the sensitivity of the MCI to potentially lower and higher lifespans (Table 2) is calculated (Figure 9). This shows that sensitivity to a 50% reduction in service life is significant when 50 years is considered the default. But also, that a longer service life of the cement concrete and treated wooden sleepers has a relatively large positive contribution to the MCI score compared to the other sleepers that already have a 50 year service life. Furthermore, it should be noted that the applied indicators do not include a factor or indicator for reduction of material use. For instance, the cement concrete baseline and the Sulphur concrete sleeper both consist of about 2-3 times more weight of material than the other sleeper types, about 285 kg versus 96-107 kg, respectively.

In conclusion the circularity compared to concrete sleepers is larger for all alternative sleeper types, except for untreated wood. The circularity of the untreated and treated wooden sleepers can be increased if a method for safe reuse can be found, although it is unlikely that this reuse will be realized for railway sleeper production. The concrete sleepers’ circularity can also be potentially increased if the granulate from old cement concrete sleepers can be used again in new concrete sleepers.

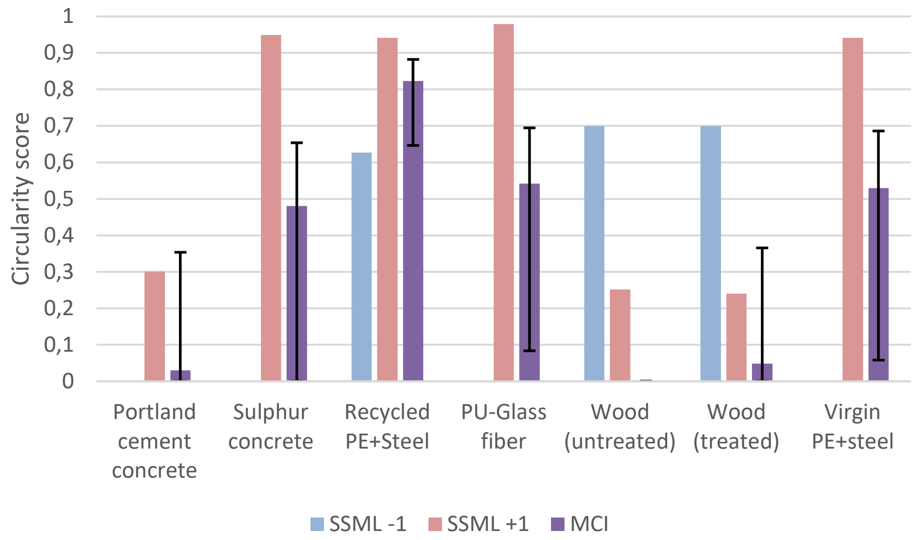

Figure 9: Circularity of different sleepers as expressed in the Material Circularity Indicator (MCI), the secondary or renewable material content (SSML -1) and future material recyclability (SSML+1). Portland cement concrete is considered the baseline scenario.

4.3 Conclusions and discussion on sustainability benefit

The environmental benefits, in terms of reduced environmental impact, discussed here relate to the comparison of different sleeper types to the baseline scenario (NS90, cement concrete sleepers). An increase in the degree of product circularity is also part of the environmental benefit. In this case the sustainability benefit is only assessed for the environment and other sustainability elements, such as the financial and societal aspects are not considered.

Benefits now and in the future
The emissions that occur during the material extraction and manufacturing are not diminished by the emissions that can be avoided in a next life cycle due to reuse, recycling or recovery. This is because the emissions from raw material extraction (A1), manufacturing (A3) and installation (A5) are emissions that occur now, whereas emissions avoided take place in the future, at the end of Life of the railway sleeper (in ~50 years). For this reason, we advise to look further than the net-impact and take both the impacts now and the future benefits into consideration as two separate criteria. These future benefits in terms of avoided emissions are dependent on the process or products that they actually help avoid in the real future. Although uncertain, the future benefits do provide an indication of the potential of the chosen sleeper material.

Reality and uncertainty
The comparison of GHG emission made here includes several uncertainties and is for a specific selection of sleeper products. This uncertainty partly comes from the use of generic data instead of product specific data.

This plays a role in the assessment of the baseline GHG emission for cement concrete. The inventory data for the Portland (CEM-I) cement (SGS Search, 2019b), contains a 30% increase in GHG emission over the producer specific EPDs following the Dutch implementation of EN-15804. This results in an overestimation of the GHG emissions related to the production of the cement concrete baseline. Another reason to expect lower GHG emissions of Portland cement concrete sleepers is the use of alternative cement types, such as CEM-III/A based on blast furnace slags. In future analysis it is advised to use product specific data here, as is done in the study by (Lindeberg *et al.*, 2018) for the Swedish market. The two concrete sleepers studied there result in an at least 30% lower GHG emission for the first life cycle. Taking these considerations into account a more optimistic baseline would likely result in a GHG emission for the first life cycle more similar to the copper treated wooden sleeper (~12 ton CO_2/FU). However, the limited benefits in the next life cycle of such an optimistic baseline, likely results in a net GHG emission (~7 ton CO_2/FU) more similar to the virgin PE-steel sleeper, meaning the Sulphur concrete, recycled PE-steel and both wooden sleepers still have a lower net GHG emission.

Also, for the wooden sleepers generic Ecoinvent data is used, although here no 30% increase is applied as there is no indication that this data is not representative for the situation in the Netherlands. Another uncertainty related to wood is the assumption that the wood is produced with sustainable forest management. Without sustainable forestry, the GHG emissions of the wooden sleepers will be higher as the carbon sequestration potential of the forest is diminished.

Similarly, for other sleeper types uncertainty in the inventory data cannot be excluded, however producer specific data is used for the Sulphur concrete, PE-steel and PU-glass fiber sleeper types. Only specific attention is given here to the uncertainty in service life of all sleeper types as most of these products have not been around for as long as they are expected to last. This is even so for the cement concrete baseline sleeper (NS90) from the 90’s from which the oldest sleepers will reach their intended service live in 2045.

Environmental impact: greenhouse gas emission and land use
Environmental impact is linked to both GHG emissions and land use. Land use has a much stronger correlation with ecosystem damage than GHG emissions. Through normalization the land use and GHG emissions associated with the sleepers can be added together to get a combined score for the environmental impact. Normalization using the ‘ILCD’ method results in only small differences in overall comparison between sleeper types with a 20% to 30% increase in single score impact of the treated and untreated wooden sleepers due to land use, respectively. Normalization with the ‘milieuprijzen’ method results in a much larger normalized environmental impact for the wooden sleepers because this normalization method puts a higher weight on land use (Figure 10). Although GHG emissions of the wooden sleepers was similar or lower compared to the baseline, the land use is so high that there is considerable uncertainty in the environmental benefit of the two types of wooden sleepers when considering the carbon footprint and land use together. Furthermore, also when normalized to the endpoint species lost per year, the treated and untreated wooden sleepers have a much higher impact on ecosystems compared to the others (see Figure A1 in appendix A).

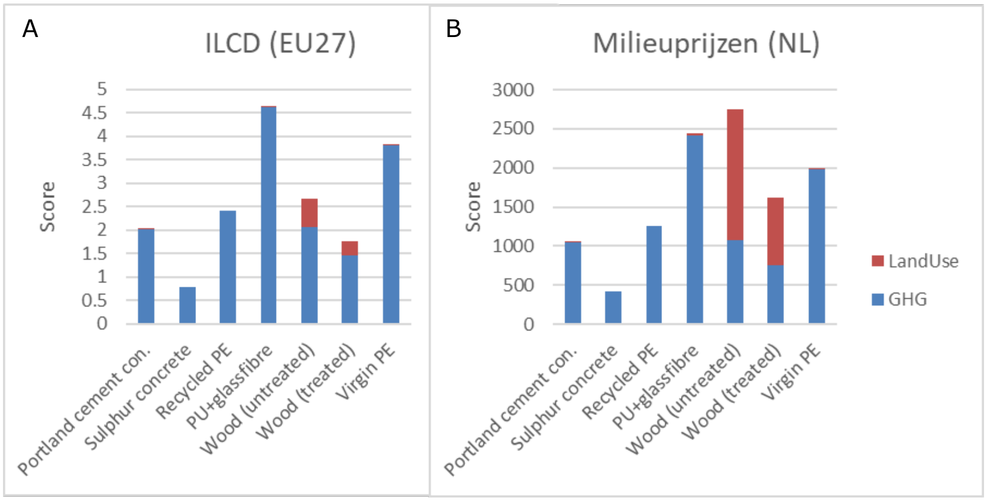

*Figure 10: Normalized score of GHG emissions and land use associated with the production of 167 sleepers. Normalization done with the "ILCD (EU27)"(A) and "Milieuprijzen (NL)" (B) set. More emission of GHG and more land use results in a higher score. Portland cement concrete is considered the baseline scenario. *No land use data was available for Sulphur concrete.*

Other alternative sleeper types

Here we compared the sleeper types based on a limited scope of designs and materials. The studied railway sleepers are not exhaustive of those currently available on the market. For instance, we included a sleeper made from Sulphur concrete with similar design to the baseline cement concrete (NS90), but there are also other material formulations being applied for this same design, such as cement concrete using CEM-III instead of CEM-I as cement, which consists of blast furnace slags, lowering the overall GHG emissions. Furthermore, the recycled PE-steel sleeper has a different design from the glass fiber reinforced PU sleeper. There are also other sleepers already on the market that follow the design of the wooden and PU-glass fiber sleeper, but apply recycled PE (Lindeberg *et al.*, 2018). In another comparison of GHG emission of railway sleeper types in Sweden, two types of glass fiber reinforced PE sleepers show a GHG emission lower than that of the two cement concrete sleepers taken into account in that study (Lindeberg *et al.*, 2018).

5 Considering safety and sustainability

5.1 Conclusions and recommendations

The aim of this study was to compare different railway sleepers considering safety and sustainability. This was done by assessing the following aspects:

- The concerns related to ZZS, biocides and other substances during use and at End of Life (Table 11)
- The carbon and land use footprint during material extraction and production of railway sleepers (Table 12)
- The material circularity considering the previous and next life cycle and sleeper service life (Table 12).

In a choice for a railway sleeper type it is advised to consider all three different aspects in addition to others that are part of a feasible business case: e.g. cost and potential practicality's related to the technical specification, installation and maintenance of railways.

Safety
The safety assessment did not identify any contaminants that pose an immediate safety concern and that most areas of concern are covered by existing regulatory safeguards. However, several sources of uncertainty where identified which should be given further consideration (Table 11). One was the lack of access to studies on composition of or leaching from the plastic and stony materials applied. It is recommended that ProRail verifies such data within the supply chain. Also, if the composition of the sleeper material should change, this should be accompanied with new tests on composition or leaching. Another source of uncertainty is the presence or emission of emerging contaminants. Existing safeguards might -in hindsight- not be adequate when emerging contaminants such as per- and polyfluoroalkyl substances or microplastics come into view. New scientific evidence or new regulatory standards may alter the future appreciation of products currently in use.

Environmental impact – first life cycle
The Sulphur concrete sleepers show a clear benefit in the reduction of environmental impact compared to the cement concrete baseline sleepers when only considering the first life cycle (Table 12). The carbon footprint of Copper treated wooden sleepers are lower than that of the concrete baseline sleeper, but the land use is considerably higher, also compared to the other sleeper alternatives. Although the contribution towards overall environmental impact of applying wooden sleepers is uncertain, e.g. this depends on the normalization method applied, land use should be explicitly considered. For the PU-glass fiber and virgin PE sleeper the initial impact of material extraction and sleeper production is almost double that of the cement concrete baseline. Here, the recycled PE-steel sleeper does benefit because it uses recycled PE, which has a much lower carbon footprint than its virgin alternative.

Overall environmental impact – first and next life cycle
All of the sleeper types have benefits related to recycling, reuse or incineration. In avoided GHG emissions after 50 years (next life cycle), all of the sleepers outperform the baseline sleeper in terms of avoided GHG emission, except for the Sulphur concrete sleeper (Figure 6). To compare the benefits of the different end of life scenario's in terms of reduced GHG emissions, the net GHG emissions are calculated based on the emission of the first life cycle and those potentially avoided in the next (Figure 7 and Table 12). This overall GHG emission indicates that the PU-glass fiber sleeper has a similar carbon footprint compared to the cement concrete baseline, where the other types have a reduced carbon footprint. It should be noted however, that this net carbon footprint should be put into perspective of the initial GHG emissions of production of the different sleeper types, as the future benefit is often uncertain. This uncertainty relates to the assumption being made on the actual avoided material or energy use after a period of 50 years. For this reason, the material circularity is also beneficial to include in this analysis.

Circularity
The material circularity of all, except the wooden sleepers outperforms, that of the concrete sleeper (Figure 9). Although wood is considered a renewable material, the lower lifespan of the wooden sleepers compared to the 50-year FU and incineration at End of Life greatly hampers the overall circularity. For instances the MCI increases from 0.05 to 0.37 when the lifespan of the copper treated sleepers is increased from 25 to 37.5 years. However, a similar increase in MCI is also seen for the baseline concrete sleeper when the service life is 50% longer (67.5 years), from 0.02 to 0.34.

The increased demand for recycled PE for the manufacturing of the 200.000 sleepers being replaced annually is considered high. This means that it is currently uncertain that the benefit of using recycled PE can be fully allocated to the recycled PE sleepers. This is because an increase in demand will likely not immediately increase the supply and thus might not result in an overall reduction in virgin PE use. This means there is a potential cause for trade-offs elsewhere in the PE material cycle. This needs to be investigated further. If this would be the case it can be expected that the environmental impact is between that of the recycled PE and virgin PE sleepers, e.g. due to the need of applying a larger fraction of virgin PE. The geographic distribution of resources is also relevant here, where the Dutch supply of wood for sleeper production would be significant, although much smaller at a European scale. Sulphur concrete sleepers have Sulphur as the key ingredient, which is a by-product of fossil fuel production and use. Sulphur emission criteria for fossil fuels demand desulphurization and thus currently does not seem to be greatly limited in supply, but this might change in the future as its basis is a fossil fuel, which warrants some further investigation.

Uncertainty
One of the aspects reducing the sustainability benefit of wooden sleepers compared to some of the others is the lack of current reuse potential of wooden sleepers in the next life cycle (R+1). This might be an area to develop further, as increasing the reuse would be an added

benefit and increase circularity of wooden railway sleepers. However, since both waste regulations and product regulations are in play, not only technical and commercial, but also regulatory obstacles need to be navigated. In this sense it is good to realize that the benefit in avoided GHG emissions due to recycling or reuse is from the material or product it replaces. Of particular interest is the energy recovery from wood as this relates to the energy it replaces. For this reason, there is a large uncertainty in the estimate of avoided GHG emissions, with a lower benefit being more likely due to the planned energy transition towards more sustainable energy sources by the end of the 50 years, currently taken as the reference life span of these railway sleepers. Indirectly this also applies to all the other railway sleeper types which indirectly also avoid energy use for production. As this is a simplified environmental impact assessment based on the carbon and land use footprint, other impact types might be considered in more thorough analysis.

The actual LCA numbers will differ in practice per time and place when put into action, e.g. depending on the opportunities of the supplier with regard to sustainability (e.g. type of energy use during production or the production plant). The main contribution of this analysis is to show the potential of the different systems: what are currently the hotspots? What are currently important tradeoffs (e.g. clearly visible in the wooden sleeper’s discussion and the fastening systems). And, what is the potential for circularity and benefits in the future? Although not precise and subject to change in the near future because of technological developments the results as such provides input for strategic decision making on the direction towards a more sustainable system and which development paths you want to explore together with the foreseen suppliers.

Table 11: overview of substances safety analysis per railway sleeper.

	Portland Cement Concrete	**Sulphur Concrete**	**Untreated wood**	**Copper treated wood**	**Recycled PE**	**Virgin PE**	**PU-glass fiber**
Outcome of assessment	No detailed analysis (Specific data* not available at the time)		In natural materials some metals can be present in trace levels, not likely to exceed background quality standards	Copper and other active substances do not leach in amounts higher than current risk limits.	No detectable leaching of some metals. No information on other contaminants.	Unclear what substances of concern would be present.	
Safeguards in place	Although ions like sulphate and of heavy metals might leach, they should meet current regulatory standards for stony construction materials.			Active substances must meet substance specific risk limits.	Presence of additives should be at levels <0.1% or meet regulatory standards under REACH.		
Considerations for further work	Common sourcing of virgin materials in sleepers reduces the emissions compared to application of often contaminated fly ashes and other waste flows.			Approval status may change, but this does not affect materials in use.	Potential release of microplastics. A wide range of additives or contaminants may be present.		

* Leaching data is available within the product/material chain.

Table 12: Overview of sustainability benefit analysis per railway sleeper type compared to the cement concrete baseline (NS90).

	Sulphur Concrete	**Untreated wood**	**Copper treated wood**	**Recycled PE**	**Virgin PE**	**PU-glass fiber**
This life cycle *(GHG emissions)*	60% Lower GHG emissions	<5% lower/higher GHG emissions	30% lower GHG emissions	20% higher GHG emissions	90% higher GHG emissions	130% higher GHG emissions
	No data	More than 100x higher land use	More than 100x higher land use	No data	2x higher land use (230%)	7x higher land use (730%)
Next life cycle *(net GHG emissions)*	Recycling potential for sleeper materials. 75% lower GHG emissions	Energy recovery results in 130% lower GHG emissions	Energy recovery results in 110% lower GHG emissions	Recycling potential for all sleeper materials. 150% lower GHG emissions	Recycling potential for most sleeper materials. 49% lower GHG emissions	Reuse or recycling potential for most sleeper materials. <5% lower GHG emissions
Circularity *(Material Circularity Index (MCI))*	MCI of 0.48, due to recyclability of sleepers at end of life and 50 year life span	MCI of 0 due to low life span (12 years) and only recycling of steel parts.	MCI of 0.05 due to lower life span (25 years) and only recycling of steel parts.	High MCI of 0.82 due to use of secondary materials and recyclability of PE and steel and 50 year life span	MCI of 0.53 due to recyclability of PE and steel at end of life and 50 year life span	Average MCI of 0.54 due to reuse of sleepers at end of life and 50 year life span.

5.2 Reflections on the SSML method

5.2.1 *Application of the SSML framework*

In presenting information on a specific recycling option or product it was envisaged that a material safety and sustainability data sheet would be beneficial, see figure A2 in the appendix. However, the goals in this analysis and application of the SSML framework was to compare different railway sleeper alternatives. This leads creating an overview that reported the most relevant and differentiating results in two tables (Table 11 and Table 12) for the safety and sustainability assessment. These tables are aimed at giving the decision maker a clear overview of all the options, but can likely be improved in the future. Although the data sheets are not provided, the results from the safety and sustainability analysis are given per sleeper type in a separate excel file: https://www.rivm.nl/bibliotheek/rapporten/2020-0181.xlsx

5.2.2 *Sustainability benefit*

5.2.2.1 Adaptation circularity module

As presented in the methods section the circularity method was changed in order to assess railway sleepers, a product, instead of recycling options, e.g. recycling of old tires to rubber infill for artificial soccer pitches. In adjusting the two indicators related to the SSML module on circularity: SSML R-1 and SSML R+1, the indicator on contribution to closing the full material cycle was left out. However, application of the Material Circularity Indicator proved helpful in assessing different railway sleepers. The MCI considers both aspects of the two SSML indicators with the additional inclusion of product life span related to a benchmark. This makes the MCI indicator a beneficial method to asses circularity for products. The adaptation to include renewable materials is deemed relevant. In the future the reuse potential in addition to recycling can be better integrated in the MCI as suggest by Bracquené *et al.* (2020). It is also recommended to include a factor for taking into account the quality of recycling materials, e.g. the use as infill in low grade applications compared to use at the same performance level as its source. This can be done in a similar way as applied for the SSML+1 indicator.

5.2.3 *Safety module*

5.2.3.1 Differences in regulating safety

The broad scope of materials and substances as part of the different railway sleepers assessed using the SSML method have highlighted the differences in current product regulations, e.g. biocide law versus the construction code. Within the safety module we saw that different materials are regulated by different legislations. Although these legislations share the same goal of a high level of protection of humans and the environment, the way in which this is safeguarded differs.

For treated articles and biocides, a risk-based approach is followed, complemented with hazard based decision making as well as – if needed - weighing risks and benefits. For stony molded construction materials, emission of certain elements is regulated, with a view to meet risk based environmental quality standards. For plastic materials, risks of contaminants are safeguarded based on composition, followed by a risk/hazard assessment. At the technical level, there may be differences in the way models operate or in the data underlying emissions or risk limits, with the result that there may be differences in acceptability of levels of contaminants between the products. However, such differences are inherent given the need to take up new scientific and societal developments, which is an ongoing process, implemented in discrete steps. It would be beneficial to develop a metric that would numerically compare a products safety 'performance', in addition to the existing product specific safeguards.

5.2.3.2 *Data requirements high for numerical comparison*

Where it comes to comparing the performance between products, a common feature of having regulations in place, is that in general the use of the products is deemed safe, or not. It is a binary assessment: yes or no. Although the performance of different products may vary with respect to 'numerical' risk quotients, this difference (e.g. the risk of product A is 10 times lower than that of Product B) is not relevant to the regulator when standards are met by both products. This creates challenges to numerically compare the performance across modules.

For treated wood, we extended the time window of the assessment from 20 years (at authorization of wood preservatives) to 50 years, which did not really change the outcome. For most materials, several pieces of information on composition and leaching were not available. Although such data should exist to meet demands in the product chain, we were not able to verify that they indeed complied with the standards set. Since all products are regulated, it is here assumed that the safety will be safeguarded.

In relation to safety we also learned that although environmental quality standards may be in place, the whole assessment should be seen against multiple backgrounds. The environmental quality standard represents a generic null-situation: as if there were no other activities, but acknowledging that background concentrations may exist. Comparison with limits for industrial soil represents a business-as-usual scenario: there is room for activities but there are – inevitably - limits. This does not stimulate a reduction in emission of substances of concern embedded in e.g. the ALARA principle: as low as reasonably achievable. Additionally, the analysis of copper in railway sleepers also highlighted the background coming from other sources, i.e. overhead lines. In the hypothetical situation that emissions from sleepers were not regulated, this would have provided a significant benchmark.

In relation to circularity we learned that repurposing of treated wood is not only regulated by waste regulations, but also by product regulations. The marketing of articles treated with biocides is governed by the Biocidal Products Regulation (BPR) 528/2012, regardless of waste regulations, and this creates major liabilities for the person placing recycled treated articles on the market.

5.2.4 *Comparing safety and sustainability*

It is already common to include information on safety and on environmental impact in decision making, e.g. in procurement. However, this information is often scattered in separate pieces of information related to a single product, e.g. an LCA study and technical safety data sheets. By applying the SSML framework, this information is simplified and restructured to make a fair comparison possible. The tiered approach also provides the possibility to first screen different options before delving into more data intensive higher tier assessments.

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7 References

Afvalfonds verpakkingen (2019). Monitoring verpakkingen resultaten inzameling en recycling 2018. Leidschendam, Afvalfonds verpakkingen.

Bolin, C. A. and S. T. Smith (2013). "Life Cycle Assessment of Creosote-Treated Wooden Railroad Crossties in the US with Comparisons to Concrete and Plastic Composite Railroad Crossties." Journal of Transportation Technologies **03**(02): 149-161 DOI: 10.4236/jtts.2013.32015.

Bracquené, E., W. Dewulf and J. R. Duflou (2020). "Measuring the performance of more circular complex product supply chains." Resources, Conservation and Recycling **154**: 104608 DOI: 10.1016/j.resconrec.2019.104608.

Bruyn, S. d., S. Ahdour, M. Bijleveld, L. d. Graaff, E. Schep, A. Schroten and R. Vergeer (2017). Handboek Milieuprijzen 2017. Delft, CE Delft.

CEN (2013). EN 335:2013 Durability of wood and wood-based products – Use classes: definitions, application to solid wood and wood-based products. Brussels, CEN.

CEN (2019). European standard EN 71 specifies safety requirements for toys. EN 71-3: Specification for migration of certain elements. Brussels., CEN.

CEN/TC 256 (2015). Railway applications — Track — Concrete sleepers and bearers — Part 1: General requirements. **FprEN 13230-1:2015**.

CO2emissiefactoren.nl. (2020). "Lijst emissiefactoren." from https://www.co2emissiefactoren.nl/lijst-emissiefactoren/#brandstoffen_energieopwekking.

CO2Logic (2009). Etude comperative des émissions de CO2 des voies posées sur traverses en bois et en béton.

Deloitte, Britisch Geological Survay, Bureau de Recherches Géologiques et Minières and Netherlands Organisation for Applied Scientific Research (2017). Study on the review of the list of Critical Raw Materials. European Comission. Brussels, European Comission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs Raw Materials, DOI: 10.2873/876644.

EC (2016). COMMISSION STAFF WORKING DOCUMENT: IMPACT ASSESSMENT Defining criteria for identifying endocrine disruptors in the context of the implementation of the plant protection products regulation and biocidal products regulation, Annex 5 out of 16, Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL on endocrine disruptors and the draft Commission acts setting out scientific criteria for their determination in the context of the EU legislation on plant protection products and biocidal products. Brussels, European Commission. SWD(2016) 211 final Part 6/16, https://ec.europa.eu/transparency/regdoc/rep/10102/2016/EN/SWD-2016-211-F1-EN-MAIN-PART-6.PDF.

ECHA (2013). Assessment Report Tebuconazole Product-type 7 (Film preservative) Helsinki, ECHA, http://dissemination.echa.europa.eu/Biocides/ActiveSubstances/0051-07/0051-07_Assessment_report.pdf.

ECHA (2015). Assessment Report Propiconazole Product-type 7 (Film preservatives). Helsinki, ECHA, https://echa.europa.eu/documents/10162/a2efc9fe-98ed-de5e-fe77-e87b8822b6d9.

Ecochain (2020). LCA background report FFU sleepers. T. v. d. Kruk, Ecochain. **05-06-2020**.

Ecoinvent (2017). Ecoinvent 3.4, https://www.ecoinvent.org/.

EFSA (2014). "Conclusion on the peer review of the pesticide risk assessment of the active substance tebuconazole." EFSA Journal **12**(1).

EFSA (2017). "Peer review of the pesticide risk assessment of the active substance propiconazole." EFSA Journal **15**(7).

Eissens, H. (1998). Diffuse pollution along the open track. MSc thesis WUR land and water management. Commissioned by the Foundation soil sanitation Dutch rail (SBNS). Plus addendum SBNS oktober 1998. Wageningen, WUR.

Ellen MacArthur Foundation (2015). Circularity Indicators - An Approach to Measuring Circularity.

Eurostat. (2020). "Roundwood removals by type of wood and assortment." Retrieved 26-6-2020, from https://ec.europa.eu/eurostat/product?code=for_remov&mode=view.

Gartiser, S., I. Heisterkamp, U. Schoknecht, N. Bandow, M. Burkhardt, M. Ratte and O. Ilvonen (2017). "Recommendation for a test battery for the ecotoxicological evaluation of the environmental safety of construction products." Chemosphere **171**: 580- - 587.

Groh, K. J., T. Backhaus, B. Carney-Almroth, B. Geueke, P. A. Inostroza, A. Lennquist, H. A. Leslie, M. Maffini, D. Slunge, L. Trasande, A. M. Warhurst and J. Muncke (2019). "Overview of known plastic packaging-associated chemicals and their hazards." Science of The Total Environment **651**(2): 3252 - 3268.

Hahladakis, J. N., C. A. Velis, R. Weber, E. Iacovidou and P. Purnell (2018). "An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling." Journal of Hazardous Materials **344**: 179-199.

Hale, R. C., M. E. Seeley, M. J. La Guardia, L. Mai and E. Y. Zeng (2020). "A Global Perspective on Microplastics." Journal of Geophysical Research: Oceans **125**(1) DOI: 10.1029/2018jc014719.

Hillier, S. R., C. M. Sangha, B. A. Plunkett and P. J. Walden (1999). "Long-term leaching of toxic trace metals from Portland cement concrete." Cement and Concrete Research **29**(4): 515-521.

Huijbregts, Z. S. A. S. M. H. S. G. G. W. M. (2017). "Resource Footprints are Good Proxies of Environmental Damage." Environmental Science and Technology **51**(11): 6360-6366 DOI: 10.1021/acs.est.7b00698.

Jang, J. G., Y. B. Ahn, H. Souri and H. K. Lee (2015). "A novel eco-friendly porous concrete fabricated with coal ash and geopolymeric binder: Heavy metal leaching characteristics and compressive strength." Construction and Building Materials **79**: 173 - 181.

Janssen, M. P. M., J. Spijker, J. P. A. Lijzen and L. G. Wesselink (2015). Plastics that contain hazardous substances: recycle or incinerate? . Bilthoven, RIVM. RIVM Letter report 2016-0025.

JRC (2003). Technical Guidance Document on Risk Assessment. Ispra, European Communities, https://echa.europa.eu/documents/10162/16960216/tgdpart2_2ed_en.pdf.

JRC (2012). Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods.

Kawecki, D., P. R. W. Scheeder and B. Nowack (2018). "Probabilistic Material Flow Analysis of Sven Commodity Plastics in Europe." Environmental Science and Technology **52**(17): 9874 - 9888 DOI: 10.1021/acs.est.8b01513.

KIWA (2016). Nationale beoordelingsrichtlijn voor het NL-bsb® productcertificaat voor de milieu-hygiënische kwaliteit van cementgebonden mortels, KIWA Nederland BV, Rijswijk.

Kuterasińska, J. and A. Król (2017). "Leaching of heavy metals from cementitious composites made of new ternary cements. ." E3S Web of Conferences **19**: 02019 DOI: 10.1051/e3sconf/20171902019.

Lalonde, B. A., W. Ernst, G. Julie, P. Jackman, K. Doe and R. Schaefer (2011). "A Comparative Toxicity Assessment of Materials Used in Aquatic Construction." Archives of Environmental Contamination and Toxicology **61**: 368 - 375.

Lankhorst (2019). Proeftuin Duurzame Dwarsliggers KLP® Hybride Kunststof Hoofdbaan Dwarsligger, Type 102. Lankhorst Doc. No.: 90F19407.

Lijzen, J., E. van der Grinten, A. van Drongelen, C. Moermond and B. Venhuis (2019). Beoordeling hergebruik van luier- en incontinentiemateriaal : Stappenplan en risicobeoordelingskader voor de mogelijke risico's van stoffen en pathogenen in producten. Assessment of recycling of diapers and incontinence materials : Step-by-step plan and risk assessment framework for potential risks of substances and pathogens in products, Rijksinstituut voor Volksgezondheid en Milieu RIVM, DOI: 10.21945/rivm-2019-0111.

Lindeberg, K., S. Welling and Y. Wikström (2018). Comparative LCA of Railway Sleepers. Stockholm, Sweden, Swedish Environmental Research Institute Ltd. (IVL).

Madaster. (2019). "Toelichting Madaster Circulariteit Indicator." from https://docs.madaster.com/files/Toelichting_Madaster_Circulariteit_Indicator_v1.0_nl.pdf.

Marion, A.-M., M. D. Lanève and A. D. Grauw (2005). "Study of the leaching behaviour of paving concretes: quantification of heavy metal content in leachates issued from tank test using demineralized water." Cement and Concrete Research **35**(5): 951-957.

Mohamed, A. M. O. and M. M. El-Gamal (2010). Sulfur Concrete for the Construction Industry: A Sustainable Development Approach. Fort Lauderdale, USA, J. Ross Publishing.

NEN (2004). Standard NEN 7375:2004 nl. Leaching characteristics - Determination of the leaching of inorganic components from moulded or monolitic materials with a diffusion test - Solid earthy and stony materials. Delft, NEN.

NIBE (2020). EPD Thiotrack NS90 [not verified]. **EPD-NIBE-20200712-10693**.

Nichols, D. (2004). Biocides in plastics. Expert overviews covering the science and technology of rubber and plastics. S. Humpfreys. Shropshire, UK., Rapra Technology. Volume 15, Number 12.

OECD (2013). OECD Series On Emission Scenario Documents Number 2. Revised Emission Scenario Document for Wood Preservatives. . Paris, OECD. ENV/JM/MONO(2013)21.

Park, C. I., H. K. Ahn, M. C. Gye and T. H. Lee (2015). "Effects of concrete materials for the stream restoration on *Bombina orientalis* embryos." Ecology and Resilient Infrastructure **2**(2): 147 - 153.

Platform CB23 (2019). Kernmethode voor het meten van circulariteit in de bouw.

Potting, J., M. Hekkert, E. Worrell and A. Hanemaaijer (2016). CIRCULAIRE ECONOMIE: INNOVATIE METEN IN DE KETEN. Den Haag, PBL Planbureau voor de Leefomgeving. PBL-publicatienummer: 2249.

Pronk, M., M. Woutersen and J. Herremans (2020). "Synthetic turf pitches with rubber granulate infill: are there health risks for people playing sports on such pitches?" J Expo Sci Environ Epidemiol **30**: 567-584 DOI: https://doi.org/10.1038/s41370-018-0106-1.

Quik, J. T. K., J. P. A. Lijzen and J. Spijker (2019). Creating safe and sustainable material loops in a circular economy: Proposal for a tiered modular framework to assess options for material recycling. Bilthoven, RIVM, https://www.rivm.nl/bibliotheek/rapporten/2018-0173.pdf.

RIVM, V., VWS (2002). Uniform System for the Evaulation fo Substances 4.9 (USES 4.0). The Netherlands, National Institute of Public Health and the Environment (RIVM), Ministry of ousing, Spatial Planning and the Environment (VROM), Ministry of Health, Welfare and Sport (VWS). RIVM Report 601450012.

SGS Search (2019a). LCA rapport voor Dwarsligger 14-002 (Ongetoetst). M. Weening and G. Vroege. Amsterdam, SGS Search Consultancy. **26.19.00174**.

SGS Search (2019b). LCA rapport voor dwarsligger NS90 (Ongetoetst). M. Weening and G. Vroege. Amsterdam, SGS Search Consultancy. **26.19.00174**.

Spijker, J., M. Janssen and M. Broekman (2015). Hergebruik beeldbuisglasgranulaat : Relatie met REACH en kaderrichtlijn Afval. Reuse of cathode ray tube glass, Rijksinstituut voor Volksgezondheid en Milieu RIVM, https://rivm.openrepository.com/handle/10029/582249.

Stenmarck, Å., E. L. Belleza, A. Fråne, N. Busch, A. Larsen and M. Wahlström (2017). "Hazardous substances in plastics – ways to increase recycling." TemaNord **505**.

Stichting Bouwkwaliteit (2019). Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken.

Szczepkowski, A. and D. Nicewicz (2008). "The content of heavy metals in the wood of healthy and dying oak trees (*Quercus robur* L., *Q. Petraea* (Matt.) Liebl.)." Acta Scientiarum Polonorum **7**(4): 55-65.

Tauw (2018). Sneek, Lankhorst CO2-footprint voor KLP materiaal. J. Kupfernagel. Capelle aan den IJssel, Tauw bv.

ten Berg, J. F. A. M. (1998). Bodemverontreiniging vrije baan door spoorwegstof en spoorwegmaterialen. [Soil pollution free rein due to rail dust and rail materials]. NS Technisch Onderzoek. Rapport NSTO/7150029/002.

ten Broeke, H. M. (2014). Een korte verkenning naar de uitloging van schadelijke componenten uit kunststof gebruikt in oeverbeschoeiingen. . Utrecht, TNO. TNO rapport R12133.

Verschoor, A. J. and R. F. M. J. Cleven (2009). Risk assessment of leaching of substances from synthetic polymeric matrices. . Bilthoven, RIVM. RIVM Report 711701096/2009.

Verschoor, A. J., J. P. A. Lijzen, H. H. V. d. Broek, R. F. M. J. Cleven, R. N. J. Comans, J. J. Dijkstra and P. H. M. Vermij (2006). Kritische emissiewaarden voor bouwstoffen. Milieuhygiënische onderbouwing en consequenties voor bouwmaterialen. [in Dutch]. Bilthoven, RIVM. RIVM report 711701043/2006.

VWN (2015). Wapeningsstaal als onderdeel van een betonnen eindproduct. Apeldoorn, Vereniging Wapeningsstaal Nederland. **1.1.0004.004**.

Xie, K. Y., D.C., D. Habib, M. Judge and C. Kriss (1997). "Environmental chemical impact of recycled plastic timbers used in the Tiffany Street Pier, South Bronx, New York." Resources, Conservation and Recycling **2**: 199 - 211.

Appendix A – figures and tables with supporting information

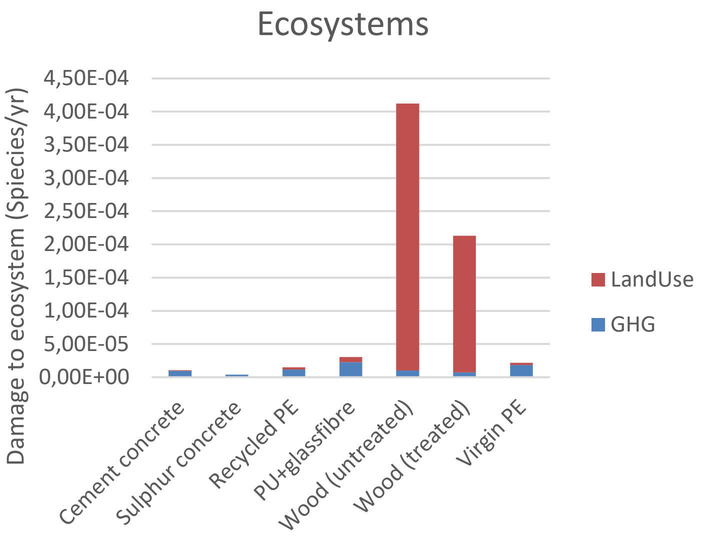
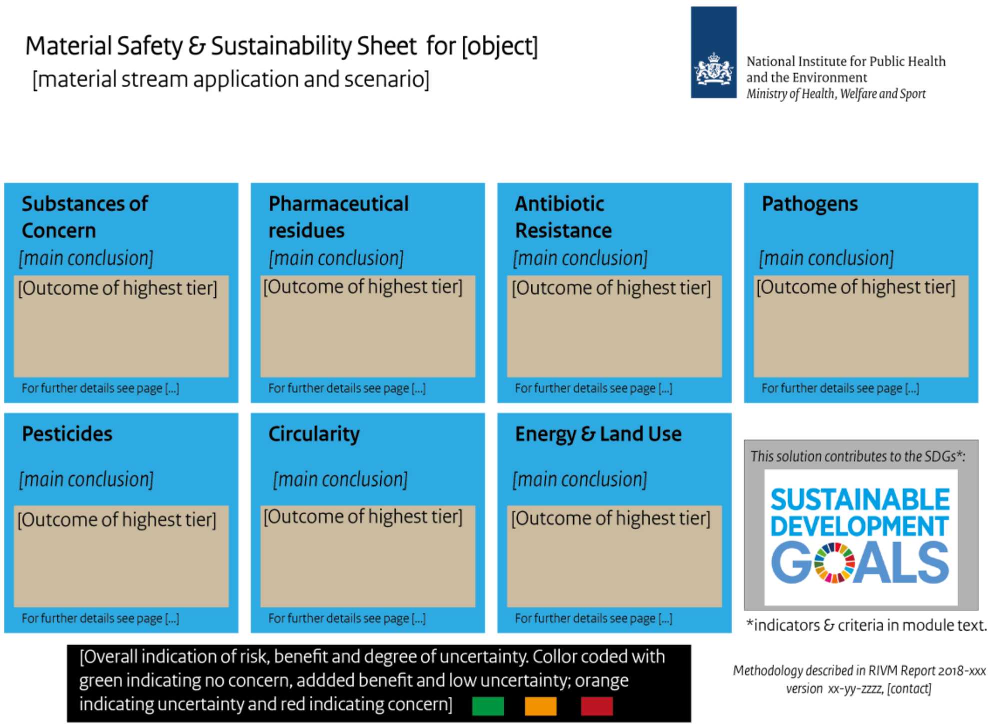


Figure A1: Damage to ecosystems in species lost per year through GHG emissions and land use associated with the production 167 sleepers.



Material Safety & Sustainability Sheet for [object]
[material stream application and scenario]

National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Substances of Concern
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Pharmaceutical residues
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Antibiotic Resistance
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Pathogens
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Pesticides
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Circularity
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

Energy & Land Use
[main conclusion]
[Outcome of highest tier]
For further details see page [...]

This solution contributes to the SDGs:*
SUSTAINABLE DEVELOPMENT GOALS
*indicators & criteria in module text.

[Overall indication of risk, benefit and degree of uncertainty. Collor coded with green indicating no concern, addded benefit and low uncertainty; orange indicating uncertainty and red indicating concern] 🟩 🟧 🟥

Methodology described in RIVM Report 2018-xxx version xx-yy-zzzz, [contact]

Figure A2. The SSML datasheet as designed for recycling options.

Table A1: LCA and inventory data used for the environmental impact analysis.

Sleeper type	**Domain**	**Functional Unit**	**Impact type**	**Value**	**Unit**	**Source**
Wood	material	1 kg Cleft timber	Carbon footprint	0,029	kg CO_2 eq	(Ecoinvent, 2017)
Wood	material	1 kg Cleft timber	Land use	0,854	m2a crop eq	(Ecoinvent, 2017)
Cement concrete	product - A1	1 sleeper (with fastening)	Carbon footprint	88,2	kg CO_2 eq	(SGS Search, 2019b)
Sulphur concrete	product - A1	1 sleeper (with fastening)	Carbon footprint	32,6	kg CO_2 eq	(NIBE, 2020)
Recycled PE	product - A1	1 kg KPL	Carbon footprint	0,31	kg CO_2 eq	(Tauw, 2018)
PU-glass fiber	product - A1	1 sleeper (with fastening)	Carbon footprint	249	kg CO_2 eq	(Ecochain, 2020)
Virgin PE	material	1 kg HDPE	Carbon footprint	1,82	kg CO_2 eq	(Ecoinvent, 2017)
Sulphur concrete	product - D	1 sleeper (with fastening)	Carbon footprint	-21,3	kg CO_2 eq	(NIBE, 2020)
Cement concrete	product - D	1 sleeper (with fastening)	Carbon footprint	-28,1	kg CO_2 eq	(SGS Search, 2019b)
Recycled PE	Product - D	1 kg KPL	Carbon footprint	-2,01	kg CO_2 eq	(Tauw, 2018)
PU-glass fiber	Product – D	1 sleeper (with fastening)	Carbon footprint	-178	kg CO_2 eq	(Ecochain, 2020)
Recycled PE	product - A3	1 kg KPL	Carbon footprint	0,63	kg CO_2 eq	(Tauw, 2018)
Sulphur concrete	product - A3	1 sleeper (with fastening)	Carbon footprint	4,05	kg CO_2 eq	(NIBE, 2020)
Cement concrete	product - A3	1 sleeper (with fastening)	Carbon footprint	6,73	kg CO_2 eq	(SGS Search, 2019b)
PU-glass fiber	product - A3	1 sleeper (with fastening)	Carbon footprint	5,73	kg CO_2 eq	(Ecochain, 2020)
					kg CO_2 eq	
Wood	product - A3	1 sleeper	Carbon footprint	1,3	kg CO_2 eq	(Lindeberg *et al.*, 2018)
virgin PE	material	1 kg HDPE	Land use	0,00992	m2a crop eq	(Ecoinvent, 2017)
Cement concrete	material	1 kg concrete	Land use	0,000739496	m2a crop eq	(Ecoinvent, 2017)
PU-glass fiber	material	1 sleeper	Land use	5,2	m2a crop eq	(Ecoinvent, 2017; Ecochain, 2020)
Recycled PE	product - A5	1 sleeper	Carbon footprint	2,4	kg CO2 eq	(Lindeberg *et al.*, 2018)
Sulphur concrete	product - A5	1 sleeper (with fastening)	Carbon footprint	2,02	kg CO_2 eq	(NIBE, 2020)
Wood	product – A5	1 sleeper	Carbon footprint	2,4	kg CO_2 eq	(Lindeberg *et al.*, 2018)
PU-glass fiber	Product – A5	1 sleeper (with fastening)	Carbon footprint	0,47	kg CO_2 eq	(Ecochain, 2020)

Sleeper type	Domain	Functional Unit	Impact type	Value	Unit	Source
Cement concrete	product – A5	1 sleeper (with fastening)	Carbon footprint	3,92	kg CO_2 eq	(SGS Search, 2019b)
Gravel	material	1 ton gravel	Carbon footprint	126.7	kg CO_2 eq	(Ecoinvent, 2017)
Transport	Rail dieseltrain	1 tonkm	Carbon footprint	0,018	kg CO_2 eq	(CO2emissiefactoren.nl, 2020)
Energy	Shreds (NL)	1 kg ds	Carbon footprint	0,054	kg CO_2 eq	(CO2emissiefactoren.nl, 2020)
Electricity	Electricity (unknown)	1 kWh	Carbon footprint	0,475	kg CO_2 eq	(CO2emissiefactoren.nl, 2020)
Electricity	Electricity (custom mix)	1 kWh	Carbon footprint	0,185	kg CO_2 eq	50 year weighted average, based on a reduction to 0.061 kg CO_2/kWh in 2050.
Steel	Material	1kg steel	Carbon footprint	2,15	kg CO_2 eq	(Ecoinvent, 2017)
Steel	Material	1 kg steel	Land use	0,0354	m2a crop eq	(Ecoinvent, 2017)
Reinforced steel	Material	1 kg steel	Carbon footprint	1,36	kg CO_2 eq	VWN 2015

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