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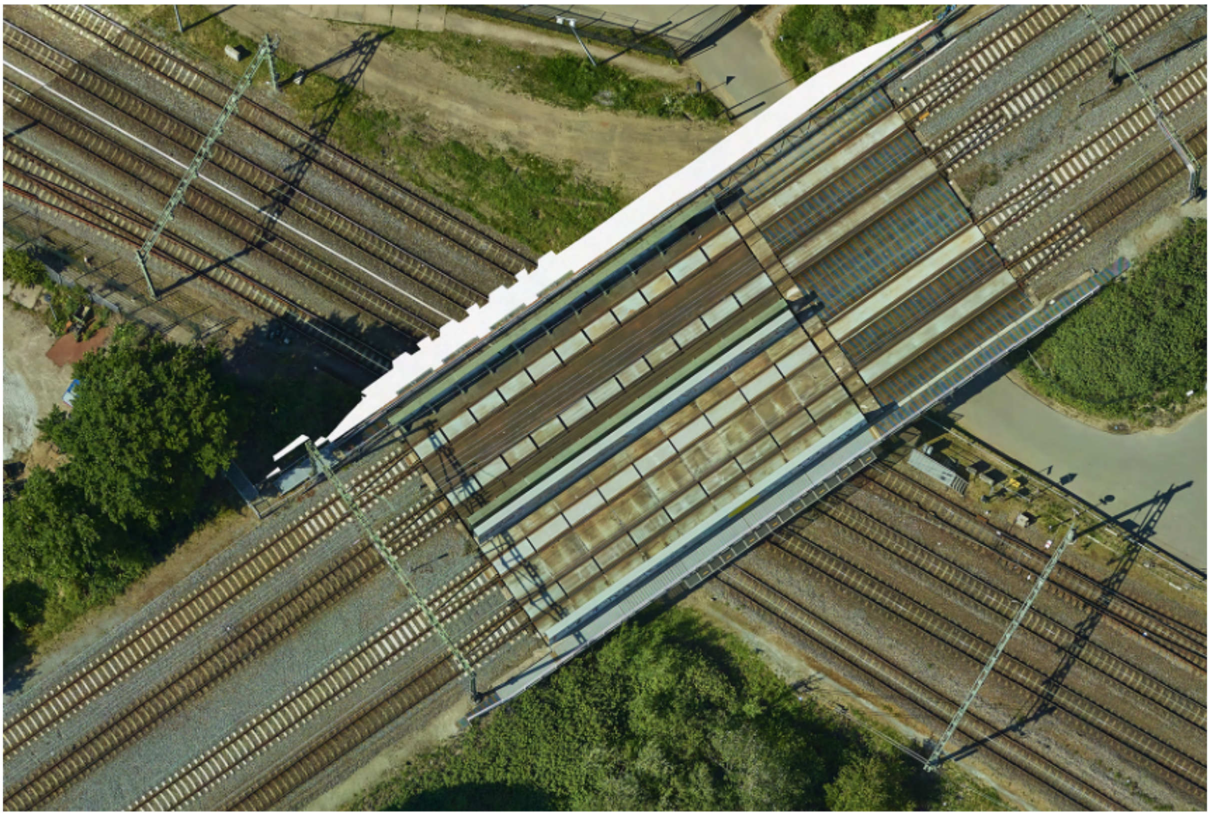
Towards a Circular Economy: Material Changes in the Dutch Railway Infrastructure until 2050



Submitted by

Lowik I. Pieters

Master Program

Industrial Ecology

Supervised by

dr. E. (Ester) van der Voet
dr. L.M. (Linda) Kamp
J. (Janneke) van Oorschot MSc

Universiteit Leiden The Netherlands

TU Delft

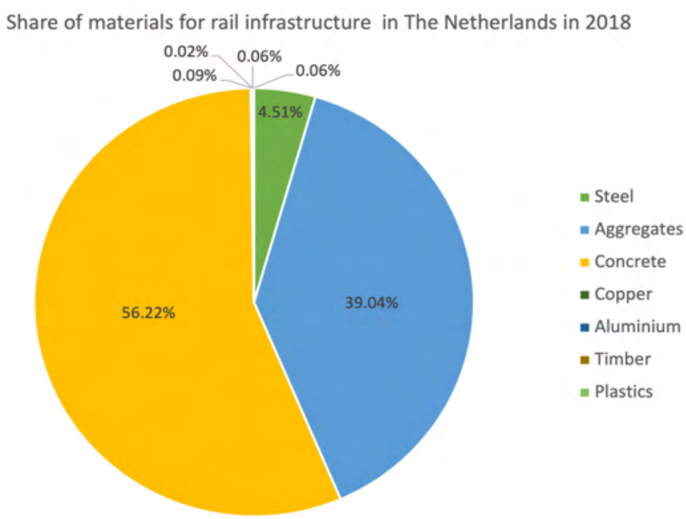
Executive Summary

In recent years, the circular economy (CE) has gained momentum among policy makers, with the Dutch government planning to have a completely circular economy, an economy that aims to minimize primary resource inputs and waste, in 2050. This thesis research focused on the potential material stock and flow changes in the Dutch railway infrastructure system until 2050. An overview of the material stock forms the first prospecting step of urban mining (the concept of mining substances from the built environment), a CE and comprehensive life cycle assessments. This thesis presented the first academic national level prospective material flow analysis on railway infrastructure with explorations of future flow characteristics and an assessment of the potential for a circular economy in rail infrastructure.

Material Flow Analysis (MFA) and Geographic Information Systems (GIS) were utilized to analyze the temporal and spatial dynamics of the materials. Stocks have been estimated through a bottom-up approach: by multiplying the length or number of railway infrastructure assets with their matching material intensities retrieved from the literature. The MFA was both retrospective and prospective, characterized by an accounting stock-driven model from 1839 to 2020 and a dynamic stock-driven model for the time frame 2021 until 2050.

Future development trajectories in the prospective part of the MFA have been explored by means of 'sociotechnical transition pathways' based on the typology for sociotechnical transitions by Geels & Schot (2007). It is a useful typology for transport studies, since the pathways help to indicate promising niche developments and their potential technological trajectories. By combining prospective material flow analysis with explorations via sociotechnical transition pathways, this thesis offers the first academic application of ex-ante transition modeling in railway infrastructure constructions. The results give insight into the potential consequences of policy, technology and behavior changes for material use in railway infrastructures.

A stock estimation for 2018 of the train, metro, light rail and tram infrastructure in The Netherlands showed that rail track related objects cover the majority of



the stock weight. Nonmetallic minerals such as concrete and aggregates (ballast) make up the bulk of the total stock mass. Steel accounts for almost 5% of the stock weight, of which 40% is found in railway tracks. Copper, aluminium, timber and plastics make up less than 0.25% of the stock mass. Despite this small share, copper and aluminium have a relatively high economic value on the secondary market. Accordingly, economic valuation plays an important role in exploring the potential of the urban mine.

The spatial distribution of the stock indicated that most railway infrastructure weight is centered in municipalities with high rail tunnel and bridge densities and urban railway systems such as metro, light rail and trams. Materials that are not associated with engineering structures, such as ballast (aggregates), gave a more even spatial distribution.

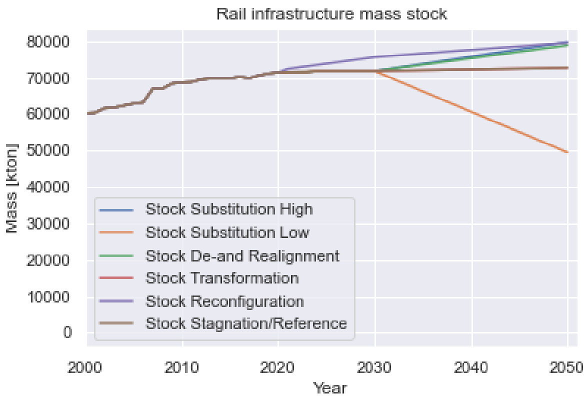
After the stock identification, this study continued with an exploration of the future stock changes from a multi-level perspective. This exploration could serve as a benchmark for strategic planning for circularity in the rail infrastructure. In doing so, the results of this study can be used for improving the management of a transition towards a circular economy in the railway infrastructure in The Netherlands.

The sociotechnical transition pathways have been explicitly specified for railway infrastructure in six pathways. Each pathway uses a set of assumptions that can alter the future material flows. These driving forces include rail passenger kilometers traveled per year, material intensities and the lifespan of the stock. The first pathway is called the Stagnation Pathway, derived from the Low Scenario on mobility development from the 'Toekomstverkenning Welvaart en Leefomgeving' (WLO, Future Exploration on Prosperity and Environment) from the Netherlands Environmental Assessment Agency (PBL 2015). The second one is the Reconfiguration Pathway, based on a policy document with targets for climate neutral and circular national infrastructure projects (Ministerie van I&W 2020).

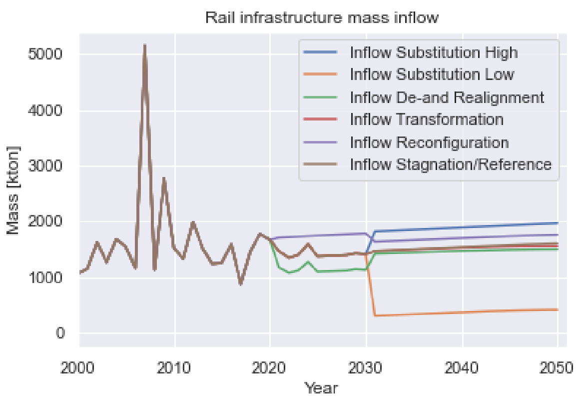
The other four pathways used in the analysis are the Technological Substitution High and the Technological Substitution Low Pathway, that assume a very high number of annual rail passenger kilometers and a very low number respectively. The De- and Realignment Pathway presumed a use in passenger kilometers according to the WLO High scenario, a 25% longer lifespan for rails and 20% lower material intensities, whereas the Transformation Pathway took the travel kilometers according to the WLO Low scenario, a 30% longer lifespan for rails and no changes in material intensities.

The results of the prospective MFA demonstrated a stock increase for pathways that assume an increasing number of passenger kilometers. The stock stabilized under stagnating rail passenger kilometers. The materials stock showed a strong decrease when the total passenger kilometers remain low for a longer period of time. It must be noted that a strong increase in passenger travel kilometers leads to a relatively lower stock change than a strong decrease in kilometers traveled.

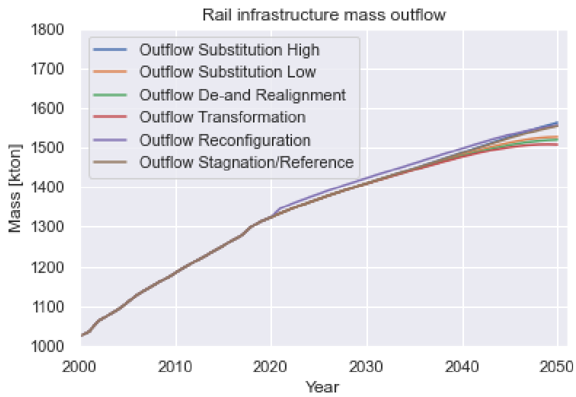
The figures on the prospective in- and outflows (the construction and demolition flows) per pathway illustrate that the inflow directions resemble the stock change directions, but can be lowered by assuming lower material intensities. The outflows of materials show a stable pattern for all pathways with subtle differences. Extensions on the lifetime of the assets lead to pathways with a lower outflow, even though the differences between the pathways are small.



Material stocks per transition pathway.



Material inflows per transition pathway.



Material outflows per pathway (note the deviating y-axis).

Compared to the current situation, the model presented how driving forces regarding policy, technology and behavior changes alter the stock and flow dynamics in railway infrastructure.

Interestingly, the Reconfiguration Pathway that models the policy measures for Dutch national circular infrastructure projects resulted in a higher material flows and a larger stock. Closing the rail infrastructure material cycle is not feasible since inflows in most pathways keep larger than the outflows. Longer lifespans make the flow sizes so small that it seems like a relatively inert system. However, the flexibility of the flows was proven with a sensitivity analysis with shorter lifespan assumptions. This resulted in much larger construction and demolition flows.

An investigation of reuse and high-grade reuse options for ballast, concrete, steel, aluminium and copper in the Dutch railway infrastructure system showed that about ⅓ of the outflows could re-enter the rail infrastructure system. Another 27% of the demolition flows can be reused in other industries at a high-grade. 40% of the outflows, of which the vast majority is ballast at the end of its life, is downcycled as embankment body and foundation material for road construction. The choice of gravel type in the ballast determines the recyclability of the material.

Improvements for more circular flows include reuse of rails, switches, foundations, concrete sleepers and tiles and high-grade recycling of the materials that cannot be reused. This study has highlighted that an important driver in the transition process toward a circular economy is the hybridization of societal realms, for example by means of interdisciplinary knowledge production on material intensities and integral policy making for a circular economy. It was recommended from this research that actors work together to set up a geospatial material stock monitoring system for rail infrastructure and to co-develop sustainable lifespan extension, reuse and recycling procedures.

In sum, the findings of this prospective analysis show that railway infrastructure responds slowly to adjustments for a transition towards a circular economy. This is due to the long lifespan of the constructions and the relatively small impact of increasing travel kilometers on the length of the network. Without further involvement in reuse, remanufacturing and recycling strategies, the policy measures for Dutch circular rail infrastructure lead to a more material intensive infrastructure rather than a minimizing material use. With a share of almost half of the stock mass, a high environmental impact, a high economic value on the secondary market and a relatively short lifespan, railway tracks show the most attractive case for design for circularity. Despite the slow response of the system, the railway infrastructure is built with large quantities of materials and therefore incremental changes may have a significant impact on the total use of materials at a national scale.

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1. Introduction

Our society uses material resources at a pace that cannot be sustained, because our consumption pattern leads to waste, emissions and shortages. Between 1970 and 2010, the global growth of material extraction and waste generation accelerated, while global population growth slowed down and economic growth stabilized (Schandl et al. 2018; Krausmann et al. 2018). Even though the material footprint per capita is declining in Europe and North-America, attempts to decouple material use from economic growth have not shown a substantial global result (Schandl et al. 2018). A socioeconomic metabolism that is stable, with well functioning in- and outflows, is essential for a sustainable planet (Krausmann et al. 2018).

A solution proposed for the resource over-extraction problem is the 'circular economy' (CE). In this thesis, a CE is defined as an economic system with high-grade reuse and recycling, where primary resource use and waste are minimized. In recent years, the CE has gained momentum among policy makers. In 2012, the Ellen MacArthur Foundation presented a *Circular Economy Framework*, which popularized the practice to study circulating material and energy flows at an economy-wide level (Brennan et al. 2015). In 2015, the European Commission launched a CE action plan (European Commission 2015). The Dutch government aims to have a completely circular economy in 2050, while reducing the use of primary abiotic resources by 50% in 2030 (Rijksoverheid 2019). The Netherlands is considered a forerunner of the CE in Europe with the largest CE investment share of its GDP of 28 European countries (Marino and Pariso 2020). The high CE investments in The Netherlands make an interesting case for a study on circular economy policies, because it indicates that there is broad support from the government and industries.

Despite these investments and the benevolence of government and industry, the Integral Circular Economy Report 2021 published by PBL Netherlands Environmental Assessment Agency concluded that many CE activities are still in their infancy and are focusing on preliminary phases, pilots and tests. Also, the voluntary and non-committal approach of the current CE policies is insufficient to reach the goals by 2050 (PBL 2021).

1.1 Problem Statement

Apart from this report on the effectiveness of current Dutch CE policies, very little is known about the material basis of a circular economy itself. This should be researched by investigating the size of the 'urban mine': prospecting valuable resources in the built environment, and assessing the recovery possibilities of these reservoirs (Klinglmair and Fellner 2010). Since the material stock from the urban mine should eventually become available for reuse or recycling, it is an essential part of a circular economy where material cycles are closed as much as possible (van Oorschot et al. 2020b). In *Appendix A* the core concepts in this research are introduced: the circular economy, the urban mine and sustainability.

The size of these material reserves, termed as 'anthropogenic stocks' (Müller 2006), and the potential for reusing them as a secondary material, are often unknown. Infrastructure networks, including roads, ports, cables and underground structures, represent a major share of global construction material stocks, from about 20% in high-density areas up to 60% in low-density living environments (Augiseau and Barles 2017; Deilmann 2009). In Europe, it is estimated that 3 tons of nonmetallic minerals per capita are connected to the total railway infrastructure stock (Wiedenhofer et al. 2015). Metallic material stocks generally have a higher economic value than the nonmetallic stocks like concrete and aggregates. This makes the metallic stock in railway infrastructure an attractive subject for urban mining. The urban mine is the primary source of materials in an economy in which material cycles are closed as much as possible. Thus, in order to have a complete overview of the potential in a CE for The Netherlands, the rail infrastructure material stock and its potential future flows must be monitored.

1.2 Relevance

This study was carried out in support of the current Dutch CE policy in the context of mapping the urban mine. A consortium led by the Netherlands Environmental Assessment Agency (PBL) is investigating what this can look like in practice. In the Policy Brief Objective Circular Economy 2030, proposals have been outlined to make the objective to reduce 50% of the primary abiotic materials by 2030 more specific and quantifiable. This policy brief specifies that the essential goals for the circularity objective are reductions in the environmental impact and supply security for critical materials (PBL 2019). Their

‘Werkprogramma Monitoring en Sturing Circulaire Economie 2019-2023’ (‘Work program for Monitoring and Steering Circular Economy 2019-2023’) is a research platform for transitioning towards a circular economy (PBL 2020). Researchers from Leiden University have contributed with case studies on the electricity grid, vehicles, textiles, household electronics, electronic machinery and the building stock (van Oorschot et al. 2020a, 2020b). This research contributes to this monitoring, because rail infrastructure has not yet been mapped out on a national scale and potentially large amounts of material are involved.

To set targets for a CE by 2050, a basic accounting step should be executed to get acquainted with the material stock and flows. This mapping shows where (virgin) material inputs can be reduced and could thereby serve as a benchmark for policies on redesigning the rail infrastructure. Forecasting is an important part of the research, as the number of passenger kilometers traveled by train in The Netherlands grew by more than 20% over the period 2010-2017 (CBS 2020b). This growing demand, projections of a growing population and the identification of bottlenecks in the rail transport capacity (ProRail 2017) suggest that future extensions of the train network infrastructure are likely. Hence, a prospective analysis can help to identify the tracks to a sustainable material supply.

The COVID-19 pandemic has led to a dramatic drop in public transport use in The Netherlands. Check-ins in public transport fell by up to 90% (CBS 2020d) and the overall public transport use in 2020 was cut in half (CBS 2021). Modeling specific shocks such as a pandemic that may have led to structural change helps to better understand the socio-technical characteristics of the infrastructure system.

Finally, this study provides the first academic estimation of the current and the future stock material development of rail infrastructure materials in The Netherlands by using transition theory. The model and the results can be used for international comparisons. The novel approach to combine Material Flow Analysis (MFA) with transition theory in railway infrastructure provides a framework with specific material intensities for railway related objects and a model that is dedicated to the analysis of railway infrastructure material stocks and flows.

1.3 Goal

The aims of this research are to present quantitative analyses of the material stocks and flows in the Dutch rail infrastructure, for the present as well as the future under certain trajectories of development. For future explorations, the 'transition pathways' are used as a typology for sociotechnical transitions (Geels and Schot 2007). These pathways explore the future change potential of the stocks and flows under different circumstances. This research provides data for policies aiming at a more circular rail construction material use and input for environmental assessments on transport modes.

The following research question applies:

What are the current material stocks and flows in the rail infrastructure in The Netherlands and how could they change towards 2050, considering different transition pathways?

1.4 Definition of a Circular Economy

Like the European Union, The Netherlands has committed to achieve a 'Circular Economy' by 2050 (Rijksoverheid 2016). The Dutch government connects CE to the goal of limiting material input, aiming that this results in a sustainable future: 'In a circular economy, we deal efficiently and socially responsibly with products, materials and resources within the carrying capacity of the earth, so that future generations also retain access to material prosperity' (Rijksoverheid 2016, 8, translated from Dutch).

The International Union of Railways announced in 2019 in the Railway Strategy for Europe that Circular Economy principles should be integrated in design, construction, operation and maintenance of the infrastructure (International Union of Railways (UIC) 2019). The circular economy principles and definitions are, however, far from crystallized (Kirchherr et al. 2017).

Korhonen et al. (2018) define the concept of circular economy (CE) as a reverse flowing version of the current linear economic system in which energy and materials are re-used. The authors admit that this is not a flawless explanation, since energy cannot be physically recycled. They argue that it can trickle down as a secondary source (e.g. waste heat). Korhonen et al. (2018) summarize CE for sustainability as an environmental goal "to reduce the production-consumption system virgin material and energy inputs and waste and emissions outputs (physical throughput) by application of material cycles and renewables-based energy cascades." (Korhonen et al. 2018, 41). This definition is limited to environmental performance improvements. Most CE definition authors do this and ignore the economic and social dimensions in their conceptualizations (Geissdoerfer et al. 2017).

Critics argue that a completely circular economy, with no virgin material inflows, is not feasible because of the thermodynamic and ecological nature of the system (Skene 2018). Dissipation (waste production) will remain due to specific material compositions that are irreversible or naturally leak to the environment over time. According to the second law of thermodynamics, this is related to an increase in entropy (a quantity showing the unavailability of a system's thermal energy for conversion into mechanical work). Another limiting factor for a circular economy is the ever growing demand for materials: in a system that is growing, even if 100% of the products at their end-of-life are recycled, a recycled content in new inflows of 100% cannot be reached.

To avoid a discussion on the completeness of a CE that can be evoked by the definition by Korhonen et al. (2018), In this thesis research, the more holistic definition of Kirchherr et al. (2017) will be adopted, who define a CE as:

"an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, [...] with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations." (Kirchherr et al. 2017, 224–225)

The Dutch Ministry of Infrastructure and Water Management defines a circular economy as an economic system where primary material inputs are limited, resources are reused at a high grade and where waste is minimized. By 2030, the Ministry aims to have halved its primary abiotic material use. For railway infrastructure projects (that are managed by ProRail), this target is set at 2050 (Ministerie van I&W 2020). In this thesis, the degree of circularity has been tested according to this definition.

1.5 Research Approach: Scope and Sub-questions

Stock dynamics are essential to know which secondary materials could become available for urban mining. The research approach of this thesis was a modeling study on the dynamics of the material stock. Müller (2006) developed a methodology on dynamic MFA modeling for estimating future stocks. This methodology is based on a retrospective multiannual stock-driven model with specific service units (e.g. meter of rails) in combination with material intensities (e.g. ton/meter or kg/capita).

This research question can be divided into four sub-questions that each answer a part of the main research question. After each research question, the specific methods for the question are explained briefly.

1) *What is the present academic state of material flow analysis for rail transit constructions, in terms of retrieved results?*

The first sub-question is dedicated to investigating the latest academic literature on MFAs in rail infrastructure. The literature review in §1.6 helps to identify this academic knowledge gap.

2) *What were the material stocks of the train, light rail, metro and tram infrastructure in The Netherlands in the period 1839 - 2020?*

The second question answers the accounting part of the MFA, where the infrastructure's stock and flows have been mapped from 1839 until 2020. Material categories are the aggregations of substances of a similar type. For example, the category 'plastics' is used to show the stocks of epoxy, PUR and PVC, among others.

3) *Which transition pathways can be conceptualized for the case of railway infrastructure material stocks and flows in The Netherlands in the period 2021-2050?*

The scenario development step of this research is outlined by using a socio-technical perspective that is based on micro (niches), meso (regime) and macro (landscape) levels of analysis for transitions as designed in a framework by Geels and Schot (2007). This multi-level perspective is applied in order to identify different trajectories of change at different levels and can be further conceptualized in a typology termed as sociotechnical transition pathways, each unique in their nature and timing of multi-level interactions (Geels and Schot 2007).

4) *How can the conceptualized transition pathways lead to adjusted material compositions, material intensities and stock dynamics that contribute to reaching a circular economy for the Dutch railway sector by 2050?*

The fourth question focuses on the dynamics of the transition pathways that influence the way that material stocks in the Dutch rail infrastructure sector could develop until 2050. This question adds numbers and calculations to the pathways to identify the chances for circular options. It shows how each pathway depicts a potential change in material content, quantities of materials used per product (material intensity) and the dynamics of the stock as an attempt to explore the best trajectory options towards a circular economy in 2050.

5) *What could the in- and outflows of materials in the railway sector be in 2021 - 2050 and how much of these material outflows might be suitable for reuse in support of the development of a circular economy?*

In the fifth sub-question, the forecasting step of the dynamic MFA is carried out in combination with a value estimation of the outflows that could re-enter the system.

overview	purpose	What is the purpose and general framework of the model?
	materials (goods, substances)	What materials (goods/substances) are included? Are materials further divided into material categories (and subcategories)?
	processes	What processes are included? Do they transform, transport, or store materials? Are processes further divided into process categories (and subcategories)?
	spatial and temporal scale and extent	What is the spatial and temporal scale and extent of the study?
	system overview	What is the structure of the system regarding processes, stocks, and flows?
design concepts	basic principles	Static or dynamic, top–down or bottom–up, retrospective or prospective?
	static or dynamic modeling approaches	How are stocks and flows modeled? What are the extrapolation methods for exogenous variables?
	dissipation	How does the model account for dissipation?
	spatial dimension	How does the model account for the spatial distribution of stocks and flows?
	uncertainty	How does the model account for data and model uncertainty?
details	initial condition	How is the initial state (e.g., the initial stocks and flows) of the model set?
	model input data	What data is used as input to the model?
	model output data	What data is generated as model output?
	evaluation	What methods (e.g., for data aggregation and visualization) are used to evaluate the results?
	detailed model description	What, in detail, is the formal description (e.g., equations) of the system and what are the algorithms (e.g., solution procedures) used for the calculations?
		What are exogenous and endogenous model variables? What are the model parameters, their dimensions, and reference values?

Table 1: The elements of the ODD protocol (Overview, Design concepts, Details) for MFA by Müller et al. (2014).

The MFA modeling approach of this study is structured according to the ODD protocol (Overview, Design concepts, Details) for Material Flow Analysis (MFA) as presented in *Table 1*. The ODD has previously been used for rail specific MFAs (Gassner et al. 2020). This protocol structures the model and data and thereby provides a generalized, systematic overview which should keep the model accessible (Müller et al. 2014). Also, this structure is used to ease comparisons. Throughout this chapter, the requirements of the ODD protocol have been marked in italics. The overview part comprises this chapter, the methods chapter includes the design concepts and details of the model.

The *purpose* of this research is to examine the Dutch railway material stock changes in a CE towards 2050, as well as the current and expected material inflows and outflows of materials in the Dutch rail infrastructure system. The material inflows are mapped to gain insight in the reduction potential of materials, whereas the outflowing materials are calculated to estimate the possibilities of re-entering the economy. The included *materials categories* are aggregates (ballast between the tracks), aluminium, concrete, copper, plastics, steel, and timber. Sand and soil are not included in the analysis due to a lack of accurate data on the use of these substances. The *processes* (*physical boundaries)* are characterized as the infrastructural needs to run trains, light rail, metros and trams in The Netherlands. This means that bridges, electricity supply, level crossings, noise barriers, platforms, platform roofs, rail tracks, signals, switches and tunnels were part of the scope.

The *spatial scale* refers to The Netherlands and the *temporal scale* covers the time intervals 1839 (when the first rail line was opened) to 2020 and a prospective part from 2021 to 2050. The spatial boundary is set at The Netherlands, because of the specific policy goal for a CE in 2050 by the government, data availability and the investments in CE that are among the highest in Europe (Marino and Pariso 2020).

This thesis follows a multidisciplinary approach by combining social science concepts like transition pathways from Geels & Schot (2007) with modeling and engineering practices, such as 'destructive testing' the model with a wildcard event to gain understanding in the complexity of critical infrastructure (Walsh et al. 2015).

The *system overview* in this sub-chapter introduced the scope of this research. The design concepts and the details of the ODD protocol are discussed in *Chapter 3* on methods and data. The research gap has been identified in the following sub-chapter on the state of academic material stock analysis in railway infrastructure.

1.6 Present State of Railway Stock Inventories

In academic research, building stocks have been studied significantly more than stocks from transport infrastructure (Gassner et al. 2020; Augiseau and Barles 2017). In comparison to buildings, railway infrastructure in particular has gained little academic attention. This sub-chapter shows that only recently, attempts have been made to estimate the material stock size of railway infrastructure.

Table 2 summarizes material stock and flow analyses that have recently been carried out on railway infrastructure. The table compares their different levels of scale, with different methods and different materials involved. The structure of the table was adapted from a literature review of 21 articles on MFA in the construction sector (Augiseau and Barles 2017).

For the national level studies, an important finding for rail infrastructure is that railway outflows make up only a fraction of modeled building, road and rail outputs in the EU25 of 2% (Wiedenhofer et al. 2015). In Japan, compared to roads, buildings and dams, railways make up a minor part of the total material stock of less than 1% (Tanikawa et al. 2015), but is still a big stock in absolute terms. Nevertheless, the analysis of material stocks and flows helps to precede a comprehensive LCA (Wang et al. 2016). In industrialized (EU) countries, maintenance inputs lead to the main infrastructure stock growth (Wiedenhofer et al. 2015). According to a study by Wiedenhofer et al. (2015), up to 75% of the maintenance inflow could include recycled content if all recycled outflowing materials would only be used for maintaining stocks. This means that the demand for maintenance materials is currently higher than could be supplied by secondary material sources.

A recent urban MFA case study was performed on the transport sector in Vienna (Gassner et al. 2020). The study elaborates on the prospective analysis of the urban mine on the subway of Vienna (Lederer et al. 2016). It encompasses a material stock analysis from 1990 to 2015, but it does not include forecasting. A primary finding is that the main source of material consumption is caused by maintenance of the infrastructure (>65%). This is an important result, since it reveals a hotspot where circularity related measures can be taken.

In terms of circular perspectives, the following has been taken into account in the studies from *Table 2*: 1) the recyclability of the material accumulation in the stock (Tanikawa and Hashimoto 2009); 2) quantitative exploration of recycling potentials by comparing the size of estimated inflows, waste, and recycling flows from 2004 to 2009 to a business-as-usual scenario for 2020 (Wiedenhofer et al. 2015); 3) the economic valuation of recyclable materials by setting the secondary raw material price for materials used in railway infrastructure (Lederer et al. 2016). These recycling explorations did not specifically focus on high-grade recycling. Schiller et al. (2017) stress the importance of monitoring anthropogenic stocks for a circular economy, but do not offer clear CE perspectives for railway infrastructure. Reuse was not discussed in the retrieved literature selection. In general, a thorough assessment of the potential for a circular economy in rail infrastructure was missing.

In short, research gaps in the studied infrastructure MFA literature are the lack of a comprehensive national level prospective rail infrastructure MFA, the lack of insights in future material flow characteristics and the lack of circular economy perspectives on the prospective railway infrastructure material flows. These gaps offer a topic of more in-depth research based on transition modeling.

Authors	Materials	Scope	Level	Prospecting	Methods for current stock	Assumptions
(Tanikawa and Hashimoto 2009)	aggregate, asphalt, brick, cement concrete, mortar, steel, wood	buildings, sewer, road and railway	Urban - Manchester (GB) & Wakayama (JP)	No (1850-2004)	bottom-up, GIS based stock analysis	Material stocks estimated with spatial-temporal data based on material intensities
(Wiedenhofer et al. 2015)	nonmetallic minerals	buildings, road and rail	National - EU25	Yes (2003-2020) flow driven model	bottom-up, retrospective, stock analysis and dynamic flow analysis	increasing recycling rate, data: only two railway types
(Tanikawa et al. 2015)	aggregate, asphalt, cement concrete, iron, timber, other	buildings, road and rail	National - Japan	No (1950-2010)	bottom-up, retrospective, stock analysis	data: GIS-based, rail types: national, high speed, subway, tram. Excl. tunnels/bridges
(Wang et al. 2016)	aggregate, aluminium, cement, concrete, copper, steel. Soil & fill are excluded	high speed rail bridges & tunnels, stations	National - China	Yes (2012-2030)	bottom-up, material flow accounting	estimate of aluminium, copper and steel in electrical rail systems, High Speed Rail density is based on GDP/cap
(Lederer et al. 2016)	aluminium, bricks, concrete, copper, gravel, iron & steel	subway	Urban - Vienna (AT)	No (2014)	bottom-up, material stock analysis	structures with lifespans >100 years are permanent (i.e. not extractable)
(Schiller et al. 2017)	minerals, metals, plastics, wood, other	buildings, infrastructures (incl. rail), consumer goods, building services	National - Germany	No (2010)	bottom-up & top-down material flow accounting	straight-line material depreciation over time
(Gassner et al. 2020)	asphalt & bitumen, aluminium, batteries, brickwork, concrete, copper, glass, gravel, sand & natural stone, iron & steel, other metals, others (e.g. rubber), plastics, wood	road and railway	Urban - Vienna (AT)	No (1990-2015)	bottom-up, retrospective multiannual flow analysis	In- & outflows for maintenance are equal in composition and intensity when the construction type doesn't change

Table 2. Overview of researched railway related studies so far, structure adapted from overview in Augiseau & Barles (2017).

2. Materials in Railway Infrastructure in The Netherlands

The materials that have been assessed in this research originate from railway infrastructure objects for train, metro and tram infrastructure. The included objects are given in *Figure 1*.

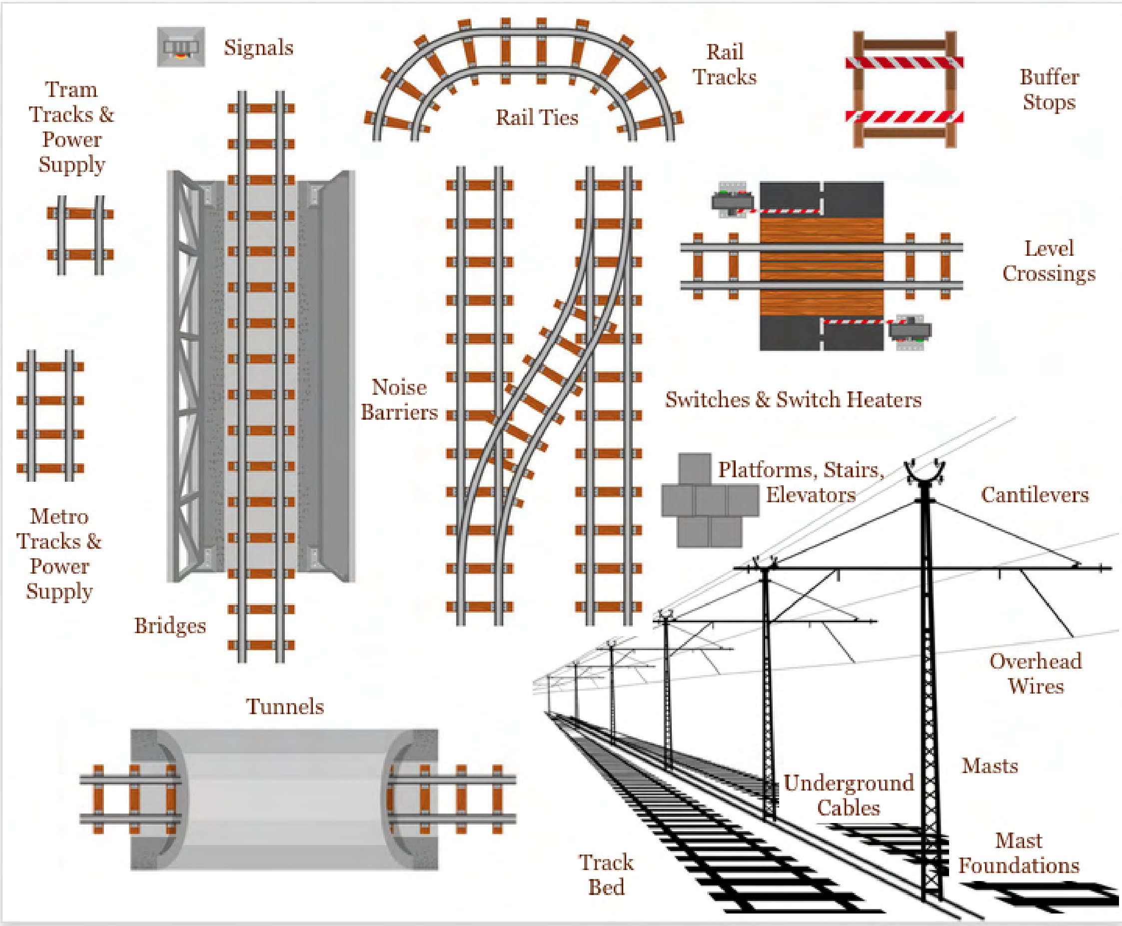


Figure 1: Scope of railway infrastructure objects included in the material flow analysis.

The materials from these objects have been categorized as follows:

Concrete:	used for tunnels and bridges, railroad ties, switches, switch heating, platforms, stairs and elevators, noise barriers, signal foundations, mast foundations and level crossing plates
Aggregates:	used as ballast for the track beds

Steel/iron:	used in rail tracks, traction wire, tunnels and bridges, masts, cantilevers, switches, switch heating, signals, buffer stops
Copper:	used in underground cables, third rails, overhead wires, switch heaters
Aluminium:	used in noise barriers, bridges and tunnels, switch heaters
Timber:	used in platform roofs, noise barriers (wood fiber concrete), rail ties, switches
Plastics:	used in rail ties (EPDM, GFRP, HDPE, PP), switches (EPDM, HDPE, PP), switch heaters (epoxy, GFRP, PVC), noise barriers and fences (EPDM, HDPE, coatings), underground cables (HDPE), platform roofs (PVC)

Materials such as porcelain, zinc, bronze, rock wool and glass were only identified in minor quantities, whereas the asphalt stock between tram tracks is meant for road vehicle transport. Therefore, these materials are left out in the rest of the analysis. Filling materials such as sand and gravel were not part of the scope of this thesis (which is similar to the considerations of Lederer et al. (2016). Water and soil use weren't considered either.

2.1 Characteristics of the Dutch Railway Infrastructure

The Netherlands has the busiest rail network in the European Union. Dutch rail is used twice as intensively as the EU average. Most of the track sections are electrified and double-track. Furthermore, 92 percent of the total train kilometers are passenger kilometers, which is above the EU average of 79 percent (CBS 2009). This means that consumer choice of transport mode plays an important role in the dynamics of rail demand.

Maintenance costs per train kilometer are relatively low compared to other EU countries and the Ministry of Infrastructure and Water Management is working on a more efficient system to reduce maintenance costs even further in the future (Rijksoverheid 2017). Like other EU countries with a well developed rail infrastructure network, the size of the network has had only minor changes over the past decades. The average change of railway network over the period 2000-2009 in The Netherlands was: +0.6% double tracks, -0.6% single tracks (Wiedenhofer et al. 2015). About 200 kilometer of train tracks and about 200.000 railroad ties are replaced annually by the national network operator, ProRail (Quik et al. 2020).

The total train network length in 2018 was 7381 km of which 99.02% was in use. Despite the small train kilometer share of cargo on the national totals, a bit more than 16% of the total network is reserved for freight trains due to the extensive railroad routes at industrial sites and railroad yards. In 2019, the country's main rail passenger carrier, NS, arranged on average about 1.3 million daily passenger journeys, of which 31% were work related and 21% were related to education (NS 2019).

The geographic locations of the railways (train, light rail, subway/metro and tram) in the Netherlands are shown in *Figure 2a* and for Randstad (detail) in *Figure 2b.* The visualizations in the figures were made in ArcGIS using geospatial data from the TOP10 NL database from 2018.

Figure 2a: Geospatial data of Dutch railways from the TOP10NL database (2018).

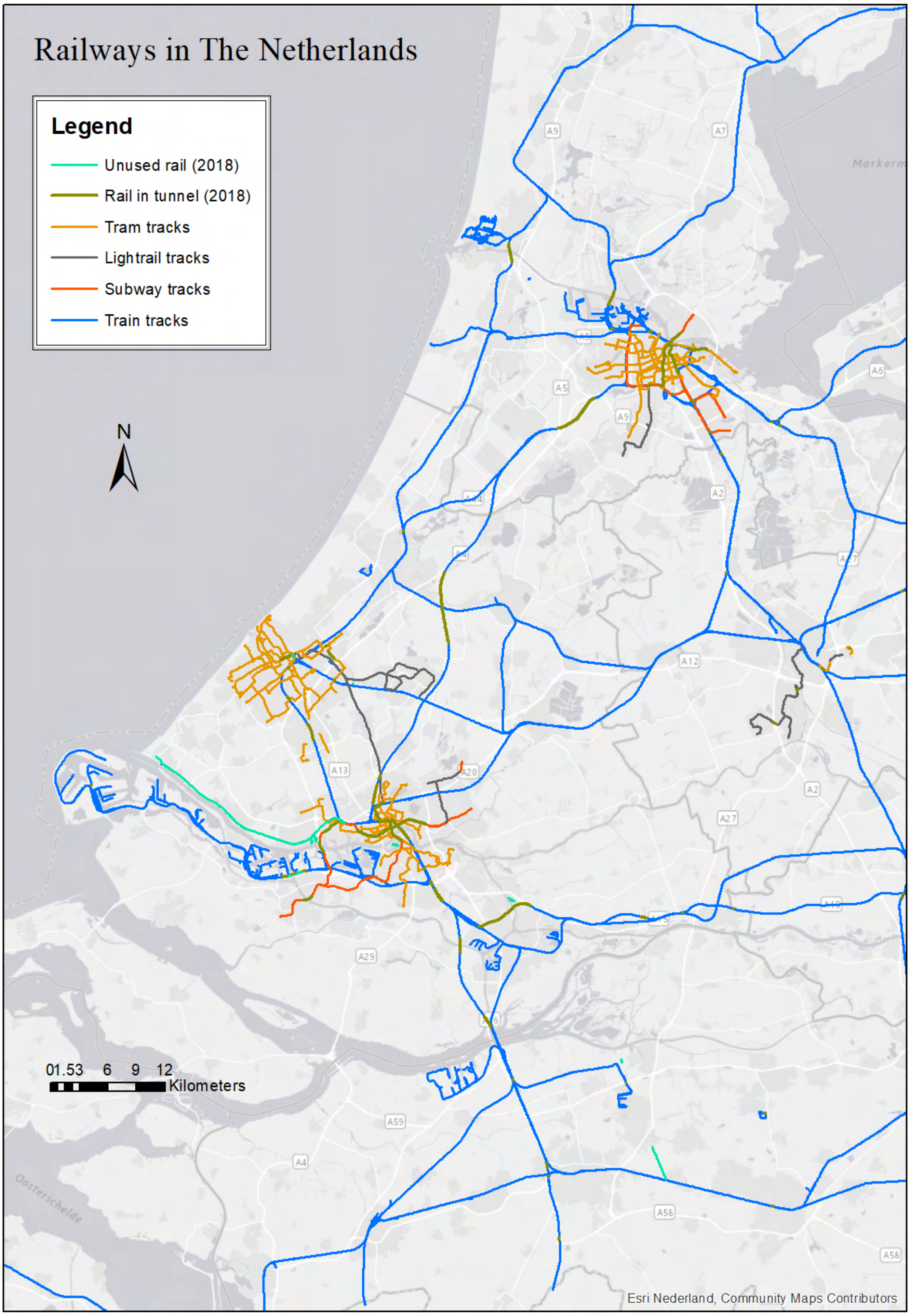


Figure 2b: Detail of the Randstad railway situation in 2018.

2.2 Bottlenecks in the Rail Infrastructure

The capacity of the rail infrastructure is reaching a limit at some routes. Hence, the Ministry of Infrastructure and Water Management published a list of infrastructure projects that need attention, called the Meerjarenprogramma Infrastructuur, Ruimte en Transport (MIRT, the Multi-Year Program for Infrastructure, Land Use and Transport) (Rijksoverheid 2020b) and in the Network Statement 2022 by ProRail with a mid term planning until 2027 (ProRail 2020). These reports contain a list with the bottlenecks in the rail network and their proposed infrastructure solutions. The full list can be retrieved in *Appendix B*.

In the longer run, the ProRail and the Ministry of Infrastructure and the Environment have calculated the likeliness of bottlenecks in the period 2030-2040 in their National Market & Capacity Analysis (ProRail 2017; Ministerie van I&M 2017). The scenarios in this analysis are based on a high growth and a low growth scenario that were first outlined in the Welvaart & Leefomgeving (WLO, Prosperity & Environment) report by the Netherlands Environmental Assessment Agency (PBL 2015). For the estimation of the bottlenecks it was assumed that all MIRT projects as mentioned before were completed (Ministerie van I&M 2017). Their results show that even when all MIRT projects until 2030 are carried out, about 400 kilometers of rail tracks will suffer from overcrowding, both in 2030 and 2040. The locations and the lengths of the bottlenecks have been listed in *Appendix B.*

Solutions for these hard bottlenecks as proposed by ProRail are: improving the transfer possibilities, increasing train frequencies or the price of the supplement at the high speed corridor between Schiphol and Rotterdam (ProRail 2017). Long term rail infrastructure extensions were not mentioned in 2017 but the proposed network extensions in the next section suggest that they will be required.

2.3 Proposed Network Extensions

The recently published ‘Ontwikkelagenda Toekomstbeeld OV’ (‘Development Agenda for the Future of Public Transport’) contains eight ‘selection menus’ and a robust basis for future proof public transport in The Netherlands by 2040 (Ministerie van I&W 2021). According to the Ministry, a robust basis is shaped by the complete rollout of the high-frequency rail program (PHS, every 10 minutes a train at the busiest routes) and the extension of the Noord-Zuidlijn light rail section from Amsterdam-Zuid to Schiphol Airport.

The eight selection menus are presented as cornerstone content for future extensions that, without prioritization, contain a selection of proposed projects with their added value to the network and implementation costs. These menus do not function as a blueprint for the developments, but are meant as a basis for discussing the public transport investments in the coming decades. The proposals for network extensions from the Development Agenda are displayed in *Appendix B*. In general, the focal point of the agenda is at facilitating high-frequency routes by track doublings and light rail section extensions.

This development agenda suggests that there is a need for rail infrastructure extensions in the near future. This knowledge served as an input for the prospective material flow modeling in this thesis.

3. Methods & Data

A typical tool used in the field of IE is a Material Flow Analysis (MFA). MFA is an important tool to study the potential for a circular economy, since it provides an overview of the material stocks and their dynamics in society. Moreover, MFA connects to the core elements of the field of Industrial Ecology, such as prospective research, a systems perspective, eco-efficiency and dematerialization (Lifset and Graedel 2002).

In this thesis research, MFA can be divided into three steps: the stock estimation, a part with retrospective dynamics, and a part with prospective dynamics. Each step covers different methods and data requirements that are summarized below in *Figure 4*. The numbers in the figure represent the sub-chapter numbers of this chapter.

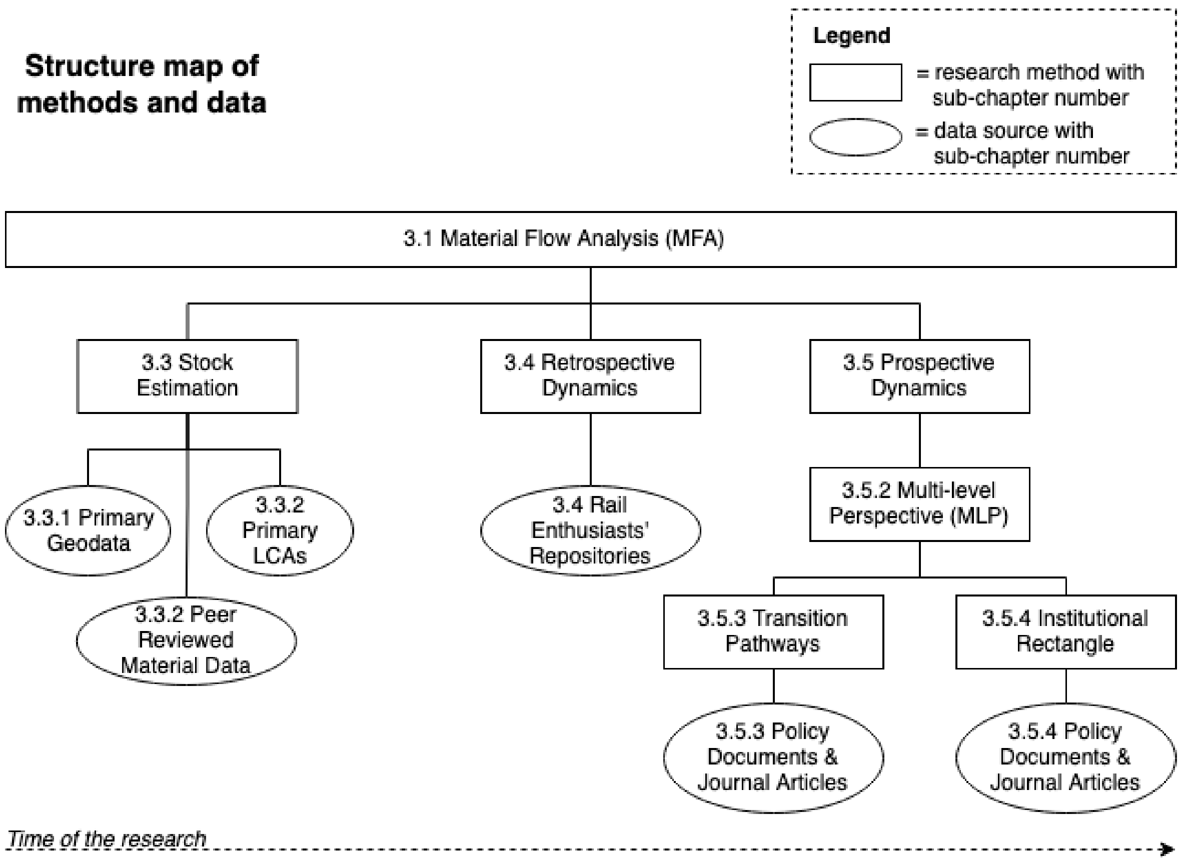


Figure 4: Overview of the data sources and methods used in this thesis.

The MFA started with the estimation of the material stock in order to explore the size of the potential urban mine: by combining geospatial data of the length of railway infrastructure with industry data on material intensities from life cycle assessments (LCAs) and peer reviewed data on material intensities for the objects that weren't included in the primary dataset, the size of the material stocks and their geographic location were defined. In analogy with geological mining, this step can be identified as the prospecting phase for the urban mine.

The historical material flow developments were calculated on a retrospective stock estimation. This estimation was based on online repositories created and managed by rail enthusiasts. As first-hand industry data was lacking, these websites offered the most detailed information on historical developments in the railway system.

In order to understand large-scale transitions to a circular economy, future oriented analytical frameworks that include multiple approaches with interaction characterizations are required. One such framework that encompasses these requirements is the multi-level perspective (MLP) (Geels 2012). In this thesis, two sub-methods are used from a multi-level perspective to help to assess the prospective dynamics of the materials: sociotechnical transition pathways and the institutional rectangle. The typology of sociotechnical transition pathways allows to categorize multiple potential future directions of change in the MLP and to make comparisons between them.

The institutional rectangle was added to the MLP, since transitions can be defined as a re-orientation of the co-evolution between the actors in the regime (Grin et al. 2010b). The institutional rectangle has four institutional realms of government, market, civil society and science & technology. The institutional rectangle classification was adopted, because such clustering of actors into different societal spheres is common for defining the actors in sustainability transitions (Fischer and Newig 2016).

The next parts of this chapter present more information on these methods, their modeling applications and data collection. The first sub-chapter introduces the application of the overarching method of dynamic MFA for railway infrastructure by finishing the ODD protocol that was presented in *Table 1* in the introduction of this report.

3.1 Dynamic Material Flow Analysis for Railway Infrastructure

The *basic principles* of this study are depicted as a dynamic, bottom-up, retrospective and prospective material flow analysis. The assessment has a retrospective and a prospective part, characterized by an accounting stock-driven model from 1839 to 2020 and a dynamic stock-driven model for the time scope 2021 - 2050.

The bottom-up approach, also termed as coefficient based approach measures stock amounts by quantifying all infrastructure assets and multiplying their number or length with their material intensity (i.e. the mass of materials used per unit of length). A bottom-up approach requires a lot of data, which is very labor-intensive (Lanau et al. 2019). Typically, it shows a more detailed result of stocks and flows than a top-down approach, which is complete but mainly addresses material flows (see also *Figure* 5).

A top-down approach focuses on resources, but does not show the applications of the used materials. It is mainly applied to research aggregated material flows, top-down modeling is difficult to apply to stocks. Since this study's goal was to identify the anthropogenic resource stocks railway infrastructure in order to show the potential for extraction and application as a secondary material, a bottom-up approach was required.

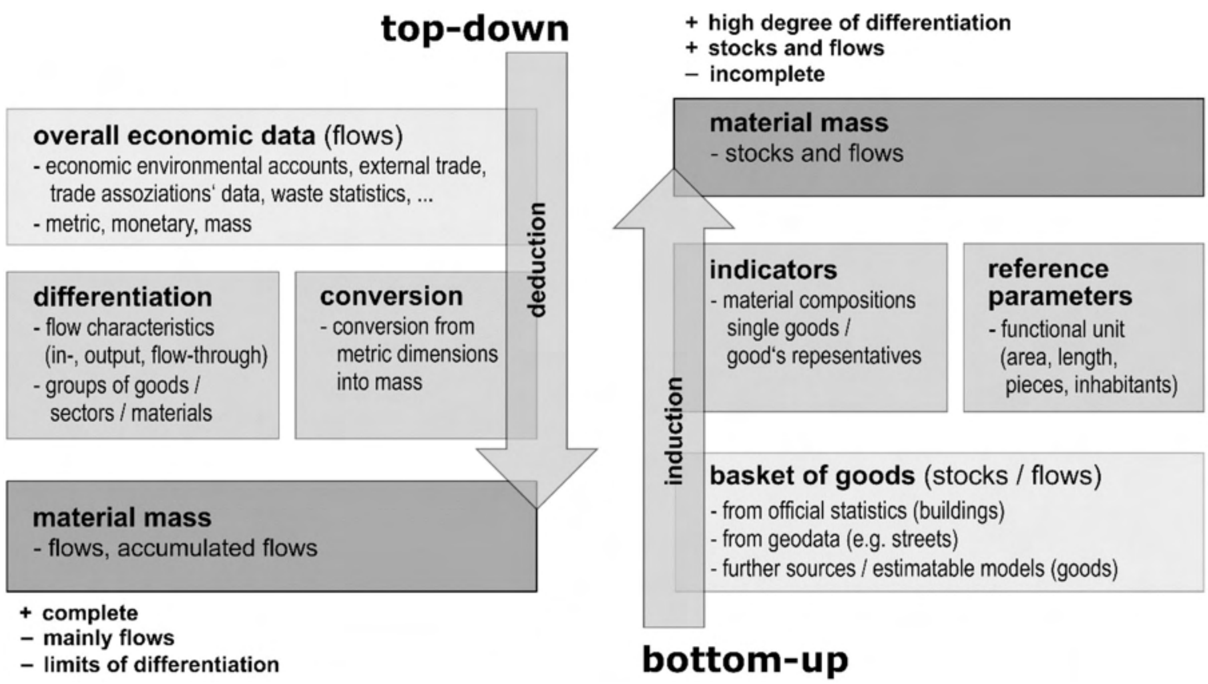


Figure 5: by (Schiller et al. 2017) explaining the (dis)advantages of each MFA method.

For the retrospective part a *stock accounting approach* was used by estimating the historical stock changes in Excel format. For the prospective part of the study, a *dynamic modeling* *approach* was adopted by using the Python program Spyder. The [Python Open Dynamic Material Systems Model] (ODYM) has been used as a basis of the model. The ODYM is an open source framework for modeling MFAs in the programming language Python, based on the Dynamic Stock Model from Stefan Pauliuk (2014). This method was adopted, because the open source ODYM code is continuously updated while it aims to integrate modeling advancements in MFA into a flexible platform.

Dissipation is the leaking of materials to the environment. Müller et al. (2014) specify dissipation as irrecoverable material losses to soil, groundwater, or surface water. Dissipation in this sense was taken into account, even though in general dissipative flows to the environment from major construction materials and bulk metals (aluminium, copper and iron) tend to be concentrated and rather small (Müller et al. 2014). Gassner et al. (2020) argue that dissipative flows in the Viennese transport infrastructure are negligible in comparison to the size of the construction material stock. However, in the railway infrastructure sector, dissipative losses seem to form a considerable flow. During the lifetime of a Dutch steel rail bar, about 4 to 6,5% of the steel content leaks to the environment due to wear of the rail (personal conversation with Voestalpine Railpro, 27-10-2020). Therefore, a total dissipation estimation of steel is given in the results chapter of this thesis, followed by a short literature review on its environmental effects in the discussion chapter.

The *spatial dimension* was taken into account by visualizing the spatial distribution of the network characteristics in 2018 in GIS, to show geo locations of where exactly potential material recovery hotspots are. *Uncertainty* was dealt with by comparing the results with academic studies and by sensitivity analyses on results that are sensitive to change, such as the lifetime distribution of the stock. A sensitivity analysis aids to determine the significance of uncertainties in the model parameters by gaining insight on how the model output responds to parameter changes (Müller et al. 2014).

3.2 Model Input and Output Data

The *initial condition* of the model was based on the available stock data on the baseline year 2018. *Model input data* for this research includes stock data at three levels: national, regional and local. At the national level, the Dutch national rail network operator ProRail and their geodata at Nationaal Georegister have been consulted. The material intensities for train infrastructure have been determined based on life cycle assessment data provided by ProRail. Missing objects were determined with the help of rail infrastructure product supplier

Voestalpine Railpro and material intensities from similar studies railways in Germany (Schmied et al. 2013) and in Vienna (Gassner et al. 2020). At the regional and local level, for trams, metros en light rail, material intensities from the latter study have been used. The initial stock length for tram, metro and light rail tracks were retrieved from the Nationaal Georegister database.

Data that was generated as *model output data* are historical, current and future stock data, among others expressed as material content in ton per capita, so that an *evaluation* could take place by means of a comparison to other studies such as Wiedenhofer et al. (2015). Hibernating stocks have been monitored as well, as these could be useful sources of secondary raw materials when not periodically taken out of service for maintenance work.

A *detailed model description* is covered in the following sections.

3.3 Inventory Analysis (Stock Estimation)

3.3.1 Using Geospatial Data

Geospatial data are utilized to help identify the location of material stocks in railway infrastructure. In this research process, initially, the location data of railway lines and complementing infrastructure such as stations, platforms, noise barriers and cables have been retrieved. Later on, these data have been coupled to material intensities within the borders of municipalities to get a clearer picture of the total stock per municipality. Distinguishing different scale levels, such as the municipality level, allows for an overview of where the material used in rail infrastructure is most dense.

ArcGIS version 13.1, a Geographical Information Systems (GIS) tool licensed by Esri, was used to visualize data on the geographical aspects. Furthermore, GIS data from the Top10NL database and ProRail's www.spoordata.nl were used to connect the spatial aspects such as surfaces of objects and section lengths to material intensities from primary LCA studies that were provided by ProRail and from peer reviewed literature. The material intensities for this research are presented in *Appendix F*. All maps in this report were made in ArcGIS.

3.3.2 Using Material Intensities

Material intensities at the train infrastructure level have been calculated based on primary life cycle assessments (LCAs) that have been commissioned by ProRail. The LCAs have been carried out between November 2018 and February 2019 by SGS Search Consultancy on noise barriers and fences, ballast (track bed), rail tracks, masts, mast foundations, anchor blocks, overhead wires, cantilevers, switches and switch heaters. ProRail furthermore gave material requirements for concrete level crossings and Voestalpine Railpro supplied data on materials in buffer stops.

Secondary material data were used if primary data weren't available. These data stem from peer-reviewed articles and generally gave more aggregated material intensities per track section. For instance, material intensities on tunnels, bridges, metro tracks and power supply, tram tracks and power supply have been retrieved from Gassner et al. (2020) for the case of Vienna. Underground cables for railway infrastructure were given in Schmied et al. (2013) for German railway infrastructure.

3.3.3 Functions for Stock Estimations

The geospatial data and the data on material intensities are combined by the following function. Stock-flow modeling based on the bottom-up equation (*equation (1)*) of the in use material stock $S(t)$ at time *t* that sums up all the material contents in the rail sector based on quantity or length *N* of the final asset in use at time *t* times the mass *m* of that asset. *I* is the total number of different assets considered (Müller et al. 2014; van der Zaag 2020).

$$S(t) = \sum_{i=1}^{I} N_i(t) \cdot m_i \qquad (1)$$

The retrospective part of this study uses *equation (1)* to model historical stock data.

3.4 Retrospective Dynamics

Historical in- and outflow data were added to make a temporal distribution of the stock change. Data on the opening, extension dates, closing and length of railway lines were retrieved from websites by rail enthusiasts (such as www.stationsweb.nl and www.railwiki.nl) since no complete historical overview was accessible. The exact source for each datapoint is provided in a note in every cell of the excel workbook 'DSM_Rail_Infra_NL.xlsx'. To test the goodness of fit of the retrieved data from online repositories, the total track length was compared to the only calculations available from ProRail for the years 2019 and 2020 (ProRail 2021). These data from ProRail match with the calculated data based on the repositories from rail enthusiasts.

3.5 Scenario Development

3.5.1 Existing Outlooks and Scenarios for Rail Transport

Until 2050, the Netherlands Environmental Assessment Agency projects that compared to 2010, train use will grow by 25% to more than 30% until 2030 due to planned frequency improvements of the trains. In their 'Toekomstverkenning Welvaart en Leefomgeving (WLO)' ('Outlook on Prosperity and Living Environment') it is expected that from 2030 to 2050 under the 'WLO Low scenario', train use will stabilize and under the 'WLO High scenario', the rapid growth will slow down (PBL 2015). Both scenarios serve to explore the realistic bandwidths of development in The Netherlands. Even though the scenarios do not assume substantial policy changes or transitions toward sustainability, the WLO High scenario presumes extensive international climate policies, albeit not enough to meet the Paris climate agreement (Ministerie van I&M 2017). The WLO scenarios are also used to project the number of railway travelers on national railway lines (Ministerie van I&W 2020).

index: 2010 = 100 unless otherwise stated	WLO High 2030	WLO High 2050	WLO Low 2030	WLO Low 2050
Population	109	116	102	98
Travel kilometers: by train	132	142	126	120
Travel kilometers: by bus/tram/metro	112	120	105	99
Tram (index= 2014)*	123	127 (in 2040)	115	115 (in 2040)
Metro (index=2014)*	167	172 (in 2040)	156	153 (in 2040)
Transported freight weight by rail (index=2011)	143	222	128	161

*Table 3: indices from the WLO scenarios (PBL 2015) and * from the NMCA for 2030-2040 that presents metro and tram indices separate from bus indices (Ministerie van I&M 2017).*

Separate tram and metro indices give different numbers than aggregated bus, tram and metro indices as presented in the WLO scenarios. In the National Market and Capacity Analysis (NMCA) it is reported that trends on tram travel kilometers are possible to grow 15-27% in 2040 compared to 2014 and that metro passenger kilometers grow by 53-72% (Ministerie van I&M 2017). An overview of the growth scenarios is displayed in *Table 3.*

A national scenario design towards circular rail was presented in January 2020. The Dutch Ministry of Infrastructure and Water Management released a report with 'transition pathways' towards climate neutral and circular infrastructure projects in 2050 (Ministerie van I&W 2020). The ministry presented eight pathways for transitioning the road- and railway infrastructure to a circular economy. In this case, the term 'transition pathways' connotes: directives outlined by the government that need to be implemented for a transition towards a CE. Four of these directives give specific call-to-actions to the network operator ProRail. The four directives for ProRail have different parts that are included in *Table 4*.

Transition directives	Systems	Parts	Proposed measures until 2050
1. Superstructure track	Superstructure system	Ballast, railroad ties, level crossing plates, rails, switches	1. deploy wheel-rail conditioning (WRC) technique by adding a greasy layer that extends the rail lifetime with approx. 20% 2. extend the network with about 5% (period 2020-2030) 3. extend lifetime of rails by improved rail cutting & maintenance 4. experiments with green railroad ties, cementless concrete ties 5. deployment to reuse rails, switches, ballast 6. developments to recycle ballast
2. Construction site and construction logistics	Construction and maintenance contractors, minor maintenance	Fuel consumption contractors	no material related measures yet other than fuel use
3. Energy supply	Energy supply system	Overhead line support structure, overhead line electrical system, switching stations, station transformers, refueling systems, traction energy supply system, train safety and control system power supply	1. more electrified tracks 2. research the reuse of power supply structure (e.g. steel portals) 3. research an alternative for copper (not yet known) 4. research the use of rolling pantographs to reduce resistance on the overhead wires. 5. increase power voltage from 1.5kV to 3kV to increase train capacity. Requires less transformators (= less material)
4. Engineering structures and other material	Crossing system, carrying system, train protection system	Engineering structures (track-bearing and non-track-bearing), entrance gates, culverts, underground, automatic half-barrier installations, security cable, relays, relay batteries, relay houses, relay boxes, signals, train protection system, lighting	1. more tunnels are expected as level crossings will be phased out 2. number of fences and noise barriers will increase with 20%

Table 4: Transition directives and the focus points of the Dutch governmental strategy (Ministerie van I&W 2020, 19).

Note that the definition of a *transition pathway* is different in this context. This policy report sees a transition pathway as a directive, whereas the definition of Geels & Schot is based on modeling developments over time with the transition pathways marking the potential directions of change.

Each of the transition directives in *Table 4* proposes specific measures per construction of the train infrastructure network. They are further explained in the paragraphs below.

The first directive for the superstructure proposes various measures on the rail tracks, such as the novel wheel-rail conditioning (WRC). This technique adds a greasy layer with fine particles to the rails to extend its lifespan. It has been tested until 2014 and is now rolled out as train equipment (Strukton Rail 2019a). Furthermore, the lifetime of rails can be extended with improved rail cutting techniques with mobile cutting units (Strukton Rail 2019b).

The second directive is concerned with the construction site and contractors. The proposed measures only depend on limiting fuel consumption, no other materials are part of the plan in this trajectory. Fuel consumption is not part of this material flow analysis on railway infrastructure.

The third directive on energy supply proposed rolling pantographs, a novel technique that should reduce electric resistance which is currently being tested by TU Delft pantograph researchers (TU Delft 2017). This technique is still in its infancy.

The fourth directive includes all other infrastructure objects than energy supply and superstructure tracks. The ministry proposes that in 2050, more tunnels replace level crossings, which will increase the demand for concrete and steel in train infrastructure.

The impact of COVID-19

In November 2020, the Netherlands Institute for Transport Policy Analysis (KiM) published its annual key figures for mobility in The Netherlands (KiM 2020b). This report also included a short term future vision for 2020-2025 with a scenario with high impact of COVID-19 and a low impact of the Coronavirus disease on mobility. For public transport, it is expected that under low impact conditions the use of public transport services will reach the level of 2019 again in 2025. For the high impact scenario for 2025, public transport use will still be 8% lower than in 2019. It was expected that the passenger kilometers traveled by train in 2020 would drop by maximum 45% (KiM 2020b), check-ins in public transport even declined by

50% in 2020 (CBS 2021). The uncertainty in traveled passenger kilometers as a consequence of the coronavirus pandemic adds bandwidth to the scenario development. The prospective modeling part of this thesis includes this bandwidth in one of the pathways with a very low passenger kilometer assumption: the Substitution Low Pathway.

All in all, short term scenarios show a negative impact on rail use in The Netherlands until 2025 due to COVID-19, whereas in the long run, both urban and international passenger kilometers by rail are projected to increase, even under low rail scenarios. In order to make the material used in railway infrastructure more circular, the Ministry of Infrastructure and Water Management has set up transition directives for the infrastructure objects.

3.5.2 The Multi-level Perspective for Transitions

The multi-level perspective (MLP) is a method that sheds light on transition processes as the result of alignments between changes at multiple levels (Geels and Schot 2007). The perspective offers a three-leveled structure to describe stabilizing factors and transition developments, starting at the level of niche-innovations (micro), prosecuted by putting pressure on the socio-technical regime (macro) that is in turn influenced by the socio-technical landscape at a meso level (Geels 2002). The three levels of the multi-level perspective are visualized in *Figure 6*. The three levels of the MLP can be specified as follows:

1. Niches are novelties, or innovations that operate outside the dominant regime level. Niches are not limited to technological innovations. They can be identified as social innovations too, such as new lifestyles, institutions, markets or cultural elements (Nykvist and Whitmarsh 2008).
2. The regime is the dominant paradigm of the socio-technical system regarding used practices, structures and assumptions. Geels & Schot (2007) describe the regime as ‘cognitive routines’ that have achieved an embedded, stabilized position in the system.
3. The landscape is classified as the exogenous context of ecological, economic and cultural conditions that influences the regime. The context of the landscape lies beyond the direct influence of the niches and the regime (Geels and Schot 2007). The landscape generally changes slowly (over decades). Over time, the regime may not fit within a landscape anymore, which pushes the regime to adapt.

An MLP approach is used for this research, because it aims to unravel complex relations in systems where innovations are adopted. It is useful to combine innovation theory with MFA, among others, since the dynamics of material flows steer the speed of adoption of niche-innovations (Pauliuk and Müller 2014). In other words: the throughput of materials in a system determines how fast technological innovations are implemented in a transitioning system. In addition, the MLP from Geels and Schot is regarded as the most influential framework in transition theory (Kamp et al. 2010).

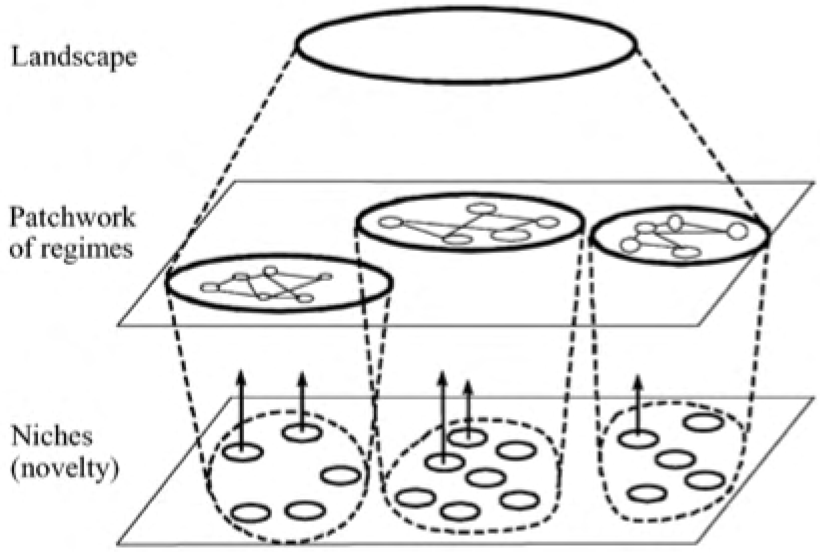


Figure 6: The multi-level perspective (MLP) as a nested hierarchy. Figure from Geels (2002, 1261).

Even though the multi-level perspective has not been designed for a particular research field, this transition theory has been adopted in transport studies, among others on shipping (Geels 2002), land-based transportation (Geels 2005) and mobility (Nykvist and Whitmarsh 2008). It is a useful framework for transport studies, since it helps to indicate promising niche developments and their potential technological trajectories. This was illustrated by a case study that assessed the multi-dimensional regime interactions in the transition process toward a low-carbon transport industry in The Netherlands and the UK (Geels 2012). Also, the MLP in combination with transition pathways has been used by fellow Industrial Ecology-student Jochem van der Zaag to execute a material flow analysis on vehicles in The Netherlands (van der Zaag 2020).

3.5.3 Transition Pathways in the Multi-level Perspective

As a methodological means to explore the myriad changes that transitions can evoke, trajectories of change, termed as 'transition pathways', can be utilized. From the MLP, Geels and Schot defined four transition pathways as trajectories that categorize transition processes based on landscape pressure (moderate and slow vs. large and sudden) and the stage of development of niche-innovations (not sufficiently developed vs. sufficiently developed). The goal of transition pathways is to understand what the future impact of current decisions could be at multi-level interactions under different combinations of nature and timing. In the MLP, transition pathways symbolize the potential transition trajectories that move away from the status-quo and alter the socio-technical system. Since a transition towards a circular economy includes future processes that are unsure by nature that could develop in different directions at a different pace, multiple options of pathways are required to explore the trajectories of future change. Hence, the single pathway for feasibility of technological solutions proposed by CE Delft (2018) or a planning with transition directives for making the current infrastructure circular in 2050 (Ministerie van I&W 2020) are not enough to explore the transitions in the socio-technical system.

Geels and Schot (2007) differentiated the MLP by proposing a typology of four different transition pathways: technological substitution, de- and realignment, reconfiguration and transformation. *Figure 7* depicts the distinctive characteristics of each transition pathway. Although in practice, a combination of the different pathways is common, as the speed and size of the disruptive changes can develop over time (Geels and Schot 2010).

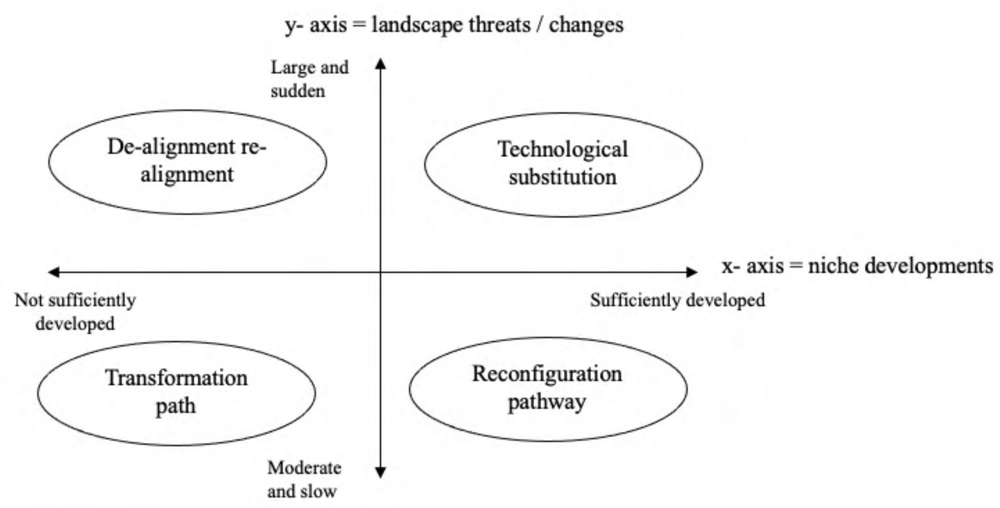


Figure 7: Matrix from Kamp et al. (2010), inspired by Smith et al. (2005) and based on Geels & Schot (2007).

The typology of transition pathways is different from scenarios. While scenarios are descriptions of results of potential events or actions in the future, transition pathways show the development of multiple events and actions *over time* (van der Zaag 2020). The exogenous factors that distinguish the developments are described by driving forces in §3.6.2 in the Methods chapter.

Typological theories such as transition pathways combine different variables that have an inherent logic of similarity. Transitions are triggered by different types of environmental change. Each pathway is based on at least one of the five environmental change types that Geels and Schot derived from Suarez and Oliva (2005) (see *Figure 8)*.

If specific shocks lead to a structural change, this change type has been identified as 'wildcard events' by Walsh et al. (2015). The MLP framework is used by Walsh et al. (2015) to study systems that have been 'broken' by wildcard events. Describing and modeling these wildcard events can help to better understand how behavior and socio-technical characteristics can change. They aid in future envisioning and with the design of adaptation measures where multiple stakeholders are involved, leading to a more sustainable infrastructure (Walsh et al. 2015). Walsh et al. (2015) mention natural disasters and extreme weather events as examples that disrupt infrastructure systems such as railways.

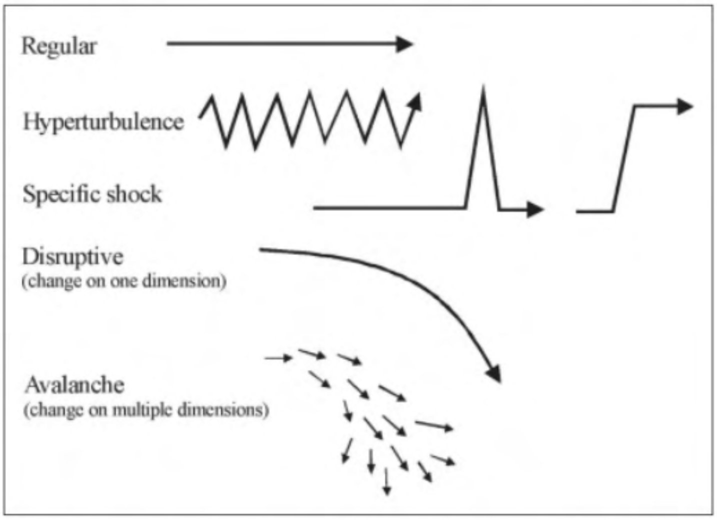


Figure 8. Environmental change types. Figure by Geels and Schot (2010) based on Suarez and Oliva (2005). Note that specific shocks leading to structural change are typical for wildcard events.

The theoretical explanation of the transition pathways can be found below:

Reconfiguration

In the reconfiguration pathway, local problems are fixed by innovations developed in niches. They are slowly adopted in the regime, thereby changing its basic structure (Geels and Schot 2010). Changing the architecture of the regime is a distinctive characteristic from this pathway relative to the transformation pathway. Similar to the transformation pathway, change in the reconfiguration path is moderate and slow, but it is more disruptive in the system's architecture, as the niche innovations have already been sufficiently developed. The main actors in the reconfiguration pathway are regime actors and suppliers (Geels and Schot 2007).

An example of the reconfiguration pathway in the transport industry is Geels' (2012) projection that the car-based transport system will adopt technical niche-innovations such as battery electric cars to survive. By doing so, the regime is eventually reconfigured to an all-electric car industry, but adopting the niche techniques of electric cars happens slowly until all characteristics, such as the driving range with a battery car, have been sufficiently developed.

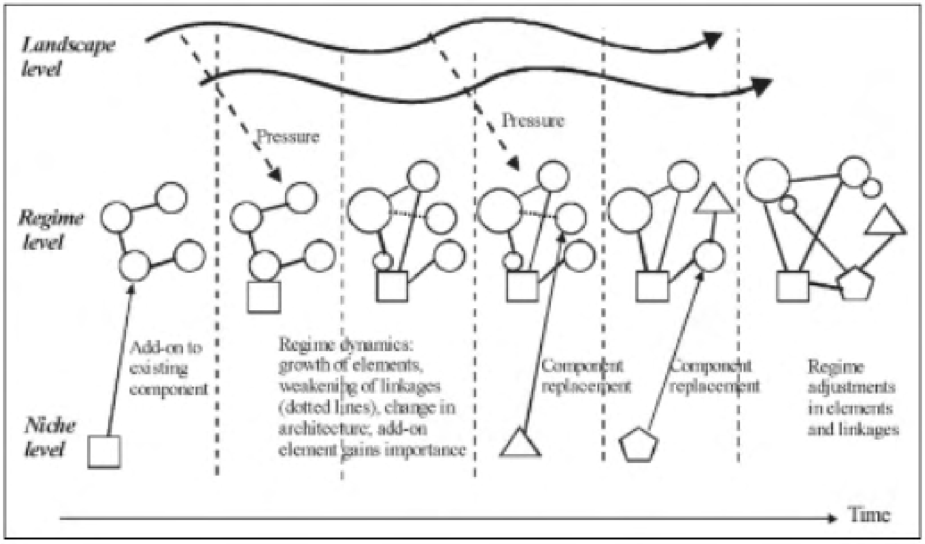


Figure 9: Reconfiguration pathway. Figure by (Geels and Schot 2010, 72).

Transformation

When the architecture of a regime remains intact, but 'disruptive change' is happening in the system, the typology of a transformation pathway is used. Transformation pathways could also function as a first step in the transition process, subsequently followed by other pathways (Geels and Schot 2010). Disruptive change is a one-dimensional change in the system (see *Figure 8*). Even though Geels and Schot (2010) characterize disruptive change as a specific aspect of transformations, The main actors in the transformation pathway are regime actors and outside groups, such as social movements, that put pressure on the regime (Geels and Schot 2007).

In the transport industry, the Dutch highway system can be taken as an example of transformation, starting with rapid expansion in the 1950s via social groups with environmental concerns in the 1970s to dynamic traffic management and more public participation as niche-innovations in the 1990s (Geels 2007). The regime of the Dutch highway system was changed over time by the regime actors themselves with pressure from outside groups and the promising niche innovation of dynamic traffic management. Regime insiders regarded dynamic traffic management as an attractive niche innovation to solve congestion problems and to prevent public protests like in the 1970s. The adoption of this niche innovation in the 1990s transformed the regime. It served as a symbiosis with the existing highway system and did not compete with it (Geels 2007).

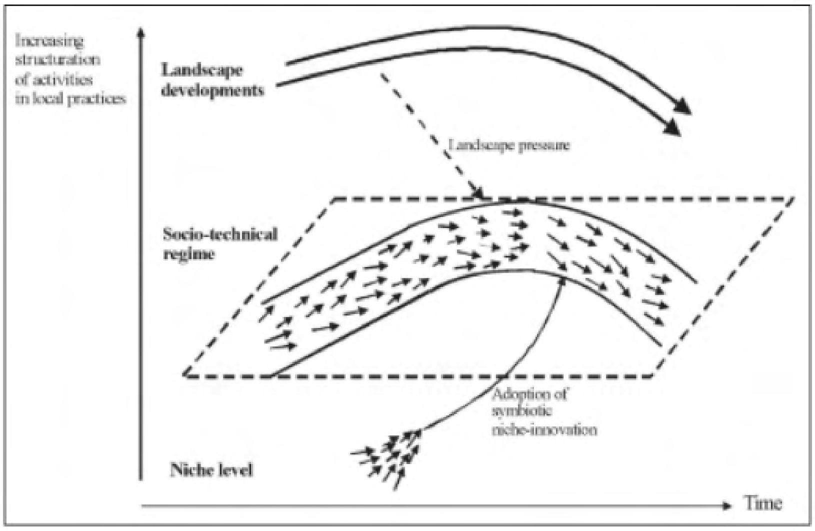


Figure 10: the transformation pathway (figure by (Geels and Schot 2010, 59).

De- and Realignment

If a diverging, sudden and large change (an avalanche change) is taking place at the regime level, regime actors are destabilized. This dealignment process is followed up by a realignment process of the regime when a niche innovation is becoming dominant (Geels and Schot 2010). *Figure 11* shows with various arrows the diverging and converging phases evoked by the avalanche change. De- and realignments could happen quickly and suddenly, depending on the degree of development of the innovations.

The transition process leading to automobiles replacing horse-drawn carriages in the USA is an example of de- and realignment in the transport industry (Kamp et al. 2010). Calling the transition from carriages to cars a technological substitution would be an oversimplification, because it neglects the intermediate steps of electric tram and bike transport (Geels 2005). Geels (2005) describes the adoption of automobiles as a process of dealignment and realignment, since the trajectory from horse-drawn carriages to automobiles has a history of widening up ('realigning') the transport alternatives from private transport and recreation to a more utilitarian way of transport with horse-trams and horse-buses at the end of the 19th century, followed by bicycle use and electric tram transport at the beginning of the 20th century. Eventually, the options for the utilitarian transport mode were narrowed down ('realigning') to a dominant use of private automobiles from the second half of the 20th century.

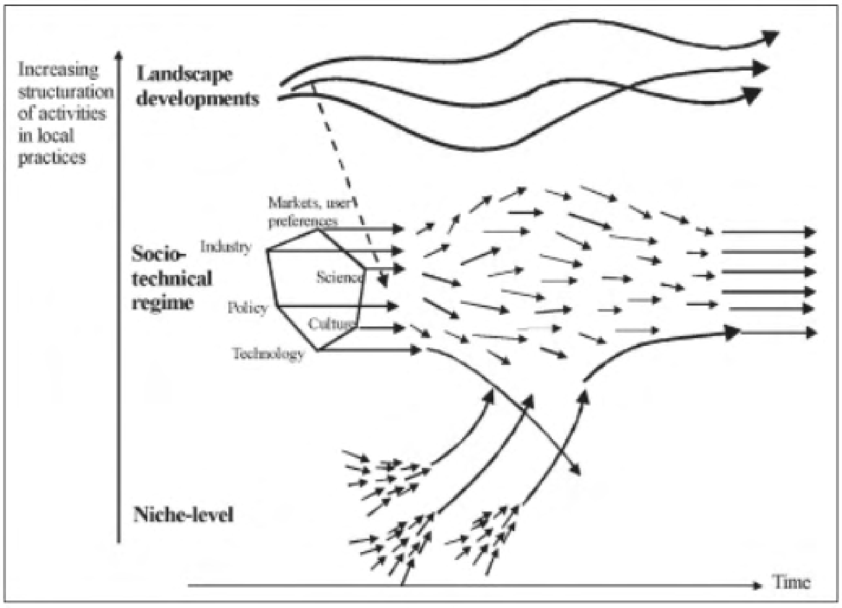


Figure 11: de- and realignment pathway. Figure by (Geels and Schot 2010, 64).

Technological Substitution

If a niche-innovation has developed enough at the niche level and a shock, avalanche or disruptive change takes place at the landscape (exogenous) level, the innovation will take over the regime (Geels and Schot 2010). In that case, the dominant regime is substituted by a new technology. Wildcard events are examples of specific shock changes leading to structural change.

An example of technological substitution in the transport industry is the transition from sailing ships to steam boats in the UK (Kamp et al. 2010). The UK was the leading shipping nation in the 19th century. A shift from sailing to niches such as steam ships was accelerated under pressure of landscape developments. In the mid 19th century for example, steam ocean transport was accelerated by migration patterns from Europe to the US as a consequence of the Irish potato famine, the gold rush in California and political revolutions in Europe (Geels 2002).

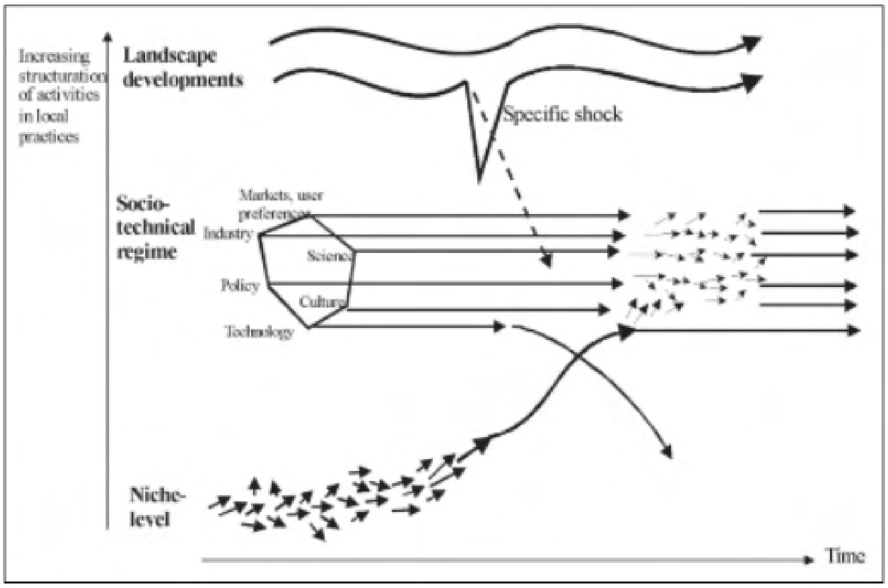


Figure 12: technological substitution pathway (Geels and Schot 2010, 69)

3.5.4 Co-evolving Actors and the Institutional Rectangle

A missing aspect in the transition pathway matrix given in the previous section are the actors that shape the regime. Having discussed the types of environmental change and their interaction with each transition pathway, this section discusses the main stakeholders for each path and how they co-evolve under different changes (i.e. development patterns in society) at the regime level. Co-evolution and multi-dimensional interactions between them are key to systemic transitions (Geels 2012).

Transitions are processes with multiple actors, each characterized by interactions and behavior change of social groups, that include policymakers, different user groups and businesses (Geels and Schot 2010). The analysis level of transitions is focused on "organizational fields", which are, among others, regulators, key suppliers, and consumers of the resources and products (Geels and Schot 2010; DiMaggio and Powell 1983).

Transitions have a macroscopic view and entail a whole 'organizational field' of multiple actors that evoke multiple changes in socio-technical systems (so-called co-evolution) (Moradi and Vagnoni 2018). These multiple actors can be summarized in societal realms shaped in the institutional rectangle of the state, market, civil society and science (See *Figure 13*). The realms in the institutional rectangle co-evolve with the environmental changes in society (termed as societal development patterns).

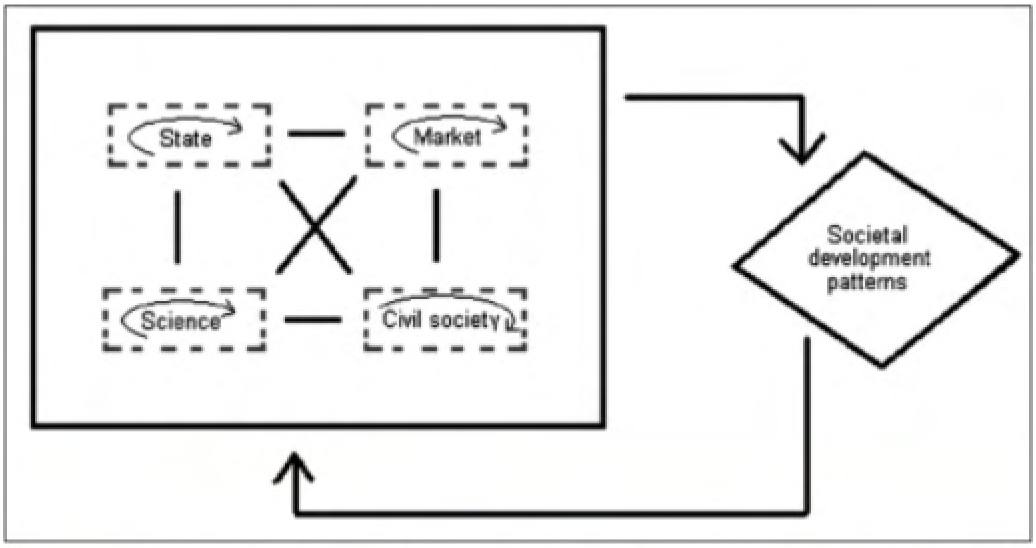


Figure 13: The institutional rectangle and its co-evolution with societal development patterns. Retrieved from Grin et al. (2010, 238).

According to Berkhout et al. (2004), regimes change due to or in reaction to pressures in the transition context and how these are characterized and integrated by key actors (Kamp et al. 2010). Changes at the regime level of the MLP often result in heterogenization and hybridization of the institutional structures, such as interdisciplinary knowledge production or integral policymaking (Grin et al. 2010a). Studying the hybridization of these institutions helps to trace novel forms of agency that influence the outcomes of the transition processes.

For the sake of unraveling the hybridization of institutions, the most important interactions are discussed in each pathway in the modeling part in the results chapter of this report. Transitions are regarded as a re-orientation of the process of co-evolution within the institutional rectangle for sustainable development (Grin et al. 2010b). Hence, the analysis of actors within the institutional rectangle supports the governance of a transition towards a circular economy.

3.6 Prospective Modeling

This section provides a detailed description of the model, starting with the driving forces (the variables that influence the model) and the functions that are required for making it quantifiable.

Figure 14 and 15 represent a flowchart with the relationships between the stock (K), its inflows (I), and outflows (O) and the driving forces (hexagons in the diagram) for the useful rail infrastructure (URI) and rail related materials (RM) in The Netherlands. The URI stock and flows depict the service provision and the RM stock and flows are the translations of these services to actual material demands. This model has been designed in analogy of the extended MFA system for the stocks dynamics model from Müller (2006). This is a method for prospective stock-driven Material Flow Analysis. The service units are expressed in kilometers (all marked with $^{(URI)}$). The lower stock and in- and outflows represent the material use in kilotons as a consequence of the use in service units (all marked with $^{(RM)}$).

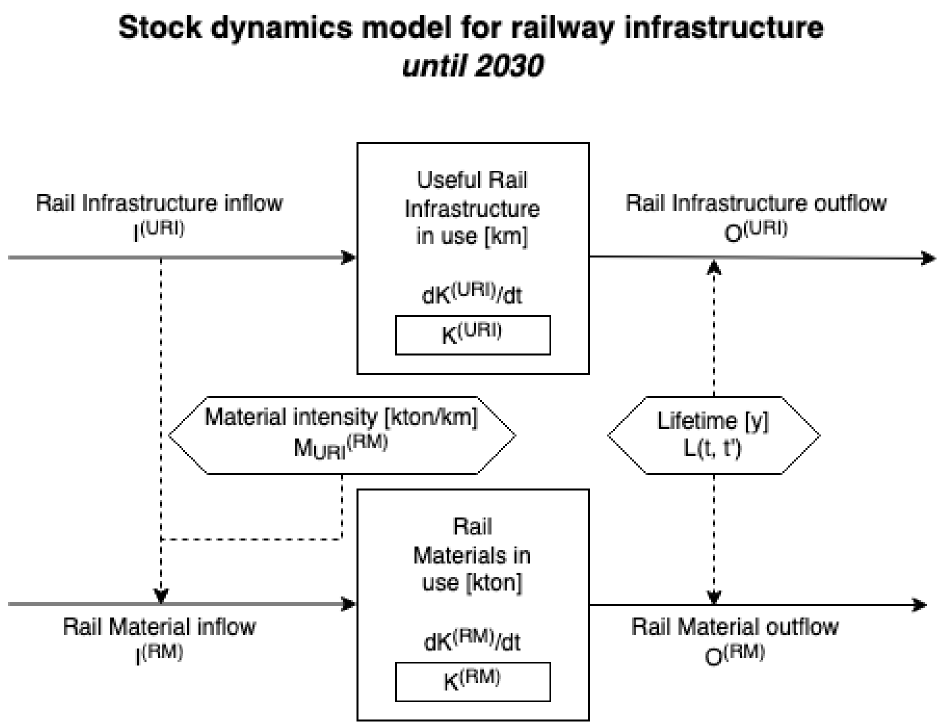


Figure 14: stock dynamics model adapted from Müller (2006) until 2030. Rectangles depict processes (with stocks), hexagons with their dashed arrows represent the driving forces and straight arrows illustrate the flows.

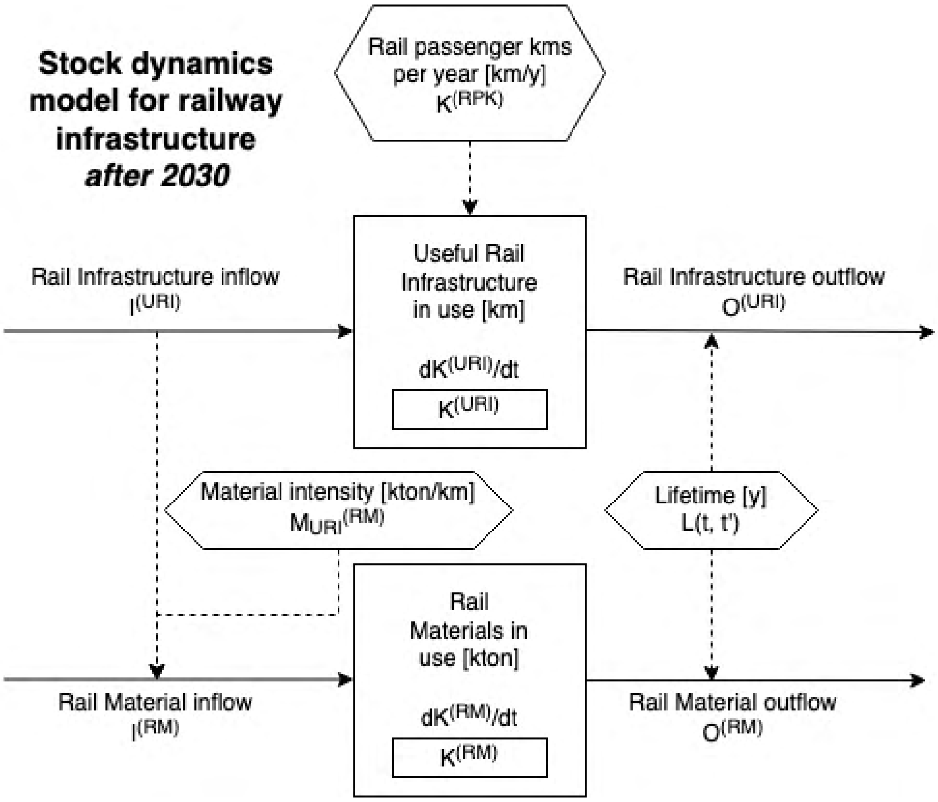


Figure 15: stock dynamics model adapted from Müller (2006) after 2030. Rectangles depict processes (with stocks), hexagons with their dashed arrows represent the driving forces and straight arrows illustrate the flows.

A distinction was made between modeling before and after 2030. The budget and planning for most rail infrastructure projects until 2030 is already made in the Meerjarenprogramma Infrastructuur, Ruimte en Transport 2021 (MIRT) (Rijksoverheid 2020b). Since rail network extensions require long-term planning, it is assumed that all railway extensions until 2030 that are in planning will come into operation. Since the planned extensions after 2030 have a high level of uncertainty, an additional driving force is introduced in *Figure 15.* The driving force rail passenger kilometers per year represents the expected growth of the rail travel demand, based on the WLO scenarios, which serves as a driving factor on which the infrastructure that is in use is dependent.

3.6.1 Functions for Dynamic Flow Modeling

This section introduces the functions that can be derived from the model in the flowchart in *Figure 14 and 15*.

To extrapolate these past flows, *equation (2)* shows how a stock-driven model is used for prospective analysis. In *equation (2a)*, the in use useful rail infrastructure stock service °F ^{ΦℙℕƐX} at year ΦX is calculated by subtracting the integral of the outflow of useful rail infrastructure $\int_{D\,ℑλ}^{ℑ} ħ^{ΦℙℕƐX}$Φō ℑ̈X from the integral of the inflow of useful rail infrastructure $\int_{D\,ℑλ}^{ℑ} Ɛ^{ΦℙℕƐX}$Φō ℑ̈). The inflows include the annual planned extensions until 2030 as given in the MIRT for 2021 In *equation (2b)* the useful rail infrastructure stock service °F ^{ΦℙℕƐX} is determined by the annual rail passenger kilometers (RPK). The annual rail passenger kilometers is one of the driving forces of the model. The application of this driving force in *equation (2b)* is explained in further detail in paragraph 3.4.2 on the model calibration.

ℙ𝐢 ℑƛ ν λ ξ λ ő °F ^{ΦℙℕƐX} ΦX$_{\nu}$ $\int_{D\,ℑλ}^{ℑ}$ Ɛ ^{ΦℙℕƐX} Φō ℑ̈X$_{\eta}$ $\int_{D\,ℑλ}^{ℑ}$ ħ ^{ΦℙℕƐX} Φō ℑ̈X (2a)

′ ℭℑÅℿ ν λ ξ λ ő °F ^{ΦℙℕƐX} ΦX$_{\nu}$ °F ^{ΦℕℑºFX} ΦX (2b)

The service units °F ^{ΦℙℕƐX} can have various lifetimes that are depicted by the lifespan (ℊ ^{ΦℙℕƐX}(t, t’)). A normal distribution was taken for this lifespan, where *t’* represents the time that a unit entered the stock and *t* the moment when the unit is discarded.

A normal distribution was used in accordance with other construction material studies (Müller 2006; Fishman et al. 2014). The lifetime distribution choice is further elaborated in the next sub-chapter. The rail infrastructure sector uses a top-down planning to decide on the lifetime of each part of the network. Since this planning was not known in this case study, the normal distribution for outflow of the stocks was used as shown in *equation 3.*

ℊΦōℑ̈X$_{\nu}$ $\frac{µ}{\&\sqrt{\nu ffl}}$ ű Å$^{\eta \frac{Φ_{\eta}\ ℑ_{\eta}\ ˋX^{\nu}}{\nu \&^{\nu}}}$ (3)

This probability density function gives $L(t,t')$ as the probability that the input at time $t'<t$ will result in an output at time t, given the lifetime of the assets has a normal distribution where τ depicts the mean lifetime and σ represents the standard deviation.

The output and input of service provision are linked by this lifespan:

$$o^{(RPK)}(t) = \int_{-\infty}^{t} L^{(RPK)}(t,t')\, s^{(RPK)}(t')\, dt' \tag{4}$$

The service system and the material system are linked by *equation (5).* This equation couples the kilometer inputs of the useful rail infrastructure $s^{(RPK)}$ to the material intensity for railway materials $M_{URI}^{(RM)}$. By doing this, the inflowing mass of railway materials $s^{(RM)}$ can be calculated. This equation can be utilized to assess the effects of material substitutions.

$$s^{(RM)}(t) = s^{(RPK)}(t) \cdot M_{URI}^{(RM)}(t) \tag{5}$$

Following this, an equation for the outflow of the railway material mass, which parallels *equation (4)* can be derived:

$$o^{(RM)}(t) = \int_{-\infty}^{t} L^{(RM)}(t,t')\, s^{(RM)}(t')\, dt' \tag{6}$$

In sum, the model has three driving forces:

$K^{(RPK)}(t)$ = Rail infrastructure used (lifestyle) expressed in annual rail passenger kilometers
$L(t, t')$ = Lifetime distribution
$M_{URI}^{(RM)}(t)$ = Material intensity per service unit

The driving forces are further explained in the next section.

3.6.2 Model Calibration: Driving Forces

Continuing with the *detailed model description*, three driving forces will influence the model's characteristics. Driving forces are exogenous variables that influence the model.

1) **Annual Rail Passenger Kilometers**

Annual rail passenger kilometers are influenced by the population growth estimates, the expected modal split and socio-economic drivers such as policy changes and changes in GDP. This section discusses these modules of rail passenger kilometers and to what extent increasing rail kilometers may lead to extensions in the railway infrastructure.

The WLO scenarios contain population growth estimates with different urbanization levels (PBL 2015). The WLO High scenario assumes a continuation of the trend of higher levels of urbanization in the Randstad (seen as the provinces of Noord-Holland, Zuid-Holland, Utrecht and Flevoland by PBL), whereas the WLO Low scenario assumes a more even spatial distribution of the population among various cities within the country. A higher spatial concentration is assumed to increase the public transport demand, while lower urbanization levels are associated with increased car use (PBL 2015).

Recent projections of the population growth show that the population in The Netherlands is growing even faster than estimated in the WLO High scenario. According to a 2020 estimate, the number of inhabitants will more likely grow to 18.5 million in 2030, 19 million in 2040 and eventually 19.6 million in 2060 (Ministerie van I&W 2021; CBS 2020d). Thus, it seems that the WLO scenarios from 2015 are becoming less accurate. However, they are still relevant in this case study, since the translation from population growth to passenger rail kilometers in the WLO scenarios can serve as a basis for pathways that assume a lower number of rail passenger kilometers under changing sociotechnical conditions, such as working from home and the coronavirus pandemic.

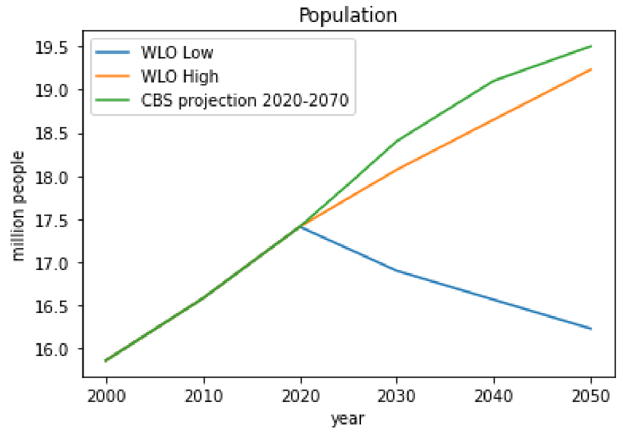


Figure 16: Population estimations in the WLO Low & High Scenario and in the more recent CBS Projection 2020-2070.

Behavior change can influence which mode of transport will be preferred and how much there will be traveled. In both WLO scenarios, the annual rail passenger kilometers are estimated to remain the same at about 1300 km per person per year from 2030 onwards (see also *figure 18*). This suggests that in both WLO scenarios a modal split with more train kilometers per capita between 2030 and 2050 is not expected.

Another variable that influences this driving force is a change in (government) policies. For example, the effects of road pricing ('rekeningrijden'), taxes on car fuels or investments in railroads could change the characteristics of the model. Business policies are also factors that influence rail use. In 2019, more than a third of the NS train journeys were business related (NS 2019). A business policy example that could promote a modal shift to rail is thus travel cost allowance restrictions on car use, and covering public transport costs.

Socio-economic drivers such as GDP growth and policy changes are forces that influence this demand of rail transport. But, following the strategy of Müller (2006), instead of using economic factors as driving forces, the driving forces are based on physical accounting of materials. Müller's (2006) stock dynamics model, that was used in this thesis, exclusively uses physical determinants to influence the stocks and flows. The in-use stock shapes the physical connection between construction inputs (resource demand) and demolition outputs (waste generation). The choice to only include physical determinants was made because GDP and policy changes can be identified as forces that indirectly change the material demand. Therefore, economic extensions would not alter the structure of the presented models in *Figure 14* and *15*.

When the passenger kilometers increase, it is likely that the material demand for infrastructure increases, as more vehicles have to use the same infrastructure. This leads to increased maintenance and sensitivity to service disruptions which may eventually lead to the expansion of rail infrastructure. However, a drop in passengers most likely has no effect on the short-term maintenance material needed, as the network operators schedule their maintenance years ahead and do not take the number of travelers into account (confirmed by ProRail during a meeting). In the long term, it is assumed that less travelers over a longer period will finally lead to less maintenance and suspension of railway lines.

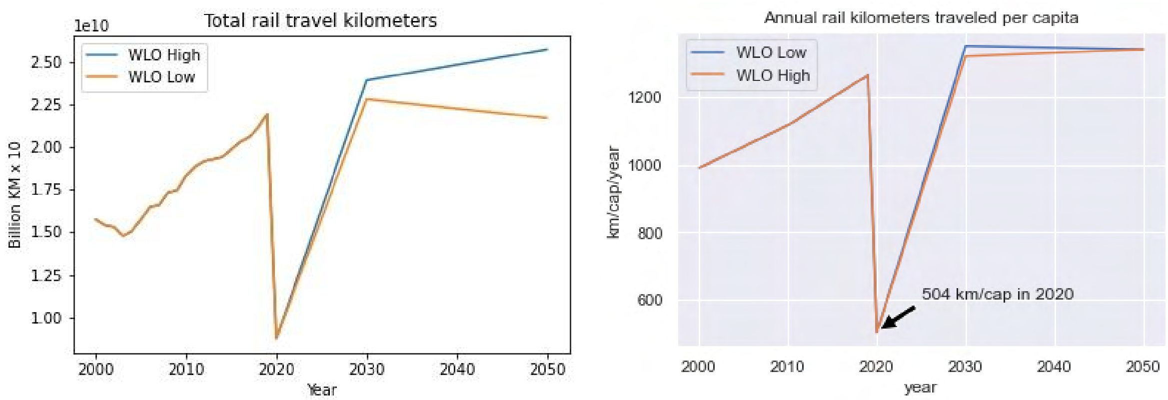


Figure 17 & Figure 18: Expected growth in total rail travel kilometers compared to the distance traveled per capita (figure 18). This shows that the population in the WLO High scenario grows faster than the travel kilometers per person.

A regression was carried out to check for a correlation between rail passenger kilometer growth and growth of the rail network length. Historical data on the period 2000-2019 were taken for train services. Metro and tram data were only available from 2014 to 2019 and these data are therefore separated from the train data in the regression. A scatter plot was made using the length of the rail network (dependent variable) and the rail passenger kilometers (independent variable). A logarithmic trend line was drawn through the plot (see *Figure 19*), since the network increase seems to slow down the more passenger kilometers are traveled. This trend line shows that metro, light rail and tram networks, for which only data between 2014 and 2019 were available, follow a similar development pattern as train data.

The fitted line in *Figure 19* corresponds well with the original data in the plot. Thus, the ratio variables annual passenger kilometers and rail network length between 2000-2019 were found to be strongly correlated, $r(24) = .99$, $p < .001$ (see *Appendix C* for the full regression analysis and statistical tests).

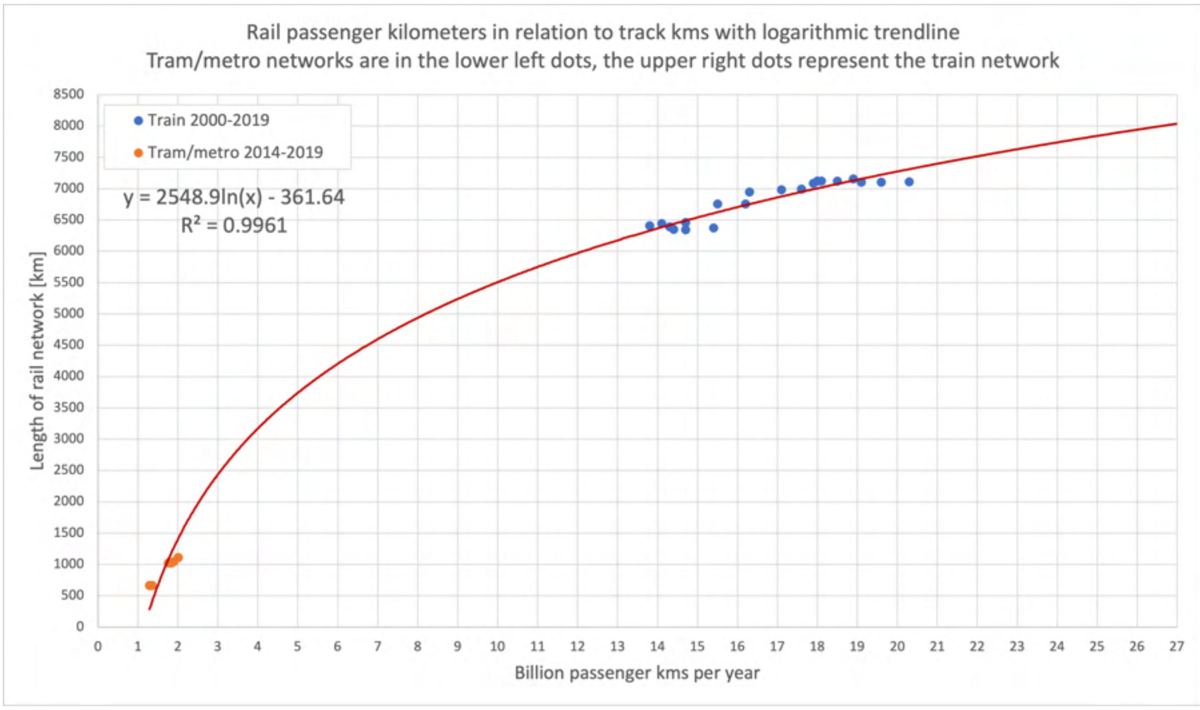


Figure 19: plot of the data points from the period 2000-2019 along with the fitted logarithmic line with an extrapolation to 27 billion annual passenger kilometers. The metro and tram data have not been added to the train data, because not enough data from all the years was available.

It is therefore assumed, in the dynamic modeling step, that each additional billion passenger kilometers (x) in the coming years until 2050 leads to extra length of the train network (y) in:

ⅆ ν ντος ϕτ λi ΦX η ξρμϕο

For this reason, the annual passenger rail kilometers (°F ΦN℥°FX ΦX that influence the useful rail infrastructure that is in use (°F ΦPNΕX ΦX can be rewritten as:

°F ΦPNΕX ΦX= ντος ϕτ λi ΦF ΦN℥°FX ΦXX η ξρμϕο

The share of overcrowded routes was utilized to check if the results in the period 2030-2050 for rail length increase based on rail passenger kilometer increase correspond with the share of overcrowded lines in the rail network.

2) **Lifetime of the Constructions**

Aggregates & concrete railroad ties are generally replaced every 47-60 years in the EU (Wiedenhofer et al. 2015). Schmied et al. (2013) mention that rail tracks in Germany are usually replaced every 30 years. However, Schiller et al. (2017) point out that in some case studies material outflows are overestimated, because infrastructures have a much longer actual lifespan than the technical service lifespan that was estimated in advance. The lifetimes of the constructions influence the annual renewal rate (RR) of rail tracks which has been at approximately 2.7% per year (200 km) over the past decade. ProRail assumes that the annual renewal rate will remain constant until 2050. However, in this thesis it is presumed that due to technological developments, the lifetime of the constructions can be further extended in the future.

Some tracks last 75 years (e.g. on a line in Limburg that is not frequently used), some 10 years (between Amsterdam - Utrecht). The average renewal rate of rail tracks is 37 years, because the LCA data from ProRail give an average lifetime of ballast of 35 years (which accounts for 79% of weight of the tracks) and the lifetime of all other parts of the track bed is 45 years (21% of the weight). This leads to a renewal rate of 37 years for all rail track materials. Ballast can be renewed when the rails and the railroad ties remain in use by using a shoulder ballast cleaning machine (in Dutch: 'kettinghor').

Figure 20: a shoulder ballast cleaning machine, also known as a ballast cleaner, can rehabilitate the ballast with a recycling rate of up to 100% (Eurailpool n.d.). The type of cleaner shown in this picture, the PM1000 URM is used in Dutch rail maintenance works by the company Swietelsky (Swietelsky 2019).

The average lifetime of all railway infrastructures (when multiplying the average age of each construction with the weight share for each rail transport mode) is estimated in this study at 47 years (46.7 years to be precise). This estimation is based on rough assumptions, therefore sensitivity analyses with much shorter and much longer average lifetimes were carried out in the discussion chapter to check the robustness of the results. The average lifetime 46.7 years was calculated by multiplying the stock weight share of the objects with their corresponding average lifetime estimates that were given in the LCAs from ProRail and in the literature. These estimates are given below:

From LCAs for ProRail:

Rails, concrete railroad ties & switches:	45 years
Aggregates (ballast):	35 years
Switch heaters:	15 years
Noise barriers & fences:	50 years
Superstructure power supply (overhead wires, poles, foundations):	50 years

The missing lifetimes were collected from Schmied et al. (2013) for the case of Germany:

Tunnels & bridges	60 years
Infrastructure cables	30 years
Station buildings (platforms, roofs)	60 years

Lifetime Distribution Choice

The distribution of the lifespans of railway infrastructure objects is not known. Like the average lifetime of the stock, the lifetime distribution choice has to be made with crude estimations that are not specified for the rail sector. There is no standard of probability distributions for modeling the accumulation of built infrastructure material stock (Miatto et al. 2017). Railway infrastructure planning is a top-down steered process. A fixed lifespan could be used that assumes that the stock flows out of the system as soon as the mean of that specific age cohort is reached. However, this would not fit in the context of railways, since many stocks remain in use much longer than the calculated end of their service life. Hence, a distribution should be used that includes these stocks as well. Since the skewness of the distribution of lifespans in railway infrastructure objects is not known and a cohort-based dataset on the lifespans is missing, a normal distribution was utilized, following the research method of other construction material stock analyses (Müller 2006; Fishman et al. 2014).

In this thesis research, a normal distribution was assumed with the calculated mean lifetime of 46.7 years (based on LCA data from ProRail) while the standard deviation was set at 30% of the mean. This assumption on the standard deviation was adopted from studies on other long living stock estimations such as the building stock in The Netherlands (Müller 2006, low scenario), China (Hu et al. 2010) and Chinese steel cycle (Pauliuk et al. 2012). A national stock accounting for the US and Japan, that includes transport infrastructure, assumes that the standard deviation is ⅓ of the mean for the material groups timber, iron, other metals and nonmetallic minerals (Fishman et al. 2014 Table 1). *Figure 23* shows the distribution of the stock with the standard deviation (σ) of 30% of the mean (μ) marked in blue. It shows a much less concentrated distribution than if a smaller standard deviation of ⅙ of the mean would have been chosen (represented by the orange line).

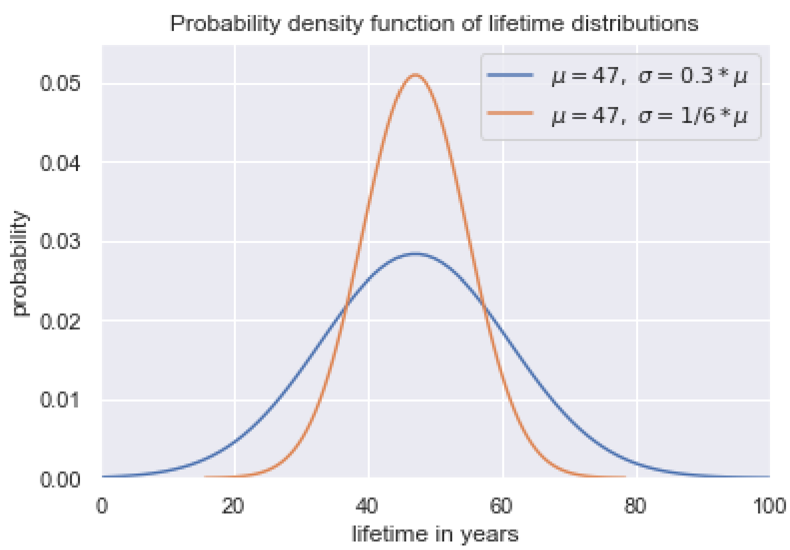


Figure 23: Probability density functions for normal distributions with average stock lifetimes of 47 years and a standard deviation of 30% of the mean (blue line) or ⅙ of the mean (orange line).

Right-skewed distributions such as Weibull, Log-normal or Gamma were not used for sensitivity, because the skewness of the data is unknown. Furthermore, right-skewed distributions have proven to work better for short-lived constructions, such as the building stock in Asian cities (Miatto et al. 2017). An example of these short-lived constructions is the building stock in the Japanese city of Wakayama that has an average lifespan of less than 30 years (Tanikawa and Hashimoto 2009). For long-lived constructions like railway infrastructure, the normal distribution is assumed to offer a proper fitted probability density function.

3) Material Intensities

Material intensities are determined by material compositions per unit of length. For example, more or less tons of a material per meter can be reached by means of a changed material composition or material reduction resulting from technological developments or change in use. Furthermore, material intensities can change when economic variables, such as costs of alternative materials, make a transition to less or different materials feasible.

Despite the projected growth of rail freight under the WLO scenarios, freight transport was not included in the modeling step, as freight transport makes up only 7% of the total rail transport (CBS 2009) and the assumption that foreseen bottlenecks until 2040 can be solved by rerouting the cargo trains (Ministerie van I&M 2017).

4. Results

This chapter starts with an application of transition theory to the rail infrastructure case study. The chapter continues with the results of an estimation of the total material stock, its spatial distribution and its historical development. Finally, the results of the dynamic analysis until 2050 are interpreted, which are based on the transition pathways specified at the beginning of this chapter.

4.1 Specifying the Multi-level Perspective and the Transition Pathways

The transition towards circular material use in the railway infrastructure sector in The Netherlands is brought into practice by key actors who have their own view and stance on the transition that can be categorized in a multi-level perspective. This part of the results chapter characterizes the main actors for each societal realm for this case study. Thereafter, the levels of the multi-level perspective in the context of railway infrastructure are set out. Subsequently, the potential trajectories of change are drawn by specifying the transition pathways for Dutch railway infrastructure.

The division of actors over societal realms for this case study are:

- State: the Ministry of Infrastructure and Water Management for the national policy strategy, ProRail being the national network operator that falls directly under the Ministry of Infrastructure and Water Management[1], metropolitan areas (multi-municipality administrative divisions) and municipalities to set circular policies for regional rail infrastructure such as metro, light rail and tram systems;
- Market: privatized rail operators that use the network such as NS, Arriva, GVB, RET, HTM and U-OV, rail material suppliers such as Voestalpine RailPro, rail contractors like Strukton Rail, travelers that demand mobility via the network infrastructure;
- Civil society: social movements, political parties to address topics of public concern, non-governmental organizations such as travelers' association Rover;
- Science: academic research supporting socio-technical niche innovations for material use in the Dutch rail sector.

[1] ProRail is a 100% subsidiary of Railinfratrust BV, of which the state holds 100% of the shares. In February 2020, the Dutch national government announced that ProRail will become an independent administrative body in 2021, thereby reversing the privatization (Rijksoverheid 2020a).

Regarding the multi-level perspective, the following levels are understood for the landscape, regime and niche-innovations for the case on railway infrastructure in The Netherlands.

The landscape level is set at mobility in The Netherlands. The mobility landscape shapes the exogenous context of the rail infrastructure sector. By rules such as laws, policies or simply cultural norms and values, the mobility landscape is shaped and maintained. Actors are not defined in the MLP for the landscape level, and whether actors play a role at the landscape level is therefore subject of academic discussion (Fischer and Newig 2016). Instead of actors, the landscape *factors* shape the background, the exogenous context as a set of ecological, economic and cultural conditions, for the regime and the niche levels. In this case study, examples of landscape factors are global resource depletion, climate change and the COVID-19 crisis that caused a specific shock at the landscape level. These exogenous factors influence the rules in the landscape of mobility in The Netherlands. The first two factors trigger a norm change and the making of policies that strive for circularity and sustainability in the Dutch mobility landscape. The COVID-19 crisis has changed the demand for mobility: the railway infrastructure regime has been destabilized by a changed cultural norm in the landscape to avoid public transport to minimize virus infections during a pandemic. On the other hand, a changing landscape for more low-carbon mobility options can help to stabilize the regime.

The regime level is defined as the railway infrastructure sector. More specifically, this level consists of three regimes: the train (national), light rail (regional) and metro/tram (regional/local) regime. This distinction was made, because the dominant actors of each regime are governments that are limited to a geospatial location and because the regimes show a certain level of mutual rivalry. For example, in recent years, national railway lines have been converted to competing regional light rail routes. Furthermore, metro and tram routes are transformed into light rail networks with a regional rather than a local function at a single municipality level. Together with market parties, such as rail operators, material suppliers and rail contractors, the governments have to design their rail infrastructure in such a way that it fits within the mobility landscape. A shared practice from the regimes to transition towards a more circular industry is to extend the planned lifespan of the rail objects, with support from developments at the niche level. For example, the rail infrastructure sector can adopt niche-innovations that help them to implement their circular economy policy objectives.

The niche-innovations level entails a set of socio-technical innovations and the niche-actors that can reduce the material demand within the rail sector. The innovations are not solely based on technological advancement, but also on social improvements. For instance, a social innovation can be a changed lifestyle with minimized rail travel kilometers by working from home. This may lead to a more sustainable use of railway infrastructure. Scientists, and the market work on individual technologies that reduce the material intensities in new rail infrastructure, often supported with state fundings. For instance, ICT innovations to offer Mobility as a Service (MaaS) as a door-to-door multi-modal mobility service (usually combined with rail) is promoted as a grassroots opportunity for the private-sector by the European Union. Pangbourne et al. (2020) stress the occurrence of data monetization and social exclusion due to privatization when MaaS is adopted without government steering.

The influence that levels have on each other is as follows. The exogenous context from the mobility landscape influences the railway infrastructure regime. Usually the pace of this change is slow, for example on regulations regarding CE policies. Sometimes, for instance during the coronavirus crisis, changed mobility norms in the landscape suddenly pressurize the steady state in the dominant regime. The regime also experiences endogenous renewal in response to perceived pressures, for instance by changing internal policies on circularity. Novelties on material use at the niche level impact the rail infrastructure regime, too. For example, as soon as MaaS innovations reach a certain level of maturity, their technologies may be adopted by rail infrastructure regimes or may completely change the dominant regimes. This is the case if private MaaS suppliers find ways to provide faster, cheaper and more efficient ways of transport than rail.

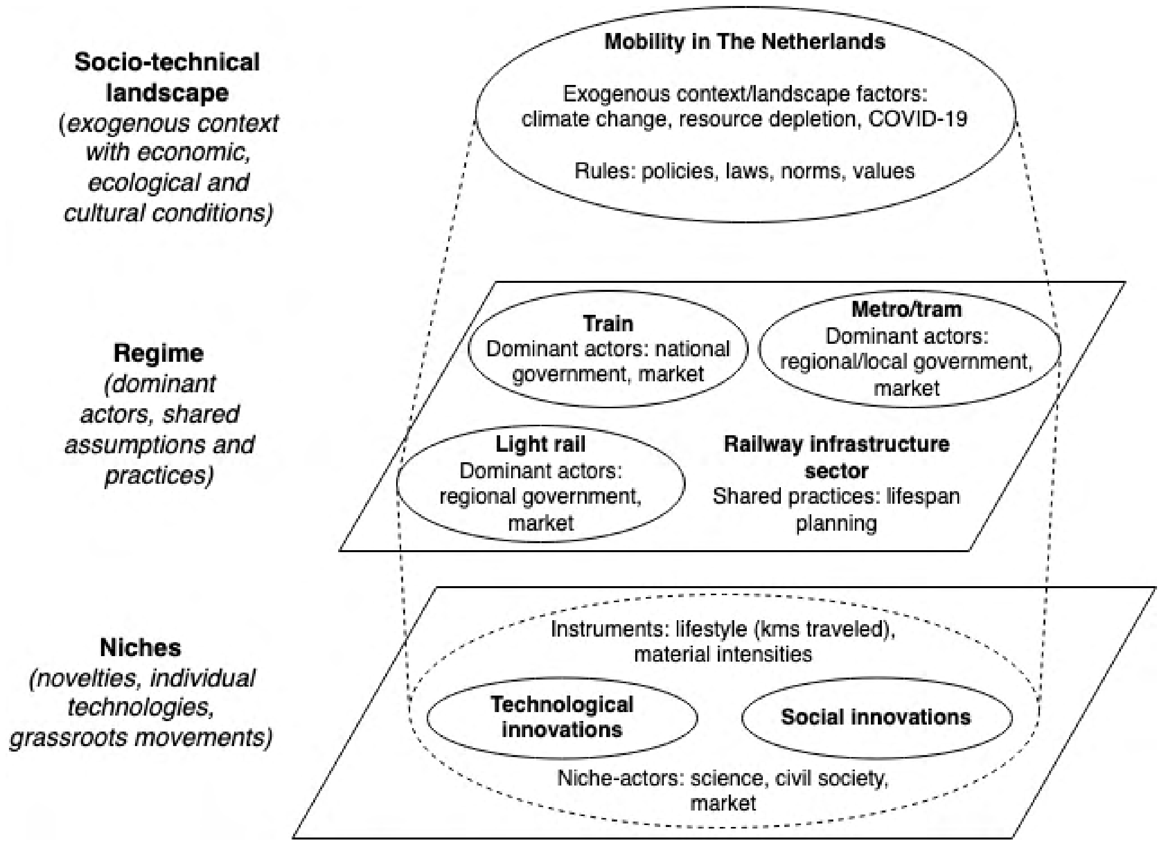


Figure 24: Interpretation of the multi-level perspective for railway infrastructure.

The four transition pathways by Geels and Schot (2007) are now used for the dynamic modelling of this study, extended by a reference pathway that is called 'Stagnation', following the example in the thesis of Van der Zaag (2020). The name 'stagnation' was used, because this pathway assumes a stagnating (even slightly declining) population in The Netherlands from the WLO Low scenario. For quantitative modeling, mid- and endpoints were attached to the transition pathways as a 'reference future' (van der Zaag 2020). These mid- and endpoints are assumptions that are based on circular economy policies and publications on future rail scenarios in The Netherlands. The pathways function as a means to show the potential of railway material developments in relation to the mobility sector as a whole.

Each pathway has its own storyline with specific level conditions. The storylines for the prospective analysis were based on circularity goals, such as changes in material use, and lifestyle changes, such as passenger kilometers traveled. Consequently, the driving forces have been added to the transition pathways, connecting to mid- or endpoints in the model. The midpoint reference was set at 2030 and the endpoint at 2050. This parallels the time frame of the Dutch circular economy policies (Rijksoverheid 2016; Ministerie van I&W 2020).

In the next part of the report, each pathway is discussed with its corresponding interactions between key actors and assumptions for railways and mid- and endpoints.

Transition Pathway 1: Stagnation (reference)

The reference pathway is based on a stagnating growth of the rail track length. For 2030, it is assumed that all already budgeted and planned rail extensions in the MIRT (see *Chapter 2*) will be built. After 2030, the WLO Low scenario from the Dutch Environmental Assessment Agency was used, with limited economic growth and climate policies, slow technological developments and limited urbanization (PBL 2015). The WLO Low scenario assumes a stabilized and in some cases even slightly lower number of rail passenger kilometers in 2050 for train rail and 2040 for the other rail modes compared to 2030. It is therefore assumed that the train infrastructure will not face big changes after 2030. The current maintenance and construction strategies are extrapolated, which will leave the lifespan and the material intensities for the objects unchanged for this scenario.

Key interactions

The main co-evolving actors are the state and the market, since the WLO mobility scenarios are hypothetical extrapolations of market developments that force governments to accommodate their policies to these changes. The government is seen as an important contributor to reach the climate policies and keep mobility affordable under the WLO scenarios (PBL 2015). In this pathway, it is expected that in civil society, no specific topics of public concern are addressed regarding the rail infrastructure and that science and technology do not provide niche innovations that are adopted by the regimes.

Assumptions

Since the stagnation pathway is based on the WLO Low scenario, similar assumptions are taken into account. The WLO Low scenario presumes that compared to 2010, travel kilometers will have increased by 26% for train passengers, mainly due to improvements in the train frequencies (the high-frequency train program that should lead to 1 intercity train per 10 minutes in 2030). In 2050, train passenger kilometers traveled will still be 20% higher than in 2010, but stagnates compared to the number of rail passenger kilometers in 2030.

In short, the Stagnation Pathway translates to the following assumptions:

Transition pathways and their characteristics	Assumptions per driving force	Midpoint (2030)	Endpoint (2050)
Stagnation (reference)	1) use according to WLO Low scenario 2) lifespan: unchanged 3) material intensities: unchanged	All planned expansions up to 2030 have been carried out	*From the WLO Low scenario:* index: 2010=100 Train pkm: 120 Tram: 115* Metro: 153* *endpoint = 2040

Transition Pathway 2: Reconfiguration

The reconfiguration pathway's main actors are the regime actors themselves and their suppliers (Geels and Schot 2007). Niche developments in the reconfiguration pathways have sufficiently developed and the process of change is moderate and slow, because it is a process of symbiotic adoption (Geels and Schot 2010), where old and new suppliers are likely to compete (Geels and Schot 2007). The regime actors get involved in the change process and survive by adopting component-innovations. These innovations could be developed by new suppliers, which triggers competition between old and new suppliers.

The national network operator ProRail has already committed to a structure of change. In the report "Naar klimaatneutrale en circulaire rijksinfrastructuurprojecten" ("Towards climate neutral and circular national infrastructure projects") (Ministerie van I&W 2020), specific transition approaches are mentioned for ProRail that are connected to quantifiable goals. These measures have been modeled in the reconfiguration pathway, as it is assumed that the measures will not evoke a shift in the architecture of the regime, but will reconfigure the system with controlled and planned changes. The assumptions for this typology are based on the proposed measures by the Ministry of Infrastructure and Water Management, as given in *Table 5* and explained in §3.5.1.

The four directives issued by this ministry use niches that are at a different stage of development. The first directive includes measures on superstructures that use a combination of carefully tested novel techniques, (e.g. wheel-rail conditioning and mobile rails cutting), and niches that are still in their infancy, such as reuse of rails and cementless concrete.

Material use for energy supply can easily be reduced by increasing the voltage of the network, which is already common in other European countries. At the same time, the energy supply directive leaves room for undeveloped niches, such as rolling pantographs.

The engineering structures and other materials that are part of the fourth and last directive only use established techniques, such as tunneling and more noise barriers, that increase the material demand rather than limit it.

Key interactions

The main interactions are between the state and the market. The market represents the businesses that collaborate with the government to achieve the circularity goals for 2050. This interaction is explicitly mentioned in the route map for circular state infrastructure projects (Ministerie van I&W 2020). The national government and regional governments are central steering actors in the regime that, in accordance with the Dutch Climate Accord, should collaborate more to influence sustainable procurement for climate neutral and circular state infrastructure projects (Ministerie van I&W 2020). For this co-evolution process, collaboration with scientists is required who develop techniques for more efficient material use. Involvement of actors from civil society is not mentioned in the policy report on circular national infrastructure projects (Ministerie van I&W 2020).

Assumptions

This pathway assumes that all projects proposed in the policy report on circular national infrastructure projects will be carried out. Therefore, the mid- and endpoints are an translation of the existing directives, which are set at a 5% larger rail infrastructure network in 2030 than in 2020 and a 20% longer lifetime of rails due to wheel-rail conditioning, 20% more noise barriers, 50% of level crossings replaced by tunnels and a 100% electric 3kV rail network in 2050 (Ministerie van I&W 2020). The Ministry of Infrastructure and Water Management assumes a growth of 30% of passenger rail kilometers in 2030 and in general 30-40% train passenger kilometer growth for the future (Ministerie van I&W 2020), which parallels with the WLO High scenario.

In short, the Reconfiguration Pathway translates to the following assumptions:

Transition pathways and their characteristics	Assumptions per driving force	Midpoint (2030)	Endpoint (2050)
Reconfiguration *Characteristics: niches sufficiently developed, moderate and slow change*	1) use according to WLO High scenario 2) lifespan: 20% longer for rails 3) material intensities: unchanged	All planned expansions up to 2030 have been carried out *From Ministerie van I&W (2020):* 5% larger train network than 2020	*From Ministerie van I&W (2020):* +20% lifetime of rails +20% noise barriers 50% of level crossings replaced by tunnels 100% electric 3kV

Transition Pathway 3: Transformation

What if the lifetime of constructions and tracks could be extended by even more than 20%? For example, lifespans could be increased more due to novel technologies that are yet unknown or as a result of pressure outside the regime. This pathway explores an extension of the policy goal of 20% lifespan extension in 2050 to the more ambitious goal of 30%.

Extreme refurbishment and extending lifetimes are part of the transformation pathway, because they are matured innovations that largely depend on outside pressure. Institutional power struggles and negotiations are keywords in transformational processes (Geels and Schot 2007). For example, institutional power struggles with higher institutions such as EU commitments could force regime actors to change. Furthermore, the innovations have not been sufficiently developed and therefore the process of change is moderate and slow.

In 2019, 30% of the journeys at the biggest passenger rail carrier in The Netherlands, NS, were work related (NS 2019). Travel avoidance can lead to 15% less travelers in the whole transport sector if half of the work related movements are substituted with working from home. It is assumed that this leads to less overcrowded routes, but no suspension of railway lines as most commuters travel during peak hours that cause the bottlenecks. Therefore, the WLO Low scenario for rail passenger kilometers is adopted for this pathway, that assumes a stagnation of the passenger kilometers.

Key interactions

This transition pathway is shaped by continuous pressure from outside the regime. For this reason, the most important co-evolving development is represented by the state and civil society, which can be understood as civilians that put pressure on the government to stick to their climate and circularity goals. Lifespan extensions can also be implemented from market and state co-evolutions. For instance, the novel wheel-rail conditioning and advanced rail cutting techniques to extend the lifespan of the rail tracks were initiated by ProRail and the rail operators in collaboration with Strukton Rail (Strukton Rail 2019a).

Assumptions

It is assumed that reverse supply chains are set up and that the lifetime of the constructions is extended by reuse or refurbishment. One of the ways to reuse rails is to not cut them in smaller parts when old rails are renewed on site and transported. Used rails from heavily traveled sections of track can be refurbished and replaced to quieter routes (Voestalpine

Railpro 2018). By further improving the existing techniques to elongate the lifetime of rail tracks as given in the Reconfiguration Pathway and refurbishing rail tracks, it is assumed that the lifetime of the rails can be improved by 30%. This number is a more extreme variant of the policy measures proposed in the Reconfiguration Pathway. It is researched in this pathway what the material effects of long-lived rail infrastructure are, by changing the policy target from 20% to a 30% longer lifespan.

In short, the Transformation Pathway translates to the following assumptions:

Transition pathways and their characteristics	Assumptions per driving force	Midpoint (2030)	Endpoint (2050)
Transformation *Characteristics: niches not sufficiently developed, moderate and slow change* Reverse supply chains and extended lifetime of the constructions by reuse or refurbishment. Transformation through pressure outside regime	1) use according to WLO Low scenario 2) lifespan: 30% longer for rails 3) material intensities: unchanged	All planned expansions up to 2030 have been carried out	Travel avoidance due to working from home = WLO Low 30% longer lifespan of rail tracks

Transition Pathway 4: De- and Realignment

An avalanche of different measures is assumed in this pathway that is based on inputs by new niche-actors. New actors implement modular designs that have a minimal virgin material input (circular design) and lead to more effective use of the infrastructure (prevent wear & tear), better maintenance and recycling. Multiple novelties from those new actors start competing, but eventually one novelty wins (Geels and Schot 2007) and causes a large and sudden landscape change.

For example, copper might be replaced by a cheaper conducting material (that is not known yet), ballastless tracks will set a new standard or concrete use can be drastically limited when more precise and efficient construction techniques will be invented. These smart material solutions can lead to a large and sudden regime change in the railway infrastructure industry, but the innovations are currently not sufficiently developed. These solutions will lead to lower material intensities flowing into the infrastructure system. Since it is not clear which material limiting techniques will set the standard, it is assumed that all inflowing material in this pathway will have a 20% lower material intensity from 2021 onwards. The percentage of 20% was used, because it was based on the assumption that primary material inflows can be replaced by secondary (reused or recycled) material inflows in ecodesign. This assumption is further discussed in §4.7 on potential circular applications of the material flows. This pathway shows a clear link to the circular economy goals of the Dutch government and assumes a net decrease in material consumption for rail infrastructure.

At the niche level of the transport sector, niche innovations will start to put pressure on the rail transport regime in this pathway of de- and realignment. Even though the niches are not sufficiently developed at the moment, such as a hyperloop that replaces long-distance rail journeys, the regime change can be large and sudden. For instance, the planning and construction of a hyperloop can take a long time, but will suddenly replace train journeys when operation becomes cheaper. However, the effects of material demand for hyperloop constructions will probably be considerable. The concrete weight of 150 km hyperloop tube (roughly the distance from Amsterdam to the Belgian border near Antwerp via Rotterdam, following the high speed rail trajectory) will be approximately 3 Mton[2].

Key interactions

The main co-evolving actors are the market and science, as the development and affordability of the niches largely depend on this interaction. The requirements for the lifespans and material intensities are designed by the state. This De- and Realignment Pathway follows a circular policy that is more ambitious than the current policy goals. This could be manifested in this way through pressure from civil society to transition faster.

The assumptions and key interactions lead to the following three endpoints in 2050. Firstly, because of assuming the WLO High scenario, the increased urban density and growth in passenger rail kilometers, the network is expected to expand following the logarithmic trendline to a total length of 9215.6 kilometers. This is 12% longer than in 2019. Secondly, better reuse, maintenance and committing to circular design policies results in a 25% longer lifespan of railway tracks compared to 2020. This number was chosen as a middle ground between the Reconfiguration Pathway with a lifespan of 20% and the Transformation Pathway with a lifespan extension of 30%. Thirdly, material intensities will be 20% lower as a consequence of the novel material efficiency solutions that require less material weight.

[2] Considering the data for concrete hyperloop tubes by (Rana 2020, 29):
$2*\pi*(2.75/2)^2 - 2*\pi*(2.55/2)^2 = 1.67\ m^2$ and 1/1.67 gives 0.6 meters of tube length equaling 2900 kg of concrete. Thus: 150000 m / 0.6 m * 2900 kg = 0.73 Megaton concrete
12 meter concrete pylons per 20 meters = 7500 pylons with a total length of 7500* 12 = 90 km and a diameter of 2.3 meters
$2*\pi*(2.3/2)^2 * 90000 * 2900$ kg = 2.17 Megaton for the pylons + 0.73 for the tubes = 2.9 Mton concrete required.

In short, the De- and Realignment Pathway translates to the following assumptions:

Transition pathways and their characteristics	Assumptions per driving force	Midpoint (2030)	Endpoint (2050)
De- and Realignment *Characteristics: niches not sufficiently developed, large and sudden change* More effective use of the infrastructure (prevent wear & tear), better maintenance and recycling New materials	1) use according to WLO High scenario 2) lifespan: 25% longer for rails 3) material intensities: -20%	All planned expansions up to 2030 have been carried out	+20% of long distance train journey kms replaced by e.g. hyperloop = WLO High as the long distance share in NL is low • 25% longer lifespan of rails • 20% material intensities

Transition Pathway 5: Technological substitution

What will happen if a lot more or less will be traveled by rail? A change in modal split can be created by large and sudden events, such as wildcard events. As has become clear during the COVID-19 pandemic, work related travel movements can be substituted by working from home. But on the other hand, more than 80% of Dutch passenger journeys are more than 15 kilometers, so a modal shift from cars to public rail transport is expected to lead to better results than a shift from cycling or walking to public transport (CE Delft 2018). This pathway is divided into two sub-pathways called Technological Substitution High, leading to very high rail use, and Technological Substitution Low, leading to a lower rail use in the future.

In 2019, train journeys had a 14% share of the work related travel kilometers. The average commuting distance by train was 41.2 km per journey. In the same year, the average cyclist covered a distance of 4.9 km for work related traveling. In total, bikes had a share of 7% of travel kilometers to work (CBS 2020a).

Key interactions

The main co-evolving actors in the Technological Substitution Low pathway are the market interacting with civil society. A pandemic such as COVID-19 is used as a starting point, leading to less public transport travelers, who fear viral spread in shared transport modes. On the other hand, the push to make more rail journeys in the Technological Substitution High pathway is expected to be caused by a co-evolution of the market and state, who will stimulate civilians by policies, regulations and expanded rail networks to travel by rail transportation modes.

Assumption: modal shift

Unlike the categorization of modal shift under the transformation typology by Van der Zaag (2020) that assumes a slow shift with underdeveloped niches, this thesis assumes that a shift of transport mode belongs to the technological substitution pathway, as traveler preferences can change suddenly due to good availability of alternatives. Rail travelers can switch easily to other developed niche innovations that are widely available and affordable, such as e-bikes or mopeds or pre-owned cars for longer distances.

Modal shifts are only part of the technological substitution pathway in this case study, since this is the only pathway that is entirely dedicated to passenger behavior. This pathway proposed three binary shifts: a shift from car use to train journeys, a replacement of short haul flights by improved high speed rail connections and a shift from short rail trips to e-bikes. Each binary shift is discussed below.

1. *Binary shift car/train*

   In 2017, more than 70% of Dutch passenger kilometers were traveled by car (see *Figure 25*). If only 13% of the car kilometers from 2017 were covered by train, the number of passenger kilometers by train would already double (CBS 2020b), which likely leads to expansions and increased maintenance of the rail infrastructure. This shift from cars to trains can be caused, for instance, by employers who suddenly decide to only pay travel cost allowances for public transport kilometers and stop leasing cars to their employees. This shift is part of the substitution pathway that leads to high rail use (presented as Technological Substitution High).

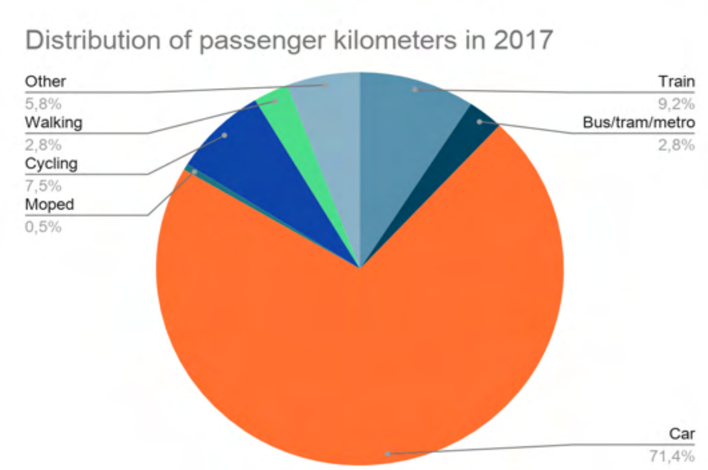


Figure 25: visualization of the passenger kilometer share in 2017 from CBS data (CBS 2020b).

2. *Binary shift aircraft/train*

   The International Energy Agency calculated that (newly built) high-speed rail lines can reduce flights on the same routes by up to 80% shortly after starting operations (International Energy Agency 2019a, 99). Also, travel avoidance by means of video calls and online conferences could lead to an entire replacement of short distance flights. This binary shift is part of the Technological Substitution High Pathway that prospects high rail use.

3. *Binary shift urban rail/e-bikes*

   In recent years, e-bike use has grown rapidly in The Netherlands. In 2019, 26% of bike kilometers were traveled with electric bikes compared to 12% in 2013 (KiM 2020a). National mobility capacity explorations in the National Market and Capacity Analysis (NMCA) assume that e-bikes will be among the passenger transport competitors with the largest effects on national mobility developments (ProRail 2017). The average distance traveled per transport mode in 2019 was almost 50 km for the train, 14.6 km for bus, tram and metro and about 4 km for all bike types (CBS 2020c). Since electric bike journeys can extend the length of an average bike trip, the Technological Substitution Low Pathway assumes that in 2050, all rail transport under 10 km will be replaced by e-bikes.

The Technological Substitution Low Pathway has the following mid- and endpoints. Due to the wildcard event of the COVID-19 outbreak, the rail travel demand dropped by 50% in 2020 compared to 2019. In the Technological Substitution Low Pathway it is assumed that this halving in passenger kilometers will remain constant from 2020 onwards. This is an extreme extrapolation of the modal shift that the COVID-19 pandemic has caused in public transport in 2020. As rail infrastructure systems tend to respond slowly to passenger kilometer changes, the first effects of this halving of the total rail passenger kilometers traveled are only visible after 2030. The endpoint in 2050 assumes that the reduction in rail kilometers has led to the suspension of routes. All short distance rail trips up to 10 km will be replaced by e-bikes. This impacts urban rail systems in particular.

In short, the Technological Substitution Low Pathway translates to the following assumptions:

Transition pathways and their characteristics	Assumptions per driving force	Midpoint (2030)	Endpoint (2050)
Technological Substitution Low *Characteristics: niches sufficiently developed, large and sudden change* Sudden change in modal split: what if a lot less will be traveled by rail? Binary shift urban rail/e-bike	1) use = -50% of 2019 2) lifespan: unchanged 3) material intensities: unchanged	All planned expansions up to 2030 have been carried out Wild card event: 50% less passenger kms from 2020 onwards	All short rail travel kms up to 10 km replaced by e-bikes. In total -50% rail passenger kms in 2050 compared to 2019

The Technological Substitution High Pathway has the following mid- and endpoints. A wild card event in the high rail use pathway assumes a sudden increase in rail travel of 100% compared to 2019 from 2030 onwards, hypothesizing that a combination of dramatically increased fuel prices and policies to reduce car travel force a modal shift towards rail transport. As a consequence of an improved pan-European high-speed rail network, all short haul flights up to 1500 km will be replaced by rail trips in 2050.

In short, the Technological Substitution High Pathway translates to the following assumptions:

Transition pathways and their characteristics	Assumptions per driving force	Midpoint (2030)	Endpoint (2050)
Technological Substitution High *Characteristics: niches sufficiently developed, large and sudden change* Sudden change in modal split: what if a lot more will be traveled by rail? Binary shift aircraft/train & car/train	1) use = +100% of 2019 2) lifespan: unchanged 3) material intensities: unchanged	All planned expansions up to 2030 have been carried out Wild card event: 100% more passenger kms compared to 2019	All short haul flight kms up to 1500 km replaced by train In total a doubling in passenger kms in 2050 compared to 2019

A summary of the assumptions per driving force for each pathway and their mid- and endpoints can be found in *Table 5*.

Transition pathways and their characteristics	Assumptions per driving force	Midpoint (2030)	Endpoint (2050)
Stagnation (reference)	1) use according to WLO Low scenario 2) lifespan: unchanged 3) material intensities: unchanged	All planned expansions up to 2030 have been carried out	*From the WLO Low scenario:* index: 2010=100 Train pkm: 120 Tram: 115* Metro: 153* *endpoint = 2040
Reconfiguration *Characteristics: niches sufficiently developed, moderate and slow change*	1) use according to WLO High scenario 2) lifespan: 20% longer for rails 3) material intensities: unchanged	All planned expansions up to 2030 have been carried out *From Ministerie van I&W (2020):* 5% larger train network than in 2020	*From Ministerie van I&W (2020):* +20% lifetime of rails +20% noise barriers 50% of level crossings replaced by tunnels 100% electric 3kV
Transformation *Characteristics: niches not sufficiently developed, moderate and slow change* Reverse supply chains and extended lifetime of the constructions by reuse or refurbishment. Transformation through pressure outside regime	1) use according to WLO Low scenario 2) lifespan: 30% longer for rails 3) material intensities: unchanged	All planned expansions up to 2030 have been carried out	Travel avoidance due to working from home = WLO Low 30% longer lifespan of rail tracks
De- and Realignment *Characteristics: niches not sufficiently developed, large and sudden change* More effective use of the infrastructure (prevent wear & tear), better maintenance and recycling New materials	1) use according to WLO High scenario 2) lifespan: 25% longer for rails 3) material intensities: -20%	All planned expansions up to 2030 have been carried out	+20% of long distance train journey kms replaced by e.g. hyperloop = WLO High as the long distance share in NL is low • 25% longer lifespan of rails • 20% material intensities
Technological Substitution Low *Characteristics: niches sufficiently developed, large and sudden change* Sudden change in modal split: what if a lot less will be traveled by rail? Binary shift urban rail/e-bike	1) use = -50% of 2019 2) lifespan: unchanged 3) material intensities: unchanged	All planned expansions up to 2030 have been carried out Wild card event: 50% less passenger kms from 2020 onwards	All short rail travel kms up to 10 km replaced by e-bikes. In total -50% rail passenger kms in 2050 compared to 2019
Technological Substitution High *Characteristics: niches sufficiently developed, large and sudden change* Sudden change in modal split: what if a lot more will be traveled by rail? Binary shift aircraft/train & car/train	1) use = +100% of 2019 2) lifespan: unchanged 3) material intensities: unchanged	All planned expansions up to 2030 have been carried out Wild card event: 100% more passenger kms compared to 2019	All short haul flight kms up to 1500 km replaced by train In total a doubling in passenger kms in 2050 compared to 2019

Table 5: summary of mid- and endpoints for each transition pathway and their main assumptions.

4.2 Estimation of the Total Material Stock

The total material stock of the railway infrastructure in The Netherlands is based on GIS data for train, tram, metro and light rail on tracks, ballast, platforms, electricity supply (overhead and underground cables), tunnels, bridges and stations. A full list of the included objects is given in *Appendix D*. The total stock was estimated for the base year 2018, the year of geodata of the track lengths that were used. The results of the estimation of the total stock can also be viewed in *Table 6* and in the excel workbook "Data_Material_Stocks_Rail_Infra_NL".

In 2018, the total railway infrastructure stock weight was 71.7Mton, which equals 4.15 ton stock weight per capita. The majority of the material stock weight consisted of nonmetallic mineral products such as concrete and ballast (aggregates). Concrete has the largest proportion of more than half of the stock weight (see *Figure 26a*) followed by ballast with almost 40%. Steel follows at a considerable distance with 4.5% of the stock weight. Copper accounts for .09% of the stock weight, timber and plastics both .06% and aluminium ends with the smallest share of .02%.

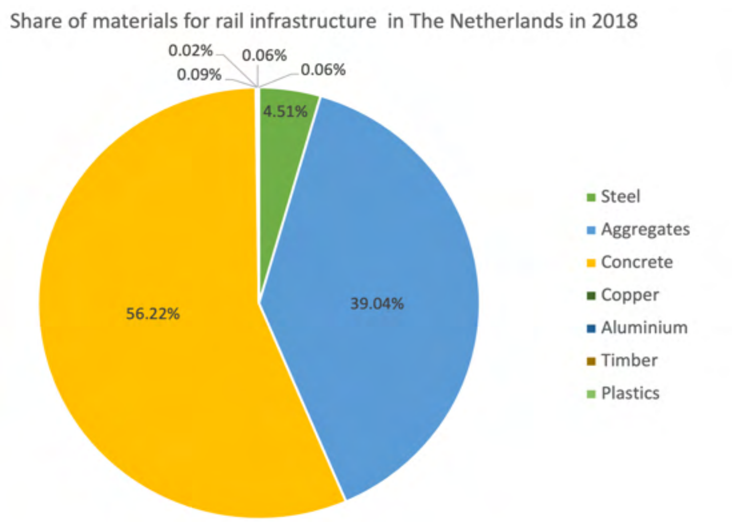


Figure 26a: material shares for the total rail infrastructure stock in The Netherlands in 2018.

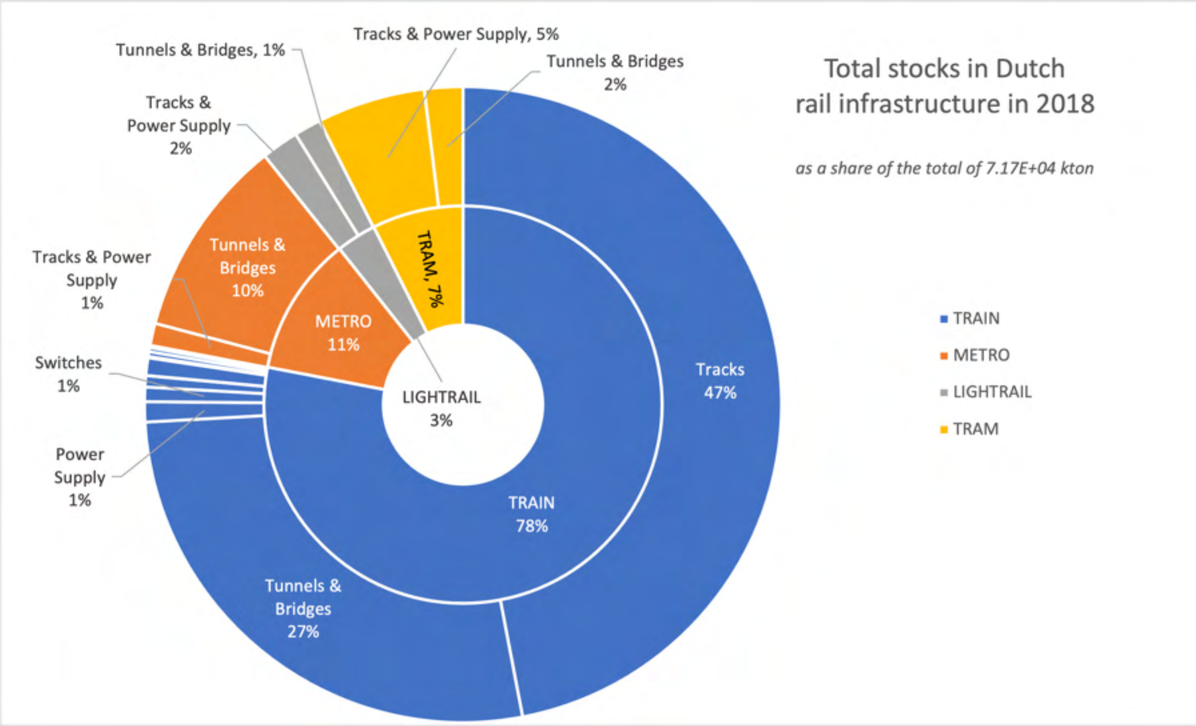


Figure 26b: total stocks in the rail infrastructure in 2018.

Sorted by object category, the tracks for train transport make up almost half of the total stock weight for all materials in the estimation (see *Figure 26b*). With a share of 47% and a relatively short lifespan of 37 years, rail tracks show the largest potential to limit material consumption in the future.

Tunnels & bridges for all modes make up 40% of the total stock weight but have a lifetime of at least 100 years. This means that the environmental impact of the construction and maintenance phase of the object's life cycle can be divided over a long period of time.

[kton]	Concrete	Aggregates	Steel	Copper	Timber	Aluminium	Plastics	*Total*
TRAIN	2.62E+04	2.69E+04	2.57E+03	5.11E+01	4.52E+01	1.08E+01	4.07E+01	*5.59E+04*
METRO	7.12E+03	5.52E+02	4.24E+02	1.30E+01	0.00E+00	1.79E+00	0.00E+00	*8.11E+03*
LIGHTRAIL	2.13E+03	1.18E+02	8.17E+01	3.02E-01	0.00E+00	4.58E-01	0.00E+00	*2.33E+03*
TRAM	4.08E+03	3.48E+02	1.53E+02	8.72E-01	0.00E+00	6.74E-01	0.00E+00	*5.30E+03*
Total	*4.03E+04*	*2.80E+04*	*3.23E+03*	*6.52E+01*	*4.52E+01*	*1.38E+01*	*4.07E+01*	*7.16E+04*

Table 6: stock results for various material categories in 2018 expressed in kilotons.

Table 6 depicts the share of the most used material categories in each part of the rail infrastructure sector. Train infrastructure accounts for the highest shares in all material categories. A visual representation of *Table 6* can be found in *Figure 27.* Note that the inset in the figure has different axis bounds, because concrete, aggregates and steel come in much bigger quantities than copper, timber, aluminium and plastics.

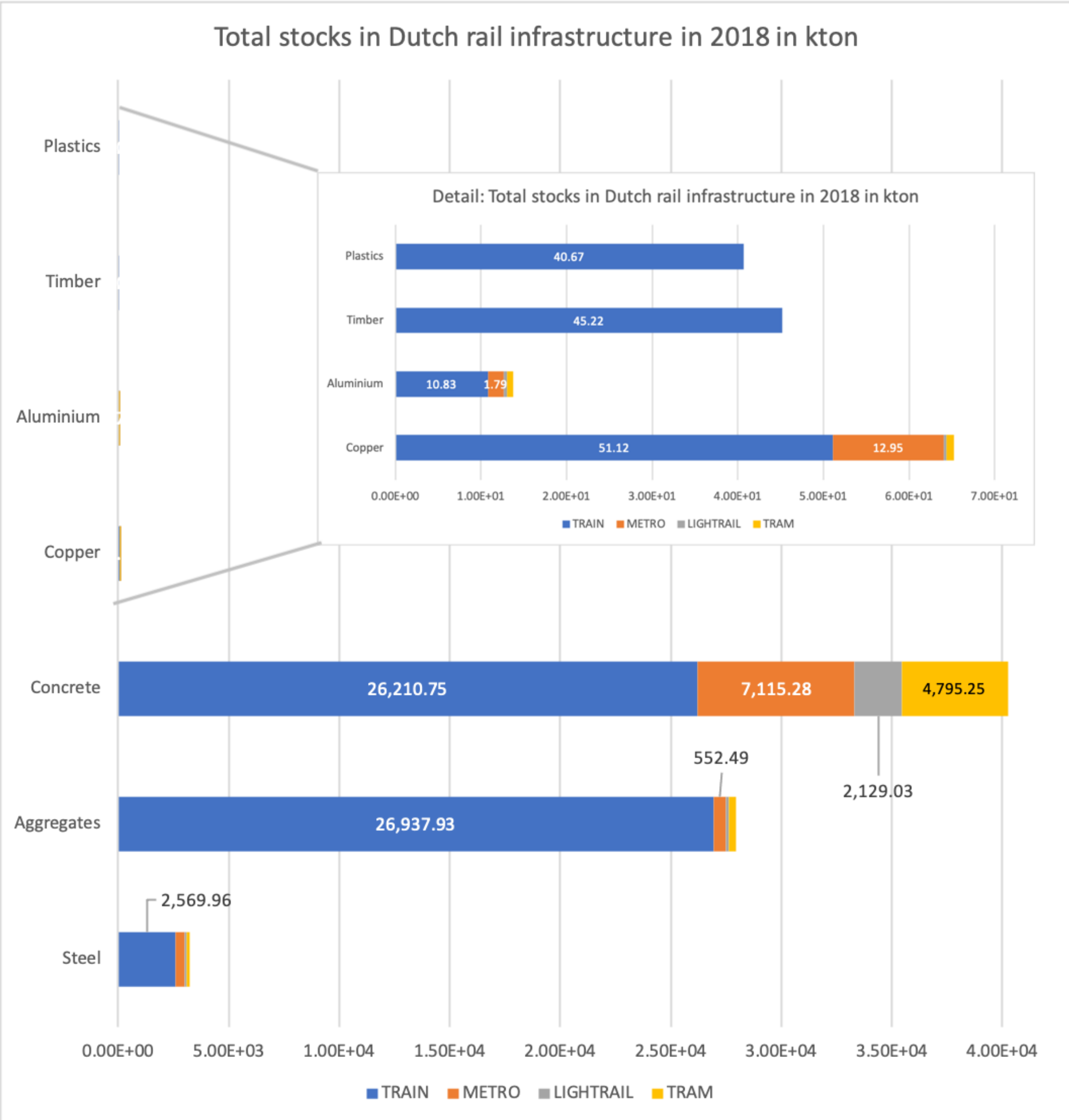


Figure 27: 2018 stock totals for material categories with big quantities: concrete, aggregates, steel and smaller quantities as depicted in the inset. Note that the inset shows a zoomed version with different axis bounds.

Based on the stock estimation results, the retrieved material intensities are given in *Table 7*. This table shows that metro lines are the most concrete and steel intensive per kilometer. This is due to the tunnels in metro systems and heavier tracks with a third rail. Also, most quantities of copper and aluminium are used per km of metro track. A reason for this is the high demand for cable infrastructure that metro systems have. Aggregates, timber and plastics use are highest per km of train track. In the MFA with material intensities for metro, light rail and tram infrastructure in Vienna, timber and plastics were not included (Gassner et al. 2020). It is therefore assumed that the timber and plastics stock in regional rail infrastructure is very small (set at 0 in this estimation). A full overview of material intensity per object in each transport mode is provided in *Appendix F*.

Material intensities per railway mode	**Concrete** kton/km	**Aggregates** kton/km	**Steel** kton/km	**Copper** kton/km	**Aluminium** kton/km	**Timber** kton/km	**Plastics** kton/km
train	3.55E+00	3.65E+00	3.48E-01	6.93E-03	1.47E-03	6.13E-03	5.51E-03
metro	3.26E+01	2.53E+00	1.94E+00	5.93E-02	8.19E-03	0.00E+00	0.00E+00
lightrail	9.62E+00	5.31E-01	3.69E-01	1.37E-03	2.07E-03	0.00E+00	0.00E+00
tram	7.51E+00	5.45E-01	2.39E-01	1.37E-03	1.06E-03	0.00E+00	0.00E+00

Table 7: material intensities for each transport mode.

The heaviest proportion of the total stock, concrete, has almost 70% of its weight from origins in tunnels and bridges (see *Figure 28*). Rail tracks follow with a share of 13%. Tram tracks show a remarkable concrete stock, as it is assumed that most tram tracks are cast-in-situ concrete constructions when used in street constructions. This equals the assumption of tram track types that was adopted from Gassner et al. (2020).

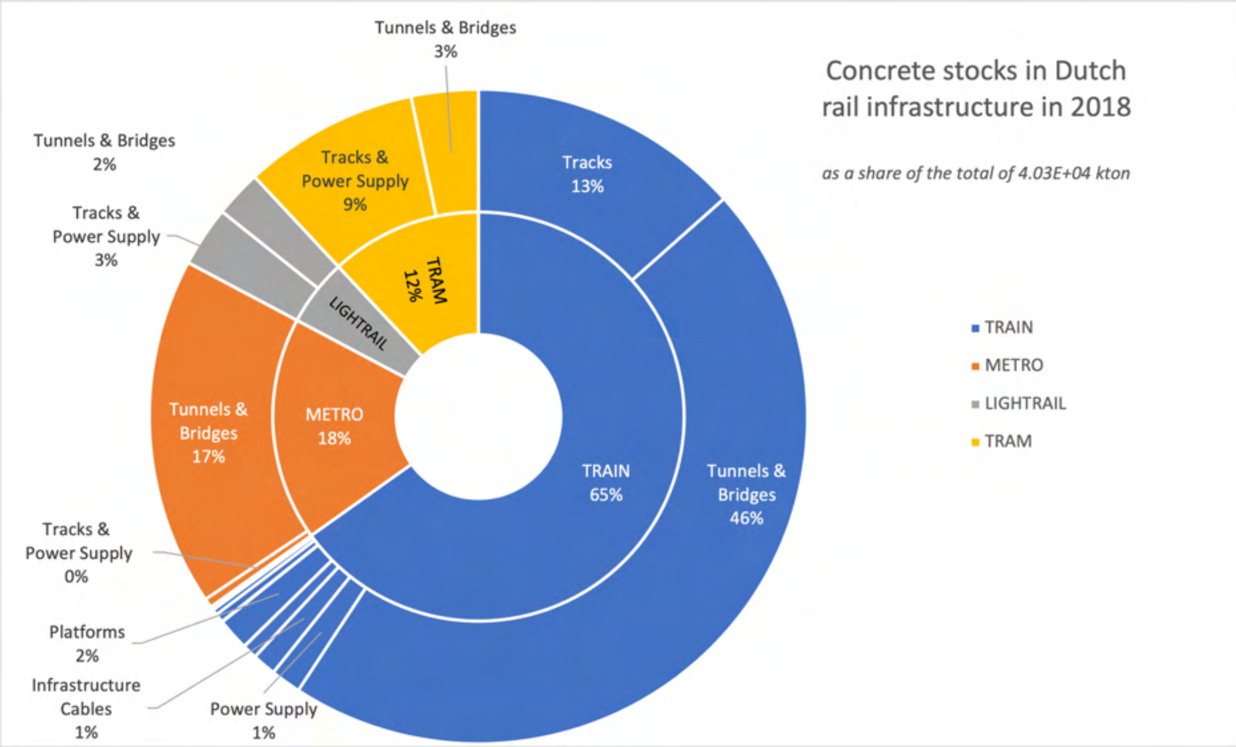


Figure 28: Concrete stock division over the different transport modes in 2018.

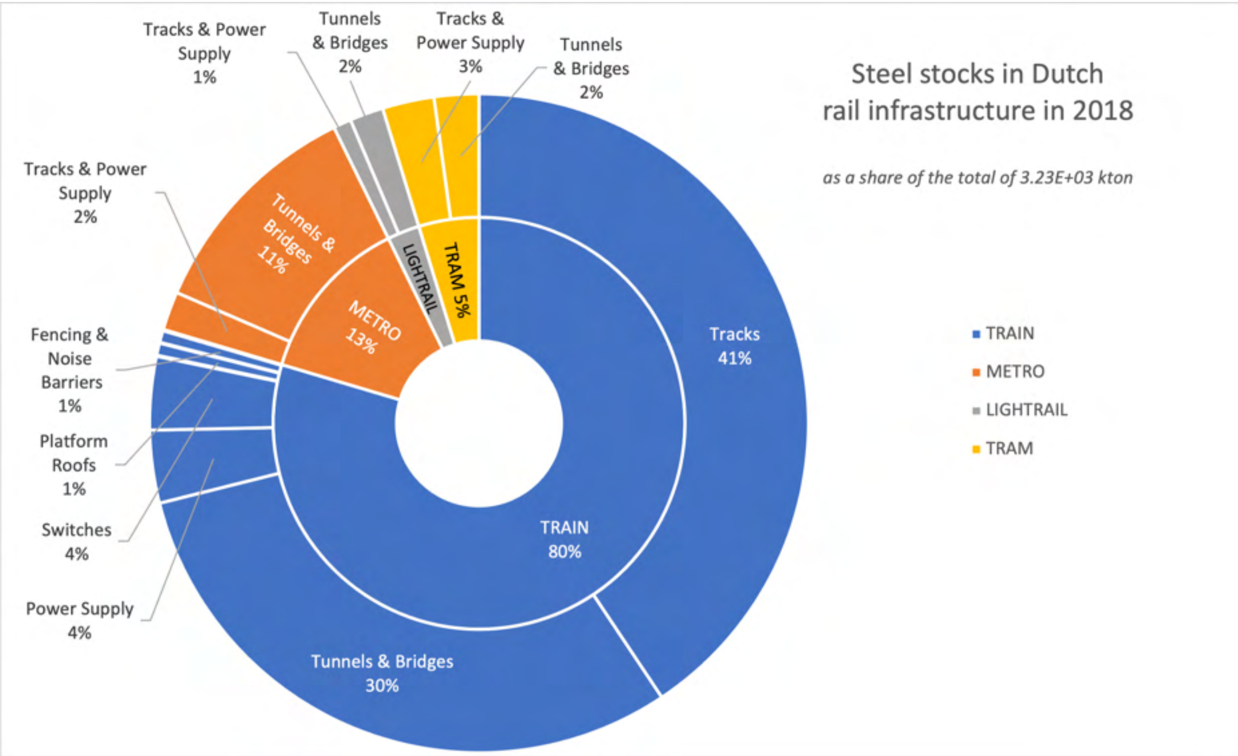


Figure 29: Hierarchic overview of the division of steel stocks in Dutch rail infrastructure in 2018.

Figure 29 shows that the largest steel stock is in the rail tracks of train infrastructure. Particularly in this stock, dissipation from weathering of rail tracks is common. Rail material Voestalpine Railpro has indicated that during its lifetime, about 4 to 6,5% of the steel rail bar content dissipates into the environment (personal conversation with Voestalpine Railpro, 27-10-2020). Compared to the stock size in 2018, this equals at least 53 kton of steel leaking to the environment over the complete life cycle of the rails. Since the average lifespan of steel rails was set at 45 years in LCA data from ProRail, it can be assumed that this dissipative flow of 53 kilotons is released over the entire train track system in The Netherlands over a time frame of 45 years if the stock size remains constant. This material loss was not included in the dynamic part of this MFA, but the environmental effects have been touched upon in the discussion.

A noteworthy – and potentially valuable – stock is the copper share in metro systems. The material intensity for subway systems were given by Lederer et al. (2016) and Gassner et al. (2020). Both publications use 0.12 ton copper per meter double track subway as a proxy, whereas Gassner also uses 0.0014 ton Cu/m for the double track tram network and the LCA data from ProRail give 0.0032 ton Cu/m in overhead wires on electrified train tracks.

Even though 0.12 ton Cu/m is a relatively high number, the authors argue that it is correct, since subway systems use a larger dimensioned traction power network (for handling peak loads of continuous braking and starting) and a denser cabling network for ventilation and lighting purposes. *Table 8* represents a specification of the copper stocks in subway systems.

Power System Categories	Tons per meter of double track subway line including stations
Traction power network	0.00686
Medium- and low voltage power network	0.08183
Signalling System	0.02990
Total	**0.11858**

Table 8: specification of copper stocks from the supporting information of Lederer et al. (2016).

The result can also be observed in *Figure 30*. The donut chart shows that almost 20% of Cu stocks are to be found in the superstructure and power supply system of subways. An advantage for mining copper as a secondary material from metro systems is that the cables are generally well mapped and accessible via the tunnels.

Note that infrastructure cables make up half of the entire copper stock, since about 9,500 km of cables are used to support the functioning of the train network. Every traction wire in train systems has almost doubled its mass amount in infrastructure cables. This makes sense, since multiple underground cables are required to make one track accessible for trains. These cables are used for communication and operation of the signals and the level crossings. Furthermore, the used copper intensity of the infrastructure cables from a study on German railways by the Öko Institut (Schmied et al. 2013) is relatively high with 3.46 t/km track compared to an average low or medium voltage cable with 1.2 and 1.08 t/km respectively (van Oorschot et al. 2020a). Underground cables for railway infrastructure are thus thicker than average electricity cables.

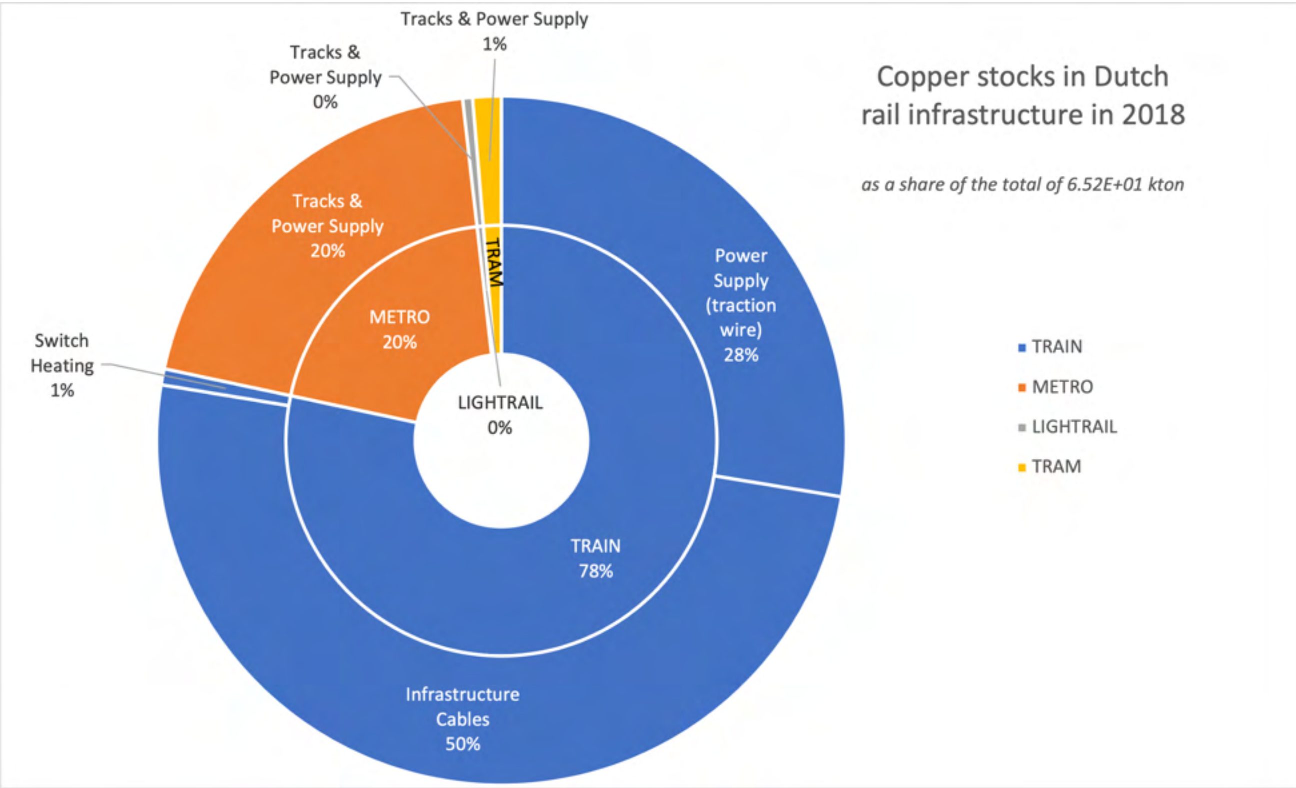


Figure 30: Hierarchic overview of the division of copper stocks in Dutch rail infrastructure in 2018.

The aluminium stock is the smallest of the researched material categories. Nevertheless, it shows interesting origins that have a high potential for reuse. The aluminium that is used for fencing and noise barriers mainly comes from aluminium cassettes. This type of noise barrier has a modular design (*Figure 31b*) that can easily be replaced. Reuse of aluminium can help avoiding high energy emissions and costs through resmelting the material (Cooper and Allwood 2012). The circularity potential of aluminium is further explored in §4.7.

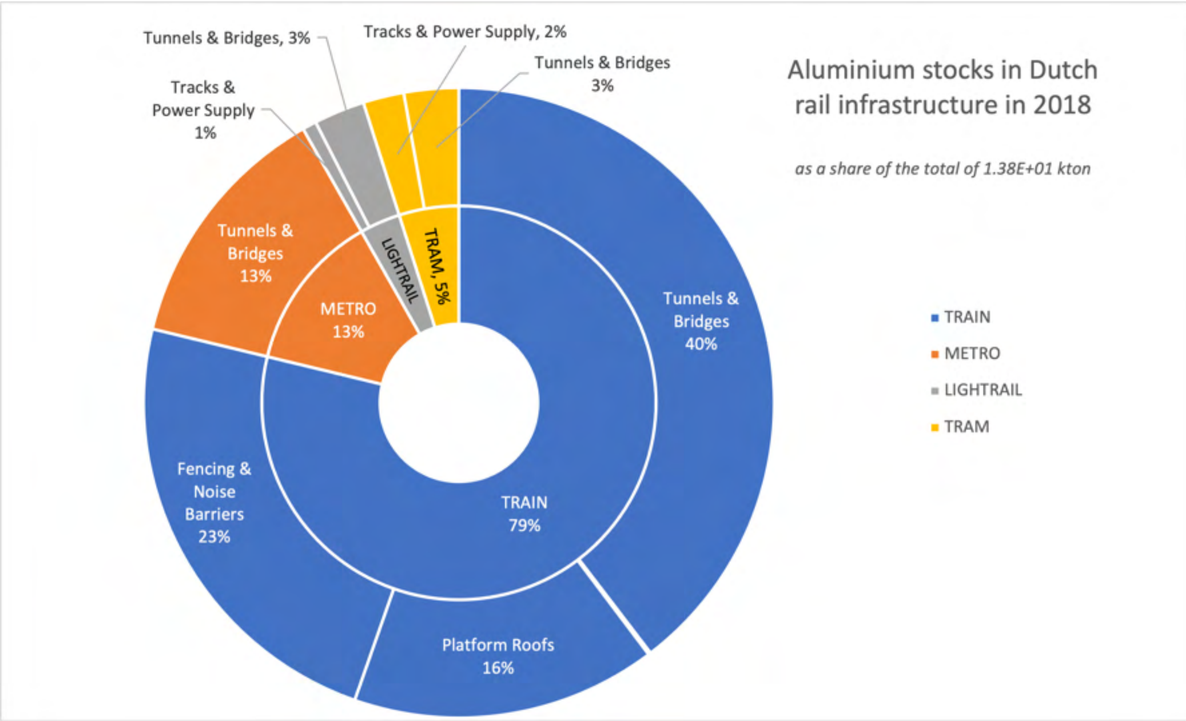


Figure 31a: Hierarchic overview of the division of aluminium stocks in Dutch rail infrastructure in 2018.

Figure 31b: aluminium cassettes have a modular design.

Hibernating Stock

The geodata that has been used for this thesis, also provided the lengths of unused rail tracks. It is assumed that these material stocks are hibernating in the system. This means that the stock is not used in the system anymore. The hibernating stock can be, if not brought into operation anymore and if feasible to reuse or recycle, used as a secondary material in new constructions. Compared to the weight of the total stock of rail infrastructure, 0,83% of this weight is unused material. In 2018, this equaled about 115 km of the rail tracks in The Netherlands.

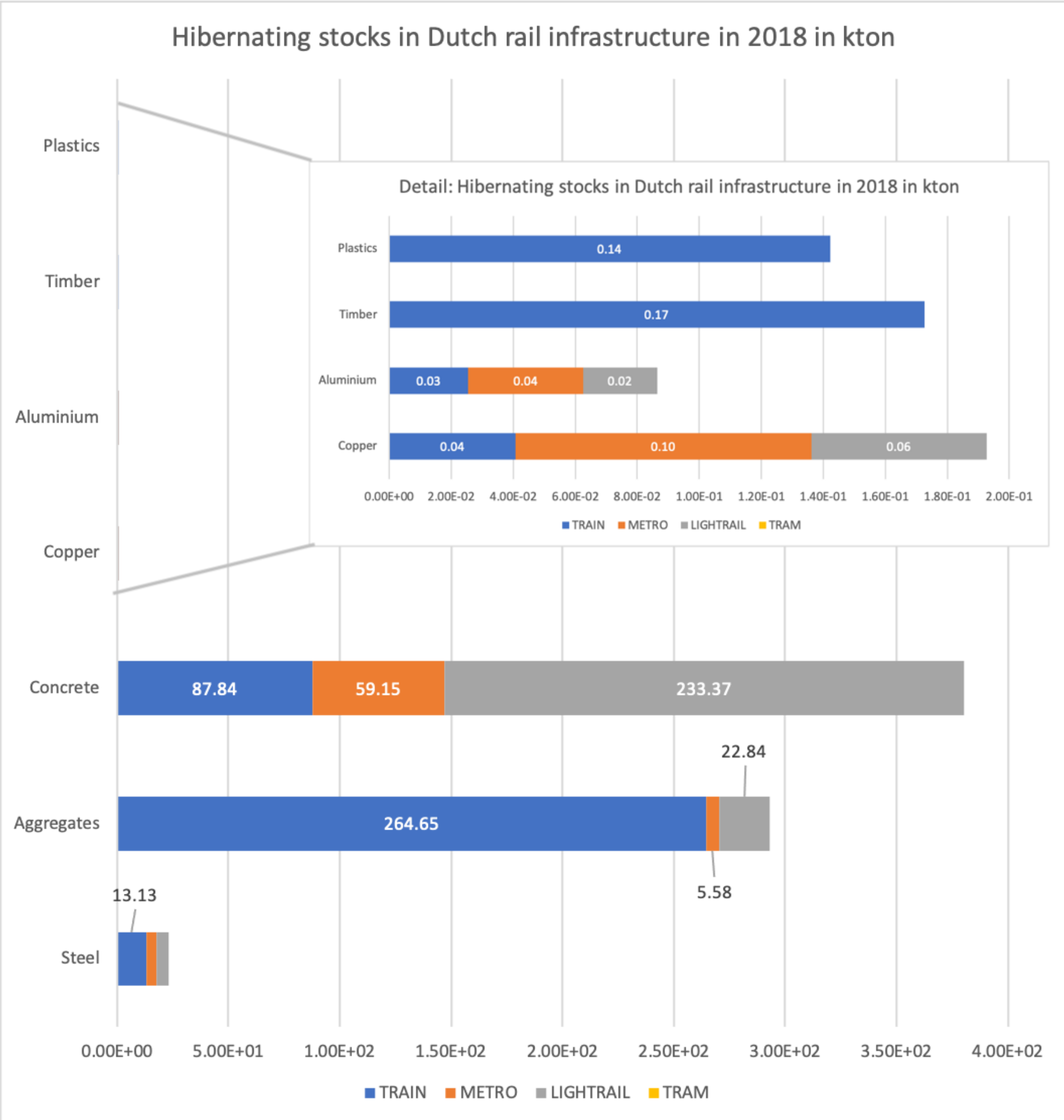


Figure 32: Hibernating stocks in large quantities in Dutch rail infrastructure in 2018.

Figure 32 provides the hibernating material stock by proportion of transport mode. Compared to its relative short track length, the light rail infrastructure shows a large hibernating stock. This is because the railway route between Schiedam and Hoek van

Holland ('de Hoekse Lijn') was in 2018 marked as an unused light rail line, while being under construction from a railway line to a light rail service. The 41 kilometers of unused light rail track for this route are in 2021 in operation for this light rail service. Other hibernating routes are industrial spurs and rail yards of which it is unknown whether they have been taken temporarily out of service or that they have been abandoned permanently.

4.3 Spatial Distribution of the Material Stock

The spatial distribution of the material stock shows which municipalities have the highest stocks of rail infrastructure material. Regional governments such as municipalities are important actors that have to implement circular economy strategies that are designed by the national government and the EU.

Regional governments stimulate and support companies in their region. In 70% of the actions of regional governments, businesses are involved (PBL 2021). Furthermore, regional governments such as municipalities and provinces have the power to demand rail transport companies that receive subsidies from them to produce in a more circular way. Regional governments use financial instruments, such as the European Fund for Regional Development, for their programs on circularity (PBL 2021).

The maps in this section show the spatial distribution per municipality of the three most applied materials in railway infrastructure: concrete, aggregates (ballast) and steel. By identifying the stock per municipality, regional governments find support to shape their programs on circularity.

Figure 33 presents the aggregate distribution over the country, showing that municipalities with railway lines for passenger and freight trains are among the governments with higher densities of ballast involved. Regions with a dense population and train network, such as Amsterdam, Rotterdam, The Hague, Utrecht, Groningen, Breda, Tilburg, Zwolle and Amersfoort score high. Whereas municipalities with industrial railway lines such as Overbetuwe, West Betuwe, Moerdijk, Roosendaal and Sittard-Geleen show high densities as well.

Figure 34 and *35* show a more focused distribution for steel and concrete on municipalities with rail tunnels and bridges. Particularly regions that are crossed by the High Speed Railway tunnels (e.g. Barendrecht, Zoetermeer, Alphen a/d Rijn, Hoeksche Waard, Dordrecht, Haarlemmermeer) and tunnels and bridges for the Betuwelijn (e.g. Zevenaar, Zwijndrecht, Hendrik-Ido-Ambacht and Papendrecht) show higher mass weights of concrete and steel that are in use. Concrete use in Amsterdam and Rotterdam is much higher, because of the metro tunnels that are located within the municipalities.

Mapping the spatial distribution of material stocks indicates the location of the urban mine. The geographic location of material stocks gives regional governments insights in which places are likely to have the biggest circular challenges, and where materials might be mined in the future. Since GIS is specific for geographic locations, it is argued that the program can serve as a basis for a raw materials information system (GRIS), a database that can be used at multiple geographic levels (van Oorschot et al. 2020b; Van Der Maas et al. 2019).

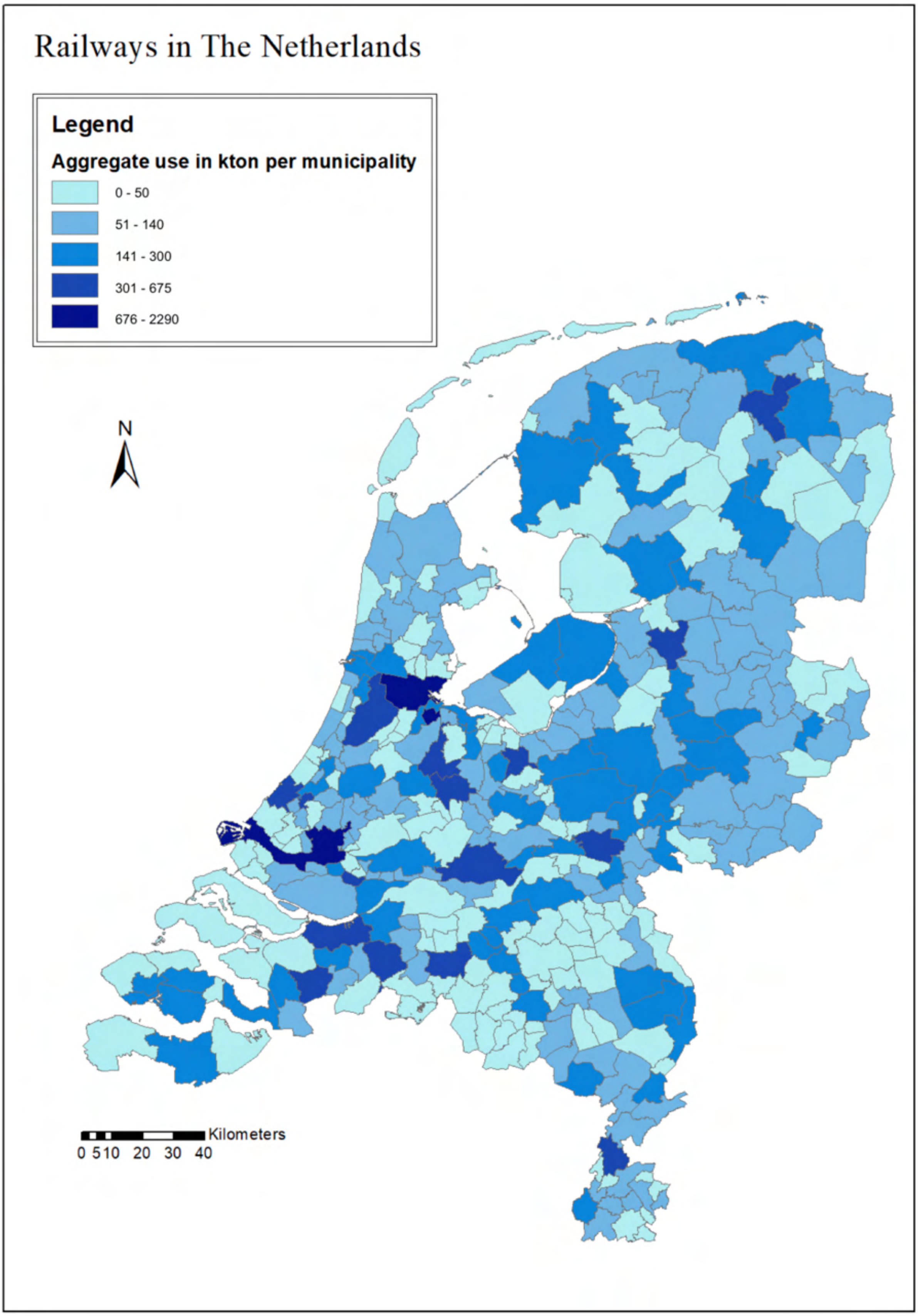


Figure 33: aggregate (ballast) stock division over municipalities in The Netherlands in 2018.

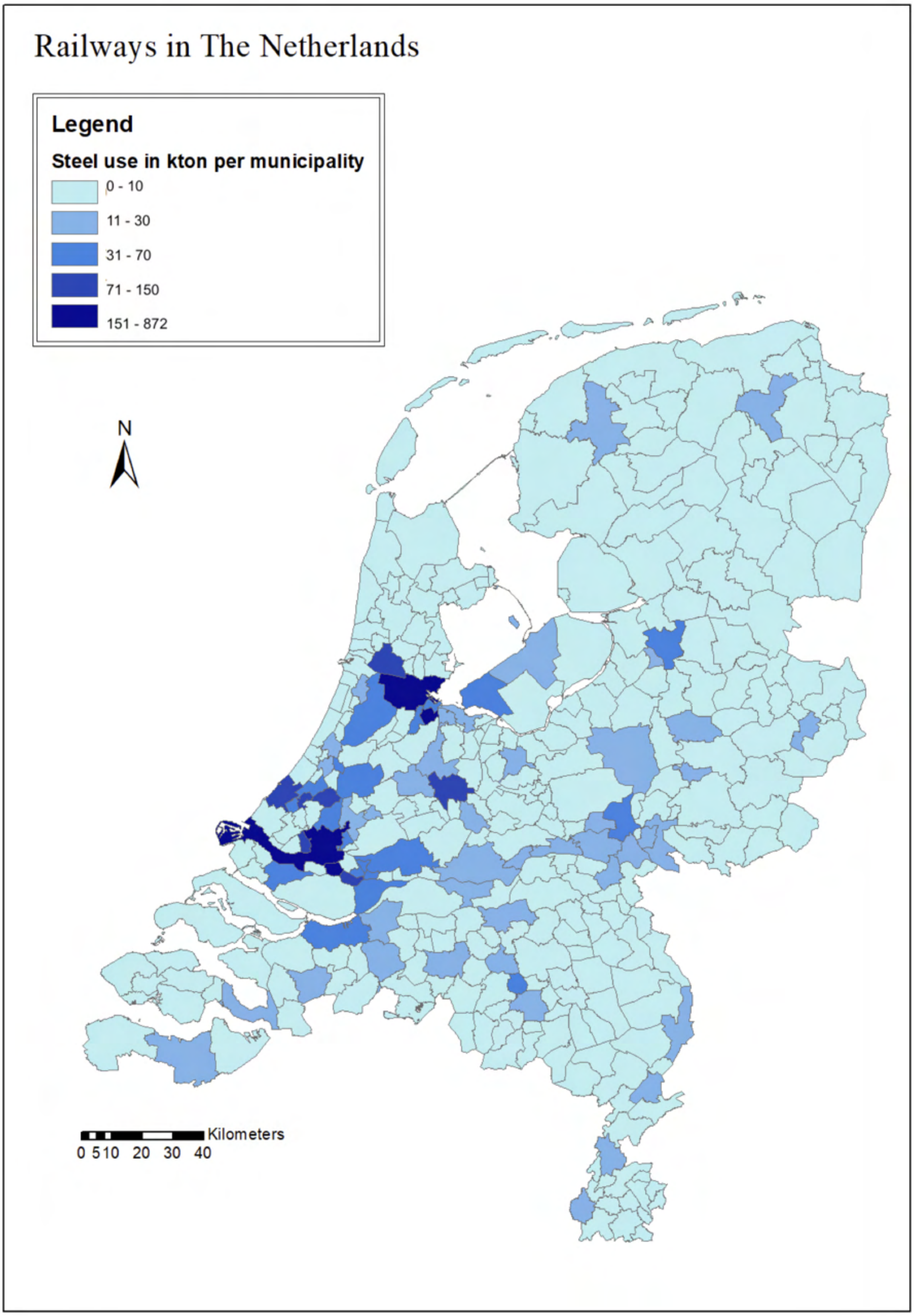


Figure 34: steel stock division over municipalities in The Netherlands is larger in municipalities with tunnels and bridges in 2018.

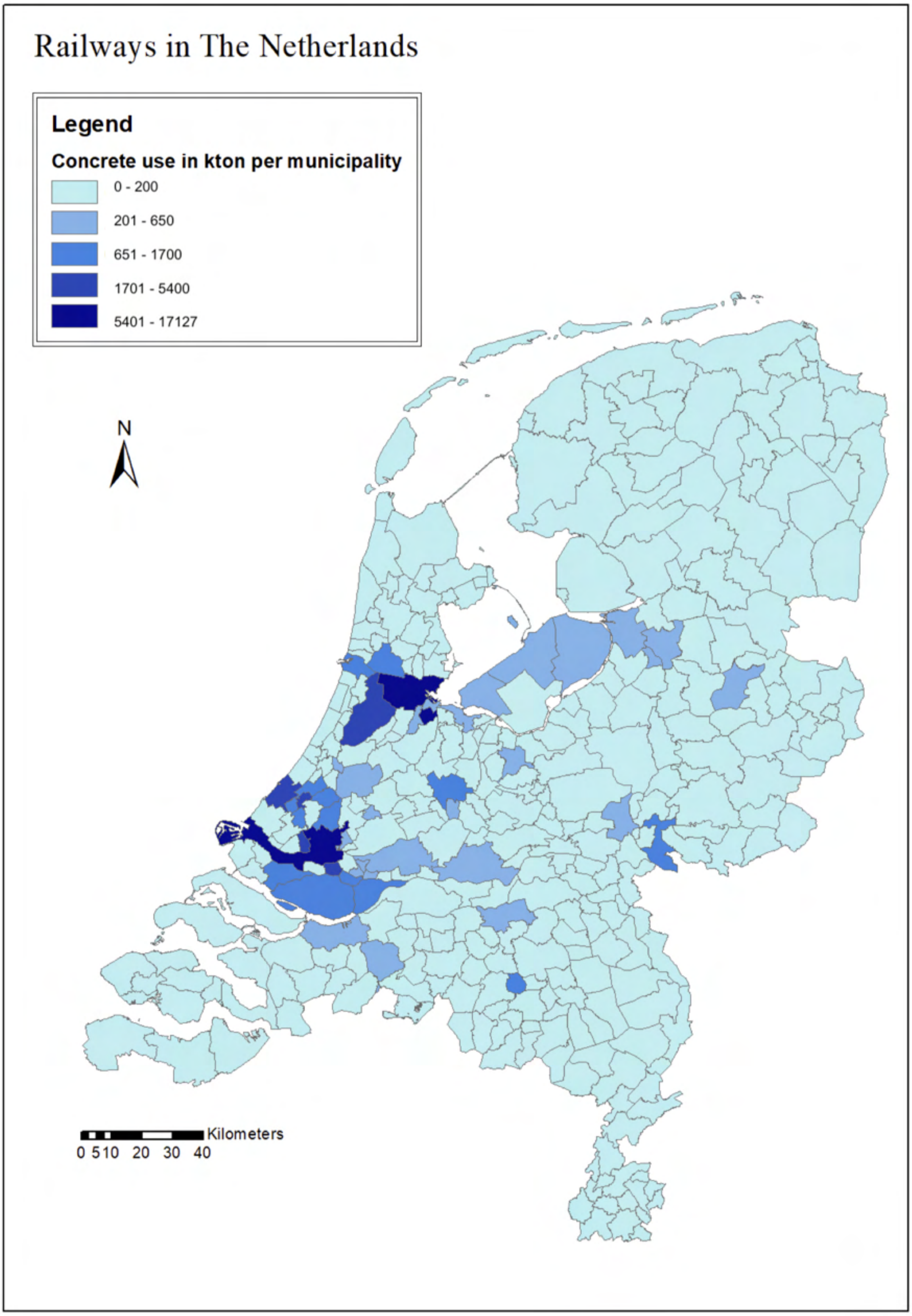
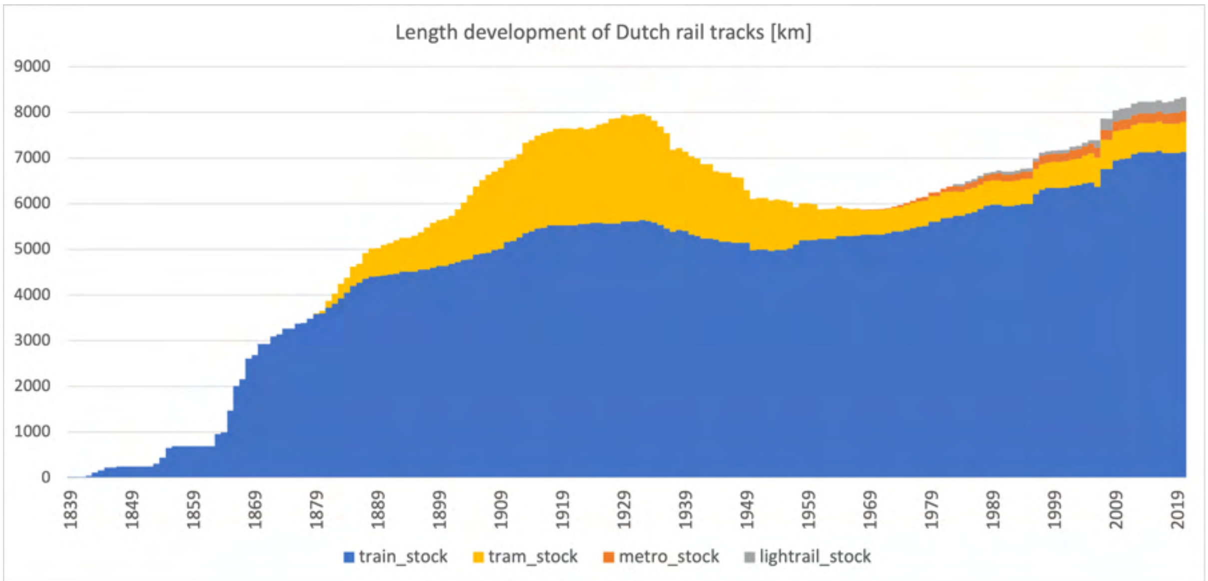


Figure 35: concrete stock division over municipalities in The Netherlands is larger in municipalities with tunnels and bridges in 2018.

4.4 Temporal Distribution of the Material Stock

The temporal distribution of the stock, historical inflows and outflows show at what moment in time the material stocks have changed. This is useful when assumptions have to be made regarding the maintenance flows of the system. A proxy for the stock estimation is the network length, of which the growth per transport mode can be found in the figures below.



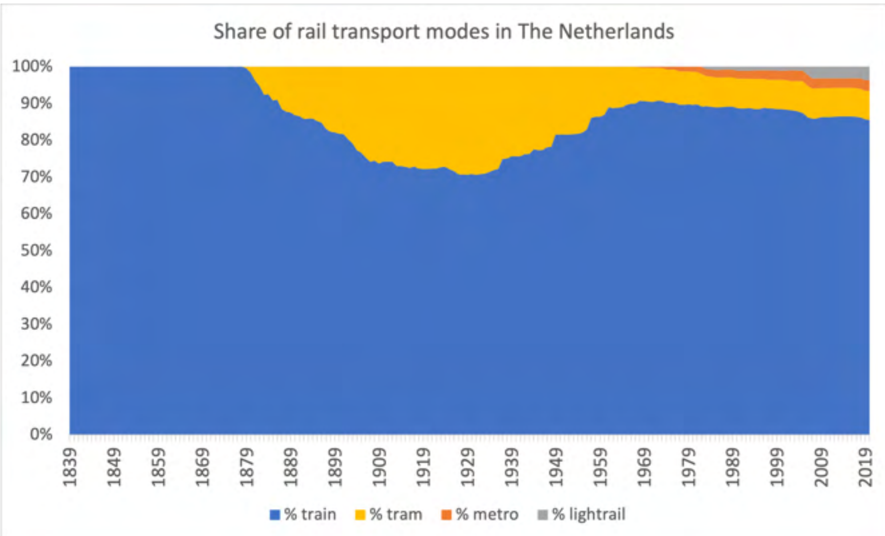


Figure 36a&b: historical share of rail transport modes in The Netherlands and the total development of the length for each transport mode since the first railway line was opened in 1839.

Historical Rail Network Changes

The first railway line in The Netherlands opened between Amsterdam and Haarlem in 1839. It was a single track broad gauge railway for trains with steam engines. The line was soon extended to Rotterdam in 1847 and was converted to normal gauge and doubled in 1866. Many private railway companies built their own lines until the state began constructing a rail network with nationwide coverage in the 1860s. This resulted in peak inflows of materials before the start of the 20th century (see also *Figure 37).* The first electric tram line opened between Haarlem and Zandvoort in 1899. Soon, the first electrified railway line began operation between The Hague and Rotterdam Hofplein in 1908. Until the 1910s, most streetcars were pulled by horses or engines. The Dutch tram network was at its largest at the beginning of the 1930s with a total share of 30% of rail transport modes (see *Figure 36b*).

Based on the stock development data in the past, the annual in- and outflows of network length were estimated in a stock-driven MFA model. *Figure 37* shows the stock, in- and outflow changes over time. The in- and outflows were calculated based on the lifetime distribution of the stock. *Figure 38* displays a detailed description of the in- and outflows only.

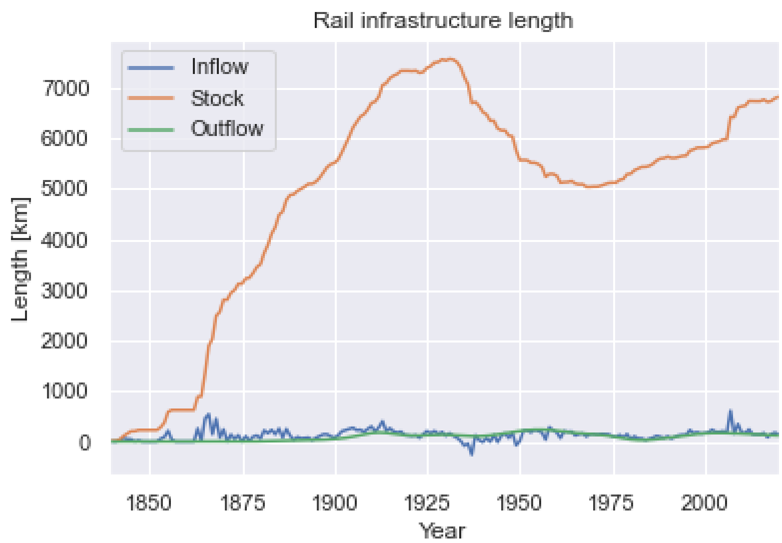


Figure 37: dynamic stock model of the historical development of rail track length in The Netherlands from the year of the first railway line: 1839.

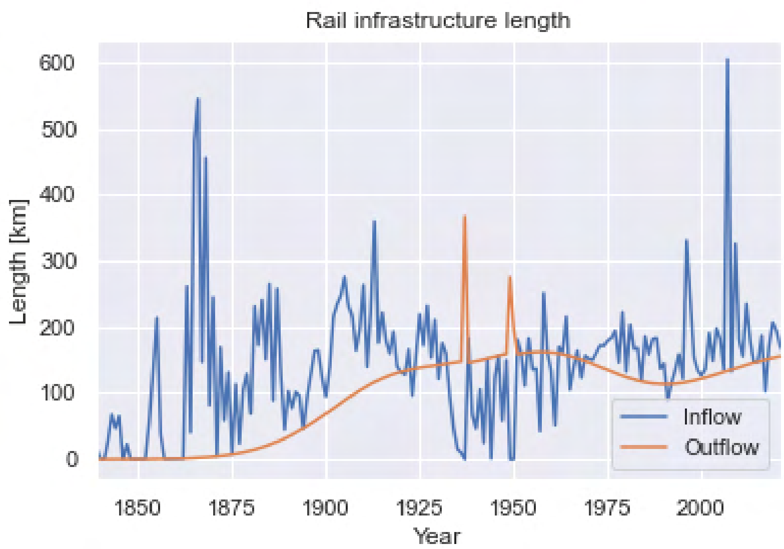


Figure 38: Dynamic stock model of rail infrastructure length in- and outflows between 1839 and 2020.

Between the 1930s and the 1970s, the closing of rail- and tramway lines led to a higher outflow than inflow of railway track. The sparks in the orange line in *Figure 38* depict the years where the closing of these lines led to even larger outflows than the decommissioning flows that were initially reserved for maintenance by the stock-driven dynamic stock model calculations, based on the lifespan of the stocks. In 2007 and 2009, a high inflow was noted because of the opening of the High Speed Line (HSL) from Belgium to Amsterdam and the Betuweroute for cargo trains.

4.5 Results of the Prospective Analysis with Transition Pathways

Figures 39 to 41 represent the expected inflows, outflows and material stock for each transition pathway. The figures depict the developments for normally distributed age cohorts with a standard deviation of 30% of the mean. Between 2000 and 2020, all pathways follow the historical flow trajectories. Since the model is stock-driven, the stock developments determine the estimations on the in- and outflows of materials.

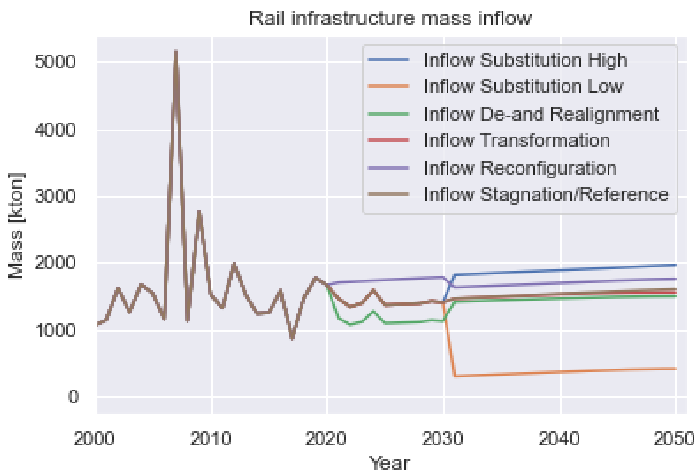


Figure 39: material inflows per pathway.

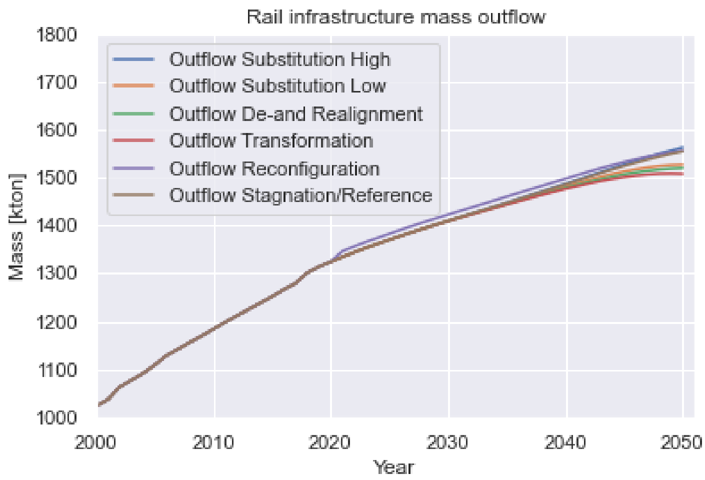


Figure 40: material outflows per pathway.

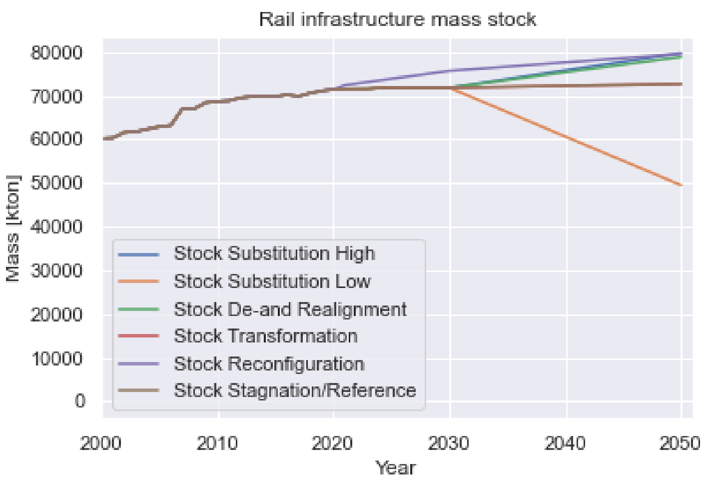


Figure 41: material stock per pathway.

Most of the inflows between 2020 and 2030 follow the same maintenance and planning scheme that was budgeted for in the MIRT. The De- and Realignment Pathway shows a lower inflow, as the assumed 20% lower material intensities from 2021 show a direct effect on the material inflows. The Reconfiguration Pathway, on the other hand, gives a higher inflow than the other pathways until 2030 due to the proposed policy target of a 5% larger network in 2030. The Transformation inflows (marked with a red line) mainly follow the Stagnation Pathway, but become slightly smaller near 2050 since the longer lifespan of 30% requires less materials to flow in.

It was observed that in the period 2030-2050, the effects of long-term altered travel kilometers will become visible. For instance, a doubling in passenger kilometers in the Substitution High Pathway results in the highest material inflows. The declining number of travel kilometers in the Substitution Low Pathway leads to a sudden drop in material inflows in 2030, which from then on is only reserved for maintaining the lines that are not decommissioned. The De- and Realignment Pathway teams up with the Transformation and Stagnation Pathways between 2030 and 2050. The lower material intensities in this pathway still lead to similar flows compared to the Stagnation Pathway, because the positive effect of the lower intensities is balanced out by the expected growth in travel kilometers under the De-and Realignment Pathway, resulting in a bigger stock.

The outflows for all the pathways are almost equal, as the lifespan changes are focused on a stock of objects that already have a long lifetime. Interestingly, pathways where most effort was taken to extend the lifespans (Transformation, De- and Realignment and Reconfiguration) show slightly lower outflows in 2050 than the pathways where lifespans are not extended. The difference is very small.

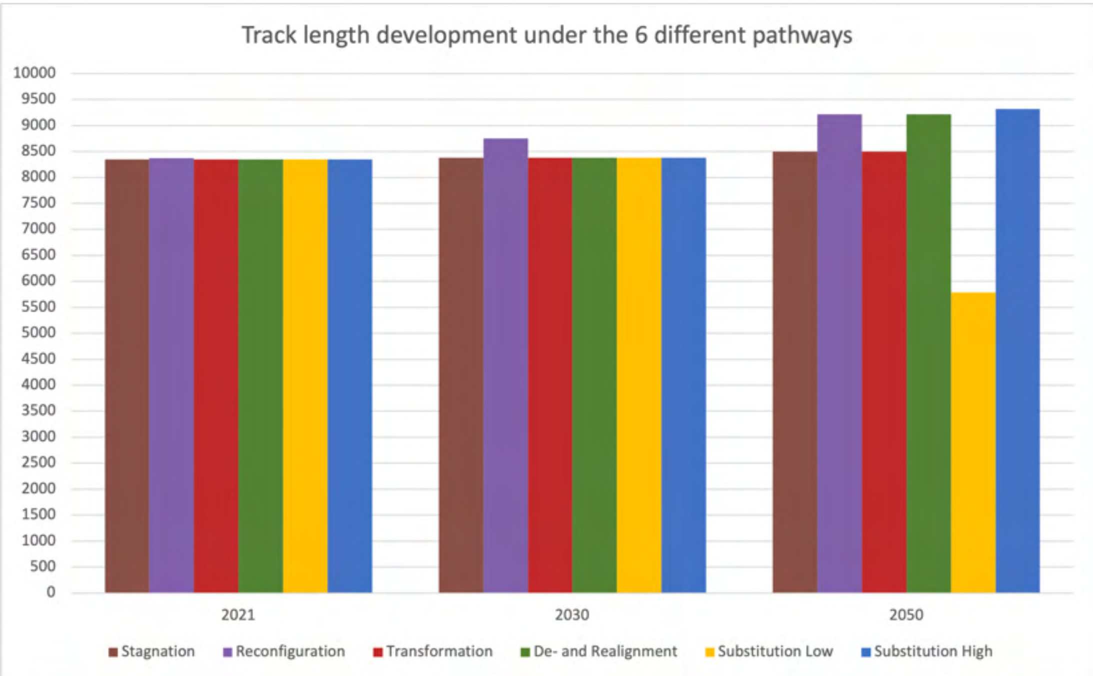


Figure 42: Track length developments for each pathway, based on the change rail passenger kilometers.

In the following sections, the dynamics of the prospective MFA are discussed per transition pathway. All pathways refer to the material in-, outflow and stock results presented in *Figures 43a-43c*. These figures are a further elaboration of the *Figures 39-41* including the materials used per pathway. The results are presented per rounded decade but start with a first future exploration of the stock and flows for 2021.

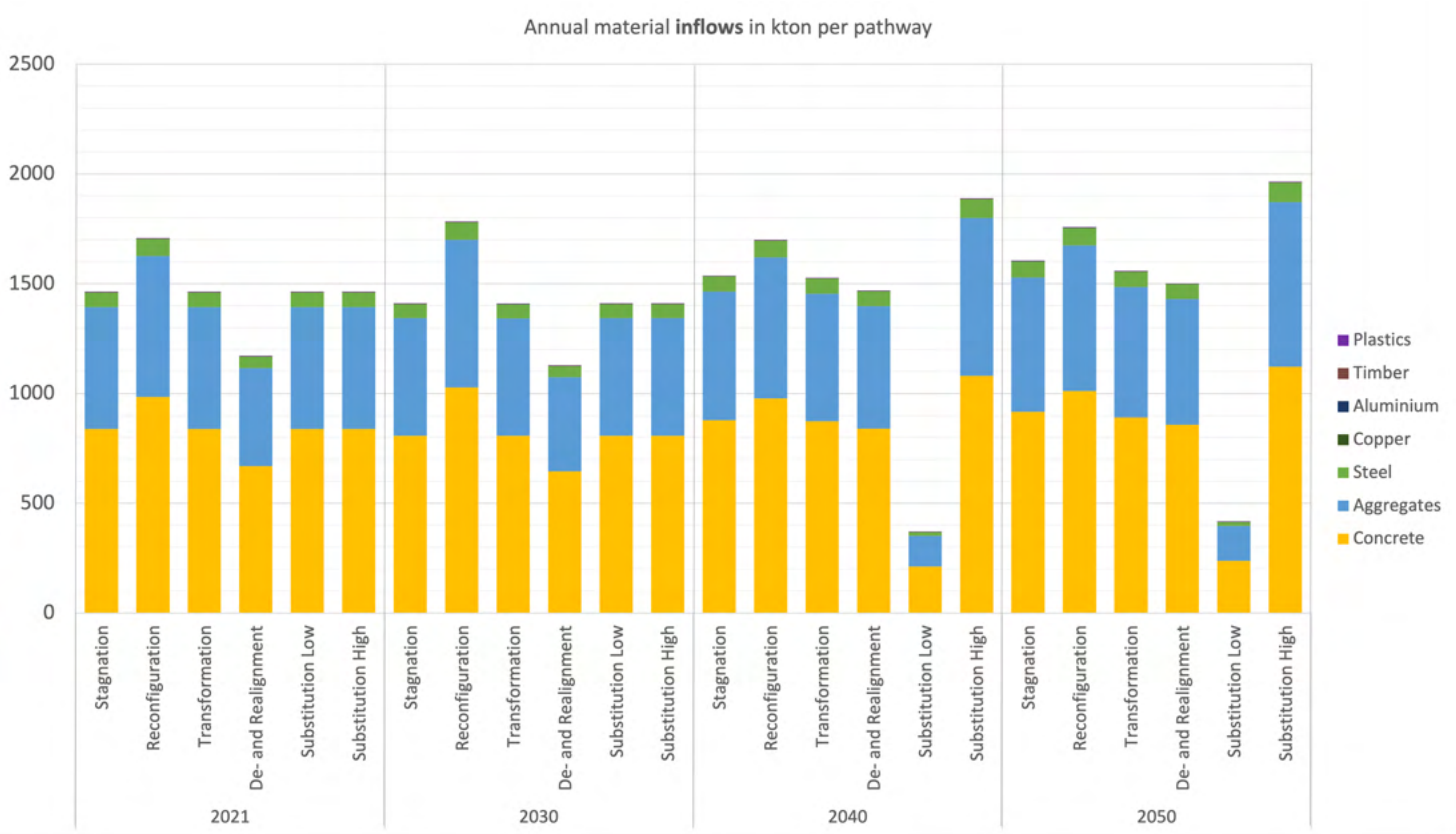


Figure 43a: Material inflows per pathway. Note the scale differences on the y-axis.

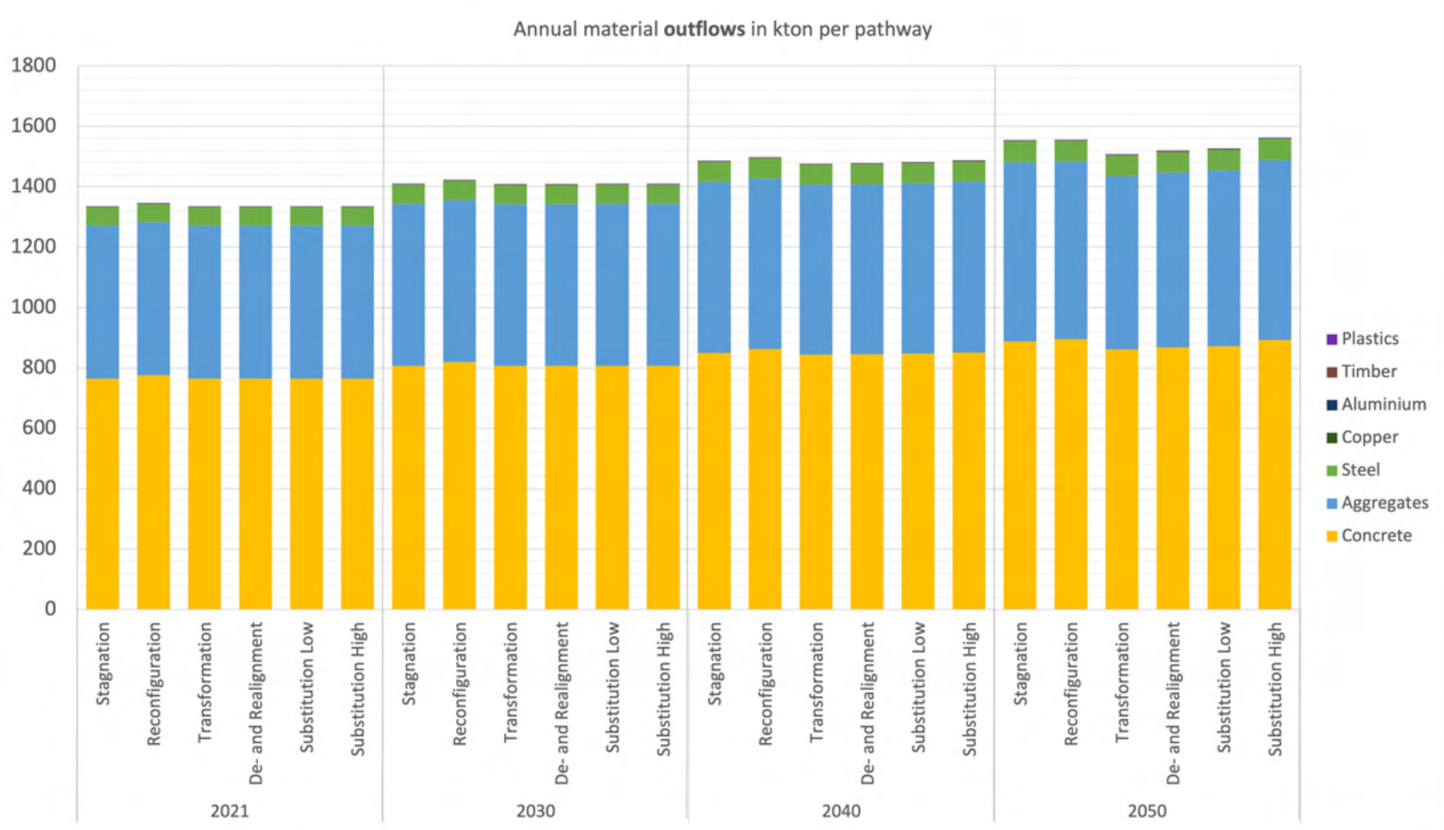


Figure 43b: Material outlows per pathway. Note the scale differences on the y-axis.

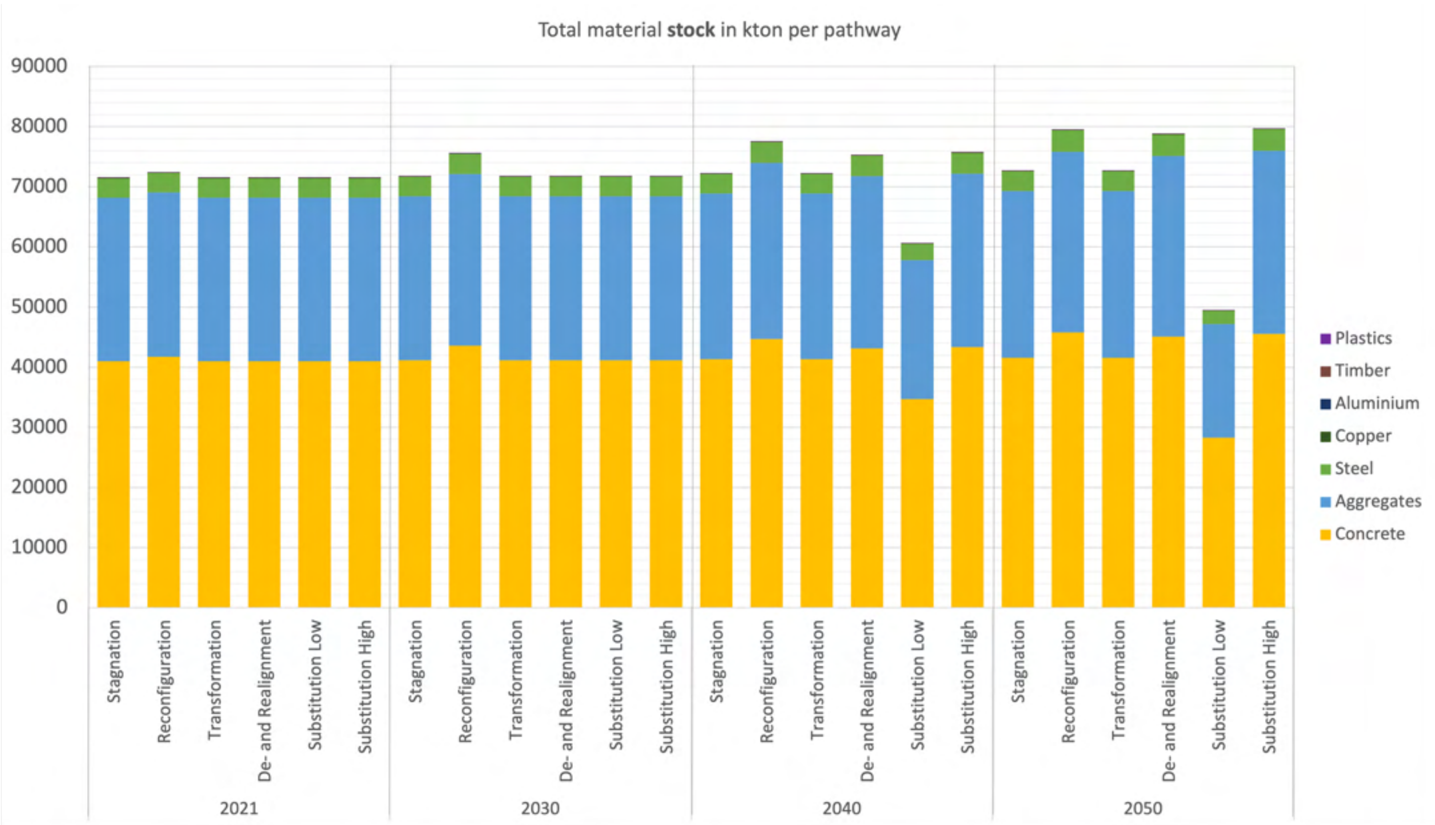


Figure 43c: Material stock per pathway. Note the scale differences on the y-axis.

Transition Pathway 1: Stagnation

In the Stagnation Pathway, the pathway that serves as a reference for the other pathways, the growth of the railway network comes to a halt as a stabilization and in 2050 even a small drop in rail passenger kilometers is assumed in accordance with the WLO Low scenario. This means that the materials that are used in the system will reach a plateau that continues to support maintenance flows. *Figures 43a-c* give the inflows, outflows and the stock per material category for the period 2021-2050.

The largest share of materials in the Stagnation Pathway remains concrete, followed by aggregates (ballast) and steel. The total concrete stock in 2050 and 2018 is 57% of the total. Aggregates for both years share 38% of the stock. Steel accounts for 4.5% of the material stock in both years.

Between 2020 and 2030 the inflows follow the budgeted extensions as planned by the government. After 2030, the inflows slowly increase each year to accommodate the engineering work for the structures that reach the end of their useful life.

The outflows of materials slowly increase under the Stagnation Pathway too, but always remain under the total inflows of that year. This results in a stabilizing stock. The flows for copper, aluminium, timber and plastics are almost invisible in the figures because of their small mass share.

Transition Pathway 2: Reconfiguration

The Reconfiguration Pathway is characterized by the proposed measures from the Ministry of Infrastructure and Water Management to make the Dutch railway infrastructure circular. When these measures are implemented, the stock, inflows and outflows for 2050 will have an increased concrete share of 57.5% compared to 57% in 2018. This small increase of 0.5% is due to the proposed replacement of level crossings by small tunnels. Also, the aluminium and timber shares will rise slightly from 0.0192% to 0.0199% and from 0.0617% to 0.0636% of the total mass respectively. This increase can be explained by the increase of noise barrier constructions.

The mass stock in *Figure 43c* develops faster than all other pathways between 2020 and 2030 but slows down after 2030 until it reaches the same level as the De- and Realignment and Substitution High Pathways in 2050. This is because it is expected that these three pathways will have a similar track length in 2050 (see *Figure 42*).

The mass inflows in *Figure 43a* show a relatively high inflow between 2020 and 2030 because of the proposed extension of 5% of the network by 2030. After 2030, the inflow slows down but remains larger than the Stagnation Pathway. Since the inflows stay consistently higher than the outflows between 2030 and 2050, the total stock will keep growing.

The outflows between 2020 and 2050 are a bit higher in the Reconfiguration Pathway than for all the other pathways, because the early start of the expansion of the network with 5% causes a higher maintenance flow. This is because the normal distribution assumes that in the first years after construction, a very small share of the objects is already demolished.

In general, the Reconfiguration Pathway leads to higher material inflows, outflows and a higher stock than the Stagnation Pathway. The share of concrete, aluminium and timber increases slightly in this pathway as a consequence of the new tunnels that should replace level crossings and newly built noise barriers.

Transition Pathway 3: Transformation

The Transformation pathway shows many similarities with the Stagnation Pathway, since the same WLO Low passenger rail kilometers were assumed. However, the outflows in this pathway are lowest in 2050 in comparison with all the other pathways, because it is assumed that the lifespan of the infrastructure can be extended by 30%. This is the largest modeled lifespan extension of all the pathways.

The material percentages remain the same in this pathway as in the Stagnation Pathway. Since the track length is estimated to be the same as the Stagnation Pathway in 2050, the material stock is equal to this pathway too.

Inflows in the Transformation Pathway get slightly smaller towards 2050 compared to the Reference Pathway, since the longer lifespan demands less inflowing materials. Though, the difference with the Reference Pathway is very small.

The outflows between 2020 and 2050 are smaller than the Reference Pathway, because the assumed 30% longer lifespan of rail constructions brings the average of the total stock to 51.9 years from 2021. With the normal lifespan distribution used in this research, this means that the outflows slightly decrease after 2021 compared to the Reference Pathway.

Transition Pathway 4: De- and Realignment

Characteristics for the De- and Realignment Pathway are a high growth between 2030 and 2050, triggered by the increased number of rail passenger kilometers taken from the WLO High scenario. Before 2030, the mass inflows are typically smaller. This is a result of the 20% lower material intensities for newly constructed infrastructure from 2021 onwards.

The division of materials is the same in this pathway as in the Stagnation Pathway, as no specific material shares are expected to change, it is only assumed that the material intensity of all materials will be lower from 2021 onwards, due to improvements in the material use in new constructions. For example, by directly reusing materials on site that have flown out from engineering works.

While the total stock is leading to the same endpoint as the Reconfiguration Pathway, this pathway assumes -20% material intensities, which strongly reduces the annual material inflows compared to the Reconfiguration Pathway. Since the length of the network is expected to grow between 2030 and 2050 due to more passenger kilometers, the inflows rise again after 2030.

The De- and Realignment Pathway leads to a smaller outflow of materials than most other pathways (except the Transformation Pathway), because of the longer lifespan of 25% of rails which leads to an average construction lifetime of 51 years.

Transition Pathway 5: Substitution Low

The Substitution Low Pathway is based on one driving force: a long-term decrease of passenger kilometers that moves from 100% in 2019 to 50% from 2020 until 2050. The effects of this drop are expected to be visible after 2030, when there is more uncertainty about the financial support to maintain the infrastructure.

The stock in *Figure 47a* is reduced by almost 30% in 2050 compared to 2030, because the continuous drop in passenger kilometers leads to suspension of railway lines. Since it is unknown how many lines will be decommissioned and in which year, it is assumed that the stock is reduced with the same size every year from 2030 until 2050. The endpoint for 2050 is derived from the logistic trend line in the methods chapter that showed the annual rail passenger kilometers in relation to the total network length.

The inflows in the Substitution Low Pathway follow the same inflows as the Stagnation pathway until 2030. After 2030, the outflow of materials is going much faster than the inflows. The only inflows that are visible after 2030 are used for maintenance of the remaining infrastructure, and are therefore very small.

The material outflows in the Substitution Low Pathway show a robust annual flow that reduces the total stock when it is bigger than the inflow, between 2030 and 2050. Compared to the other pathways, this absolute outflow is smaller in 2050 than the Stagnation pathway, because by then, the stock will already be a lot smaller than in the Stagnation Pathway.

Transition Pathway 6: Substitution High

The Substitution High Pathway shows what happens to the material stock and flows if the rail passenger kilometers double in 2050 compared to 2019. To accommodate for this growth, network extensions will be needed.

The stock development in the Substitution High Pathway follows the same path as the Stagnation Pathway until 2030. After 2030, the annual stock growth follows the De- and Realignment Pathway, that assumes a similar total track length by 2050.

The annual inflows of materials for the Substitution High Pathway follow the same flows as the Stagnation Pathway until 2030. Between 2030 and 2050, the Substitution High Pathway requires a stable increase of inflows, since these are the decades in which construction works are expected to take place to cope with the growing number of rail passenger kilometers.

The material outflows in the Substitution High Pathway do not show much difference with the outflows from Stagnation Pathway, because the growth of the network does not lead to a bigger outflow yet. In 2050, the first results of the network extension become visible in the outflows, when the Substitution High outflow overtakes the outflows from the other pathways. This development can be explained by the larger network from 2030 onwards. The higher inflow of infrastructure needs more replacements in 2050 than the other pathways that assume a smaller rail infrastructure network.

4.6 Interpretation of the Results

The results of this study show that the vast majority of railway infrastructure materials are nonmetallic stocks such as concrete and ballast. The stock estimation presents that more than 75% of the total stock weight is in train infrastructure, particularly in rail tracks. This section elaborates on the interpretation of the results of the prospective modeling part of this study. It compares the results of the different pathways and seeks to explain why we see differences among them. Furthermore, the pathways are related to the current stock context and the present material flow characteristics.

Pathway	SN: Stagnation	RF: Reconfiguration	TF: Transformation	DR: De- and Realignment	SL: Substitution Low	SH: Substitution High
Total stock in 2050 [Mton]	72.73	79.57	72.73	78.86	49.51	79.74
Cumulative inflows 2021-2050 [Mton]	44.94	51.47	44.63	40.67	21.54	52.01
Cumulative outflows 2021-2050 [Mton]	43.50	43.83	43.19	43.27	43.35	43.55
Concrete inflow compared to SN		15.28%	-0.70%	-9.52%	-52.05%	15.72%
Concrete outflow compared to SN		1.41%	-0.72%	-0.55%	-0.37%	0.11%
Aggregates inflow compared to SN		13.49%	-0.70%	-9.51%	-52.10%	15.73%
Aggregates outflow compared to SN		-0.15%	-0.72%	-0.55%	-0.37%	0.11%
Steel inflow compared to SN		13.63%	-0.70%	-9.51%	-52.07%	15.72%
Steel outflow compared to SN		-0.04%	-0.72%	-0.55%	-0.37%	0.11%
Copper inflow compared to SN		13.50%	-0.70%	-9.51%	-52.07%	15.72%
Copper outflow compared to SN		-0.15%	-0.72%	-0.55%	-0.37%	0.11%
Aluminium inflow compared to SN		18.65%	-0.70%	-9.51%	-52.07%	15.72%
Aluminium outflow compared to SN		4.38%	-0.72%	-0.55%	-0.37%	0.11%
Timber inflow compared to SN		18.55%	-0.70%	-9.51%	-52.10%	15.73%
Timber outflow compared to SN		4.30%	-0.72%	-0.55%	-0.37%	0.11%
Plastics inflow compared to SN		13.69%	-0.70%	-9.51%	-52.10%	15.73%
Plastics outflow compared to SN		0.03%	-0.72%	-0.55%	-0.37%	0.11%

Table 9: Comparison of stocks and cumulative flows for the different pathways. The smaller the stock and flow size compared to the Stagnation pathway, the better from a material use perspective.

Table 9 presents the total stock for each pathway and their cumulative in- and outflows in the near future (2021-2050). Over the coming 29 years, the cumulative flows are larger than half the size of the stock in 2050 for all pathways. This indicates that the potential scale of circularity measures such as reducing, reusing and recycling materials is large. In the table, a comparison was made between the cumulative in- and outflows for the alternative pathways compared to the Stagnation Pathway, which serves as a reference. The options that involve the least materials are marked in green. At the other end of the color scale, the pathways requiring the most materials are marked in red. In this color hierarchy, green boxes show the best options, as lower material outflows lead to less waste and lower inflows require less primary materials.

Main Differences in Stocks and Flows

The total stock and the cumulative inflows in the period until 2050 are smallest in the Substitution Low Pathway. This pathway assumes a suspension of a third of the railway track lengths (see also *Figure 42*), which leads to a lower stock size in 2050 and the lowest cumulative inflows of all pathways, since a smaller maintenance flow is needed for a smaller stock. The outflows in this pathway remain similar to the other pathways.

The differences in cumulative outflows are very small. The cumulative outflows are smallest in the Transformation Pathway that has the longest track lifespans (+30%) for all the pathways in combination with a rail passenger kilometer stabilization according to the WLO Low scenario. However, the De- and Realignment Pathway that uses the WLO High scenario for passenger kilometer growth and a 25% longer lifespan of the rail tracks combined with lower material intensities follows closely. It can thus be said that, even in a scenario with growing passenger kilometers, the outflows can be limited by extending the lifespans of rail tracks and by lowering material intensities for new materials that are flowing in.

The six transition pathways in the prospective modeling part of this study show three directions material use change: stagnation, increase and decrease. The results show that the three driving forces, lifespan change, material intensity change and railway passenger kilometer change, each alter this material use in a different way.

Main Differences in Driving Forces

The main driving force differences between material use in the pathways are caused by rail passenger kilometers. The substitution pathways both show the largest differences compared to the Stagnation Pathway. The other two driving forces, lifespans and material intensities have smaller impacts.

For lifespan changes, this small impact may be explained by the fact that only lifespan changes of rail tracks have been considered. Even though these assets cover almost 50% of the stock weight, a 20% longer lifespan of rail tracks shifts the average of all objects in the infrastructure from 46.7 to 50.2 years. A 30% longer track lifespan brings the average to 51.9 years. This shows that despite big lifespan changes in the railway tracks, the overall average lifespan shows only minor changes and therefore only limited differences in the material in- and outflows.

Lower material intensities, as modeled in the De- and Realignment Pathway, do result in smaller inflows of construction materials. However, the effect of this driving force cannot be completely specified as this pathway combines multiple driving forces.

Policy Implications of the Pathways

It was observed that the proposed circularity policies by the Dutch national government in the Reconfiguration Pathway lead to an overall increase of material stock, material inflows and material outflows. If no improvements on reusability, remanufacturing or recyclability will be implemented, this pathway will lead to a higher primary material demand and a larger waste flow than in the Stagnation Pathway. This is the opposite of the circularity definition of minimizing material flows.

Relation to the Current Context

In relation to the current situation, the transition pathways have shown that the factors lifespan and material intensity do not lead to extreme changes in the (primary) material flows in railway infrastructure. The model showed that rail passenger kilometer developments can significantly affect the construction and demolition flows of railway infrastructure in the long run.

In short, pathways with a longer lifespan lead to slightly lower outflows and pathways with lower material intensities immediately lead to lower inflows. However, the material effects until 2050 of these two driving forces seem to be small. The railway passenger kilometers traveled show much more long term effects regarding the material use. Pathways with an increase in passenger rail kilometers require more material flows and a larger stock, while the decline in material flows and the decline in the material stock is even larger for pathways that assume a long term decrease in passenger rail kilometers. Although, as demonstrated by the De- and Realignment Pathway, in a growing system, the lifespan extensions and lowered material intensities do have a limiting effect on the material use. The reusability and recyclability of the structures must be studied in order to assess the circularity potential of the railway infrastructure system. A first exploration of the circular applications of the demolition flows is carried out in the following sections.

4.7 Potential Circular Applications of the Material Flows

The material outflows from railway infrastructures at their end-of-life can be valuable for reapplication within the system, by reusing, repairing/remanufacturing or recycling the materials. The potential for circular applications of materials in rail infrastructure may be more restricted than in other industries, such as buildings, because of the durability of the structures and the stress that they need to handle during their lifetime (International Energy Agency 2019b). Fatigue and corrosion of the materials limit reuse at their end-of-life (EoL). Hence, it is estimated for instance that only 11% of steel from infrastructure can be reused compared to 38% of the steel in buildings (Cooper and Allwood 2012; International Energy Agency 2019b).

Nevertheless, several scholars and consultants have presented ways to reuse materials within the rail infrastructure system. This sub-chapter presents these options for end-of-life processing of the demolition flows in railway infrastructure. In the paragraphs below, several existing circular options are discussed for concrete, ballast, steel and aluminium and copper.

Reuse

- *Concrete* paving slabs, such as tiles on platforms and in stations, offer a high reuse potential of more than 50% whereas precast (prefab) structures in construction and demolition waste generally offer a medium reuse potential of 50% (Iacovidou and Purnell 2016). Concrete pipes and structural concrete are usually cast-in-situ and therefore do not offer reuse possibilities (Iacovidou and Purnell 2016). A supply chain analysis for Voestalpine Railpro estimated that approximately 30% of the current concrete railroad ties in The Netherlands can be reused at the end of their service life (Havik 2020). The same study mentions that there are no current numbers on reuse shares in railroad ties, but stresses that it is probably lower than 30% due to a lack of central agreements. For example, a directive from ProRail prohibits reusing railroad ties that are more than 20 years old (RLN00415) (Havik 2020).
- *Railway ballast* deteriorates over time and wears out. An empirical study on the shear behavior proved that mixing fresh ballast with reused ballast leads to a negligible effect on shear stress as long as the concentration of recycled ballast remains under 30% (Jia et al. 2019). Interestingly, the LCA data from ProRail mention that during engineering work, usually half of the ballast is renewed, which already blends the fresh ballast with ballast that is longer in use (Weening and Vroege 2019).

- For *steel* constructions in stations, reusing old steel constructions has resulted in 30% savings of steel in a case study on a new Italian railway station built with a reclaimed steel construction from an industrial complex. The old construction had to remain under the same tension as it was before, which means it needed additional steel support from primary steel sources (Pongiglione and Calderini 2014). As the reuse potential for this structural steel connection is lower than 50%, its reuse potential is marked as low (Iacovidou and Purnell 2016). Steel rebar in other infrastructure applications than precast concrete has no reuse potential (Iacovidou and Purnell 2016). Reusing steel rails and switches in railroad yards is possible, because these tracks are less heavily stressed and lower safety requirements apply (Havik 2020). Reusing the steel track bars at secondary routes in combination with higher strength steels could double the lifetime of the rail tracks (International Energy Agency 2019b; Milford et al. 2013).
- *Non-ferrous metals:* aluminium cladding has a reuse potential of 50% (Cooper and Allwood 2012). Aluminium in the metro system in Vienna is used for traction supply bars that have a shorter lifespan, relatively high economic value and easy extractability (Lederer et al. 2016). It is assumed that, in metro systems in The Netherlands, the characteristics of the aluminium stock will be similar.

Recycling

Only the high-grade recycling options are discussed, which is in line with the definition on circularity from the Ministry of Infrastructure and Water Management (Ministerie van I&W 2020). Thus, downcycling materials at a lower grade is not part of the objectives of this thesis research. The recycling options found in the literature and industry reports are as follows:

- *Concrete:* A test on recycling concrete railway sleepers as a basis in new high-grade concrete showed promising results (Yang and Lim 2018). Though, Zhang et al. (2020) state that in The Netherlands, high-grade concrete recycling is generally not economically feasible.

  In a static MFA with end-of-life scenarios for construction and demolition waste (CDW) of concrete in The Netherlands, Zhang et al. (2020) reported that most CDW concrete is downcycled (i.e. recycled to a lower value application) to secondary aggregates such as road foundation. Nevertheless, the paper's best scenario shows that in The Netherlands, a high grade recycling rate of concrete is technologically feasible up to 21%-32%.
- *Railway ballast* recycling. The most common type of ballast used in The Netherlands is Bestone, the brand name of granulite from Norway. 75% of all ballast in The

Netherlands is from Bestone (Bosma 2021 32:44; Weening and Vroege 2019). Second comes porphyry that is mined in the Belgian town of Quenast. Weather-beaten rail ballast from porphyry that can't be reused is usually recycled as a gravel substitute for new concrete (De Hoop Bouwgrondstoffen n.d.). The porphyry rocks that are commonly applied in rail ballast improve the wear resistance in concrete products (De Hoop Bouwgrondstoffen n.d.). It is unknown to what extent weathered Bestone can be recycled. Therefore it is assumed that only porphyry, which is the remaining 25% is of ballast material (Weening and Vroege 2019), can be recycled at a high grade in other industries. Thus, if 50% of both ballast material types is directly reused within the rail sector, another 12.5% of the porphyry ballast becomes available for recycling in concrete. The LCA on ballast from ProRail mentions that at its end-of-life, ballast material is downcycled as embankment body and foundation material for road construction. 5% of the ballast consists of too fine particles for reuse or downcycling and is disposed of in landfills (Weening and Vroege 2019).

- *Steel:* Steel reinforcements can be recycled after the reinforced concrete has been crushed. Foundations with reinforced steel are left in the ground at their end-of-life, but can be reused when designed for multiple building types (Cooper and Allwood 2012) such as a design that fits multiple types of rail stations.
- *Non-ferrous metals*: To meet the requirements for conductors of cables, copper in energy system cables has to be of very high quality. Reclaimed high-purity copper from waste cables (copper content >94%) can be further refined by using fire-refining methods making fire-refined high conductivity (FRHC) rod. This refining process through smelting, constant casting and constant rolling improves the quality to above 99.93% which is enough to meet the European standard of high conductivity copper (Li et al. 2017). Despite these promising technological advancements, it was concluded in a master's thesis on the circularity of electricity cables in The Netherlands that high purity recycling is impossible due to the industry's collection scheme that combines multiple copper alloys in one batch (Verschelling 2020).

EoL options in railway infrastructure	*Current*	*Optimal (under current technological conditions)*
Concrete	- downcycling for road reinforcement	- reuse of prefabs (ties, tiles etc.) and foundations - high-grade recycling
Ballast	- reuse (50%) - downcycling for road reinforcement - landfilling (5%)	- reuse - high grade recycling in concrete (porphyry)
Steel	- open-loop recycling at a lower grade	- reuse of rails and switches on secondary routes - high-grade recycling
Non-ferrous metals	- open-loop recycling at a lower grade	- reuse of cladding - high-grade recycling

Table 10: Overview of the end-of-life (EoL) options in railway infrastructure.

Circularity potential

Lederer et al. (2016) found that only 3% of the built-in materials in the Viennese subway system are extractable within 100 years time. However, this research has shown that the potential for extracting materials from the entire Dutch railway system is higher, given the larger estimated cumulative material flows between 2021 and 2050.

The reuse and recycling options discussed in the previous sections can be combined to the following circularity potentials:

- Assuming that 50% of the platform tiles is reused while the other 50% is recycled and that all outflowing concrete railway sleepers are a basis for new concrete used in the railway infrastructure system, it can be derived from the material intensities that 23% of the concrete outflows can re-enter the circular economy as a high value secondary product (in *Appendix F*, by taking the concrete in rail tracks and concrete in platforms combined as a share of the total train concrete intensity).
- A life cycle assessment on high-speed rail infrastructure in France assumed that at the end-of-life of rails, 20% is reused in secondary rail network parts and 80% is recycled for the production of secondary electric steel. This is a different quality than primary converter steel and it is therefore not used in the rail infrastructure industry anymore (de Bortoli et al. 2020). Thus, it is assumed that 100% of the outflowing steel can re-enter the circular economy, but a limited amount of high-grade steel re-enters the railway infrastructure system.

- Non-ferrous metals: it can be interpreted that copper waste from railway infrastructure cables can be fully recycled and reused as a secondary high-quality copper material within the system, as long as the alloys are separated well upon collection for resmelting.

A first evaluation demonstrates that 33% of the outflows can re-enter the railway infrastructure system in high-grade applications. This share was calculated by the multiplying the the previous assumptions that 23% of the concrete stock, at least 50% of the aggregate stock, 20% of the steel and 100% of non-ferrous metal can be technically be reused by the total outflows in 2018 from the rail infrastructure that have been estimated in this thesis research (the 2018 division of materials that remains more or less the same in each pathway). Since the outflows are smaller than the inflows in all the transition pathways, except the Substitution Low Pathway, and since virgin materials are required for the strength and stability of new constructions, closing the material cycles in railway infrastructure is not an option with the current technologies for circularity and if the material inflows remain larger than the outflows.

Furthermore, another 27% of the demolition materials could re-enter the economy outside the rail infrastructure. This number was calculated by multiplying the previous assumptions of a best-case scenario that 32% of the concrete can be recycled at a high-grade, that 12.5% of the porphyry ballast is recycled and that the residual 80% of the steel is recycled for other industries, by the total rail infrastructure material outflows from 2018. The economic value of the material outflows, knowledge that is useful when the demolition materials are traded for applications in other industries, is estimated in the following sections.

The remaining 40% of material outflows are granite ballast, timber and plastics. The vast majority of this share consists of the ballast that is at the end of its lifetime. This material is downcycled for road bed reinforcement. 5% of the ballast material has a very small fraction of less than 2 mm and is too polluted to reuse (Weening and Vroege 2019; Bodemplus 2011). Therefore it is disposed of in landfills.

Economic value of the secondary raw materials

The economic value of the demolition materials of subway infrastructure has been estimated by Lederer et al. (2016). Their results are based on secondary building material market prices from 2013 in Austria. This data may not be directly applicable to The Netherlands, but it helps to give an indication of the economic value of secondary materials from railway infrastructure. In this thesis research, these prices have been adopted to make a first estimation of the cumulative secondary market value of the outflowing materials in the Stagnation Pathway. This pathway is representative for the other pathways, since the share of outflowing materials does not differ much over all the pathways. The results are presented in *Table 11* and in *Figure 44*.

Material category	*Value per kton (from Lederer et al. 2016)*	*Cumulative secondary market value (2021-2050) in the Stagnation Pathway*	*Share of secondary market value in the Stagnation Pathway*
Concrete	€ 5,000.00	€ 124,481,059.95	18%
Aggregates	€ 4,000.00	€ 66,215,611.75	9%
Steel	€ 170,000.00	€ 332,597,890.27	47%
Copper	€ 4,500,000.00	€ 177,365,632.64	25%
Aluminium	€ 1,150,000.00	€ 9,614,561.54	1%

Table 11: Secondary market values of the cumulative rail infrastructure outflow for 2021-2050.

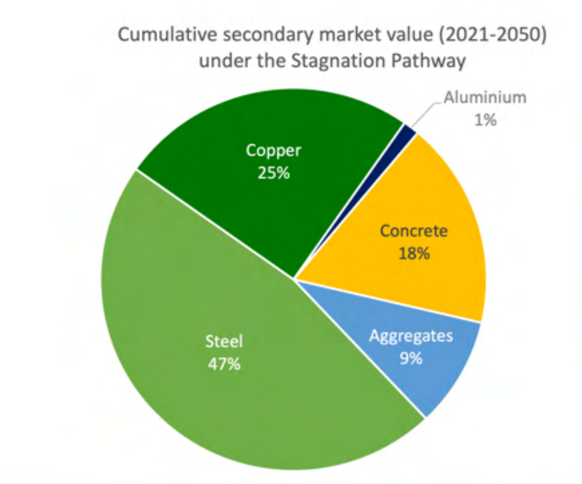


Figure 44: First estimation of market value shares of the cumulative outflowing materials 2021-2050.

For subway systems, Lederer et al. (2016) state that aggregates, copper and aluminium are the most likely to be extracted in the anthroposphere, since these stocks are not in permanent structures and generally have short lifespans of less than 50 years. This thesis research has shown that 41% of the steel stock is in train rails that have generally have life spans of less than 50 years as well. Considering that at least all aggregates, copper, aluminium and 41% of the steel are extractable in the next half century, these stocks share a worth of 54% (see *Figure 44*) of the total secondary raw material value of railway infrastructure.

Given the secondary market prices of the materials, steel, copper and aluminium offer the most feasible options for circular applications. With 41% of the steel stock in accessible train rails, much of the steel mine is reusable or highly recyclable and readily available in the foreseeable future. Furthermore, the estimated value share at the secondary market for steel is highest for all the material categories. These factors make steel from rail bars the most attractive and productive case for reuse applications.

In short, the reuse and recycling options make it technologically feasible to have a directly re-entering flow of 33% of the outflowing materials. For the reusable and recyclable materials that cannot re-enter the railway infrastructure, relatively short-cycled materials such as aggregates, rail bar steel, copper and aluminium have a share of 54% in the secondary market prices for the outflows. In particular, steel rails show an attractive reuse potential because of their market price and accessibility.

5. Discussion

The discussion chapter of this thesis comprises three sections. The first part consists of the modeling choices with sensitivity analyses on the lifespan and the infrastructure length estimates. Thereafter, the use of rail passenger kilometers as a driving force in the model is discussed, followed by a discussion and comparison on the material intensities. In the second part, the results of the analysis are discussed and compared with academic literature. It includes a discussion on the application of the sociotechnical transition pathways for railway infrastructure, data uncertainty in the stock and prospective modeling analyses, a comparison with other material stocks in The Netherlands, a discussion on the actor relationships, a discussion on the urban mining potential of the stock, the pathways and the circular economy goals. In the third part, the environmental effects of dissipation and the impact of rail infrastructure material emissions are addressed.

5.1 Modeling Choices

The prospective part of the MFA in this thesis was based on three driving forces: the lifespan of the stock, the material intensity and the annual passenger rail kilometers traveled. These modeling choices are discussed at the end of this sub-chapter. First, sensitivity analyses are performed on the lifespan, the temporal scope and the infrastructure length developments, followed by a discussion of the modeling choices regarding the spatial analysis and the stock-driven material flow analysis.

Sensitivity of the Lifespan

The choice to use the normal distribution can be validated as follows. The log-normal distribution presents the inertial nature of material stocks with long lifetimes (e.g., the housing stock) better than a normal distribution (Pauliuk et al. 2012). The log-normal distribution has a longer tail than a normal distribution, which can include lifetime age cohorts over a longer period of time. However, the normal distribution was used instead, as this is also used in other long-lifespan building stock studies (Müller 2006; Hu et al. 2010) and product lifetimes that have an uncertain demolition rate, such as steel use in the transportation sector (Pauliuk et al. 2012).

Constructions generally have a lifespan with a wide range. A comprehensive literature review of commodity lifespan data even showed in a box plot of lifespans on automobiles, consumer durables, buildings and constructions in Europe, Japan and the rest of Asia that constructions in Europe show the widest lifespan range of all commodities with 50% of the construction lifespans between 15 and 95 years (Murakami et al. 2010). This makes a choice for the best fitting lifespan distribution highly uncertain. In fact, it is unknown how the lifespans of the objects are distributed in railway infrastructure. Therefore, a sensitivity analysis was carried out on the lifespans to check how sensitive the model is to different lifespans.

To check the robustness of the model, a sensitivity check was done with longer lifespans in the Stagnation Pathway: a 20 year longer lifespan (leading to a mean of 66.7 years) and a 20 year shorter lifespan (leading to a mean of 26.7 years). The results in *Figures 47a-48b* show that the longer lifespan leads to minor decreases in mass in- and outflow, but a shorter leads to almost a doubling in material in- and outflows compared to the other pathways. It seems that the more the lifespan of the objects is extended, the more slower the material flows and the more inert the system becomes.

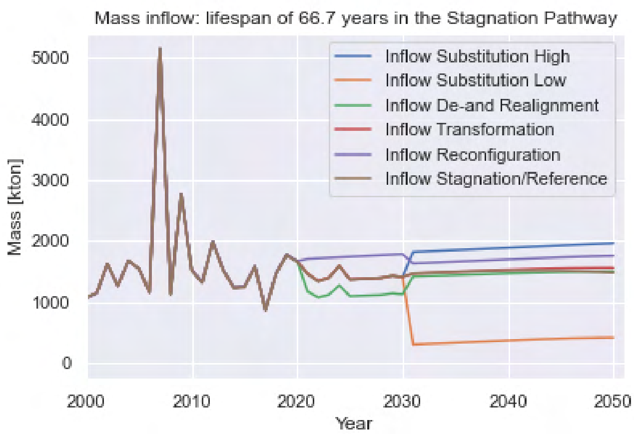


Figure 47a: Material inflows with a 20 year longer lifespan

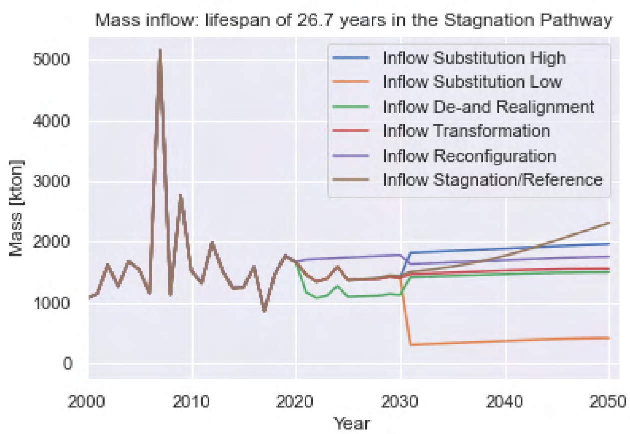


Figure 47b: Material inflows with a 20 year shorter lifespan

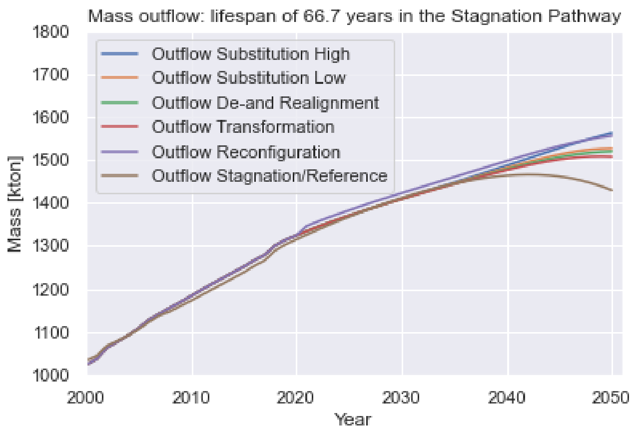


Figure 48a: Material outflows with a 20 year longer lifespan

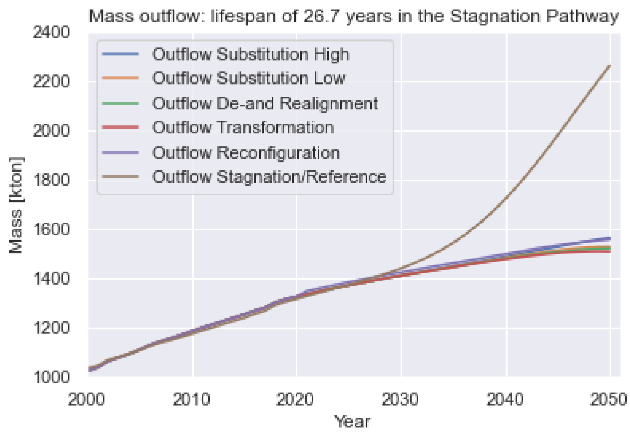


Figure 48b: Material outflows with a 20 year shorter lifespan

Sensitivity of the temporal scope

Since the results depicted that the material flows respond slowly to the driving forces, a sensitivity analysis was carried out with an extended temporal scope until 2070. This sensitivity analysis shows interesting results for the material in- and outflows of the pathways if the stock remains constant between 2050 and 2070 for each pathway (see *Figure 49a-c*). This sensitivity check demonstrates that the pathways with the longest lifespans compared to the Stagnation Pathway (Transformation with +30%, De- and Realignment with +25% and Reconfiguration with +20%) all manage to limit the in- and outflows in 2070. Especially the Transformation Pathway shows a decline in the size of the material flows as a consequence of the slowdown of the material cycle. This last sensitivity analysis demonstrates that a more circular use of materials in the long term can best be realized by improving the lifespan of the structures by means of repair and remanufacturing.

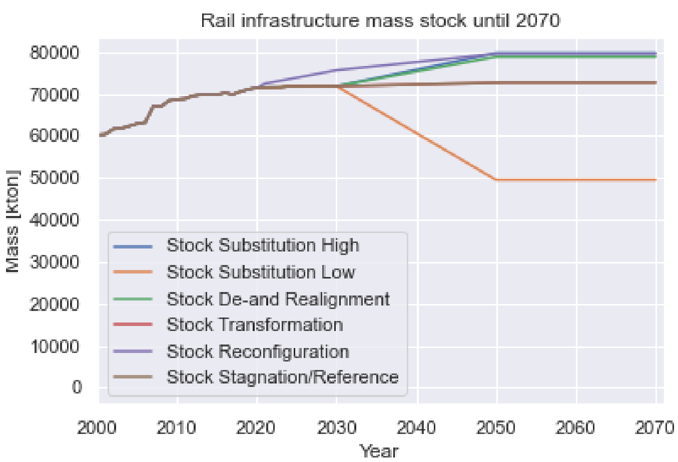


Figure 49a: Sensitivity with a constant stock between 2050-2070

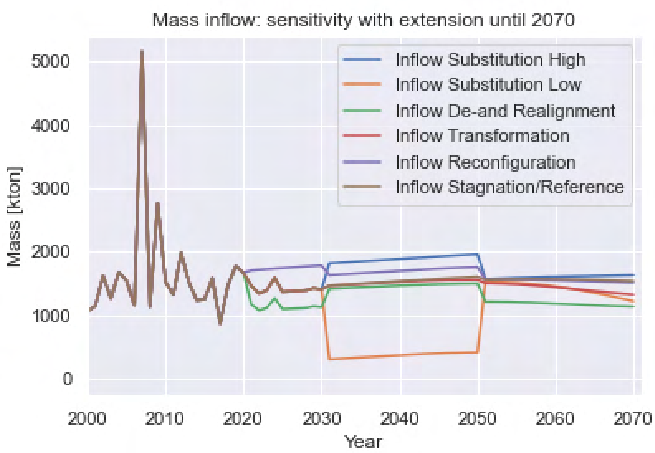


Figure 49b: sensitivity of inflows until 2070

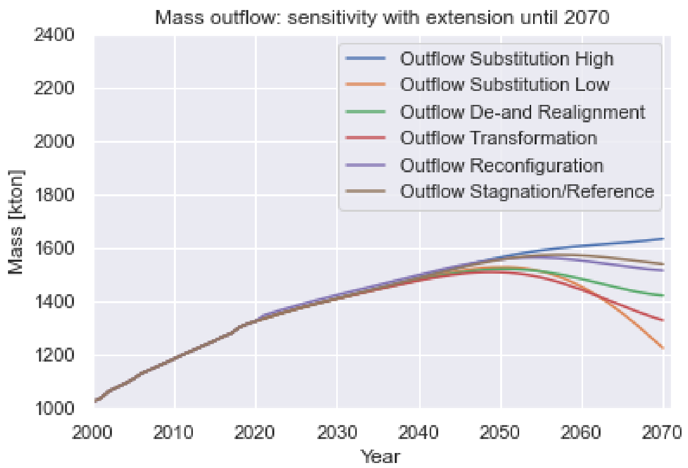


Figure 49c: sensitivity of outflows until 2070

Sensitivity of the Infrastructure Length Developments

The share of overcrowded routes that were given in *Chapter 2* is here utilized to check if the results in the period 2030-2050 for rail length increase based on rail passenger kilometers correspond with the share of overcrowded lines in the rail network. Between 2021 and 2050, the Stagnation and Transformation Pathways both lead to a small network length increase of about 153 km in total. On the contrary, the stock length declined by more than 2500 km in the Substitution Low Pathway. The most growth length is observed in the Reconfiguration Pathway (+842 km), the De- and Realignment Pathway (+869 km) and finally the Substitution High Pathway (+972 km). The Pathways with an increase of more than 400 kilometers cover the actual length of the expected bottlenecks in the WLO Low and the WLO High scenario as presented in the sub-chapter on proposed bottlenecks in the Dutch rail system in §2.2. The length growth of the pathways with a stagnating or growing number of travel kilometers therefore show that the bottlenecks identified in the WLO scenarios and the National Market and Capacity Analysis can be solved within the scope of the pathways.

Discussion on the Spatial Analysis

A disadvantage of this prospective MFA research is that it does not include the geospatial location of the stock length developments. A spatial approach that modeled the stock increases near the current overcrowded routes would have been useful. In this geospatial prospective MFA, an exploration of the future stock developments could be mapped and thereby the potentially interesting locations of the urban mine over time. For example, if a lot of rail infrastructure has been built in the last thirty years near the town of Almere, the pathways in a geospatial MFA could show, based on the age cohorts of the tracks, when the stock may become available for urban mining. A geospatial prospective MFA could not be carried out, since the passenger kilometer demand per railway route was not known, nor were the age cohorts of the railroad tracks.

Discussion on Stock-Driven Material Flow Analysis Modeling Choices

This stock-driven material flow analysis shows two findings that have to be discussed in further detail. Firstly, the division of outflows remains very similar over all the pathways. This can be explained by the modeling choice to use a mass weighted average of the lifespans of the objects from the material stock in 2018. Using this lifespan for prospective modeling presents an adequate overview of the stock mass that has to be replaced per year, but is not specific enough on which material has to be replaced in which year. A model with lifespan cohorts per railway object could have given more representative information on the specific timing of material replacements. However, such detailed lifespan information was not available.

Secondly, since the model was stock-driven, the material stock for the De- and Realignment Pathway, where the material intensity is considered 20% lower from 2021 onwards, is not accurate. In this pathway, the future stock should have been lower if it had been determined by the lowered material inflows. An inflow-driven model for this pathway could have solved this issue. This modeling choice was not made in this study in order to keep the stock-driven conditions the same under all the pathways.

Discussion on Using Rail Passenger Kilometers as a Driving Force

Using rail passenger kilometers as a main indicator of the rail network length development is based on the correlation between the past length developments of the network and its matching rail passenger kilometers. It is important to take in mind that correlation does not necessarily mean causality. Even though the log-linear regression analysis in this thesis shows a relationship between the rail passenger kilometers and the length of the railway network, the correlation coefficient does not include other factors that could cause the network length to change. Other factors influencing the rail length are land availability, spatial planning and (public) budget. A multiple regression analysis would be favored to test the strengths of these correlations on the network length. This regression could not be carried out in this thesis, since data on the considerations for railway infrastructure are lacking.

Another side note must be made regarding the limited data for metro and tram passenger kilometers. Since rail passenger kilometers in metro and tram networks have only been measured for five years, these data were limited to a smaller range of years compared to the train passenger kilometers.

In this research, rail passengers kilometers were used as a proxy for length development of the tracks. If the demand for rail travel (expressed in rail passenger kilometers) increases, more rail routes are constructed. Ideally, a time-lagged regression would be used to include the delay between the moment that more rail passenger kilometers are traveled and the new tracks are built. This study tried to take this delay into account by only including this proxy after 2030, so that there is time to plan for new constructions as the passenger kilometers grow. In future research, the optimal time lag for a regression could be determined by plotting a correlogram. A downside of this method is that it reduces the number of sampling points.

Discussion on Material Intensities as a Driving Force

Compared to the materials used in railways in the EU25 and an investigation of the subway system in Vienna, the quality of the data results on material intensities for The Netherlands can be further reviewed.

The material intensities (in metric tons per kilometer) for the EU25 were estimated at 308 t of concrete per km of single track and 616 t/km for double tracks. Other construction materials were estimated at 3,419 t/km single track and 6,837 t/km double track (Wiedenhofer et al. 2015). This thesis estimates a material intensity of 4,940 t/km single ballasted track for all materials combined in railways excluding the tunnel and bridge constructions. Compared to a total of 3,727 t/km from Wiedenhofer et al. (2015), the difference can be explained by the fact that the aggregate estimation in their study is lower. This higher estimation of aggregate use in The Netherlands was based on the first-hand data on life cycle assessments from ProRail. Research data on a double track ballasted high speed rail track in China give a material intensity estimate of 8,503 t/km. When dividing this intensity by two, 4,251.5t/km single track would be an estimation that resembles the material intensity estimate of this thesis better. Thus, in comparison to other rail material intensity estimates, the material intensities presented in this thesis research are based on reasonable assumptions.

With 37.1 t/m (or 37,100 t/km) the material intensities for the Dutch metro system are a lot higher than for trains. Still, this intensity is considerably lower than the material intensity for the Viennese subway network of 147 t/m (or 147,000 t/km). The difference is caused by the fact that more than half of the network length in Vienna was built in tunnels, whereas less than 20% of the Dutch metro network is built underground.

5.2 Discussion of the Results and Comparison with Literature

Transition Pathways in the Context of Railway Infrastructure MFA

In the context of this research, transition pathways aid in exploring the effects of technology, policies and behavior on railway infrastructure use. The typology of sociotechnical transition pathways from Geels and Schot (2007) is particularly useful in this context, because this typology makes a distinction in combinations of nature and timing of the multi-level interactions in the transition towards a circular economy in national infrastructure projects. This distinction helps to understand the dynamics of sociotechnical changes (such as technology, policies and behavior) and supports the decision-making process. More specific for this research: the model with transition pathways showed important distinctions in the development of the railway infrastructure stock and construction and demolition flows under different conditions of technology advancement, policies implemented and travel behavior. The pathways include premises on the sociotechnical dynamics of the system, which are functional for designing policies on circularity and further research on the sustainability of the system.

The theory and the application of the typology of sociotechnical transition pathways do have constraints, which are discussed in the following paragraphs.

The transition pathways each show a distinct model of the future in an idealized way. As with all simulations on future changes the pathways are theoretical extrapolations of past developments. In reality, the development will probably show a pattern that differs from the pathways explored in this thesis. It is likely that pathways occur in a sequence over time, which makes mixing of the pathways possible. Geels & Schot (2010) even state that a combination of various pathways is one of their propositions for well configured pathways.

The MLP and transition pathways are often used to show the internal logic of transitions that have taken place in the past (*ex-post*). Though, in this thesis research, the pathways were used for an *ex-ante* analysis of the trajectories of a transition towards circular material use that is yet to take-off. Describing premature transition pathways to influence transitions is promoted by Grin et al. (2010c). In their view, an *ex ante* analysis on the regime changes may aid in anticipating difficulties and to take collective action with stakeholders.

A disadvantage of the typology of transition pathways from Geels & Schot as mentioned by Kamp et al. (2010) is that the fixedness of the typology, where each pathway follows the same sequence of niches only entering the regime when regime actors lose their stable position and where landscape pressure defines the disruptiveness of the transition (Kamp et al. 2010). For this case study, the fixed typology with rigid sequences forms a good starting point for calculations, as it provides a theoretical structure to analyse hypothetical transition processes.

An interesting question is: which of the pathway designs is the most circular one? In terms of circularity, the Substitution Low Pathway is favored. This pathway leads to lower material in- and outflows than the Stagnation Pathway in 2050. The outflows are even lowest compared to all other alternatives, because of very low passenger kilometers traveled, leading to suspension of railway lines. However, this does not seem to be a realistic scenario. After all, the latest population projection by CBS estimates an even larger population growth than the WLO High scenario. Therefore, the De- and Realignment Pathway seems most feasible. This pathway assumes a passenger kilometer growth according to the WLO High scenario and a reduction in the material intensities while the lifetime of the assets is extended. Considering the mixing of the pathways, a form of disruptive change may have been started due to the effect of COVID-19 on rail passenger kilometers. This could have triggered a sequence of transition pathways, starting with the Transformation Pathway that has an immediate effect on the passenger kilometers and eventually leading to the De- and Realignment Pathway.

A blind spot in the retrieved results is the effects of modal shifts on material use for other transportation modes. The assumed doubling in rail passenger kilometers in the Substitution High Pathway is only a fraction (13%) of the annual car kilometers in The Netherlands. Therefore, it seems unlikely that a modal shift from cars to public transport leads to a smaller road infrastructure. Moreover, if a modal shift from cars to public transport is assumed, Geels (2012) argues that this demands a stronger emphasis on spatial planning strategies and significant regulatory and tax changes.

Data and Uncertainty

The information used in this thesis was based as much as possible on primary sources that provided data from first-hand evidence. However, data on the material content specifically tied to The Netherlands was very difficult to find. Even though the LCA reports with material contents and lifespans of the objects from ProRail gave a comprehensive impression of the objects used in railway infrastructure, various material stocks were estimated based on industry data and other European studies, of which the exact applicability to The Netherlands remains uncertain. The wide range of materials, different objects and transport modes involved in this study are other factors of uncertainty, which may have caused under- or overestimations of the stock.

Due to limited data availability, some assumptions have been made for a simplification of the analysis. For example, it was assumed that all railroad ties were made of concrete, since it is expected that wooden sleepers will soon be replaced by concrete variants. The latter expectation is based on the lifetime of a wooden sleeper of about 25 years and the fact that at the end of the 20th century construction techniques of railroad ties already switched almost entirely to concrete.

No data on larger stations was found for the analysis, except for data on Rotterdam's Central Station on the website of the National Steel Prize. The construction of German stations from the report by Schmied et al. (2013) could have been used, but the problem is that large stations in The Netherlands generally have unusual constructions and can therefore not be assumed from an international comparative study. Since no field data on the material mass of these constructions was available, it was decided to leave them out of the analysis, except for the central station in Rotterdam. This has probably led to an underestimation of the steel, concrete, aluminium, timber and glass stock. The glass stock has been excluded from the reporting, since the absence of material intensity data on stations and noise barriers with glass panels led to a negligibly small stock.

More underestimations are likely, since only the level crossings in centrally served areas, tall light signals, and fencing and noise barriers that were specified in the geodatabase (such as wire mesh and bar fencing) have been included. It must be stated that not including the other types of level crossings, signals and fencing and noise barriers leads to an underestimation of the steel, concrete, glass and aluminium stock.

Despite the assumptions and data uncertainty, the order of magnitude of the results have been confirmed by ProRail and academic studies show similar stock results. The estimation of the metro stock in this thesis is very similar to the estimation of Vienna's subway lines. These consist of 90% concrete, 5% aggregates (gravel), 5% steel and less than 1% of other materials, such as copper and aluminium (Lederer et al. 2016). It should be noted that, despite this similarity with other studies, the analysis is an estimation of the stock and cannot be interpreted as a complete calculation of the material stock in railway infrastructure.

In the prospective part of the modeling, uncertainty in the retrieved scenario data led to additional assumptions. For instance, the passenger rail kilometer development scenarios for trams and metros were used until 2040 instead of 2050, since this was the last year of the WLO scenarios for local rail transport modes. It was therefore assumed in this thesis that the passenger kilometers for metro and tram will be the same in 2050 as in 2040. This possibly erroneous assumption was used because no estimations were available for the years 2040 to 2050 for metro and tram passenger kilometers and because the share of these transport modes is small in relation to annual train passenger kilometers. Hence, it was presumed that this extrapolation would not drastically change the final result of the analysis if proper data were available.

Furthermore, an estimation of the future pathways of freight network infrastructure material was not part of the analysis due to the fact that there was no clear driving force for stock expansions or reductions. The ton kilometers of the transported goods have a smaller effect on the infrastructure demand than passenger kilometers, because cargo transports can be distributed more evenly during the day than travelers. Another reason to omit separate freight developments from the dynamic analysis is that there is only one bottleneck expected in the infrastructure near the German border and a solution to this bottleneck is currently under construction. This extension was included in the analysis for all the transition pathways, but in order to get a better view on circularity in the rail freight infrastructure a separate analysis should be carried out.

Comparison with Other Material Stocks in The Netherlands

As presented in *Figure 45,* the Dutch railway infrastructure stock weight is with its 71.7 Mton almost twice as big as Dutch vehicle stocks (36.3 Mton, Van der Zaag, 2020) and nearly 10 times as big as the Dutch electricity infrastructure stock (7.5 Mton, Van Oorschot et al., 2020).

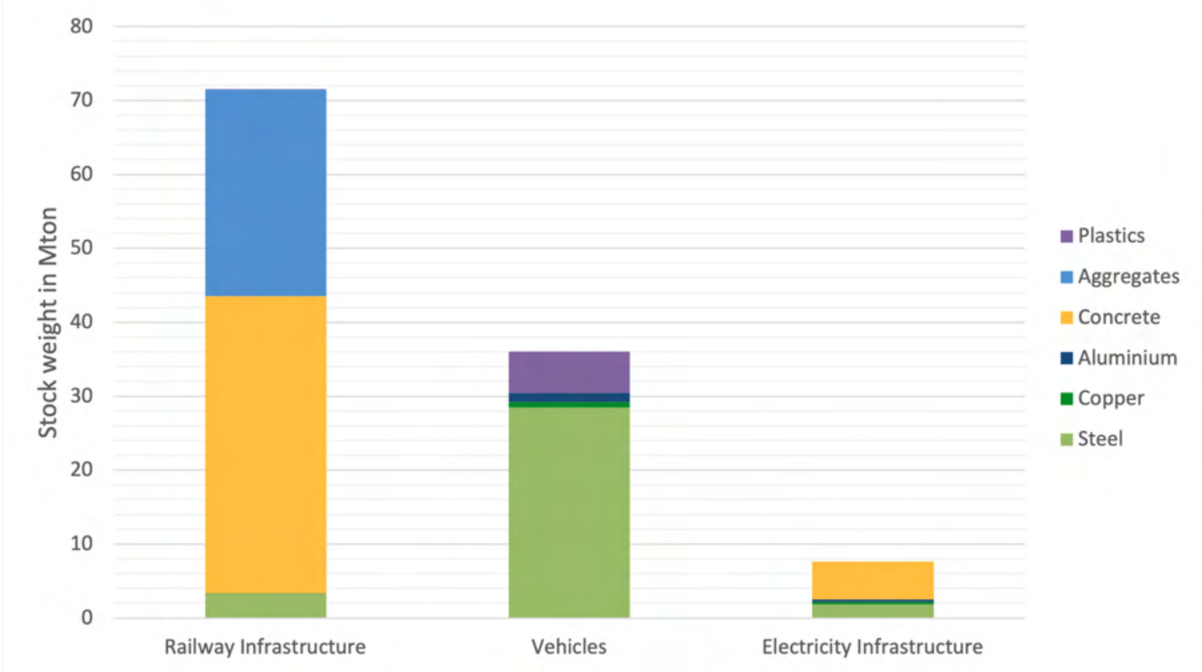


Figure 45: comparison of total stock weight of rail infrastructure (stock year 2018) with vehicles (2017) and electricity infrastructure (2017) in The Netherlands from Van Oorschot et al. (2020a).

Wiedenhofer et al. estimate the road stock in the EU25 at 128 t/capita (Wiedenhofer et al., 2015). This estimation suggests that the road infrastructure in The Netherlands would be, with about 2186.2 Mton, more than 30 times bigger than rail stocks. It must be reported that more than half of the rail infrastructure stock consists of nonmetallic minerals. This division is probably similar for the road infrastructure stock.

The literature on material weight use *per capita* shows similar results for The Netherlands and the EU. The stock estimation in this thesis of 4.15 ton rail infrastructure weight per capita is close to the EU25 estimation of 3 t/c in railways, which did not include rail tunnels and bridges (Wiedenhofer et al., 2015). The difference between the estimation from this thesis and the study from Wiedenhofer et al. (2015) can be explained by the missing mass of tunnels and bridges, which contribute to 40% of the stock weight in The Netherlands.

In relation to research on other material stocks in Dutch society (van Oorschot et al. 2020a), it can be observed that the steel content in Dutch rail infrastructure equals 3.25% of the steel stock in buildings and slightly more than 10% of the stock in vehicles in The Netherlands (see *Figure 46b*). For copper, railway infrastructure accounts equals almost 10% of the building stock and a similar percentage of the vehicle stock. Aluminium stocks are very small compared to buildings and vehicles, with a share of 0.65% and 1.08% of their totals respectively (see *Figure 46)*.

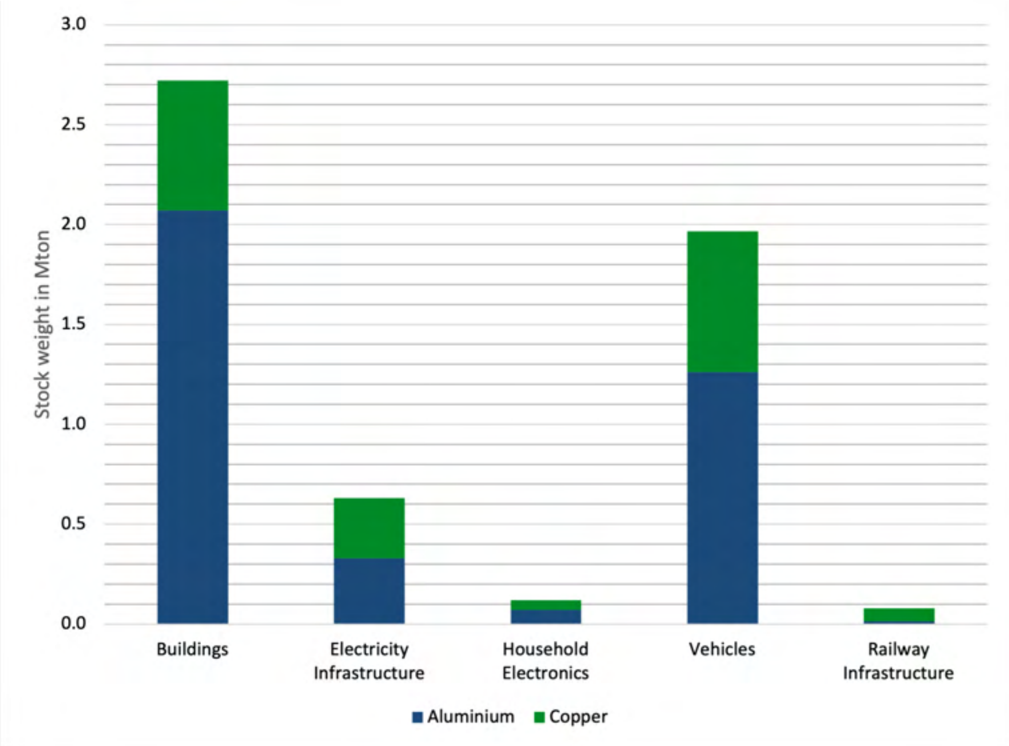


Figure 46a: Copper and aluminium stock of railway infrastructure (2018) compared to other Dutch material stocks (data from 2017).

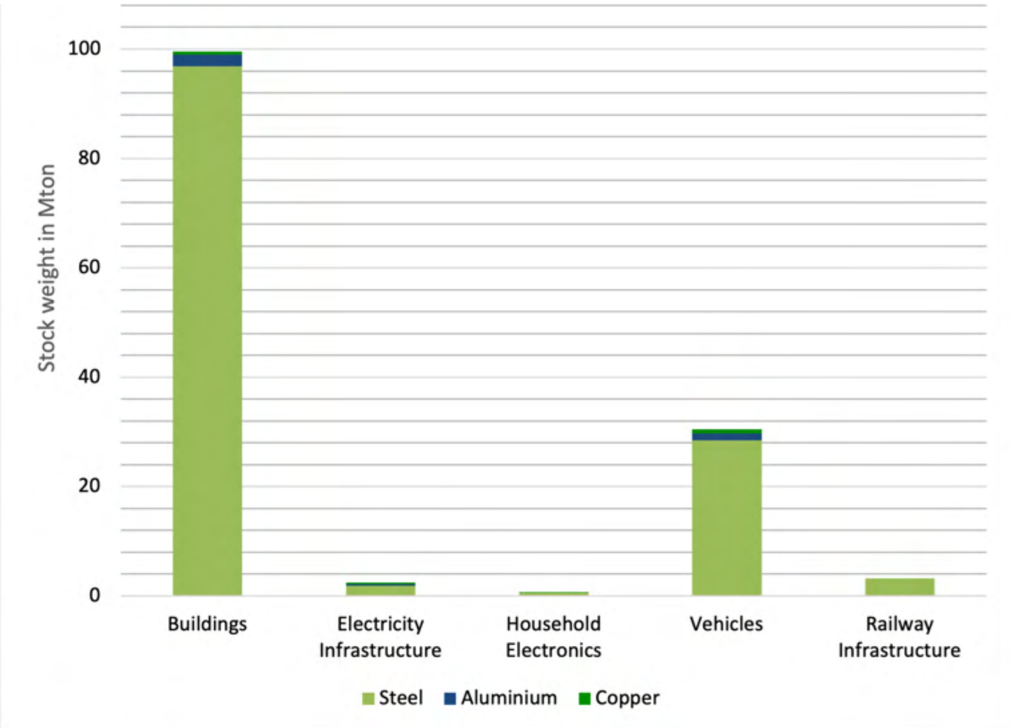


Figure 46b: Steel, copper and aluminium stock for railway infrastructure (2018) compared to other Dutch material stocks (data from 2017) (van Oorschot et al. 2020a, 2020b).

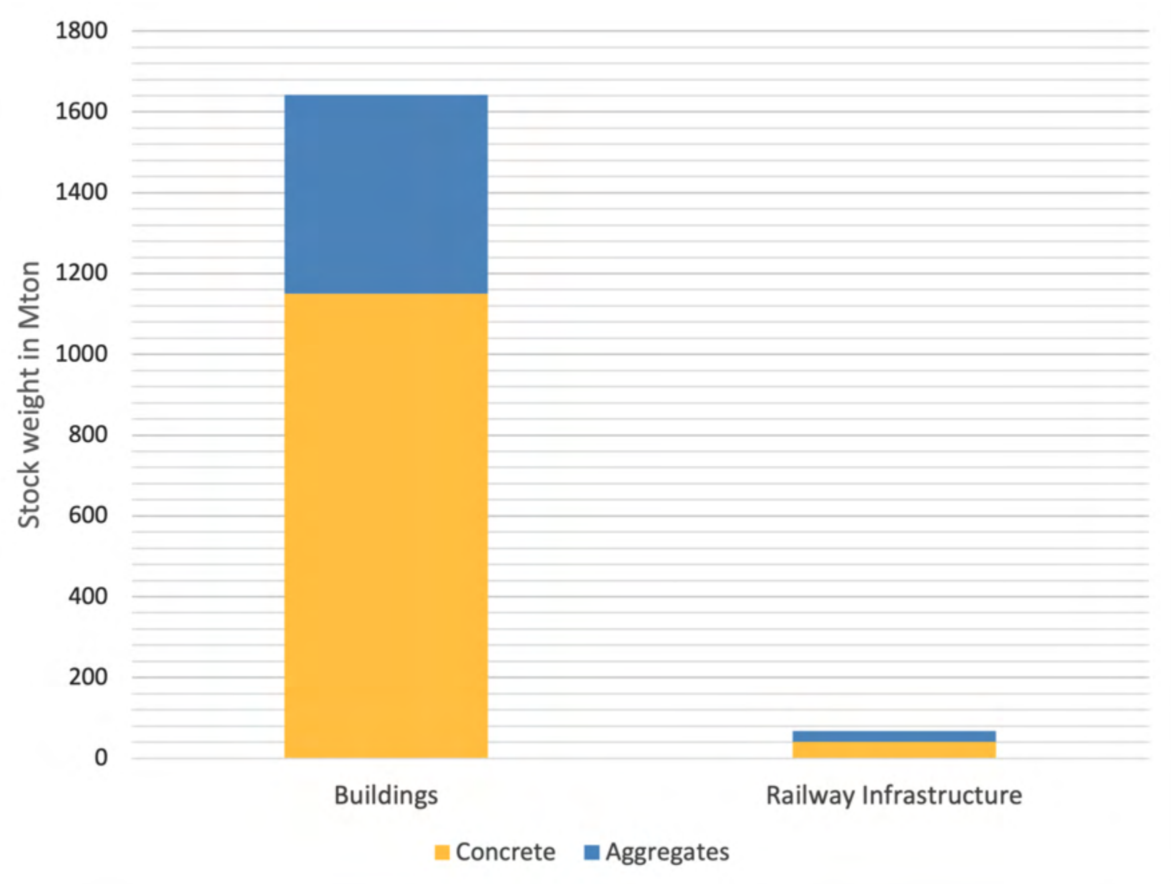


Figure 46c: Concrete and aggregates for railway infrastructure (2018) compared to the Dutch building stock (van Oorschot et al. 2020b).

The size difference between concrete and aggregates in the rail infrastructure versus buildings is demonstrated in *Figure 46c.* It is important to note, however, that aggregates in buildings were retrieved from the category 'other construction minerals' in Heeren & Fishman (2019), which combine aggregates, gypsum, asbestos and mineral filling in this category rather than only gravel that was used for aggregates in this research on railways.

Comparison of the Material Intensities

Material intensities for the railroads, without tunnels and bridges, in the EU25 have been estimated at 7,453 t/km for a *double track* railroad (Wiedenhofer et al. 2015). In this study, a *single track* railroad including tunnels and bridges had a material intensity of 7,570 t/km. This difference is explained by including the tunnels and bridges and a higher estimation of aggregate. In comparison, material intensities in railways (in metric tons per km) are considerably lower than material intensities for roads. For example, while an average European double rail track uses 7,453 t/km of construction materials, motorways use 40,205 t/km and even average provincial roads have a higher material intensity, with 9,212 t/km respectively (Wiedenhofer et al. 2015).

Discussion of the Actor Relationships

Governance is the process of steering that is not shaped by central control (from a government), but implies the assignment of a prominent role to an interacting state, market and society (Grin et al. 2010a). In this thesis, the actor realms for good governance were shaped around the institutional rectangle of market, state, science and civil society. Grin et al. (2010) understand this structure as a result of a historical co-evolution process within these four actor groups. Therefore, governing transitions, such as the material transition towards a circular economy, is based on a re-orientation of interactions within the institutional rectangle. The actor relationships that were stressed in each pathway of this research influence the effectiveness of the driving forces in the model. Their role is discussed in the paragraphs below.

Actor Analysis for the Driving Forces

Since the rail sector is a much more state steered market, compared to other modes of transport, it was expected that state designed policies and regulations will dramatically impact the transition directions to a circular economy in Dutch rail. The actor analysis in this section discusses the co-evolution in the societal realms for each of the three driving forces.

A longer lifespan of the objects leads to a delayed outflow of demolition materials. Lifespan elongation requires a strong governance structure with committed actors that help to coordinate a longer lifetime of the railway infrastructure objects. This also involves a behavior change: planning schemes must be centered around optimizing the lifespan of all objects. While currently the materials of an entire track section are replaced for reasons of cost and time efficiency, an integral CE policy should lead to less material waste. Key actors are the state that secures the budget and planning for national infrastructure projects, and the market, which are the contractors.

A lowered material intensity immediately results in smaller inflows. Using less materials can be a market-driven process based on efficiency, but requires adequate safety and lifespan testing by the industry and scientists under the responsibility of authorities. The societal realms that play a key role in this driving force are the market and science with support from the state.

Finally, changes in the rail passenger kilometers are directly linked to behavior of market actors such as travelers that demand mobility via the railway network and the railway operators that supply in mobility capacity. These operators (such as NS or Arriva) can facilitate a growing number of passenger kilometers by offering an expanded timetable and longer vehicles. Also, the number of rail passenger kilometers can be influenced by the state, such as the government that called to travel by public transport only when strictly necessary during the coronavirus pandemic.

Thus, the driving forces of the pathways have some extent of hybridization of the institutional structures, such as integral policymaking for a circular economy and interdisciplinary knowledge production on material intensities.

Urban Mining Potential of the Rail Infrastructure Stock

The current and potential circular applications of railway infrastructure have been discussed in §4.7 in the results chapter. The railway infrastructure stocks in The Netherlands have, contrary to building stocks, a small number of owners. This can be advantageous for urban mining as this makes material extraction and network management easier and better to plan. Moreover, limited ownership makes it easier to monitor stocks and flows in the railway infrastructure. A final discussion point on the urban mining potential is that the hibernating stock does not seem a relevant source for urban mining in railway infrastructure, since the stock is relatively small and a considerable part of the hibernating stock appears to have been taken out of service only temporarily.

Comparison with Circular Economy Policy Goals

The premise of this study is the definition of a circular economy from Kirccherr et al. (2017) that materials at their end-of-life are reduced, reused, recycled and recovered in order to create social equity, economic prosperity and a liveable environment. The requirements for circular national infrastructure projects as designed by Dutch policy makers are 50% less primary material input in 2030, minimizing waste and high-grade reuse of resources (Ministerie van I&W 2020).

A comparison of the feasibility of this circular economy goal with the material flow explorations and their urban mining potential gives insight into the potential of urban mining for a circular economy. The Reconfiguration Pathway in this thesis research assumed that the proposed Dutch national CE policies for infrastructure projects are carried out. The pathway shows that a growing number of passenger kilometers will lead to more material inflows. This is problematic for a circular economy, as is presented by the following example. Zhang et al. (2020) studied future concrete flows for The Netherlands and in their most optimistic scenario for 2025, inflows of new concrete could have reached a recycled aggregate content up to 16% of its weight, whereas maximum ⅓ of all concrete outflows can be recycled at a high grade for such aggregates (i.e. recovered to use again in concrete manufacturing). The rest downcycled as a road base.

For railways, in a most optimistic scenario, 84% of concrete inflows will be of virgin material, leading to a total virgin material inflow of 50% in the railway infrastructure in 2030 in the Stagnation Pathway. Under all pathways, concrete is an essential inflow for maintenance work. This means that even under optimal circumstances with novel recycling technologies, the short-term inflow for concrete, the largest material category by weight for rail infrastructure, will be largely dependent on virgin materials from conventional mining sources. The virgin concrete demand threatens the potential of the circular economy goal of 50% reduced abiotic inflows in 2030 (Rijksoverheid 2019). This goal can only be reached if the general demand for construction materials is significantly reduced, such as in the Technological Substitution Low Pathway, or if *all* other material inflows than concrete consist almost completely of recycled content. It can thus be concluded that the reduction goal cannot be reached as long as the stock remains the same size or is growing and as long as concrete is the main inflowing material.

A general remark on the circular economy objectives from the Ministry of Infrastructure and Water Management is that not all environmental, social and economic dimensions are covered in their definition for a CE. As presented in the definition from Kirchherr et al. (2017) in the introduction of this thesis, a circular economy should include the dimensions of sustainability, too. As this thesis shows, the narrow definition used by the ministry also works its way into practice. By way of illustration, a number of topics of environmental concern regarding the proposed circularity measures are presented in the next sub-chapter.

5.3 Environmental Effects

As shown in this thesis research, dissipation may lead to large concentrations of heavy metals (such as iron) in soil and water. Plants in the vicinity of rail tracks take up these heavy metals in their aerial parts and roots (Wiłkomirski et al. 2011). Wiłkomirski et al. (2011) state that the contamination of plants near rail sites with heavy metals is too high, but generally not as alarming as the concentrations of carcinogenic polycyclic aromatic hydrocarbons (PAH). PAHs are released from coal-tar creosote that was commonly used in wooden railroad ties and in machine grease and fuel oils. One application that uses machine grease is the wheel-rail conditioning technique that is rolled out in The Netherlands to extend the lifespan of rail tracks.

Wheel-rail conditioning is an application of grease and fine particles to lubricate the rails. These oils, grease and particles are emitted into the environment, but to the author's best knowledge, no emission factor data are available for these substances in railways. A study on the environmental emissions of railways in Switzerland used the inflow of these substances to get an impression of the use, but has no dissipation data either (Burkhardt et al. 2008). The oils used for lubrication in Switzerland are a mixture of inorganic synthetic oils with an undefined part of additives and solid particles that do not contain priority pollutants such as halogen compounds, heavy metals or polycyclic aromatic hydrocarbons (PAH). However, synthetic oils can be hazardous to the environment (Nowak et al. 2019). To estimate the environmental threats of the application of greasy substances in railways, the leaching effects of bioaccumulation must be studied in further detail.

A study on the environmental hazards of railways mentioned that railway infrastructures are associated with substances leaking from railway ballast to groundwater or surface water (Burkhardt et al. 2008). The same study shows that the composition of rails is >97% iron and about 1% chromium and 1% manganese, which leads to a total emission of the Swiss railway track of 475 tons per year due to wheel-rail contact. The Swiss train railway system measures about 7200km, which is comparable to the length of the Dutch network. It is therefore assumed that the abrasion quantities from rail tracks will be similar for The Netherlands.

Human health is another condition that is important to take into account during reuse and recycling work in the railway sector. As presented in this report, a ballast cleaning machine (in Dutch: kettinghor) can recycle up to 100% of the ballast on site, which is circular from a material perspective. However, both the granulite and porphyry ballast material used in the tracks in the Netherlands release significant amounts of the carcinogenic respirable crystalline silica (RCS) when they are moved with a ballast cleaner. Hence, circularity does not necessarily lead to sustainability in terms of human health if no safety measures such as dust masks or ballast material without silica are used.

A life cycle assessment (LCA) on high-speed rail infrastructure in France identified that the environmental hotspots are in rails, construction of the roadbed, civil engineering constructions and end-of-life choices. The largest environmental impact was assessed from rails (10-71%, minoring and majoring the effects of eutrophication and ecotoxicity respectively), with the largest share during the maintenance and end-of-life stages (de Bortoli et al. 2020). A dominance analysis on the materials used in the infrastructure of a passenger railway line in Sweden also showed that steel use in rail tracks contribute most to the environmental impact category global warming (Stripple and Uppenberg 2010). Cement came second with a more than 20% contribution to global warming of infrastructure material in tunnels and bridges. As these LCAs show, again, steel reuse offers the most attractive case for design for circularity, also from an environmental impact perspective.

6. Conclusion & Recommendations

This thesis applied an accounting and prospective material flow analysis (MFA) model to railway infrastructure in The Netherlands in order to explore the potential for a circular economy based on anthropogenic stocks from the urban mine. The accounting step resulted in an estimation of the current material stock in railway infrastructure. The prospective analysis explored pathways for a transition towards a circular railway infrastructure. Driving forces for the model were based on lifespan of the stock, rail passenger kilometer development and material intensities.

The conclusion section answers the main research question on the size of the material stock and flows in the rail infrastructure in The Netherlands and how these could change towards 2050, considering different transition pathways.

6.1 Synthesis and Conclusion

The current material stock in the Dutch railway infrastructure is dominated by heavy-weight nonmetallic materials, such as concrete and ballast material. With almost half of the total stock weight, railway track infrastructure covers the majority of the mass estimation. The steel share of the total stock weight is almost 5%, of which 40% is stored in railway tracks. With less than 0.25% of the total mass share, copper, aluminium, timber and plastics cover a small mass proportion, but non-ferrous metals have a relatively high economic value on the secondary market.

This thesis has highlighted the centralized spatial distribution as potential recovery hotspots in the railway infrastructure stock. The material stock is centered in municipalities with high densities of engineering constructions such as tunnels and bridges and in municipalities with a dense urban rail network of metro, light rail and trams. This spatial concentration provides more information on where secondary materials could be mined from the anthroposphere.

It can be concluded from retrospective stock analysis that while inflows of rail infrastructure materials have been fluctuating over the past decades, the outflows of materials (demolition flows) at the beginning of the 21st century have been increasing steadily. The increasing outflow marks the maintenance flow of objects that are at the end of their lifetime and offers an interesting target for policies on the circular economy.

Future development trajectories in a dynamic stock-driven Material Flow Analysis (MFA) were explored in 'transition pathways': transition trajectory explorations based on pathways for sociotechnical transitions by Geels & Schot (2007). A reference pathway was derived from the Low Scenario on mobility development from the 'Toekomstverkenning Welvaart en Leefomgeving' (WLO, Future Exploration on Prosperity and Environment) published by the Netherlands Environmental Assessment Agency (PBL 2015). The Reconfiguration Pathway adopted national policy targets for climate neutral and circular national infrastructure projects (Ministerie van I&W 2020). Each pathway used a combination of driving forces that can alter the future material demand: rail passenger kilometers traveled per year, material intensities and the lifespan of the stock.

The other four pathways in the prospective MFA were the Technological Substitution High Pathway, assuming a doubling in annual rail passenger kilometers and the Technological Substitution Low Pathway, which assumed a very low number of annual passenger kilometers. The De- and Realignment Pathway adopted the WLO High scenario on rail passenger kilometers, a 25% longer lifespan for rails and 20% lower material intensities. The Transformation Pathway presumed annual passenger kilometer developments according to the WLO Low scenario, no changes in material intensities and a 30% longer lifespan for rails.

The De- and Realignment Pathway offers, to current knowledge and projections, the most potential for a more circular railway infrastructure in terms of minimizing material in- and outflows while the network keeps growing. In this pathway, a high population growth with an increasing number of rail passenger kilometers is assumed, while the material in- and outflows slowly decline toward 2050 in comparison to the Stagnation Pathway. By comparing different hypothetical trajectories of change, this thesis tried to find a best practice scenario for railway material use. It should be noted, however, that this theoretical approach only serves as an exploration of the options. In reality, a combination of pathways will probably better represent the developments.

The prospective part of the MFA showed that the railway infrastructure system responds slowly to adjustments such as lifespan extension or lowered material intensities for a circular economy. This is due to the long lifespan of the constructions and the relatively small impact of increasing travel kilometers on the length of the network. Still, based on the cumulative prospective flows, it is expected that in all pathways except the Substitution Low Pathway, about half of the stock mass in 2050 will consist of materials in objects that have been constructed between 2021 and 2050.

The urban mining potential for the analyzed materials estimated that 33% of the outflowing material mass from the railway infrastructure stock can re-enter the rail infrastructure system. Another 27% of the materials can be recycled at a high-grade for applications in other industries than railways. In general, an advantage of the urban mining potential for rail stocks is that railway infrastructure in The Netherlands has, contrary to buildings, a small number of owners. Closing the material loop is not feasible due to the fact that inflows in most pathways keep larger than the outflows.

Furthermore it was observed that, even with the current highest recycling techniques, the Dutch national policy goal to reduce the inflow of primary abiotic resources by 50% in 2050 is not feasible in the railway infrastructure, since the main construction material is concrete. The potential environmental effects of the researched circularity measures prove that circular options for lifespan extension do not necessarily lead to sustainability. This research highlights that ecotoxicity and human health should be taken into account when material efficiency techniques are implemented.

In short, managing the transition toward circular railway infrastructure materials urgently demands a clear strategy to limit the material in- and outflows. Lifespan elongation proved to limit the material outflows in the long run, whereas inflows can be limited immediately by lowering the material intensities. Railway tracks show the most productive case for design for circularity, because they cover almost half of the stock weight, have a high environmental impact when virgin material is used and they have a relatively short lifespan.

Ultimately, this study has stressed that hybridization of societal realms, such as interdisciplinary know-how on material intensities and comprehensive policy making for a circular economy, are important drivers in the transition processes. Therefore, recommendations for a transition towards a circular economy in the railway infrastructure have been given in the final paragraph of this thesis for each societal realm in the institutional rectangle (state, science, market, civil society).

6.2 Recommendations

Based on the lessons learned from this thesis research, the following actions are recommended for academics, decision makers, businesses and the general public.

Recommendations for Academics (Science)

Five knowledge gaps identified in this research need more academic attention. First, more research is needed on material extraction from the railway infrastructure as an urban mine for a circular economy. In doing so, the environmental, economic, and social impacts of the EoL railway infrastructure material management have to be studied. In particular, the environmental hazards from dissipation must be researched extensively when lifetime extension techniques of railway tracks are considered. Second, a hotspot analysis is needed that explores the future geospatial development of the material stocks. Inflow-driven modeling of the stocks is used if material intensities are expected to change in the future. A geospatial database based on these prospective MFAs aids in finding locations that may become future hotspots of outflowing materials. Third, the blind spots of this study, future material developments in rail freight infrastructure and the change in materials in other transport infrastructure systems caused by modal shifts deserve more attention in academia. Fourth, academics should participate in niche development that could close the loop for material use in the railway infrastructure sector, starting with the assets that have the shortest average lifespans: railway tracks. The technological innovations, but also the social innovations should be subject of further study. Fifth, the environmental hazards of lifespan extension techniques and dissipation must be studied in further detail. An example of how the environmental impacts of circular options in railway infrastructure have been researched before is the safety and sustainability analysis of railway sleeper alternatives that has been carried out by the Dutch National Institute for Public Health and the Environment (Quik et al. 2020).

Recommendations for Decision Makers (State)

For decision makers, as they are the most powerful actor in the railway infrastructure sector, three improvements are recommended for a more circular rail sector. First, decision makers should demand circularity standards when procuring rail infrastructure materials. Such a standard may require a minimum recycling content in new material applications. Second, strategic planning policies should prioritize lifespan extensions of the stock. Caution is advised regarding measures that can pose a threat to the environment. This thesis research has demonstrated that pathways that focused on elongating the short-lived material cycles in railway tracks had a larger circular economy potential. Therefore, pathway choices that extend the lifespan of the stocks are recommended. Third, the power of local governments has to be taken into account. Local governments play an important role in the transition. Municipalities with high rail infrastructure densities have the power to force circular procurement of materials for infrastructure renewals. A national framework on circular and sustainable procurement for railway infrastructure should aid municipalities in this task.

Recommendations for Businesses (Market)
Currently, a lot of money is invested on research and development of niche innovations for circularity and it is recommended to businesses to keep involved in these processes. In accordance with De Bortolli et al. (2020) particularly more research and development on life cycle improvements in the steel and concrete industries are recommended. On the other hand, business plans to successfully implement innovations at a larger scale are lagging behind. It is recommended that niche innovations, such as reusing rails on site, are implemented faster through public-private partnerships. Furthermore, it is recommended to put up a material stock monitoring scheme in railway infrastructure. This thesis estimated the order size of the stocks, but structurally calculating the use of materials helps to identify the exact potential of a sustainable and circular economy. For example, this monitoring could be combined with the geospatial database that is one of the recommendations for academics. Moreover, as a general remark for the recycling industry, it is recommended to separate the collection schemes of non-ferrous metals such as copper by different alloys. This makes high-grade copper recycling for rail infrastructure possible.

Recommendation for the General Public (Civil Society)
Behavior change to switching to or abandoning rail transport influences the materials used in the railway infrastructure. By choosing more rail transportation, the demand for materials in railway infrastructure increases. However, this increase in construction material demand is smaller than the amount of infrastructure material released by demolition if travelers switch to less rail travel. From a sustainability perspective, more rail travel is favored. Thus, since most of the construction and demolition waste presently cannot be reused or recycled at a high grade, a travel option that leads to a minimum of outflowing materials over time that can accommodate a growing number of rail passenger kilometers should be favored.

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Lowik
Delft, April 2021

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Front page image

Aerial view of the intersection near The Hague Central Station. 2017. *ProRail aerial photographs of the Dutch Railway.* https://twiav.nl/nl/luchtfoto_prorail.php#14/52.0751/4.3343 Accessed April 8, 2021.

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Appendix A: Core Concepts

The core concepts of this research are the circular economy, sustainability, and urban mining. The definitions and their relationship with the Dutch policies are discussed in this section.

Circular economy

Like the European Union, The Netherlands has committed to achieve a 'Circular Economy' by 2050. The Dutch government connects CE to the goal of limiting material input, aiming that this results in a sustainable future: 'In a circular economy, we deal efficiently and socially responsible with products, materials and resources within the carrying capacity of the earth, so that future generations also retain access to material prosperity' (Rijksoverheid 2016, 8, translated from Dutch).

The International Union of Railways announced in 2019 in the Railway Strategy for Europe that Circular Economy principles should be integrated in design, construction, operation and maintenance of the infrastructure (International Union of Railways (UIC) 2019). As mentioned in the introduction, the circular economy principles and definitions are, however, far from crystallized (Kirchherr et al. 2017).

Korhonen et al. (2018) define the concept of circular economy (CE) as a reverse flowing version of the current linear economic system: in which energy and materials are re-used. The authors admit that this is not a flawless explanation, since energy can't be physically recycled, but they argue that it can trickle down as a secondary source (e.g. waste heat). They summarize CE for sustainability as an environmental goal "to reduce the production-consumption system virgin material and energy inputs and waste and emissions outputs (physical throughput) by application of material cycles and renewables-based energy cascades." (Korhonen et al. 2018, 41). This definition is limited to environmental performance improvements. Most CE definition authors do this and ignore the economic and social dimensions in their conceptualizations (Geissdoerfer et al. 2017).

Critics argue that a completely circular economy, with no virgin material inflows, is not feasible because of the thermodynamic and ecological nature of the system (Skene 2018). Dissipation (waste production) will remain due to specific material compositions that are irreversible or naturally leak to the environment over time. According to the second law of thermodynamics, this is related to an increase in entropy (a quantity showing the unavailability of a system's thermal energy for conversion into mechanical work).

To avoid a discussion on the completeness of a CE that can be evoked by the definition by Korhonen et al. (2018), I will use the more holistic definition of Kirchherr et al. (2017) for this research, who define a CE as:

"an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, [...] with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations." (Kirchherr et al. 2017, 224–225)

Sustainability

The CE definition by Kirchherr et al. tries to incorporate all three dimensions of sustainability in an economic system. The triple bottom line of sustainability: people, planet, profit (Elkington 1998) is paraphrased Kirchherr et al.'s definition: "environmental quality, economic prosperity and social equity". Geissdoerfer et al. (2017) summarize the concept of sustainability as "the balanced integration of economic performance, social inclusiveness, and environmental resilience, to the benefit of current and future generations" (Geissdoerfer et al. 2017, 766). The Brundtland report echoes in both definitions, that was the first to define 'sustainable development' as a concept that "meets the needs of the present without compromising the abilities of future generations to meet their own needs" (World Commission on Environment and Development 1987).

Moreover, Geissdoerfer et al. (2017) explained the differences and similarities between the concepts of circular economy and sustainability, based on a literature review of 67 publications. Both concepts are based on a multidisciplinary research field with multiple stakeholders involved to achieve their goals. Sustainability and CE have in common that their scope is both inter- and intragenerational and that regulations and incentives are among the main implementation strategies. Businesses are a key player for both concepts because of their competences and resources. Innovation and system redesign and change are at the core of both concepts (Geissdoerfer et al. 2017).

Whereas the main goal for sustainability is an open-ended system that is defined by the interests of its agents, the CE's ideal aims are a closed-loop system that has no virgin resource input and no leakages. In a sustainable system, agency is more diffused while the main influencers of a CE are companies, governments and NGOs. Sustainability is a concept that uses 'vague framing' (sic) that is applicable in a broad context, while the CE mainly focuses on environmental and economic benefits (Geissdoerfer et al. 2017).

Urban mine

Material stocks for a CE are likely to be found in the 'urban mine'. The 'urban mine' is seen by the Dutch government as 'the built environment as a mine for new materials' (Rijksoverheid 2016, 56). Similarly, during a course on GIS and Urban Mining the urban mining approach was defined as: "considering stocks of materials in society as a resource for the future, comparable to geological stocks" (Van der Voet 2019, 5). Urban mining isn't a practice yet, but the concept mainly follows the methodologies of traditional mining, starting with exploration and prospecting, followed by analyzing the economic feasibility and finally obtaining permits and starting operations. According to Cossu & Williams (2015), urban mining will offer a way to extract anthropogenic stock materials while bringing it back into the economy as a secondary raw material resource.

An advantage of urban mining is that secondary stocks in urban locations could function as an alternative to traditional mining and can be recovered for environmental benefits (UNEP 2011).

Appendix B: Railway Bottlenecks and Proposed Extensions

Bottlenecks and short-term proposed extensions that have already been budgeted from the Meerjarenprogramma Infrastructuur, Ruimte en Transport (MIRT) (Rijksoverheid 2020b) and in the Netverklaring 2022 by ProRail with a mid term planning until 2027 (ProRail 2020).

Bottleneck	Solution	Finished
• Groningen - Europapark	Extending from 2 to 4 tracks	2020
• Driebergen - Zeist	Extending from 2 to 4 tracks	2020
• Theemswegtracé	Extension	2021
• Calandbrug	Replacement	2021
• Zwolle - Herfte	Extending from 2 to 4 tracks	2021
• Amstelveenlijn	Conversion of metro to tramline	2022
• Zevenaar - German border	Connect to three-track rail	2022
• Nijmegen - Roermond	Electrification	2023
• Nijmegen - Roermond	Partial track extension	2024
• Rijswijk - Delft Zuid	Extending from 2 to 4 tracks	2024
• Station Den Haag CS	Adjustment railroad yard	2024
• Station Haarlem	Adjustment railroad yard	2024
• Station Ede-Wageningen	New station	2024
• Almelo - Mariënberg	Electrification	2025
• Station Amsterdam CS	Reorganization of the tracks	2025
• Zutphen - Hengelo	Electrification	2025
• Station Amsterdam Zuid	Extension	2027
• Meteren - Boxtel	4 tunneled tracks near Den Bosch	2030

Figure 3 depicts the expected average occupancy rate of overloaded lines in 2030 and 2040. The map shows the routes where the average occupancy rate of all trains during the busiest hour of the day exceed 90% of their capacity. The figures were made by ProRail and show the bottlenecks in the WLO High scenario in light green and the bottlenecks in both the WLO High and Low scenarios in dark green. These dark green routes, indicating bottlenecks at the routes under both scenarios, were termed by ProRail as 'hard bottlenecks'.

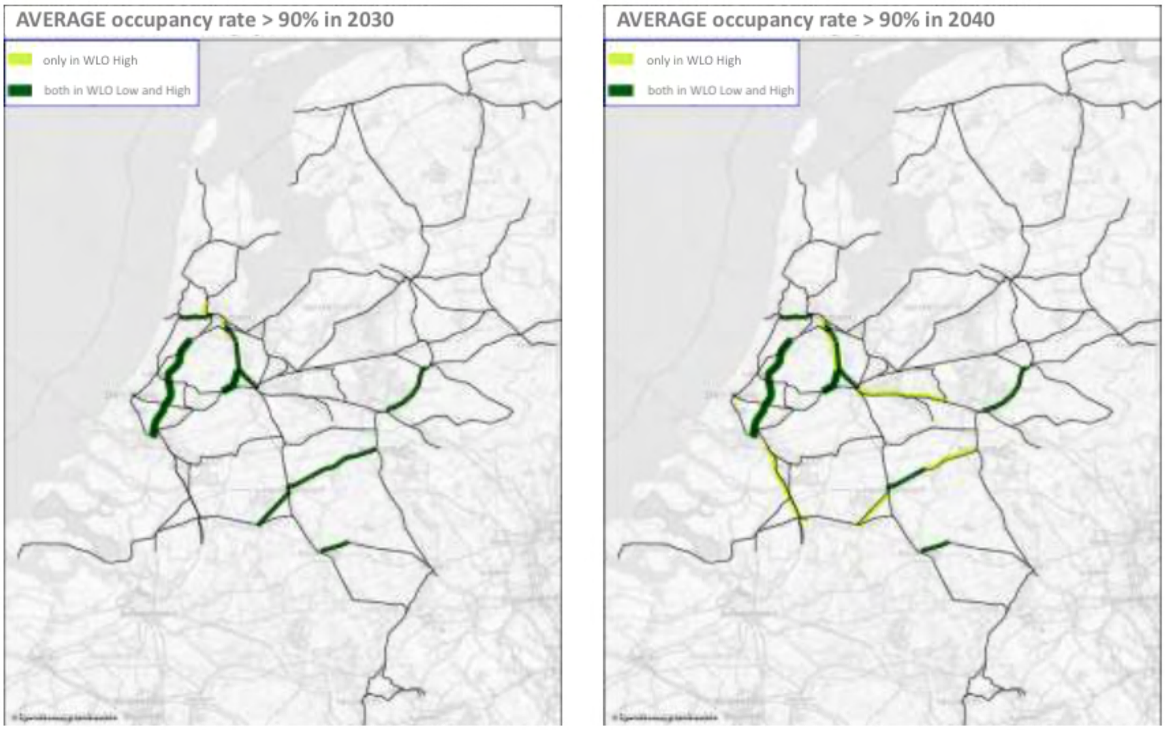

Figure 3: expected bottlenecks for train lines in 2030 and 2040 under the WLO scenarios (ProRail 2017).

The following bottlenecks are expected in both the WLO High and the WLO Low scenarios in 2030 and 2040 (as shown in dark green in *Figure 3*):

Train bottlenecks	**Number of tracks**	**Route length [km]**
• Haarlem - Amsterdam Sloterdijk	2	13.7
• Schiphol - Rotterdam Centraal	2	52
• Utrecht Centraal - Amsterdam Amstel	4	33.4
• Woerden - Breukelen	2	8.3
• Arnhem - Zutphen	2	27.5
• Oss - ‘s-Hertogenbosch	2	18.9
• Helmond - Eindhoven	2	13.2

A combined length of the overloaded rail lines measures 400.8 km (calculated by multiplying the route length by the number of tracks). Thus, the assumed percentage of tracks with bottlenecks in 2040 is set at 6.7% (when taking 400.8 km as a percentage of the total train track length in 2018 of 5941 km that was only used for passenger transport).

In 2030, also the line Tilburg - Nijmegen is expected to be overloaded, which brings:

- Tilburg - Nijmegen 2 65.9

to an assumption of 8.6% overloading of tracks in 2030 under both scenarios (when taking 513.7 km as a percentage of the total train track length in 2018 of 5941km that was only used for passenger transport).

For cargo, it is expected that bottlenecks until 2040 for both a high and a low scenario will be located between Duivendrecht - Amersfoort and Utrecht - Amersfoort and at the German border near Zevenaar. Re-routing the freight trains via Venlo is mentioned as an option to alleviate the bottleneck (ProRail 2017). In general, the expected demand for freight transport via rail should be able to be accommodated with the available infrastructure (Ministerie van I&M 2017).

Transfer capacity at railway stations

The transfer capacity (i.e. the amount of passengers that can be handled) is also expected to be limited at stations in the coming decades. *Figure 4* represents the expected bottlenecks at stations in 2030, out of the current 400 stations, 23% is expected to have capacity problems. 69 stations will suffer from transfer bottlenecks and 24 from severe overloading in their capacity. Since no accurate data on the materials used in larger station constructions was available, the transfer capacity is not used in the material flow analysis of this research.

Figure 4: 69 stations with transfer bottlenecks and 24 severe transfer bottlenecks in 2030. Adapted from ProRail (ProRail 2017).

Potential bottlenecks for tram, light rail and metro after 2030 (Ministerie van I&M 2017)

Expected bottlenecks

- Tram track Rotterdam Erasmus bridge - Rotterdam City Center
- Tram track The Hague Central Station - The Hague Hollands Spoor
- Tram track The Hague Central Station - Madurodam
- Light rail line E Rotterdam - The Hague

The following infrastructure extensions are proposed in the menus in the Development Agenda for 2040:

Proposed train infrastructure extensions

- Extension Noord/Zuid metro line to Schiphol — asap
- Koningscorridor (light rail Scheveningen - Zoetermeer/Delft) — 2040?
- New train stations (Barneveld-Noord, Berkel-Enschot, Staphorst, Veenendaal-Zuid, Woerden-Molenvliet) — 2040?
- Lelylijn (improved connection Randstad to Groningen/Leeuwarden) — 2035
- Double tracks for Sallandlijn (to speed up IC Enschede - Amsterdam) — 2035

- Wunderline (Groningen - Bremen (DE)) 2024?
- IJmeerverbinding (metro line Amsterdam - Almere) 2040?
- Close circle line Amsterdam Metro (Isolatorweg - Centraal Station) 2040?
- Extend Noord-Zuid metro line from Schiphol to Hoofddorp 2040?
- New tram or metro connection to Rotterdam's South Bank 2040?
- Circle light rail line Utrecht (with Merwedelijn & Papendorplijn) 2040?
- Nedersaksenlijn (Stadskanaal - Emmen - Almelo) 2040?

Appendix C: Log-linear Regression Analysis on Rail Lengths with Statistical Tests

This appendix contains the summary output of the log-linear regression analysis on rail lengths (dependent) and billion passenger kilometers per year (independent). The log-linear regression results for 2000-2019 of the transformed passenger kilometers and length of the train network are presented in the table below.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.99803474
R Square	0.99607334
Adjusted R Square	0.99590973
Standard Error	162.79547
Observations	26

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	161348300.3	161348300	6088.07176	2.16957E-30
Residual	24	636056.7618	26502.3651		
Total	25	161984357.1			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-361.64032	81.02040971	-4.4635707	0.00016249	-528.858232	-194.42242	-528.85823	-194.42242
ln(billions_passenger kms)	2548.9351	32.66772537	78.0260966	2.1696E-30	2481.512226	2616.35797	2481.51223	2616.35797

A log-linear relationship between the traveled passenger rail kilometers and the actual network length was observed when drawing a trend line through the scatter plot. Hence, a transformation to a natural logarithm of the x-values (billions_passenger kms) was needed.

The correlation coefficient R gives a very high correlation of .998. The R^2 shows that 99.6% of the variance in *railway length* can be explained by the *passenger kilometers* traveled. The regression coefficient of billion passenger kilometers per year was 2548.93 and significant (t (24) = 78.03; $p < .001$).

The residual plot in *Figure 200* gives the observed values minus the predictions. This plot shows that the values related to the train network (on the right side of the x-axis) are more clustered around the lower digits of the y-axis. The metro and tram data, depicted on the left side of the plot, show much more scattered residuals. This means that the metro and tram observation data fit less well to the predicted data in the trend line than the train data does.

The line fit plot in *Figure 210* shows how well the observations match with the predicted network length. Again, the metro and tram data points in the lower-left side of the plot show more deviations than the train data in the upper right corners of the plot. A less accurate fit with the trend line for metro and tram systems can be explained by the fact that there are less observations used for metro and tram. This smaller number of observations was used because less year data were available on the passenger kilometers traveled for tram and metro. Less observations make accurate predictions more difficult.

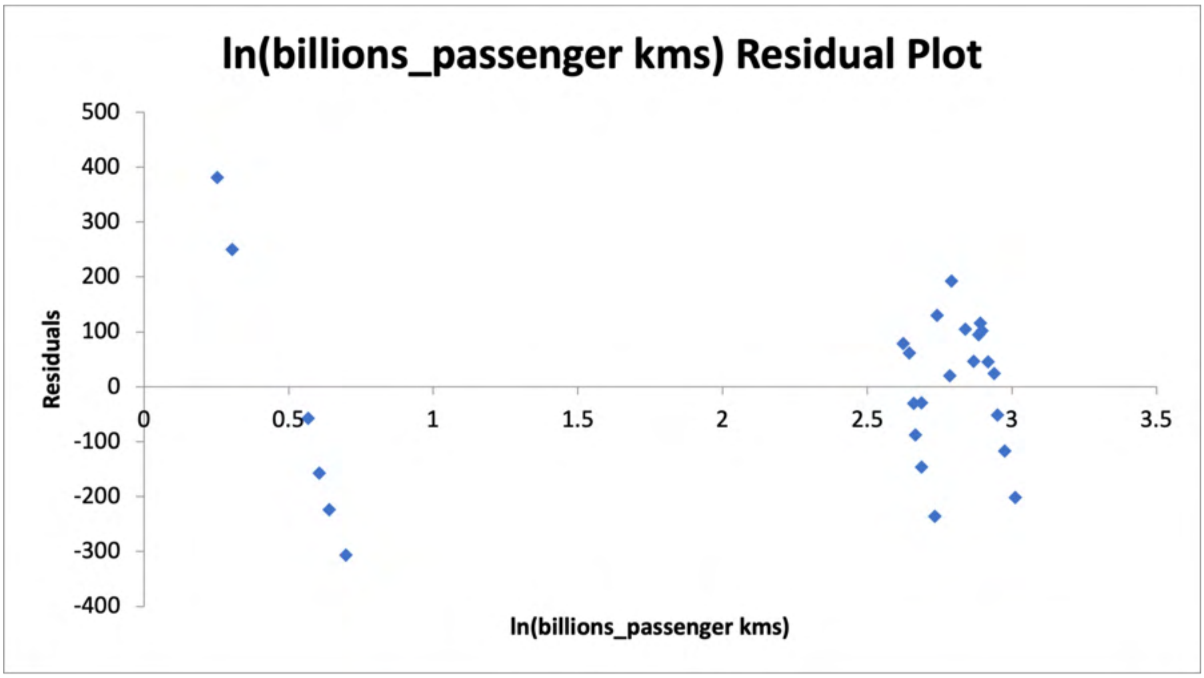

Figure 200: residual plot of the natural logarithm of billion passenger kilometers. The residuals represent the observed values minus the predictions from the trend line.

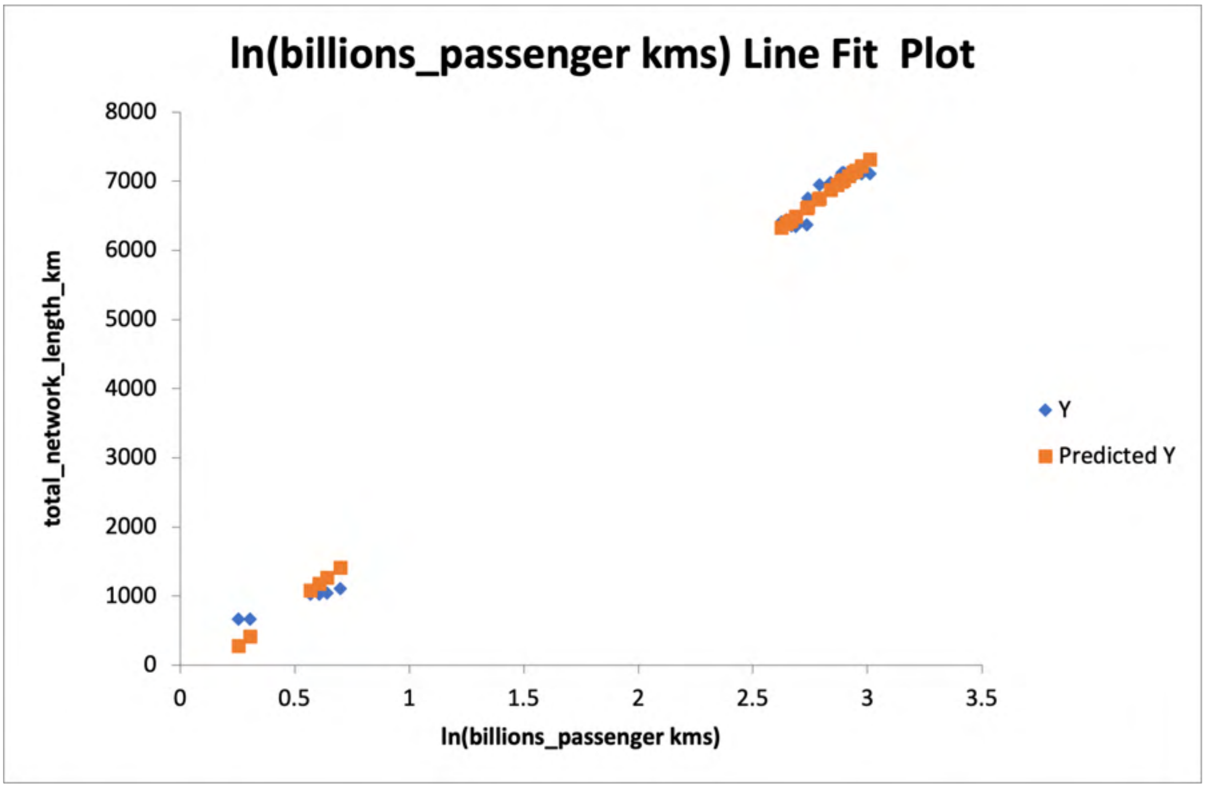

Figure 210: line fit plot of transformed passenger kilometers in relation to rail network lengths in km for the years 2000-2019.

Appendix D: Assumptions on Material Intensities

Based on GIS data and LCAs from ProRail, the following objects have been taken into account:

Train:

- rail tracks, railroad ties, ballast, superstructure power supply (overhead wire, anchor blocks, poles, arms)
- switches and switch heaters
- signal & communication cables
- platforms, platform walls, platform roofs, platform ramps, elevators, staircases

- moveable bridges, elevated positions (rail viaducts), tunnels (also separated in cut-and-cover and tunnel bore machine tunneling techniques), tunnels in stations
- signals, level crossings, buffer stops

Metro, Lightrail & Tram:

- superstructure (incl tracks an power supply)
- stations
- moveable bridges, elevated positions (rail viaducts), tunnels (also separated in cut-and-cover and tunnel bore machine tunneling techniques)

All material intensities, their calculations and their references can be found in the worksheet "material_intensities" in the excel file "Data_Material_Stocks_Rail_Infra_NL".

Rail tracks: - 80% is UIC54 with 54.8 kg steel per meter rail
- 10% is UIC60 (HSL, high speed track) with 60 kg steel per meter rail
- 10% is UIC46 outdated from the 80s with 46 kg steel per meter rail

Considering this share division, the material intensity for 1 average meter railway track (two rails) = 0.0001096 kton/m rail

Furthermore it is assumed that
- 'enkel' in TOP10NL GIS database = 1 rail track
- 'dubbel' in TOP10NL GIS database = 2 rail tracks
- 'meervoudig' in TOP10NL GIS database = 4 rail tracks

Ballast: 1 ton ballast (aggregates) is used for 0.274 meter single track. So per 1 meter of rail track 0.0036497 kton ballast is assumed.

Rail ties: The two most commonly used railroad ties are NS90 concrete tie (assumption that it is used in 90% of track length) and the 14-002 concrete tie is used for heavy load bearing tracks (tight curving tracks, switches, level crossings and engineering works, assumed that they account for 10% of the tracks). Wooden sleepers are left out, because they should all be replaced very soon.

The center-to-center distance for concrete sleepers is 62 cm, so each meter rail holds approx. 1.6129 ties.

Power

Supply: Supporting constructions for traction wire consist of galvanized poles and beams (that include cross braces) and steel reinforced concrete foundations. Anchor blocks are used to get the overhead wires tensioned. Other construction types (e.g. concrete portals) are not considered because of their limited quantities.

Infra & Signal Cables Cables for infrastructure are protected by concrete gutters (cable trays). It was assumed that the same type of cables for signals and communication is used as in Germany, based on Schmied et al. (2013).

Level Crossings For level crossings, primary data from ProRail was used to calculate the mass of level crossing plates that are made of concrete. Because of data limitations, saltires (Saint Andrew's Crosses), crossing lights and barrier gates are not included.

Signals Primary data from ProRail on the pole length and foundations allowed for calculation of the steel and concrete mass of signal structures. Due to data limitations on signal lights, these have been excluded in the calculations.

Switches: The most commonly used types of switches are 1:09 (70%) and 1:15 (15%). In all other cases, it is assumed that switches of the type 1:09 are used. About 6500 of the 8900 switches in The Netherlands are heated. For this reason, switch heaters are also taken into account. The average of two LCAs on different types of switch heaters (used for types 1:09, 1:12 & 1:15) is calculated for the heaters.

Platforms: Concrete used for 30x30 extra heavy load tiles (weighing 12.5 kg each) is calculated based on the surfaces of platforms, platform ramps. Platform wall data was taken from the website from the website of one of the suppliers (Zeus Beton). Sand and soil are not included in the calculations.

Fencing & Noise Barriers Wire mesh fencing is the most commonly used type of fencing. If data is not provided in the data set (<blanks>) it is assumed that this is a wire mesh fence of 1 meter height. ProRail owns a lot of land (surrounding the rail tracks) that is usually equipped with fences, so hence the high numbers.

For noise barriers, 58% is a standard noise absorbing cassette barrier (assumed from aluminium), 33% is made from (wood fiber) concrete. Only 1 % is gabions, but they are still included because of the volume of concrete that they use and their recycling potential.

Buffer stops It is assumed that all buffer stops in The Netherlands (about 1700) are the yellow designed buffer stops from Voestalpine Railpro ("Fixstop OK").

Elevated Positions & Bridges Calculations for elevated positions (non movable bridges) and bridges are taken from Gassner et al. (2020). They used the same material intensities for rail engineering constructions.

Tunnels Calculations for tunnels (cut-and-cover and tunnel bore machines) are taken from Gassner et al. (2020). They used the same material intensities for rail engineering constructions.

Stations Material intensities for train stations in Vienna are used from Gassner et al. (2020)

Metro, Lightrail & Tram

Same as in Vienna (based on Gassner et al., 2020):

- Tunnel constructions (cut-and-cover tunneling and tunnel bore machine)
- Bridge constructions (elevated positions and moveable objects)
- Material intensities for metro & tram superstructure (incl. power supply) and stations

Appendix E: Material Developments per Pathway

This appendix gives more detailed information on the material developments per pathway for each year in the period 2000 - 2050.

Transition Pathway 1: Stagnation

In the reference pathway, the growth of the railway network comes to a halt as a stabilization and in 2050 even a small drop in rail passenger kilometers is assumed in accordance with the WLO Low scenario. This means that the materials that are used in the system will reach a plateau that continues to support maintenance flows. *Figures 43a-d* give the stock, inflows and outflows per material category for the period 2020-2050.

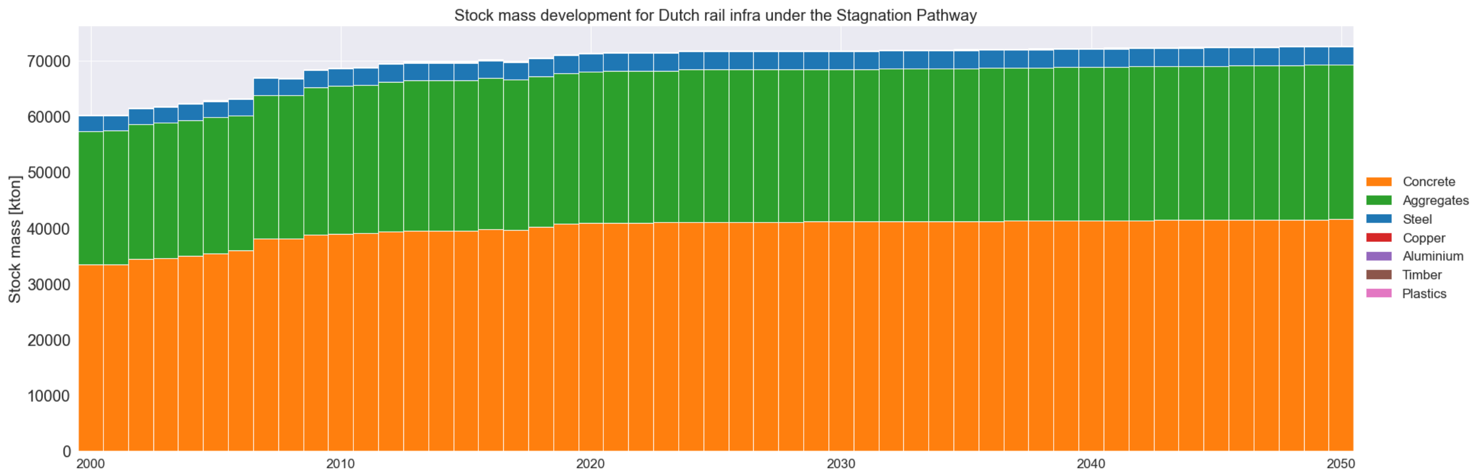

Figure 43a: stock mass development under the Reference Pathway.

The largest share of materials in the Stagnation Pathway remains concrete, followed by aggregates (ballast) and steel. The total concrete stock in 2050 and 2018 is 57% of the total. Aggregates for both years share 38% of the stock. Steel accounts for 4.5% of the material stock in both years.

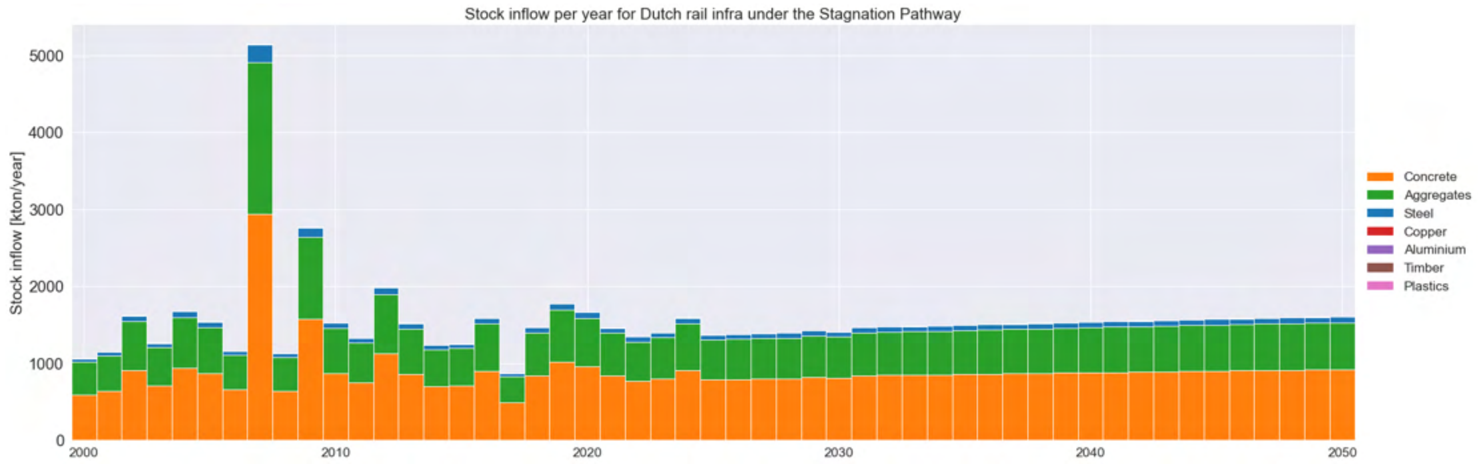

Figure 43b: annual inflows under the Reference Pathway. Note the high inflow in 2007 (opening Betuwelijn) and 2009 (HSL).

Between 2020 and 2030 the inflows follow the budgeted extensions as planned by the government. After 2030, the inflows slowly increase each year to accommodate the engineering work for the structures that reach the end of their useful life.

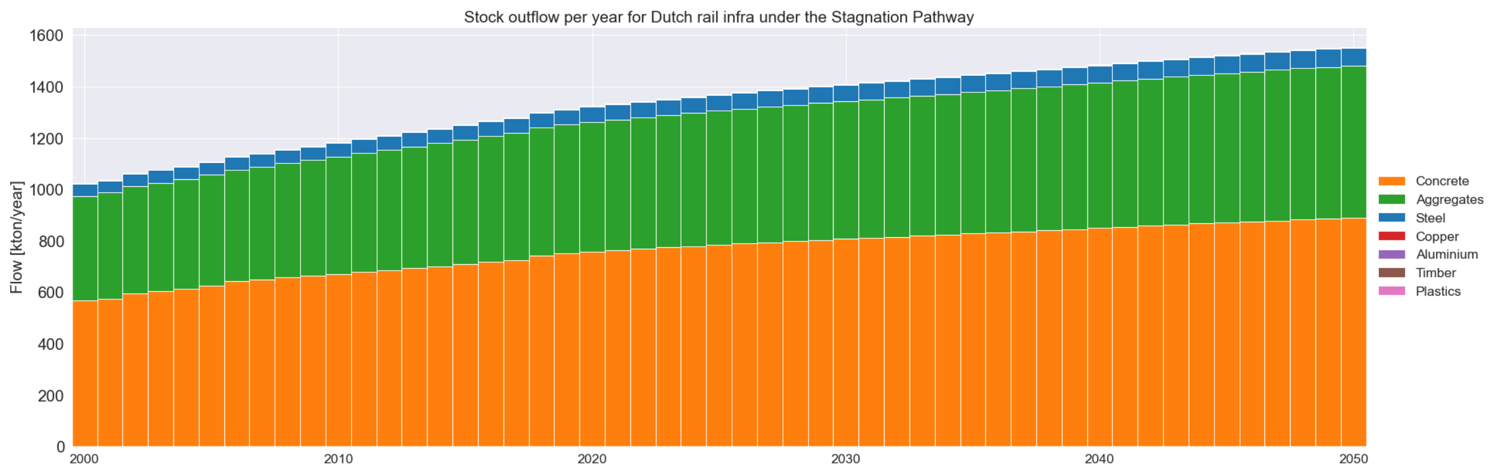

Figure 43c: annual outflows of rail material under the Reference Pathway.

The outflows of materials slowly increase under the Stagnation Pathway too, but always remain under the total inflows of that year. This results in a stabilizing stock. Note that the scale in *Figure 43c* is different from *43b.* Yet invisible because of their small share, the outflows for copper, aluminium, timber and plastics are shown in *Figure 43d.* These flows follow the same path as the outflows in *Figure 43c*. Since no changes in shares are expected for these materials in all the pathways, this is the only figure where they are shown separately.

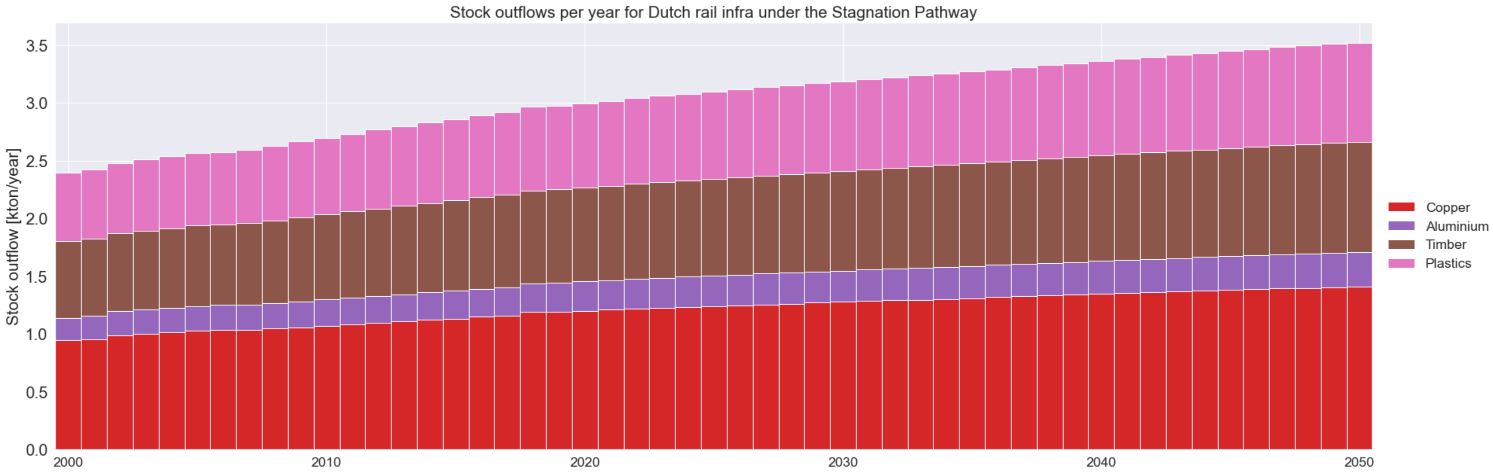

Figure 43d: detail of the annual outflows of smaller material stock quantities in the Stagnation Pathway. Note the scale difference on the y-axis.

Transition Pathway 2: Reconfiguration

The Reconfiguration Pathway is characterized by the proposed measures from the Ministry of Infrastructure and Watermanagement to make the Dutch railway infrastructure circular. When these measures are implemented, the stock, inflows and outflows for 2050 will have an increased concrete share of 57.5% compared to 57% in 2018. This is due to the proposed replacement of level crossings by small tunnels. Also, the aluminium and timber shares rose slightly from 0.0192% to 0.0199% and from 0.0617% to 0.0636% of the total mass respectively. This increase can be explained by the increase of noise barrier constructions.

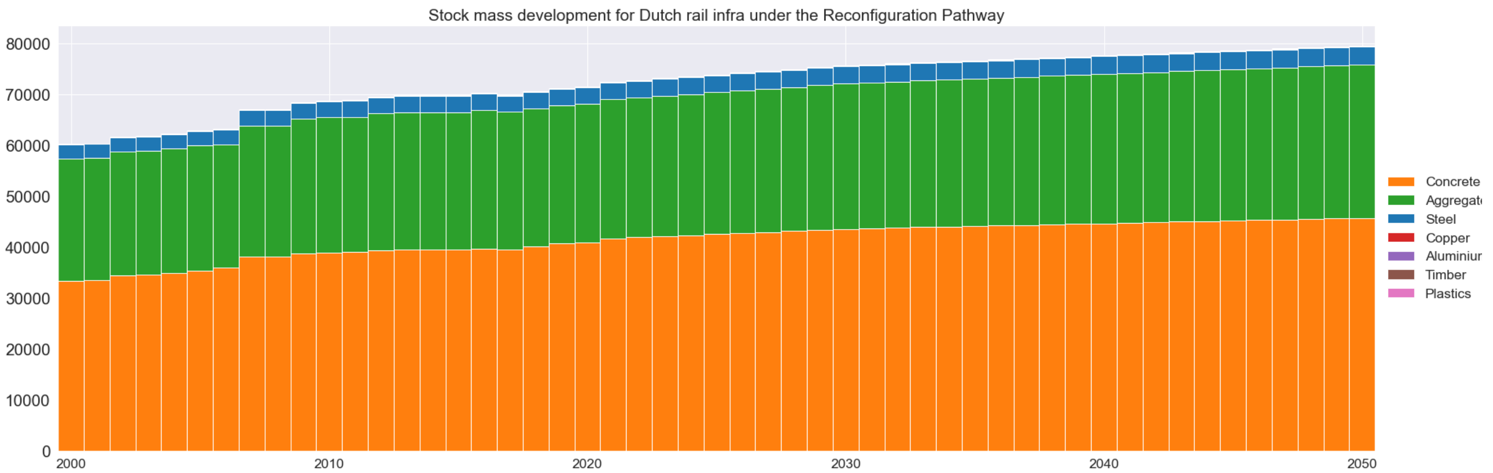

Figure 44a: stock mass development under the Reconfiguration Pathway.

The mass stock in *Figure 44a* develops faster than all other pathways between 2020 and 2030 but slows down after 2030 until it reaches the same level as the De- and Realignment and Substitution High Pathways in 2050. This is because it is expected that these three pathways will have a similar track length in 2050 (see *Figure 42*).

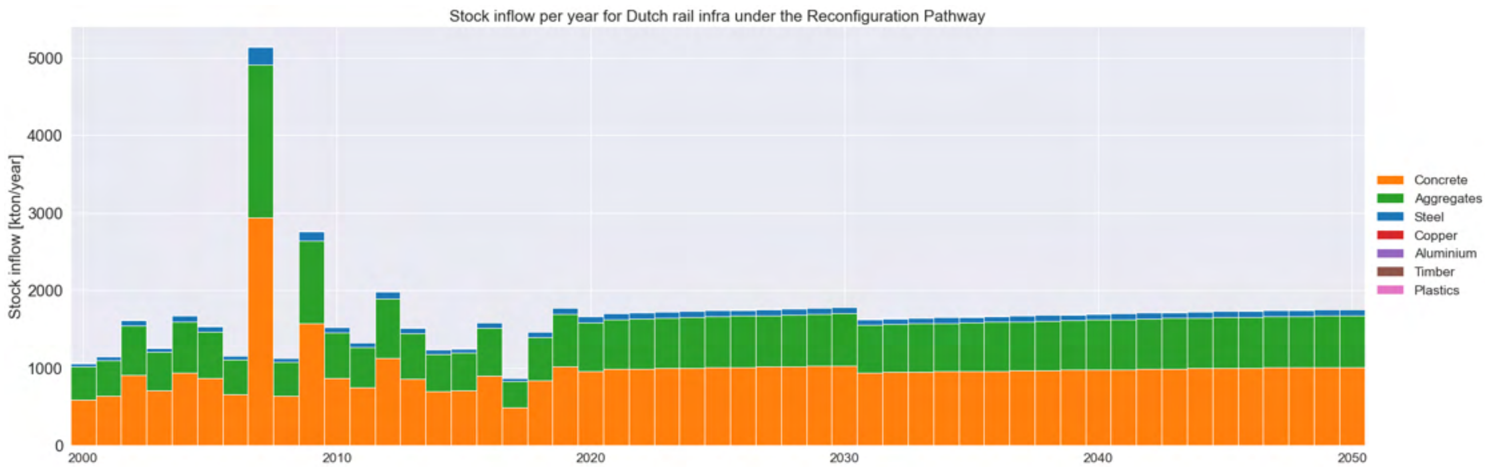

Figure 44b: annual inflows under the Reconfiguration Pathway. Note the high inflow in 2007 (opening Betuwelijn) and 2009 (HSL).

The mass inflows in *Figure 44b* show a relatively high inflow between 2020 and 2030 because of the proposed extension of 5% of the network by 2030. After 2030, the inflow slows down but remains larger than the Stagnation Pathway. Since the inflows keep consistently higher than the outflows between 2030 and 2050, the total stock will keep growing.

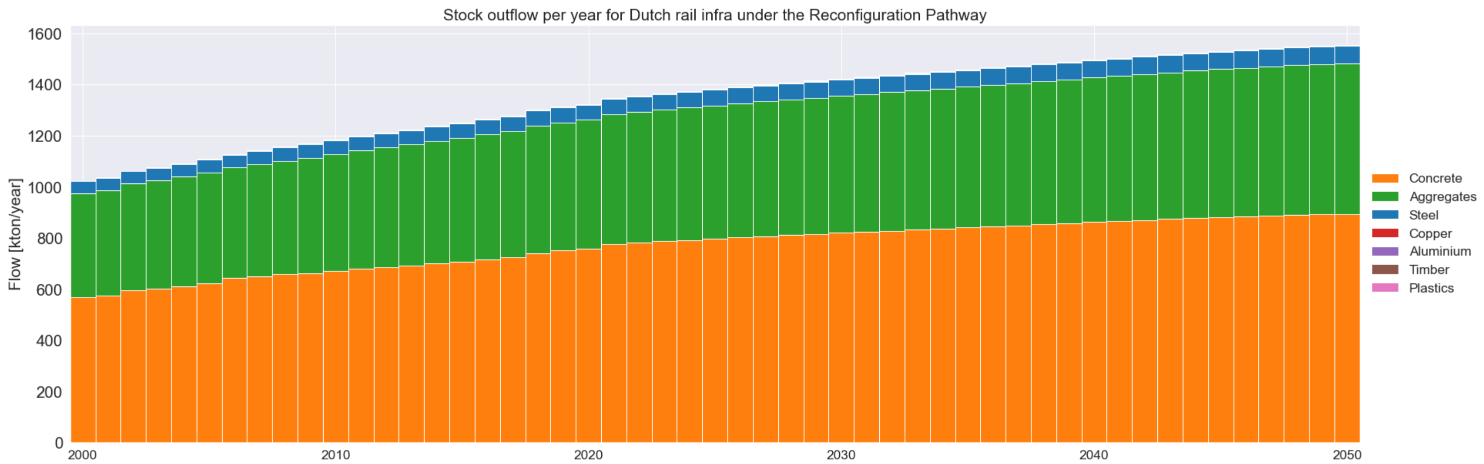

Figure 44c: annual outflows of rail material under the Reconfiguration Pathway.

The outflows between 2020 and 2050 are a bit higher in the Reconfiguration Pathway than for all the other pathways, because the early start of the expansion of the network with 5%

causes a higher maintenance flow. This is because the normal distribution also assumes that in the first years after construction, a very small share of the objects is already demolished.

In general, the Reconfiguration Pathway leads to higher material inflows, outflows and a higher stock than the Stagnation Pathway. The share of concrete, aluminium and timber increases slightly in this pathway as a consequence of the new tunnels that should replace level crossings and newly built noise barriers.

Transition Pathway 3: Transformation

The Transformation pathway shows many similarities with the Stagnation Pathway, since the same WLO Low passenger rail kilometers were assumed. However, the outflows in this pathway are lowest in 2050 in comparison with all the other pathways, because it is assumed that the lifespan of the infrastructure can be extended by 30%.

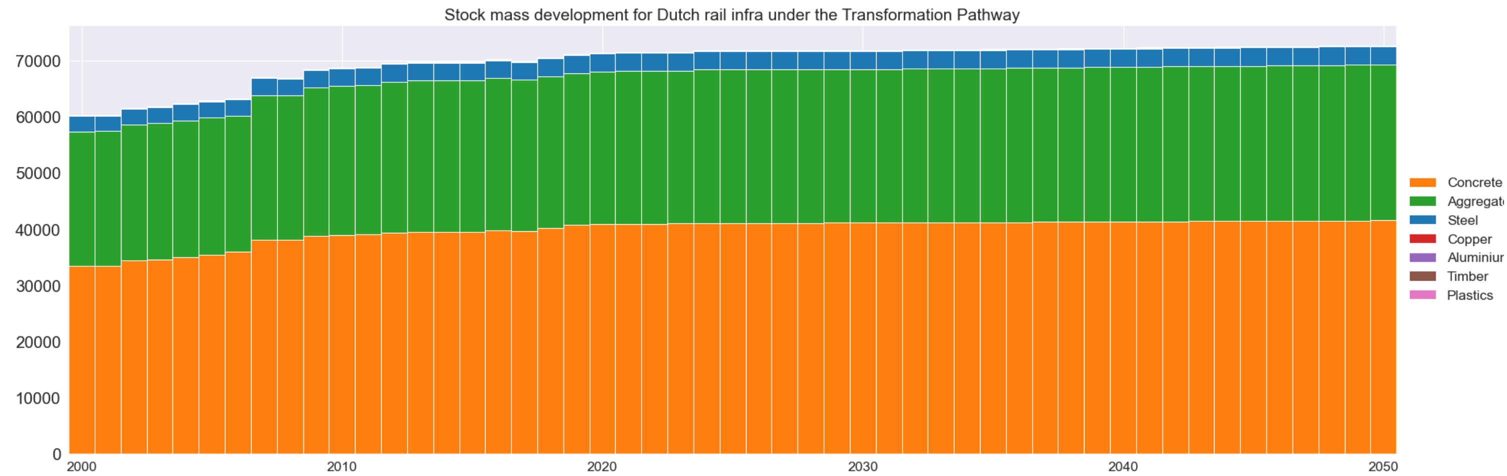

Figure 45a: stock mass development under the Transformation Pathway.

The material percentages remain the same in this pathway as in the Stagnation Pathway. Since the track length is estimated to be the same as the Stagnation Pathway in 2050, the material stock is equal to this pathway too.

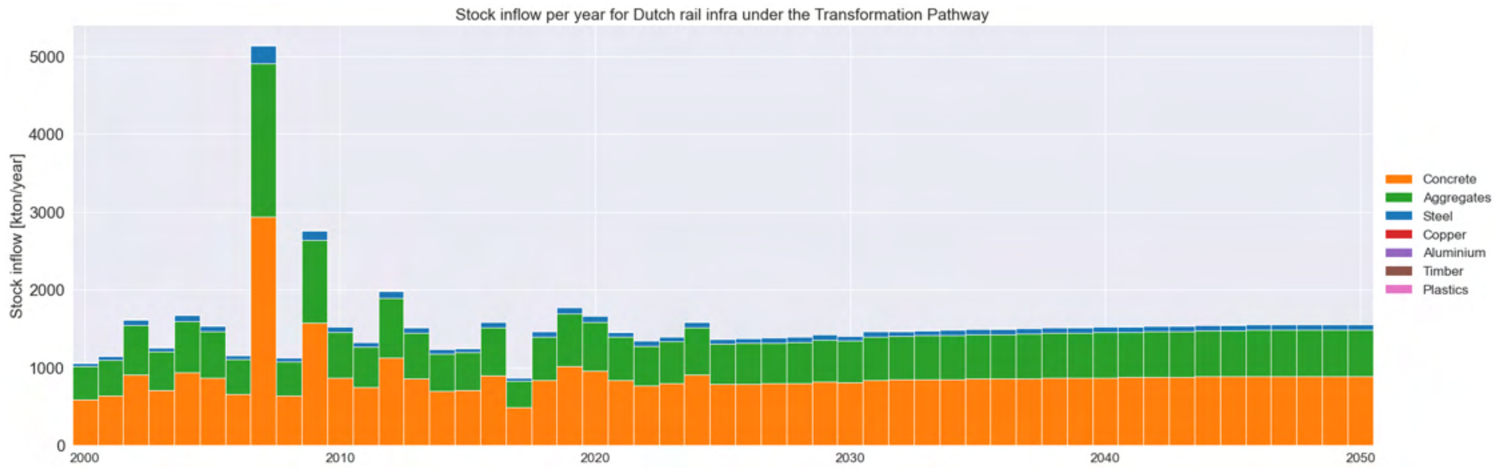

Figure 45b: annual inflows under the Transformation Pathway. Note the high inflow in 2007 (opening Betuwelijn) and 2009 (HSL).

Inflows get slightly smaller towards 2050 compared to the Reference Pathway, since the longer lifespan demands less inflowing materials. Although the difference with the Reference Pathway is very small.

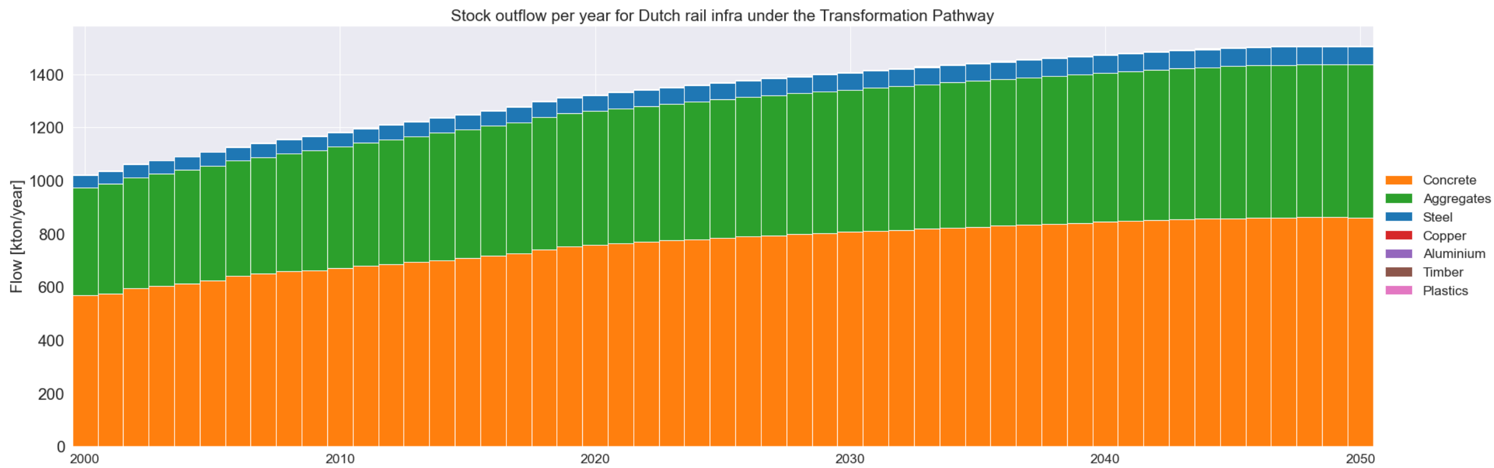

Figure 45c: annual outflows of rail material under the Transformation Pathway.

The outflows between 2020 and 2050 are smaller than the Reference Pathway, because the assumed 30% longer lifespan of rail constructions brings the average of the total stock to 51.9 years from 2021. Assuming a normal distribution, this means that the outflows slightly decrease after 2021 compared to the Reference Pathway.

Transition Pathway 4: De- and Realignment

Characteristics for the De- and Realignment Pathway are a high growth between 2030 and 2050, triggered by the increased number of rail passenger kilometers taken from the WLO

High scenario. Before 2030, the mass inflows are typically smaller. This is a result of the 20% lower material intensities for newly constructed infrastructure from 2021 onwards.

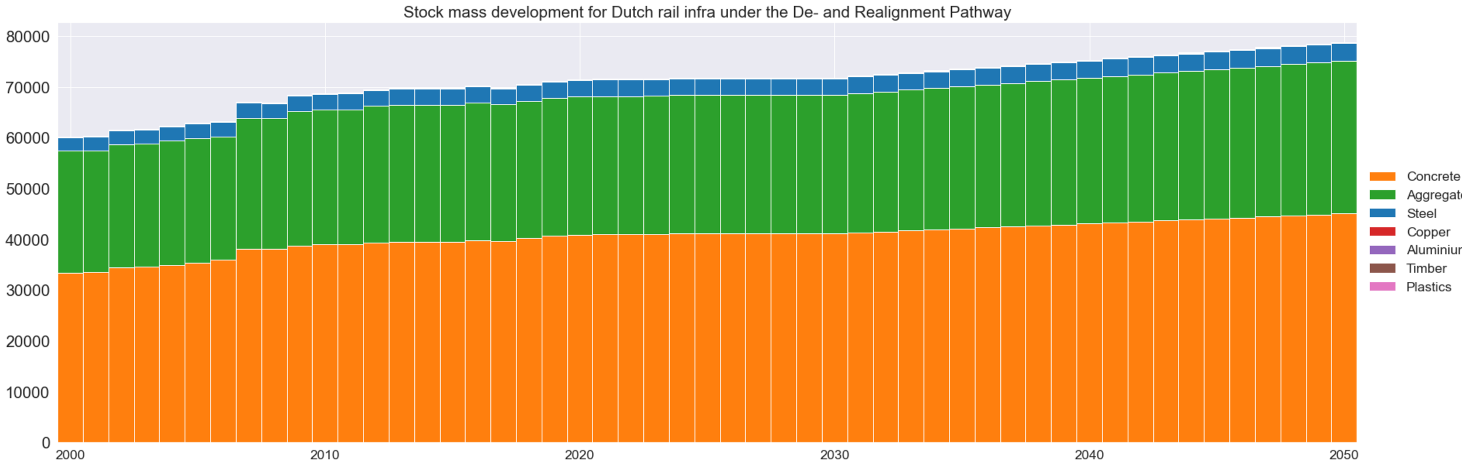

Figure 46a: stock mass development under the De- and Realignment Pathway.

The division of materials is the same in this pathway as in the Stagnation Pathway, as no specific material shares are expected to change, it is only assumed that the material intensity of all materials will be lower from 2021 onwards, due to improvements in the material use in new constructions. For example, by directly reusing materials on site that have flown out from engineering works.

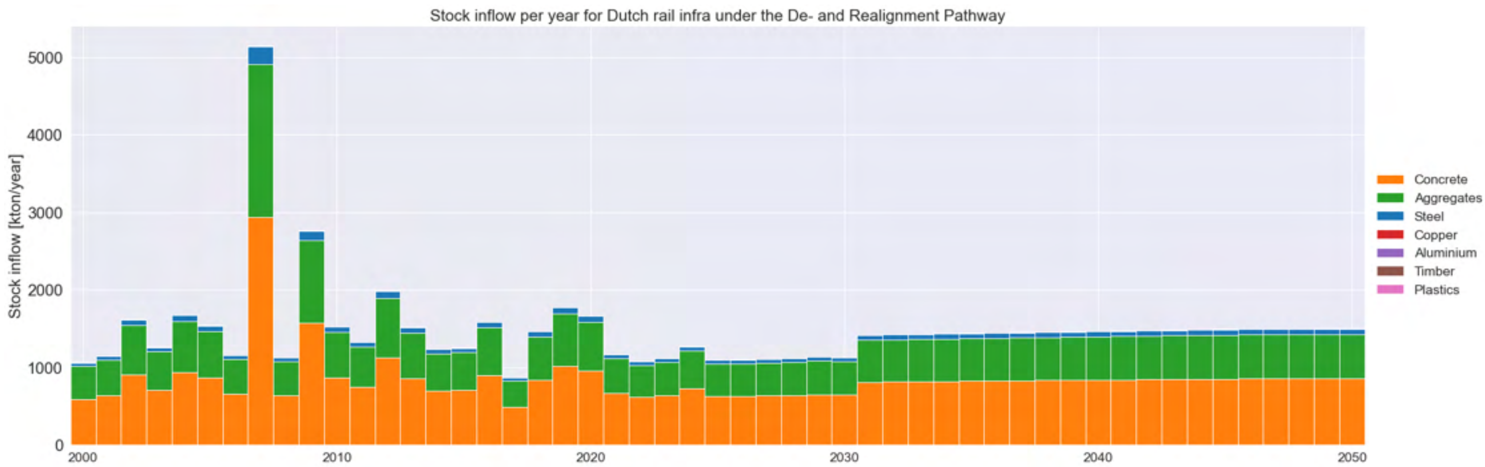

Figure 46b: annual inflows under the De- and Realignment Pathway.

While the total stock is leading to the same endpoint as the Reconfiguration Pathway, this pathway assumes -20% material intensities, which strongly reduces the annual material inflows compared to the Reconfiguration Pathway. Since the length of the network is expected to grow between 2030 and 2050 due to more passenger kilometers, the inflows rise again after 2030.

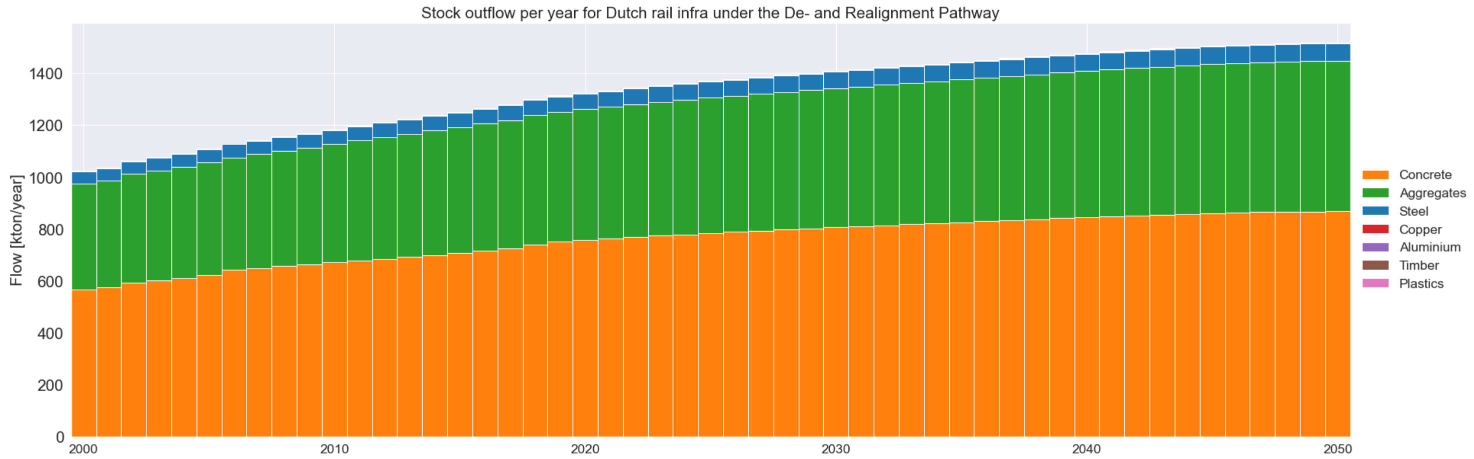

Figure 46c: annual outflows of rail material under the De-and Realignment Pathway.

The De- and Realignment Pathway demonstrates a smaller outflow of materials than most other pathways (except the Transformation Pathway), because of the longer lifespan of 25% of rails which leads to an average construction lifetime of 51 years.

Transition Pathway 5: Substitution Low

The Substitution Low Pathway is based on one driving force: a long-term decrease of passenger kilometers that moves from 100% in 2019 to 50% from 2020 until 2050. The effects of this drop are expected to be visible after 2030, when there is more uncertainty about the financial support to maintain the infrastructure.

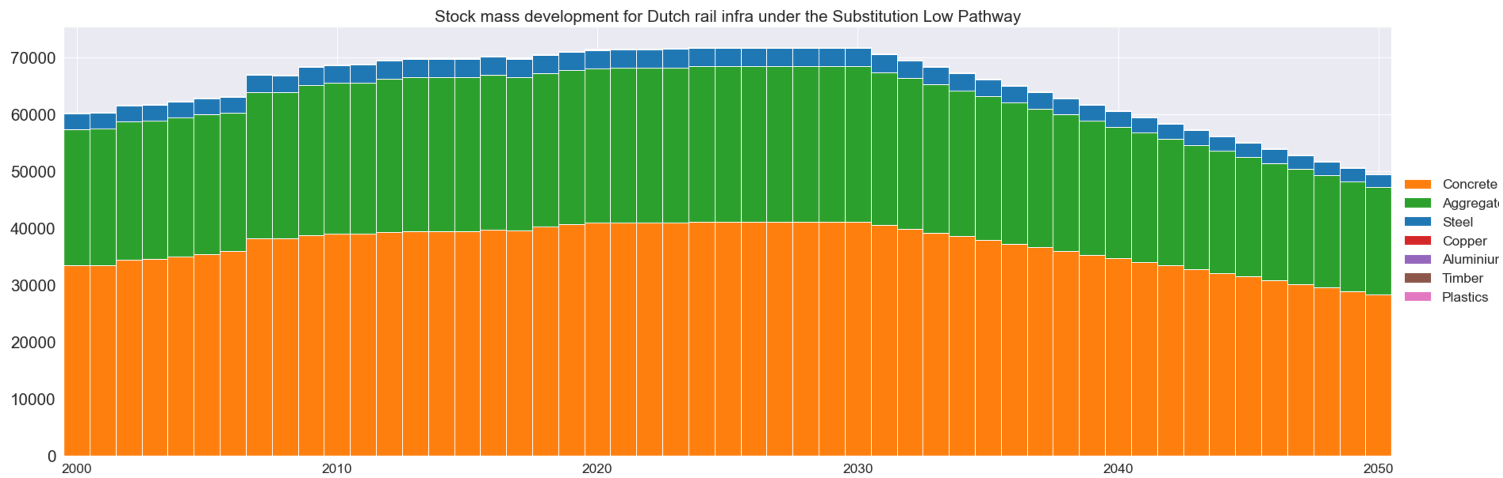

Figure 47a: stock mass development under the Substitution Low Pathway.

The stock in *Figure 47a* is reduced by almost 30% in 2050 compared to 2030, because the continuous drop in passenger kilometers leads to suspension of railway lines. Since it is unknown how many lines will be closed and in which year, it is assumed that the stock is reduced with the same size every year from 2030 until 2050. The endpoint for 2050 is derived from the logistic trend line in the methods chapter that showed the annual rail passenger kilometers in relation to the total network length.

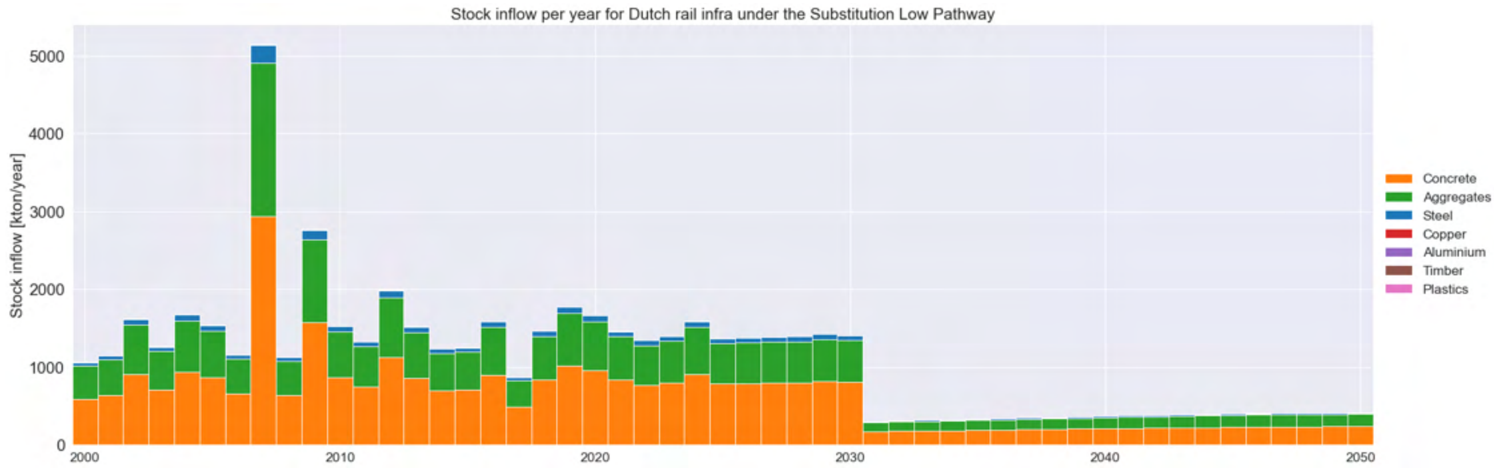

Figure 47b: annual inflows under the Substitution Low Pathway.

Figure 47b shows the inflows under the Substitution Low Pathway. Until 2030, this pathway follows the same inflows as the Stagnation pathway. After 2030, the outflow of materials is going much faster than the inflows. The only inflows that are visible after 2030 are used for maintenance of the remaining infrastructure, and are therefore very small.

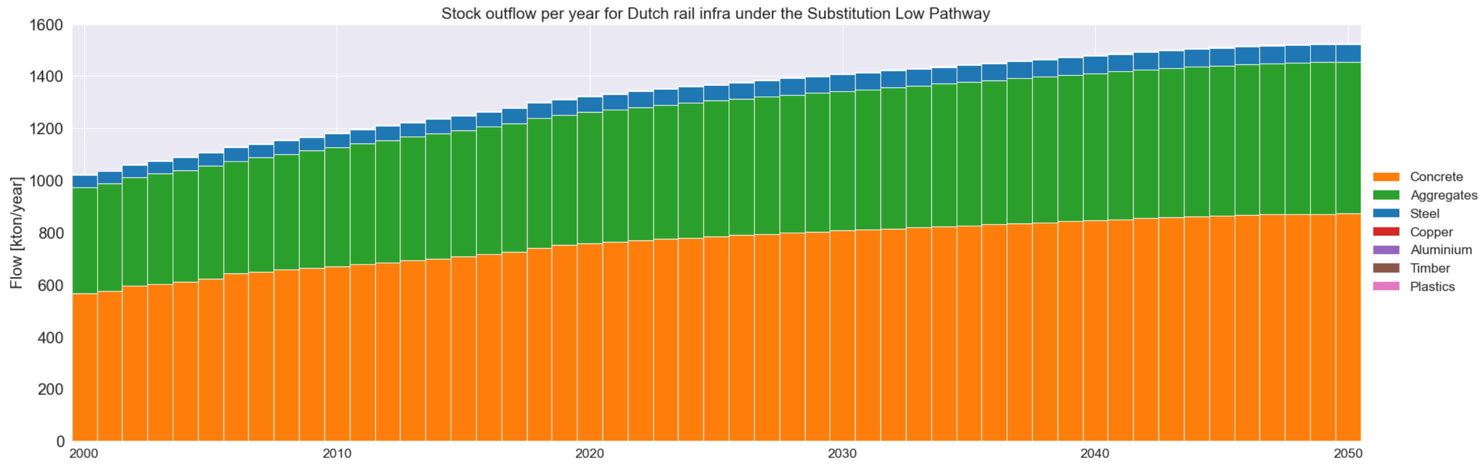

Figure 47c: annual outflows of rail material under the Substitution Low Pathway.

The flows in *Figure 47c* show a robust annual outflow of materials that reduces the total stock when it is bigger than the inflow, between 2030 and 2050. Compared to the other pathways, this absolute outflow is smaller in 2050 than the Stagnation pathway, because the stock will by then already be a lot smaller than in the Stagnation Pathway.

Transition Pathway 6: Substitution High

The Substitution High Pathway shows what happens to the material stock and flows if the rail passenger kilometers double in 2050 compared to 2019. To accommodate for this growth, network extensions will be needed.

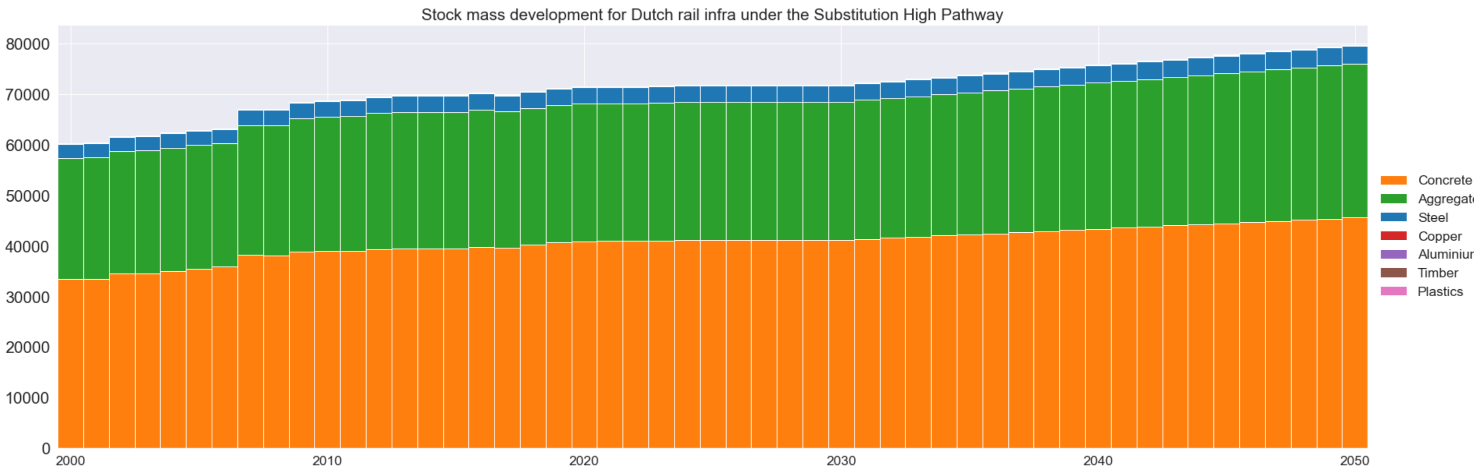

Figure 48a: stock mass development under the Substitution High Pathway.

The stock development in the Substitution High Pathway follows the same path as the Stagnation Pathway until 2030. After 2030, the annual stock growth follows the De- and Realignment Pathway, that assumes a similar total track length by 2050.

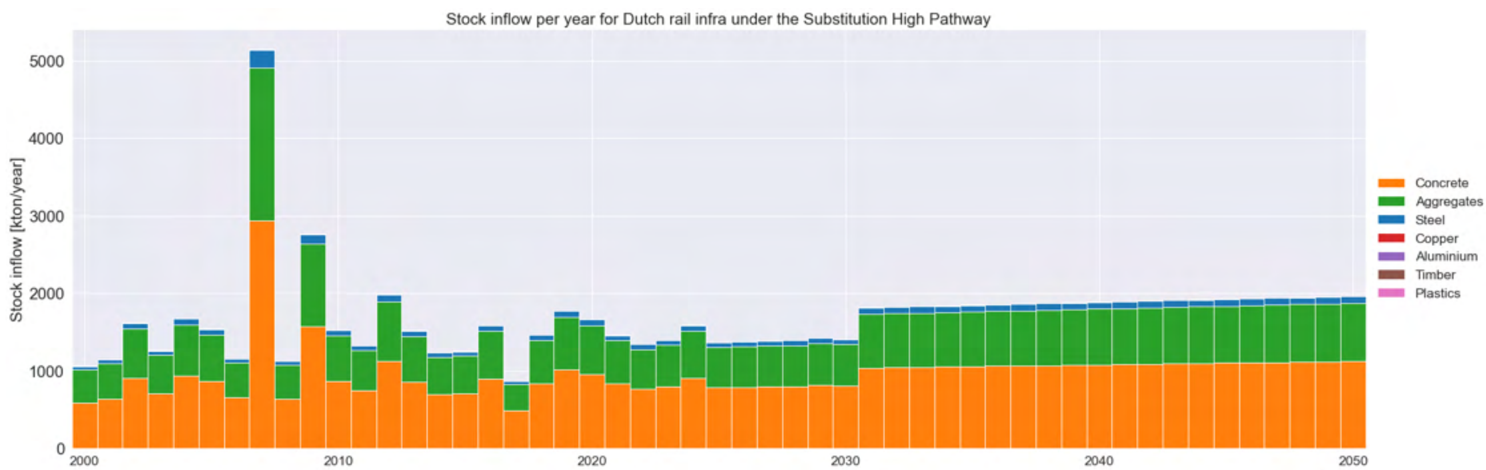

Figure 48b: annual inflows under the Substitution High Pathway.

Figure 48b depicts the annual inflows of materials for the Substitution High Pathway. Until 2030 it follows the same flows as the Stagnation Pathway. Between 2030 and 2050, the Substitution High Pathway requires a stable increase of inflows, since these are the decades in which construction works are expected to take place to cope with the growing number of rail passenger kilometers.

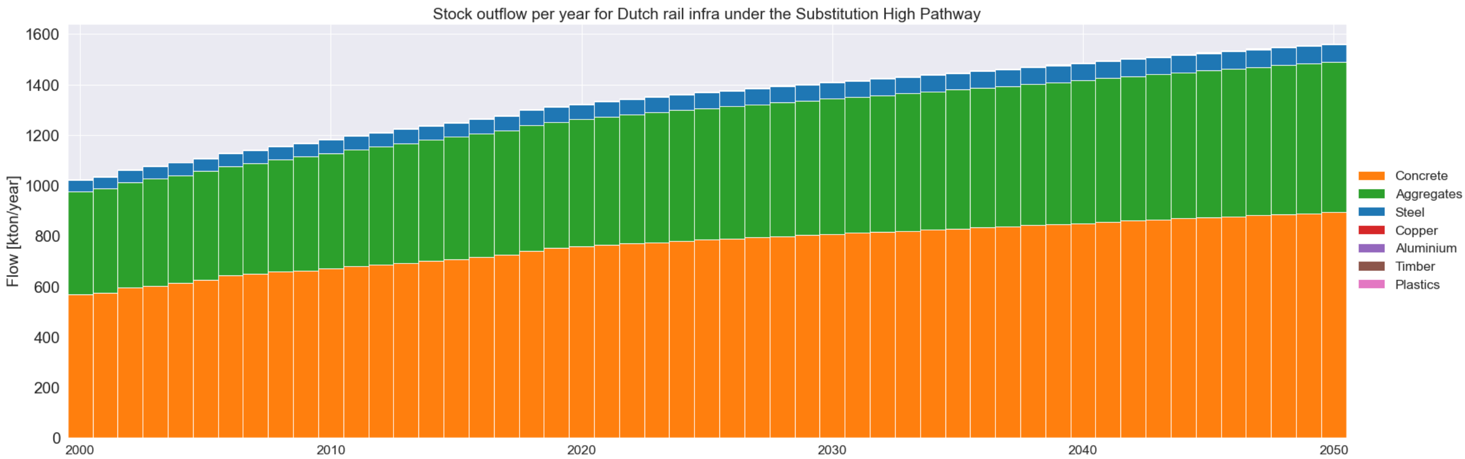

Figure 48c: annual outflows of rail material under the Substitution High Pathway.

Figure 48c does not show much difference with the outflows from Stagnation Pathway, because the growth of the network does not yet lead to a bigger outflow. In 2050, the first results of the network extension become visible in the outflows, when the Substitution High outflow overtakes the outflows from the other pathways. This development can be explained by the larger network from 2030 onwards. The higher inflow of infrastructure needs more replacements in 2050 than the other pathways that assume a smaller rail infrastructure network.

Appendix F: Material Intensities for Railway Objects

This table provides the material intensities for each material category in a railway related object. The intensities are expressed in kilotons per kilometer and were calculated by dividing the total stock weight over the track length for the networks in The Netherlands. Each transport mode (marked in bold) represents the sum of all objects of that mode.

	Concrete	**Aggregates**	**Steel**	**Copper**	**Aluminium**	**Timber**	**Plastics**
	kton/km	kton/km	kton/km	kton/km	kton/km	kton/km	kton/km
train	**3.55E+00**	**3.65E+00**	**3.48E-01**	**6.93E-03**	**1.47E-03**	**6.13E-03**	**5.51E-03**
train_tracks	7.31E-01	3.65E+00	1.78E-01	0.00E+00	0.00E+00	2.38E-03	1.96E-03
train_tunnels_bridges	2.50E+00	0.00E+00	1.33E-01	0.00E+00	7.38E-04	0.00E+00	0.00E+00
train_power_supply	8.13E-02	0.00E+00	1.56E-02	2.44E-03	0.00E+00	0.00E+00	0.00E+00
train_infra_cables	6.39E-02	0.00E+00	0.00E+00	4.42E-03	0.00E+00	0.00E+00	3.00E-03
train_switches	3.96E-02	0.00E+00	1.57E-02	0.00E+00	0.00E+00	5.02E-04	2.96E-04
train_switch_heating	2.96E-04	0.00E+00	2.38E-04	6.65E-05	2.22E-06	0.00E+00	3.92E-05
train_platforms	8.65E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
train_platform_roofs	1.35E-03	0.00E+00	2.61E-03	0.00E+00	2.91E-04	1.88E-03	1.62E-04
train_elevators_stairs	2.36E-02	0.00E+00	1.80E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
train_noise_barriers	1.48E-02	0.00E+00	2.56E-03	0.00E+00	4.36E-04	1.37E-03	4.94E-05
train_signals	1.11E-03	0.00E+00	5.70E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
train_level_crossings	9.08E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
train_buffer_stops	0.00E+00	0.00E+00	2.10E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
metro	**3.26E+01**	**2.53E+00**	**1.94E+00**	**5.93E-02**	**8.19E-03**	**0.00E+00**	**0.00E+00**
metro_tracks_and_power	8.36E-01	2.53E+00	2.80E-01	5.93E-02	0.00E+00	0.00E+00	0.00E+00
metro_tunnels_bridges	3.17E+01	0.00E+00	1.66E+00	0.00E+00	8.19E-03	0.00E+00	0.00E+00

lightrail	**9.62E+00**	**5.31E-01**	**3.69E-01**	**1.37E-03**	**2.07E-03**	**0.00E+00**	**0.00E+00**
lightrail_tracks_and_power	5.42E+00	5.31E-01	1.28E-01	1.37E-03	4.46E-04	0.00E+00	0.00E+00
lightrail_tunnels_bridges	4.20E+00	0.00E+00	2.41E-01	0.00E+00	1.62E-03	0.00E+00	0.00E+00
tram	**7.51E+00**	**5.45E-01**	**2.39E-01**	**1.37E-03**	**1.06E-03**	**0.00E+00**	**0.00E+00**
tram_tracks_and_power	5.44E+00	5.45E-01	1.28E-01	1.37E-03	4.52E-04	0.00E+00	0.00E+00
tram_tunnels_bridges	2.07E+00	0.00E+00	1.11E-01	0.00E+00	6.04E-04	0.00E+00	0.00E+00