Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Yiru Yiru

The resource requirements and environmental impacts of rail infrastructure

Master's thesis in Industrial Ecology
Supervisor: Edgar Hertwich
Co-supervisor: Lola Rousseau
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Kunnskap for en bedre verden

Abstract

The transport sector is one of the main contributors to climate change. Amongst all types of transport modes, the railway is considered as the greenest one and therefore has been expanded in many countries to decarbonize their transport sector. However, despite the operation of the railway causes less environmental burdens comparing with other types of transports, such as road-based transport, the environmental costs from building railway infrastructure should not be overlooked due to the huge amounts of environmental impacts associated with material/energy production.

This study collected the material and energy intensity data of construction and maintenance stages of three types of railways i.e. high-speed rail (HSR), commuter, and subway to try to build archetypes for each type of railway. The archetypes would be used to estimate the resource consumptions of the railway infrastructure construction and be the basis of the estimation of environmental impacts. The components of railway infrastructure consist of foundation, track system (ballasted track and ballastless track), electrification system, bridges, and tunnels. The data were only collected from literature and documentation, no data were collected from companies due to confidentiality reasons. After collecting the data, pedigree matrices were built to evaluate the data quality. In the end, life cycle assessment was conducted on HSR, and the two other types of railway i.e. commuter and subway were not considered due to the inadequate data.

The main findings from this study are 1) bridges and tunnels are the most material-intensive components; 2) ballastless track consumes more materials, precisely concrete and steel, than ballasted track; 3) concrete, steel, and rubber are the top three contributors to environmental impacts; 4) the main factor influences the uncertainty of the data is completeness, which means lack of data sources causes the uncertainty of data in this study; 5) the environmental studies regarding railways conducted in previous years are mostly about HSR, and other types of rails have not received much attention yet, which leads to lack of information to conduct further studies.

Preface

This master thesis has been carried out at the Industrial Ecology Programme at the Norwegian University of Science and Technology (NTNU) in the spring semester of 2021.

The process of writing this thesis allowed me to stretch my comfort zone as well as my knowledge about railway engineering, and also to gain experience in conducting research work. Therefore, I would like to express my deepest appreciation to my supervisor Professor Edgar Hertwich and co-supervisor Lola Rousseau. This thesis would not have been completed without their great guidance and feedback.

I am also grateful to Professor Albert Lau, from the Department of Civil and Environmental Engineering at NTNU, for kindly and patiently answering my questions.

It has been a tough year due to COVID-19, but I am lucky that I have my beloved IndEcolers who were always there to support each other. I have had a perfect two years in Norway because of them. Therefore, I must also thank my best IndEcolers. Especially, I would like to thank Tazrin Ahmed for offering her valuable advice.

I am deeply indebted to my parents and my sister for always encouraging and supporting me to pursue my dream.

Yiru Yiru

Trondheim, June 2021

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List of Abbreviations (or Symbols)

GHG	Greenhouse Gas
LCA	Life Cycle Assessment
HSR	High-speed Rail
LCI	Life Cycle Inventory
HBL	Hydraulic Bound Layer
TBM	Tunnel Boring Machine
NATM	New Austrian Tunneling Method
CV	Coefficient of Variation
RECC	Resource Efficiency and Climate Change

1 Introduction

1.1 Context

The transport sector is one of the main contributors to global warming. In 2015, the direct greenhouse gas (GHG) emissions from transportation accounted for approximately 23% of total energy-related CO_2 emissions and 14% of total global GHG emissions (IPCC, 2014). To achieve the goal of the Paris Agreement, "…holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels…", it is urgent to decarbonize the transport sector (*Paris Agreement*, 2015).

According to (International Energy Agency, 2019), the railway is considered as the greenest transport, it accounts for 4.2% of CO_2 emission from the transport sector. Therefore, expanding railway infrastructure has a great potential to achieve the climate change mitigation goal. Besides the advantages regarding global warming, the build-out of railway infrastructure has many other benefits, such as addressing traffic congestion issues, meeting the increasing demand for transportation as the consequence of population growth and social development.

Despite the environmental-friendly aspect of railway transport, the huge amounts of material requirements of railway infrastructure construction should not be neglected because of the environmental impacts associated with material production, i.e. around 23% of global GHG emissions is generated from material production and 80% of it related to the production of construction and manufactured goods materials (Hertwich et al., 2020). Besides material requirements, energy consumption should also be taken into consideration because of the significant environmental impacts generated from energy production, i.e. the energy sector is responsible for two-thirds of global GHG emissions (*IRENA*, 2017).

1.2 Aim and scope

Although there are already a considerable number of studies conducted on the environmental impacts generated from railway transport, especially the studies in terms of the GHG emissions from railway services, the construction, and maintenance stages of railway associated with large amounts of material and energy use, still have not received enough attention (Bizjak et al., 2016; Chester & Horvath, 2010; Jonsson, 2007). In addition, thanks to the increasing use of renewable energy and reduced carbon intensity of the operation, the environmental impacts generated from the railway infrastructure construction stage might have a larger share than before. Therefore, to fill the research gap mentioned above, it is important to have a comprehensive understanding of the resource consumption of railway infrastructure. With this purpose, this study tried to build archetypes for different railway types, i.e. high-speed rail (HSR), commuter, and subway by collecting material and energy intensity data.

While a number of life cycle assessment (LCA) and material stock studies provided material use data, there are few studies collecting life cycle intensity (LCI) data as a purpose to build archetypes. Most of them were only conducted within a specific region or component e.g. railway track bed or sleepers in the UK. Therefore, the LCI data of railway infrastructure including foundation, track system, tunnels, and bridges as well as electrification systems have been collected in this study. Also, LCA was carried out to calculate the environmental impacts by using archetype data.

The outcome of this study would help decision-makers or engineers to have a clear understanding of the material and energy consumptions of railway infrastructure to improve material efficiency as well as to estimate the environmental impacts from historical and future railway infrastructure.

The aim and scope of this study can be summarized as follows:

The aim and scope of this study are to build archetypes for different types of the railway infrastructure, considering construction and maintenance phases. In addition, LCA will be carried out to calculate the environmental impacts generated from these two life cycle stages.

The research aims to answer the following questions:

- What are the definitions of archetypes of rail infrastructure, including type, characteristics, composition in terms of elements?
- What are the life cycle inventories of different elements of the railway infrastructure and how is the data quality?
- What are the environmental impacts of railway infrastructure per km of the double track?

1.3 Outline

To answer the research questions mentioned above, this thesis is structured as follows:

Chapter 2 presents the previous studies conducted on railway infrastructure.

Chapter 3 presents each component of railway infrastructure as well as the definitions of construction and maintenance activities.

Chapter 4 is the archetypes part. This chapter consists of the following sections: In the first section, the methodologies to build archetypes and pedigree matrices are shown; in the second section, the material intensity data of each component of railway infrastructure are presented; in the third section, the results of different railway archetypes are showed and the three types of railways i.e. HSR, commuter, and subway are compared; lastly, data quality is presented by using pedigree matrices.

In chapter 5, environmental impacts from high-speed railway are estimated by using life cycle assessment methodology.

In chapter 6, the challenges encountered in this thesis and the future work are discussed.

2 Literature review

In this chapter, the relevant studies conducting environmental impact assessments or material stock research on railway infrastructure are presented.

Life cycle assessment of German high-speed passenger train, ICE (von Rozycki et al., 2003): the cumulative energy use, material consumption, and CO_2 emissions of German ICE trains in construction, operation, and maintenance stages are evaluated in this study. The results showed that the material consumption of railroad infrastructure does not have a high share of the whole life cycle resource consumption, which is not consistent with other studies. While the material consumption of the ballastless track is higher than the ballasted track in the construction stage, the longer life expectancy, and less maintenance of the ballastless track make it compete well with the ballasted track. The tunnel construction and the heating of rail points are the main energy-intensive activities.

Life cycle assessment of Chinese high-speed rail (Yue et al., 2015): this study used the Chinese Core Life Cycle Database (CLCD) to calculate the environmental impacts of the Beijing-Shanghai high-speed rail (HSR) system. The following stages are included in the scope of the study: construction and operation of the railway infrastructure, manufacturing, maintenance, operation, and disposal of the vehicles. The results showed that vehicle operation is the main contributor to most of the environmental impacts since the electricity in China is generated from coal-fired power plants. The infrastructure construction is responsible for around 50% of the chemical oxygen demand (COD) impact due to the consumption of concrete, steel, and copper.

Life cycle assessment of French high-speed rail (de Bortoli et al., 2020): this study calculated the environmental impacts from the infrastructure of the French HSR, Tours-Bordeaux Railway. The following conclusions are drawn from the study: the components contributing to environmental impacts are mainly rails, roadbed, and civil engineering structures. Transportation is responsible for 18% of the total impacts. The production and maintenance phases have almost equal contribution to the environmental deterioration. While concrete is the main contributor in the construction stage, steel is the main contributor in the whole life cycle.

Life cycle assessment of Norwegian high-speed railway- the Follo Line (Asplan viak AS 2011): a life cycle assessment was conducted on the Norwegian HSR-the Follo (Oslo-Ski) Line in this study. The line mainly consists of tunnels which account for 79% of the total length. The scope includes the construction, maintenance, operation, and disposal of the railway infrastructure of the Follo Line. The results presented that the most significant contributor to global warming is the construction stage, and it is mainly from the tunnel construction. The materials that make the greatest CO_2 impacts are steel, concrete, and cement.

Life cycle assessment of Swedish railway- the Bothnia Line (Stripple & Uppenberg, 2010): a LCA model was developed to calculate the environmental impacts of the Swedish railway-the Bothnia Line in this study. The factors considered in this study are track foundation, track, electric power and control system, tunnel, bridge, railway station, and freight terminal, as well as the train operation. The main results are as following: the construction phase is one of the largest contributors to the GHG emissions; the operation of the train has fewer emissions due to the clean electricity power used; the production of the trains also makes significant impacts due to the large amounts of steel used for manufacturing trains; the source of CO_2 is mainly from the production of construction materials while the construction activity itself has fewer impacts.

Life cycle assessment of freight railway in Belgium (Merchan A. L. et al., 2020): this study used LCA methodology to compare the environmental impacts of electric and diesel trains as well as the impact of electricity mix on the environmental impacts of Belgium freight rail. The scope includes rail equipment, rail infrastructure, and rail transport operation. Life cycle stages include construction, operation, and disposal. The study got the results that the electric trains have 26% fewer impacts regarding climate change. The electricity mix has a significant influence on the environmental impacts of freight rail.

Life cycle assessment of Indian suburban railway (Shinde et al., 2018): this study conducted LCA on the Mumbai suburban railway in India. The study scope consists of the construction and maintenance stages of the railway infrastructure, as well as manufacturing, maintenance, and operation of Electric Multiple Unit (EMU). The following conclusions were drawn: the operation phase is the largest contributor to the total environmental impacts due to the non-renewable electricity sources in India. With regards to construction and maintenance phases, rails have the largest environmental impacts.

The greenhouse gas emissions of commuter rail materials in the US (Hanson et al., 2016): this study calculated the GHG emissions of the railway infrastructure including tracks, railway station platforms, bridges, tunnels, catenary, and parking facilities of five New Jersey commuter rail lines. The results showed that the catenary system is responsible for the main GHG emissions due to the production of copper used in this system.

The greenhouse gas emissions of the Sheppard railway line in Canada (Saxe et al., 2017): the study calculated the net impact of GHG impacts of subway infrastructure in Toronto, Canada. The construction and operation of infrastructure, ridership, as well as the changes in residential density, are considered. The GHG payback period is estimated as nine years, which means it takes nine years to pay back the initial GHG investment under the optimistic situation.

Life cycle assessment of railway track beds in the UK (Kiani et al., 2008): the study used LCA methodology to calculate the environmental impacts of three types of railway track beds in the UK, i.e. ballasted track, cast-in sleeper track, and embedded track. The results showed that compared with the ballasted track, concrete slab tracks have less global warming potentials. Despite the energy-intensive character of the concrete slab, the environmental impact can be offset due to the longer lifetime.

The greenhouse gas emissions of concrete and timber sleepers in Australia (Crawford, 2009): this study assessed the greenhouse gas emissions of timber and reinforced concrete sleepers by using life cycle assessment. The results showed that the GHG emission of reinforced concrete sleepers is six times less than those of timber sleepers.

Besides the above-mentioned studies related to environmental impacts, several studies are conducting on the material stock of railway infrastructure, i.e. material stock of HSR in China (Wang et al., 2016), resource deposits of Vienna’s subway network (Gassner et al., 2020; Lederer et al., 2016), which provided part of the material consumption data in this study.

The abovementioned studies are chosen due to the reasons as following:

- Provided relatively detailed definitions as well as material/energy input data of each component of railway infrastructure.
- Calculated the environmental impacts from each life cycle stage and materials/energy use, which gave an understanding of what the main contributors are. It helps to define the goal and scope of this study as well as to compare the results at the end.

The main findings that can be concluded from these studies are:

- The operation of the vehicle usually causes the largest environmental impacts unless the energy has clean sources.
- Construction of railway infrastructure also generates huge amounts of environmental impacts; however, those are mainly the consequences of material production instead of construction activity itself.
- Despite ballastless track is more resource-intensive than ballasted track, the long lifetime of the ballastless track makes it have less environmental costs than the traditional track.
- The environmental impacts from the electrification system are mainly from the production of copper.
- For the whole life cycle of the railway, concrete and steel are the materials having the largest contributions to the environmental impacts.

However, there are some limitations in these studies:

The study (von Rozycki et al., 2003) aggregated the sleepers, ballast, as well as foundation into rail driveway and gave the total material input data, which makes it hard to reuse the data as life cycle inventories. The study (Yue et al., 2015) has the same issue, i.e. it only provided the total material input data of ballasted track and ballastless track instead of giving the data broken down into components such as rails, sleepers. The study (de Bortoli et al., 2020) aggregated the bridges, tunnels, and viaducts into civil engineering structures. Therefore, the data provided as civil engineering structures are not very helpful since the material inputs from tunnels, bridges, and viaducts might vary a lot. As for the study (Asplan Viak AS, 2011), although it is project-specific, the results might not be reliable due to the provisional data used in the study. The study (Saxe et al., 2017) conducted life cycle assessment on the Sheppard subway line in Canada, however, it only provided material input data of tunnels and subway stations. As for the study (Mao et al., 2021), since it focused on the material stock of subway, only aggregated material consumption data were provided instead of breaking down into components such as rails and fastenings.

Besides, most of these studies are conducted on the HSR while other types of rails have not received enough attention so far. Especially for the subway, there are only a few studies that studied the material stocks (Lederer et al., 2016; Mao et al., 2021) and environmental impacts (Saxe et al., 2017) of the subway. This limitation results in lack of material input and environmental impacts data regarding the other types of railway except for HSR.

The summary table of the literature review is shown in Table 1.

Study	**Title**	**Project**	**Foundation**	**Track**	**Bridge**	**Tunnel**	**Electrification system**
(von Rozycki et al., 2003)	Ecology Profile of the German High-speed Rail Passenger Transport System, ICE	Hanover-Wuerzburg, HSR		√	√	√	
(Yue et al., 2015)	Life cycle assessment of High-speed Rail in China	Beijing-Shanghai, HSR	√	√	√	√	Not specified
(de Bortoli et al., 2020)	A life cycle model for high-speed rail infrastructure: environmental inventories and assessment of the Tours-Bordeaux railway in France	Tours-Bordeaux railway, HSR	√	√	Not specified	Not specified	√
(Asplan Viak AS, 2011)	Life Cycle Assessment of the Follo Line–Infrastructure	The Follo Line, HSR	Not specified	√		√	√
(Stripple & Uppenberg, 2010)	Life cycle assessment of railways and rail transports - Application in environmental product declarations (EPDs) for the Bothnia Line	The Bothnia Line, HSR	√	√			√
(Merchan A. L. et al., 2020)	Life cycle assessment of rail freight transport in Belgium	Freight rails in Belgium	√	√	√	√	√
(Shinde et al., 2018)	Life cycle analysis based comprehensive environmental performance evaluation of Mumbai Suburban Railway, India	Mumbai Suburban Railway		√			√
(Saxe et al., 2017)	The net greenhouse gas impact of the Sheppard Subway Line	The Sheppard Subway Line				√	
(Kiani et al., 2008)	Environmental life-cycle assessment of railway track beds	Railway track beds in the UK		√			
(Crawford, 2009)	Greenhouse Gas Emissions Embodied in Reinforced Concrete and Timber Railway Sleepers	Railway sleepers in Australia		Only sleepers			

(Wang et al., 2016)	Weight under Steel Wheels: Material Stock and Flow Analysis of High-Speed Rail in China	Chinese high-speed rails	√	√	√	√	√
(Lederer et al., 2016)	Prospecting and Exploring Anthropogenic Resource Deposits- The Case Study of Vienna's Subway Network	Subway network in Vienna		√	√	√	√
(Mao et al., 2021)	Global urban subway development, construction material stocks, and embodied carbon emissions	Global subway network				√	

Table 1 Reviewed literature: Authors, publication titles, project names, and components

Note: "√" means the life cycle inventory data of the components are provided; "not specified" means only aggregated data are provided, for example, in the study (de Bortoli et al., 2020), the bridges and tunnels are included in civil engineering structures and no breakdown data were given regarding the bridges and tunnels.

3 Definition of railway types, components, and maintenance activities

3.1 Definition of railway types

Rail service can be categorized into two main categories based on the service types, i.e. passenger rail and freight rail. Passenger rail is used to transport human passengers while freight rail is used to transport cargo.

Passenger rail can be distinguished into three categories: conventional rail, high-speed rail, and urban rail according to their speeds and driving distances. Conventional rail has a relatively low speed, i.e. under 250km per hour, and it usually runs medium to long distances. Conventional rail can be further divided into sub-urban rail and intercity rail (International Energy Agency, 2019). High-speed rail has a speed higher than 250km/hour for new lines and higher than 200km/hour for existing lines (*UIC*, 2020). Urban rail runs short distances, which includes metro/subway and light rail. Subway is propelled by electricity and has a separate right of way to avoid conflicts with other transports (N. Sharma et al., 2013). Comparing with the subway, light rail has a relatively low speed and capacity. It usually runs on street level. Light rail includes tram and other types of urban rail (International Energy Agency, 2019). The figure is cited from the last semester's project (Yiru, 2020) (Figure 1).

Freight rail usually runs long distances with low speed comparing with passenger rail.

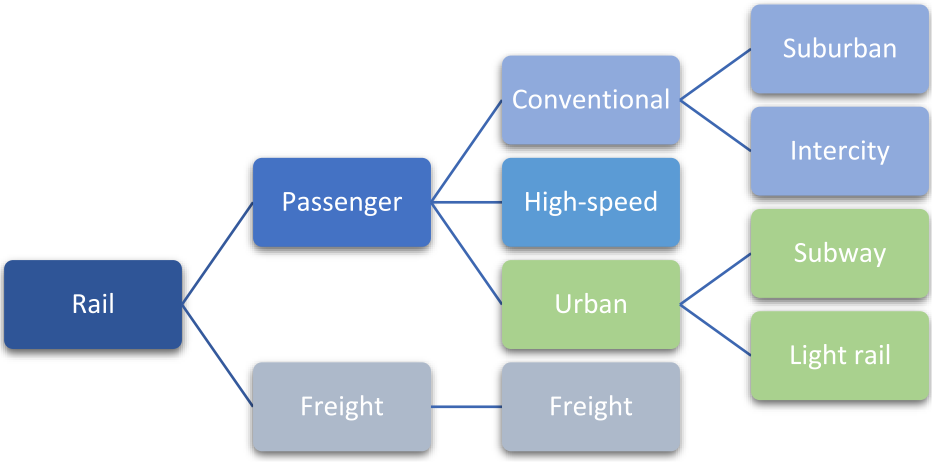

Figure 1 Classification of different rail services

3.2 Definition of the components of railway infrastructure

Railway infrastructure includes foundation, track system, electrification systems as well as civil engineering structures (bridges, tunnels). All of the components considered in this study are shown in Figure 2.

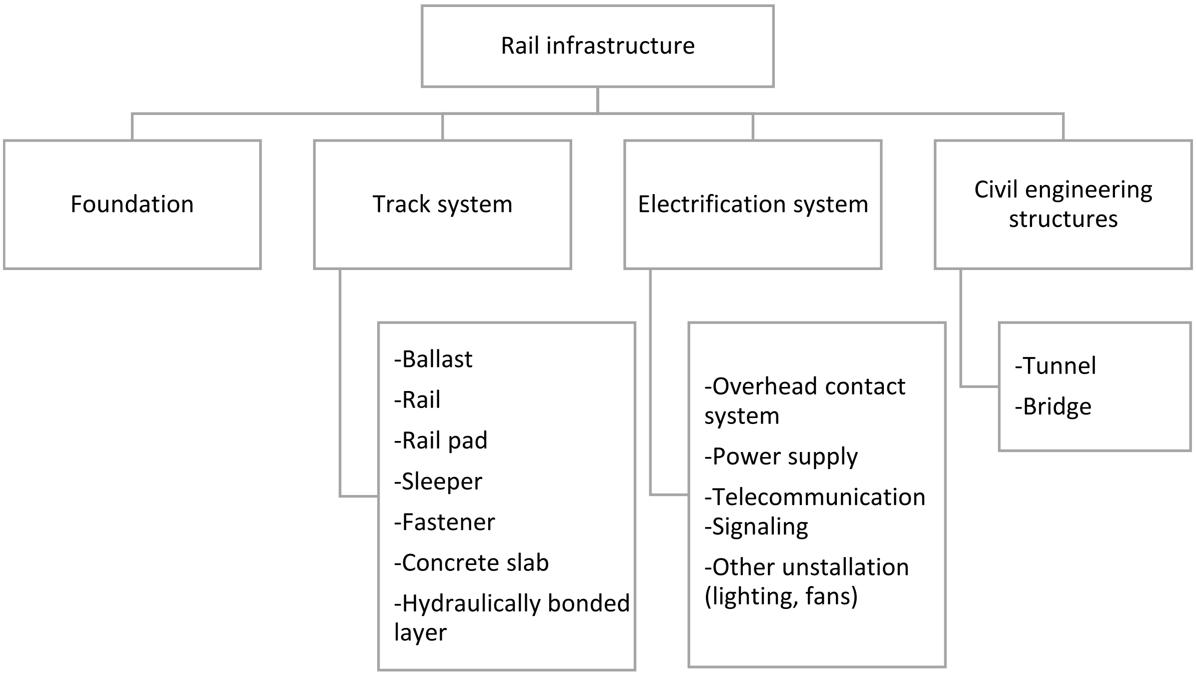

Figure 2 The components of railway infrastructure

3.2.1 Foundation

Track foundation is constructed to set a stable base for the track when the track is constructed at ground level (Stripple & Uppenberg, 2010; Wang et al., 2016). According to (Wang et al., 2016), two types of foundation can be distinguished: shallow foundation and deep foundation. The type of foundation is determined by soil conditions. A shallow foundation is the most commonly used type, which is usually made of a layer of blanket and subgrade underneath the blanket. The traditional blanket uses a sub-ballast or graded-sand layer. Sub-ballast is made of a granular layer with the function of preventing interpenetration between ballast and subgrade (Björkquist & Janjua, 2020; Burrow et al., 2007). The thickness of the sub-ballast is around 15cm; however, some railways do not use sub-ballast and rather use a thicker subgrade layer (Profillidis, 2014). The subgrade is made of certain amounts of cement and lime mixed with soil underneath the blanket and above the sub-soil. For the railway constructed in areas with soft soil, concrete piles are used to increase the stabilization of subgrade, this type of structure is defined as a deep foundation (Wang et al., 2016).

The cross-section of the railway foundation is shown in Figure 3.

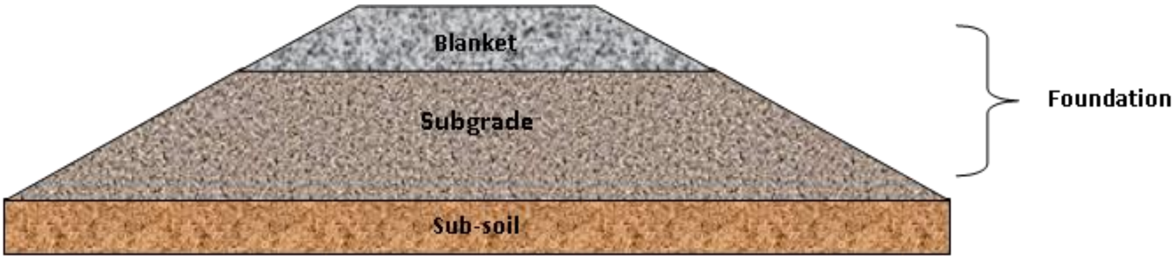

Figure 3 Cross-section of track foundation

The following main activities are needed to construct a railway foundation:

- Open soil/ hard rock excavation.
- Production of materials for building sloping surfaces.
- Ground stabilization with concrete piles or cement/lime columns.
- Filling of stabilization materials.

3.2.2 Track system

Railway tracks can be distinguished into the ballasted track and ballastless track according to the superstructure. The main difference between the two types of track is that ballasted track uses ballast under the sleepers while the ballastless track uses concrete or asphalt slab instead of ballast.

3.2.2.1 Ballasted track

The ballasted track consists of a ballast, rails, sleepers, fastenings, and rail pads (see Figure 4).

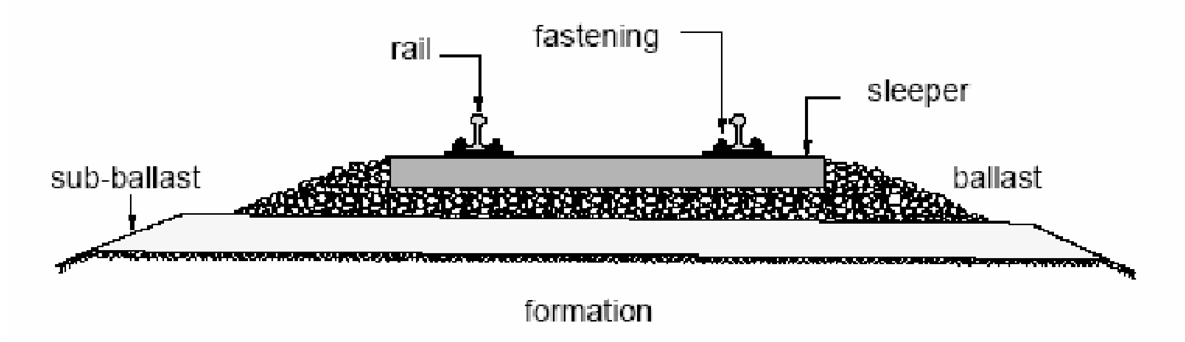

Figure 4 Ballasted track components (copied from (Sadeghi & Babaee, 2006))

The ballast is a layer structure above the sub-ballast/subgrade and is laid underneath the sleepers. It is usually made of uniform-sized crushed granular material (Burrow et al., 2007). Ballast not only helps to distribute the load from the train and maintain track stability but also has drainage capability. Due to the important functions mentioned above, the ballast needs to be maintained regularly which, at the same time, results in high costs (Burrow et al., 2007). Due to different territory conditions, the depth of ballast varies from region to region, for example, it is 0.35m in China (Wang et al., 2016) while 0.3m in the UK (Kiani et al., 2008). However, the minimum thickness should be not less than 0.2-0.3m (Burrow et al., 2007).

Sleepers are also called crossties or railway ties. While there are four types of sleepers used in railway track over the world, i.e. concrete, timber, steel, and synthetic sleepers, concrete sleepers are the most commonly used type (Profillidis, 2014). Concrete sleepers are made of reinforced concrete. Spacing of the sleepers refers to the distance from the center of one sleeper to the another and the optimal spacing is 0.6m or 1.67 sleepers per km of track (Profillidis, 2014).

Rails are made of hot-rolled steel (Shinde et al., 2018). The function of rail is to support the wheels and transfer the loads from the trains to the sleepers (Björkquist & Janjua, 2020). For standard gauge[1] tracks, UIC54 and UIC60 are the most commonly used rail profiles, of which UIC 54 is used in low traffic load tracks and UIC60 is used in medium to high traffic load tracks (Profillidis, 2014). The numbers i.e. 54,60 represent the weight of the rails, for example, UIC60 refers to the weight of one meter of rail is 60kg.

Fastenings are made of steel. The function of the fastenings is to fix the sleepers to the rails. Fastenings can be categorized into two types, i.e. rigid fastenings, and elastic fastenings. Rigid fastenings are only used in timber and steel sleepers while elastic sleepers are mandatory in concrete sleepers. Elastic fastenings have many varieties, such as Vossloh fastening (Figure 5) (Profillidis, 2014). Each rail has two fastenings, or each sleeper has four fastenings (Ortega et al., 2018).

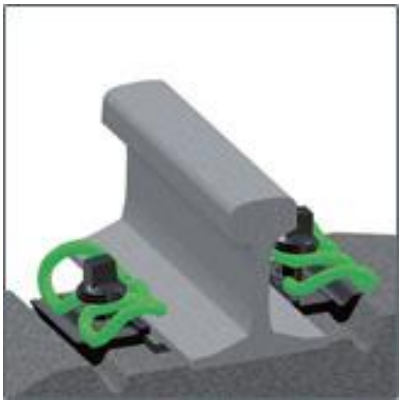

Figure 5 Vossloh fastening (copied from (*Aveng Infraset*, 2017))

Rail pads are usually made of rubber, placed between rails and sleepers, having the functions of absorbing vibrations and providing electrical insulation (Profillidis, 2014). In addition, it also helps to reduce the noise generated from the structure. The thickness of the rail pad is from 10 to 15mm (Björkquist & Janjua, 2020). Each sleeper has two rail pads (Ortega et al., 2018).

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[1] Standard gauge is defined as the track with distance of 1.435m between inner sides of heads of two rails.

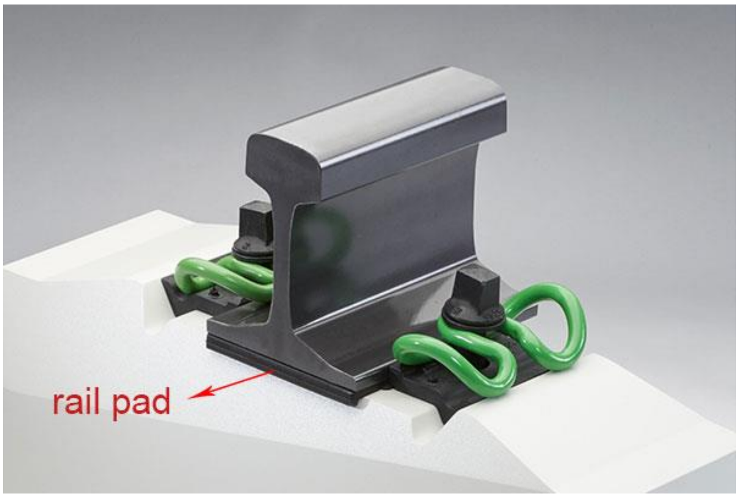

Figure 6 Rail pad (copied from (*AGICO GROUP*, 2021))

3.2.2.2 Ballastless track

Ballastless track, also known as slab track, becomes popular with the increasing loads and speeds of railways. Ballastless track is distinguished from the traditional ballasted track by replacing the ballast with concrete or asphalt slab (von Rozycki et al., 2003); however, asphalt slab is only used on very special occasions (Serdelová & Vičan, 2015). Rails can be laid on either sleepers or slabs without sleepers in a ballastless track system (Profillidis, 2014). Regardless of the ballastless track requires more material resources comparing to ballasted track, it has the following advantages (Profillidis, 2014; von Rozycki et al., 2003):

- Long life expectancy, usually 50-60 years which is more than two times the lifetime of ballast having a lifetime between 15-30 years.
- Fewer maintenance activities are needed throughout the entire lifespan.
- The reduced thickness of the concrete slab comparing to the ballast results in less cross-section area of tunnels, which reduces the total costs of tunnel construction.

For the ballastless track, the slab track can be distinguished into two types: slab track with sleepers and slab track without sleepers. The former one is usually used in high-speed rail and metro; the techniques include the Rheda technique, the Züblin technique, and the Stedef technique. As for the latter one, rails are directly embedded into the prestressed concrete slab.

Despite there are multiple types of ballastless track, the following common components are usually used regardless of the slab track types: rails, fastenings, frost protection layers (FPL), hydraulic bound layers (HBLs), and concrete/asphalt slabs. The profile of slab tracks is shown in Figure 7 (Ižvolt et al., 2013).In a ballastless track system, the material intensities of rails and fastenings are supposed to be the same as those of ballasted track (Wang et al., 2016). HBL is laid between the concrete slab layer and FPL or subgrade to degrade the loads from the trains. FPL prevents the penetration of frost to the subsoil. In addition, it has a similar function to sub-ballast which helps to distribute the loads from the passing trains. The materials used in FPL can be gravel, cinders, peat, bark. (Profillidis, 2014).

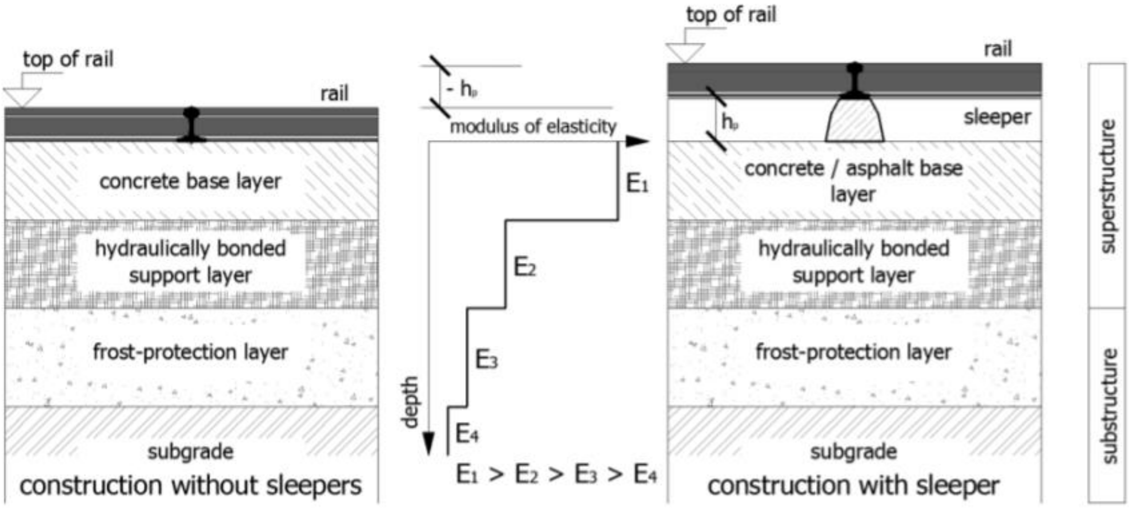

Figure 7 Profiles of slab tracks

3.2.3 Bridges and tunnels

Bridges and tunnels are the most material-intensive components. In addition to the construction materials, bridge and tunnel construction require large quantities of soil or rock to be excavated (von Rozycki et al., 2003).

Railway bridges play an important role when the railway is constructed in the area where the terrain is uneven or has subsidence areas, to keep the track straight (Wang et al., 2016). Materials of railway bridges are determined by specific national codes; but steel and composite structures are most widely used due to their simplicity of construction, light weight, and fewer maintenance needs (Pipinato & Patton, 2016).

The tunnel is a tube-shaped civil engineering structure built to pass through a river, mountain, or underwater. The size and shape of a tunnel are determined by the ground type as well as the number of railway tracks. Usually, in solid rock areas, any type of tunnel can be built. In rocky terrains, a semicircular arch with vertical sidewalls tunnel should be built. In the area with soft ground such as soft clay or sand, a circular tunnel would be the best option, however, for railway track, the bottom of the circular tunnel should be leveled (Chandra & Aqarwal, 2008).

The construction methods of tunnels have cut and cover tunneling, drill and blast tunneling, tunneling by tunnel boring machine (TBM), New Austrian tunneling Method (NATM) (P. D. Sharma, 2011).

- The cut and cover method is usually used to construct shallow tunnels. It constructs tunnels in the following methods: excavating trenches, constructing the tunnel, and covering the roof over.
- Drill and blast method involves the following methods: first, drill blast holes where explosives to be placed; second, place the explosives in the blast holes and then start blasting; third, after blasting the waste rocks should be removed from the tunnel; in the last step, structure support measures would be carried out by applying shotcrete and bolting (Putzmeister, 2016).
- TBM method uses a tunnel boring machine to build tunnels. It is usually adopted in long tunnel construction which is longer than 4.5km while the drill and blast method is used in tunnels no longer than 1.5km (Putzmeister, 2016; P. D. Sharma, 2011). This method is suitable for excavating hard rock tunnels without

structural support. But extremely hard rocks would slow down the tunneling speed and also results in the wear of the rock cutter of the machine (P. D. Sharma, 2011).

- NATM, also known as the sequential excavation method, can only be applied when the ground is fully dry. In addition, the ground needs to be stabilized by grouting or ground freezing before the excavation (P. D. Sharma, 2011).

3.2.4 Electrification system

The electrification systems of the railway consist of an overhead contact system, power supply system, telecommunication system, signaling system as well as other installations. Other installations are only considered in the tunnel section including lighting and fans. The main resources used in electrification systems include copper, aluminum, steel, UPS (batteries), and diesel (Eslami Ebrahimi, 2014).

3.3 Definition of maintenance activities

To guarantee the normal operation of the railway system, regular maintenance activities are inevitable, especially for the ballasted track which needs relatively frequent maintenances. This section gives the definitions of the maintenance activities that are considered in this study (Table 2).

Activity	**Definition**
Rail milling	Rail milling is a maintenance process of removing the damaged steel from the rail surface.
Ballast stabilizing	Ballast stabilizing refers to using a ballast stabilizer to consolidate the ballast aggregates to make the track bed stable.
Ballast tamping	Ballast taming is used to packing, lining, and lifting the ballast.
Ballast cleaning and changing	Ballast cleaning is cleaning out the worn ballast and replacing the dirty ballast with fresh ballast.

Table 2 Definitions of maintenance activities (Krezo et al., 2018)

4 Developing archetypes for rail infrastructure

To have a clear understanding of the resource requirements of the railway infrastructure, it is necessary to build archetypes for different types of the railway. Building archetypes helps not only to estimate the material stock of railway networks but also to estimate the future resource consumption of railway infrastructure construction associated with huge amounts of environmental impacts due to the material production. In addition, railway archetypes would be able to provide a scientific basis to improve the material efficiencies of the transport sector.

Similar to the definition of the archetypes of buildings in the study (Monteiro et al., 2015): "… an archetype is a virtual representation of a number of buildings that share similar characteristics in the stock", railway archetypes can be defined in the same way as " railway archetypes are the representations of railways which share similar characteristics in the stock." Take the railway services introduced in chapter 3 as an example, those rails are classified into different groups based on their speeds, driving distances, and functions, and these factors might result in different resource requirements. Besides, even for the same type of railways, the material intensities of each component might vary significantly due to geographical conditions. Therefore, based on the available data collected from literature and documentations, this study has built archetypes for HSR, commuter, and subway in terms of the components i.e. foundation, track system, civil engineering structures (bridges, tunnels), and electrification systems.

According to the International Union of Railways (UIC), HSR is defined as a type of transit mode that the new lines run faster than 250 km/h and the existing lines run at a speed higher than 200 km/h (railways, 2020). A commuter is a transit mode propelled by electricity or diesel running between the city center and suburban areas (*National Transit Database Glossary*, 2013). Metro/subway is a form of transit being propelled by electricity and has its right of way to avoid conflicting with other transports (N. Sharma et al., 2013).

4.1 Methodology

4.1.1 Data collection

The life cycle stages considered in this study are the construction stage and maintenance stage. The operation stage and end-of-life stage are out of the scope for the reasons that this study mainly focuses on the resource inputs of the railway infrastructure, and also due to the reason that it is hard to collect end-of-life data for the long lifetime of railway infrastructure.

Both material and energy consumption data (diesel, electricity) are collected.

The unit of material intensity adopted in this study is kilogram per meter of double track. The units of electricity are all converted to kWh per meter of double track and the units of diesel are all converted to MJ per meter of double track. The density of concrete is assumed as 2420kg/m^3 (Weidema et al., 2013). Excavation soil density is 2800kg/m^3 (Schmied & Mottschall, 2013). 1liter of diesel is assumed to be equal to 36MJ of energy, which is calculated as following (Weidema et al., 2013):

1l of diesel= 42.8MJ/kg* 0.84kg/l = 36MJ

- The net calorific value of diesel: 42.8 MJ/kg
- Density of diesel: 0.84 kg/l

Despite the widths of double tracks vary from country to country due to the different national standards of railway construction, but since no adequate data provided by literature, all single tracks are converted to double tracks by simply multiplying by two.

4.1.2 Building archetypes

After collecting the material/energy intensity data of railway infrastructure of construction and maintenance stages, all data are converted into the same units to make them comparable to each other. Then the median of material/energy intensity of each component (except foundation and electrification system) is calculated to represent the archetypes. But there are two exceptions: as for foundation, the data of the shallow foundation from the study (Wang et al., 2016) are adopted directly instead of using median value. It is because the study provided relatively concrete data, e.g. categorized the foundation into the shallow foundation and deep foundation; provided the breakdowns of materials while most studies only provide total material consumption; on the other hand, the shallow foundation is the most widely used foundation type. As for the electrification system, since the previous studies used different scopes which makes it challenging to compare between different studies, this study only adopted the data provided from the study (Eslami Ebrahimi, 2014) due to the comprehensiveness of the data. But all of the data collected from literature and documentation are shown in section 4.2 to give an impression of the difference between different studies.

4.1.3 Data quality evaluation

Data quality determines how reliable your results are. However, uncertainties always exist in every step so that it is important to identify and understand the uncertainties to improve the credibility of the results. In the Ecoinvent database, a semi-quantitative approach based on the pedigree matrix is used to quantify uncertainty (Muller et al., 2016). However, a pedigree matrix only tells where the uncertainty occurs, but does not tell how serious the problem is, therefore it needs to be combined with the information on the uncertainty of the data (variation of the data sample). In this approach, uncertainty is distinguished into two types: basic uncertainty and additional uncertainty. Basic uncertainty refers to the intrinsic variability and stochastic errors of the parameters resulting from measurement errors or normal fluctuations while additional uncertainty is caused by the use of data that are estimated, extrapolated, or lacking verifications. According to the study (Muller et al., 2016), the coefficient of variation (CV), expressed as the ratio of arithmetic standard deviation to mean, is used to combine the basic and additional uncertainties to express the dispersion of a specific sample. The higher the CV, the greater the dispersion of the data set. In addition, CV is dimensionless so it allows the comparison between different data samples (Muller et al., 2016).

This study applied the same approach to calculate the uncertainty of the collected data. It was calculated in the following methods:

- According to the sources of the collected data, pedigree matrices were built based on five indicators i.e. reliability, completeness, temporal, geographical, and further technical correlations scored from 1 to 5. The higher the scores, the worse the data quality is (see Table 3).
- Then the pedigree matrices were converted into uncertainty factors based on experts' judgments by using Table 4.
- The uncertainty factors are used to calculate the total uncertainty expressed by the square of the standard geometric deviation by the formula (Frischknecht et al., 2005):

$$SD_{g95}{}^{2} = \delta_{g}{}^{2} = \exp\left(\sqrt{ln^{2}U_{b}^{2} + \sum_{i=1}^{5} ln^{2}U_{i}^{2}}\right)$$

  U_1: uncertainty factor for reliability
  U_2: uncertainty factor for completeness
  U_3: uncertainty factor for temporal correlation
  U_4: uncertainty factor for geographical correlation
  U_5: uncertainty factor for further technological correlation
  U_b: basic uncertainty factor
  δ_g : geometric standard deviation
- The CV is then calculated by using the formula (Muller et al., 2016):

$$CV = \sqrt{exp(ln^{2}\delta_{g}) - 1}$$

Indicator score	**1**	**2**	**3**	**4**	**5**
Reliability	Verified[2] data based on measurements[3]	Verified data partly based on assumptions ***or*** non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial ex-pert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods	Representativeness unknown or data from a small number of sites ***and*** from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown ***or*** distinctly different area (North America in-stead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes and mate-rials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale ***or*** from different technology

Table 3 Pedigree matrix to assess the data quality (cited from **(Weidema et al., 2013)**)

Indicator score	**1**	**2**	**3**	**4**	**5**
Reliability	1	1.54	1.61	1.69	1.69
Completeness	1	1.03	1.04	1.08	1.08
Temporal correlation	1	1.03	1.1	1.19	1.29
Geographical correlation	1	1.04	1.08	1.11	1.11
Further technological correlation	1	1.18	1.65	2.08	2.8

Table 4 Uncertainty factor of pedigree matrix (Mutel, 2013)

4.2 Resource consumption of railway infrastructure construction and maintenance

4.2.1 Foundation

The material inputs of the HSR railway foundation collected from different studies are shown in Table 5. (Wang et al., 2016) provided material intensities of two types of foundation i.e. shallow foundation and deep foundation. Since (de Bortoli et al., 2020) provided the total material use of the foundation, the material intensities are calculated

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[2] "Verification may take place in several ways, e.g. by on-site checking, by recalculation, through mass balances or cross-checks with other sources." (Weidema et al., 2013)

[3] "Includes calculated data (e.g. emissions calculated from inputs to an activity), when the basis for calculation is measurements (e.g. measured inputs). If the calculation is based partly on assumptions, the score would be 2 or 3." (Weidema et al., 2013)

by dividing total material use by total track length (302km of HSR+38km of standard line, double track).

The results show that a shallow foundation has much less material input comparing to a deep foundation in China. However, the material consumption of the foundation of the French railway is even less than the shallow foundation in China. The reasons might be the difference in soil conditions or the variations of the study scopes.

Author	Country	Concrete	Cement	Stone	Sand	Lime	Gravel	Total
(Wang et al., 2016)	China	2440	6800	24000	10000	3000		43800
(Wang et al., 2016)	China	80520	17000	34000	14000	1600		147120
(de Bortoli et al., 2020)	France		149			68	12382	12599

Table 5 Life cycle inventory of HSR railway foundation (unit: kg/m double track)

Apart from material consumption, the energy use of the machinery also needs to be considered (Table 6). (Stripple & Uppenberg, 2010) provided the total consumption of renewable and non-renewable energy use of foundation construction. Since it also includes ballast into the scope of the foundation, the total energy use is higher than the actual energy consumption. The energy use per meter of double track is calculated by dividing the total energy use by the total length of the foundation. Because the data were given of a single track, it was converted to double track through multiplying by two. The study (de Bortoli et al., 2020) provided the total energy consumption of onsite building machinery (Table 6). The collected data regarding the railway foundation is only for HSR because there are no data found regarding commuter and subway.

The results show that the energy uses of foundation construction machinery are in the same order so that they do not vary a lot.

Author	Country	Rail type	total energy use
(Stripple & Uppenberg, 2010)	Sweden	HSR	18859
(de Bortoli et al., 2020)	France	HSR	11765

Table 6 Energy consumptions of building machines (unit: MJ/m double track)

4.2.2 Ballasted track

The material intensities of the ballast of HSR and commuter are shown in Table 7. The ballast data of the subway were not found. The study (Asplan Viak AS, 2011) provided the provisional data of the Follo line in Norway. This line consists of three sections i.e. entry to Oslo (open section), tunnel section (one/two tubes), and entry to Ski (open section).

The results show that the material intensities of ballast from different studies do not vary a lot except the Norwegian HSR- the Follo Line, the open section (entry to Oslo), and two tunnel sections' ballast inputs are one order larger than those of other studies. The ballast intensities of commuters are in the same order but are relatively smaller than those of HSR rail.

Type	Author	Country	Section	Ballast
HSR	(Wang et al., 2016)	China		7200
	(Kiani et al., 2008)	UK		5304
	(de Bortoli et al., 2020)	France		8088
	(Bosquet et al., 2014)	France		8300
	(Merchan A. L. et al., 2020)	Belgium		6400
	(Asplan Viak AS, 2011)	Norway	Open section (entry to Oslo)	13200
			Tunnel (one tube)	31213
			Tunnel (two tubes)	40074
			Open section (entry to ski)	6600
Commuter	(Shinde et al., 2018)	India		4446
	(Hanson et al., 2016)	US		5283

Table 7 Material intensities of ballast (unit: kg/m double track)

Material intensities of rails, fastenings, and rail pads of HSR, commuter, and subway are shown in Table 8. Table 8 Material intensities of rails, fastenings, and rail pads (unit: kg/m double track)As for the subway, only the data of the rails were found.

The material intensities of rails of HSR and commuter are very similar, no large differences are observed. However, the material intensity data of subway rails are more than 3 times larger than those of HSR and commuter rails. Since only one data source was found regarding the subway, this data might not be reliable.

Type	Author	Country	Rails	Fastenings	Rail pads
HSR	(Stripple & Uppenberg, 2010)	Sweden	240	8.02	0.92
	(Wang et al., 2016)	China	240		
	(von Rozycki et al., 2003)	Germany	282		
	(Merchan A. L. et al., 2020)	Belgium	200/240	13.36	4
	(Kiani et al., 2008)	UK	240	26.46-27.69	3.14
	(Ortega et al., 2018)	UK	240	7.04	2.04
	(Bosquet et al., 2014)	France	240		
	(de Bortoli et al., 2020)	France	240	8.61	2.59
	(Asplan Viak AS, 2011)	Norway	240	40	
Commuter	(Shinde et al., 2018)	India	208/240	12	1.4
	(Hanson et al., 2016)	US	228/236	10.64	
Subway	(Lederer et al., 2016)	Austria	760		

Table 8 Material intensities of rails, fastenings, and rail pads (unit: kg/m double track)

The material intensities of the sleepers are shown in Table 9Table 9 Material intensities of the sleepers (unit: kg/m double track). In some studies, the units of the sleepers were given in kg/(sleeper*single track), in this case, they were converted into kg/m of double track. The formula used for the conversion is:

Weight of sleepers/m double track = Weight/sleeper*[1/spacing(m)]*2

The concrete intensities of HSR sleepers are from 770-1153 kg/m of double track, and the steel intensities are from 18-26.05 kg/m of double track. Most of the spacings are 60cm. Commuter rail also has similar material intensities with HSR while subway’s material requirements are two times larger than those of HSR and commuter sleepers. However, this conclusion is only from the observation of the collected data.

Type	Author	Country	Concrete	Steel	Spacing (cm)
HSR	(Stripple & Uppenberg, 2010)	Sweden	833	20.4	60
	(Wang et al., 2016)	China	1040	26	60
	(Merchan A. L. et al., 2020)	Belgium	956	26.05	60
	(Kiani et al., 2008)	UK	770	18.82	65
	(Du & Karoumi, 2013)	Sweden	802	20.32	60
	(de Bortoli et al., 2020)	France	1153	25	60
	(Asplan Viak AS, 2011)	Norway	882	18	60
Commuter	(Shinde et al., 2018)	India	858.8	27.6	60
	(Hanson et al., 2016)	US	1010		50
Subway	(Lederer et al., 2016)	Austria	1920	46	No data found

Table 9 Material intensities of the sleepers (unit: kg/m double track)

Energy consumptions during the track construction of HSR are shown in Table 10. The maintenance activities considered in the study (Kiani et al., 2008) are ballast changing, ballast cleaning, and ballast tamping (Kiani et al., 2008). The study (Krezo et al., 2018) considered ballast tamping, regulating, and stabilizing. Apart from the activities mentioned above, the studies (Stripple & Uppenberg, 2010) and (de Bortoli et al., 2020) provided the energy consumptions of rail milling and machinery for replacing rails, sleepers, and fastenings. The machinery used to replace the rails, sleepers, and fasteners with only one machine is called track renewal train. The video showing how this machine works can be found on Youtube (HD1080ide, 2019).

From the table, we can find that the energy consumptions in different studies vary significantly. This is probably because of the reason that different types of machinery or technologies were used in different regions so that the fuel consumptions are distinct from one another.

Author	(Stripple & Uppenberg, 2010)	(Kiani et al., 2008)	(Krezo et al., 2018)	(de Bortoli et al., 2020)
Country	Sweden	UK	Australia	France
Track laying	234			
Rail laying		13.32		
Sleeper laying		5.04		
Rail milling	8.376			0.126
Ballast stabilizing			6.79	
Ballast spreading		8.64	11.06	
Ballast changing		18.36		
Ballast cleaning		18.36		
Ballast tamping		34.56	16.95	3.24
Rails, sleepers, fasteners replacement				1520

Table 10 Energy consumptions of ballasted track construction and maintenance activities/equipment of HSR (unit: MJ/m double track)

4.2.3 Ballastless track

This section only presents the material intensities of hydraulically bonded layers (HBLs) and concrete slabs. Each type of slab track has a different flexural stiffness, thus the type of track used in railway construction depends on the soil condition of the area (Köllő et al., 2015). The study (Wang et al., 2016) provided the types of slab tracks used in China, which are CRTS Ⅰ and CRTS Ⅱ. Due to the material intensities of these two types of track are quite similar, only the CRTS Ⅱ material inputs data were given. The study (Kiani et al., 2008) considered two types of ballastless track i.e. Rheda 2000 and Balfour Beatty Embedded Slab Track (BBEST) (Table 11). The data show that the material intensities of concrete slabs are similar. Since the HBL data were found from only one source, thus they are not comparable.

Author	Country	Type	Concrete slab		Hydraulically bonded layer	
			Concrete	Steel	Concrete	Steel
(Wang et al., 2016)	China	CRTSⅡ[4]	2586	128	4410	160
(Kiani et al., 2008)	UK	Rheda 2000	2586	43		
(Kiani et al., 2008)	UK	BBEST	2872	232		

Table 11 The material intensities of concrete slab track of HSR (unit: kg/m double track)

Rail laying machine, in situ slabs former, and concrete train are used in construction activities of the ballastless track system. With regards to the maintenance of the ballastless track, no other activities but rail and rail pad replacement are needed (Table 12).

Author	Country	Rail laying	In situ slab former	Concrete train
(Kiani et al., 2008)	UK	13.32	15.84	13.32

Table 12 Energy consumption of ballastless track construction and maintenance activities/equipment (unit: MJ/m double track)

4.3 Bridges and tunnels

4.3.1 Bridges

There are two studies (Schmied & Mottschall, 2013; von Rozycki et al., 2003) providing German railway bridge material intensity data. The former one distinguished railway bridges into concrete bridges, steel bridges, and viaducts while the latter one distinguished them into rail glen bridges and road/railway bridges. The study (Hanson et al., 2016) provided the data of commuters in New Jersey, USA. Material intensities of different railway bridges are shown in Table 13. The diesel uses of HSR bridge construction are shown in Table 14. No energy use data found regarding commuter and subway.

The material intensities of railway bridges vary significantly from study to study. Even for the same type of bridge, e.g. for concrete bridge, the concrete, and steel inputs are 12458 and 2819 kg/m of double track in the study (Bizjak et al., 2016) while they are 33390 and 1500kg/m of double track in the study conducted by (Schmied & Mottschall, 2013).

The energy consumption data from the French railway (Bosquet et al., 2014) is two orders of magnitude higher than the German study (Schmied & Mottschall, 2013). It might be due to the different types of machinery were used in different countries.

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[4] CRTSⅡ slab track has the rails fixed directly to the slab track.

Type	Author	Country	Type	Concrete	Steel	Excavation soil
HSR	Von Rozycki et al. (2003)	Germany	Glen bridge	55000	3000	
	Von Rozycki et al. (2003)	Germany	Road/railway bridges	89000	4900	
	Bizjak et al. (2017)	Croatia	Concrete bridge	12458	2819	
	Schmied and Mottschall (2013)	Germany	Viaducts	75366	3510	73276
	Schmied and Mottschall (2013)	Germany	Concrete bridge	33390	1500	
	Schmied and Mottschall (2013)	Germany	Steel bridge		7200	
	Bosquet et al. (2014)	France	Viaducts	56048	6800	
Commuter	(Hanson et al., 2016)	US	Not specialized	178000	9800	
Subway	(Lederer et al., 2016)	Austria	Concrete bridge	140000	8000	
	(Lederer et al., 2016)	Austria	Steel bridge	20000	14100	

Table 13 LCI of bridges (unit: kg/m double track)

Author	Country	Type	Diesel
(Schmied & Mottschall, 2013)	Germany	Viaducts	302.4
(Schmied & Mottschall, 2013)	Germany	Concrete bridge	219.6
(Schmied & Mottschall, 2013)	Germany	Steel bridge	219.6
(Bosquet et al., 2014)	France	Viaducts	10440

Table 14 Energy uses of HSR bridge construction (unit: MJ/m double track)

4.3.2 Tunnels

The study (von Rozycki et al., 2003) and (Bosquet et al., 2014) distinguished tunnels into mined tunnels and trenched tunnels. Mined tunnels are constructed by blasting or drilling or using a tunnel boring machine (TBM) while trenched tunnels are constructed through cut and cover tunneling (Schmied & Mottschall, 2013). The excavated soil is usually used to fill the ramps of entrances and exits of tunnels (Schmied & Mottschall, 2013) (Table 15). The energy uses of HSR tunnel construction activities are shown in Table 16. No data found regarding other types of rail.

The results show that trenched tunnels require more material inputs than mined tunnels. The material intensities of different types of rails are not determined by the railway type, instead, they are relevant to the technology used in the construction. Besides tunneling technology, the region where the construction takes place also has an impact on material use, for example, the cut & cover tunnel in Austria needs 482000 and 20000 kg of concrete and steel while in Canada only 52800 and 17600 kg of concrete and steel are needed.

The results of energy consumption of tunneling show that trenched tunnels consume less energy than mined tunnels. The conventional tunneling approach uses significantly higher energy than using a tunnel boring machine. Two tubes tunnel construction uses more energy than monotube tunnel construction but not as twice as higher.

Type	Author	Country	Type	Excavation soil	Concrete	Steel
HSR	(von Rozycki et al., 2003)	Germany	Mined	270000	44000	2100
	(von Rozycki et al., 2003)	Germany	Trenched	700000	71000	2800
	(Schmied & Mottschall, 2013)	Germany	Mined	358120	88722	1600
	(Schmied & Mottschall, 2013)	Germany	Trenched	840000	116865	6100
	(Bosquet et al., 2014)	France	Two-tube tunnel dug with TBM		113288	2100
	(Bosquet et al., 2014)	France	Two-tube tunnel dug conventionally		166950	4300
	(Bosquet et al., 2014)	France	Trench covered with two tubes		209880	8800
	(Bosquet et al., 2014)	France	Monotube tunnel dug conventionally		138330	3600
	(Bosquet et al., 2014)	France	Converted trench monotube		138330	5800
	(Asplan Viak AS, 2011)	Norway	One-tube tunnel		20523	1090
	(Asplan Viak AS, 2011)	Norway	Two-tube tunnel		29817	1539
Commuter	(Hanson et al., 2016)	US	Not specialized	540000	88000	4200
Subway	(Lederer et al., 2016)	Austria	Cut & cover		482000	20000
	(Lederer et al., 2016)	Austria	NATM		354000	18000
	(Lederer et al., 2016)	Austria	TBM1C[5]		44000	2400
	(Lederer et al., 2016)	Austria	TBM2C[6]		88000	4600
	(Saxe et al., 2017)	Canada	Cut & cover		52800	17600
	(Mao et al., 2021)	China	Not specialized		36768	2289

Table 15 Material inputs of tunnels (unit: kg/m double track)

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[5] TBM1C: tunnel bore machine with one concrete tunnel.

[6] TBM2C: tunnel bore machine with two concrete tunnels.

Author	Country	Type	Diesel use (MJ)	Electricity (kWh)
(Schmied & Mottschall, 2013)	Germany	Mined	5040	7920
(Schmied & Mottschall, 2013)	Germany	Trenched	3600	1800
(Bosquet et al., 2014)	France	Two-tube tunnel dug with TBM	720	
(Bosquet et al., 2014)	France	Two-tube tunnel dug conventionally	18000	
(Bosquet et al., 2014)	France	Trench covered with two tubes	16200	
(Bosquet et al., 2014)	France	Monotube tunnel dug conventionally	9360	
(Bosquet et al., 2014)	France	Covered trench monotube	15120	
(Asplan Viak AS, 2011)	Norway	One-tube tunnel	3744	
(Asplan Viak AS, 2011)	Norway	Two-tube tunnel	4644	

Table 16 Energy consumption of tunneling equipment

4.3.3 Electrification system

As for electrification system of railway infrastructure, different studies adopted different scopes i.e. the study (Wang et al., 2016) provided the material inputs of signaling, communication and electric systems; the study (Eslami Ebrahimi, 2014) included overhead contact system, power supply, telecommunication, signaling and lighting system and provided the material intensity data of electrification system in term of different sections i.e. open section and tunnel section as well as different speeds of HSR i.e. 330km/h and 250km/h in Norway; the study (de Bortoli et al., 2020) considered power supply and signaling systems including trenches, catenary cables, catenary poles, connecting cables as well as signs; in the study (Bosquet et al., 2014), cables, signaling and catenary systems are included; the study (Asplan Viak AS, 2011) considered signaling system, telecommunication system, lighting system, fire ventilation system as well as transformers of the commuter line and also distinguished the data into open/tunnel section and one/tube tunnel; the study (Hanson et al., 2016) only provided the material inputs of catenary systems of commuter rails; the study (Shinde et al., 2018) provided power supply system and overhead contact system data while the study (Lederer et al., 2016) gave power supply system and signaling system data. These result in the material inputs of the electrification system vary significantly from study to study. The LCI data are shown in Table 17.

Type	Author	Country	Type	Steel	Copper	Aluminum	Concrete
HSR	(Wang et al., 2016)	China		98.00	26.00	24.00	
	(Eslami Ebrahimi, 2014)	Norway	Re330, open section	12.32	7.72	3.76	0.03
	(Eslami Ebrahimi, 2014)	Norway	Re330, tunnel section	6.15	7.24	5.15	0.00
	(Eslami Ebrahimi, 2014)	Norway	S25, open section	12.32	6.97	3.73	0.03
	(Eslami Ebrahimi, 2014)	Norway	S25, tunnel section	4.75	6.63	5.00	0.00
	(Bosquet et al., 2014)	France		42.00	5.20	0.11	179.00
	(de Bortoli et al., 2020)	France		87.10	10.71	0.02	214.21
	(Asplan Viak AS, 2011)	Norway	Open section (entry to Oslo)		3.43	2.00	
	(Asplan Viak AS, 2011)	Norway	Tunnel section (one-tube)		3.37	2.18	
	(Asplan Viak AS, 2011)	Norway	Tunnel section (two-tube)		3.35	2.17	
	(Asplan Viak AS, 2011)	Norway	Open section (entry to Ski)		3.18	1.59	
Commuter	(Hanson et al., 2016)	US			138	70.0	500.00
	(Shinde et al., 2018)	India			8.14		
Subway	(Lederer et al., 2016)	Austria		2.00	242.00	100.00	

Table 17 LCI of electrification system (unit: kg/m double track)

4.4 Archetypes of railway infrastructure

4.4.1 HSR archetype

The archetype of the HSR track system is shown in Table 18. The archetypes of bridges, tunnels as well as electrification systems are shown in Table 19. In addition, bar charts are built to visualize the material consumption of each component (Figure 8Figure 9Figure 10). Uncertainty bars expressing standard deviations are also added. The components with values lower than 500kg/double track were not illustrated in the figures since the values are so small compared with other components that cannot give clear information.

Material	Foundation	Ballast	Rails	Sleepers	Fastenings	Rail pads	Hydraulically bonded layer (HBL)	Concrete slabs	Electrification system (open section)
Concrete	2440			894.5			4410	2729	0.03
Steel			240	22.7	10.99		160	128	12.32
Cement	6800								
Sand	10000								
Gravel		7200							
Stone	24000								
Lime	3000								
Rubber						2.59			
Copper									7.35
Aluminum									3.75

Table 18 Material uses of track section of HSR construction stage (unit: kg/m double track)

Material/energy	Tunnel	Bridge	Electrification system (tunnel section)
Excavation soil	529060	73276	
Concrete	113288	55524	
Steel	2800	3510	5.45
Copper			6.94
Aluminum			5.08
Diesel (MJ)	5040	302.4	
Electricity (kWh)	4860		

Table 19 Material and energy use of HSR tunnel and bridge sections of HSR construction stage (unit: kg/m double track)

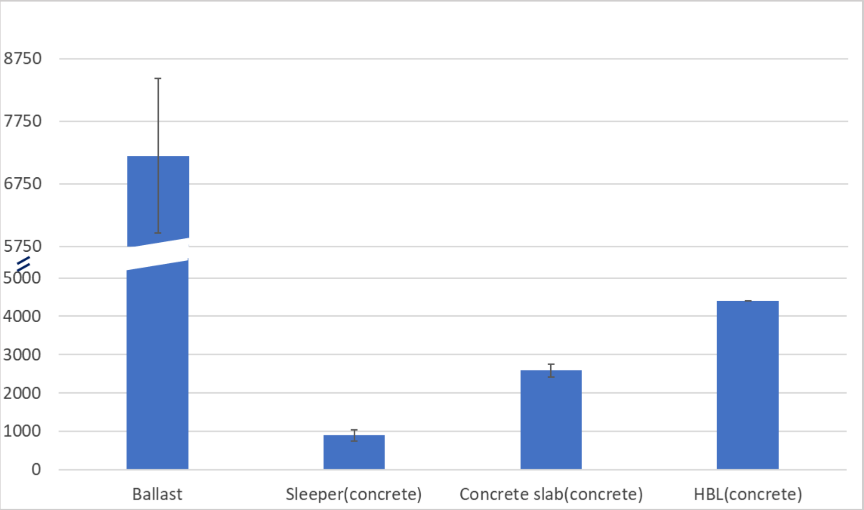

Figure 8 Material uses and their uncertainties of the components of HSR track (unit: kg/m double track)

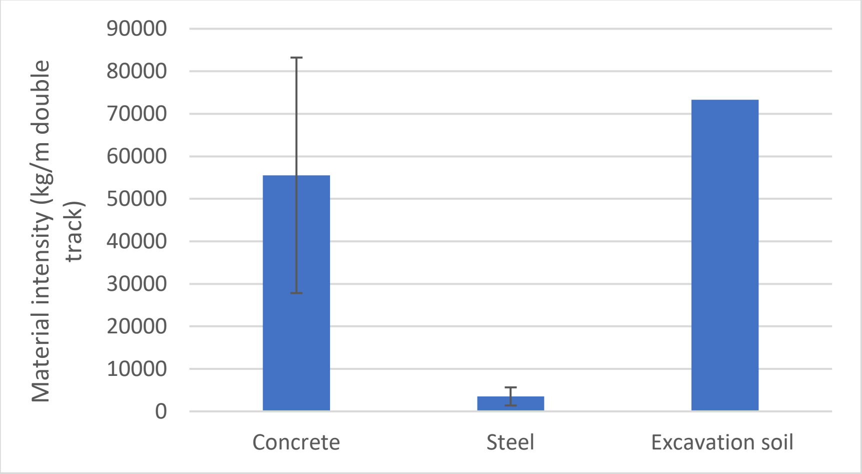

Figure 9 Material uses and their uncertainties of HSR bridges

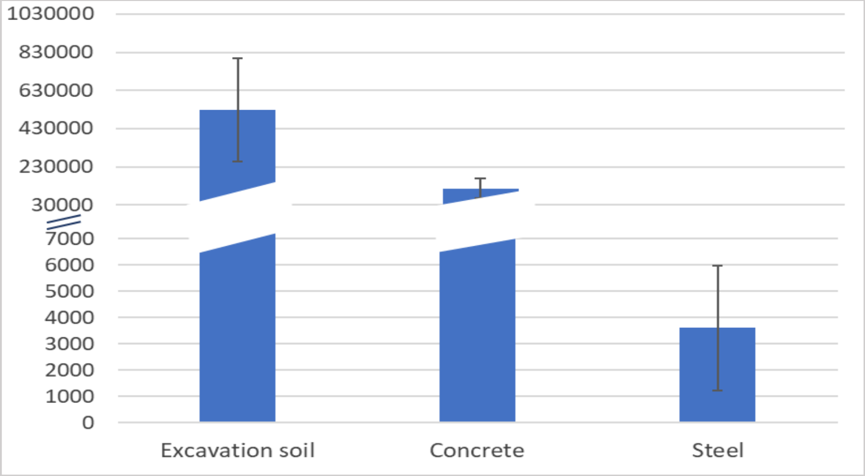

Figure 10 Material uses and uncertainties of HSR tunnel (unit: kg/m double track)

The material inputs of each section i.e. ballasted track section, ballastless track section, bridge section, and tunnel section are compared in order to give an impression of the differences of material uses between each section. The components of each section are illustrated in Table 20. Data are presented in Table 21, Figure 11. The table and figure show that tunnels and bridges are the most material-intensive sections and tunnels are even more intensive than bridges. Comparing the two types of tracks, the result shows that the concrete and steel consumptions of the ballastless track are higher than those of ballasted track.

Section	**Components**
Ballasted track section	Foundation, ballasted track system, electrification system
Ballastless track section	Foundation, ballastless track system, electrification system
Bridge section	Ballasted track system, bridge, electrification system
Tunnel section	Ballasted track system, tunnel, electrification system

Table 20 Components of different sections

Material	**Ballasted track**	**Ballastless track**	**Bridge**	**Tunnel**
Concrete	3334.53	10330.53	56418.53	116865
Cement	6800	6800		
Lime	3000	3000		
Sand	10000	10000		
Stone	24000	24000		
Gravel	14350	14350	7200	7200
Steel	271.02	571.34	3793.34	3876.47
Rubber	2.59	2.59	2.59	2.59
Copper	7.35	7.35	7.35	6.94
Aluminum	3.75	3.75	3.75	5.08
Excavation soil			73276	529060

Table 21 Material uses of each section (unit: kg/m double track)

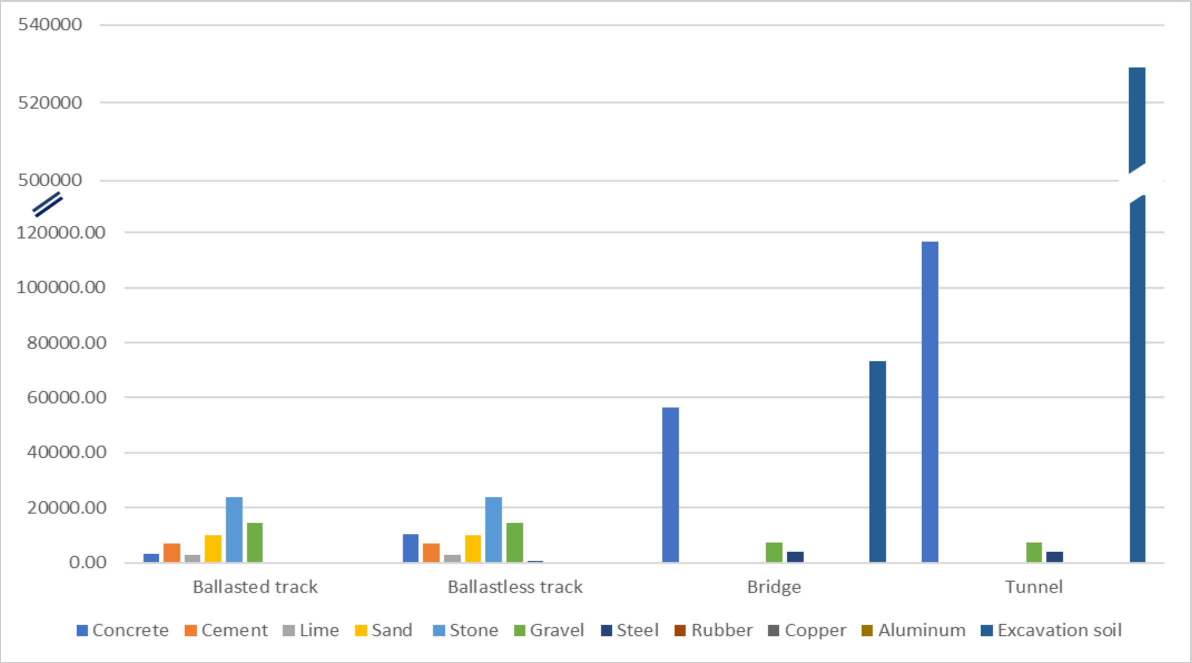

Figure 11 Comparison of material uses of each section

The energy uses of the construction and maintenance activities of HSR infrastructure are shown in Table 22.

Activity	Diesel consumption
Foundation construction	15312
Ballast spreading	9.85
Ballast tamping	16.95
Ballast changing	18.36
Ballast stabilizing	6.79
Ballast cleaning	18.36
Rail milling	4.251
Rail laying	13.32
Sleeper laying	5.04
Track laying	234
In situ slab former	15.84
Concrete train	13.32
Tunnel construction	5040
Bridge construction	261

Table 22 Energy consumptions (unit: MJ/m double track)

4.4.2 Commuter and subway archetypes

The archetypes data of commuter and subway are shown in Table 23 and Table 24 respectively.

Comparing to HSR, the archetypes of commuters do not have foundation material intensity data as well as the energy use of construction and maintenance activities. As for the subway, data for only ballast, rails, sleeper, electrification system, bridges, and tunnels data were found.

Material	Ballast	Rails	Sleepers	Fastenings	Rail pads	Electrification systems	Bridges	Tunnels
Gravel	9900							
Steel		236	22.8	12			9800	4200
Concrete			882			500	178000	88000
Rubber					1.4			
Excavation soil								540000
Copper						3.4		
Aluminum						2.17		
Electricity(kWh)								7050.6
Diesel(MJ)								116.48

Table 23 Material and energy use of commuter infrastructure (unit: kg/m double track)

Material	Ballast	Rails	Sleepers	Electrification systems	Bridges	Tunnels
Gravel	13800					
Steel		760	46	2	11050	11100
Concrete			1920		80000	70400
Rubber						
Excavation soil						
Copper				242		
Aluminum				100		

Table 24 Material uses of subway infrastructure (unit: kg/m double track)

4.4.3 Comparison between different archetypes

In this section, the material inputs of HSR, commuter as well as subway are compared. However, due to the lack of data regarding commuters and the subway, only the material inputs of track systems, electrification systems, and civil engineering structures are compared. comparison of track systems and electrification systems of three types of railways are shown in Figure 12 and the comparison of bridges and tunnels are shown in Figure 13 and Figure 14.

As for the track system, the figure illustrates that the material inputs of the subway are higher than those of commuters and HSR. The material intensities of the track system of commuter and HSR do not show a large difference between each component.

As for bridges, commuter requires huge amounts of concrete comparing to two other railways.

As for tunnels, the material requirements of the three types of rails are very similar.

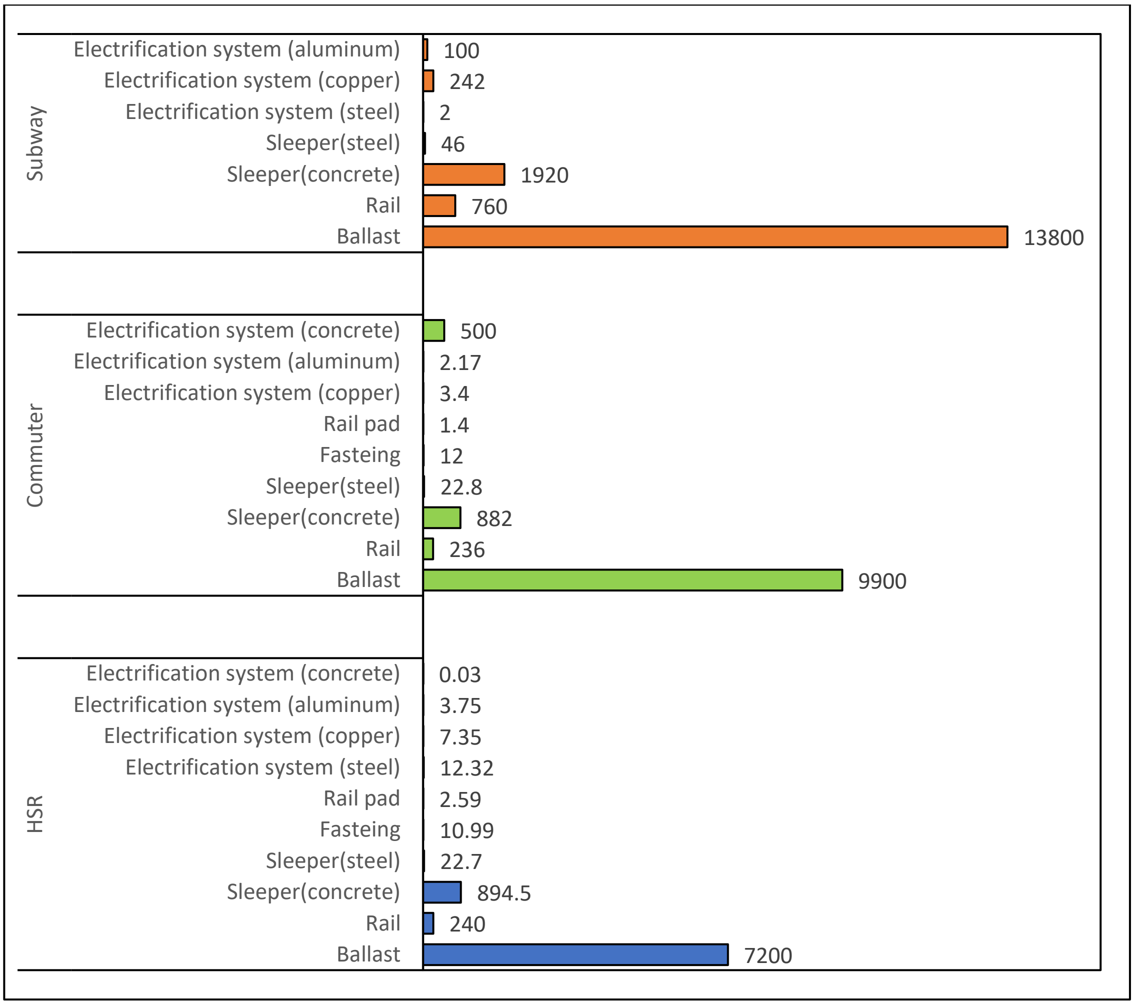

Figure 12 Comparison of tracks and electrification systems between HSR, commuter, and subway (unit: kg/m double track)

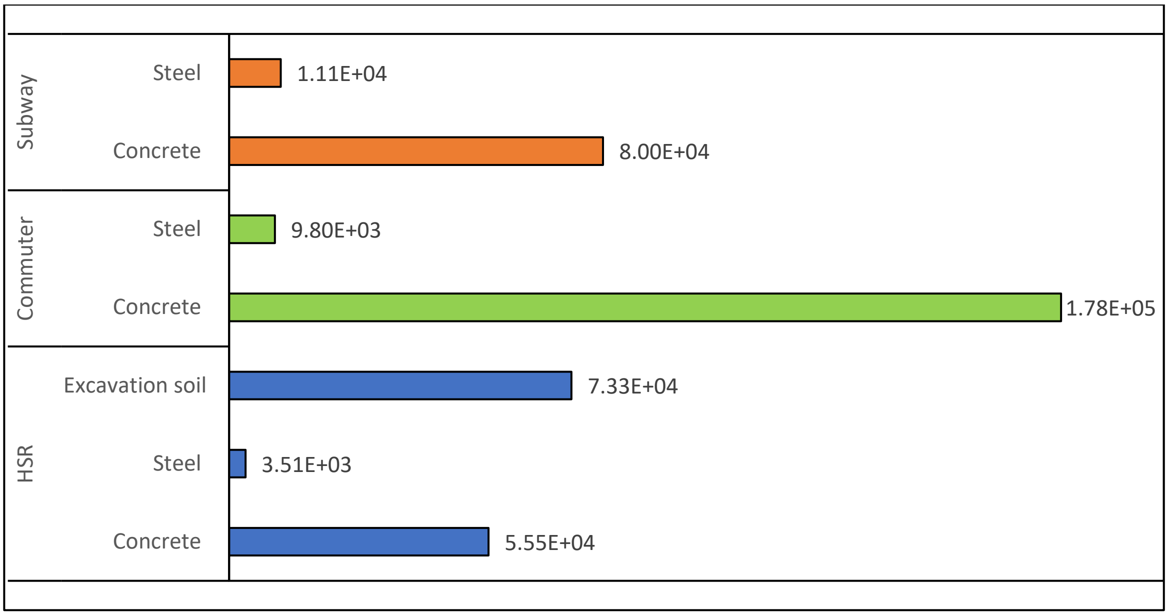

Figure 13 Comparison of bridges between HSR, commuter, and subway (unit: kg/m double track)

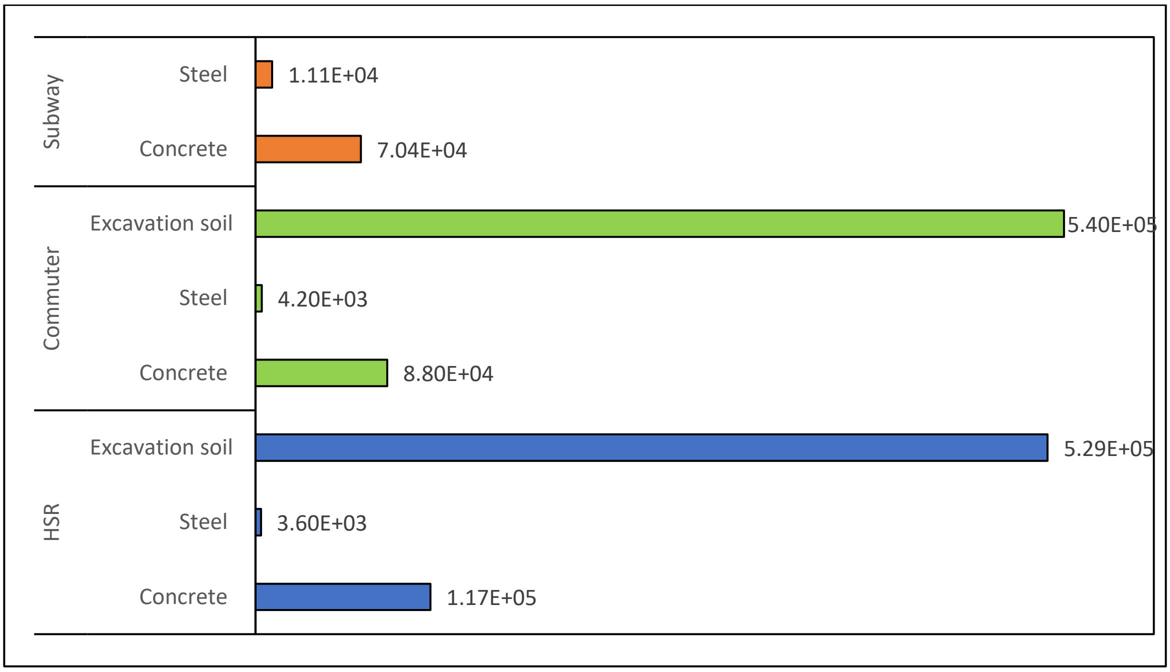

Figure 14 Comparison of tunnels between HSR, commuter, and subway (unit: kg/m double track)

4.5 Pedigree matrix

The scores in terms of reliability in most cases are chosen as 2 due to the data in this study are all collected from literature, which means these data are all assumed verified data or data based on measurements.

Regarding the completeness, since the data are collected from all over the world, but the majority of the data are from the countries like Germany, France, Japan, China, India, so the completeness is considered as "representative data from only some sites (<<50%) relevant for the market considered or >50% of sites but from shorter periods".

For the indicator temporal correlation, since the data are from many different sources conducted in different years, we chose the earliest study. Take the data of rails as an example, the data from the study (von Rozycki et al., 2003) were collected in the year 1999 while the study (Ortega et al., 2018) was collected the data in the year 2013, in this case, the data collection year is considered as "age of data unknown or more than 15 years of difference to the time period of the dataset".

As for geographical correlation, since data are collected from different countries and then the median data are chosen to represent the archetypes, the geographical correlation is considered as "average data from a larger area in which the area under study is included".

As for further technological correlation, if the data were collected directly from the studies conducting life cycle assessments, they are considered as "data from processes and materials under study (i.e. identical technology) but from different enterprises", but if the data are collected from the studies conducting material stock analysis, they would be considered as "data from processes and materials under study but from different technology".

The pedigree matrix presenting the data quality of each infrastructure material of HSR is shown in Table 25. The results show that the temporal correlation and completeness have relatively high scores. However, since the technologies of railway infrastructure production do not change significantly over the years, in addition, most components have a long lifetime (more than 20 years) resulting in the indicator temporal correlation has high scores, which might mislead the results by telling the data quality is low. Therefore, to improve the data quality collecting adequate data and improve the data completeness is the most optimal solution.

Component	Material	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation
Foundation						
	Cement	2	3	4	2	2
	Stone	2	3	4	2	2
	Sand	2	3	4	2	2
	Lime	2	3	4	2	2
	Gravel	2	4	4	2	1
Energy	Construction equipment	2	3	4	2	2
Track system						
Ballast	Gravel	2	3	4	2	2
Energy	Ballast stabilization	2	4	2	2	2
	Ballast spreading	2	3	4	2	2
	Ballast changing	2	4	4	2	2
	Ballast cleaning	2	4	4	2	2
	Ballast tamping	2	3	4	2	2
	Replacing rails, sleepers, fastenings	2	4	2	2	2
	In situ slab former	2	4	4	2	2
	Concrete train	2	4	4	2	2
Rails	Steel	1	2	2	2	1
Energy	Rail milling	2	3	4	3	2
Sleepers	Concrete	2	3	4	2	2
	Steel	2	3	4	2	2
Fastenings	Steel	2	3	4	2	2
Rail pads	Rubber	2	3	4	2	2
Energy	Track laying	1	4	4	2	2
	Rail laying	1	4	4	2	2
	Sleeper laying	1	4	4	2	2
Concrete slab	Concrete	2	3	4	2	2
	Steel	2	3	4	2	2
HBL	Concrete	2	4	4	2	2
	Steel	2	4	4	2	2
Bridges						
	Concrete	2	3	5	2	2
	Steel	2	3	5	2	2
	Excavation soil	2	4	3	2	2
Energy	Construction equipment	2	3	3	2	2
Tunnels						
	Concrete	2	3	3	2	2
	Steel	2	3	3	2	2
	Excavation soil	2	3	3	2	2

Energy	Construction equipment	2	3	3	2	2
Electrification system						
	Steel	2	4	3	2	2
	Copper	2	4	3	2	2
	Aluminum	2	4	3	2	2
	Concrete	2	4	3	2	2

Table 25 Data quality indices of each component material of HSR

The empirical results including the basic uncertainty, the geometric standard deviation (δg), and the coefficient of variation (CV) are shown in Table 26. The results show that most of the materials have relatively low CV meaning the data set is less dispersed. The zeros in the table mean the data having only one source so that the dispersion does not exist. The materials that have high CV are concrete and cement of foundation as well as the energy use of rail milling, it is due to the high variations of the material use data of these materials.

Component	Material	U_b	SD_{g95}^2	δg	CV
Foundation					
	Concrete	11.85	24.05	4.90	3.40
	Cement	12.34	26.58	5.16	3.70
	Stone	1.28	1.17	1.08	0.08
	Sand	1.27	1.16	1.08	0.08
	Lime	1.56	1.25	1.12	0.11
	Gravel	0.00	0.00	0.00	0.00
Energy	Construction equipment	1.40	1.20	1.09	0.09
Track system					
Ballast	Gravel	1.20	1.15	1.07	0.07
Energy	Ballast stabilization	0.00	0.00	0.00	0.00
	Ballast spreading	1.19	1.15	1.07	0.07
	Ballast changing	0.00	0.00	0.00	0.00
	Ballast cleaning	0.00	0.00	0.00	0.00
	Ballast tamping	3.37	2.37	1.54	0.45
	Replacing rails, sleepers, fastenings	0.00	0.00	0.00	0.00
	In situ slab former	0.00	0.00	0.00	0.00
	Concrete train	0.00	0.00	0.00	0.00
Rails	Steel	1.10	1.01	1.00	0.00
Energy	Rail milling	19.45	92.68	9.63	12.95
Sleepers	Concrete	1.17	1.15	1.07	0.07
	Steel	1.16	1.14	1.07	0.07
Fastenings	Steel	1.73	1.32	1.15	0.14
Rail pads	Rubber	1.76	1.33	1.15	0.14
Energy	Track laying	0.00	0.00	0.00	0.00
	Rail laying	0.00	0.00	0.00	0.00
	Sleeper laying	0.00	0.00	0.00	0.00
Concrete slab	Concrete	1.06	1.13	1.06	0.06
	Steel	2.35	1.63	1.28	0.25
HBL	Concrete	0.00	0.00	0.00	0.00
	Steel	0.00	0.00	0.00	0.00

Bridges					
	Concrete	2.39	1.68	1.30	0.26
	Steel	1.97	1.45	1.20	0.19
	Excavation soil	0.00	0.00	0.00	0.00
Energy	Construction equipment	6.58	6.60	2.57	1.20
Tunnels					
	Concrete	2.30	1.59	1.26	0.23
	Steel	2.40	1.64	1.28	0.25
	Excavation soil	1.60	1.25	1.12	0.11
Energy	Construction equipment	2.77	1.88	1.37	0.32
Electrification system					
	Steel	1.63	1.26	1.12	0.12
	Copper	1.07	1.12	1.06	0.06
	Aluminum	1.19	1.14	1.07	0.07
	Concrete	1.00	1.12	1.06	0.06

Table 26 Empirical results of the pedigree matrix (HSR)

Note: U_b: basic uncertainty; SD_{g95}^2: Square of the geometric standard deviation; δ_g : geometric standard deviation; CV: coefficient of variation.

The pedigree matrix presenting the quality of commuter material input data is shown in Table 27. The results show that most indicators have low scores except completeness. It means the data quality is reasonably high and the main factor influencing the data quality is the number of data sources, in another word, lack of data is the main reason affecting the data quality in terms of commuter.

Component	Material	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation
Rails		2	3	2	2	2
Fastenings		2	3	2	2	2
Rail pads		2	4	2	2	2
Sleepers	Concrete	2	3	2	2	2
	Steel	2	4	2	2	2
Bridges	Concrete	2	4	2	2	2
	Steel	2	4	2	2	2
Tunnels	Concrete	2	4	2	2	2
	Steel	2	4	2	2	2
	Excavation soil	2	4	2	2	2
Electrification system	Steel	2	4	2	2	2
	Copper	2	3	2	2	2
	Aluminum	2	3	2	2	2
	Concrete	2	4	2	2	2

Table 27 Data quality indices of each component material of commuter

The empirical results of the pedigree matrix of commuters are shown in Table 28. The CV of the materials is all very low in terms of commuter. It is because of lack of data sources.

Component	Material	U_b	SD_{g95}^2	δg	CV
Rails	Steel	1.07	1.01	1.00	0.0026
Fastenings	Steel	1.09	1.01	1.00	0.0033
Rail pads	Rubber	0.00	0.00	0.00	0.00
Sleepers	Concrete	1.12	1.01	1.00	0.0048
	Steel	0.00	0.00	0.00	0.00
Bridges	Concrete	0.00	0.00	0.00	0.00
	Steel	0.00	0.00	0.00	0.00
Tunnels	Concrete	0.00	0.00	0.00	0.00
	Steel	0.00	0.00	0.00	0.00
	Excavation soil	0.00	0.00	0.00	0.00
Electrification system	Steel	0.00	0.00	0.00	0.00
	Copper	7.40	7.43	2.73	1.3170
	Aluminum	0.00	0.00	0.00	0.00
	Concrete	0.00	0.00	0.00	0.00

Table 28 Empirical results of the pedigree matrix (commuter)

Note: U_b: basic uncertainty; SD_{g95}^2: Square of the geometric standard deviation; δ_g : geometric standard deviation; CV: coefficient of variation.

The pedigree matrix indices and empirical results of the subway are shown in Table 29 and Table 30 respectively. The pedigree matrix indices of the subway are similar to commuter, the main contributor to the uncertainty also comes from lack of data sources, which then results in the CVs or dispersions of the data of each material are low.

Component	Material	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation
Rails	Steel	2	4	2	2	2
Sleepers	Concrete	2	4	2	2	2
	Steel	2	4	2	2	2
Bridges	Concrete	2	3	2	2	2
	Steel	2	3	2	2	2
Tunnels	Concrete	2	3	2	2	2
	Steel	2	3	2	2	2
	Excavation soil	2	3	2	2	2
Electrification system	Steel	2	4	2	2	2
	Copper	2	4	2	2	2
	Aluminum	2	4	2	2	2

Table 29 Data quality indices of each component material of subway

Component	Material	U_b	SD_{g95}^2	δg	CV
Rails	Steel	0.00	0.00	0.00	0.00
Sleepers	Concrete	0.00	0.00	0.00	0.00
	Steel	0.00	0.00	0.00	0.00
Bridges	Concrete	3.96	2.58	1.61	0.50
	Steel	1.49	1.09	1.04	0.04
Tunnels	Concrete	3.03	1.86	1.36	0.32
	Steel	2.83	1.72	1.31	0.28
Electrification system	Steel	0.00	0.00	0.00	0.00
	Copper	0.00	0.00	0.00	0.00
	Aluminum	0.00	0.00	0.00	0.00
	Concrete	0.00	0.00	0.00	0.00

Table 30 Empirical results of the pedigree matrix (subway)

Note: U_b: basic uncertainty; SD_{g95}^2: Square of the geometric standard deviation; δ_g : geometric standard deviation; CV: coefficient of variation.

4.6 Discussion and conclusions

The following conclusions can be drawn from this chapter:

- The material intensities of the components of the track system except ballast do not vary considerably between different types. The inputs of ballast, as well as foundation materials, highly depend on soil conditions.
- Ballastless track consumes more concrete and steel than ballasted track due to the high concrete and steel intensity of concrete slab and hydraulically bonded layer of ballastless track.
- Bridges and tunnels are the most material-intensive components. The material intensities of bridge construction materials are determined by the types of bridges, e.g. concrete bridge, steel bridge. The material intensities of tunnels are mainly determined by tunneling technologies. The results showed that conventional tunneling methods are more material intensive than TBM. In terms of tunnel types, trenched tunnels are more material intensive than mined tunnels. Besides, the construction region also determines the material inputs of tunnels due to different soil conditions. However, since these conclusions are drawn from the observation of the collected data, it is hard to give an exact number of the difference between the material intensities.
- The scope of the electrification system varies from study to study. Therefore, it is challenging to compare between different studies.
- The results from pedigree matrices of three types of railways show that with regards to the additional uncertainties of the data, the main contributor the indicator completeness, which means there are not enough data sources to make the archetypes reliable and robust. Besides, the scores of temporal correlations might cause overestimating the uncertainties due to the long lifetime and little change of the technologies of railway infrastructure. Therefore, the effectiveness of the pedigree matrix needs to be further discussed in future work.
- The biggest challenge encountered in this chapter is the available data sources regarding commuter and subway. Therefore, the built archetypes regarding these two rails might not be representative enough to be used work to estimate the material stocks or the material requirements of the future constructions.

5 Life cycle assessment methodology

5.1 Methodology

The International Organization for Standardization (ISO) defined Life Cycle Assessment as "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (*ISO*, 2006). According to ISO 14044, there are four phases set up in an LCA study: 1) the goal and scope definition phase, 2) the inventory analysis phase, 3) the impact assessment phase, and 4) the interpretation phase (Figure 15).

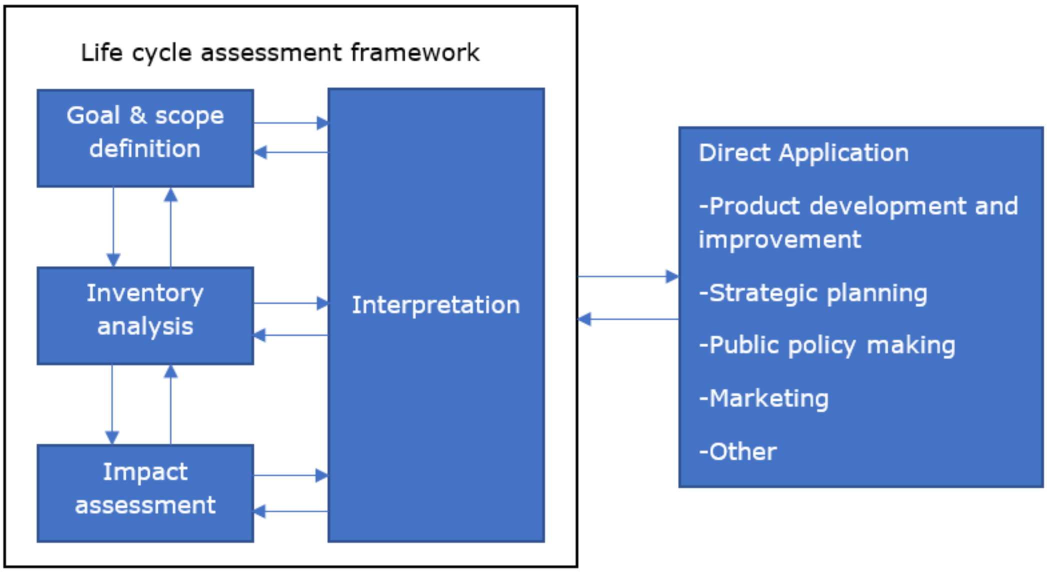

Figure 15 The framework of an LCA study

5.1.1 Goal and scope definition

The goal and scope definition is the first phase to conduct a life cycle assessment. The goal of this study is to estimate the environmental performance of railway infrastructure and assess the main contributors to environmental impacts in terms of material consumption and energy use. A process-based attributional method is adopted in this study.

The system boundary consists of construction and maintenance phases of railway infrastructure. Railway types include HSR, commuter, and subway. The infrastructure components include foundation, track system, bridges, tunnels, and electrification system. See the definitions in sections 3.2 and 3.3.

The functional unit adopted in this study is constructing and maintaining 1km of double-track railway over 60 years.

5.1.2 Data collection and inventory

Material and energy input data have been collected from the literature. The data collected to use in LCA are shown in 4.1.1. The estimated lifetime and maintenance times of each component are shown in Table 31. The transportation distances of foundation materials, as well as ballast, are assumed as 50km while the distances of the rest of the materials are considered as 150km.

Component	Life expectancy: year	Replacement times over 60 years
Ballast	20	2
Rail	25	2
Sleeper	40	1
Fastener	25	2
Rail pad	20	2
Ballast tamping		85% of ballast is tamped every year[7]
Ballast cleaning		5
Ballast spreading		2
Ballast stabilizing		60
Rail milling		59

Table 31 Assumed life expectancy and maintenance frequency of the components

5.1.3 Environmental impact assessment

In this step, the environmental impacts associated with the construction and maintenance of infrastructure are calculated. The LCA software Arda developed by the Industrial Ecology Programme at the Norwegian University of Science and Technology was used to process the data and the model was combined with Ecoinvent 3.6 database. The ReCiPe Midpoint (H) V1.13 method was adopted in this study. See the summary of material and energy uses as well as Ecoinvent processes in the Appendix section.

13 types of environmental categories are adopted, i.e. climate change (GWP), fossil depletion (FDP), freshwater ecotoxicity (FETPinf), freshwater eutrophication (FEP), human toxicity (HTPinf), marine ecotoxicity (METPinf), marine eutrophication (MEP), metal depletion (MDP), ozone depletion (ODPinf), particulate matter formation (PMFP), photochemical oxidant formation (POFP), terrestrial acidification (TAP100), terrestrial ecotoxicity (TETPinf).

5.2 Results

The contributions of each component of railway infrastructure to 13 types of environmental categories over the 60-year lifetime are shown in Figure 16. Bridges and tunnels are the biggest two contributors to all types of environmental impacts. The impacts from bridges account for 21-32% of total impacts, minoring on ozone depletion and majoring on terrestrial ecotoxicity (TETPinf). Tunnels account for 20-46% of total impacts, minoring on metal depletion and majoring on freshwater ecotoxicity. The impact values are shown in Table 32.

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[7] This data is from the study (de Bortoli et al., 2020).

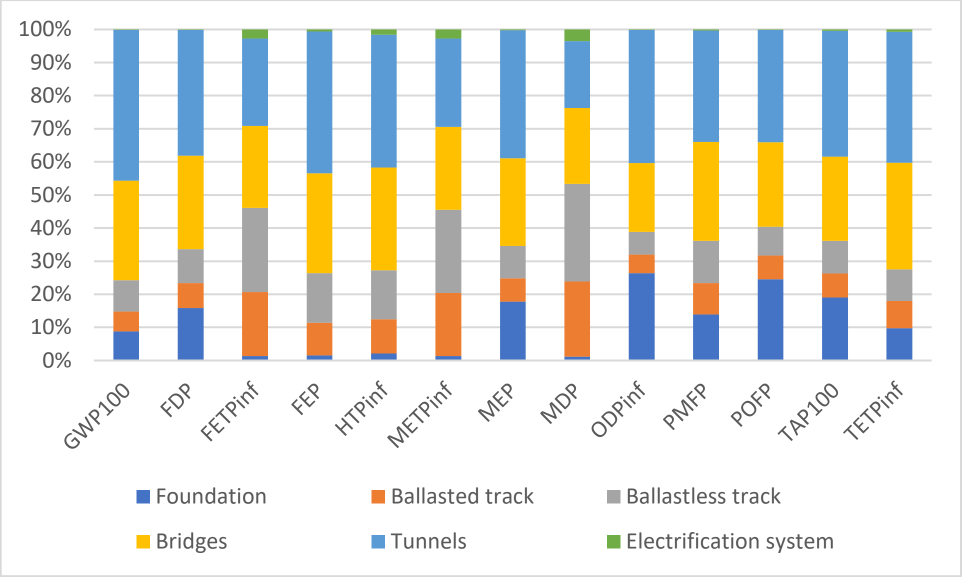

Figure 16 Environmental impacts from 1km of each component

The environmental impacts from the foundation broken down into materials, energy, and transportation are shown in Figure 17. Limestone is the biggest contributor followed by energy use of the construction activities. The impacts from limestone account for 27-48%, minoring and majoring on terrestrial ecotoxicity and marine eutrophication. Impacts from energy use account for 22-44%, minoring on freshwater eutrophication, human toxicity, metal depletion, and terrestrial ecotoxicity and majoring on photochemical oxidant formation. Besides, transportation has a large impact on terrestrial ecotoxicity, accounting for 38% of the total impact.

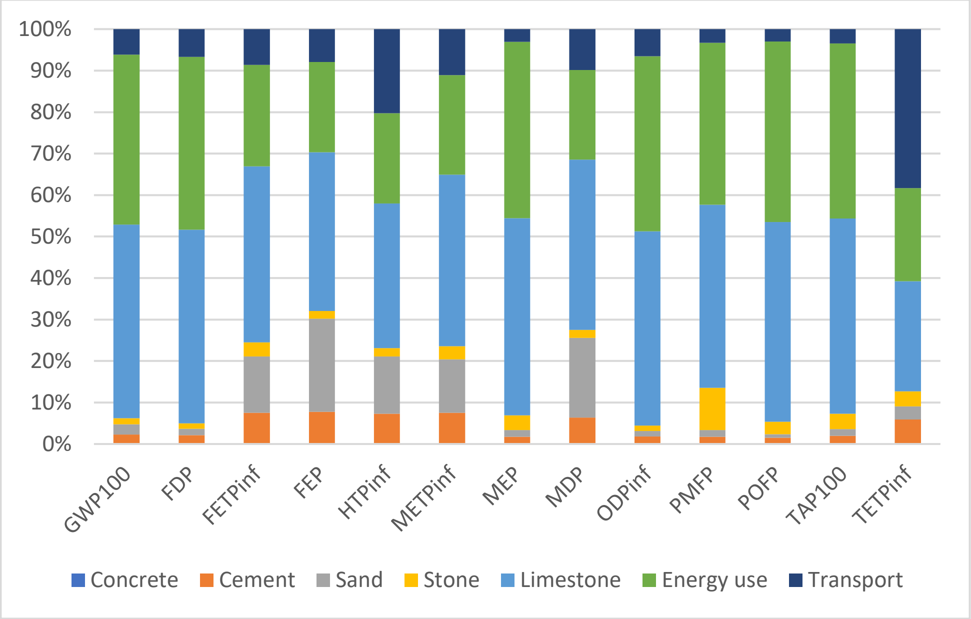

Figure 17 Environmental impacts of foundation broken down into materials

Impact category	Unit	Foundation	Ballasted track	Ballastless track	Bridges	Tunnels	Electrification system	Total
GWP100	kg CO2-Eq	3.38E+06	2.33E+06	3.63E+06	1.16E+07	1.76E+07	4.96E+04	3.86E+07
FDP	kg oil-Eq	1.06E+06	5.08E+05	6.83E+05	1.89E+06	2.54E+06	9.59E+03	6.68E+06
FETPinf	kg 1,4-DC.	2.37E+04	3.51E+05	4.62E+05	4.49E+05	4.79E+05	5.01E+04	1.82E+06
FEP	kg P-Eq	2.34E+02	1.51E+03	2.28E+03	4.59E+03	6.53E+03	9.54E+01	1.52E+04
HTPinf	kg 1,4-DC.	3.10E+05	1.48E+06	2.14E+06	4.47E+06	5.79E+06	2.25E+05	1.44E+07
METPinf	kg 1,4-DB.	2.21E+04	3.11E+05	4.09E+05	4.07E+05	4.36E+05	4.41E+04	1.63E+06
MEP	kg N-Eq	1.57E+03	6.29E+02	8.59E+02	2.34E+03	3.41E+03	2.52E+01	8.83E+03
MDP	kg Fe-Eq	9.88E+04	1.94E+06	2.52E+06	1.95E+06	1.73E+06	3.00E+05	8.54E+06
ODPinf	kg CFC-11.	5.66E-01	1.19E-01	1.48E-01	4.46E-01	8.61E-01	3.22E-03	2.14E+00
PMFP	kg PM10-Eq	1.48E+04	1.01E+04	1.36E+04	3.18E+04	3.58E+04	3.62E+02	1.07E+05
POFP	kg NMVOC-.	4.49E+04	1.31E+04	1.60E+04	4.66E+04	6.21E+04	3.30E+02	1.83E+05
TAP100	kg SO2-Eq	2.64E+04	1.01E+04	1.37E+04	3.53E+04	5.27E+04	5.86E+02	1.39E+05
TETPinf	kg 1,4-DC.	2.67E+02	2.22E+02	2.59E+02	8.76E+02	1.08E+03	1.99E+01	2.72E+03

Table 32 Environmental impacts from 1 km of railway infrastructure broken down into components

The environmental impacts from the ballasted track are shown in Figure 18, Figure 19, and Figure 20. Figure 18 shows the results broken down into construction stage and maintenance stage; Figure 19 was broken down into different components while Figure 20 was broken down into materials.

The results broken down into life cycle stages show that the maintenance stage has larger contributions than the construction stage, accounting for 62-68% of the total impacts.

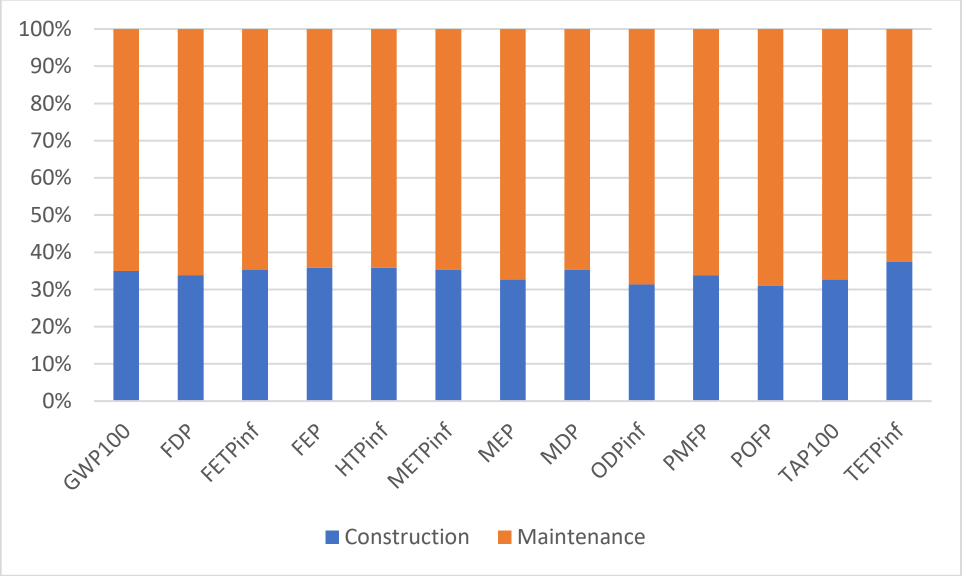

Figure 18 Environmental impacts of construction and maintenance stages of 1km of ballasted track

In terms of the components of the ballasted track system, rails are the largest contributors to all environmental impact categories accounting for 45-88%, majoring on metal depletion and minoring on ozone depletion. Besides rails, ballast and energy use also have relatively large impacts. Transportation has a significant impact on territorial ecotoxicity.

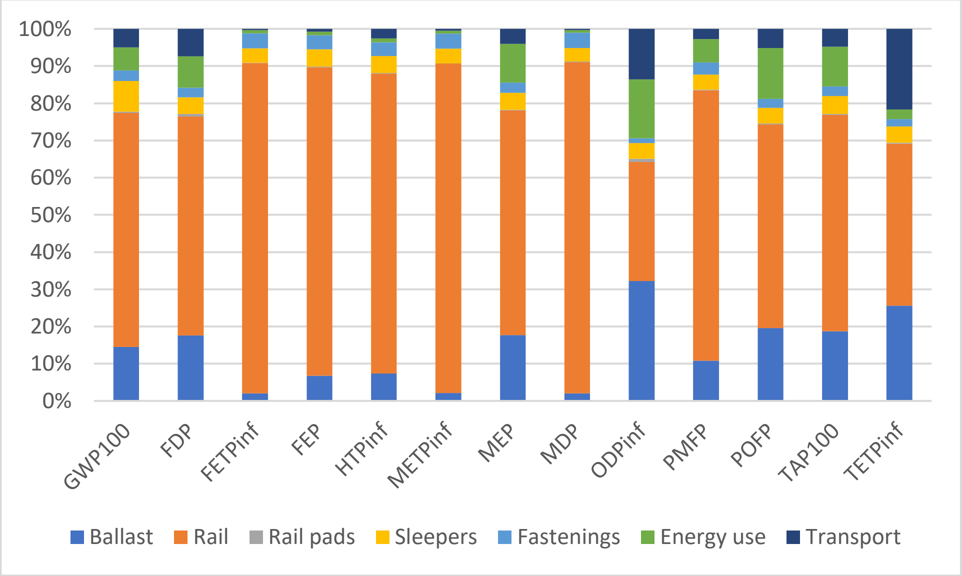

Figure 19 Environmental impacts of ballasted track broken down into components

With regards to the materials, steel has the biggest contributions followed by rubber. Steel accounts for 34% (ozone depletion) to 60% (freshwater ecotoxicity and metal depletion) while rubber is responsible for 39% (freshwater ecotoxicity, freshwater eutrophication marine ecotoxicity, and metal depletion) to 55% (ozone depletion) of total impacts. Gravel and concrete have very low impacts comparing to steel and rubber.

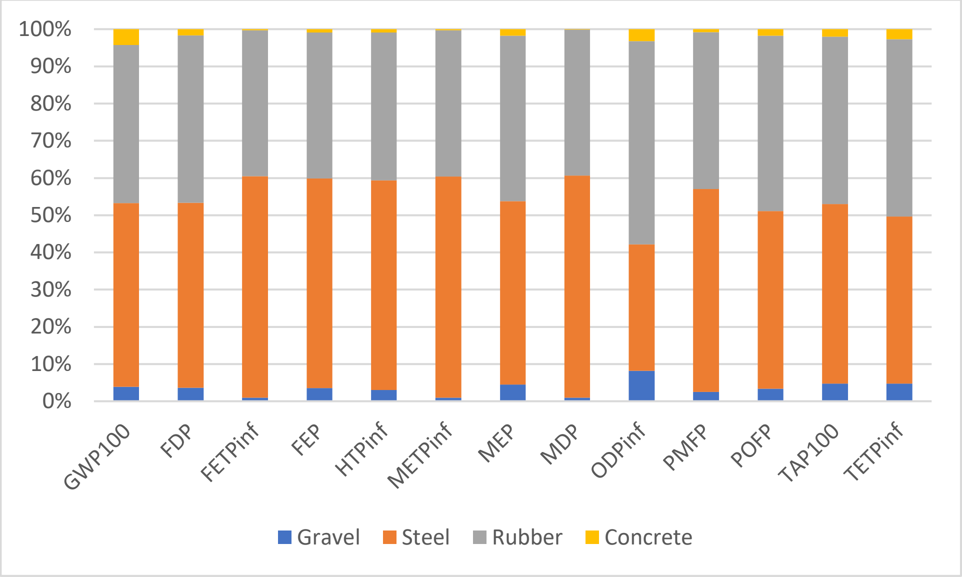

Figure 20 Environmental impacts of ballasted track broken down into materials

Figure 21 and Figure 22 show the environmental impacts of the ballastless track. The former one is presented in terms of components while the latter one is broken down into materials. Regarding the contribution of the components, rails, hydraulically bonded layer, and concrete slab are the major contributors.

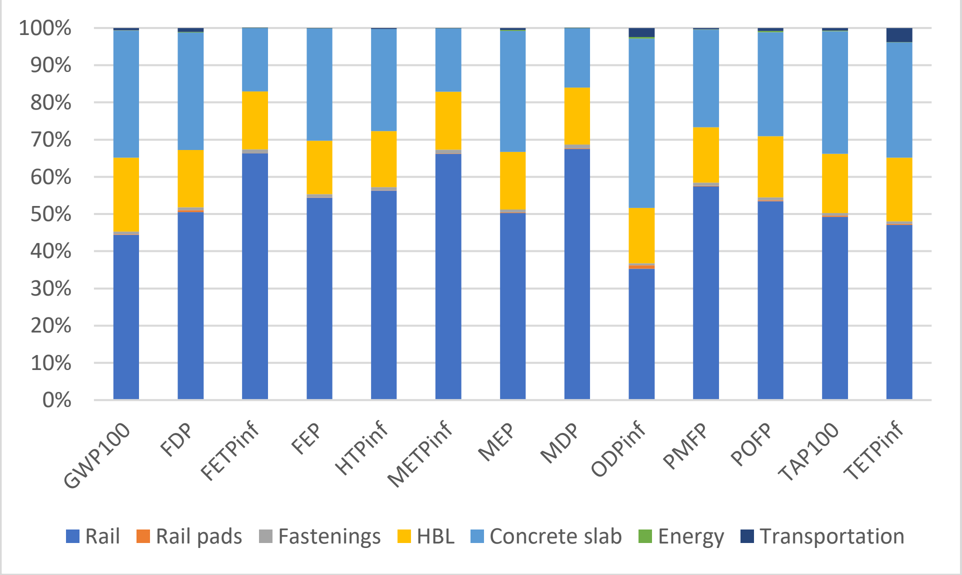

Figure 21 Environmental impacts of 1km of ballastless track broken down into components

If we see the results broken down into materials, steel has a significant contribution followed by concrete, while the impacts from rubber are negligible. The impacts generated by steel are responsible for 47% (ozone depletion) to 96% (metal depletion). Concrete accounts for 4% (metal depletion) to 52% (ozone depletion).

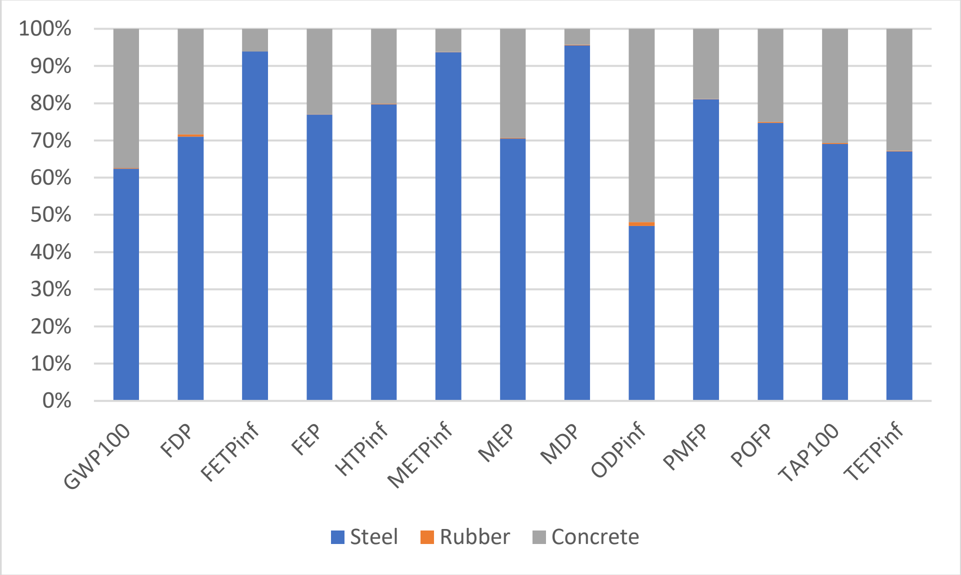

Figure 22 Environmental impacts of ballastless track broken down into materials

Figure 23 shows the environmental impacts from the construction and maintenance stages. The construction stage generates larger impacts than the maintenance stage, it is responsible for 55-75% of the total impacts.

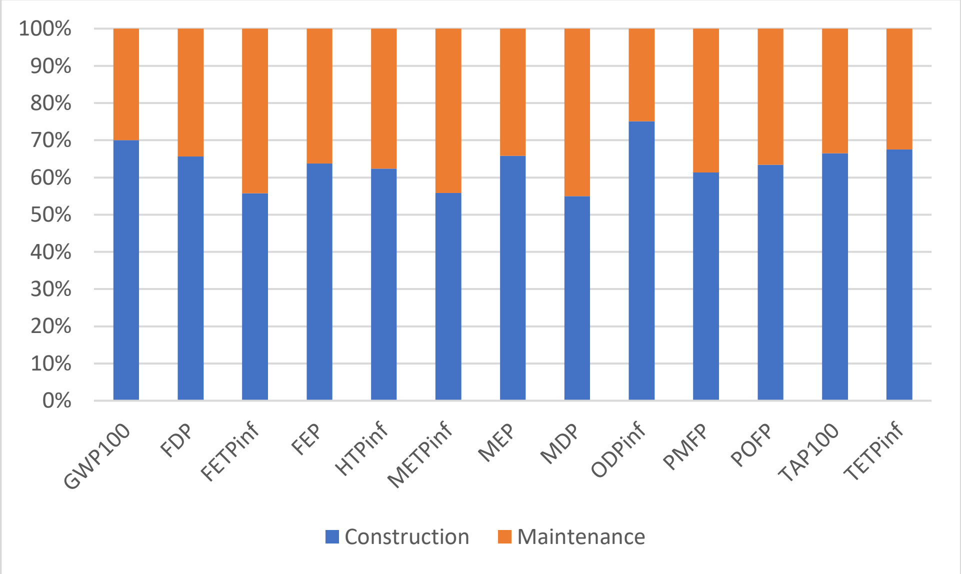

Figure 23 Environmental impacts of ballastless track broken down into life cycle stages

Figure 24 shows the environmental impacts generated from bridges. The main contributor of bridges to the environmental impacts is steel. It accounts for 59% (climate change) to 94% (metal depletion) of the total impacts. Concrete accounts for 6% (metal depletion) to 40% (climate change). The impacts related to excavation soil are very small comparing to steel and concrete so that it can be neglected.

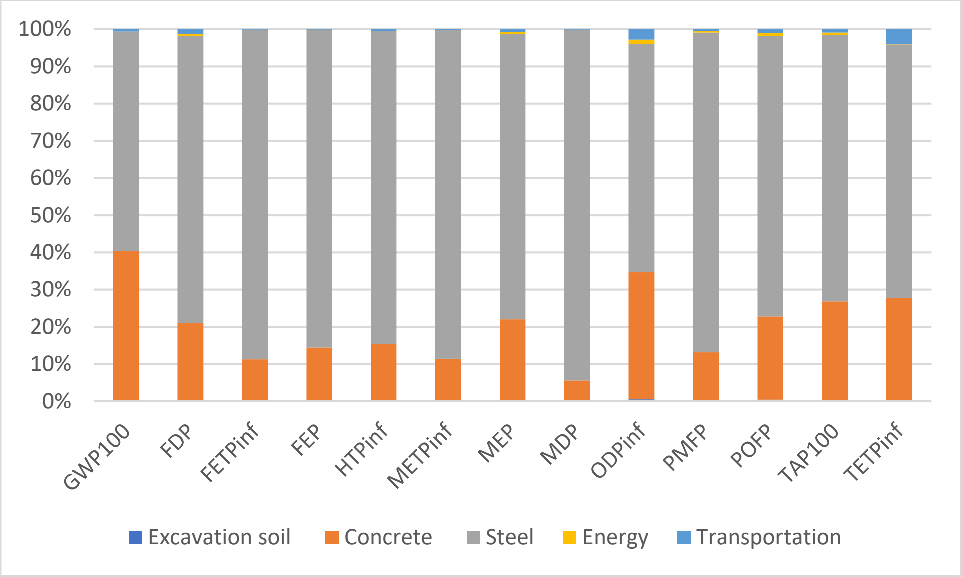

Figure 24 Environmental impacts of 1km of bridges broken down into materials

As for the environmental impacts from tunnels shown in Figure 25. The results show that steel is the largest contributor to all types of categories accounting for 25-85% of total impacts minoring on ozone depletion and majoring on metal depletion. It is followed by concrete accounting for 13-54% of total impacts minoring on metal depletion and majoring on global warming.

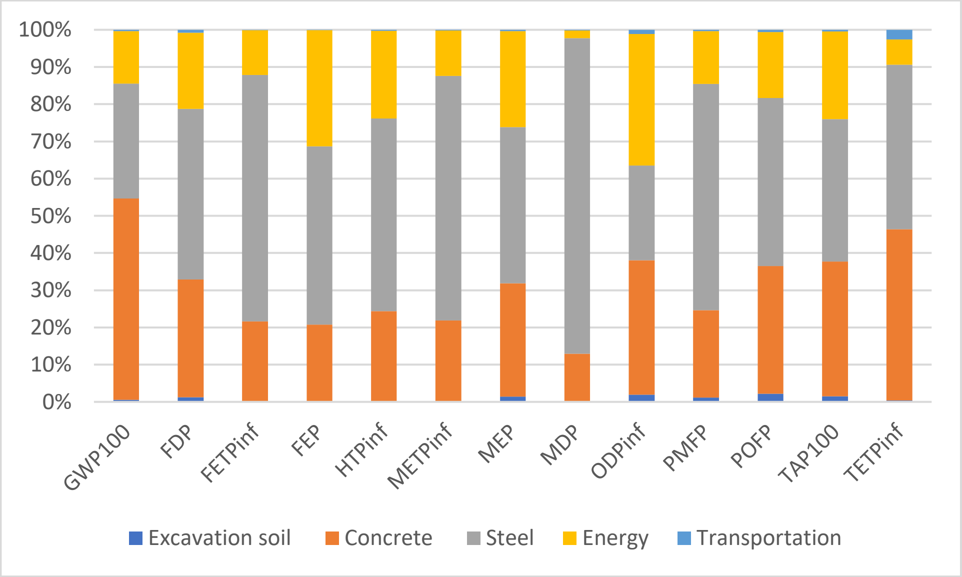

Figure 25 Environmental impacts of 1 km of tunnels broken down into materials

With regards to the environmental impacts of the electrification system shown in Figure 26, copper is the major contributor to most of the environmental impacts except global warming potential, fossil depletion potential, and ozone depletion potential. As for climate change impact, aluminum, steel, and copper are responsible for 40%, 39%, 21% respectively. As for fossil depletion, aluminum, steel, and copper account for 38%, 43%, and 18% respectively. In terms of ozone depletion, these three materials are responsible for 50%, 26%, and 24% respectively. Transportation has negligible impacts.

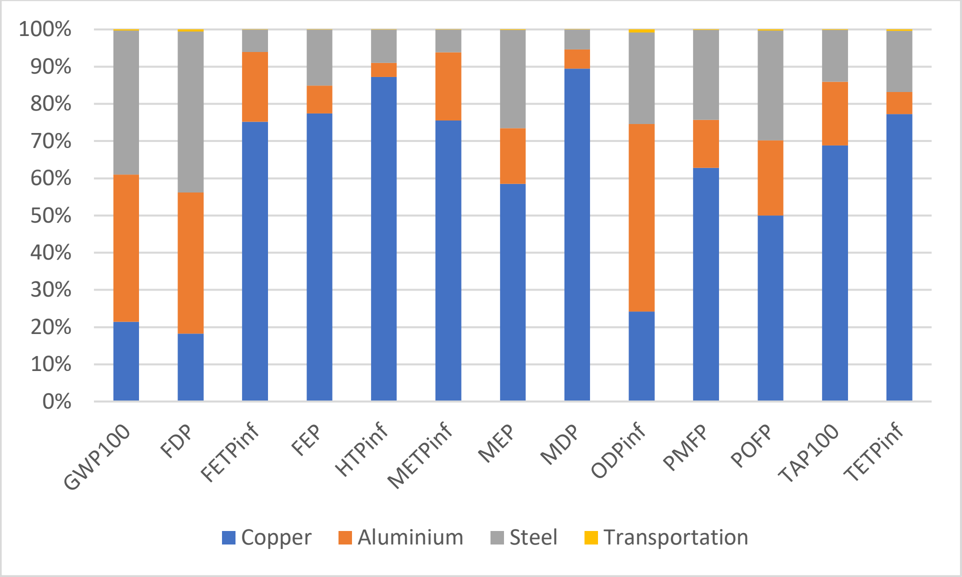

Figure 26 Environmental impacts from electrification system broken down by materials

Figure 27 and Table 33 present the contributions of each material to the environmental impacts. In all types of environmental impact categories, concrete and steel are the two major contributors. Concrete accounts for 44-55% while steel accounts for 46-51%. Rubber is responsible for 1-4% of total impacts. The impacts from other materials are responsible for 0-10% of total impacts.

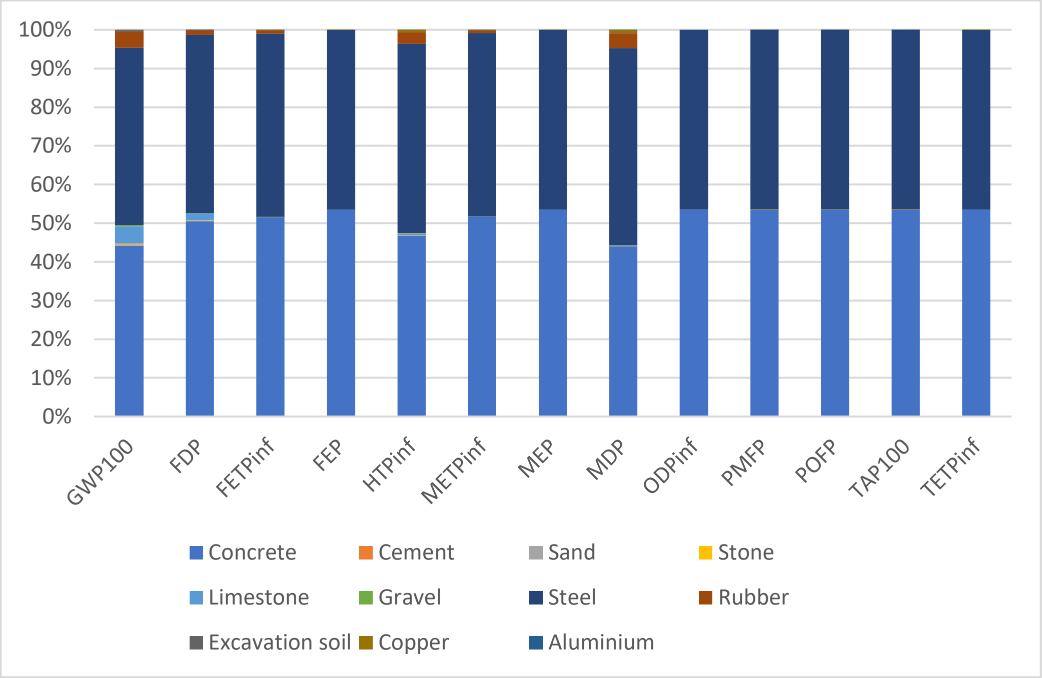

Figure 27 Total environmental impacts broken down into materials

Impact categories	Concrete	Cement	Sand	Stone	Limestone	Gravel	Steel	Rubber	Excavation soil	Copper	Aluminum
GWP100	44%	0%	0%	0%	4%	0%	46%	4%	0%	0%	0%
FDP	51%	0%	0%	0%	2%	0%	46%	1%	0%	0%	0%
FETPinf	52%	0%	0%	0%	0%	0%	47%	1%	0%	0%	0%
FEP	54%	0%	0%	0%	0%	0%	46%	0%	0%	0%	0%
HTPinf	47%	0%	0%	0%	0%	0%	49%	3%	0%	1%	0%
METPinf	52%	0%	0%	0%	0%	0%	47%	1%	0%	0%	0%
MEP	54%	0%	0%	0%	0%	0%	46%	0%	0%	0%	0%
MDP	44%	0%	0%	0%	0%	0%	51%	4%	0%	1%	0%
ODPinf	54%	0%	0%	0%	0%	0%	46%	0%	0%	0%	0%
PMFP	54%	0%	0%	0%	0%	0%	46%	0%	0%	0%	0%
POFP	53%	0%	0%	0%	0%	0%	46%	0%	0%	0%	0%
TAP100	54%	0%	0%	0%	0%	0%	46%	0%	0%	0%	0%
TETPinf	54%	0%	0%	0%	0%	0%	46%	0%	0%	0%	0%

Table 33 Contributions of each material to the environmental impacts

5.3 Discussion and conclusions

From the results of LCA, the following conclusions are drawn:

- In terms of the components of the railway infrastructure, bridges and tunnels are the major components causing environmental burdens due to the resource-intensive reason of these civil engineering structures.
- In terms of track systems, no matter for the ballasted track or ballastless track, rails have the largest responsibility to the environmental impacts. However, the maintenance stage has larger contributions than the contribution stage regarding ballasted track due to the more frequent maintenance activities comparing to ballastless track.
- In terms of the environmental impacts generated from materials, concrete, and steel rank the top two positions, followed by rubber. Other materials have negligible impacts comparing with these three materials.
- From the observation of the results, concrete has the largest impact on ozone depletion and the least impact on metal depletion while steel is the opposite, i.e. it has the largest impact on metal depletion and the least impact on ozone depletion. Transportation has a large impact on territorial ecotoxicity.

The factors that lead to uncertainties are the following:

- Since this study is not project-specific and the data are collected from the studies conducted in European countries and a few Asian countries such as China, India, and Japan, it results in uncertainties due to the different standards adopted by the countries.
- In addition, the life cycle inventory data are the median data calculated in section 4.4.1 and the types of each component used in infrastructure were not considered despite there are some specific combinations of the components that might be required in the real world. Therefore, this also causes uncertainties.

In conclusion, the results of the LCA in this study can only give an approximate impression of the environmental costs of HSR infrastructure.

6 Discussion and future work

This paper has defined each component of railway infrastructure and has collected material/energy intensity data for the infrastructure of high-speed rail, subway, and commuter. After collecting data, archetypes were built for each type of railway. Then environmental impacts were calculated by using life cycle assessment methodology.

However, some challenges were encountered during the process of writing this paper: due to lack of data, the archetypes of commuter and subway are not robust enough to use it to estimate the material consumption of historical and future railway infrastructure. The missing data of commuter and subway infrastructure were not assumed the same as those of high-speed rail, for there is no evidence was found that those components are similar between different types of railways. Thus life cycle assessment was only conducted on high-speed rail due to the same reason.

For writing this thesis, the most energy-consuming and challenging process is collecting data. First, it is because this process needs the researcher to have a thorough understanding of the structure of railway infrastructure. Second, it is due to lack of data sources, especially when the companies are not able to share the data for confidentiality reasons and literature has become the only source to obtain data in this study. Besides, even if some data are collected, lack of project-specific data, or in another word, most of the studies reused the data from previous studies, led to the uncertainties occurred in the results. So the biggest challenge encountered in this thesis can be concluded as lack of high-quality data.

In short, the research questions have been answered. However, the robust results are only limited to high-speed rail and the archetypes of two other types of rail i.e. commuter and subway, still need to be completed by collecting more data.

Based on this conclusion, future work should be focusing on conducting more project-specific research. Another way to get more data is to build an open dataset as the Resource Efficiency and Climate Change project did for collecting material intensity data of buildings (Heeren, 2018/2021) from researchers all over the world.

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Appendices

Appendix 1: Summary of material and energy consumptions of components in the construction stage

- **Appendix 1.1:** Summary of material and energy consumption of foundation
- **Appendix 1.2:** Summary of material and energy consumption of ballasted track
- **Appendix 1.3**: Summary of material and energy consumption of ballastless track
- **Appendix 1.4:** Summary of material and energy consumption of bridges
- **Appendix 1.5:** Summary of material and energy consumption of tunnels
- **Appendix 1.6:** Summary of material and energy consumption of the electrification systems

Appendix 2: Summary of material and energy consumption in the maintenance stage

Appendix 1.1: Summary of material and energy consumption of foundation

Foreground process name	Ecoinvent process	Value	Unit
Foundation/concrete	concrete, high exacting requirements/market for concrete, high exacting requirements/CH/m3	1.00E+00	m3/m double track
Foundation/cement	cement, Portland/cement production, Portland/Europe without Switzerland/kg	6.80E+03	kg/m double track
Foundation/sand	sand/market for sand/GLO/kg	1.00E+04	kg/m double track
Foundation/stone	gravel, crushed/gravel production, crushed/Row/kg	2.40E+04	kg/m double track
Foundation/limestone	limestone, unprocessed/market for limestone, unprocessed/GLO/kg	3.00E+03	kg/m double track
Foundation/energy	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	1.53E+04	MJ/m double track
Foundation/transport of foundation materials	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	1.54E+03	tkm/m double track

Appendix 1.2: Summary of material and energy consumption of ballasted track

Foreground process name	Ecoinvent process	Value	Unit
Track/ballasted/ballast/gravel	gravel, crushed/gravel production, crushed/Row/kg	7.20E+03	kg/m double track
Track/ballasted/ballast/ballast spreading	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	9.85E+00	MJ/m double track
Track/ballasted/ballast/transport	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	3.60E+02	tkm/m double track
Track/ballasted/rail/steel	steel, low-alloyed/steel production, converter, low-alloyed/RoW/kg	2.40E+02	kg/m double track
Track/ballasted/transport of rail	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	3.60E+01	tkm/m double track
Track/ballasted/rail laying/diesel	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	1.33E+01	MJ/m double track
Track/ballasted/rail pad/rubber	synthetic rubber/synthetic rubber production/RoW/kg	2.59E+00	kg/m double track
Track/ballasted/transport of rail pad	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	3.89E-01	tkm/m double track
Track/ballasted/sleeper/concrete	concrete, high exacting requirements/market for concrete, high exacting requirements/CH/m3	3.67E-01	m3/m double track
Track/ballasted/sleeper/steel	steel, low-alloyed/steel production, converter, low-alloyed/RoW/kg	2.27E+01	kg/m double track
Track/ballasted/transport of sleeper	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	3.41E+00	tkm/m double track
Track/ballasted/sleeper laying/diesel	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	5.04E+00	MJ/m double track
Track/ballasted/fastening/steel	steel, low-alloyed/steel production, converter, low-alloyed/RoW/kg	1.10E+01	kg/m double track
Track/ballasted/transport of fastening	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	1.65E+00	tkm/m double track

Appendix 1.3: Summary of material and energy consumption of ballastless track

Foreground process name	Ecoinvent process	Value	Unit
Track/ballastless/rail/steel	steel, low-alloyed/steel production, converter, low-alloyed/RoW/kg	2.40E+02	kg/m double track
Track/ballastless/transport of rail	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	3.60E+01	tkm/m double track
Track/ballastless/rail laying/diesel	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	1.33E+01	MJ/m double track
Track/ballastless/fastening/steel	steel, low-alloyed/steel production, converter, low-alloyed/RER/kg	1.10E+01	kg/m double track
Track/ballastless/transport of fastening	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	1.65E+00	tkm/m double track
Track/ballastless/rail pad/rubber	synthetic rubber/synthetic rubber production/RoW/kg	2.59E+00	kg/m double track
Track/ballastless/transport of rail pad	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	3.89E-01	tkm/m double track
Track/ballastless/hydraulically stabilized layer /concrete	concrete, normal/market for concrete, normal/RoW/m3	1.82E+00	m3/m double track
Track/ballastless/hydraulically stabilized layer/steel	reinforcing steel/reinforcing steel production/RoW/kg	1.60E+02	kg/m double track
Track/ballastless/transport of hydraulically stabilized layer material	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	2.40E+01	tkm/m double track
Track/ballastless/concrete slab/concrete	concrete, sole plate and foundation/market for concrete, sole plate and foundation/RoW/m3	1.13E+00	m3/m double track
Track/ballastless/concrete slab/steel	reinforcing steel/reinforcing steel production/RoW/kg	1.28E+02	kg/m double track
Track/ballastless/in situ slab former	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	1.58E+01	MJ/m double track
Track/ballastless/concrete train	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	1.33E+01	MJ/m double track
Track/ballastless/transport of concrete slab materials	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	1.92E+01	tkm/m double track

Appendix 1.4: Summary of material and energy consumption of bridges

Foreground process name	Ecoinvent process	Value	Unit
Bridge/excavation soil	excavation, hydraulic digger/market for excavation, hydraulic digger/GLO/m3	2.62E+01	m3/m double track
Bridge/concrete	concrete, high exacting requirements/market for concrete, high exacting requirements/CH/m3	2.28E+01	m3/m double track
Bridge/steel	reinforcing steel/reinforcing steel production/RER/kg	3.51E+03	kg/m double track
Bridge/diesel	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	3.02E+02	MJ/m double track
Bridge/transport of material	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	5.27E+02	tkm/m double track

Appendix 1.5: Summary of material and energy consumption of tunnels

Foreground process name	Ecoinvent process	Value	Unit
Tunnel/excavation soil	excavation, hydraulic digger/market for excavation, hydraulic digger/GLO/m3	1.89E+02	m3/m double track
Tunnel/concrete	concrete, high exacting requirements/market for concrete, high exacting requirements/CH/m3	4.64E+01	m3/m double track
Tunnel/steel	reinforcing steel/reinforcing steel production/RER/kg	2.80E+03	kg/m double track
Tunnel/diesel	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	5.04E+03	MJ/m double track
Tunnel/electricity	electricity, medium voltage/market for electricity, medium voltage/Europe without Switzerland/kWh	6.42E+03	kWh/m double track
Tunnel/transport of materials	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	4.20E+02	tkm/m double track

Appendix 1.6: Summary of material and energy consumption of the electrification system

Foreground process name	Ecoinvent process	Value	Unit
Electrification system/copper	copper/copper production, primary/RER/kg	7.35E+00	kg/m double track
Electrification system/aluminum	aluminum, cast alloy/market for aluminum, cast alloy/GLO/kg	3.75E+00	kg/m double track
Electrification system/steel	reinforcing steel/reinforcing steel production/RoW/kg	1.23E+01	kg/m double track
Electrification system/transport of materials	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	1.10E+00	tkm/m double track

Appendix 2: Summary of material and energy consumption in the maintenance stage

Foreground process name	Ecoinvent process	Value	Unit
Ballast maintenance/ballast changing/gravel	gravel, crushed/gravel production, crushed/Row/kg	9.27E+03	kg/m double track
Ballast maintenance/ballast changing machine	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	3.67E+01	MJ/m double track
Ballast maintenance/transport of ballast	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	4.63E+02	tkm/ m double track
Ballast maintenance/ballast tamping machine	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	8.64E+02	MJ/m double track
Ballast maintenance/ballast spreading machine	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	1.97E+01	MJ/m double track
Ballast maintenance/ballast cleaning machine	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	9.18E+01	MJ/m double track
Ballast maintenance/ballast stabilizer	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	3.46E+02	MJ/m double track
Rail maintenance/rail replacement/steel	steel, low-alloyed/steel production, converter, low-alloyed/RoW/kg	4.80E+02	kg/m double track
Rail maintenance/rail replacement/transport of rail	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	7.20E+01	tkm/m double track
Rail maintenance/milling	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	2.55E+02	MJ/m double track
Rail maintenance/rail laying/diesel	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	1.33E+01	MJ/m double track
Rail pad maintenance/renewal/rubber	synthetic rubber/synthetic rubber production/RoW/kg	5.18E+00	kg/m double track

Rail pad maintenance/renewal/transport of pads	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	7.77E-01	tkm/ m double track
Sleeper maintenance/renewal/steel	steel, low-alloyed/steel production, converter, low-alloyed/RER/kg	2.27E+01	kg/m double track
Sleeper maintenance/renewal/concrete	concrete, high exacting requirements/market for concrete, high exacting requirements/CH/m3	3.67E-01	kg/m double track
Sleeper maintenance/sleeper laying/diesel	diesel, burned in building machine/diesel, burned in building machine/GLO/MJ	5.04E+00	MJ/m double track
Sleeper maintenance/transport	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	3.41E+00	tkm/m double track
Fastener maintenance/fastener/steel	steel, low-alloyed/steel production, converter, low-alloyed/RoW/kg	2.20E+01	kg/m double track
Fastener maintenance/transport of fastener	transport, freight, lorry, unspecified/market for transport, freight, lorry, unspecified/GLO/metric ton*km	3.30E+00	tkm/ m double track

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